Journal of Posthumanism
2024
Volume: 4, No: 3, pp. 2318–2332
ISSN: 2634-3576 (Print) | ISSN 2634-3584 (Online)
posthumanism.co.uk

DOI: https://doi.org/10.63332/joph.v4i3.4137

Dynamic Cone Penetrometer and California Bearing Ratio Correlation for Andean Volcanic Subgrades: Local Calibration Study and Application to Mountain Road Design in Southern Colombia.

Jhon Henry Hernandez Ortiz[1], Edwin Vladimir Rivera Canacuan[2], Jorge Luis Argoty Burbano[3]*

Abstract

Adequate geotechnical characterization of subgrade bearing capacity on secondary and tertiary mountain roads represents an ongoing challenge in resource-limited contexts, where the cost and logistical complexity associated with conventional in situ California Bearing Ratio (CBR) testing significantly restrict the number of characterization points. This work documents the calibration and statistical validation of an empirical correlation between the dynamic cone penetration index (PDC INV-172) obtained through an 8-kilogram dynamic cone penetrometer and in situ CBR values measured according to Colombian technical standards (INV E-169), specifically developed for silty-sandy volcanic soils in the Andean Nariño region. Through execution of 18 paired tests along the road sections Pasto-Jongovito and Pasto-Obonuco (approximately 4 km), a dynamic penetration index range between 5.40 and 61.00 mm/blow was identified, correlated with undisturbed CBR values ranging from 3.40% to 49.27%. Application of logarithmic regression analysis transformed the relationship into a power-law model of the form CBR = 381.2 × (PDC)−1.05 with Pearson correlation coefficient r = 0.953 and coefficient of determination R² = 0.908, statistically significant at the 5% confidence level using Student's t-test. The model adequately captures the nonlinear behavior between dynamic penetration resistance and bearing capacity, positioning within the upper performance range relative to international correlations reported in the literature. Furthermore, implementation of PDC equipment augments subsurface characterization capacity, strengthening research infrastructure and academic training in Andean pavement geotechnics. The results support PDC as an efficient tool for rapid subgrade evaluation during prefeasibility phases, preliminary design, and quality control of flexible pavements on mountain corridors.

Keywords: *Dynamic Cone Penetrometer (PDC); Penetration index; California Bearing Ratio (CBR); Subgrade; Volcanic soils; Empirical correlation; Flexible pavements; Andean road design.*

Introduction

The quality and resistance of the soils that make up the subgrade are determining factors for the design and durability of the landways. Traditionally, the California Support Ratio (CBR) test has been the standard method for assessing soil bearing capacity, due to its accuracy and international acceptance. However, this procedure requires altered samples, specialized laboratories, and long times, which can delay projects and increase their costs (Osorio Martínez & Casas Gerena, 2013). In contrast, the dynamic cone penetrometer (PDC) offers a practical and economical alternative, allowing in situ measurements that reflect real ground conditions in real time (Peña Marín, 2017).

[1] Universidad de Nariño, Facultad de Ingeniería, Programa de Ingeniería Civil, Pasto, Colombia
[2] Universidad de Nariño, Facultad de Ingeniería, Programa de Ingeniería Civil, Pasto, Colombia
[3] Universidad de Nariño, Facultad de Ingeniería, Programa de Ingeniería Civil, Pasto, Colombia. Email: jlargoty@udenar.edu.co, https://orcid.org/0000-0001-6661-1398

CC BY NC ND

However, for the PDC to be a reliable tool in structural design, it is necessary to establish precise correlations with CBR values, since these relationships can vary according to the composition and geotechnical characteristics of the soil. Recent studies have shown that standard equations do not always fit specific soils, especially in regions with Andean volcanic soils, where mineralogy and texture significantly influence mechanical behavior (Contreras-Ávila & García-García, 2019; De la Cruz Vega et al., 2023). Therefore, the local calibration of these correlations is essential to avoid errors in the dimensioning of pavements, which can result in premature failures or unnecessary costs.

This work focuses on the geotechnical evaluation of the Pasto-Jongovito-Obonuco road section, seeking to establish an adjusted correlation between the penetration index of the PDC and the CBR in situ, in order to optimize the design and maintenance of roads in mountainous areas with soils of volcanic origin

In response to these constraints, rapid and low-cost auscultation techniques have been developed for decades to estimate resistance parameters with acceptable accuracy under real field conditions. Among these alternatives, the dynamic cone penetrometer (PDC or DCP) has acquired special relevance due to its portability, ability to generate continuous profiles of resistance to penetration, reduced execution time, minimal personnel requirements and reasonable initial equipment cost. The PDC has been incorporated into Colombian technical regulations (INV E-172) as a valid tool for the evaluation of subgrade, sub-base and base layers in shallow pavements, formally recognizing its applicability under controlled field conditions.

However, the potential of the PDC for rapid estimation of bearing capacity depends critically on the availability of robust empirical correlations between the dynamic penetration index DCPI or ND, expressed in mm/stroke, and the CBR for soils representative of the geographical area of interest. Since the 1970s, multiple correlations have been reported in the international technical literature (Alva and Tupia, 2001), most of which adopt logarithmic potential forms of the type $\log(CBR) = \alpha + \beta \times \log(DCPI)$, whose α and β parameters vary significantly according to the type of soil, the range of granulometry, the state of moisture, and local soil factors. Systematic review studies have documented that the extrapolation of generic correlations beyond the contexts for which they were calibrated introduces appreciable biases that can lead to over- or under-dimensioning of pavement structures, with significant economic and safety consequences.

In the specific context of the department of Nariño, located in the mountainous southwest of Colombia, silt-sandy subgrades derived from volcanic materials and colluvion influenced by Andean geomorphological processes predominate, with particular mineralogical and granulometric characteristics that differ from typical soils of other regions of Colombia and from internationally studied materials. These soils are remarkably sensitive to variations in moisture, moderate contents of clay minerals of low plasticity, presence of altered volcanic ash, and fragile structures that degrade under wetting-drying cycles. Consequently, PDC-CBR correlations developed for materials from other regions may not be directly applicable without local validation, perpetuating the information gap that limits informed design decisions for regional road projects.

