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Correlation Between Dynamic Cone Penetrometer (DCP) and California Bearing Ratio (CBR) for Subgrade Soil Material in Cambodia

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Abstract: *This research study investigates the correlation between the Dynamic Cone Penetrometer (DCP) and the California Bearing Ratio (CBR) for subgrade soil material in Cambodia, which is essential for optimizing road pavement design. In Cambodia, there is a lack of a localized standard correlation equation customized to its unique soil and environmental conditions for estimating CBR value using DCP. This gap is particularly relevant with the recent requirement to use the DCP-9kg, replacing the previously used DCP-8kg, as specified in the updated Cambodian design specification D3 102-2024. The study aims to establish and evaluate a correlation equation of CBR obtained from the DCP-9kg, formulate predictive equations, and investigate a correlation between DCP-8kg and DCP-9kg. Field experiments were conducted across Cambodia using the DCP-8kg, DCP-9kg, and in-situ CBR equipment on various soil types, excluding gravel. From 127 field experimental data that were collected from various test locations across all 25 provinces and the capital city covering diverse subgrade soils, 98 data passed the criteria. DCP penetration depth measurements at increments of 50 mm to 250 mm were correlated with in-situ CBR tests. Results indicate a strong correlation at a 50mm depth, which aligns closely with the Australian standard equation. However, there were deviations of 5-7% for CBR values of 50-60% and 0.35-0.5% for 1-5%. Variations at deeper depths showed moderate to good correlations, with sandy soils showing weaker consistency. A correlation between DCP-8kg and DCP-9kg was also developed, noting that DCP-8kg produces higher CBR when CBR exceeds 20%. Field validation indicates that the predictive equation provides an accurate estimation of CBR values for non-sandy soils. The findings contribute to the development of a localized standard for using DCP in Cambodia, which will enhance pavement design, road construction, and maintenance quality by providing a strong, site-specific CBR prediction model under local conditions.*

Keywords: Dynamic Cone Penetrometer(DCP), California Bearing Ratio(CBR), In-situ CBR, Correlation Equation, Subgrade Soil

1. INTRODUCTION

In pavement design, investigating the strength of subgrade soil material is necessary to optimize structural safety and economic aspects of road infrastructures. The Dynamic Cone Penetrometer (DCP) test and the California Bearing Ratio (CBR) test are the key methods to evaluate subgrade material strength throughout the site investigation [1].

The Dynamic Cone Penetrometer (DCP), introduced by Scala (1956) [2] in Australia, is a device used to evaluate the resistance of soil at the actual site by driving a steel cone (20-30mm diameter) into the ground using a series of hammer blows to determine the in-situ CBR values, shear strength of soils, strata thickness, and bearing capacity of foundations and buildings [3]. The California Bearing Ratio (CBR) measures the strength of subgrade or base soil materials and its ability to support loads, commonly used in road design. It is obtained as the load ratio required to penetrate the

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compacted soil sample at a given moisture content and density compared to a standard crushed materials sample [4].

Since the laboratory CBR test is time-consuming and it cannot be readily determined in the field and the in-situ CBR test is also expensive, slow to conduct, DCP, being light and portable, takes a very short time to analyze and interpret, and cost-effectiveness with higher repeatability make it preferable for field use [1,5]. The DCP test quickly generates a continuous profile of in-situ subgrade and base strength measurements [6].

As shown in Table 1, the Dynamic Cone Penetrometer (DCP) is utilized globally, including in Cambodia for road construction, however there is no official local standard or any study that clearly defines the correlation equation for CBR resistance using DCP. Previously, Cambodia used DCP-8kg equations, in accordance with Overseas Road Note 31 [7], which is derived from research in neighboring countries and other countries where environmental conditions, weather, soil, humidity, and materials are different, and the accuracy is limited compared to that used in the local. According to the new road design specification (D3 102-2024) [8] of the Ministry of Public Works and Transport (MPWT), which was updated in 2024 in accordance with the Australian standard [9], requires the use DCP-9kg instead of the previously used DCP-8kg, which differs in the In-situ CBR resistance correlation equation, analysis, and application.

