
Louisiana Transportation Research Center

Final Report 656

Quality Control/Assurance on Base Course and Embankment with the Dynamic Cone Penetrometer

by

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13. Abstract

Nuclear moisture-density gauges (NDG) operate with the use of radioactive materials that may be hazardous to the health of the operators under certain circumstances. There is a need for test procedures using devices that are accurate, easy-to-use, economically sound, and nonradioactive. This research investigated using the Dynamic Cone Penetrometer (DCP) as a possible alternative for current quality assurance (QA) processes in embankment and base course test procedures, which currently utilize radioactive devices.

The DCP as a QA compaction tool has several advantages over a nuclear gauge. These advantages include reduced safety concerns, reduced training requirements, and no intense federal regulations or licensing.

The Indiana and Minnesota Departments of Transportations both have established specifications utilizing the DCP as an acceptance tool for soil layers, which guided researchers toward establishing a procedure for Louisiana. LTRC researchers determined a “Limiting DCP Index” (mm/blow) parameter for different types of soil layers. These limiting thresholds were developed based on field acceptance compaction test results from the NDG and comparisons/similarities. The project’s fieldwork correlated well with these existing

specifications, and thus, DOTD TR 645, a test method for utilizing the DCP, was modified to include a method (Method B) for compaction acceptance.

Costs and benefits were also evaluated in this research. The DCP's cost was significantly less than that of the NDG. The NDG requires approximately \$9,000 per year for thermoluminescent dosimeters and licensing certification and roughly \$9,000 - \$25,000 for safety training classes that run on a three-year training cycle. The DCP does not require these safety measures.

Based on the results and conclusions, researchers recommend the DCP as an alternative tool for compaction acceptance to the current NDG acceptance testing process. The DCP acceptance procedure is outlined in the modified specification: TR-645 Method B. In following this recommendation, pilot projects should be selected to test and refine the draft specification and test method. In this case, the project could utilize the DCP for acceptance and pay, and have the NDG shadow the DCP for research purposes.

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Each research project will have an advisory committee appointed by the LTRC Director. The Project Review Committee is responsible for assisting the LTRC Administrator or Manager in the development of acceptable research problem statements, requests for proposals, review of research proposals, oversight of approved research projects, and implementation of findings.

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Nuclear moisture-density gauges (NDG) operate with the use of radioactive materials that may be hazardous to the health of the operators under certain circumstances. There is a need for test procedures using devices that are accurate, easy-to-use, economically sound, and nonradioactive. This research investigated using the Dynamic Cone Penetrometer (DCP) as a possible alternative for current quality assurance (QA) processes in embankment and base course test procedures, which currently utilize radioactive devices.

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Based on the results and conclusions, researchers recommend the DCP as an alternative tool for compaction acceptance to the current NDG acceptance testing process. The DCP acceptance procedure is outlined in the modified specification: TR-645 Method B. In following this recommendation, pilot projects should be selected to test and refine the draft specification and test method. In this case, the project could utilize the DCP for acceptance and pay, and have the NDG shadow the DCP for research purposes.

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Implementation Statement

Density is often considered an important parameter for compaction, but not necessarily the determining factor for long-term pavement performance. Stiffness, in contrast, is a more performance-based parameter.

Other states have developed alternative QA/QC methods for pavement layers. They developed methods to substitute current QA test methods with the radioactive NDG to one with the Dynamic Cone Penetrometer (DCP). This research evaluated the accuracy and correlations between the DCP and NDG and developed a specification for DOTD to utilize. DOTD TR645: Method B utilizes the DCP (along with the Smart DCP auto reader) as an acceptance tool. The method will be shared at the next District Lab Engineers meeting and pushed for full implementation into policy.

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Introduction

Current quality assurance/control processes (QA/QC) on base courses and subgrades are based on densities and moisture contents obtained from the Proctor Compaction test and the nuclear moisture-density gauge (NDG). NDGs utilize radioactive materials to determine the density and moisture contents. These gauges can be expensive to maintain and have extensive licensing and safety requirements. These requirements can often limit the number of staff available to operate them and add considerable time and costs (training, tedious paperwork, etc.) to the department. Utilizing a simple tool, like the Dynamic Cone Penetrometer (DCP) that is not electronic or nuclear, could help save DOTD time and funds over the long term.

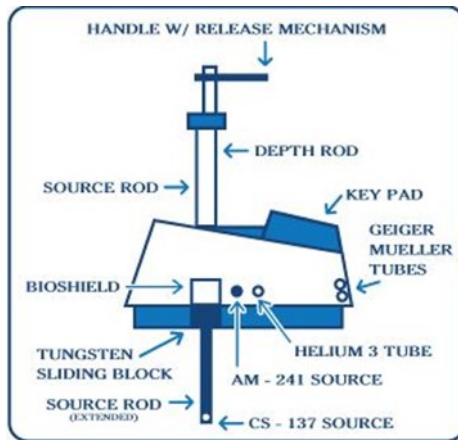
Background

NDG

The nuclear moisture-density gauge (NDG) is a tool used in civil construction and the petroleum industry. The device consists of a radiation source that emits a cloud of particles and a sensor that counts the received particles to measure density and moisture [1]. It is important to know that radiation, though very low, is always being emitted from the nuclear gauge, in use or not. These radiation levels are very low and relatively safe to the operator if used and stored properly.

The NDG has a source rod that lowers into the ground to measure wet-density, which represents the mass-over-volume of the soils and moisture in the ground that is compacted. The nuclear gauge determines the level of moisture by releasing “fast” neutrons that are slowed down (thermalized) when they interact with the nucleus of hydrogen (hydrogen part of water in the soil), which represents moisture [1]. Figure 1 is a diagram of a typical NDG sourced from the American Portable Nuclear Gauge Association (APNGA)’s website; notice the source rod is extended only in application of compacted soils or aggregates.

Figure 1. APNGA's NDG diagram



The Louisiana Department of Transportation and Development (DOTD) and the Louisiana Transportation Research Center (LTRC) have used NDGs across Louisiana for field and laboratory tests for over 30 years. The advancement in nuclear technology was significant for DOTD and others as nuclear density and moisture measurements could be found in approximately five minutes or less and provide “real-time” quality control, rather than with sand cones and overnight oven moisture contents. However, it is known that when using radioactive devices there comes an increased amount of safety measures and expenses, such as certification classes, badge testing and replacements, and special maintenance, storage, and transportation requirements. LTRC research investigated a lower-nuclear moisture-density gauge and found some advantages, but the lifespan and the reduced depth capability of the low-nuclear gauge did not meet DOTD current needs [2].

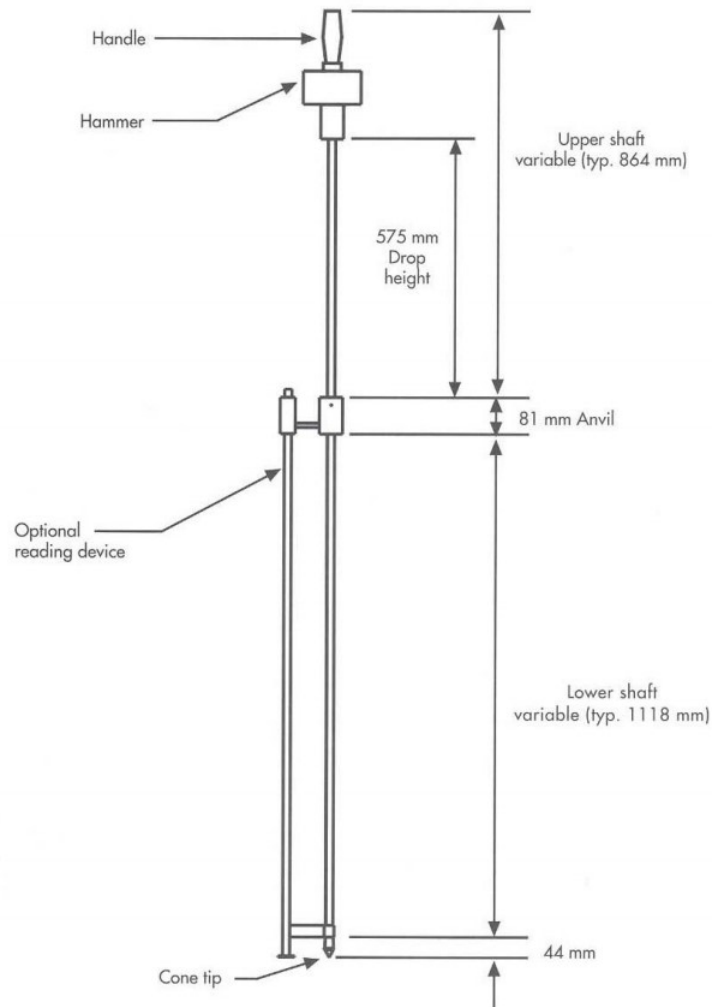
DCP

The Dynamic Cone Penetrometer (DCP) is a simple, minimally-destructive, hand-held device used for penetrating the soil to find the stiffness of the in-situ soil [3]. See Figure 2. The DCP is relatively inexpensive and easily transportable; and it doesn't require safety classes, certifications, or special radioactive storage and transfer procedures. The device consists of the following parts:

- **Upper and lower steel shafts:** Both have diameters of 5/8 in. The upper rod allows a consistent drop of approximately 22.5 in. The lower rod is typically 44 in. but can vary with an extension rod.
- **Handle:** located at the top of the device, aids in stabilizing and ensuring plumbness.

- **Hammer:** weighs 17.6 lb. and is manually raised to the handle (bottom), then released to freefall and impact the anvil, transferring a repeatable amount of energy.
- **Anvil:** serves as a connector between the two shafts, catches the hammer, and transfers energy.
- **Cone:** connected to the lower rod, has a diameter of 0.787 in., is angled at 60 degrees, and is the penetration point into the soils.

Figure 2. DCP design



The DCP is driven into the soil by the sliding hammer up, then dropping it onto the anvil. The penetration length of the lower shaft into the soil after each hammer drop is recorded, and the rate represents that soil layer's stiffness. The unit of measurement for the DCP stiffness is mm/blow. The smaller mm/blow value, the stiffer the material; the higher

mm/blow values indicate weaker material. Stiff material requires more drops because the rate of change (mm/blow) is smaller.

While the DCP test will yield the layer thickness through the change of plotted slopes, the slope of the curve is the mm/blow stiffness measurement. Another way to visualize stiffness parameter is through a calculated term known as the DCP Penetration Index (DCPI). The DCPI is calculated by the change in penetration depth divided by the amount of blows taken, as seen in the equation below.

$$\text{DCPI} = \frac{P*(i+1)-P(i)}{B*(i+1)-B(i)} \quad [1]$$

where, P = penetration depth and B = blow count.

The DCP has been utilized in both research and construction projects for over 10 years in Louisiana. Currently, DCP readings are required on subgrade soil surveys and on projects assessed for rubblization. Test results can be correlated to California Bearing Ratios, in-situ density, resilient modulus, and bearing capacity [4]. The DCP can be used to measure the stiffness of cohesive and non-cohesive soils, base course aggregates, recycled concrete pavement, blended calcium sulfate, and in some instances, chemically (cement or lime) stabilized or treated soils. The DCP, however, cannot be used for applications dealing with concrete pavements, asphalt pavements, or large size aggregates [5], as the tip of the DCP cannot penetrate these stiffer materials.

Furthermore, “smart” devices, called auto readers, can be attached to the DCP for easier testing and will be reviewed as a possible improvement to the conventional DCP. The auto readers may offer another alternative for easier testing and more accurate results for DOTD vs. manual recording, where a goal is always “to do more with less.”

Significance

Departments of Transportation (DOTs) across the nation look to replace NDGs with other non-radioactive devices and test procedures. Specifically, the Minnesota Department of Transportation (MnDOT) has used the DCP as an acceptance tool for compaction of pavement edge drain trenches since 1993 (test procedure G&B-201) [6]. MnDOT states that the DCP method is an appropriate substitute for the specified density method when assessing aggregate base materials, and it is recommended that its use should be increased across the state [6].

Using the DCP as a QA/QC acceptance compaction tool has several advantages over using the NDG. The DCP can penetrate the layer for acceptance, in contrast, a pilot hole rod is driven and removed to allow the NDG probe to enter the pavement layers. Unlike the NDG, the DCP collects information as it is driven for each layer to depths below the standard NDG's capability. NDGs produce average density values for the investigated layer, while the DCP produces the entire stiffness profile. Other advantages include reduced safety concerns, no intense federal regulations, no extra licensing, no intense training necessary, and minimal destructive testing. In the field, the DCP is visually intuitive. The DCP shows how stiff the soil is with each hammer blow, while the NDG collects the data after setting the device on the ground, which to some, can appear to be a "black box." Overall, the non-nuclear method would hopefully save DOTD time and money, while ensuring pavement layer performance.

Literature Review

A literature review was conducted to understand and build on what other state DOTs have considered as using the DCP as an alternative for acceptance testing. It is important to find an alternative to current QA/QC procedures utilizing devices that require radioactive energy. However, what are QA and QC procedures, and why are they important?

The concept of quality assurance (QA) refers to the combined efforts of the contractor through quality control (QC) and the department through inspection, verification, and acceptance to produce a given project that will provide suitable use for the public [7]. To reiterate, the contractor constructs quality and has control of what goes on in a project (QC), and the transportation department inspects and assures specifications are met. It is important to meet specifications to ensure quality for applications on roadways and other structures to provide safety and proper use for the public (QA) [8]. One example of QA testing is the acceptance test, and this test verifies suitable compaction for roadways. Adequate compaction of roadway materials plays a major role in the performance and life of a roadway.