The present work is aimed at closing this gap through a systematic case study that executes paired tests of PDC and CBR in situ at 18 points strategically distributed along a representative Andean road section such as the Pasto Jongovito and Pasto Obonuco road, approximately 4 km in length), then a local record of unaltered DCP and CBR pairs is generated. A representative model of volcanic silt-sandy soils of the areas surrounding the city of Pasto under natural humidity conditions is calibrated, a nonlinear (potential) regression model is calibrated that relates these variables and validates their statistical significance through hypothesis analysis and proceeds to compare the proposed local correlation with models reported in the international literature. evaluating their relative performance and delimiting their range of applicability. This combined approach of scientific contribution with transfer of research infrastructure and human capital training is valued by high-impact engineering journals that publish research aimed at strengthening professional practice and regional technical capacity in development contexts.

THEORETICAL FRAMEWORK

Methods for Evaluating the Bearing Capacity of Subgrades

The strength of the subgrade is the foundational parameter for estimating thicknesses of flexible pavement structure according to widely disseminated methodologies such as that of the Asphalt Institute, the AASHTO (American Association of State Highway and Transportation Officials), and contemporary mechanistic-empirical procedures.

The CBR (California Bearing Ratio), defined as the ratio expressed as a percentage between the load produced by a standard penetration (typically 2.54 mm or 0.1 inch) in the soil under study and the load required to produce equal penetration in a reference material normalized to a crushed stone pattern curve, synthetically captures the ability of a soil to resist compressive deformations under quasi-statically applied point loads.

Although the CBR as an index has conceptual limitations recognized in the international technical literature, it does not discriminate between failure mechanisms, it does not incorporate load time effects, it is not invariant with respect to the state of moisture, its simplicity of execution, availability of equipment in laboratories, and decades of empirical correlation with the performance of constructed pavements have consolidated it as a de facto standard in regional and national professional practice. Colombian regulatory frameworks, specifically the National Institute of Roads (INVÍAS), have adopted the CBR as a reference parameter in flexible pavement design methodologies.

CBR determination can be performed in the laboratory under standardized conditions with samples remolded to specified densities, under controlled saturation, or in situ on undisturbed soil under natural moisture conditions, allowing the capture of real resistance under field requests. Although the latter modality offers greater representativeness of in situ conditions, its practical application is restricted by the requirements of heavy equipment mentioned above, load rings, mechanical jacks, energy storage systems, limiting the spatial density of characterization points typically to a certain separation in meters between them, which may be insufficient to capture the geotechnical variability in heterogeneous mountain corridors.

Dynamic Cone Penetrometer (PDC)

The Dynamic Cone Penetrometer (PDC) is a portable auscultation device that records the resistance of terrestrial materials to penetration driven by controlled free fall of a known mass, expressing the results in terms of the dynamic penetration index (DCPI or ND), i.e. the number of blows required to achieve a specified penetration.

The configuration of the PDC specified in the Colombian standard INV E-172 includes: 8 kg hammer with free fall from 575 mm, 16 mm linkage, 20 mm conical point with a base diameter with a 60° angle, vertical guide system, and graduated scale in millimeters. The procedure records

the number of blows necessary for specified penetration, expressing results as dynamic penetration index (DCPI or ND) in mm/stroke, interpreted as an inverse measure of resistance.
The relevance of the PDC in road engineering lies in its ability to evaluate the vertical variability of the bearing capacity with excellent spatial resolution, allowing the identification of weak layers, deficient compaction or stratigraphic changes at small scales. Recent studies have shown that PDC is especially efficient in contexts where stratification is complex, particularly in colluvial and alluvial deposits characteristic of the Colombian Andean region (Al-Refeai & Al-Suhaibani, 1997)
The INVÍAS E-172 technical standard establishes the standardized protocols for the realization of the Dynamic Cone Penetrometer in Colombia, specifying parameters of hammer impact energy, precise geometry of the conical tip, registration procedures, acceptance criteria, and interpretation methods that guarantee repeatability and comparability of results. This standardization is critical for the metrological reliability of data from different survey campaigns.
The California Bearing Ratio (CBR) is the most widely used design parameter in pavement engineering worldwide and is the de facto standard for sizing flexible pavement structures in virtually all jurisdictions. The CBR test was originally proposed by the California Division of Highways in the 1930s and has remained in scientific and regulatory force to this day, being incorporated into flexible pavement design specifications since then (AASHTO, 1993).
The INVÍAS E-123 technical standard regulates the execution of the California Support Ratio test in Colombia, specifying in detail the sample preparation and compaction procedures, the soaking conditions that simulate seasonal saturation, the load parameters of the penetration test, the criteria for acceptance of results, and the required reports. The versatility of CBR as a design parameter comes from its demonstrated relationship with fundamental soil shear strength parameters and its incorporation into pavement structure sizing methodologies developed over decades of experimental validation (Burnham & Anderson, 2002).