To respond to new road design specification with the actual Cambodia's condition of road materials and soil conditions combined with hot and humid weather factors, new research is required. However, this research will fill the gap in the study on Dynamic Cone Penetration (DCP) for Cambodian conditions that has not been studied before and to provide the information for choosing between using the existing correlation equations in the new road design specification (D3 102-2024) from the Australian standard and new correlation equation that will be obtained from this research. This paper objectively investigates a correlation between CBR result of the DCP-8kg and DCP-9kg for subgrade soil material testing in Cambodia, both featuring a 16mm rod diameter and a cone tip with 60° apex angle and 20mm diameter The devices differ in drop height (575mm for DCP-8kg and 510mm for DCP-9kg). Additionally, the research establishes and validates a correlation equation of in-situ CBR resistance using a Dynamic Cone Penetration (DCP-9kg) based on the new road design specification (D3 102-2024) using a nonlinear regression model.

Table 1. Summary of previous relationship between CBR and DCPI (Dynamic Cone Penetration Index) [6]

Author	Correlation	Field or laboratory-based study	Material tested	Study Location
Scala (1956) [2]	log (CBR) = 0.881 + 1.16 x log (25/DCPI)	Field	Cohesive subgrade soil	Australia
Kleyn (1975) [10]	log (CBR) = 2.62 – 1.27 x log (DCPI)	Laboratory	Subgrade soil	South Africa
Smith & Pratt (1983) [11]	log (CBR) = 2.555 – 1.145 x log (DCPI)	Field	Subgrade material	Australia
Harison (1987) [12]	log (CBR) = 2.56 – 1.16 x log (DCPI)	Laboratory	Cohesive	Indonesia
Harison (1987) [12]	log (CBR) = 2.70 – 1.12 x log (DCPI)	Laboratory	Granular	Indonesia
Livneh et al. (1995) [13]	log (CBR) = 2.46 – 1.12 x log (DCPI)	Field and Laboratory	Granular and cohesive	Israel
Ese et al. (1994) [14]	log (CBR) = 2.44 – 1.07 x log (DCPI)	Field and Laboratory	Aggregate base course	Norway
NCDOT (1998) [15]	log (CBR) = 2.60 – 1.07 x log (DCPI)	Field and Laboratory	Cohesive	United States
Coonse (1999) [16]	log (CBR) = 2.53 – 1.14 x log (DCPI)	Laboratory	Piedmont residual soil	United States

Gabr (2000) [17]	log (CBR) = 1.40 – 0.55 x log (DCPI)	Field and Laboratory	Aggregate base course	United States

2. METHODOLOGY

2.1 Materials

The study begins with selecting an appropriate site for conducting tests and data collection. The Dynamic Cone Penetrometer (DCP-9kg and DCP-8kg) test and the in-situ CBR test were conducted to measure soil strength directly in the field. Afterward, the data derived from DCP-9kg and the in-situ CBR were taken to formulate correlation modeling and do the field validation to confirm accuracy. Concurrently, a separate Dynamic Cone Penetrometer test is conducted using the DCP-8kg. All data from both DCP-9Kg and DCP-8Kg tests undergo correlation analysis to determine the relationship between the two instruments.

The study will be conducted on different type of subgrade soils such as road subgrade, rural road, natural soil, field soil etc., except gravel soil, located in Cambodia. At each selected site, the DCP-8kg, DCP-9kg, and in-situ CBR experiments were conducted within the range of a circle with a radius 580 mm of the selected site as shown in Fig.1. For this experiment, we need to conduct three in-situ CBR tests first with approximately 150 mm spacing. Then, we conduct both DCP tests positioned at the vertices of an equilateral triangle, each side measuring 1000 mm. At each vertex, the DCP-8kg test and the DCP-9kg test are conducted at least 100 mm apart from each other. This experiment is to comply with Australia's original reference by Smith & Pratt (1983) [11].

