HNSJ Humanities & Natural Sciences Journal
ISSN: (e) 2709-0833
www.hnjournal.net

Peer-Reviewed Journal
Indexed at: NSP - SJIF
Impact Factor 2022 = 4.91

RESEARCH TITLE

Estimating California Bearing Ratio from Dynamic Cone Penetrometer Tests: A Site-Specific Correlation for Subgrade Soils in Port Sudan, Sudan

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HNSJ, 2026, 7(5); https://doi.org/10.53796/hnsj75/45

Received at 15/04/2026 Accepted at 22/04/2026 Published at 01/05/2026

Abstract

The California Bearing Ratio (CBR) is a fundamental laboratory parameter for evaluating subgrade strength in flexible pavement design. However, its reliance on controlled compaction, extended soaking periods, and specialized laboratory equipment often limits its application during preliminary site investigations. The Dynamic Cone Penetrometer (DCP) offers a rapid, cost-effective field alternative, but its practical use requires reliable site-specific correlation equations. This study develops a predictive correlation between DCP penetration index and laboratory CBR values for subgrade soils in Port Sudan, Sudan. Four representative soil samples were collected from distinct urban and quarry locations, classified according to the Unified Soil Classification System (USCS) and AASHTO standards, and tested using both in-situ DCP (ASTM D6951) and laboratory CBR (ASTM D1883) procedures. Regression analysis yielded a logarithmic correlation model: **CBR = 80.773−62.653log10(DCP)**, with a coefficient of determination **(R^2) of 0.74** The model confirms a statistically meaningful inverse relationship between DCP penetration and CBR values, demonstrating its utility for rapid field-based strength estimation. While the equation provides a practical tool for preliminary pavement design, further validation across broader soil types, moisture regimes, and compaction states is recommended to enhance generalizability and design reliability.

Key Words: California Bearing Ratio; Dynamic Cone Penetrometer; Subgrade Characterization; Field-Laboratory Correlation; Pavement Engineering; Port Sudan.

عنوان البحث

تقدير نسبة التحمل الكاليفورنية من اختبارات مقياس الاختراق المخروطي الديناميكي: علاقة ارتباط خاصة بالموقع لترب التأسيس في بورتسودان، السودان.

المستخلص

تُعد نسبة التحمل الكاليفورنية (CBR) من المعايير المخبرية الأساسية لتقييم مقاومة تربة التأسيس في تصميم الرصفات المرنة. غير أن اعتماد هذا الاختبار على الدمك المنضبط، وفترات الغمر الطويلة، والمعدات المخبرية المتخصصة، يحدّ غالبًا من إمكانية تطبيقه خلال مراحل الاستكشاف الموقعي الأولية. ويُعد اختبار مقياس الاختراق المخروطي الديناميكي (DCP) بديلًا حقليًا سريعًا وفعالًا من حيث التكلفة، إلا أن استخدامه العملي يتطلب معادلات ارتباط موثوقة ومحددة بحسب طبيعة الموقع. تهدف هذه الدراسة إلى تطوير علاقة تنبؤية بين مؤشر اختراق اختبار DCP وقيم CBR المخبرية لترب التأسيس في مدينة بورتسودان، السودان. جُمعت أربع عينات تربة ممثلة من مواقع حضرية ومحاجر مختلفة، وصُنفت وفق نظام تصنيف التربة الموحد (USCS) ومعايير الجمعية الأمريكية لموظفي الطرق والنقل(AASHTO) ، ثم اختُبرت باستخدام اختبار DCP الحقلي وفق معيار ASTM D6951 واختبار CBR المخبري وفق معيار ASTM D1883. وقد أسفر تحليل الانحدار عن نموذج ارتباط لوغاريتمي بالصيغة الآتية:

$$CBR = 80.773 - 62.653 \log_{10}(DCP)$$ ،

مع معامل تحديد بلغ $R^2 = 0.74$. ويؤكد النموذج وجود علاقة عكسية ذات دلالة إحصائية بين اختراق DCP وقيم CBR، مما يبرز فائدته في التقدير السريع لمقاومة التربة اعتمادًا على القياسات الحقلية. وعلى الرغم من أن المعادلة توفر أداة عملية للتصميم الأولي للرصفات، فإن الدراسة توصي بإجراء مزيد من التحقق على أنواع أوسع من الترب، وظروف رطوبة مختلفة، وحالات دمك متعددة، بما يعزز قابلية تعميم النتائج وموثوقية التصميم.

الكلمات المفتاحية: نسبة التحمل الكاليفورنية؛ مقياس الاختراق المخروطي الديناميكي؛ توصيف تربة التأسيس؛ الارتباط بين الاختبارات الحقلية والمخبرية؛ هندسة الرصفات؛ بورتسودان.