PDC-CBR Correlations Reported in International Literature

The functional relationship widely documented in international studies between the dynamic cone penetration index (DCP) and the California support ratio (CBR) predominantly adopts a logarithmic potential form, expressed by the equation:
$\log(\mathrm{CBR}) = \alpha + \beta \times \log(\mathrm{DCP})$)
where the y coefficients exhibit significant variability depending on the specific geotechnical context, soil characteristics, particle size distribution, content and type of clay fraction, degree of weathering of the parent material, and prevailing moisture conditions at the time of the execution of the test (Webster et al., 1992; Kleyn, 1975; Smith & Pratt, 1983).αβ
Among the correlation equations most widely cited in the specialized technical literature are the following:
U.S. Army Corps of Engineers (USACE). Webster et al. (1992) developed a fundamental correlation under the supervision of the Waterways Experiment Station (WES) in Vicksburg, Mississippi, supported by extensive databases linking results from electrically calibrated penetrometers (ECPs) to CBR values:

$$\mathrm{CBR} = \frac{292}{\mathrm{ND}^{1.12}}$$

or equivalently, in logarithmic form:

$$\mathrm{Log(CBR)} = 2.465 - 1.12\ \mathrm{xlog(ND)}$$

where ND (Dynamic Number) represents the PDC index expressed in mm/stroke. This correlation applies in a general way for most soil typologies, with specific exceptions for materials of high plasticity. For clays of high plasticity (CH according to USCS classification), Webster et al. (1994) refined the expression by:

$$\mathrm{CBR} = \frac{1}{0.002871\,\mathrm{xND}}$$

In the case of low plasticity (LC) clays and cohesive soils with CBR values less than 10%, Webster et al. propose a specific correlation that replaces the general USACE equation. In these materials, it is recommended to use the expression:

$$\mathrm{CBR} = \frac{1}{0.017019\,\mathrm{x\,ND}}$$

This formulation is better suited to the behavior of clays of low plasticity, in which the general equation tends to overestimate the bearing capacity.

Kleyn's South African Research (1975) conducted pioneering research for the Transvaal Highway Department in South Africa, analysing approximately 2,000 samples of pavement materials. Their correlation, which represents one of the first systematic propositions of DCP-CBR relationship, is expressed as:

$$\mathrm{CBR} = \frac{156}{\mathrm{ND}^{0.79}}$$

This equation demonstrated applicability to subgrade materials and granular layers under conditions typical of the South African geotechnical context (Kleyn, 1975; Paige-Green, 2009).
Contributions from the Australian Road Research Board (ARRB). Smith and Pratt (1983) developed a correlation through field studies that linked in situ CBR testing with FAD measurements for road subgrade investigations in Australia:

$$\mathrm{Log(CBR)} = 2.56 - 1.15\mathrm{xlog(ND)}$$

Harison then refined these correlations by differentiating between soil typologies and developed specific equations. For soils with clayey behavior with penetration rates greater than 10 mm/blow, he proposed:

$$\mathrm{Log(CBR)} = 2.56 - 1.16\mathrm{xlog\,(ND)}$$

while for granular materials with penetration rates of less than 10 mm/blow, the recommended expression was:

$$\mathrm{Log(CBR)} = 2.70 - 1.12\mathrm{xlog\,(ND)}$$

Harison also proposed a unified general equation:

$$\mathrm{Log(CBR)} = 2.81 - 1.32\mathrm{xlog\,(ND)}$$

Research by Livneh and Ishai conducted correlation studies using a wide range of samples of undisturbed and compacted fine-grained soils, under saturated and unsaturated conditions, with variable controlled lateral pressures in flexible molds. Their analysis resulted in a characteristic nonlinear expression:

$$\mathrm{Log(CBR)} = 2.20 - 0.71\mathrm{xlog\,(ND)}^{1.5}$$

This formulation incorporates an exponential term of order 1.5 over the logarithm of the penetration index, reflecting nonlinear behaviors observed in fine soils under variable confinement conditions (Livneh, 1989).
Regarding the variability of Correlations and Conditioning Edaphic Factors, the significant divergences between these documented correlations of the order of 50-100% for given values of Dynamic Number (ND) show a critical dependence on local edaphic factors (Al-Refeai et al.,

1997; Zohrabi & P L Scott, 2004). Among the parameters that exert a determining influence on the PDC-CBR relationship are the particle size distribution of the material, particularly the relative proportion of fine and coarse fractions (Taskiran, 2010; Al-Hamdani, 2018); the content, mineralogical type, and activity of the clay fraction (Breytenbach et al., 2010); the degree of chemical and physical weathering of the parent material (De Silva & Kay, 2018); the history of stresses and consolidation status of the deposit (Vakili et al., 2021) and the humidity and saturation conditions prevalent at the time of the test (Livneh, 1989; Feleke & Araya, 2016).

FAD and CBR assays, both penetration tests involving localized shear failure mechanisms, exhibit differential sensitivity to modifications in soil moisture content. Recent research has shown that increases in in situ humidity lead to substantial reductions in both dynamic penetration resistance and CBR value, although the relative magnitude of these reductions is not necessarily proportional, which introduces additional dispersion into empirical correlations.

Contemporary technical literature recognizes that the extrapolation of generic correlations beyond the specific soil and geological contexts for which they were calibrated introduces appreciable biases that can lead to oversizing or undersizing of pavement structures, with significant economic and operational performance consequences (Wu & Sargand, 2007; Mousavi et al., 2016).

Considerations for Special Soils and Regional Contexts

The specialized geotechnical literature documents that volcanic soils, clays of high plasticity, granular materials with bimodal distributions and soils with chemical cementation present PDC-CBR relationships substantially different from the international generic correlations. Soils derived from Andean volcanic ash, characterized by mineralogies dominated by allophanes, imogolite, and organo-mineral complexes, exhibit anomalous mechanical behaviors attributable to their vesicular microstructure, low relative density, and high porosity (Shoji et al., 1993).

The variability documented in exponents of PDC-CBR correlations for soils of volcanic origin with values ranging from -0.79 to -1.27 contrasts sharply with the range -1.12 to -1.32 characteristic of international correlations developed for residual soils from weathering of crystalline or sedimentary igneous rocks (Kleyn, 1975; Harison, 1986; Smith & Pratt, 1983). Regional research in Ecuador analyzed 30 granular soil samples throughout the Andean highlands, concluding that the DCP-CBR correlation requires specific regional calibration due to the high variability observed (Portilla Yandún et al., 2022). This evidence supports the need to support pavement designs in Andean volcanic regions through locally calibrated correlations, rather than adopting generic relationships developed for different site geotechnical conditions (Herrera, 2006).