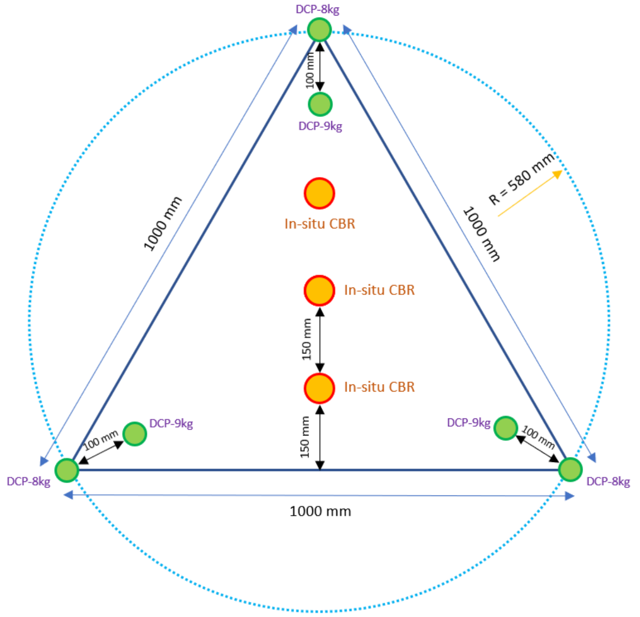

Fig. 1. Method testing of the DCP and the in-situ CBR at the site

Fig. 2. Dynamic Cone Penetrometer (DCP) testing at the site

Fig. 3. In-situ CBR testing at the site

The in-situ CBR test was carried out in accordance with the American Standard ASTM D4429-09a [18] and was set up includes a loading machine, a 50mm diameter CBR plunger, load and penetration dial gauges, and surcharge plates. After setting up, perform the compression by press the plunger into the soil at a controlled rate, measuring the load at penetration depths of 2.54mm and 5.08mm. Calculate CBR is the ratio of the compressive strength of the soil at 2.54mm and 5.08mm compared to the standard compressive strength, which is shown in the formula below:

$$\mathrm{CBR}(\%) = \frac{\text{Test Unit Load(kN)}}{\text{Standard Unit Load (kN)}} \times 100 \qquad \text{(Eq. 1)}$$

Where the standard compressive strength at 2.54mm is 13.44kN and the standard compressive strength at 5.08mm is 20.15kN.

The DCP-8kg consists of an 8kg hammer weight, a dropping height of 575mm, a calibrated 16mm stainless steel penetration rod, and replaceable hardened steel cone with 60°

apex angle, 20mm diameter. This device was test according with Overseas Road Note 31 standard [7], which has the correlation equation is shown below:

$$\log(\mathrm{CBR}) = 2.48 - 1.057\log(\mathrm{DCPI}) \qquad \text{(Eq. 2)}$$

Where the DCPI is the Dynamic Cone Penetration Index (mm/blow). It is defined as the mean penetration per hammer blow over a specified depth window. If Δz is the cumulative penetration (mm) produced by N blows, then DCPI = Δz/N (mm/blow). Unless otherwise noted, all logarithms are base 10.

For DCP-9kg test was carried out in compliance with the Australian Standard AS 1289.6.3.2 [9], which consists of a 9kg hammer mass with a dropping height of 510mm, a 16mm steel rod, steel cone with a 20mm base diameter and 60° cone tip is attached. The standard correlation equation for predicting CBR from the DCP-9kg is shown below:

$$\log(CBR) = 2.5117 - 1.1456\log(DCPI) \quad \text{(Eq. 3)}$$

2.2 CBR-DCPI correlation equation

After conducting field experiments between the depth of DCP and the in-situ CBR, the data obtained were analyzed by observing their relationship using the regression method to establish the relationship equation between DCP and in-situ CBR as well as the relationship between DCP-8kg and DCP-9kg. According to previous studies, as in Table 1, the data between DCP and in-situ CBR have a nonlinear relationship. Therefore, in this study, the equation to be established uses the Nonlinear Regression Model, which is expressed by the following equation:

$$log(CBR) = A * \log(DCPI) + B \qquad \text{(Eq. 4)}$$

Where CBR is the predicted value of soil resistance at the site (%), DCPI is the value of the depth of penetration per hammer (mm/blow), and A, B are constant coefficients analyzed from the data to predict the CBR value.