MnDOT

The Minnesota Department of Transportation (MnDOT) conducted research to find a non-nuclear alternative for some of their test methods: specified density method, quality compaction method, and nuclear control strip method for aggregate base layers. Base specifications for the DCP as a quality control device for the compaction of backfill for pavement edge drain trenches and granular base layers were developed in 1996. Originally, a penetration rate of 19 mm/blow was accepted. In 1998, MnDOT revised their limiting penetration rates for base materials after performing more than 700 DCP tests for Minnesota road Research. DCPI limiting value ranges for particular and common soil layers from MnDOT can be seen in Table 1 [6]. MnDOT's specification utilizing the DCP as an acceptance tool can be found in Appendix II.

Table 1. Limiting DCPI by MnDOT

Material	Limiting DCPI (mm/blow)
Silty/Clay subgrade	<25

Select Granular Clay	<7
Class Special Gradation Granular Base	<5

In 1998, MnDOT further revised their limiting penetration rate based on an agreement between the DCPI and percent compaction. Table 2 indicates an average DCPI for certain thicknesses of test layers; MnDOT’s test recommendations include that tests should be performed no more than one day after compaction, and at least two DCP tests should be conducted within 3 ft. of each other for verification [6].

Table 2. Limiting DCPI based on depth of test layer

Depth of Test Layer (inches)	Average DCPI (mm/blow)
3	<15
3 - 6	<10
6 or more	<5

UT Arlington

The University of Texas at Arlington conducted research in 2014 that monitored a few alternative devices for measuring pavement performance, including the DCP. The DCP was considered effective for in-situ testing and followed similar trends for similar types of pavement material in flexible pavement structures. The DCPI ranges for base and subgrade layers from this study can be seen in Table 3 [9].

Table 3. UT Arlington’s DCPI ranges for base layers

Base or Subgrade	DCPI ranges (mm/blow)
Cement Stabilized Base Layer	0.5 - 8
Lime Treated Subgrade	2 - 22
Compacted Subgrade	8 - 47

MoDOT

Missouri Department of Transportation (MoDOT) established a DCP specification similar to Minnesota’s specification, which dealt with aggregate base materials (limestone, crushed stone, sand, and gravel bases). The MoDOT specification states that materials

need to be compacted to achieve an average DCPI less than or equal to 10.0 mm/blow (0.4 in/blow). The MoDOT specification also states that DCP testing should be completed within 24 hours after compaction [10].

InDOT

Indiana Department of Transportation (InDOT) developed a specification for DCP acceptance of clay, silt, sand, and granular soils. The InDOT specification also includes the depth that the DCP should be tested to for each material type (see Table 4) [11]. InDOT's specification utilizing the DCP as an acceptance tool can also be found in Appendix II.

Table 4. InDOT test depth by material

Material	Depth Tested
Clay	6 in. (152 mm)
Chemically Modified Soils	8 in. (203 mm)
Silty or Sandy Soils	12 in. (305 mm)
Granular Materials	12 in. (305 mm)

Objective

This project will evaluate the Dynamic Cone Penetration Index (DCPI) stiffness against the NDG density results of unbound layers and embankments. The research will compare the DCP to the NDG for technical accuracy, precision, consistency, economical benefits, and ease-of-use. As a subtask, researchers will evaluate two auto readers: 1) the Mag Ruler by Kessler and 2) the Smart DCP by Vertek for correlation amongst themselves as well as compared to standard DCP results without an auto reader. The research will utilize intensive field tests to determine if there are benefits and implementation potential for DCP QA/QC applications within DOTD. In addition, a specification subpart for these applications will be developed for DOTD.

Scope

The research team visited 12 sites with ongoing NDG QA/QC testing across south Louisiana. Stone base course, soil-cement base course, and embankment layers were tested with the DCP to determine correlations. Other elements including performance, cost, reporting, and training requirements were also evaluated.

Methodology

QA/QC testing for DOTD highway projects involves many facets. Researchers reviewed highway project lists to determine applicable sites. Each site had different soil properties which were evaluate by the districts under their normal/current QA/QC specifications and operations. Researchers contacted local staff and obtained information about each site, including laboratory tests required to make sure specifications, such as cement content, compaction, and water requirements are met [12]. Field testing by the DOTD districts often includes an NDG per DOTD Method TR 401: Determination of in-place Density [13].

LTRC mobilized on available and compatible projects to conduct research tests. Tests included the stiffness determination by dynamic cone penetration index (DCPI), shadowing nuclear density gauge acceptance testing locations on each site. Shadowing refers to the fact that the research DCPs will not affect construction acceptance, pay, or progress as determined by the district inspectors. In this shadowing, the researchers are searching for a new relationship or correlation with an existing and established DOTD test procedure. The DCP method utilized by researchers was based on the aforementioned DOTD TR 645 [4].

In this research, DCP testing was conducted adjacent to the locations of NDG tests performed at various construction sites. Conducting the DCP at nearly the same location (~2 ft. apart) as the NDG would aid in the search for an acceptance correlation. Field data from both devices was compared and analyzed. The shadowing DCPI readings were compared with the adjacent NDG QA density and moisture readings to determine correlations.

District NDG testing determines acceptance (pass or fail) based if the required ranges of density and moisture content are met. The DCP can utilize this pass or fail method as well. For example, one could compare the field DCP results to an appropriate target value or maximum allowable DCPI for a particular layer. The maximum DCPI for certain soil layers and types will be determined and compared to other state DOTs. Cost-benefits, ease of utilization, and other factors will be evaluated between the DCP and NDG.

Devices

Kessler DCP with Mag Ruler

DOTD currently utilizes the Kessler DCP and its auto reader, the Magnetic Ruler (Mag Ruler). The Mag Ruler collects stiffness measurements in millimeters per blow (mm/blow). The device works with sound to determine blow count and magnetics to record depth at each hammer impact on the anvil. As seen below in Figure 3, the device has a liquid crystal display (LCD) interface [14].

Figure 3. Mag Ruler interface



Smart DCP by Vertek

LTRC evaluated a secondary DCP recording device, the Smart DCP for Dual-Mass Penetrometers developed by Vertek. This device similarly automatically counts blows, reducing/eliminating the need for pen and paper. The Smart DCP, like the Mag Ruler, reduces labor and can even be operated with one individual operator. However, DOTD technicians often go in pairs (buddy system), which also splits hammer lifting efforts.

The Vertek device, in contrast to the Mag Ruler, works with a laser (vs. magnetics) to record depth measurements automatically. The Smart DCP utilizes a mounting base and laser range finder (Figure 4) attached to the DCP to track the depth of the probe. The assembly of the Smart DCP consists of inserting the upper plate just below the anvil. The heavier bottom plate or base is placed onto the ground with the laser range finder attached and pointed upwards. The bottom plate has a hole, which allows the operator to slide the cone of the DCP for testing. As the DCP is advanced through drops of the

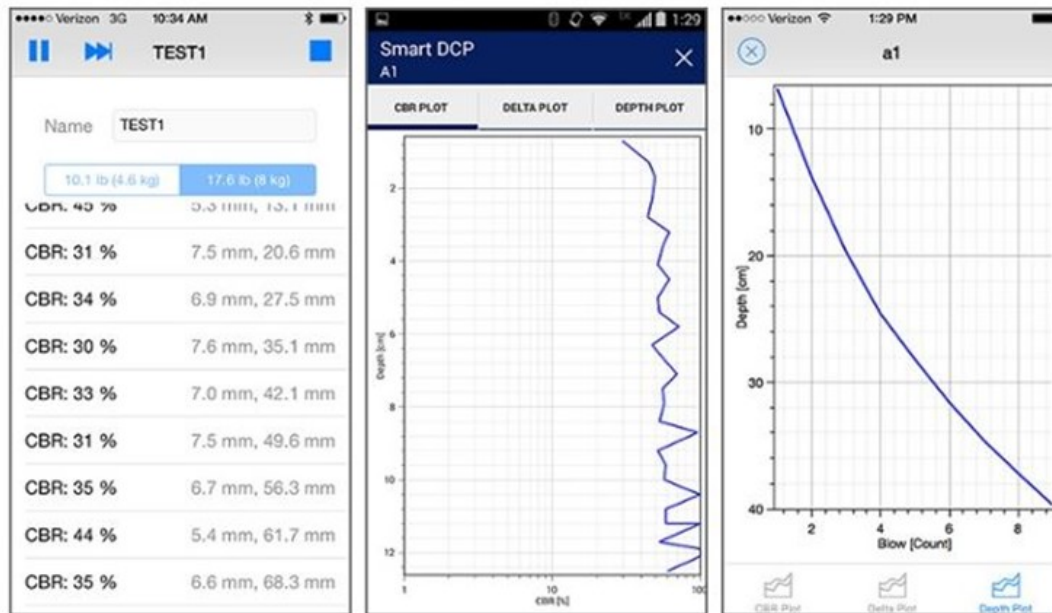
hammer, the plates get closer together and the laser range finder measures the change in distance per blow. The Smart DCP kit also includes wrenches, a manual, and a bag to carry everything (excluding the actual DCP).

Figure 4. Smart DCP kit



For the Smart DCP to work, a download of the Vertek application from the iPhone or Android online stores is required as well as a connection via Bluetooth. The laser range finder utilizes Bluetooth technology to transmit the displacement between hammer blows to a smart phone/device using the Vertek application. The application also alerts the operator with a beep and vibration from the phone/device when it is ok to proceed with the next hammer drop. The Vertek application allows operators to quickly record accurate measurements. Figure 5 shows an example of the Vertek Smart DCP application [15].

Figure 5. Smart DCP real-time test data



The Vertek application has a few screens of informative data. The left screenshot shows what the application displays during the test, including the name of the test, depth per blow, total depth, and a CBR correlation. The other two screenshots are examples of automatically generated graphs created when a test is completed and saved. The middle graph shows the depth of the DCP's penetration and the calculated California Bearing Ratio (CBR). The CBR is a percentage and it is a comparison of the bearing capacity of a certain material to a well-graded crushed stone considered as 100%. The right graph in Figure 5, shows a relationship between blow count and depth of the penetration throughout the DCP test.

It is critical that the laser mounted base be lined up with the upper plate for proper readings. If the ground is uneven, the operators can rotate the base to where the laser can hit the upper plate. Accidental recordings can occur if an operator's arm gets in the way of the laser sight; however, this can be remedied with a screen swipe (left) to delete the most recent, unwanted reading. Other corrections and edits can be made when processing the data, if necessary.

Test Plan

The test plan consists of collecting DCP data from various sites across the state. The LTRC Geotechnical research team conducted DCP tests adjacent to NDG tests with and without smart devices to search for comparisons. This will also compare the aforementioned Mag Ruler and Smart DCP auto readers.

The main procedure will be to shadow the NDG QA/QC acceptance testing at DOTD construction sites with the DCP. Suitable construction sites were picked out to shadow NDG QA/QC acceptance tests with the DCP tests taken immediately after to provide viable comparisons in data. Other state DOT methods were analyzed, as well, for QA/QC with the DCP. Test procedure TR 645-10: The Determination of In-Place Stiffness by the Dynamic Cone Penetrometer (DCP) is primarily for finding the stiffness of our soil subgrades. Ultimately, this project may lead to the development of a new DOTD TR method (TR 645 Method B) for the DCP QA/QC procedures.

Auto Reader Comparisons

As a side task, soil testing will be conducted at the Pavement Research Facility (PRF) in Port Allen to evaluate the two auto readers for the DCP. A comparison of the Mag Ruler and Smart DCP will be evaluated for efficiencies and ease of utilization for the technicians. Aesthetics with the interface and cost of each device and repairs will also be considered.

Sites with Acceptance Testing

The researchers selected several sites with the help of district personnel as test sites with relevant QA testing. The shadow field-testing was conducted adjacent to district field-testing to determine if there are appropriate DCPI correlations to their nuclear gauge QA tests. The DOTD website provides lists of current projects by district location, state roads and highways included, type of construction (such as concrete new pavement or asphalt widening and overlay), project engineers overseeing a project, length of construction site, start date, end date, etc.

Sites were selected that utilized nuclear density gauge for acceptance testing and were sorted/ranked by travel distance, project time and percent complete, safety for technicians, and length of the project. Selected locations include, LA 42 in Prairieville, I-

10 near Blue Bayou in Prairieville, and others spanning from districts: 02 New Orleans, 03 Lafayette, 05 Monroe, 58 Chase, 61 Baton Rouge, and 62 Hammond.

Prior to acceptance testing, a Proctor curve is required to determine key material properties. District technicians conduct DOTD TR 418 [16] to find the maximum dry density (MDD) and optimum moisture content (OMC). DOTD TR 401 [13] is the in-place density test method utilized by DOTD. QA for compaction is conducted in the field immediately after mixing with the pulverizer and before cement hydration really gets started (same day). If NDG acceptance tests meet the required compaction (pass), the contractor receives confirmation and can proceed with construction.

The LTRC research team collected various information about each site and its materials. Table 5 presents an example of the data and how it will be presented (only four sites are shown in this example). The collected data will be analyzed to create and validate a specification (TR 645 Method B), comparing the various soil types, layers, and the DCP Index values to other state specifications by MnDOT, InDOT, etc.