Geotechnical Context of the Nariño Region

The Nariño region, located in the southwestern Andes of Colombia, presents particular geological conditions derived from the activity of the Galeras Volcanic Complex and other Quaternary eruptive centers (Calvache et al., 1997). The predominant subgrade materials correspond to volcanic ash deposits and altered pyroclastic flows, as well as volcanic colluviums; these materials favor the development of Andisols in the Andean region (Herrera, 2006).

These soils exhibit distinctive geotechnical properties: high porosity (60-77%), low bulk density (0.45-0.90 g/cm^3), anomalous plasticities associated with allophanic minerals, marked sensitivity to moisture variations, and fragile structures susceptible to degradation under wet-dry cycles characteristic of the Andean tropics (Wesley, 1973; Bommer et al., 2001; Herrera, 2006). The characteristic microstructure of these volcanic materials, with vesicular pumiceous particles and aggregates stabilized by organo-mineral complexes, substantially modifies the response to dynamic penetration compared to soils of conventional quartz-feldspathic composition (Shoji et al., 1993). Researchers have pointed out that traditional geotechnical design criteria are inadequate for these materials, requiring complementary methods of integral characterization (Herrera, 2006; Guerrero et al., 2018).

GEOTECHNICAL CHARACTERISTICS OF THE STUDY AREA

The road section is located in southern Colombia (Nariño), in a corridor that connects San Juan de Pasto (2,527 m a.s.l.) with the rural townships of Jongovito and Obonuco (2,600–2,700 m a.s.l.). The road, classified as tertiary, has a total length of approximately 4 km with moderate to steep slopes (5–12%) and undulating topography.

It corresponds to a cold humid climate (12–14 °C average per year), precipitation > 1,000 mm/year distributed in two rainy seasons, relative humidity 75–85 %. These conditions exert a determining influence on the mechanical behavior of the subgrade, particularly in times of heavy rainfall.

Regarding the Geological Context and Material Characteristics, there are predominantly silt-sandy deposits derived from volcanic ash, colluvial deposits, and altered materials of volcanic rocks. Textural characteristics: silt-sandy with moderate clay contents (IP ≈ 5–15%), gray to yellow-brown colors, brittle structure, sensitivity to humidity variations.

METHODOLOGY

Paired tests (PDC + CBR in situ) were carried out at 18 points distributed along the 4 km section, with average spacing of 220–250 m. The first 12 apiques (K0+076 to K2+600) used available CBR data; The last 6 (K2+850 to K4+010) included new unchanged CBR assays.

- PDC Test Procedure: In accordance with INV E-172 standard: removal of surface material, execution of test with 8 kg hammer from a fixed height of 575 mm, penetration registration every 5 strokes (variable interval according to resistance), extension up to 800 mm depth or rejection.
- CBR In Situ Test Procedure. For points with available data: regional database information. For new points: excavation of 1.2×1.2×1.0 m apique, extraction of unaltered sample at a depth of 0.80 m using cylindrical mold (152.4 mm diameter), waterproof protection, immediate transport (30–90 min), penetration test in laboratory according to INV E-169 with mechanical jack (2,700 kg capacity) up to 5.08 mm penetration, recording load versus displacement.
- Calculation of Dynamic Penetration Index. Based on records (cumulative number of blows versus cumulative penetration): construction of evolution graphs, identification of homogeneous strata, calculation of ND = ΔPenetration/ΔGolpes (mm/stroke), selection of representative value at 800 mm depth.
- Statistical Analysis and Correlation Adjustment. Evaluation of five models (linear, exponential, logarithmic, polynomial, potential) by least squares regression, R^2 calculation

and Pearson correlation coefficient r. Model selection by theoretical congruence, alignment with international literature, and linearity on a log-log scale.

- Statistical Validation by Hypothesis Test Null hypothesis (H_0): $\rho = 0$; Alternative hypothesis (Ha): $\rho \neq 0$. Statistic $t = [r\sqrt{(n-2)}]/\sqrt{(1-r^2)}$, t-Student distribution with $\nu = n-2 = 16$ degrees of freedom, $\alpha = 0.05$ (bilateral), t_crítico = 2.1199.

RESULTS

Field Data Distribution

Database of 18 paired trials:
ND range: 5.40 to 61.00 mm/stroke (outlier in K4+010: filler material)
Rango CBR: 3,40 % a 49,27 %
Predominance of silt-sandy textures (15 out of 18 apiques)
Inverse Visual Correlation: Higher NDs ↔ Lower CBRs

Evaluation of Regression Models

Model	Equation	R^2	r
Linear	CBR = -0.797×ND + 47.15	0,773	0,879
Exponential	CBR = 61.01×e^(-0.04×ND)	0,983	0,991
Logarithmic	CBR = -20.0×ln(ND) + 83.53	0,944	0,972
Polynomial (grade 2)	CBR = 0.032×ND² - 2.963×ND + 64.24	0,954	0,977
Potential	**CBR = 381,2 × ND^(-1,05)**	**0,908**	**0,953**

The potential model was selected by theoretical congruence with Hiley's dynamic equation, which is aligned with the international literature, in addition to linearity on a log-log scale and conceptual validity versus empirical coefficients.

