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Feasibility of Using Hand-Held Dynamic Cone Penetrometer for Analyzing Soft Subgrade Quickly

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16. Abstract

Colorado Department of Transportation (CDOT) does not have evidence how the Dynamic Cone Penetrometer (DCP) test results correlate to other test methods (say, *R*-value) for Colorado's pavement subgrade. Even, the correlation between single-mass, and dual-mass DCP (which are two ways of conducting DCP test) is still unknown. Pavement Mechanistic-Empirical Design (PMED) guide provides some correlations among different subgrade tests. However, those correlations are derived from national data. Research was thus needed to investigate the correlation between single-mass, and dual-mass DCP, and determine correlations among other subgrade tests for Colorado's pavement soils.

Suitable test sites were found out from ongoing construction projects. Both single-mass, and dual-mass DCP, CBR, *R*-value, and Soil Classification testing were conducted. Results show that the single–mass DCP produces an average of 62% penetration compared to that of dual–mass DCP. The calculated *R*– values and CBR using the PMED equations and the developed equations are statistically equal at 95% confidence interval. The developed regression equations to calculate the *R*–value yield more accurate and statistically equal *R*–value compared to that by the PMED equations. The *R*–value calculated by PMED equation using the soil's gradation, and plasticity index are less accurate compared to other methods. However, the *R*–value calculated by developed equation using the soil's gradation, and plasticity index are the most accurate compared to other methods.

Implementation Statement

The single-mass DCP can be used while assessing subgrade because it is now known that the single-mass DCP produces an average of 62% penetration compared to that of dual-mass DCP. DCP and CBR testing could be used to evaluate subgrade instead of *R*-value as these tests were found accurate and statistically equal to the PMED-calculation.

17. Keywords
Soils, Soft subgrade, DCP, CBR, R-value

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Executive Summary and Implementation Statement

Quick determination of soil's stiffness/strength is very often required during pavement construction, especially when soft subgrade is encountered. There are several ways of determining soil's stiffness/strength such as Dynamic Cone Penetrometer (DCP), Resistance value (*R*–value), California Bearing Ratio (CBR), resilient modulus (M_R), etc. DCP is a very quick test for determining in–situ soil's stiffness/strength. Currently, Colorado Department of Transportation (CDOT) does not have evidence how the DCP test results correlate to other test methods (say, *R*–value) for Colorado's pavement subgrade. Even, the correlation between single–mass, and dual–mass DCP (which are two ways of conducting DCP test) is still unknown. Pavement Mechanistic–Empirical Design (PMED) guide provides some correlations among different subgrade tests. However, those correlations are derived from national data. Research was thus needed to investigate the correlation between single–mass, and dual–mass DCP, and determine correlations among other subgrade tests for Colorado's pavement soils.

Suitable test sites were found out from ongoing construction projects. Both single–mass (10.1 lb/4.6 kg), and dual–mass (17.6 lb/8 kg) DCP, CBR, *R*–value, and soil classification testing were conducted. Results show that the single–mass DCP produces an average of 62% penetration compared to that of dual–mass DCP. The calculated *R*– values and CBR using the PMED equations and the developed equations are statistically equal at 95% confidence interval. The developed regression equations to calculate the *R*–value yield more accurate and statistically equal *R*–value compared to that by the PMED equations. The *R*–value calculated by PMED equation using the soil's gradation, and plasticity index are less accurate compared to other methods. However, the *R*–value calculated by developed equation using the soil's gradation, and plasticity index are the most accurate compared to other methods.

The single–mass DCP can be used while assessing subgrade because it is now known that the single–mass DCP produces an average of 62% penetration compared to that of dual–mass DCP. DCP and CBR testing could be used to evaluate subgrade instead of *R*–value as these tests were found accurate and statistically equal to the PMED–calculation.

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INTRODUCTION

Background

During pavement construction, occasionally soft subgrade is encountered. Solutions to mitigate the situation are frequently desired in a rapid time frame. For rapid mitigation, quick determination of the soil's strength is essential. Soil's strength can be determined in direct ways such as resilient modulus (M_R), or indirect ways such as Dynamic Cone Penetrometer (DCP), Resistance value (*R*–value), California Bearing Ratio (CBR), etc. The M_R of soil is the most accurate method of determining the strength of soil. Even for pavement design, M_R is the most desired input property of soil. It is determined by applying cyclic haversine loading at different deviatoric stresses and confining pressures on a laboratory compacted cylindrical sample using the American Association of State Highway and Transportation Officials (AASHTO), AASHTO T 307 test protocol. The ratio of the applied cyclic stress and the resulting strain is considered the M_R. However, this test is very costly considering the skilled manpower, testing time, and costly equipment. The Pavement Mechanistic–Empirical Design (PMED) software allows determination of M_R using one of the following options:

- *R*–value
- DCP Penetration (in./blow, or mm/blow)
- CBR (percent)
- Plasticity Index (PI) and Gradation (i.e., Percent Passing No. 200 sieve, P_{200})
- Layer Coefficient–a_i

The *R*–value is widely used in Colorado. The test procedure expresses a material's resistance to deformation as a function of the ratio of transmitted lateral pressure to applied vertical pressure. It is essentially a modified triaxial compression test. The test procedure to determine the *R*–value requires that the laboratory prepared samples are fabricated to a moisture and density condition representative of the worst possible in situ condition of a compacted subgrade following the AASHTO T 190 or American Society for Testing and Materials (ASTM), ASTM D 2844 test standards. The *R*–value is calculated from the ratio of the applied vertical pressure to the developed lateral pressure and is essentially a measure of the material's resistance to plastic flow. The M_R can be predicted as follows using the *R*–value:

$$M_R \text{ (psi)} = 1{,}155 + (555)(R\text{–value})$$

where, *R*–value is a value ranging from 0 to 100 and M_R is in psi.

The DCP may provide a tool to help quickly determining structural needs of the subgrade section. The DCP test provides a measure of in–situ resistance to penetration. The test is conducted by driving a metal cone into the ground by repeated striking it with a dual–mass (17.6 lb/8 kg) or single–mass (10.1 lb/4.6 kg) weight dropped from a height of 23 in. (575 mm), following the ASTM D6951 test protocol, as shown in Figure 1.

Figure 1. Conduction of DCP on Interstate 25 (I–25) in New Mexico

The penetration of the cone is measured after each blow and is recorded. Once the penetration rate becomes stable with the blow, the test is stopped. DCP test results can be correlated to M_R, which is used by the current PMED software, as follows:

Equation 1

$$M_R\,(\text{psi}) = 2555\left(\frac{292}{DCP^{1.12}}\right)^{0.64}$$

Formula 1

where, DCP is in mm/blow and M_R is in psi.