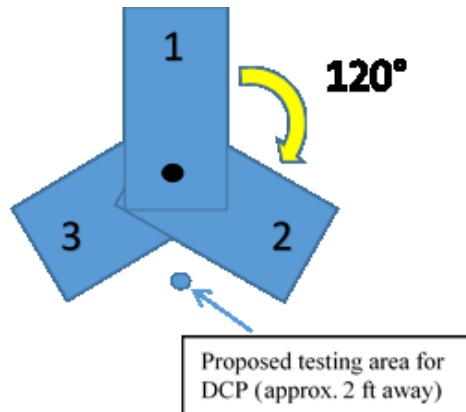
Table 5. Site data example

District	Route	Station / Zone	Layer / Base Course	Proctor		Average Dry Density, ADD (pcf)	Percent Compaction, Avg. %NPR (% Required)	Avg. Test Layer DCPI (mm/blow)
				MDD* (pcf)	OMC (%)			
61	I-10	Zone 117	Lime Cut Subbase	96.6	24.5	93.9	97.3% (93%)	10.11
61	I-10	Zone 134	Lime Cut Subbase	95.2	22.2	82.3	86.6% (93%)	34.46
62	LA 22	Zone 1	Recycled PCC Base Course	121	13	118.2	97.6% (95%)	9.58
62	LA 22	Zone 2	Recycled PCC Base Course	121	13	115.5	95.4% (95%)	12.29

*MDD = Max Dry Density or Theoretical Density, PR

The district acceptance test results consist of an average of three NDG tests for average dry density (ADD) and percent compaction (%NPR). Figure 6 shows how the NDG would be rotated 120° two times within the same field hammered hole. The NDG testing probe for Independent Assurance (IA) went 10 inches into the ground; this depth will be referred to as “tested layer.”

Figure 6. NDG acceptance test diagram



As an example of the data, from Table 5 – Zone 117, that soil has a Maximum Dry Density (MDD) or Theoretical Dry Density (PR) of 96.6 pcf. From the three field NDG tests, each determines a nuclear dry density (NDD) for the layer; and the average of those, the average dry density (ADD), was 93.9 pcf. The average percent density or percent compaction (%NPR) is calculated by the formula below.

For the example in Table 5, a %NPR of 97.3% was calculated. The required passing percentage for lime treated subgrade according to DOTD specifications is 93%. The %NPR is a measure of how close the contractor has replicated the density of the field soil in comparison to the ideal laboratory conditions. Figure 7 shows an excerpt from a DOTD test procedure further clarifying abbreviations. Efforts are optimized with proper moisture control and the amount of energy applied by their compaction machine.

Figure 7. DOTD test procedure terminology

DOTD TR 401
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Method B

V. Calculations

Calculate the percent density (%NPR) using the following formula.

$$\%NPR = \frac{NDD}{PR} \times 100$$

Where:

PR = theoretical dry density, kg/m³ (lb/ft³)

ND = dry density of test, kg/m³ (lb/ft³)

III. Report

- A. Optimum moisture content (OM) DOTD TR 418 or TR 415 to the nearest 0.1%.
- B. Average dry density (ADD) to the nearest 1 kg/m³ (0.1 lb/ft³).
- C. Maximum dry density (PR) to the nearest 1 kg/m³ (0.1 lb/ft³).
- D. Percent density (%PR) to the nearest 0.1%.
- E. Nuclear device number and Inspector Nuclear Film Badge number.
- F. Family of curves number (if applicable).

Field testing values from the district include the average dry density (ADD) and percent compaction (%NPR). Red numbers (in Table 5) indicate failed field test densities that did not reach the required percent compaction from the specifications dependent on material utilization (usually ranges from 93 or 95% compaction). For example, Zone 134's material was a lime treated subgrade that required a density of 93% compaction, but only reached 86.6%, therefore failing acceptance testing.

The "average test layer DCPI" column in Table 5 represents the average drop per blow for the test layer of the NDG's acceptance test. Smaller DCPIs equal stiffer layers. The NDG and DCPI data from each site will be compared against each other and against DCPI value ranges for common materials in relation to MnDOT and other standards.

Discussion of Results

The DCP has been utilized by the DOTD for several years, primarily for soil subgrade investigations associated with design. DOTD mainly utilizes the Kessler DCP, but in recent years has added their Mag Ruler to reduce the required labor to two technicians (vs. three). More recently another auto reader, manufactured by Vertek, has been purchased by LTRC to evaluate its potential.

Comparison of Auto Readers

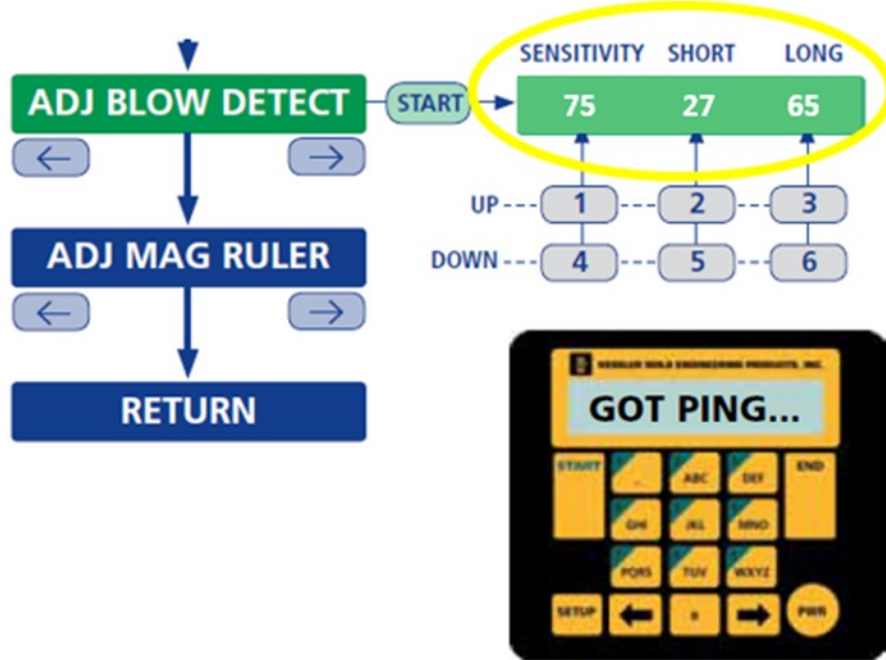
To start the project, the LTRC Geotechnical group ran comparisons tests with the DCP and two auto readers: Kessler's Mag Ruler and Vertek's Smart DCP. The largest difference between the two devices is that one (Kessler) utilizes sound to determine blow count and magnetics to determine depth; and the other (Vertek) utilizes a laser to measure distance per blow and indicates to the operator to drop the hammer for the next blow with a sound on the smart phone application.

Mag Ruler

Prior to this project, District 02, District 61, and LTRC experienced issues with the Mag Ruler, primarily related to the microphone sensitivity, which can lead to data not being recorded. Construction projects can be loud and this may have been the issue, but settings can be adjusted to resolve the issue. LTRC had a battery leak that damaged the Mag Ruler and required shipment to the manufacturer. After repair, the Mag Ruler worked well and made it easy to take quick notes on the device, rather than just pen and paper routine with a standard DCP (no auto reader).

Setup of the Mag Ruler apparatus is somewhat tedious when attaching the auto reader to the DCP, but it only takes about five minutes. The most important aspect is knowing what scale for sound sensitivity for the blow detector, which listens for a "ping" after each hammer drop. Figure 8 presents LTRC and Kessler's recommended settings for adjusting the blow detector are **75** for sensitivity, **27** for "ping" reading if too short, and **65** for "ping" reading if too long.

Figure 8. Mag Ruler recommended sensitivity



Advantages/Disadvantages. The auto reader eliminates the pen and paper data collection, which can produce uncertainties. Parallax can occur with visual scale readings and movement of the DCP rod during the test. Transposition errors in read and hand written data collection can also occur. The Mag Ruler makes it possible to perform a test with just two people, one to lift the hammer and one to follow along on the LCD monitor of the auto reader device (reduced labor vs. three technicians). The amount of time for testing is greatly reduced with digital data collection; and the Mag Ruler can even accept quick notes, such as date, operator’s name, and station number. As stated earlier, a disadvantage with this device is that the auto reader utilizes sound for data recordings, and can be confused when around/near loud traffic or construction noise. Knowing how to adjust the sensitivity scales of the Mag Ruler is imperative for accurate and complete results.

Smart DCP

The Smart DCP auto reader cost roughly \$1,700 as compared to the Mag Ruler’s approximate cost of \$3,000. Downloading the application on a smart phone is easy; however, you can only use one smart phone device per hole to record data.

Similar to the Mag Ruler, the setup of the top plate for the Smart DCP can be tedious but only requires an additional few minutes. The bottom base with the laser mount is a quick and easy setup. As for the smart phone application, Bluetooth is required to link with the Smart DCP laser device, and test information can be inputted easily, if not instantaneously for each test. One crucial element is to make sure the laser sight is in line with the top plate for accurate readings; this means to keep clear of any possible obstructions including tall grass or even a helpful hand holding the DCP in the wrong spot. There is a level on each of the two plates to keep them level, and help the operator perform the DCP test vertically.

Advantages/Disadvantages. Like the Mag Ruler, this automation provides consistent results and reduces possible human errors when reading the ruler (parallax, transposition, etc.). It also reduces movement of the DCP measurement rod during testing, as both smart devices remove human measuring. The Smart DCP manufacturer proposes that the amount of time for testing is greatly reduced with instantaneous data collecting instead of measuring by hand. It is also possible to perform the test with a single operator, though two operators are recommended to reduce physical fatigue when performing multiple DCP tests [13]. The Vertek results displayed on the smart phone application are visually appealing and intuitive. As for disadvantages, operators will have to pay attention to ensure the laser mount is lined up with the read plate and keep up with battery life for both the laser and smart phone. The recorder will also have to make sure the sound on the application is loud enough to hear.

DCP Test Comparisons

The research team performed three DCP tests (two with the different auto readers and one without) at two different areas (A and B) within the LTRC Pavement Research Facility (PRF). All three tests were conducted approximately 3 ft. apart to see the correlation in the data. The setup of each standard DCP test varied. The DCP without an auto reader was the quickest to setup as it didn't require a smart device attachment. Additional setup time is necessary for the smart devices, but negligible between auto readers as it takes approximately three minutes to attach either the Mag Ruler rod or the Smart DCP top plate to the standard Kessler DCP. The standard DCP, however, requires longer test times due to clearing the ruler from the hammer, then returning for reading the change in distance after each blow and writing each result on paper. This can produce inconsistent results dependent upon the reader. In the end, the auto readers appear to save time by collecting data each blow, providing notes for each test, and instantly sending results to

the office via the Smart DCP application. Utilizing an auto reader can reduce labor, requiring two operators vs. three. An auto reader could even be operated by a single person when road safety not an issue.

With the Mag Ruler, there are notes that can be taken before and after testing; however, changes cannot be done during a DCP test. As for the Smart DCP, changes can be made during the test, such as if a blow was not registered due to user error or depth limitation.

The Smart DCP system is limited to four millimeters (mm) in change of penetration index for it to record the data on its own; however, the operator can “force” record a blow and collect the data due to a refusal point [15]. It should be noted any blow can also be deleted with a finger screen swipe. This proved useful when an operator accidentally placed his arm in the laser sight that records the distance.

Comparison tests were conducted at the PRF in Port Allen, Louisiana. Figure 9 and Figure 10 show the test results and their similarities with respect to the depth as each blow count can be seen. The slope of each plot is similar, indicating similar stiffness for adjacent DCPs. The tests prove to be nearly identical with proper technique.