Statistical Validation

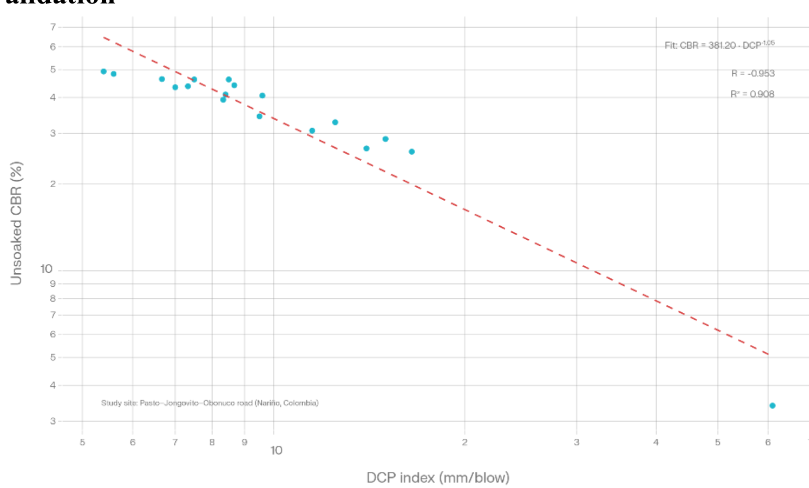

Figure 1. Inverse Relationship between DCP index and CBR

As shown in Figure 1, from 18 paired observations (n=18) of the dynamic penetration index (PDC, mm/blow) and the unchanged CBR (%) obtained for the Pasto Jongovito and Pasto

Obonuco section, the relationship was evaluated using a potential CBR=a·PDCb model, estimated by ordinary least squares in the logarithmic space ln(CBR) = α+b ln (PDC), equivalent to an original scale power law. The adjustment was $CBR=381.20\cdot PDC^{-1.052}$, evidencing an inverse dependence, i.e., the higher the penetration per hit, the lower the support capacity with correlation in the log-log domain, r = −0.953 and R2log = 0.908. The slope was highly significant (p=1.02×10−9), with a 95% confidence interval b ∈ [−1.229; −0.875], and the scale parameter showed ∈ [250.53; 580.01], confirming the stability of the exponent and the nonlinear nature of the PDC–CBR relationship in the sampled range.
The global significance of the association was further corroborated with the t-test for the correlation coefficient (t=−12.59, df = 16, $p = 1.02 \times 10^{-9}$), rejecting H0: ρ = 0 to α=0.05. On the original scale, the model produced moderate mean errors (MAE ≈ 4.90 CBR points; RMSE ≈ 6.35 CBR points; ASM ≈ 14.9%), while the R2 on the untransformed scale was lower (R2≈0.669), consistent with the retransformation from an adjustment in logarithms and the typical heteroskedasticity in this type of correlations. Finally, the diagnosis of influence suggests a highly influential observation (PDC ≈ 61 mm/stroke; CBR ≈ 3.4

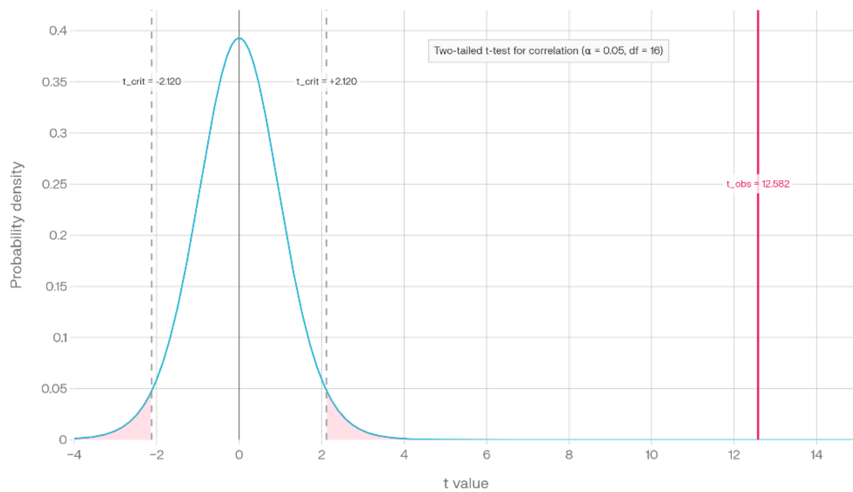

Figure 2. Student´s Distribution for Hypothesis Test

Correlation coefficient r = 0.953; t = [0.953 × √16]/√(1-0.908) = 12.582;
t_crítico (α=0.05, n=16) = 2.1199
Therefore, the decision to t_observed (12.582) > t_crítico (2.1199) → Reject H_0 and therefore if there is a correlation, it is concluded that the significant statistical evidence ($p < 0.001$) of population correlation is not null.
The residual analysis and the diagnosis of the model indicate that, on the log-log scale, the relationship presents an approximately linear alignment, without evidence of systematic curvature that suggests poor functional specification. Likewise, the visual inspection of the residues suggests a behavior compatible with normality, approximately symmetrical distribution around zero and homoscedasticity, since the residual dispersion remains relatively constant throughout the range of adjusted values. However, a potentially atypical and influential value was identified corresponding to apique 18 (ND = 61 mm/stroke; CBR = 3.40%), associated with an anomalous fill material, which could disproportionately affect the slope and the global

adjustment indicators if its influence is not evaluated through sensitivity analysis.

COMPARISON WITH OTHER INTERNATIONAL CORRELATIONS

The comparison between the locally calibrated correlation for Nariño, $CBR = 381.2 \cdot ND^{-1.05}$, and the international reference equations shows a coherent inverse dependence between the unchanged CBR and the DCP index (ND), as expected for subgrade and granular layer materials. In the representative range ND = 5 - 20 mm/blow, the equation of this research provides intermediate CBR estimates against the two hyperbola models: USACE/INVIAS (CBR=292/ND) and MOPT (CBR=567/ND); that is, it is located between a more conservative prediction and a higher one. This behavior suggests that regional calibration captures the local mechanical response without substantially departing from accepted trends in international practice.