The CBR test is another simple strength test that compares the bearing capacity of a material with that of a well–graded crushed stone (thus, a high quality crushed stone material should have a CBR of 100). AASHTO T 193 and ASTM D 1883 test standards are used to determine the CBR value. It is primarily intended for, but not limited to, evaluating the strength of cohesive materials having maximum particle sizes less than 0.75 in. (19 mm). CBR test result can be correlated to M_R, which is used by the current PMED software, as follows:

Equation 2

$$M_R\,(\text{psi}) = 2555\left(CBR\right)^{0.64}$$

Strength of soil can also be determined using the soil gradation and PI, which is used by the current PMED software, as follows:

Equation 3

$$M_R\,(\text{psi}) = 2,555\left(\frac{75}{1+0.728\left(P_{200}\right)\left(PI\right)}\right)^{0.64}$$

Formula 2

where,

P_{200} = Percent passing No. 200 sieve (used as decimal)

PI = Plasticity Index

These tests are also related among them as follows:

$$CBR = \frac{75}{1 + 0.728(P_{200})(PI)}$$

$$CBR = \frac{292}{DCP^{1.12}}$$

Rearranging the above equations, the *R*–value can be determined using one of the following equations:

$$R = 174(DCP)^{-0.7168} - 2.08$$

$$R = 4.6(CBR)^{0.64} - 2.08$$

$$R = 4.6\left(\frac{75}{1 + 0.728(P_{200})(PI)}\right)^{0.64} - 2.08$$

The above discussion shows there are separate ways of strength characterization of subgrade, which is used by the current PMED software. However, the PMED software manual mentions that "If the resilient modulus values are estimated from the DCP or other tests, those values may be used as inputs to the PMED software, but should be checked based on local material correlations and adjusted to laboratory conditions." Therefore, local study is essential for the most accurate characterization of soil. DCP, CBR, *R*–value, P_{200}, PI, etc. tests results can provide adequate information to make decisions to restart stalled construction projects. The data generated by these tests can either be used independently to determine strength of subgrade/foundation or analyzed and processed as input to the PMED software. The goal is to establish a Colorado procedure that employs the PMED approach using DCP, CBR, and P_{200} and PI etc. for quick and reasonably accurate analysis of subgrade stiffness and strength if feasible.

Objectives

Specific objectives are mentioned below:

1. To evaluate the merit of using a dual–mass DCP versus a single–mass DCP.
2. To complete comparison tests with the *R*–value that measures the in–situ strength of pavement foundation materials in various construction projects.
3. To establish a range of DCP, CBR, and P_{200} and PI measured stiffness and strength values for pavement foundation materials that CDOT can use as input to the PMED program and in defining target values for the development of pilot specifications.
4. To develop a synthesis of past research studies completed on this topic and utilize information gathered to establish guidelines in using DCP, CBR, and P_{200} and PI.

Research Methodology

To accomplish the above objectives, the proposed research methodology is shown in Figure 2. The following tasks are completed in accordance with the objectives stated above.

1. Develop a detailed plan and schedule of activities to be followed in completing the research work; present the activity plan and schedule to the CDOT Study Panel for approval before performing the work; provide a clear and definitive statement of what they should accomplish with the data that they collect, what the data means, and how the data will be used to address the soft subgrade conditions at construction sites;
2. Perform a literature search to gather relevant information to help accomplish the objectives of the study; review applicable published information on DCP that may be of use to Colorado; and review other information from Federal Highway Administration (FHWA), other national research organizations/ institutes, state and local government agencies, and academic institutions that may be useful in achieving the objectives of this research project;
3. Based on the results of the literature review, prepare a synthesis and develop guidelines for using DCP, CBR, and P_{200} and PI results as input to the PMED program;
4. Coordinate with CDOT Study Panel Leader/Champion/Members for possible test sites selected from different construction projects that were active during the scheduled field work;

5. Perform tests using DCP, CBR, and P_{200} and PI and *R*–value equipment to evaluate the subgrade strength of various roadway construction projects and analyze/correlate the test results to determine the possibility of replacing the traditional test parameters and equipment with the DCP method; and

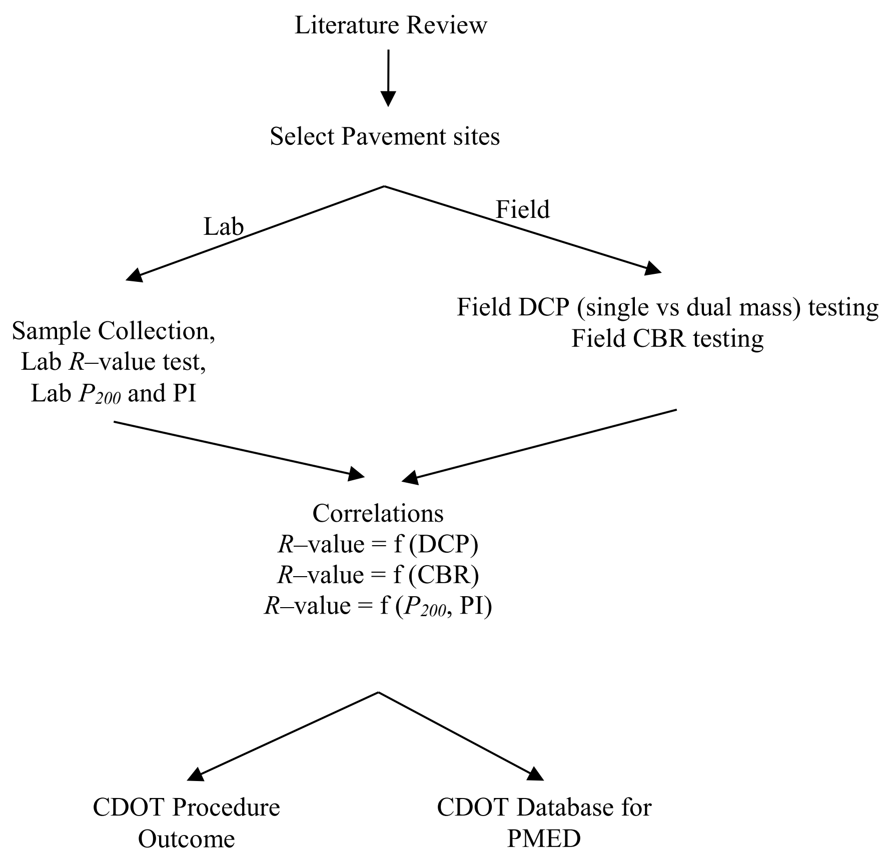

Figure 2. Research Methodology Adopted in this Study

6. Establish a correlation of the penetration index values obtained by the DCP, CBR, and P_{200} and PI with *R*–values derived from these demonstration/comparison tests using applicable standard procedures to determine soil strength properties.

LITERATURE REVIEW

DCP test has been used widely for field exploration and for measuring the strength of unbound layers of subgrade soils and granular materials. There are several advantages of DCP testing. The most important advantage of the DCP device is that it can provide a continuous record of relative soil strength with depth. DCP device is very economical and easy to operate. It is capable of providing repeatable results and rapid property assessment. It can also be used for the assessment of compaction quality for sand backfilling.

On the contrary, there are some problems associated with DCP test such as the removal of the instrument after deep tests in some cases and the test results are influenced by the maximum aggregate size. Ayers et al. (1989) suggest that the DCP is no longer a viable test where the maximum aggregate size is of around 1.5 in. (38 mm). However, Webster et al. (1992) reports that DCP is not suitable for soils having significant amount of aggregates greater than 50 mm. Besides, the physical raise and drop of the hammer might be a source of error in a DCPT. Ayers et al. (1989) also stated that care should be taken during the test so that no downward or upward force is exerted on the handle by the worker and free fall of the hammer is not influenced by hand movement. The manual reading and recording the number of blows and depth of the DCP could also cause some mistakes.