The MATLAB software was used to calculate the coefficients A, B in the proposed equation model by maximizing the coefficient of determination R^2. In this study, MATLAB's Curve Fitter toolbox was employed to establish a mathematical relationship between the Dynamic Cone Penetrometer Index (DCPI) and the California Bearing Ratio (CBR). A nonlinear regression approach was used by fitting a custom logarithmic model of the form:

$$f(x) = 10^{(A*\log(x)+B)} \qquad \text{(Eq. 5)}$$

Where $f(x)$ is CBR value derived from in-situ CBR test and x is the penetration index of DCP-9kg (DCPI, mm/blow). The fitting process was conducted using the Custom Equation option within the Curve Fitter app, allowing for flexible model definition and optimization based on the input dataset.

To verify that the proposed equation is acceptable, field validation was conducted. It should be noted that the development of this equation is to compare it with existing equations to evaluate whether the previous equation can be used on actual sites.

3. RESULTS AND DISCUSSION

In total, 127 field experimental data points were collected from a diverse range of subgrade soils except gravel in Cambodia. After conducting the on-site experiments, we calculated and analyzed the experimental data to find the CBR value from each instrument. Generally, the nature of testing always has error data or too much scattering data and in order to check the error data and the scattering data, we need to conduct the scatter plot of the experimental data, and use the visualization method to check the data so we can randomly remove the outlier data. Moreover, we also removed the data that didn't have pairs (some locations have DCP testing more than in-situ CBR testing, or vice versa). So, we have removed 29 data, and for the rest of the 98 data, we have randomly split and taken 15 data for field validation on the established model and taken the 83 data for modeling.

The in-situ CBR values varied widely, ranging from very low strengths of around 1% in weak subgrade soils to higher strengths exceeding 60%, reflecting the diversity of soil conditions across Cambodia. The DCP penetration index (DCPI, mm/blow), was also very variable, indicating the soils' sensitivity to different load conditions. This range of values provides an importance basis for establishing reliable correlation models.

3.1 Correlation Between DCP-9kg and In-situ CBR

The variation of penetration depth of the DCP was analyzed at depths of 50 mm (Fig. 4), 100 mm (Fig. 5), 150 mm (Fig. 6), 200 mm (Fig. 7), and 250 mm (Fig. 8), with the purpose of studying the relationship of the influence of the compressive strength of the In-situ CBR. Furthermore, the variation of penetration depth with the In-situ CBR was also analyzed by comparing it with the Australian standard.

Following scatter plots show how well the regression equations (lines) describe the observed relationship between the variation of settlement depth of the DCP and In-situ CBR for the subgrade soils, and to compare the proposed equation with the Australian standard equation.