ND (mm/golpe)	USACE	MOPT	**Nariño**
5,0	58,4	113,4	70.3
10,0	29,2	56,7	34.
20,0	14,6	28,4	16.4

In the log-log scale graphs, the research model shows a slightly greater slope in magnitude than the ND−1 trend (exponent −1.05 vs. −1.00), which implies a slightly higher sensitivity of the CBR to increases in ND, but without generating extreme divergences with respect to the reference curves. The experimental data are mainly concentrated in the ND interval where the calibration was developed, and the adjusted curve accompanies that point cloud without marked systematic biases, while MOPT tends to overestimate the CBR in much of the observed domain and USACE tends to underestimate it in the midrange. An isolated spot with high ND and very low CBR (ND ≈ 61 mm/stroke; CBR ≈ 3.4%) stands out as an atypical condition associated with filler material, which reinforces the need to interpret these correlations within their domain of validity and to treat anomalous observations through sensitivity or influence analysis when making design decisions.

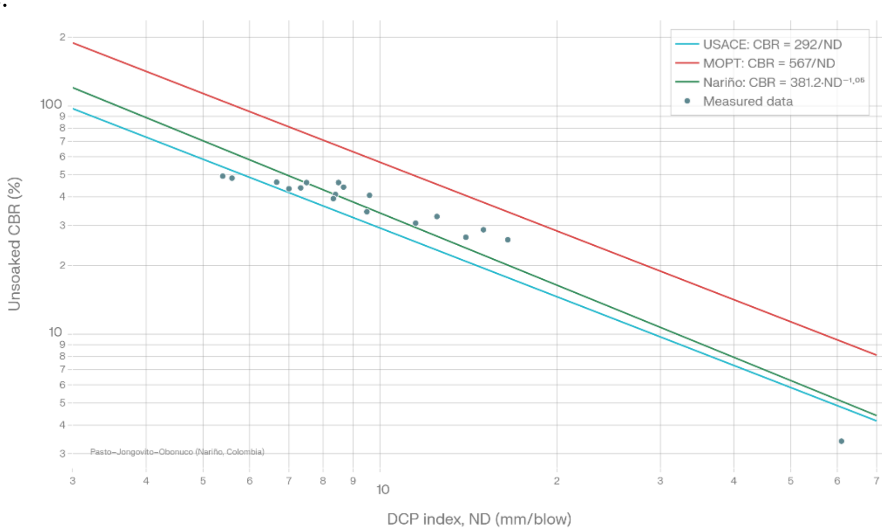

Figure 3. DCP – CBR Correlations Compared

DISCUSSION

The locally calibrated correlation equation, $CBR = 381.2 \times ND^{-1.05}$, $R^2 = 0.908$; $r = 0.953$; $p < 0.001$, captures more than 90% of the variability observed in the relationship between the dynamic penetration index and the bearing capacity of volcanic silt-sandy soils of the sectors studied under natural moisture conditions. Statistical validation by bilateral Student's t-test, $t\_obs = 12.582$; $t\_crit = 2{,}120$; $\nu = 16$; $\alpha = 0.05$, rejects with greater than 99.9% confidence the null hypothesis of the absence of population correlation, confirming that the documented association has robust statistical significance.

From a practical engineering perspective, the calibrated potential model exhibits theoretical congruence with Hiley's dynamic equation, which conceptually supports the inverse relationship between penetration resistance and hit penetration in dynamic driving tests. The empirically obtained exponent -1.05 is consistent with the range -0.79 to -1.32 reported in widely cited international correlations (Kleyn, 1975; Webster et al., 1992; Smith & Pratt, 1983; Harison, 1986), being close to the theoretical value -1.00 that would correspond to an idealized system without energy losses.

The operational efficiency of the PDC as a tool for rapid characterization of subgrades is demonstrated when compared with the conventional in-situ CBR methodology. A typical PDC assay requires approximately 30 to 45 minutes of total time and an estimated cost of 50,000 to 100,000 COP per characterization point. In contrast, an on-site CBR test in accordance with INV E-169 requires 2 to 3 hours of effective execution and represents a cost per test of the order of 500,000–1,000,000 COP, without considering the costs of mobilizing heavy equipment.

This difference of an order of magnitude in execution time and operational cost translates directly into an increase in the spatial density of feasible characterization under restricted budgets. In pre-feasibility and preliminary design road projects for secondary and tertiary Andean corridors, the adoption of the PDC with validated local correlation would allow 8 12 tests per kilometer to be carried out with an equivalent budget, substantially improving the capture of geotechnical variability inherent in heterogeneous colluvial and volcaniclastic deposits characteristic of the region.

The relative position of the correlation obtained for the sectors near the city of Pasto with respect to the international reference equations provides valuable information on the distinctive geomechanical characteristics of the volcaniclastic materials studied. For a representative value of ND = 10 mm/stroke, the local equation predicts $CBR \approx 34.0\%$, while USACE/INVIAS ($CBR = 292/ND$) projects $CBR \approx 29.2\%$ and MOPT ($CBR = 567/ND$) estimates $CBR \approx 56.7\%$. This intermediate position, closer to USACE than to MOPT, suggests that the volcanic silt-sandy soils adjacent to the city of Pasto exhibit resistance to dynamic penetration slightly higher than that of conventional granular materials.

This difference in behavior can be attributed to multiple specific soil factors of materials of volcanic origin. Previous research on soils derived from Andean volcanic ash has documented vesicular microstructures with pumiceous particles of low relative density, moderate contents of allophanic minerals with anomalous cohesive properties, and aggregates stabilized by organo-mineral complexes that confer apparent rigidity under short-lived loads.