There have been several studies on the correlations of the DCP test results with resilient modulus, CBR, unconfined compressive strength, and shear strengths, as well as performance evaluation of pavement layer. Hassan (1996) studied existing correlations between DCP and resilient modulus for sand and fine–grained soils. They prepared 6 in. (150 mm) diameter and 400 mm height specimen in the laboratory using Oklahoma soils. The experimental results show that in fine–grained soils, the increase in moisture content above the optimum values significantly increase DCP, while an increase in soil dry density decreases DCP. However, Puppala (2008) warned that the majority of the correlations were site specific and empirical in nature and careful examination and engineering decision are required for their use for other soils. A correlation between the M_R from laboratory test and field DCP may be very helpful.

Some other researchers also studied to determine the correlation among different tests. New Mexico Department of Transportation (NMDOT) conducted Clegg Impact Hammer (CIH), GeoGauge, and DCP tests to determine the in–situ stiffness of subgrade (Lenke et al. 2005). They also performed *R*–value test to develop correlation among them. They found that GeoGauge with sand, DCP, and CIH can predict *R*–value. The GeoGauge without sand and the NMDOT soil classification based empirical chart can predict *R*–value of 0.89. They also found that GeoGauge produces the most consistent results compared to DCP and CIH. In fine grained soil, CIH test repeatability is better than that of DCP; this is opposite in course grained soil.

Hamid et al. (2015) conducted DCP and nuclear density test in two areas of Saudi Arabia. They found that there is a good correlation between the dry density obtained from the nuclear gauge and the DCP readings, which proves that the DCP is an effective and reliable tool in the assessment of in situ compaction of sand backfills.

Ohio Research Institute for Transportation and the Environment collected DCP data from 10 road projects in Ohio (Wu and Sargand 2007). They found that the DCP is a viable alternative device to evaluate in–situ base and subgrade materials during construction. They also concluded that engineers can use the DCP to quantify the construction quality of the as–built materials. George and Uddin (2000) correlated automated DCP predicted resilient modulus with the laboratory determined resilient modulus for 12 pavement sites in Mississippi. Their DCP results could weakly correlate the modulus of soils.

Hasan et al. (2016) conducted DCP test and laboratory resilient modulus tests in New Mexico and found that the DCP predicted resilient modulus is 1.8 times of that from laboratory resilient modulus test. Some correlations obtained by different researcher are listed in Table 1.

Table 1. Literature Summary

Reference	Agency	Correlations
Smith and Pratt (1983)	Australian Road Research Board	Log (CBR) = 2.56 – 1.15 Log (DCP)
Wu (1987)	North Carolina Department of Transportation (NCDOT)	Log (CBR) = 2.64 – 1.08 Log (DCP)
Harison (1989)	Australian Road Research Board	Log (CBR) = 2.81 – 1.32 Log (DCP)
Webster et al. (1992)	U.S. Army Corps of Engineers (USACE)	Log (CBR) = 2.465 – 1.12 Log (DCP)
Webster et al. (1994)	U.S. Army Corps of Engineers (USACE)	$CBR = \frac{1}{0.002871(DCP)}$ **Formula 3** for high plastic clay $CBR = \frac{1}{(0.017019DCP)^2}$ **Formula 4** for low plastic clay
Kleyn (1992)	—	Log (CBR) = 2.62 – 1.27 Log (DCP)
Livneh et al. (1992)	—	Log (CBR) = 2.20 – 0.71 Log (DCP)
Ese et al. (1994)	Norwegian Road Research Laboratory	Log (CBR) = 2.669 – 1.065 Log (DCP) Log CBR_{lab} = 2.438 – 1.65 Log DCP
Coonse (1999)	—	Log (CBR_{field}) = 2.53 – 1.14 Log (DCP)

The above discussion especially Table 1 shows that there are numerous researches on pavement subgrade. However, different researches produce different outcomes which dictates the need of current research that pavement subgrade should be evaluated locally. This study thus attempts to evaluate the Colorado's pavement subgrade.

MATERIALS AND TESTING

Pavement Sites

Several suitable pavement sites have been found out in Region 2 (Pueblo Area). DCP, and CBR testing were conducted on sites. Samples were collected. *R*–value, and P_{200} and PI testing were conducted in laboratory. This section presents the sites, and testing conducted.

US 50. The site is located at the US Highway 50/Colorado 45 interchange in the city of Pueblo. This is a new pavement construction site replacing the westbound bridge over Wildhorse Dry Creek. Figure 3 shows the Eastbound of this highway. The soil type is A–1–a.

Figure 3. US 50 Highway in Pueblo, CO.

Rio Grande River North. This site (Figure 4) is the haul way of construction vehicles working for the Rio Grande river improvement project. As discussed with the site manager, this road was compacted to access the construction sites. The soil type is A–2–4(0).

Figure 4. Riogrande River North Site in Pueblo, CO.

Rio Grande River South. This site (Figure 5) is another haul way of construction vehicles working for the Rio Grande river improvement project. As discussed with the site manager, this road was compacted to access the construction sites. The soil type is A–2–4(0).

Figure 5. Riogrande River South Site in Pueblo, CO.

Gleenwood Blvd. This site (Figure 6) is a waterline replacement project by the Board of Water Works Pueblo. The existing old pipelines were taken off, and new pipelines were placed. After applying flow fill, there is a 6.0 in. (150 mm) subgrade on which asphalt layer is to be paved. Testing was conducted on the subgrade layer. The soil type is A–6(5).

Figure 6. Gleenwood Street Test Site in Pueblo, CO.

Orman Street. Similar to the Gleenwood site, the Orman Street (Figure 7) is a waterline replacement project by the Board of Water Works Pueblo. The existing old pipelines were taken off, and new pipelines were placed. After applying flow fill, there is a 6.0 in. (150 mm) subgrade on which asphalt layer is to be paved. Testing was conducted on the subgrade layer. The soil type is A–2–4(0).

Figure 7. Orman Street Test Site in Pueblo, CO.

School Parking Lot. This site is located in Pueblo in the Parking lot (Figure 8) of Bella Villa Expeditionary School. The soil layer was compacted by the contractor and was ready to be paved. The soil type is A–6(5).

Figure 8. School Parking Lot Test Site in Pueblo, CO.

Main Street. This site is located in Pueblo in Main Street (Figure 9) close to Pueblo Riverwalk. The soil type is A–6(3). A part of the street was replaced by new materials and decorative surface was made to attract more tourists. The soil layer was compacted by the contractor and was ready to be paved.

Figure 9. Main Street Test Site in Pueblo, CO.

Denver Street. This site is located in Pueblo in Denver Street (Figure 10), a gas line replacement project by Xcel Energy. The soil layer was compacted by the contractor and was ready to be paved. The soil type is A–6(2).

Figure 10. Denver Street Test Site in Pueblo, CO.

I–25 South Gap. This site is located at Interstate 25, station 2417 (Figure 11). A new lane was being added both ways from Monument to Castle Rock. The soil layer was compacted by the contractor and was ready for base layer. The soil type is A–2–4(0).

Figure 11. Interstate 25 South Gap Test Site in Larkspur

Sample Collection

Representative samples have been collected from each of the selected test sites for laboratory *R*–value testing at the Ground Engineering and Soil Classification testing at the CSU–Pueblo laboratory. A test sample collected from US 50 is shown in Figure 12.

Figure 12. Sample from US 50 and Pueblo Blvd.