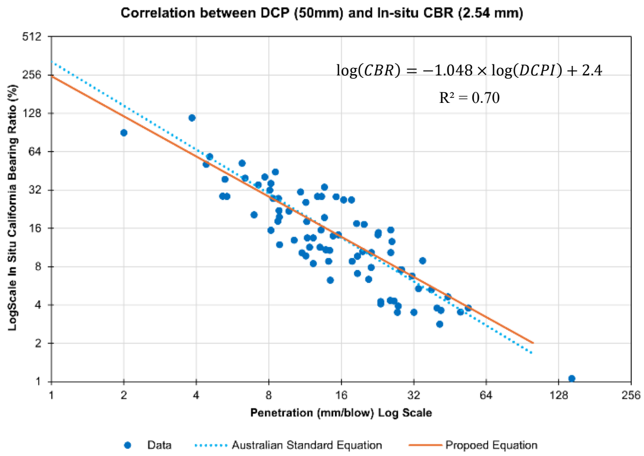

Fig. 4. Correlation between DCP-9kg (50mm) and in-situ CBR

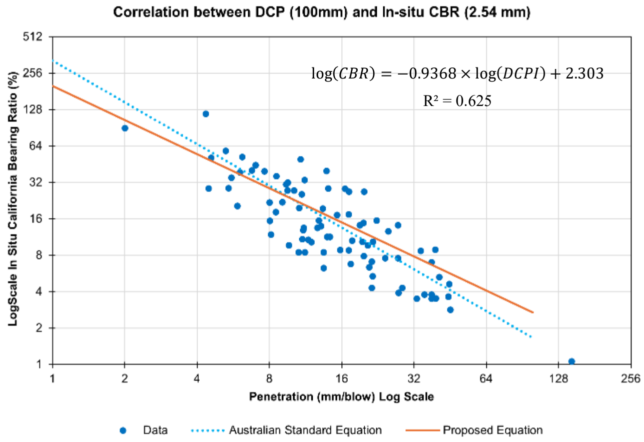

Fig. 5. Correlation between DCP-9kg (100mm) and in-situ CBR

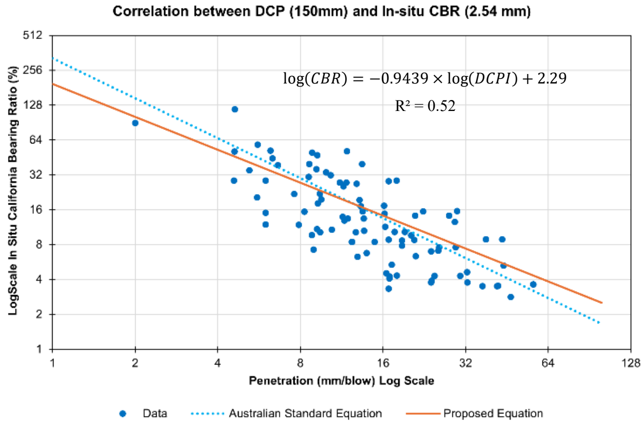

Fig. 6. Correlation between DCP-9kg (150mm) and in-situ CBR

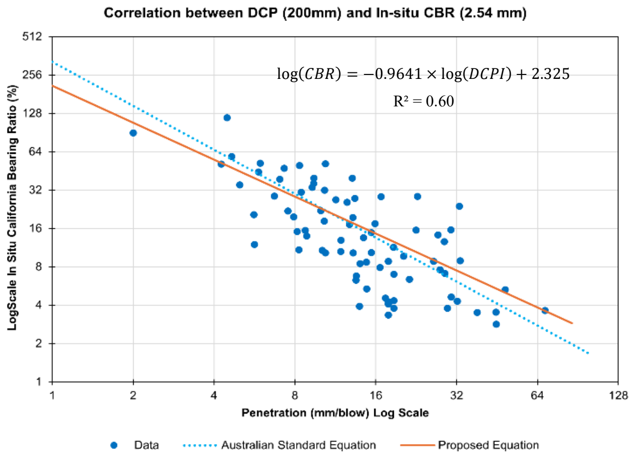

Fig. 7. Correlation between DCP-9kg (200mm) and in-situ CBR

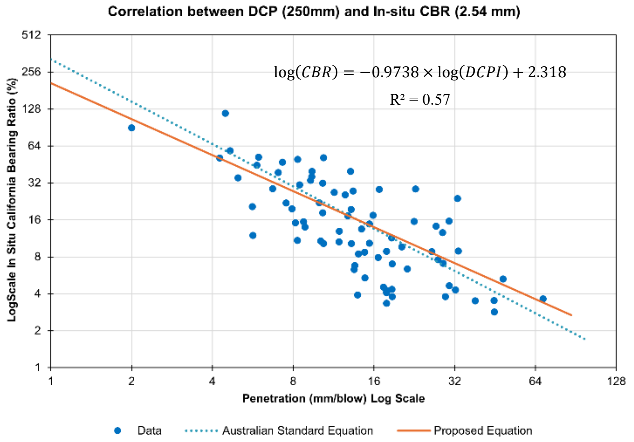

Fig. 8. Correlation between DCP-9kg (250mm) and in-situ CBR

Based on the data analysis, we observed that the correlation equation between the variation of 50mm settlement depth and In-situ CBR exhibits a strong correlation with the highest R² coefficient (R^2=0.70), where the calculated equation coefficient is approximately similar to the equation from the Australian standard (R^2=0.85). However, upon examining the relationship between these two technical parameters, it is evident that the 50mm settlement depth shows the strongest correlation, as demonstrated in Table 2 and Fig. 4. Nevertheless, some data points exhibit a degree of scattering and do not respond consistently. In this experiment, we investigated various soil types, but a noteworthy observation is that sandy soil showed results that did not strongly correspond to the correlation between these two technical parameters. Therefore, we can preliminarily propose an equation for predicting CBR strength at the site based on the relationship with 50mm settlement depth, applicable to soil types other than sandy soil.

Table 2. Summary of the calculated equation coefficients and the existing Australian equation

Description	Correlation Equation	R²
Equation Australian Standard [9]	$\log(CBR) = -1.1456 \times \log(DCPI) + 2.512$	0.85
Proposed Equation for DCP-50mm and CBR	$\log(CBR) = -1.048 \times \log(DCPI) + 2.4$	0.70
Proposed Equation for DCP-100mm and CBR	$\log(CBR) = -0.9368 \times \log(DCPI) + 2.303$	0.625
Proposed Equation for DCP-150mm and CBR	$\log(CBR) = -0.9438 \times \log(DCPI) + 2.29$	0.52
Proposed Equation for DCP-200mm and CBR	$\log(CBR) = -0.9641 \times \log(DCPI) + 2.325$	0.60