Recent regional studies in Ecuador have reported significant variabilities in DCP–CBR correlations for Andean granular soils, concluding that international generic equations introduce systematic errors in the order of 30–50% when applied without local calibration in volcanic deposits. Research in Colombia has documented anomalous geotechnical behaviors in soils

derived from volcanic ash in southwestern Colombia, reinforcing the recommendation to support pavement designs in Andean volcanic regions through locally calibrated correlations.
The interpretation and application of the results obtained must be strictly limited to the domain of experimental validity. The following main limitations are identified:

- The equation was calibrated with 18 paired observations distributed in the ND interval ∈ [5.4; 61.0] mm/stroke. However, 17 of the 18 observations (94.4%) are concentrated in the ND subinterval ∈ [5.4; 16.5] mm/stroke. It is recommended that the application of the equation be limited to the ND range ∈ [5; 17] mm/stroke, corresponding to the coreof the calibration set.
- All the characterized materials correspond to silt-sandy textures with moderate clay fraction contents (IP ≈ 5–15%), derived from weathering of volcanic ash. The equation is not applicable without experimental validation to clays of high plasticity, coarse granular materials, residual soils of sedimentary or metamorphic rocks, or chemically stabilized materials.
- The tests were carried out under conditions of natural humidity. Extrapolation to conditions of close saturation (Sr > 95%) or severe desiccation (w < 15%) would require additional experimental validation.
- The mean square error of prediction (RMSE ≈ 6.35 CBR points; ASM ≈ 14.9%) indicates that the proposed equation does not capture 100% of the observed variability. For executive design applications that require high accuracy, it is recommended to incorporate conservative safety margins or complement PDC characterization with selective in-situ CBR testing at critical points.
- The results obtained have direct implications for the evolution of regional geotechnical practice and the updating of Colombian technical regulatory frameworks. The equation for the areas near San Juan de Pasto aligns with the philosophy underlying the INV E-172 standard, which explicitly recognizes the need for regional correlations.
- Regional technology transfer occurs with the dissemination of results that facilitates the gradual adoption of the PDC methodology in regional professional practice, closing the gap between academic research and effective application in infrastructure projects.

CONCLUSIONS

- The empirical equation was obtained, specifically calibrated for silt-sandy soils derived from volcanic ash and volcanic colluvial deposits of the Andean region adjacent to the city of Pasto, under conditions of natural humidity. The correlation was statistically validated by bilateral Student's t-test, rejecting with greater than 99.9% confidence the null hypothesis of the absence of population correlation.
- The selected potential functional form and the resulting exponent -1.05 are fully consistent with Hiley's dynamical equation. The correlation in the areas surrounding Pasto is positioned intermediately between USACE/INVIAS and MOPT, closer to the former, reflecting distinctive geomechanical characteristics of Andean volcanic materials without substantially departing from internationally accepted trends.
- The adoption of the PDC with validated local correlation allows to substantially increase the spatial density of geotechnical characterization of subgrades in Andean road projects, reducing execution time from 2 to 3 hours to 30–45 minutes. This enables 8 to 12 PDC tests per kilometer to be carried out with a budget equivalent to 1 to 2 conventional CBR tests.

- Clear delimitation of limitations and range of applicability:
  - PDC Index Range: ND ∈ [5; 17] mm/stroke (coreof calibration set)
  - Soil type: Volcanic silt-sandy with IP ≈ 5–15%
  - Humidity status: Variable natural humidity characteristic of the Andean tropics
  - Predictive uncertainty: RMSE ≈ 6.35 CBR points; ASM ≈ 14.9%
- The calibrated equation is recommended for pre-feasibility and preliminary design phases of Andean road projects. For final executive design of high-profile projects, a combined strategy is recommended: systematic characterization by PDC complemented by selective in-situ CBR assays
- This research provides formal statistical support consistent with the philosophy of the INV E-172 standard. The results constitute a valuable precedent for future research aimed at calibrating PDC–CBR correlations in other Colombian geotechnical contexts, strengthening the stock of validated regional equations and reducing dependence on generic international correlations.

References

Al-Hamdani, D. (2018). Correlation of cbr value with particles size and compaction characteristics of cohesionless soil. Kufa Journal of Engineering, 9(1), 158-174.https://doi.org/10.30572/2018/KJE/090111

Al Refeai, T., & Al Suhaibani, A. (1997). Prediction of CBR using dynamic cone penetrometer. Journal of King Saud University. Engineering Sciences, 9(2), 191–203. https://doi.org/10.1016/S1018-3639(18)30676-7

Alva Hurtado, J., & Tupia Córdova, C. A. (2001). Evaluation of the ground-bearing capacity by means of dynamic penetration equipment. Journal of the Faculty of Engineering, National University of Engineering, Peru.

American Association of State Highway and Transportation Officials (AASHTO). (1993). AASHTO Guide for the Design of Pavement Structures. Washington, D.C., USA. https://www.fhwa.dot.gov/engineering/geotech/pubs/05037/ac.cfm

Ampadu, S. I. K., Ackah, P., Nimo, F. O., & Boadu, F. (2017). A laboratory study of horizontal confinement effect on the dynamic cone penetration index of a lateritic soil. Transportation Geotechnics, 10, 47-61. https://doi.org/10.1016/j.trgeo.2016.12.002

Bommer, J. J., Rolo, R., Mitroulia, A., & Berdousis, P. (2001). Geotechnical properties and seismic slope stability of volcanic soils. En Proceedings of the 12th European Conference on Earthquake Engineering (Paper No. 695). Elsevier Science.

Breytenbach, I J, Paige-Green, P, & Van Rooy, J L. (2010). The relationship between index testing and California Bearing Ratio values for natural road construction materials in South Africa. Journal of the South African Institution of Civil Engineering, 52(2), 65-69. Retrieved February 04, 2026, from http://www.scielo.org.za/scielo.php?script=sci_arttext&pid=S1021-20192010000200008&lng=en&tlng=en.