Dynamic Cone Penetration (DCP) Testing

DCP test provides a measure of a material's in–situ resistance to penetration following the ASTM D 6951. DCP testing device is shown in Figure 13. It consists of a rod with a standard sliding weight called hammer attached to the top and a disposable cone tip to penetrate the soil on the bottom. The weight of the hammer is 17.6 lb (8 kg) for dual–mass, 10.1 lb (4.6 kg) for single–mass, and it slides on a 0.64–in. (16–mm) driving rod. The tip has an included angle of 60 degrees and a diameter at the base of 0.80 in. (20 mm). The hammer is lifted up and dropped from a standard height of 23 in. (575) mm which causes the cone at the bottom of the device to be forced into the ground. The weight is dropped multiple times till there are enough blows to determine the soil characteristics or the cone has reached a depth of interest. With each blow the new depth of the device is recorded. The depths and corresponding blow numbers are then plotted in Microsoft Excel where a best linear fit is applied. The slope is considered the DCP value and is usually measured in mm/blow or in./blow. Both single–mass and dual–mass DCP testing have been conducted at each of the sites.

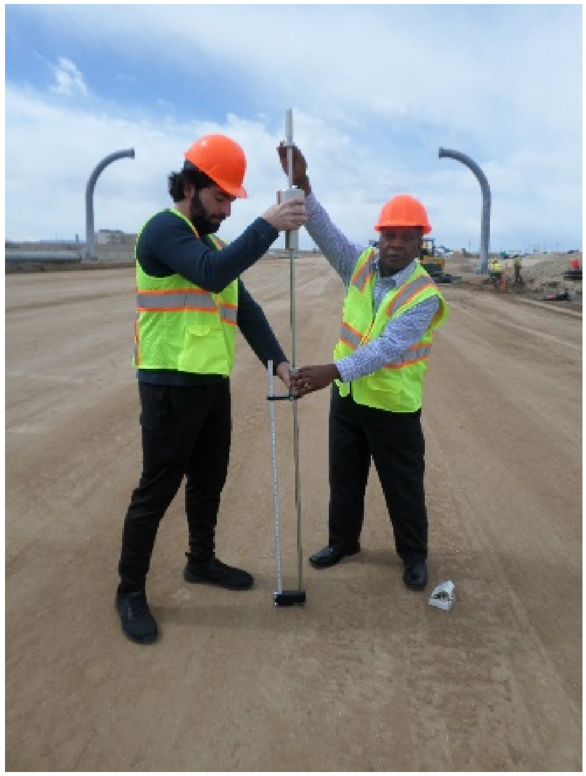

Figure 13. DCP testing

An example of penetration with the blow for a dual-mass DCP testing at a point of a site is shown in Figure 14. The penetration increases with the number of blow. At the beginning of the penetration, the penetration rate (penetration per blow) is very high and irregular. After about 4 to 6 blows, a consistent penetration rate (penetration per blow) is mostly obtained. In other words, the penetration versus number of blow curve becomes linear. The slope of the penetration versus number of blow curve is then considered the DCP value at this point.

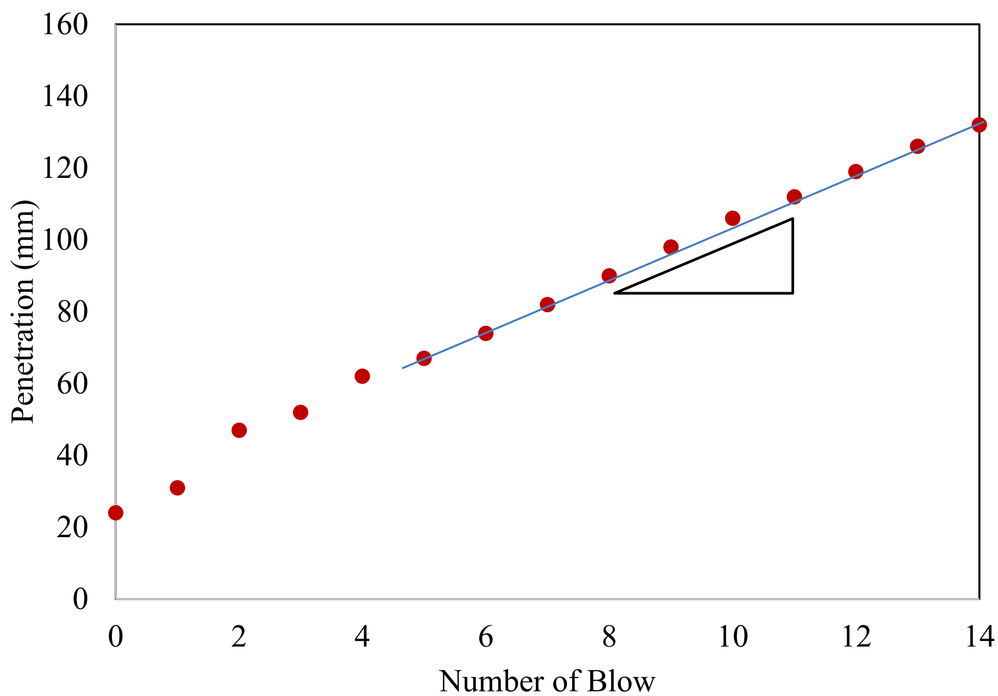

Figure 14. Variation of penetration with the number of blow of a point

In–situ California Bearing Ratio (CBR) Testing

CBR is a penetration test for evaluation of the mechanical strength of natural ground, subgrades and base courses beneath new carriageway construction. A 1.95–in. (49 mm) diameter piston is penetrated 0.1 in. (2.5 mm) in the soil, and the resulting stress is measured (Figure 15). The resulting stress is then compared with the stress (1,000 psi or 6.89 MPa) required to penetrate the piston by 0.1 in. (2.5 mm) in a standard rock. The ratio of the stress is expressed as a percentage, and called CBR. The following procedure was followed:

- Remove from the test area any material which is not representative of the soil to be tested, and prepare a circular area of about 20 in. (500 mm) in diameter such that it is flat and horizontal, taking special care with the central area on which the plunger will bear.
- Position the reaction load and its supports such as the jacks when using a vehicle, so that the cylindrical piston after assembly is directly over the central area to be tested.

- Fit the jack (in the fully retracted position), extension rods, force–measurement device and cylindrical plunger on to the reaction load such that the whole assembly hangs vertically with the lower face of the plunger about 1 in. (25 mm) above the soil surface to be tested.
- Carefully lower the cylindrical plunger so that its lower surface just comes into contact with the soil. Ensure the assembly is vertical.
- Place a sufficient number of surcharge discs, one on top of another, around the central test area and plunger to correspond with the specified overburden pressure for the test. Select the number nearest to the specified value.
- Record the reading of the force–measuring device as the initial zero reading (because the seating force is not taken into account during the test) or reset the force measurement device to read zero.
- Reset to zero the penetration measurement gauge or record its initial zero reading.
- Start the test so that the plunger penetrates the soil at a uniform rate of 0.04 in. (1 ± 0.2 mm) per minute, and at the same instant start the clock.
- Record the force measurement in kN at intervals of penetration of 0.01 in. (0.25 mm), to a total penetration not exceeding 7.5 mm.