Figure 9. PRF (A) DCP comparisons

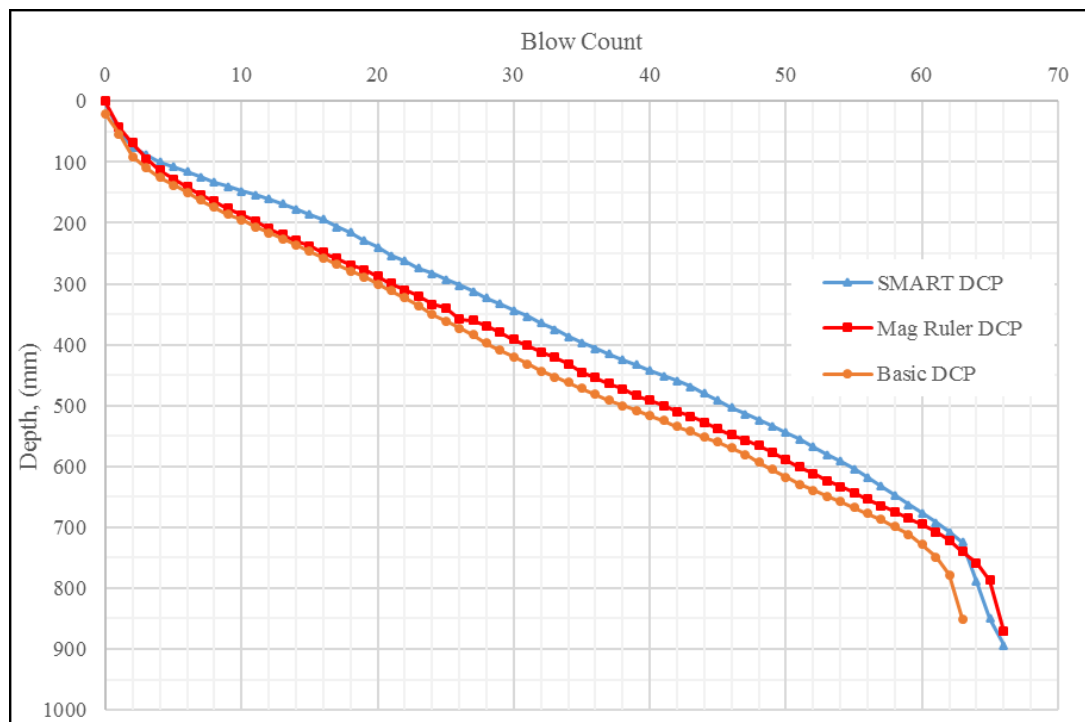
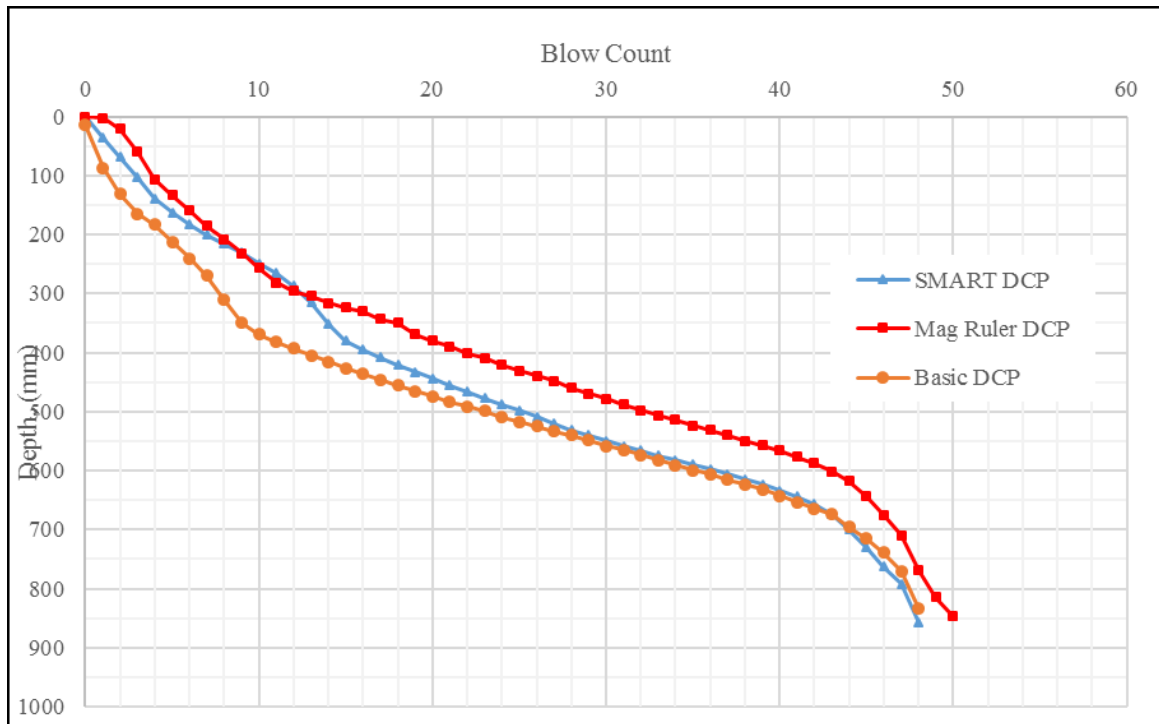
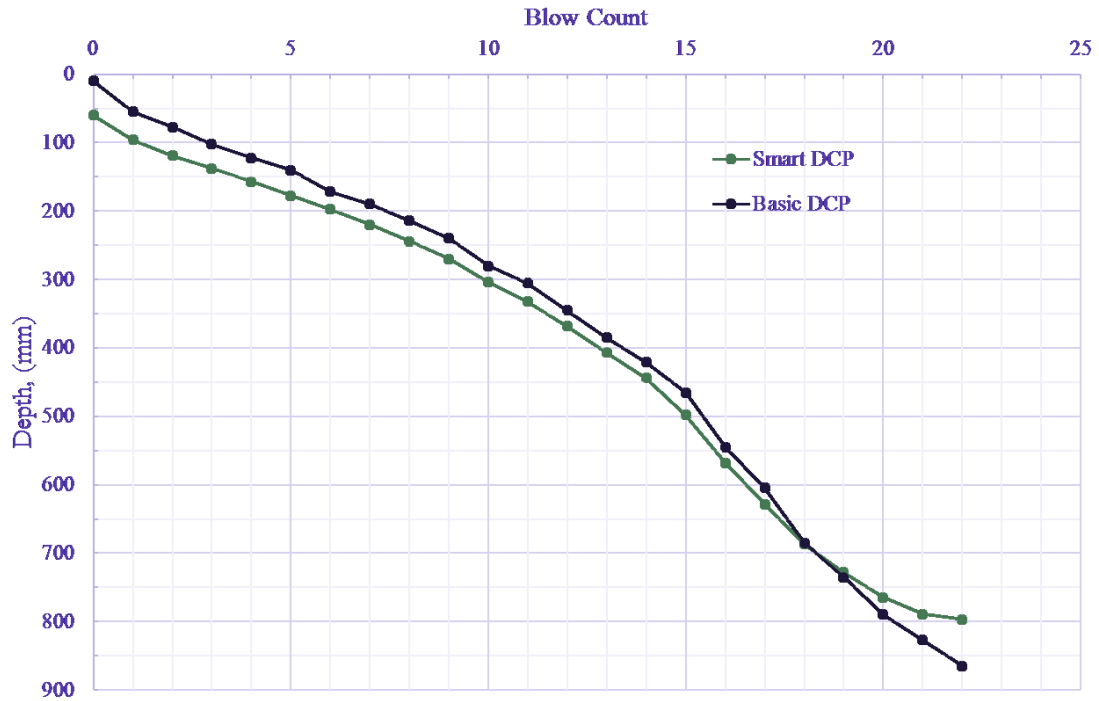


Figure 10. PRF (B) DCP comparisons



The Smart DCP was also compared with standard DCP testing performed by New Orleans District 02 personnel on LA 90. Figure 11, shows two DCP plots with similar slope changes as the depth changes. The flatter the slope, the stiffer the soil; the steeper the slope, the weaker the soil layer.

Figure 11. DCP comparison with the Smart DCP



Comparison of NDG for Acceptance Testing

Proper compaction is required to meet the appropriate percent compaction specifications for base course or soil layer roadway requirements. If acceptance tests do not meet compaction requirements, that test fails, and more energy and/or moisture modifications are necessary as part of the contractors QC. Louisiana soils are often wet of optimum moisture. Other times, more energy is required through more compaction passes of, for example, a padfoot roller shown in Figure 12.

Figure 12. Pad foot roller for compaction



NDG acceptance test depths depend on the thickness of the layer. For 8.5- and 12-in. layers, tests generally go to 8 – 10 in., respectively. Note that the DCP without an extension rod can go two or three times deeper than the NDG. Lower DCPI values represent stiffer soil; higher DCPI values represent weaker soils. Stiffness is not directly equal to compaction, but a correlation likely exists near optimum moisture and max dry density. This logic is promoting QA measurements with the DCP, and stiffness determinations for soils underneath a layer undergoing acceptance testing.

Each district NDG acceptance test consists of three density tests as shown in Figure 6. Depending upon project length, some sites required multiple density tests as required by specifications. Depending upon the project, testing types can vary. QA consists of roadway inspectors for the department, which owns the construction site. Owner Verification (OV) is often for the private industry lab overseeing a Design-Build project. Independent Assurance (IA) is represented for the nearby district lab only to further verify by a third party (not directly responsible for quality control and acceptance) [7].

Subgrade Layer Testing Sites

I-10: Highland to LA 73 (H.009250) – lime treated subgrade

This project is located in East Baton Rouge and Ascension parishes in District 61, and it includes widening I-10 from two lanes to three in each direction.

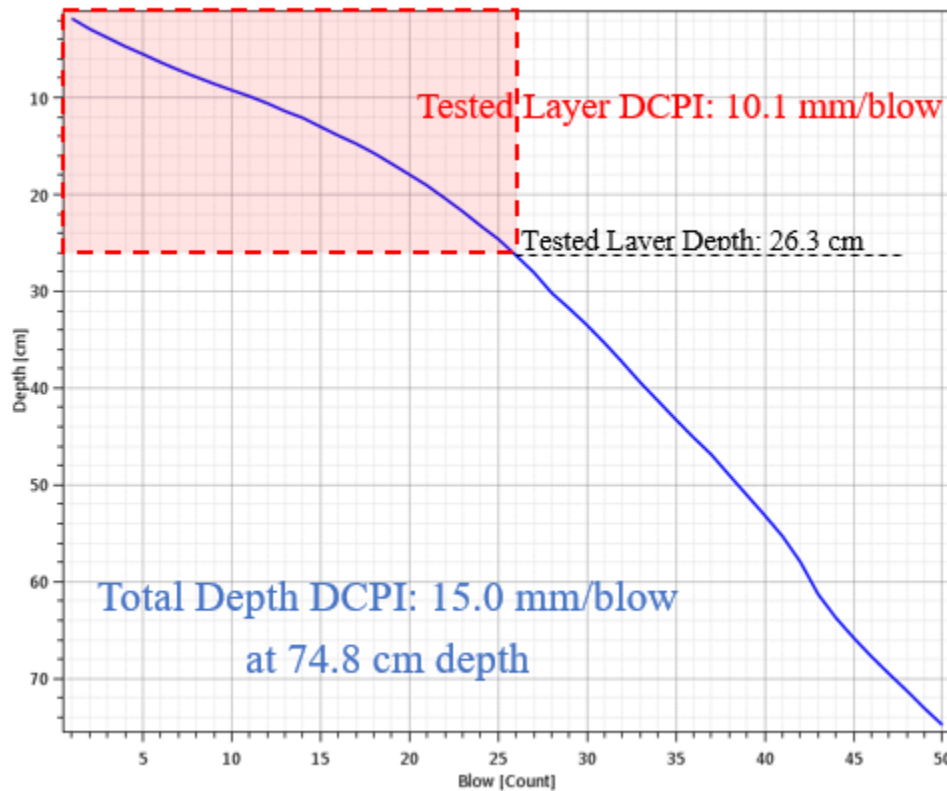
The layer was lime treated subgrade at 12-in. depth in accordance with Section 305 in *Louisiana Standard Specifications for Roads and Bridges* [12]. The 12-in subgrade had a Proctor results of 96.6 pcf for MDD and 24.5% for OMC. The layer had a plasticity index (PI) of 26. The layer requires 93% compaction and it was tested to 10 in. with the NDG.

First visit. The I-10 construction zones' subgrade was cut with 9% lime and had a 48-hour curing, before being re-pulverized and compacted with sheep-foot and smooth rollers. NDG results for the lime treated subgrade layer at Zone 117 Eastbound indicated that it was 97% compacted.

LTRC conducted a Smart DCP test about 2 ft. away from the District NDG, and recorded an average DCPI of 15.0 mm/blow for the total depth of 29.4 in. (74 cm) of penetration. The DCP rod can go further into the ground, but for the ease of removing the DCP rod safely, the test depth was limited to 29.4 in. (about triple the depth of the NDG test).

Figure 13 shows the entire DCP test results (blow count vs. depth) from the Smart DCP application, annotated to show the depth and DCPI (10.1) of the tested layer. The DCP penetration blows vary, hence the DCP test layer is 26.3 cm (beyond the 10 in. benchmark).

Figure 13. Smart DCP results from I-10 Zone 117



The DCP test extended deeper than the tested layer. Figure 13 shows a slight change in the slope where the 10-in. tested layer ends. The average DCPI in this upper portion is 10.2 mm/blow, and the slope is flatter and stiffer than the lower portion of the curve. The average DCPI of the tested layer was 10.2 mm/blow and took 25 blows to penetrate the 10-in. layer. Table 6 shows both the results from the NDG and the Smart DCP. This format will be used throughout the report to present each site's data. The average dry density (ADD) is a value representing the average of the three field density tests for acceptance. Average Percent compaction (%NPR/3) is calculated in relation to the Proctor's MDD, and is shown in the next column. Field DCP results are shown in the next column.

Table 6. Site data for Zone 117 on I-10

Lab Proctor	Field NDG Testing		Field DCP Testing		
	MDD: 96.6 pcf OMC: 24.5%	Dry Density	%NPR	Full Depth	Average DCPI (mm/blow)
94.3		97.6	Depth (in.)		29.4
93.9		97.2	Number of Blows		50
93.6		96.9	Tested Layer Depth	Average DCPI (mm/blow)	10.1
ADD		(%NPR/3)		Depth (in.)	10.0
93.9	97.2%	Number of blows		26	

Second visit. Researchers revisited I-10 and tested 12 more zones. The density testing occurred on the same lime treated subgrade. The required (passing) percent compaction was still 93% compaction, and the NDG testing went 10-in. into the 12-in. layer. Figure 14 shows the Smart DCP base and the NDG testing in close proximity of each other.