1. Introduction

The California Bearing Ratio (CBR) remains one of the most widely adopted indices for evaluating the load-bearing capacity of subgrade and base materials in road and airfield pavement design. The test quantifies soil shear strength by measuring the pressure required to penetrate a compacted specimen at standardized rates, normalized against crushed aggregate reference values (ASTM D1883, 2021). Despite its engineering reliability, the CBR test is labor-intensive, requires strict moisture-density control, and typically demands 4–7 days to complete, making it unsuitable for rapid preliminary assessments or remote site investigations.

To address these limitations, the Dynamic Cone Penetrometer (DCP) has gained prominence as a lightweight, in-situ testing device that evaluates soil resistance through dynamic penetration. The DCP records the penetration depth per hammer blow, producing a DCP index (mm/blow) that correlates inversely with soil stiffness and bearing capacity. Due to its speed, minimal equipment requirements, and direct field applicability, the DCP is increasingly used for quality control, layer differentiation, and rapid strength estimation in pavement engineering (ASTM D6951, 2018).

Numerous empirical correlations between DCP and CBR have been proposed globally; however, these relationships are highly sensitive to soil type, gradation, moisture content, compaction history, and regional geological conditions. Consequently, applying generalized equations to new locations often yields significant prediction errors. In Port Sudan, a rapidly developing coastal city with diverse alluvial and quarry-derived soils, no validated DCP–CBR correlation currently exists in the literature or local design manuals. This gap hinders efficient preliminary pavement design and increases reliance on delayed laboratory testing.

This study aims to: (1) characterize representative subgrade soils from four locations in Port Sudan using USCS and AASHTO classification systems; (2) conduct paired in-situ DCP and laboratory CBR tests under standardized conditions; and (3) develop a site-specific regression equation to estimate CBR from DCP measurements. The resulting model provides engineers with a practical, time-saving tool for initial site evaluation while highlighting the necessity for expanded regional validation.

2. Materials and Methods

2.1 Study Area and Soil Sampling

Soil samples were collected from four distinct locations within Port Sudan City, Red Sea State, Sudan:

- **Sample 1 & 3:** Rotana Quarry (southwest of Port Sudan)
- **Sample 2:** Sudatel Building site (city center)
- **Sample 4:** Farmers Bank Building site (downtown Port Sudan)

Sampling was conducted at depths ranging from 2.0 cm to 61.7 cm below existing ground level. Each sample was sealed to preserve in-situ moisture and transported to the geotechnical laboratory for classification and testing.

2.2 Soil Classification

Grain size distribution was determined via sieve analysis (ASTM D6913, 2017), and Atterberg limits were measured following ASTM D4318 (2017). Soils were classified according to the Unified Soil Classification System (USCS) and the AASHTO M 145 system. Results are summarized in Table 1.

Table 1. Soil classification of tested samples

Sample	USCS Classification	AASHTO Classification	Description
1	GP-GM	A-1-a	Poorly graded gravel with silt, little to no fines
2	SP-SM	A-1-b	Poorly graded sand with silt, little to no fines
3	GW-GC	A-1-a	Well-graded gravel with clay, gravel-sand-clay mixtures
4	SP-SC	A-2-4	Poorly graded sand with clay, gravel-sand-clay mixtures

2.3 Dynamic Cone Penetrometer (DCP) Testing

DCP tests were conducted in-situ following ASTM D6951 (2018). The device comprised an 8 kg hammer dropped from a standard height of 575 mm onto a driving rod connected to a 60° conical tip with a 20 mm base diameter. Penetration was recorded after each blow, and the DCP index (mm/blow) was calculated as the cumulative penetration divided by the number of blows over representative depth intervals.

2.4 California Bearing Ratio (CBR) Testing

Laboratory CBR tests were performed in accordance with ASTM D1883 (2021). Specimens were prepared at optimum moisture content (determined via Standard Proctor compaction, ASTM D698, 2012), compacted in five equal layers within a 152 mm diameter mold, and subjected to a 4-day soaking period under a 4.54 kg surcharge. Penetration resistance was measured at 2.54 mm and 5.08 mm, and the CBR value was calculated as the ratio of test load to standard crushed stone load, expressed as a percentage.

2.5 Data Analysis

Paired DCP and CBR results were plotted to visualize the relationship. Logarithmic regression analysis was applied to derive a predictive equation. Model performance was evaluated using the coefficient of determination (R^2), which quantifies the proportion of variance in CBR explained by the DCP index.

3. Results and Discussion

3.1 Test Results

Table 2 presents the paired DCP and CBR results for the four sampled locations. DCP penetration indices ranged from 4.2 to 14.0 mm/blow, while corresponding laboratory CBR values varied between 14% and 50%.