Testing setup — Penetration after testing

Figure 15. In–situ CBR Testing to Measure the Required Load for Certain Penetration

R–value Testing

The Resistance Value (*R*–value) test is a material stiffness test conducted by following the AASHTO T 190 or the ASTM D 2844. The test procedure expresses a material's resistance to deformation as a function of the ratio of transmitted lateral pressure to applied vertical pressure. Materials tested are assigned an *R*–value.

The *R*–value test was developed by the California Division of Highways and first reported in the late 1940's. During this time rutting (or shoving) in the wheel tracks was a primary concern and the *R*–value test was developed as an improvement on the CBR test.

The test procedure to determine *R*–value requires that the laboratory prepared samples are fabricated to a moisture and density condition representative of the worst possible in situ condition of a compacted subgrade. The *R*–value is calculated from the ratio of the applied vertical pressure to the developed lateral pressure and is essentially a measure of the material's resistance to plastic flow. The testing apparatus for *R*–value test is shown in Figure 16 below:

$$R = 100 - \left\{ \frac{100}{\left(\frac{2.5}{D}\right)\left[\left(\frac{P_V}{P_H}\right) - 1\right] + 1} \right\}$$

where:

R = Resistance value

P_V = Applied vertical pressure

P_H = Transmitted horizontal pressure

D = Displacement of stabilometer fluid necessary to increase horizontal pressure from 5 to 100 psi (34.5 kPa to 700 kPa).

Figure 16. *R*–value Testing Equipment at CDOT, Pueblo.

Soil Classification

For soil classification, liquid limit, plastic limit, and gradation have been determined in the laboratory as shown in Figure 17.

Figure 17. Soil Gradation.

RESULTS AND DISCUSSION

Dual– versus Single–Mass DCP

DCP testing was conducted on 17 testing sites. The average penetration for dual–mass DCP vary from 3.9 mm/blow to 55.7 mm/blow from site to site, with a combined average penetration of 12.0 mm/blow. The single–mass DCP vary from 2.2 mm/blow (0.09 in./blow) to 20.4 mm/blow (0.82 in./blow) from site to site, with a combined average penetration of 7.4 mm/blow (0.3 in./blow). The penetration by single–mass vary from 37% to 76% to that of the dual–mass as shown in Figure 18.

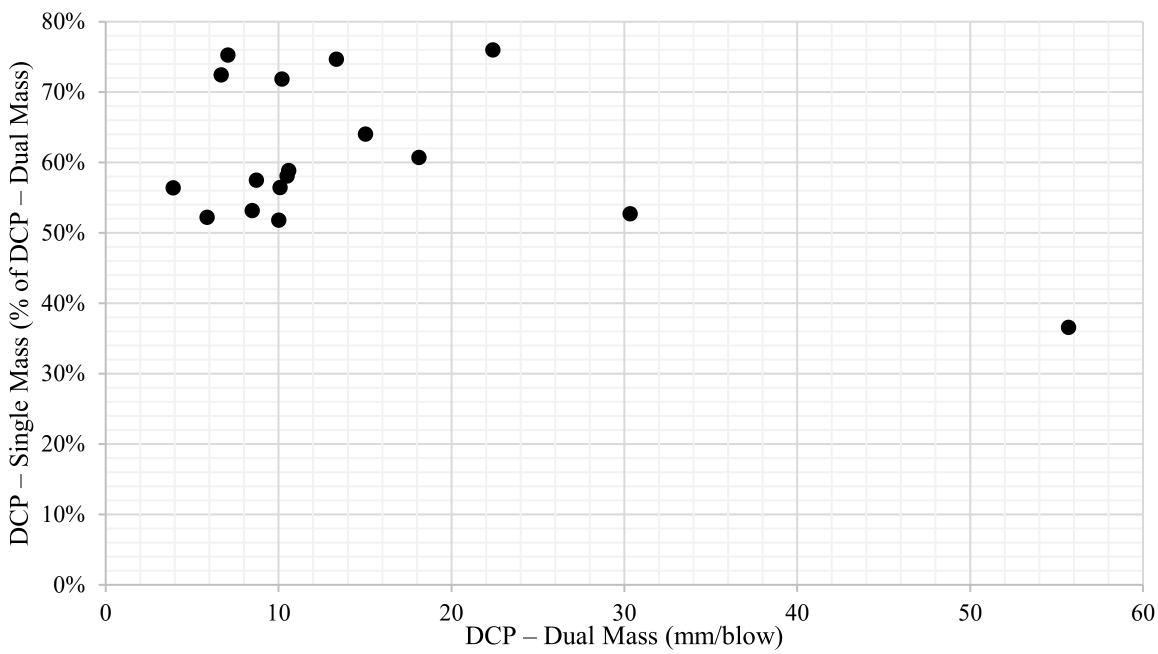

Figure 18. Percentage of Single–Mass Penetration compared to Dual–mass

Recalling the mass used in dual–mass DCP is 17.6 lb (8.0 kg), and in single–mass DCP is 10.1 lb (4.6 kg), the ratio of energy used in single–mass DCP is 57.5% of that in dual–mass. Thus, theoretically, single–mass DCP should produce 57.5% penetration of that in dual–mass. This study found the single–mass DCP produces an average of 62% penetration of that in dual–mass.

Examination of the PMED Equations

The dual–mass penetration was used to calculate the CBR value. The calculated–CBR value and the measured CBR values were compared. Figure 19 shows the comparison where it apparent that the calculated CBR and the measured CBR are fairly well–correlated. However, the statistically best–fit regression linear line is very close to the equal line. The equal line represents the line where the measured and the calculated values are equal. It is seen from Figure 19 that most of the data points are below the equal line. This means the PMED equation over estimates the CBR values compared to the measured CBR values.

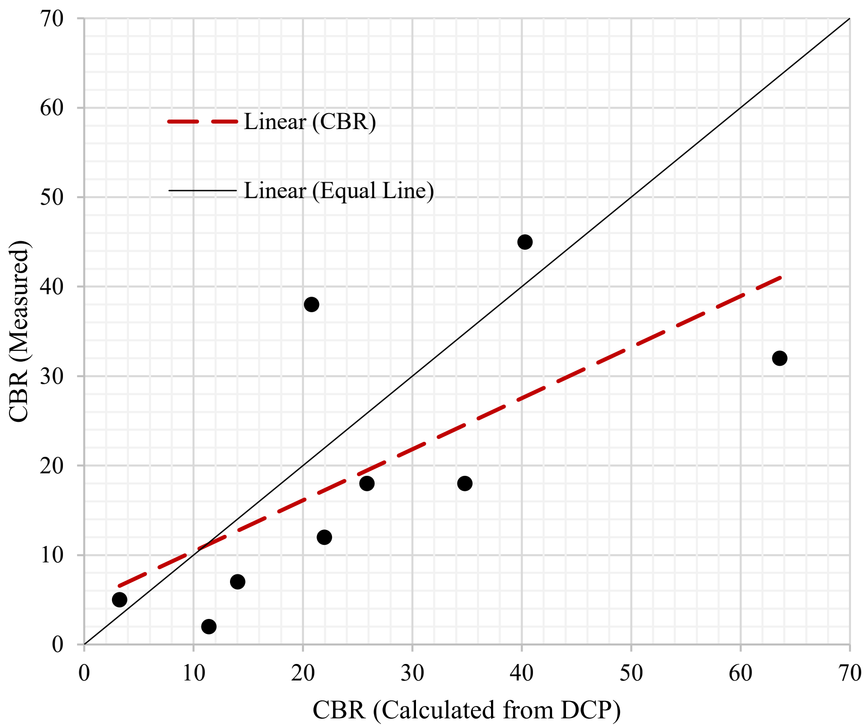

Figure 19. Measured versus Dual–Mass–DCP Calcualted CBR value

The dual–mass penetration was used to calculate the *R*–value, and the calculated *R*–value and the measured *R*–values were compared. Figure 20 shows that the calculated *R*–value and the measured R–value are well–correlated with the best–fit linear line is close to the equal line. This means the measured *R*–value well–fit the calculated *R*–value. Another observation is that the PMED equation to calculate R-value using DCP under predicts it which is conservative.