Proposed Equation for DCP-250mm and CBR	$\log(CBR) = -0.9739 \times \log(DCPI) + 2.318$	0.57

This new proposed equation (DCP-50mm) aligns with the Australian standard. When the CBR value ranges between 50% to 60%, the difference in CBR values between the Australian standard (Derived from equation Eq. 3) and the local experimental results (Proposed equation DCP-50mm) is approximately 5% to 7% (of the CBR value). Meanwhile, when the CBR value ranges between 1% and 5%, the difference in CBR values between the Australian standard and the local experimental results is approximately 0.35% to 0.5% (of the CBR value)) as shown in Fig. 9. However, the Australian standard equation aligns well with the equation derived from the local experiment in cases where CBR ranges between 8% and 32%.

The validation of the proposed equations, as in Table 2, has been evaluated through the above discussion. To assess the reliability of the derived predictive equation under real-world conditions, a field validation was conducted by comparing predicted CBR values against in-situ CBR measurements obtained from field testing. The resulting scatter plot is shown in Fig. 10 where each orange point represents a paired dataset of predicted versus actual in-situ CBR values. We observed that the validation of these two values is the predicted CBR values shows acceptable accuracy for practical engineering purposes, particularly for preliminary assessments or where rapid estimations are required, as shown by the regression line and R^2 value. However, the proposed equation also has certain limitations under specific assumed conditions, especially for certain soil types (e.g., sandy soils), where the model's predictions may be less accurate.

The model provides a statistically valid method for estimating in-situ CBR values from field measurements. The validation process confirms that the equation can serve as a reliable predictive tool in pavement and geotechnical applications, with reasonable consistency across a practical range of CBR values.