Figure 14. I-10 Zone 124 NDG and Smart DCP setup



Out of 12 zones density acceptance tests on the lime-treated subgrade, three locations failed to meet the required percent compaction. Table 7 shows the data from Zones 123 – 134. Notice that three of the four highest average DCPIs (bold and italicized in the table) are amongst the failed zones (with the lone exception of Zone 127). These four highest average DCPIs penetrated through the tested layer with the four fewest number of blows, therefore, fewer blows equal higher average DCPIs values, (and weaker layers). Zones 131, 132, and 134 failed, and thus are indicated in red*. However, Zone 127 could be noted as having a possible test error, since it took fewer blows and produced a high DCPI value. This could be due to spatial variability of soil, so another DCP test may have confirmed and/or produced a lower DCPI, meaning more blows required to penetrate through a test layer.

Table 7. I-10 Zones 123 - 134 data

Zone	OMC (%)	MDD (pcf)	%NPR (%)	ADD (pcf)	Average DCPI of Test Layer (mm/blow)	Number of Blows (#)
123	17.3	98.6	93.2	91.9	11.56	22
124	18.1	97.1	93.0	90.3	11.95	21
125	20.0	95.1	94.2	89.6	13.41	19
126	20.2	95.0	97.7	92.8	8.80	29
127	22.2	95.0	94.4	89.7	18.11	14
128	20.0	95.8	95.1	91.1	15.55	17
129	20.7	95.1	99.8	94.9	14.73	18
130	21.0	95.2	95.7	91.1	13.74	19
131	21.4	95.9	91.7*	87.9	17.49	15
132	20.5	97.6	90.0*	87.8	16.85	16
133	22.8	96.7	96.4	93.2	12.64	20
134	22.2	95.2	86.4*	82.3	34.46	7
Note: * Indicates that the layer failed to meet specification.						

LA 42 (H.002370.6) – cement treated subgrade

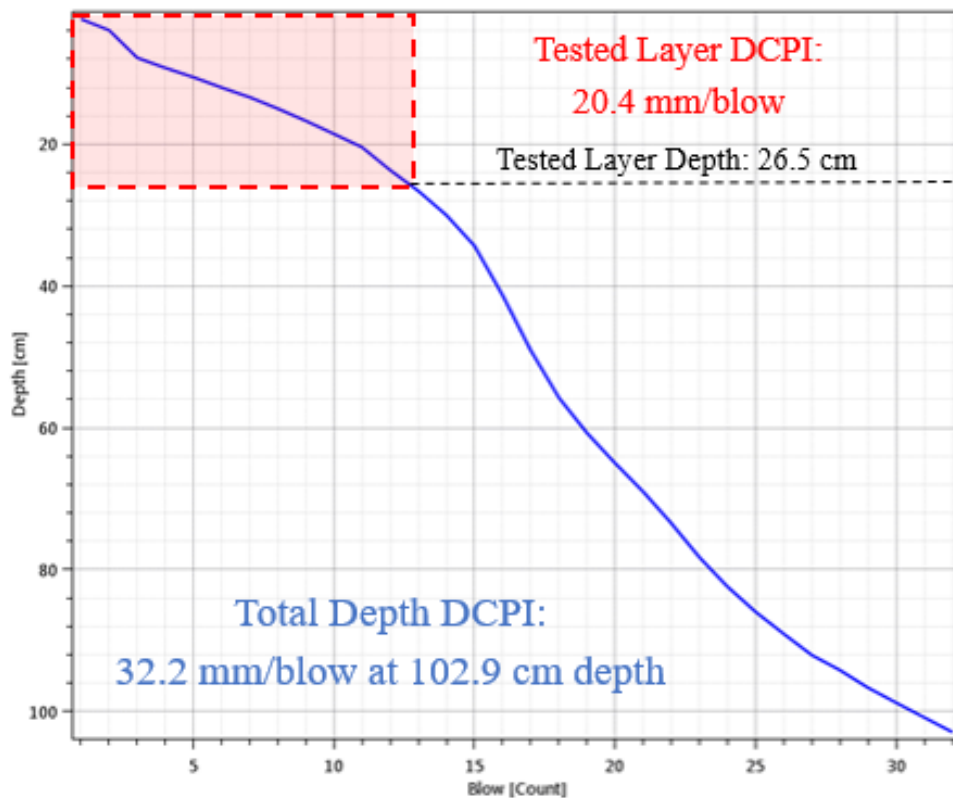
The LA 42 project is located in Ascension Parish in District 61 and includes the widening from two to four travel lanes from US 61 to LA 44 (approximately 3.6 miles).

Researchers visited the site on March 27, 2019.

The layer was cement treated subgrade at 12-in. depth in accordance with Section 305 in *Louisiana Standard Specifications for Roads and Bridges* [12]. At Station 170+20, the 12-in. subgrade layer had Proctor results of 98.4 pcf for MDD and 23.8% for OMC. The layer requires 95% compaction. The cement treated subgrade layer was tested at 10 in. with the NDG.

First visit. It was concluded that the acceptance tests failed with a percent compaction of 93.5%. Immediately after, LTRC performed two DCP tests each with different auto reader. The DCP tests were performed within two feet of the NDG pilot hole. The Smart DCP had an average DCPI of 20.4 mm/blow and only required 13 blows to penetrate through the 10-in. test layer. The Mag Ruler had an average DCPI of 18.36 mm/blow and required only 14 blows through the 10-in. layer. Both results show poor (high) DCPI values, which likely indicate why the percent compaction did not meet specifications. Figure 15 shows DCP graph data directly from the Smart DCP application. This graph can be sent via email from the field from the app, and is useful for fast review of data and results. In the figure, it has been annotated with summary text and values.

Figure 15. Smart DCP result for LA 42 Zone 8



Second visit. Researchers revisited LA 42 and tested two more zones on the same cement treated subgrade. Station 147+59 Proctor values were 110.2 pcf and 17.2% for the MDD and OMC, respectively. The 12-in. test layer yielded an ADD of 104.7 pcf and a passing percent compaction of 95.1% (95% was required). The DCP took 24 blows to penetrate through the layer resulting in an average DCPI of the test layer of 13.6 mm/blow. Station 156 required three tries for a passing acceptance test of the NDG. Station 156 had Proctor values of 110.2 pcf for MDD and 10.3% for OMC. The results from the NDG and DCP are shown in Table 8. The *red* numbers indicate failed NDG acceptance tests. The passing zone (156+20) could be a result of the lower moisture content percentage in the area compared to the first two zones (156+00 and 156+10).

Table 8. LA 42 Station 156 NDG and DCP results

Station	%NPR (%)	ADD (pcf)	Moisture Content (%)	Average DCPI of Test Layer (mm/blow)	Number of Blows (#)
156+00	<i>93.1</i>	102.6	14.6	15.4	20
156+10	<i>92.1</i>	101.5	14.3	15.5	20
156+20	96.9	106.9	11.8	10.9	29

I-12: US 190 to LA59 (H.011152) – untreated subgrade

The I-12 project in St. Tammany Parish (District 62) is a 3.3-mile project involving the widening of the roadway and overlay, as well as bridge widening/replacement. Researches visited the site twice on October 22, 2020, and January 19, 2021.

The layer was untreated subgrade at 12-in. depth in accordance with *Louisiana Standard Specifications for Roads and Bridges* [12]. The 12-in. subgrade had a Proctor results of 109.4 pcf for MDD and 16.2% for OMC. For a non-treated layer, a compaction of 95% is required, and the NDG testing conducted to a depth of 10 in.

For the first visit, researchers tested two zones at stations 248+80 and 245+94 on the eastbound side of I-12. Three months later, researchers revisited to test three zones between stations 113 – 130 on the westbound side of I-12. Results can be seen in Table 9. Blow counts were at the highest yet for a subgrade during this research, and there were no failed NDG acceptance tests.

Table 9. I-12 DCP and NDG data

Station	%NPR (%)	Pass or Fail Accept. Test	ADD (pcf)	DCP Test Number	Average DCPI of Test Layer (mm/blow)	Number of Blows (#)
STA 248+80 (Zone 20) [EB]	97.5	Pass	106.7	1	7.15	36
				2	5.94	43
STA 245+94 (Zone 21) [EB]	95.4	Pass	104.4	3	6.07	43
				4	6.57	40
STA 130+00 (Zone 4) [WB]	95.3	Pass	104.3	5	7.98	32
				6	7.97	32
STA 125+25 (Zone 3) [WB]	98.7	Pass	108.0	7	11.23	24
				8	12.84	20
STA 113+50 (Zone 2) [WB]	95.4	Pass	104.4	9	14.91	18
				10	12.91	20

Base Course Testing Sites

LA 22: Dalwill Blvd. – US 190 (H.000506) – RPCC base course

The LA 22 project calls for widening and drainage improvements in District 62 near Mandeville, LA. Researchers visited and tested two zones at the site on May 2, 2019.

The base course tested was an 8.5-in. Class II Base Course in accordance with Section 302 in *Louisiana Standard Specifications for Roads and Bridges* [12]. The layer consisted of recycled Portland cement concrete (RPCC). The Proctor results for Zone 1 and Zone 2 indicated that the OMC was 13% and the MDD was 121 pcf. The layer requires 95% compaction. The total depth of NDG testing onsite was 8 in.

The field NDG indicated ADD values for Zone 1 and 2 of 118.2 and 115.5 pcf, respectively. Zones 1 and 2 passed with average %NPR values of 97.7% and 95.4%, respectively.

The Smart DCP was utilized for both zones to avoid holding up District 62 personnel. Both tests were performed within 2 ft. of the NDG pilot holes to depths of about 20 inches. The average DCPI for Zones 1 and 2 were 12.2 and 13.8 mm/blow for the 20-in.

test, respectively. More importantly, the average DCP for the test layer (8 in.) were 9.6 and 12.3 mm/blow, respectively. Penetration through the test layer for Zone 1 took 22 blows, and Zone 2 took 17 blows. Both zones passed NDG testing showed good correlation with DCPI values and number of blows required.

Westwood Drive: (H.011795) – RPCC base course

The Westwood Drive project required concrete rehabilitation and is located in the city of Marrero, LA. Researchers visited and tested two locations at the site on August 20, 2019.

The base course was an 8.5-in. Class II Base Course in accordance with Section 302 in *Louisiana Standard Specifications for Roads and Bridges* [12]. The layer consisted of recycled Portland cement concrete (RPCC). The Proctor results for Station 15+00 and Station 18+00 were both 112.5 pcf for MDD and 5.6% for OMC. The Class II base course requires 95% compaction. The total depth of testing was 8 in.

The field NDG indicated ADD values for Station 15+00 and 18+00 of 112.1 and 116.0 pcf, respectively. Station 15+00 and 18+00 passed with average %NPR values of 99.6% and 103.1%, respectively.

Researchers conducted Smart DCP tests at the above locations. Tests were within 2 ft. of the NDG pilot holes to depths of approximately 34 in. The average DCPIs for the tested layer (8 in.) at Stations 15+00 and 18+00 were 8.4 and 13.6 mm/blow, respectively. Penetration through the test layer for Stations 15+00 took 21 blows, and Station 18+00 took 15 blows.

Second visit. Researchers revisited Westwood drive and tested one more Station. Station 14+60 had Proctor values of 112.5 pcf for the MDD and 5.6% for the OMC. The 8-in. test layer yielded an ADD of 113.1 pcf and a passing percent compaction of 100.5% (95% is required). The DCP took 19 blows to penetrate through the layer resulting in an average DCPI of the test layer of 10.9 mm/blow.

LA 347: Roundabout @ Melancon Road (H.009456) – stone base course

The LA 347 project in St. Martin Parish (District 03) included the installation of a roundabout in-place of a current 4-way stop. Researches visited the site on two consecutive days, October 22 – 23, 2019.

The base course tested was a Class II Base Course in accordance with Section 302 in *Louisiana Standard Specifications for Roads and Bridges* [12]. The stone base course had Proctor values of 136.8 pcf for MDD and 9.9% for OMC. The layer requires 95% compaction and tested to 10 in. with the NDG.

Researchers conducted Smart DCP tests to a depth of 10 in. through the stone base course. Testing was stopped by the top of the soil cement subbase layer. The DCP is unable to penetrate through a fully-cured soil cement layer. Table 10 shows the results of the NDG and DCP. The NDG could not be conducted at location 2 due to a collapsing pilot hole, whereas the DCP did not have that problem. The NDG technician suggested waiting a day for the layer to dry (the surrounding areas were noticeably wet even though the NDG technician stated “the moisture is reading lower than the OMC”). At location 5, the research team conducted a DCP test under the impression a NDG test will later be taken; however, no NDG test was required because there was no soil cement underneath this layer due to being in close proximity with a sewer system.

Table 10. LA 347 NDG and DCP results

Date	Test Location	%NPR (%)	ADD (pcf)	Average DCPI of Test Layer (mm/blow)	Number of Blows (#)
Oct 22	1	97.0	132.7	12.8	20
	2	Couldn't test		19.9	13
Oct 23	3	97.4	133.2	7.74	33
	4	97.1	132.9	12.18	21
	5	Test not taken		9.87	26

Arkansas Road: Caldwell Road – LA 143 (H.002622) – stone interlayer

The Arkansas road project is a 3.16-mile-long construction project located in Ouachita Parish (District 05) in West Monroe, LA. The Geotechnical research team visited the project and tested the DCP alongside six density tests from Station 101 to 104+35 (about 350 linear ft.) on June 06, 2020. A second visit occurred later in August of 2020.