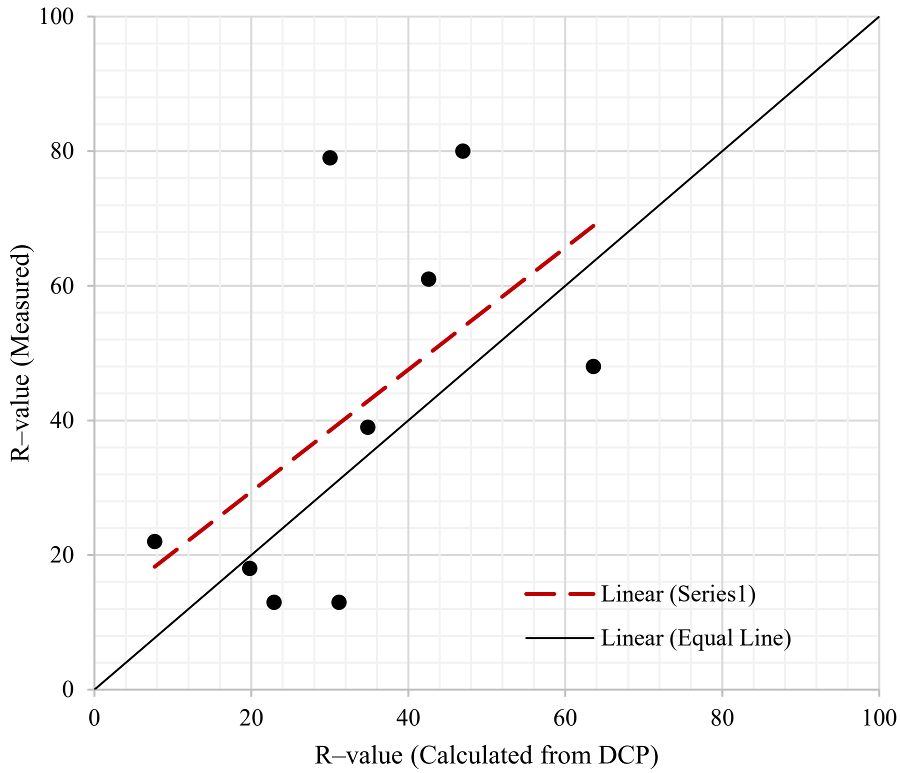

Figure 20. Measured versus Calcualted *R*–value using the PMED equation

The P_{200} and *PI* were used to calculate the *R*–value. The calculated *R*–value were compared with the measured *R*–value. Figure 21 shows that the calculated *R*–value and the measured *R*–value are not well–correlated with the best–fit linear line although close to the equal line. This means the measured *R*–value does not well–fit the calculated *R*–value.

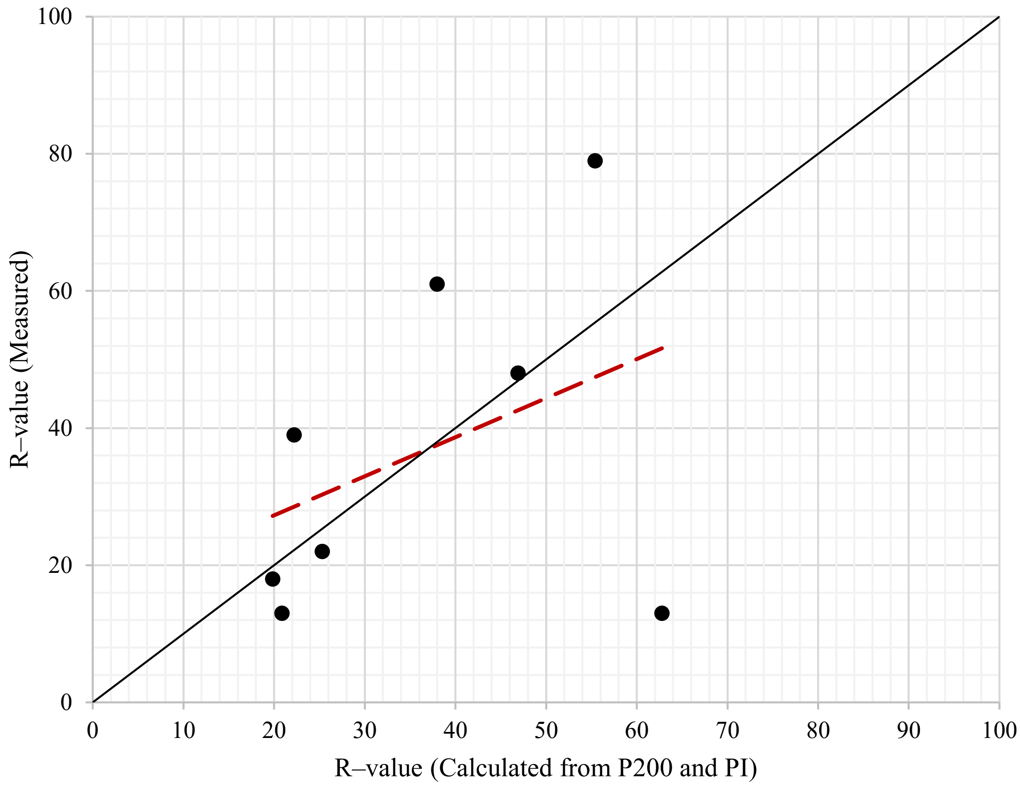

Figure 21. Measured versus Calcualted *R*–value using the PMED equation

Correlations

The summary of the test data from the nine sites (where all types of testing were conducted) is listed in Table 2. The measured *R*–value ranges from 13 to 80; DCP (dual mass) ranges 3.9 to 55.7 mm/blow; CBR ranges 2 to 45 and so on. Soil types vary from A–1–a to A–6(5).

Table 2. Measured Test Results

Sites	Soil Types	DCP– Dual (mm/blow)	DCP– Single (mm/blow)	CBR	*R*–value	P_{200}	PI
US 50	A-1-a	5.86	3.06	45	80	7.1	-
Rio Grande North	A–2–4(0)	6.68	4.84	18	82	12.1	-
Rio Grande South	A–2–4(0)	10.08	5.69	12	61	26.6	8
Gleenwood	A-6(5)	15.03	9.63	7	13	58.2	12
Orman	A-2-4(0)	10.58	6.23	30	79	10.3	6
I-25	A-2-4(0)	3.9	2.2	32	48	16.9	7
School	A-6(5)	18.11	11	2	18	58.5	13
Main	A-6(3)	8.71	5.01	18	39	44.8	14
Denver	A-6(2)	55.69	20.37	5	22	45.1	11

These data were used in regression analysis, and the obtained regression equations along with their coefficients of regression are listed below:

Single Mass DCP = 0.62 x Dual Mass DCP

$R = 330.66(\text{DCP})^{-0.924}$ (coefficient of regression = 0.43)

$R = 20.78 \ln(\text{CBR}) - 3.544$ (coefficient of regression = 0.57)

$R = 72.14 - 1.50\, P_{200} + 235\, \text{PI}$ (coefficient of regression = 0.79)

$\text{CBR} = -21.89 \ln(\text{DCP}) + 68.30$ (coefficient of regression = 0.59)

where

DCP is in mm/blow of the dual mass DCP.