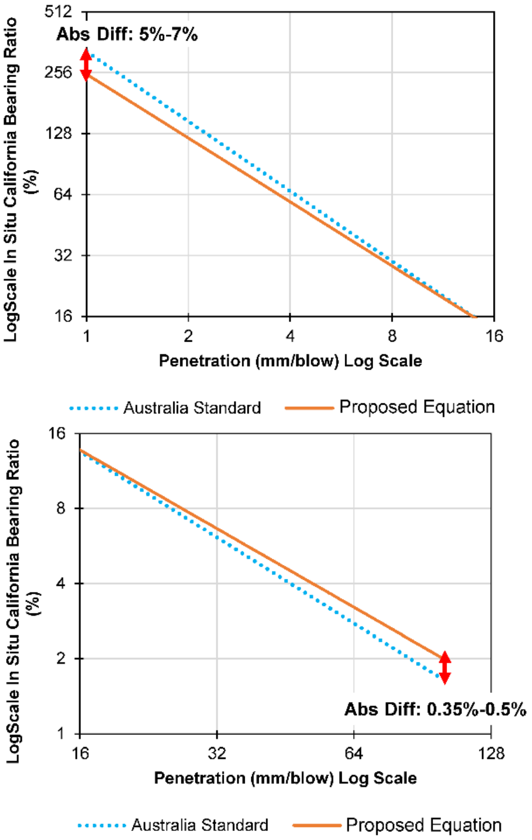

Fig. 9. The difference between CBR values of Australian equation and proposed equation (DCP-50mm)

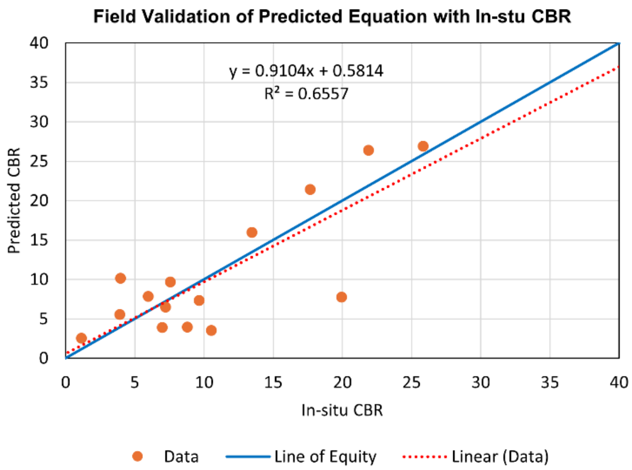

Fig. 10. Field validation of the predicted CBR with in-situ CBR

3.2 Correlation Between DCP-9kg and DCP-8kg

Taking into account the previous discussion and the experiment's aim of exploring the relationship between the DCP-9kg and DCP-8kg, this section describes the relationship between these two instruments. Fig. 11 illustrates the correlation between the CBR values of DCP-9kg derived from equation DCP50 and the CBR values of DCP-8kg derived from equation Eq. 2. We observe that the data from these two instruments exhibit a correlation with each other, which can be preliminarily used to predict In-situ CBR values by using the DCP-8kg to estimate the predicted In-situ CBR values of the DCP-9kg. However, based on the correlation equation with a coefficient of determination R^2=0.6219. This indicates a moderately strong linear relationship, where approximately 62.2% of the variability in the DCP-9kg readings can be explained by the DCP-8kg values. The slope of the regression line being less than unity suggests that, on average, the DCP-9kg yields slightly lower CBR values compared to the DCP-8kg for the same soil condition. The positive intercept of 1.24 implies a baseline elevation in the DCP-9kg results even when the DCP-8kg value is near zero, possibly due to higher energy input during impact.

While the general trend suggests strong correlation, the spread of data points indicates some level of inconsistency, especially at higher CBR values. These deviations may arise from several factors including soil variability, moisture content, and operational factors such as alignment or drop height consistency. Moreover, the deviation of the regression line from the line of equity highlights the necessity for calibration or correction when using measurements from different DCP setups interchangeably.

This analysis shows that the DCP-8kg test can be used to estimate DCP-9kg results with reasonable accuracy, though care should be taken when interpreting results at higher CBR values. Further analysis with larger datasets could improve the model's accuracy. However, from the visual comparison on scatter plot as shown in Fig. 11, we noted that the DCP-8kg tends to yield slightly lower values than the DCP-9kg when the CBR values below 10%, the DCP-8kg has the similar values with the DCP-9kg when the CBR values range between 10% to 20% and the DCP-8kg yields higher values than the DCP-9kg when CBR values exceeding 20%.