The base course serves as an interlayer, which consists of 4 in. of Class II stone base course in accordance with Section 302 of *Louisiana Standard Specifications for Roads and Bridges* [12]. The stone interlayer is an unbound layer that is directly above a soil-cement subgrade layer and is utilized to dissipate any cracks from the soil cement layer

below and reduce potential reflective cracking on the surface. The 4-in. stone base course had Proctor values of 140 pcf for MDD and 6.2% for OMC, and the stone layer requires 95% compaction.

First visit. On June 06, 2020, the researchers met up with the District 05 personnel to perform side-by-side NDG and DCP tests on the interlayer that was placed earlier that same morning. Normally, two DCP tests are conducted for verification for research, but due to time constraints that day, DCP testing were cut from two tests to one at each NDG location that passed. The results from the NDG (shaded in *blue*) and DCP (shaded in *yellow*) are shown in Table 11. The *red* numbers indicate failed NDG acceptance tests. There is a direct relationship between higher moisture contents and lower ADD values from the NDG results, however this is not true for all research sites. It can also be noted that District 05 in north Louisiana has rolling hill terrains compared to its flatter land counterpart in south Louisiana. The two highest DCPI values were discovered at Station 104+25. The Arkansas road test section sloped downhill from Stations 101 to 104+35, so Stations 103+30 to 104+35 were at the bottom of the slope away from other test sites. This resulted in higher moisture values from water sprayed on the roadway, prior to NDG testing.

Table 11. Arkansas Road NDG and DCP results (Day 1)

Station	%NPR (%)	ADD (pcf)	Moisture Content (%)	DCP Test Number	Average DCPI of Test Layer (mm/blow)	Number of Blows (#)
101+00	97.7	136.7	4.6	1	8.7	6
				2	7.3	7
102+10	98.3	137.6	4.3	3	4.0	13
				4	4.8	11
102+88	93.1	130.3	5.9	5	5.1	10
103+25	95.1	133.1	5.4	6	3.9	13
103+30	95.5	133.6	5.4	7	5.4	11
104+25	91.8	128.5	6.1	8	10.8	5
				9	58.5	2
104+35	93.1	130.3	5.6	10	8.4	7
				11	7.4	7

Second visit. On August 03, 2020, the researchers revisited the Arkansas road project where more 4-in Stone Class II interlayer was placed the day before to avoid any possible issue of higher moisture areas like the previous visit.

Table 12 shows the Day 2 results; two DCP tests are conducted at each zone to verify. However, Station 70+75 also required a lesser amount of blows (higher DCPI), even though the NDG passed it. Excluding Station 70+75, all stations with higher than 12 blow counts passed NDG acceptance requirements. Day 2 results also show lower moisture contents, likely due to testing the day after the stone interlayer was placed and watered. The NDG could have issues testing on stone due to its inconsistent and angularity particle size.

Table 12. Arkansas road NDG and DCP results (Day 2)

Station	%NPR (%)	ADD (pcf)	Moisture Content (%)	DCP Test Number	Average DCPI of Test Layer (mm/blow)	Number of Blows (#)
76+00	91.7	128.4	3.3	1	4.4	12
				2	5.1	10
73+90	95.1	133.2	3.0	3	3.9	14
				4	3.8	14
72+85	95.1	133.2	3.4	5	3.2	16
				6	3.6	15
72+20	95.3	133.4	3.2	7	3.6	15
				8	3.6	15
70+75	95.1	133.1	3.6	9	4.9	11
				10	6.0	9
69+90	94.2	131.9	4.0	11	5.4	10
				12	6.8	8

Embankment Testing Sites

LA 15: At Deer Park - South of US 65 – Levee (H.006187)

This project realigns LA 15 in District 58 in Concordia Parish near Deer Park to straighten the roadway. The new embankment will remove curves and straighten the roadway that is dangerous at night. This project has been significantly delayed due to the high Mississippi River water levels along the levee. The preconstruction process started in February 2020, and the LTRC Geotechnical research team visited the project site on August 11, 2020.

The embankment was classified as A-2-6 Sandy Loam. A loam is considered a sandy-silt with less than 20% clay. The embankment was compacted in a series of 1-ft. lifts. District staff tested each lift with the NDG in accordance with Section 203 in *Louisiana Standard Specifications for Roads and Bridges* [12]. The Proctor values were 119.6 pcf for MDD and 11.5% for OMC. The layer requires 95% compaction. DOTD District personnel only conducted QA NDG tests to depth of 8 in. Researchers conducted two DCP tests at each zone to a depth of approximately 12 in. (305 mm) on lift 7. The results from the NDG and DCP can be found below in Table 13.

Table 13. Deer Park road NDG and DCP data

Station	%NPR (%)	Pass or Fail Accept. Test	ADD (pcf)	DCP Test Number	Average DCPI of Test Layer (mm/blow)	Number of Blows (#)
16+10	95.6	PASS	114.3	1	7.03	29
				2	8.92	23
17+20	91.5	FAIL	109.4	3	11.16	19
				4	15.14	14
17+95	96.2	PASS	115.0	5	7.54	30
				6	5.57	37
18+70	95.0	PASS	113.6	7	5.83	35
				8	7.01	29

LA 16: Roundabout at LA 447 (H.010124)

This project is a realignment project at the intersection of LA 16 and LA 447 in District 62 in Livingston Parish near Port Vincent. The embankment will create additional turn lanes for a roundabout and better traffic flow. The LTRC Geotechnical research team visited the project site in October 2019 and October 2020, as the project was significantly delayed due to the ongoing Covid-19 pandemic.

The embankment was classified as A-6 Silty Clay and had a plasticity index of 11. Figure 16 shows of the test site that was compacted in a series of 1-ft. lifts. District staff tested each lift with the NDG in accordance with Section 203 in *Louisiana Standard Specifications for Roads and Bridges* [12]. The Proctor values were 118.6 pcf for MDD and 16.0% for OMC. The layer requires 95% compaction. DOTD District personnel conducted QA NDG tests to depth of 8 in. Researchers conducted a DCP test(s) at each zone. Table 14 presents the NDG and DCP results.

Figure 16. LA 16-447 clay embankment photo



Table 14. LA 16 & 447 roundabout NDG and DCP data

Lift No.	STA	%NPR (%)	ADD (pcf)	Average DCPI of Test Layer (mm/blow)	Number of Blows (#)
Lift 1	50+00	99.7	118.2	13.8	15
				16.2	13
Lift 2	108+00	97.2	115.2	<i>34.6</i>	<i>7</i>
				<i>33.7</i>	<i>7</i>
Lift 3	107+75	96.9	114.9	17.6	12
				18.9	11
Lift 4	106+55	97.8	116.0	13.8	16
				12.0	17
	51+35	96.4	114.3	17.7	12
				18.5	14
107+25	96.1	114.0	22.6	10	
Lift 5	50+75	<i>93.5</i>	110.9	20.5	10

The italicized red DCPI values are significantly higher than the rest, even though the zone passed acceptance with the NDG. The lone bold and italicized number under the %NPR column (93.5%) failed to reach the required 95% compaction. Note, however, that this lift actually passes since it will be utilized for the 12-in. subgrade treated layer with a 93% compaction requirement. In accordance with *Louisiana Standard Specifications for Roads and Bridges* – Section 303: In-place Cement Stabilized and Treated Base Course, the prepared roadbed has to be at least a 93% compaction of the maximum dry density prior to mixing cement [12].

US-90: Floodwall to South Kenner (H.012051)

This project is a widening project to add turn lanes along US-90 in District 02 in St. Charles Parish. The LTRC Geotechnical research team visited the project site in November 2020. The embankment was classified as A-6 (9) Silty Clay and was located along the shoulder of both eastbound and westbound lanes. The embankment was compacted in a series of 1-ft. lifts. District contracted-staff tested each lift with the NDG in accordance with Section 203 in *Louisiana Standard Specifications for Roads and Bridges* [12]. The Proctor values were 102.1 pcf for MDD and 20.7% for OMC. The layer requires 95% compaction, and contracted-staff conducted QC NDG tests to the

depth of 8 in. Researchers conducted two DCP tests at each zone. The results show a huge disparity (noted in red font) between the DCPI values, even though the NDG passed acceptance for both locations. The NDG and DCP results can be found below in Table 15. This huge disparity could have been caused by the compaction of the shoulder—this is the first time researchers have tested on a roadway shoulder. The surface was flattened before testing to follow suit with the QA procedure of utilizing the NDG.

Table 15. US-90 shoulder embankment NDG and DCP data

STA	%NPR (%)	ADD (pcf)	Average DCPI of Test Layer (mm/blow)	Number of Blows (#)
82+34 Eastbound	98.5	100.6	9.4	22
			<i>26.1</i>	<i>8</i>
89+90 Westbound	99.4	101.5	<i>24.2</i>	<i>9</i>
			<i>35.0</i>	<i>7</i>

I-55: 0.2 Mile S US 190 Overpass Slope Repair (H.013260)

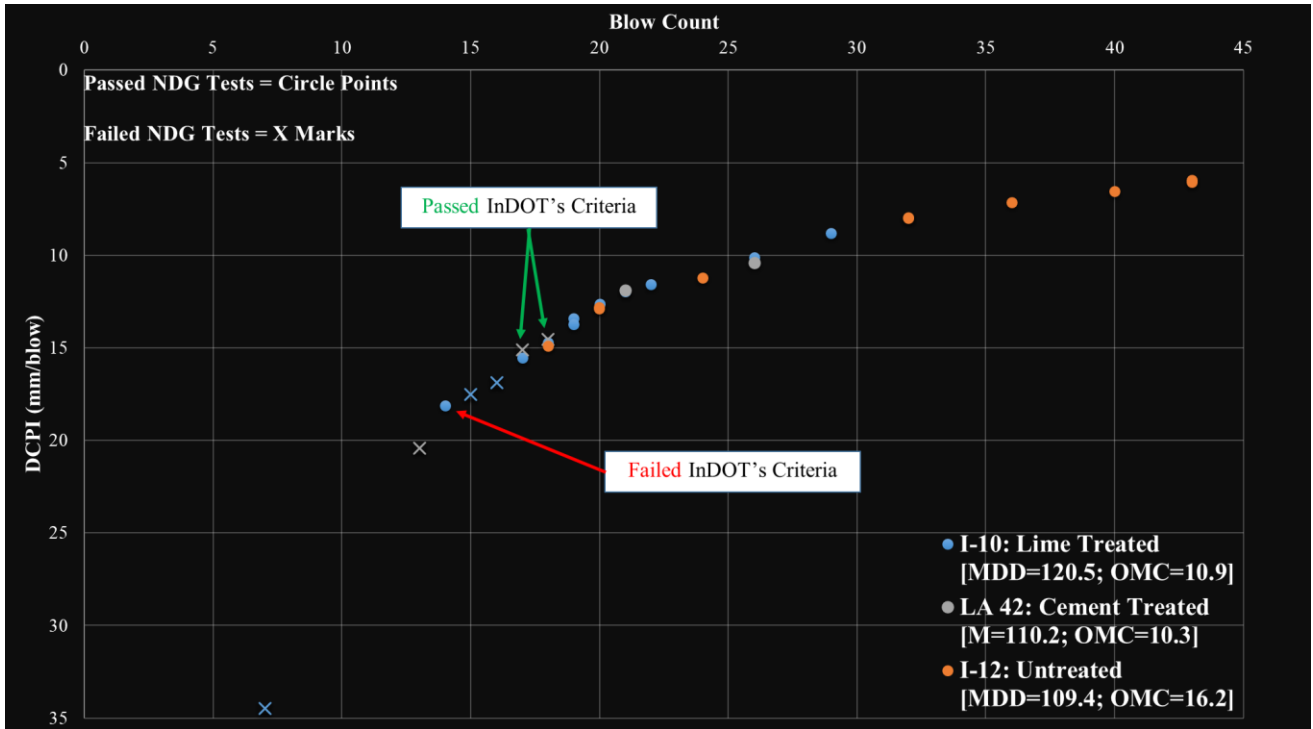
This project is an embankment repair utilizing fine sand, which is a rarity for DOTD projects. Results were inconsistent for both the NDG and DCP, and thus, were excluded from the final conclusion. More testing would be required to recommend the DCP to be utilized as an alternative for QA/QC acceptance testing for this type of application and material. Results and analysis for the sand embankment project can be found in Appendix III.

District Data Analysis & Specification Comparison

Subgrade Layer Comparison with InDOT Specifications

All the subgrade DCP data was plotted by color and type of treatment (lime, cement, or untreated) for thorough analysis. Figure 17 shows all DCP tests (taken within 2 ft. of an NDG test) in relation to whether or not its corresponding NDG test passed acceptance. Failed NDG acceptance test locations are represented by an “X,” while passing location are designated by circular points. The X-axis is the number of hammer blows required for the DCP to get through the predetermined test layer depth, and the Y-axis is the DCPI (mm/blow). Each point represents a different DCP test and the plotted value is the average DCPI calculated by the Smart DCP. A few points are indicated where the NDG and InDOT’s criteria have a disagreement. Comparing the graph to InDOT’s criteria, data points with a DCPI value of 16 mm/blow or less would pass acceptance.

Figure 17. DCP tests in relation to NDG acceptance tests on subgrade layers



Note: Four of the five LA 42 data points were normalized to reflect a 10-in. test layer as all other subgrade tests. As mentioned in the second site visit reading, these NDG acceptance tests were tested to 12 in.