Burnham, K. P., & Anderson, D. R. (2002). Model selection and multimodel inference: A practical information-theoretic approach (2nd ed.). Springer-Verlag. https://doi.org/10.1007/b97636

Calvache, M. L., Williams, S. N., & Schaefer, S. J. (1997). Stratigraphy and chronology of the Galeras volcanic complex, Colombia. Journal of Volcanology and Geothermal Research, 77 (1-4), 5–19. https://doi.org/10.1016/S0377-0273(96)00083-2

Contreras-Ávila, J. F., & García-García, A. E. (2019). Correlation of the dynamic cone penetrometer (P.D.C.) with California support ratio (C.B.R.) test for soils in the town of Engativá in the city of Bogotá, using the standard of the National Institute of Roads [Undergraduate project, Universidad Católica de Colombia]. https://hdl.handle.net/10983/23933

De la Cruz Vega, S. A., Siello Vega Neyra, C., Garrido Oyola, J. A., Pezo Morales, P. A., & Mejía Guerrero, H. (2023). Comparison of the resistance of California Bearing Ratio and dynamic cone penetrometer in the Cusco-Paruro subgrade. Journal of the Selva Andina Biosphere, 11(2), 150–165. https://doi.org/10.36610/j.jsab.2023.110200150

De Silva, S., & Kay, S. M. (2018). Turning up the heat: High-flux magmatism in the Central Andes. Elements, 14(4), 245–250. https://doi.org/10.2138/gselements.14.4.245

Feleke, A. A., & Araya, G. F. (2016). Prediction of CBR using DCP for local subgrade materials. Department for International Development (DFID), UK.

Guerrero, Cristian Camilo, & Cruz Velasco, Lucio Gerardo. (2018). Experimental study of classification of soils derived from volcanic ash in southwestern Colombia with the SUCS method, the AASHTO and a new soil classification method. Engineering & Development, 36(2), 378-397. https://doi.org/10.14482/inde.36.2.10377

Harison, J. A. (1986). Correlation of CBR and dynamic cone penetrometer strength measurement of soils. Australian Road Research, 16(2). https://trid.trb.org/view/1194609

National Institute of Roads (INVÍAS). (2012). INV E-172: Use of the dynamic cone penetrometer in shallow pavement applications. INVÍAS, Bogotá, Colombia.

National Institute of Roads (INVÍAS). (2012). INV E-169: Soil support ratio in the field—CBR in situ. INVÍAS, Bogotá, Colombia.

Kleyn, E.G. (1975) The Use of the Dynamic Cone Penetrometer (DCP). Transvaal Roads Department, Pretoria, Report L2/75. (In Afrikaans)

Herrera Ardila, M. (2006). Soils derived from volcanic ash in Colombia - fundamental study and implications in engineering. Uniandes. https://doi.org/10.57784/1992/7812

Livneh, M. (1989). Validation of correlations between a number of penetration tests and in situ California-Bearing Ratio tests. Transportation Research Record, 1219, 56–67.

Livneh, M., & Ishai, I. (1987). Pavement and material evaluation by a dynamic cone penetrometer. Proceedings of the 6th International Conference on Structural Design of Asphalt Pavements, 1, 665–674.

Mousavi, S. H., Gabr, M. A., & Borden, R. H. (2016). Field verification of undercut criteria and alternatives for subgrade stabilization in the Piedmont Area (Reporte Final FHWA/NC/2011-05). North Carolina Department of of Civil, Construction, and Environmental Engineering.

Osorio Martínez, J. F., & Casas Gerena, C. (2013). PDC correlation with CBR for soils in the town of Suba. Universidad Militar Nueva Granada, Bogotá. http://unimilitar-dspace.metabiblioteca.org/handle/10654/3653

Paige-Green, P., & Plessis, L.J. (2009). Use and interpretation of the dynamic cone penetrometer (DCP) test.. Transportek, CSIR, South Africa.

Peña Marín, M. Á. (2017). Correlation between the dynamic cone penetration index (P.D.C.) and the California support ratio (C.B.R.) value of clay soils on the roads of the city of Cúcuta, Francisco de Paula Santander University. http://repositorio.ufps.edu.co/handle/ufps/2088

Portilla Yandún, F. P., Ordoñez, A. E. G., & Medina, M. F. C. (2022). Correlation between the laboratory CBR, the DCP index and physical and mechanical properties of granular soils. Digital Awareness, 5(4.1), 45–59. https://doi.org/10.33262/concienciadigital.v5i4.1.2396
Shoji, S., Nanzyo, M., & Dahlgren, R. A. (1993). Volcanic Ash Soils: Genesis, Properties and Utilization. Developments in Soil Science 21 (288 p). Amsterdam: Elsevier.
Smith, R. B., & Pratt, D. N. (1983). A field study of in situ California Bearing Ratio and Dynamic Cone Penetrometer testing for road subgrade investigations. Australian Road Research, 13(4), 285–293.
Taskiran, T. (2010). Prediction of California bearing ratio (CBR) of fine grained soils by AI methods. Advances in Engineering Software, 41(6), 886–892. https://doi.org/10.1016/j.advengsoft.2010.01.003
Vakili, A. H., Salimi, M., & Shamsi, M. (2021). Application of the dynamic cone penetrometer test for determining the geotechnical characteristics of marl soils treated by lime. Heliyon,7(9), e08062. https://doi.org/10.1016/j.heliyon.2021.e08062
Webster, S. L., Brown, R. W., & Porter, J. R. (1994). Force projection site evaluation using the Electric Cone Penetrometers (ECP) and the Dynamic Cone Penetrometer (DCP) (Reporte Técnico GL-94-17). U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
Webster, S. L., Grau, R. H., & Williams, T. P. (1992). Description and application of dual mass Dynamic Cone Penetrometer (Reporte de Instrucción GL-92-3). U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.
Wesley, L. D. (1973). Some basic engineering properties of halloysite and allophane clays in Java, Indonesia. Géotechnique, 23(4), 471–494. https://doi.org/10.1680/geot.1973.23.4.471
Wu, S., & Sargand, S. (2007). Use of Dynamic Cone Penetrometer in Subgrade and Base Acceptance (Informe n. FHWA/ODOT-2007/01). Ohio Department of Transportation, Bureau of Research and Development. https://rosap.ntl.bts.gov/view/dot/39670
Zohrabi, M.,& P L Scott (2004). The correlation between the CBR value and penetrability of soils (Reporte TRL587). Transport Research Laboratory, Crowthorne, UK.