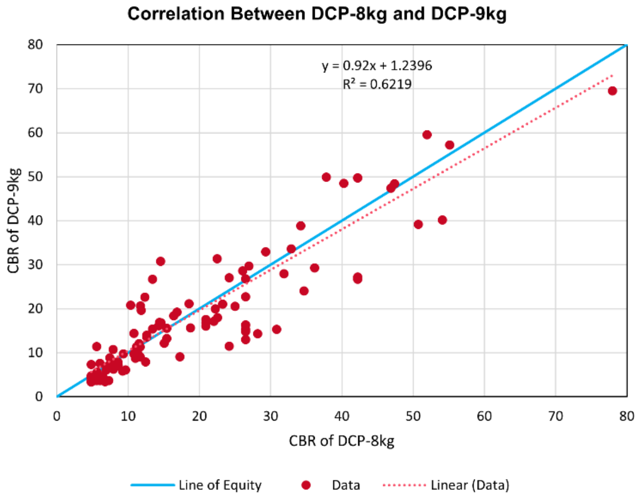

Fig. 11. Correlation Between DCP-8kg and DCP-9kg

4. CONCLUSION

The output of this study is a significant part of contributing to the evaluation of correlation equations between Dynamic Cone Penetrometer (DCP) and California Bearing Ratio (CBR) for subgrade soil materials used under Cambodian conditions, with the following conclusions:

- This research was conducted to confirm and establish standards for the use of the DCP (Dynamic Cone Penetrometer) tool to assess the quality of road layers, aiming to ensure the quality of road construction and maintenance. It provides concrete information about the condition and load-bearing capacity of soil layers.
- The research demonstrates the use of the DCP tool in analyzing CBR (California Bearing Ratio) values. It is observed that in-situ CBR values correlate with DCP penetration depth, which can be applied to predict actual CBR values at the site.
- The correlation equation between the DCP-9kg and in-situ CBR is effective at penetration depths ranging from 50mm to 150mm.
- The equation for the variation of 50mm penetration depth with in-situ CBR has the highest R^2 coefficient, with the equation's coefficient being approximately similar to the equation from the Australian standard.
- Based on the data analysis, the correlation equation between the DCP-9kg and In-situ CBR is:

$$\mathbf{Log}(\boldsymbol{CBR}) = -\mathbf{1.048} \times \mathbf{Log}(\boldsymbol{DCPI}) + \mathbf{2.4} \qquad \text{(Eq. 6)}$$

- Sandy soil types (sandy soil and fine-grained soil) cannot be applied, as the experimental results at the site show errors consistent with the equation Australian standard.
- Soil properties differ somewhat when compared to equation Australia standard, when CBR values range between 50% and 60%, the difference in CBR values between Australian standard and the local experimental results is approximately 5% to 7% (of the CBR value). When CBR values range between 1% and 5%, the difference in CBR values between Australia standard and the local experimental results is approximately 0.35% to 0.5% (of the CBR value). However, the equation Australian standard aligns with the equation derived from the local experiment in cases where CBR ranges between 8% and 32%.
- The study on the correlation between DCP-9kg and DCP-8kg confirms that the DCP-9kg data can be predicted from the DCP-8kg values with reasonable accuracy. However, the CBR from the DCP-8kg yields higher values than the DCP-9kg when CBR exceed 20%, though caution should be taken especially at higher CBR values. Further studies with larger datasets and controlled conditions are recommended to refine the conversion model and account for possible influencing factors.

Future study should focus on expanding data collection on specific soil type and across a broader range of soil types, including sandy and gravelly materials, larger data collection samples covering additional geographic locations within Cambodia to further validate and refine the correlation equation under varying environmental conditions, such as seasonal moisture fluctuations. Moreover, the future study should systematically investigate the impact of moisture content, soil compaction levels, seasonal climatic variations, and environmental conditions on the correlation between DCP and CBR values. Such analysis would facilitate adjustments or calibrations of the equations, enhancing their accuracy under varying environmental scenarios.

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