InDOT's "Field Testing of Soil, Granular Soil, and Coarse Aggregate," "acceptance for chemically modified soils require a minimum DCP blow count of 20 for 12 in. and a minimum blow count of 8 for the top 6 in., respectively" [17]. This converts to a DCPI of 0.6 in/blow (15.24 mm/blow) for 12 in. and a DCPI of 0.75 in/blows (19 mm/blow) for the top 6 in.

LTRC plugged Louisiana subgrade site data into the InDOT specifications. There was an agreement between the District NDG pass/fail results and whether the layer would have passed under the InDOT specification for most locations. Table 16 shows the comparison of the DOTD acceptance tests, DCP results by depth, and InDOT's requirements on chemically modified soils. InDOT's requirements are represented by the two yellow columns, in which both columns must pass to meet the required specification. In our case, InDOT standards would have passed two failing DOTD NDG acceptance tests, and failed a passing DOTD NDG acceptance test.

All but three instances (highlighted red in Table 16) equate when comparing the DOTD NDG acceptance and DCP testing against InDOT's requirements. Of those three highlighted, I-10: Zone 127 had an unusually high DCP Index, even though NDG acceptance test has passed. Stations 156 and 156+10 passed InDOT's standards of having at least 20 blows to penetrate through 12 in., but the DCPI values are slightly higher than the 15.24 mm/blow criteria mentioned above. However, InDOT primarily relies on the maximum blow count rather than stiffness for a type of soil layer. For Louisiana, these issues could be utilized as a cautionary verification if/when the minimum number of blows is reached.

A second DCP test, when questionable results arise at a test location could add more confidence but require more time. Researchers incorporated this logic in the latter half of their site visits (as seen in the I-12 subgrade data). In fact, MnDOT's DCP test procedure requires two DCP tests in one zone for verification. However, MnDOT's procedure also requires gradation/sieve analysis, which will be mentioned in embankment comparison in the next section. LTRC's subgrade data is not compared with MnDOT's specification for this reason.

Table 16. InDOT comparison for DOTD NDG subgrade layer data

Site: Test Layer	STA / Zone	NDG Testing			DCP Testing (6 in)		InDOT (6 in)	DCP Testing (12 in)		InDOT (12 in)
		%NPR (%)	Req. (%)	Pass / Fail	Blows (#)	DCPI (mm/b)	Pass / Fail	Blows (#)	DCPI (mm/b)	Pass / Fail
I-10: Lime Treated Subgrade	117	97.2	93	PASS	18	8.7	PASS	29	11	PASS
	123	93.2		PASS	14	11.2	PASS	26	12.7	PASS
	124	93.0		PASS	13	12.3	PASS	26	12.3	PASS
	125	94.2		PASS	10	15.3	PASS	23	13.3	PASS
	126	97.7		PASS	18	8.8	PASS	34	9.1	PASS
	127	94.4		PASS	7	22.4	FAIL	18	17	FAIL
	128	95.1		PASS	10	15.8	PASS	20	16	PASS
	129	99.8		PASS	10	15.5	PASS	21	14.6	PASS
	130	95.7		PASS	10	15.5	PASS	23	13.7	PASS
	131	91.7		FAIL	7	22.4	FAIL	18	17.4	FAIL
	132	90.0		FAIL	9	17.5	PASS	19	16.6	FAIL
	133	96.4		PASS	11	14.3	PASS	24	13	PASS
	134	86.4		FAIL	6	31	FAIL	9	37.9	FAIL
LA 42: Cement Treated	147+59	95.1	95	PASS	15	10.7	PASS	24	13.6	PASS
	156+00	93.1		FAIL	9	17.5	PASS	20	15.4	PASS
	156+10	92.1		FAIL	11	14	PASS	20	15.5	PASS
	156+20	96.9		PASS	18	9.1	PASS	29	10.9	PASS
	170+20	93.5		FAIL	9	18.5	PASS	15	22.9	FAIL
I-12: Un-Treated	248+80	97.5	95	PASS	19	8.22	PASS	43	7.20	PASS
					26	5.98	PASS	50	6.18	PASS
	245+94	95.4		PASS	26	6.00	PASS	48	6.46	PASS
					24	6.43	PASS	45	6.85	PASS
	130+00	95.3		PASS	22	7.25	PASS	36	8.83	PASS
					23	6.72	PASS	36	8.80	PASS
	125+25	98.7		PASS	16	9.95	PASS	26	12.16	PASS
					14	11.34	PASS	23	13.80	PASS
113+50	95.4	PASS	12	12.93	PASS	20	15.52	PASS		
			14	11.20	PASS	23	13.59	PASS		

Note: For the purpose of this study, the InDOT specification for minimum blow counts (8 for 6 in., 20 for 12 in.) has been equated with the maximum allowable DCPI.

Clay Embankment Comparison with InDOT & MnDOT Specifications

InDOT also has a textural classification as part of their specification. Table 17 shows InDOT’s typical values for Proctor tests and DCP blow counts for types of material (i.e., clay, sand, granular) [17]. Acceptable moisture ranges for all materials are included and differ from DOTD QA/QC NDG acceptance, where the material has to fall within 2% of the OMC.

Table 17. InDOT's textural specification

Textural Classification	MDD (pcf)	OMC (%)	Acceptable Minimum DCP Blow Count		Acceptable Moisture Compaction Range
			for 6 in.	for 12 in.	
Clay	< 105	19 - 24	6		-2% to +2% of OMC
	105 - 110	16 - 18	7		-2% to +1% of OMC
	111 - 114	14 - 15	8		
Silty	115 - 116	13 - 14		9	-3% of OMC
	117 - 120			11	
Sandy	121 - 125	8 - 12		12	
	> 125			15	
No. 30	Granular Soils - Structure Backfill & A-1, A-2, A-3 Soils			6	
No. 4			7		
1/2 in.			11		
1 in.			16		

Each DOTD site was compared to these InDOT specifications to see if the DOTD DCP data would pass InDOT’s standards. For example, the LA 16 roundabout embankment had seven NDG tests where all have passed acceptance. The silty clay material fell within a OMC range of 16 – 18%, which InDOT indicates should have an acceptable blow count of at least 7 for a 6-in. test. One test zone produced only six blows according to two different DCP tests, which would result in a failure for InDOT specifications.

The LTRC research team also compared DCP results against MnDOT standards for embankment data. MnDOT has a specification utilizing the DCP as a compaction acceptance tool, where two requirements have to be met. All MnDOT non-granular material must pass the first requirement of “seat” value. The seat is considered the first two blows of the DCP test, and if the maximum allowable seat is exceeded, then the test area must be compacted again. It is our understanding that the seat helps eliminate from

the calculations loose unconfined material at the surface, which could skew results in granular material. The second requirement is the maximum allowable DPI, which is similar to the DCPI, however only measures the readings after five blows. The DPI is calculated in the equation below [17].

$$DPI = \frac{\text{Reading after 5 blows} - \text{Reading after 2 blows}}{3} \quad [2]$$

Another initial step for MnDOT is calculating the grading number (GN) of the material for the tested soil layer. Table 18 and Table 19 are excerpts from MnDOT’s Grading & Base Manual for gradation data and penetration requirements [18]. Table 18 shows a spreadsheet that helps to calculate the GN for any soil. Table 19 shows the MnDOT penetration requirements.

Table 18. MnDOT's gradation data

Gradation Data (use % passing in formulas)

$$GN = \frac{1" + \frac{3}{4}" + \frac{3}{8}" + \#4 + \#10 + \#40 + \#200}{100}$$

Sieve	% Passing
1 Inch	100
3/4 Inch	99
3/8 Inch	99
# 4	97
# 10	96
# 40	66
# 200	0.0
GN =	5.6

Table 19. MnDOT's penetration classification

Penetration Requirements

Grading Number	MC (% dry)	Maximum Allowable Seat (mm)	Maximum Allowable DPI (mm/blow)	Approx. Test Layer (inch)	Grading Number	MC (% dry)	Maximum Allowable Seat (mm)	Maximum Allowable DPI (mm/blow)	Approx. Test Layer (inch)
< 3.1	0 - > 8.0	40	10	4 - 6					
3.1 - 3.5	< 5.0	40	10	4 - 6	4.6 - 5.0	< 5.0	65	15	6 - 12
	5.0 - 8.0	40	12			5.0 - 8.0	75	19	
	> 8.0	40	16			> 8.0	85	23	
	> 8.0	40	16			< 5.0	85	17	
3.6 - 4.0	< 5.0	40	10	4 - 6	5.1 - 5.5	5.0 - 8.0	95	21	7 - 12
	5.0 - 8.0	45	15			> 8.0	105	25	
	> 8.0	55	19			< 5.0	100	19	
4.1 - 4.5	< 5.0	50	13	5 - 6	5.6 - 6.0	5.0 - 8.0	115	24	8 - 12
	5.0 - 8.0	60	17			> 8.0	125	28	
	> 8.0	70	21						

An MnDOT Excel spreadsheet (shown in Table 20) allows data input (blue boxes) to calculate the GN and pass/fail criteria automatically according to their specification. Table 20 shows DCP data from the La 16-447 roundabout embankment site and the calculated GN 5.6. Table 19 indicates that MnDOT specification would require a maximum allowable SEAT of 125 mm and a maximum allowable DPI of 28 mm/blow (for a material with a MC > 8.0). The InDOT comparison shows all DCP tests passed, except for the one, where a high DPI was found and thus failed. The DOTD NDG passed acceptance for this test location.

Table 20. MnDOT's specification criteria results for LA 16-447

Test Information			Requirements		DCP Data (mm)		Test Results				
Test Layer Depth (mm)	GN	MC (%)	Maximum Allowable SEAT (mm)	Maximum Allowable DPI (mm/blow)	Reading after seating (2 Blows)	Reading after 5 Blows	SEAT (mm)	SEAT: Pass or Fail	DPI (mm/blow)	DPI: Pass or Fail	TEST: Pass or Fail
203	5.6	13.9	125	28	62	103	62	Pass	14	Pass	Pass
203	5.6	13.9	125	28	27	67	27	Pass	13	Pass	Pass
203	5.6	15.6	125	28	52	150	52	Pass	33	Fail	Fail
203	5.6	15.6	125	28	44	118	44	Pass	24	Pass	Pass
203	5.6	14.6	125	28	38	92	38	Pass	18	Pass	Pass
203	5.6	14.6	125	28	31	80	31	Pass	17	Pass	Pass
203	5.6	15.4	125	28	24	52	24	Pass	9	Pass	Pass
203	5.6	15.4	125	28	23	58	23	Pass	12	Pass	Pass
203	5.6	14.1	125	28	40	79	40	Pass	13	Pass	Pass
203	5.6	14.1	125	28	34	75	34	Pass	13	Pass	Pass
203	5.6	15.7	125	28	41	92	41	Pass	17	Pass	Pass
203	5.6	15.5	125	28	33	102	33	Pass	23	Pass	Pass

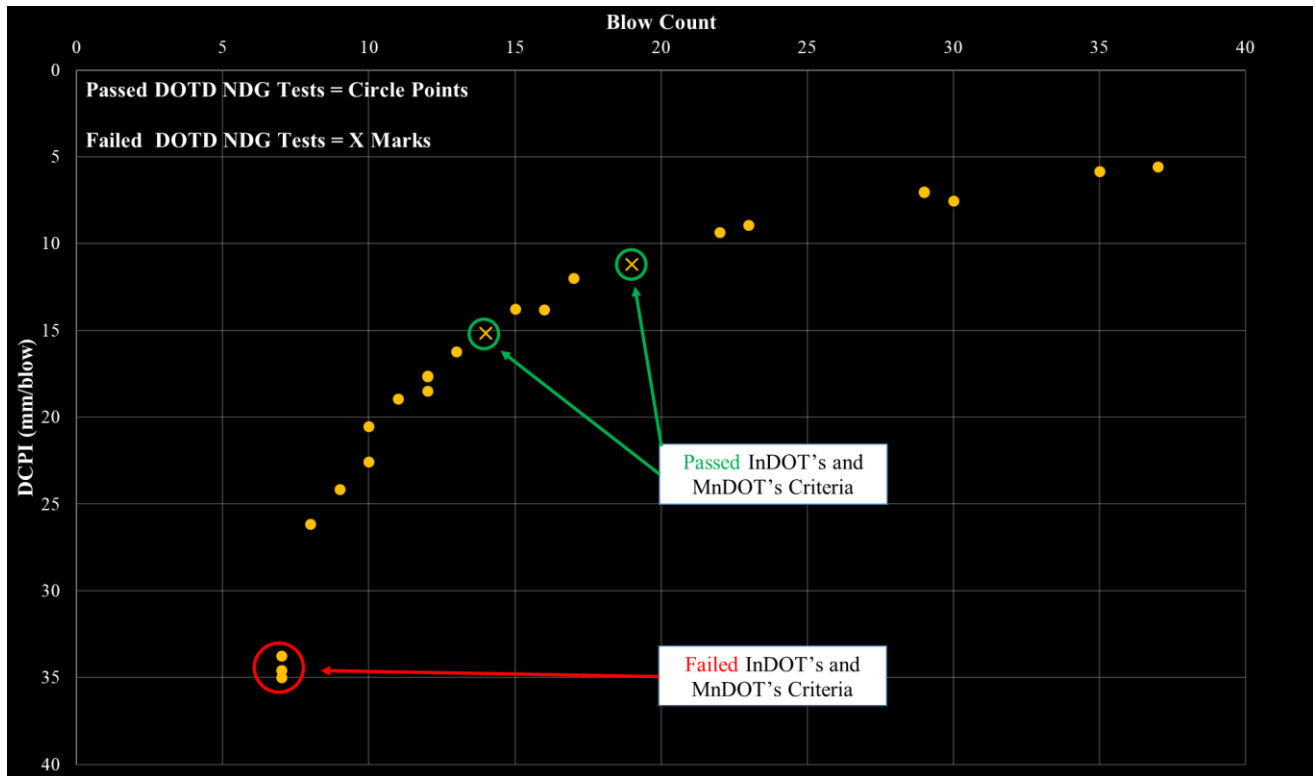
All clay embankment DCP data was compared with both InDOT and MnDOT standards as seen in Table 21 and Figure 18. In Table 21, all but three instances (highlighted red) match when comparing the DOTD NDG acceptance and DCP testing against InDOT's and MnDOT's requirements. There is one instance (STA 89+90 from the US-90 site) where two DCP tests show one pass and one fail in other states' standards. A third DCP test can be taken to verify or repeat compaction could be requested. Figure 18 is an alternative visual of how failed DOTD NDG points (represented by "X") actually passed according to both InDOT and MnDOT standards. In addition, a group of three points are shown to have failed InDOT and MnDOT's criteria, even though these have passed DOTD NDG's acceptance test. The DCP data seen in Figure 18 are compiled from the embankment DCP results found in Table 13, Table 14, and Table 15.