P_{200} = Passing No. 200 sieve expressed in decimal.

PI = Plasticity index

CBR = California Bearing Ratio (0 to 100)

The calculated *R*–Value by the PMED equation using the P_{200} and PI equations are not well fit. However, the developed equation to calculate the *R*–value using the P_{200} and PI yield the highest coefficient of regression (0.79). Note that these equations are for use with recently compacted embankment or subgrade per the test areas. Different correlations are presented in Figures 22 to 24.

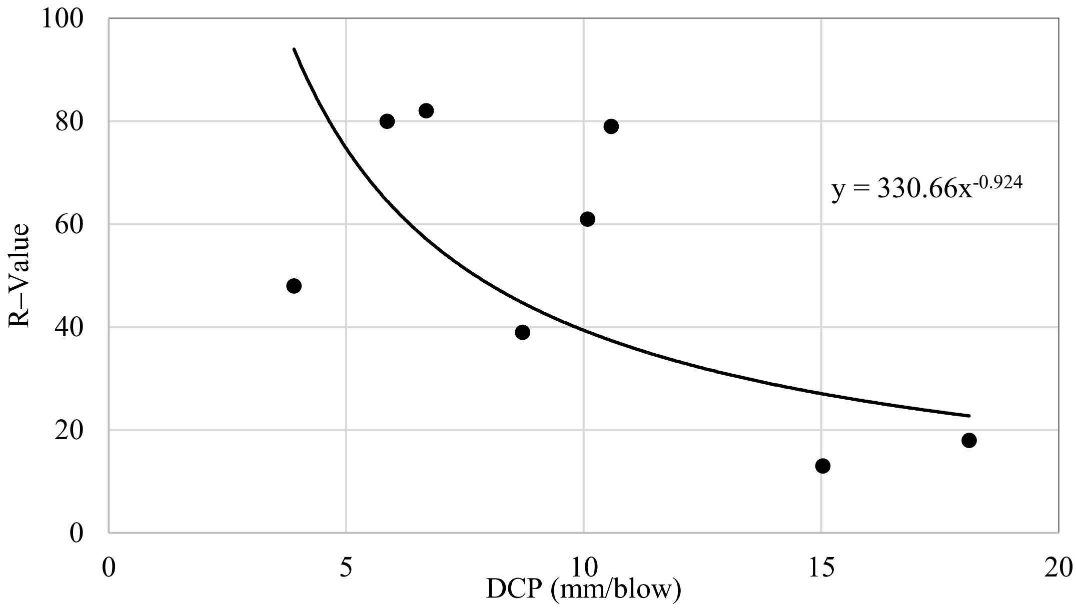

Figure 22. Variations of R–value with Dual–Mass DCP

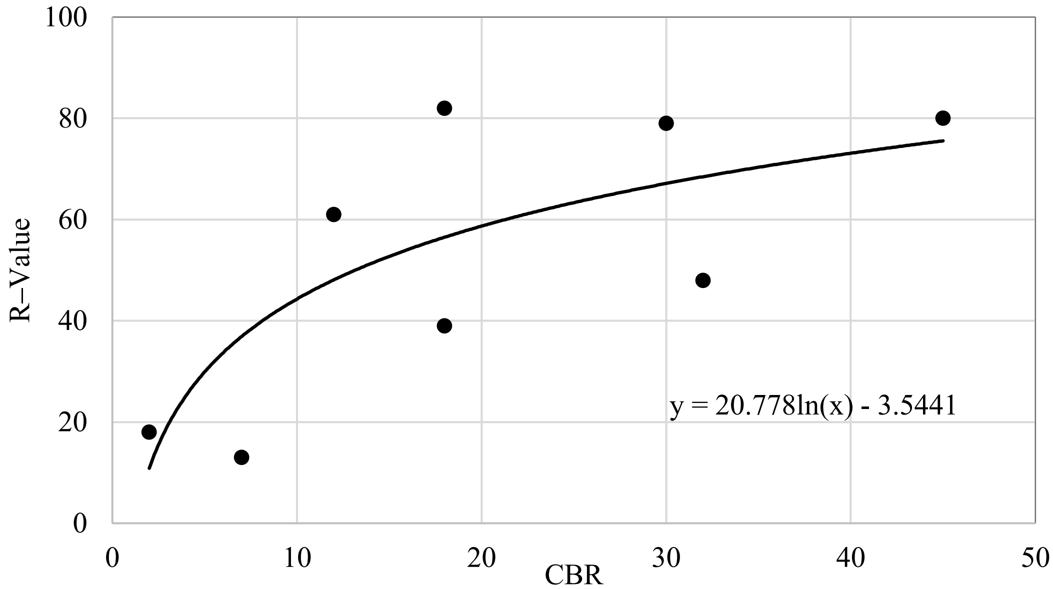

Figure 23. Variations of R–value with CBR

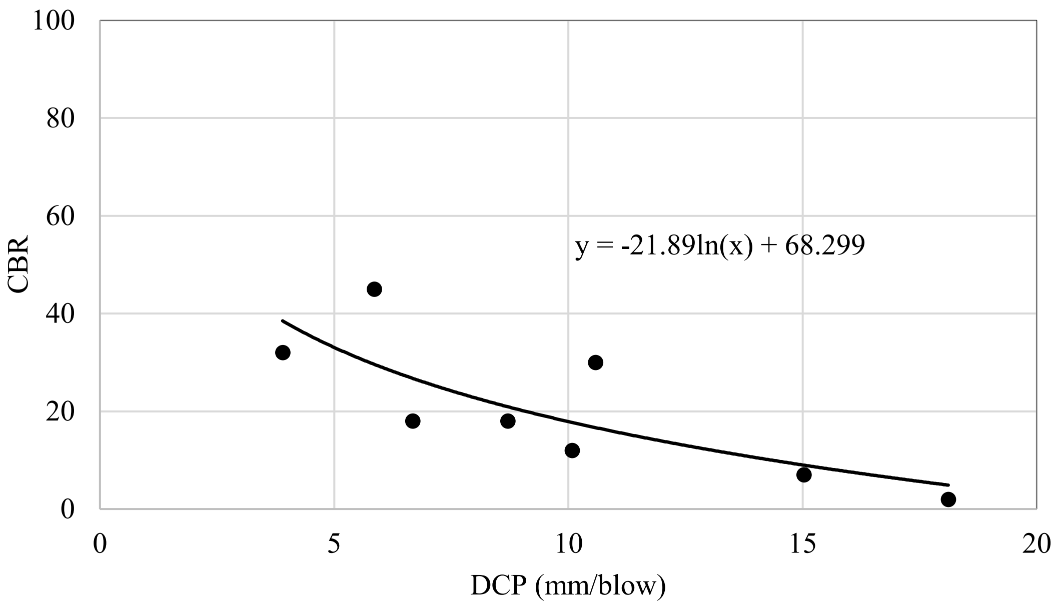

Figure 24. Variations of CBR with Dual–Mass DCP

The comparisons of *R*–value such as the measured *R*–value, the predicted *R*–value by PMED equations and the predicted *R*–value by the developed equations are listed in Table 3. Values listed in the parentheses are the predicted *R*–value minus the measured *R*–value. A positive error means the predicted *R*–value is larger than the measured value. A negative error means the predicted *R*–value is smaller than the measured *R*–value.