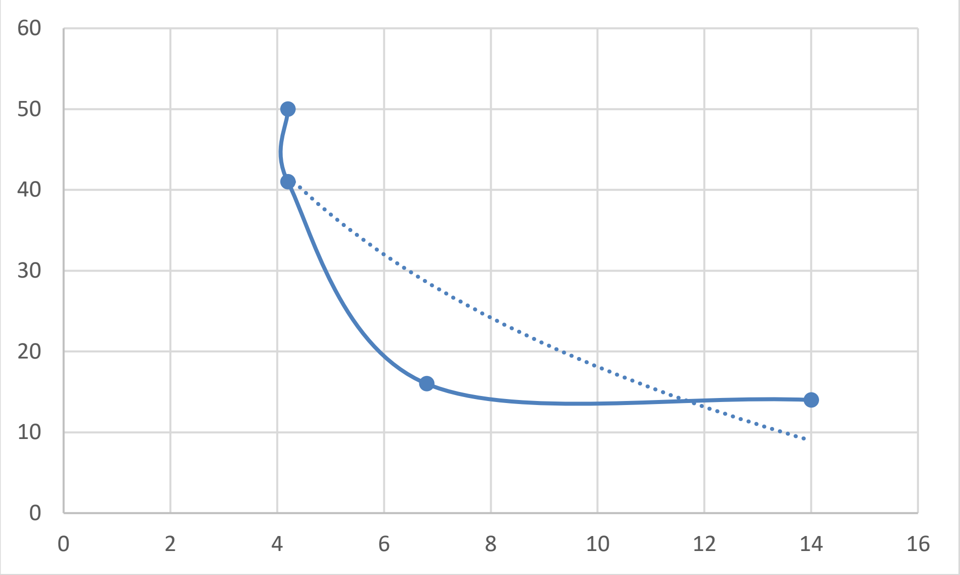

Figure 1: Dispersion diagram and correlation curve between DCP and CBR

Table 2. Paired DCP and CBR test results

Sample	DCP (mm/blow)	CBR (%)	Depth Interval (cm)	Test Date
1	4.2	50.0	14.5 – 37.5	02/06/2024
2	4.2	41.0	2.0 – 19.0	07/08/2024
3	6.8	16.0	13.3 – 37.3	07/08/2024
4	14.0	14.0	13.6 – 61.7	10/09/2024

(Note: Figure 1 should be inserted here as a scatter plot with the fitted logarithmic curve, labeled "Dispersion diagram and correlation curve between DCP and CBR".)

3.2 Correlation Model

Logarithmic regression yielded the following site-specific equation: **CBR = 80.773−62.653log10(DCP)**

The model achieved a coefficient of determination **R^2 = 0.74**, indicating that approximately 73% of the variability in laboratory CBR values is explained by the DCP penetration index. This aligns with established geotechnical behavior, where higher DCP values (greater penetration per blow) correspond to weaker, more compressible soils and lower CBR percentages.

3.3 Discussion

The inverse logarithmic relationship observed in this study is consistent with global DCP–CBR correlations (e.g., Livneh & Ishai, 1987; Harison, 1989; ASTM D6951). The R^2 value of 0.74 suggests a moderate-to-good fit for preliminary engineering applications, particularly in regions with limited laboratory infrastructure. The remaining 27% unexplained variance likely stems from factors not explicitly controlled in this study, including natural moisture variability, local compaction heterogeneity, and fine content differences among samples.

Compared to generalized equations, the Port Sudan-specific model accounts for regional soil characteristics (coastal alluvial deposits, quarry gravels, and silty/clayey sands) and local climatic influences. Its practical value lies in enabling rapid field estimation of subgrade strength during early project phases, feasibility studies, and routine quality checks. However, engineers should apply the model within the tested DCP range (4.2–14.0 mm/blow) and avoid extrapolation beyond these bounds.

4. Conclusions

1. A site-specific logarithmic correlation between DCP penetration index and laboratory CBR was successfully established for subgrade soils in Port Sudan, Sudan: **CBR = 80.773−62.653log10 (DCP)**.
2. The model demonstrated a coefficient of determination **R^2 = 0.74**, confirming a statistically meaningful inverse relationship where higher DCP values correspond to lower CBR strength.
3. The derived equation provides a rapid, cost-effective alternative to laboratory CBR testing for preliminary pavement design and field strength assessment in the Port Sudan region.
4. Due to the limited dataset (n=4) and narrow soil classification range, the model should be applied cautiously and validated under varied moisture, compaction, and geological conditions before use in final design stages.

5. Recommendations for Future Research

- **Dataset Expansion:** Conduct additional paired DCP–CBR tests across a broader range of soil types, moisture contents, and compaction states to improve model robustness and generalizability.
- **Alternative Regression Forms:** Evaluate polynomial, power-law, and exponential models to determine whether they yield higher predictive accuracy (R^2) for regional soils.
- **Environmental Validation:** Investigate seasonal moisture fluctuations and their impact on DCP–CBR relationships, particularly in coastal and semi-arid climates like Port Sudan.
- **Integrated Field Testing:** Combine DCP measurements with lightweight deflectometers or nuclear density gauges to develop multi-parameter strength estimation frameworks.
- **Design Guidelines Integration:** Encourage local transportation authorities to incorporate validated field correlation equations into preliminary pavement design manuals to reduce testing delays and project costs.

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