Table 3. Comparison of R–values

Sites	Soil Types	Measured *R*–value	Predicted *R*–value by PMED Equations			Predicted *R*–value by Developed Equations		
			using DCP	using CBR	using P_{200} and PI	using DCP	using CBR	using P_{200} and PI
US 50	A–1–a	80	47 (–33)	50 (–30)	–	65 (–15)	76 (–4)	–
Rio Grande North	A–2–4(0)	82	43 (–39)	27 (–55)	38 (–44)	57 (–25)	57 (–25)	-
Rio Grande South	A–2–4(0)	61	31 (–30)	20 (–30)	21 (–40)	39 (–22)	48 (–13)	51 (–10)
Gleenwood	A–6(5)	13	23 (10)	14 (1)	63 (50)	27 (14)	37 (24)	13 (0)
Orman	A–2–4(0)	79	30 (–49)	45 (–34)	55 (–24)	37 (–42)	67 (–12)	71 (-8)
I–25	A–2–4(0)	48	64 (16)	40 (–8)	47 (–8)	94 (46)	68 (20)	63 (15)
School	A–6(5)	18	20 (2)	5 (–13)	20 (2)	23 (5)	11 (–7)	15 (-3)
Main	A–6(3)	39	35 (–4)	27 (–12)	22 (–17)	45 (6)	57 (–18)	38 (–1)
Denver	A–6(2)	22	8 (–14)	11 (–11)	25 (3)	8 (–14)	30 (8)	30 (8)
Average Errors			22	22	24	21	15	6

The average errors (Predicted value minus the Measured value) produced by PMED equations using DCP, CBR, and P_{200} and PI to predict the *R*–value are 22, 22 and 24 respectively. The developed equations produce the errors of 21, 15 and 6 respectively. This means the prediction of *R*–value improves while using the developed equations. Another observation is that the PMED equations underestimate the *R*–value and thus, the PMED equations are conservative.

Nonetheless, the predicted *R*–values using the developed regression equations are closer to the measured R–values. Statistical analysis was performed to examine whether the predicted *R*–values using the developed regression equations are equal to the predicted *R*–values using the PMED equations. It was found that the predicted *R*–values using the developed regression equations are statistically equal to those calculated by the PMED equations at 95% confidence interval.

Another observation while DCP testing has been found that single-mass DCP testing on stiff soil (say, A-1 or A-2) is very difficult as the penetration rod jumps and results may be erroneous. This is why single-mass DCP is not recommended for stiff soil. For soft soil, single-mass DCP can be preferred for being easier. This recommendation is illustrated in Figure 25.

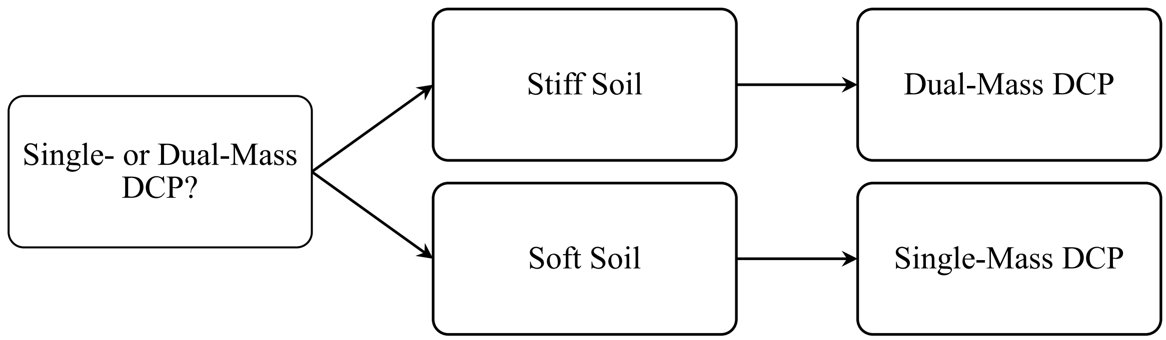

Figure 25. Selection of Single-Mass or Dual-Mass DCP

An example of how the result finding is to be practiced is now presented here. Let us consider an in-situ soil is to be tested to determine its possible *R*-value and the soil is most probably stiff. As the soil is stiff the dual-mass DCP is preferred. If the soil is expected to be soft then the single-mass DCP is preferred. Then, follow the following procedure:

Step 1. Hold the penetration rod vertical; make sure the reading scale is clear; note the initial reading.
Step 2. Raise the hammer up to the top of the sliding bar. Let it fall freely; make sure your finger is not at the point of fall.
Step 3. Record the penetration reading.
Step 4. Repeat Steps 1 to 3 until you get a consistent penetration per blow.
Step 5. Repeat Steps 1 to 4 for nearby other points (at least 1 ft away)
Step 6. Calculate the average penetration per blow.
Step 7. If you used the single-mass DCP, convert your single-mass DCP value to dual-mass DCP by using Dual-Mass DCP = 1.61 x Single-Mass DCP.
Step 8. If you used the dual-mass DCP, then, the DCP value as is.

Step 9. Calculate the R-value using, $R = 330.66(\mathrm{DCP})^{-0.924}$, where DCP is dual-mass DCP value in mm/blow.

One example, say, one conducted single-mass DCP test on a site. The average single-mass DCP value is measured to be 6.5 mm per blow. Then, the dual-mass DCP value is 1.61 x 6.5 = 10.5 mm per blow. The *R*-value will be $330.66(10.5)^{-0.924} = 38$.

Another example, say, one conducted dual-mass DCP test on a site. The average dual-mass DCP value is measured to be 8.5 mm per blow. Then, the R-value will be $330.66(8.5)^{-0.924} = 46$.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Based on this limited study, the following conclusions can be made:

- The single–mass DCP produces an average of 62% penetration compared to that of dual–mass DCP, that is *Single Mass DCP = 0.62 x Dual Mass DCP*
- The calculated *R*– values and CBR using the PMED equations and the developed regression equations are statistically equal at 95% confidence interval.
- The developed regression equations to calculate the *R*–value yield more accurate and statistically equal *R*–value compared to that by the PMED equations.
- The *R*–value calculated by PMED equation using the soil's gradation, and plasticity index are less accurate compared to other methods. However, the *R*–value calculated by developed equation using the soil's gradation, and plasticity index are very competitive compared to other methods.

Recommendations for Future Studies

Recommendations for future researches obtained from this study are listed below:

- More sites could be tested to obtain more test data that would make the findings more reliable.
- More varieties of subgrade especially soft–subgrade could be tested.

Implementation Plans

Some implementation plans proposed by the study are listed below:

- The single–mass DCP can be used while assessing subgrade considering the fact that the single–mass DCP produces an average of 62% penetration compared to that of dual–mass DCP.

- The developed regression equations could be used to predict *R*–value for pavement design as these equations found more accurate and statistically equal to that by the PMED–calculations.

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