Table 21. InDOT & MnDOT comparison for DOTD NDG clay embankment data

Site: Test Layer	STA / Lift	NDG Testing		DCP Testing		InDOT		DCP Testing		MnDOT	
		%NPR (%)	Pass or Fail	Depth (in)	Blows (#)	Req.	Pass or Fail	SEAT (mm)	DPI (mm/b)	Req.	Pass or Fail
Deer Park Road Realignment: Sandy Loam Embankment	16+10	95.6	PASS	12	43+	12 Blows for 12-in. test	PASS	23	9	< 125 mm for SEAT < 28 mm/blow for DPI	PASS
					36+		PASS	23	9		PASS
	17+20	91.5	FAIL		40		PASS	23	9		PASS
					36		PASS	31	13		PASS
	17+95	96.2	PASS		49		PASS	36	10		PASS
					51		PASS	33	11		PASS
	18+70	95.0	PASS		38+		PASS	20	8		PASS
					44		PASS	21	6		PASS
LA 16-447 Roundabout: Silty Clay Embankment	50+00 (Lift 1)	99.7	PASS	6	10	7 Blows for 6-in. test	PASS	62	14	< 125 mm for SEAT < 28 mm/blow for DPI	PASS
					10		PASS	27	13		PASS
	108+00 (Lift 2)	97.2	PASS		6		FAIL	52	33		FAIL
					6		FAIL	44	24		PASS
	107+75 (Lift 3)	96.9	PASS		9		PASS	38	18		PASS
					9		PASS	31	17		PASS
	106+55 (Lift 4)	97.8	PASS		13		PASS	24	9		PASS
					14		PASS	23	12		PASS
	51+35 (Lift 4)	96.4	PASS		10		PASS	40	13		PASS
107+25 (Lift 4)	96.1	PASS	10	PASS	34	13	PASS				
50+75 (Lift 5)	93.5*	PASS	8	PASS	41	17	PASS				
US-90: Sandy Clay Shoulder Embank.	82+34	98.5	PASS	6	18	6 Blows for 6-in. test	PASS	18	7	< 105 SEAT < 25 DPI	PASS
					7		PASS	22	18		PASS
	89+90	99.4	PASS		7		PASS	40	25		PASS
					5		FAIL	48	38		FAIL

*In accordance with the Louisiana Standard Specifications for Roads and Bridges - Section 303: In-place Cement Stabilized and Treated Base Course, it states the prepared roadbed has to be at least a 93% compaction of the maximum dry density prior to mixing cement [12].

Figure 18. DCP test data comparison with InDOT and MnDOT standards on embankment layers



Base Course Layer Comparison with InDOT & MnDOT Specifications

Utilizing InDOT specification for chemically modified soils, which includes the addition of RPCC and crushed stone in base course layers, LTRC plugged in the Louisiana base course data in Table 22. All but three instances (highlighted red) match when comparing the DOTD NDG acceptance and DCP testing against InDOT's requirements. All of the US-190 RPCC base course data would have passed InDOT's criteria, even though the DOTD has two out of four failing NDG acceptance tests. Only one test location at LA 347 didn't match between DOTD and InDOT, however a second DCP could have helped verify if standards are met for compaction acceptance. That same test location on LA 347 had an unusually high DCP Index, even though NDG acceptance test has passed. One additional information about the LA 347 site is that there was standing water near the NDG and DCP testing. Stone base course can be tricky when it comes to moisture, however, the DCP does not collect moisture and is only based on performance.

Table 22. InDOT comparison for DOTD NDG base course data

Site: Test Layer	STA / Zone	NDG Testing			DCP Testing (6 in)		InDOT (6 in)	DCP Testing (12 in)		InDOT (12 in)	
		%NPR (%)	Req. (%)	Pass or Fail	Blows (#)	DCPI (mm/b)	Pass or Fail	Blows (#)	DCPI (mm/b)	Pass or Fail	
LA 22: RPCC	Zone 1	97.7	95	PASS	16	9.6	PASS	28	11	PASS	
	Zone 2	95.4	95	PASS	12	12.6	PASS	24	13.3	PASS	
Westwood: RPCC	15+00	99.6	95	PASS	19	7.8	PASS	34	9.1	PASS	
	18+00	103.1	95	PASS	11	14.0	PASS	24	12.6	PASS	
	14+60	100.5	95	PASS	14	11.0	PASS	26	12.0	PASS	
US-190: Recycled PCC	21+50	89.6	95	FAIL	15	10.8	PASS	27	11.3	PASS	
					15	10.2	PASS	Didn't test past 10 in.			
					12	13.3	PASS	25	12.6	PASS	
					14	12.3	PASS	24	12.9	PASS	
	21+60			93.3	FAIL	13	12.3	PASS	28	11.4	PASS
						18	8.5	PASS	31	9.9	PASS
	21+85			95.7	PASS	18	8.7	PASS	31	9.8	PASS
						32	4.8	PASS	47	6.5	PASS
21+55	95.8	PASS	31	5.0	PASS	48	6.4	PASS			
27	5.7	PASS	43	7.3	PASS						
LA 347: Crushed Stone	Zone 1	97	95	PASS	7	22.7	FAIL	Base layer was only 10 in.			
	Zone 2	null*	95	FAIL	6	27.8	FAIL				
	Zone 1 (day 2)	97.4	95	PASS	8	19.0	PASS				
	Zone 2 (day 2)	97.1	95	PASS	13	17.8	PASS				

Note: For the purpose of this study, the InDOT specification for minimum blow counts (8 for 6 in., 20 for 12 in.) has been equated with the maximum allowable DCPI. Red color indicates a non-comparison.

*The NDG Acceptance test was deemed a failure, because the pilot hole collapsed due to being too wet.

Louisiana Standard Specifications for Roads and Bridges requires stone and recycled PCC to comply with the gradation shown in Table 23 and Table 24, respectively [12]. Following these standards, LTRC researchers determined the equivalent MnDOT GN range for both stone and RPCC to be 3.0 to 4.5.

Table 23. DOTD specification for stone base course gradation

Table 1003-6
Gradation for Base Course Aggregates, Stone

U.S. (Metric) Sieve Size	Percent Passing By Weight (Mass)
1 ½ inches (37.5 mm)	100
1 inch (25 mm)	90 - 100
¾ inch (19.0 mm)	70 - 100
No. 4 (4.75 mm)	35 - 65
No. 40 (425 µm)	12 - 32
No. 200 (75 µm)	5 - 12

Table 24. DOTD specification for RPCC base course gradation

Table 1003-7
Gradation for Base Course Aggregates, RPCC

U.S. (Metric) Sieve Size	Percent Passing By Weight (Mass)
1 ½ inches (37.5 mm)	100
1 inch (25.0 mm)	90 - 100
¾ inch (19.0 mm)	70 - 100
No. 4 (4.75 mm)	35 - 65
No. 40 (425 µm)	12 - 32
No. 200 (75 µm)	0 - 8

Utilizing MnDOT’s procedure, the stone base course at LA 347 (moisture contents greater than 8%) all failed to fall below MnDOT’s maximum allowable DPI from GN ranging from 3 – 4.5. In Table 19, a 3.0 grading number material allows a DPI under than 10 mm/blow, while a GN of 4.5 allows a max DPI of 21 mm/blow [18]. A higher grading number means finer material, so theoretically, a coarse stone base course should fall below a GN of 4.5. LTRC imported five DCP location results from Table 10 into MnDOT’s excel spread sheet; it was indicated that all five had a DPI of greater than 21 mm/blow.

The LA 22, Westwood, and US-190 RPCC sites had passing NDG acceptance test and moisture contents greater than 8%. In Table 25, LTRC compares these sites’ DCP results against MnDOT requirements assuming the GN to be 3.0, which has the strictest criteria (maximum SEAT of 40 mm and DPI of 10 mm/blow). All but one DCP test meets the MnDOT requirement for maximum seat, however the test location passes due to four-out-of-five DCP tests indicating a seat value below 40 mm.

Table 25. MnDOT specification comparison for RPCC base course tests

Site	STA/ Zone	NDG Pass or Fail	Seat (mm)	MnDOT Pass or Fail	DPI (mm/blow)	MnDOT Pass or Fail
LA 22	Zone 1	PASS	36	PASS	9	PASS
	Zone 2	PASS	31	PASS	11	FAIL
Westwood Drive	15+00	PASS	21	PASS	9	PASS
	18+00	PASS	24	PASS	15	FAIL
	14+60	PASS	33	PASS	11	FAIL
US-190: Turn Lane	21+50 (12-Dec)	FAIL	34	PASS	10	PASS
			33	PASS	11	FAIL
			38	PASS	14	FAIL
			33	PASS	12	FAIL
			43	FAIL	12	FAIL
	21+60 (7-Jan)	FAIL	22	PASS	8	PASS
			22	PASS	10	PASS
	21+85 (9-Jan)	PASS	15	PASS	5	PASS
			14	PASS	5	PASS
	21+55 (9-Jan)	PASS	12	PASS	6	PASS
			12	PASS	4	PASS

Note: MnDOT's Pass/Fail criteria for the above data are assumed for a material with a GN of 3.0 and have a moisture content greater than 8%. The maximum allowable seat is 40 mm, and the maximum allowable DPI is 10 mm/blow.

At least one test location at each DOTD site fails MnDOT's DPI requirement. However, this strict DPI is not the case if the GN is assumed to be 3.1 or higher. A GN of 3.1 grants a maximum allowable DPI of 16 mm/blow (for material above 8% moisture content) according to MnDOT's standard in Table 19 mentioned before. A maximum DPI of 16 mm/blow means that all the DCP tests in Table 25 would pass MnDOT's standards and agree more with InDOT's comparison results.

GN ranges for the other Louisiana tested soil layers could not be accurately compared because the MnDOT specifications deal more with granular materials as opposed to clay subgrade material tested by LTRC.

This MnDOT specification for compaction acceptance utilizing the DCP is well established, however it requires both gradation number and moisture content. The MnDOT DPI calculation only requires five DCP blows rather than testing the full layer thickness. The MnDOT's procedure is fast in that it only requires several blows, but it does require a second test for verification. This may produce more confidence (two tests), while roughly equaling the time of a single test through the full layer thickness.

Interlayer Comparison with MnDOT Specifications

The InDOT specification for chemically modified soils is not sufficient for the stone interlayer from the Arkansas road site, because the layer itself does not reach the minimum of 6 in. Since the layer is so thin, the granular DCP penetration index method from MnDOT is utilized. This method follows the same requirements from Table 19 (mentioned before), while eliminating the requirement for seat. Thus, the DPI is calculated in the equation below [18].

$$DPI_{Granular} = \frac{\text{Reading after 3 blows}}{3} \quad [3]$$

Table 26 compares the stone interlayer DCP results against MnDOT requirements assuming the GN to be 3.0, which has the strictest criteria for DPI (10 mm/blow). Only one test location (two DCP tests) fails MnDOT's DPI requirement at Station 104+25, even though there were five failing DOTD NDG locations.

Table 26. Interlayer DCP data comparison with MnDOT

Date	STA / Lift	NDG Testing			DCP Testing	MnDOT	
		%NPR (%)	Pass or Fail	Depth (in)	Reading after 3 blows (mm)	Req.	Pass or Fail
6/05 2020	101+00	97.7	PASS	2 (51 mm)	9	Maximum of 10 mm/blow for DPI	PASS
					10		PASS
	102+10	98.3	PASS		7		PASS
					7		PASS
	102+88	93.1	FAIL		9		PASS
	103+25	95.1	PASS		5		PASS
					7		PASS
	103+30	95.5	FAIL		43		FAIL
	104+25	91.8			13		FAIL
	104+35	93.1	FAIL		9		PASS
8				PASS			
8/03 2020	76+00	91.7	FAIL	8	PASS		
				7	PASS		
	73+90	95.1	PASS	6	PASS		
				6	PASS		
	72+85	95.1	PASS	5	PASS		
				8	PASS		
	72+20	95.3	PASS	6	PASS		
				6	PASS		
	70+75	95.1	PASS	7	PASS		
				7	PASS		
69+90	94.2	FAIL	8	PASS			
			9	PASS			

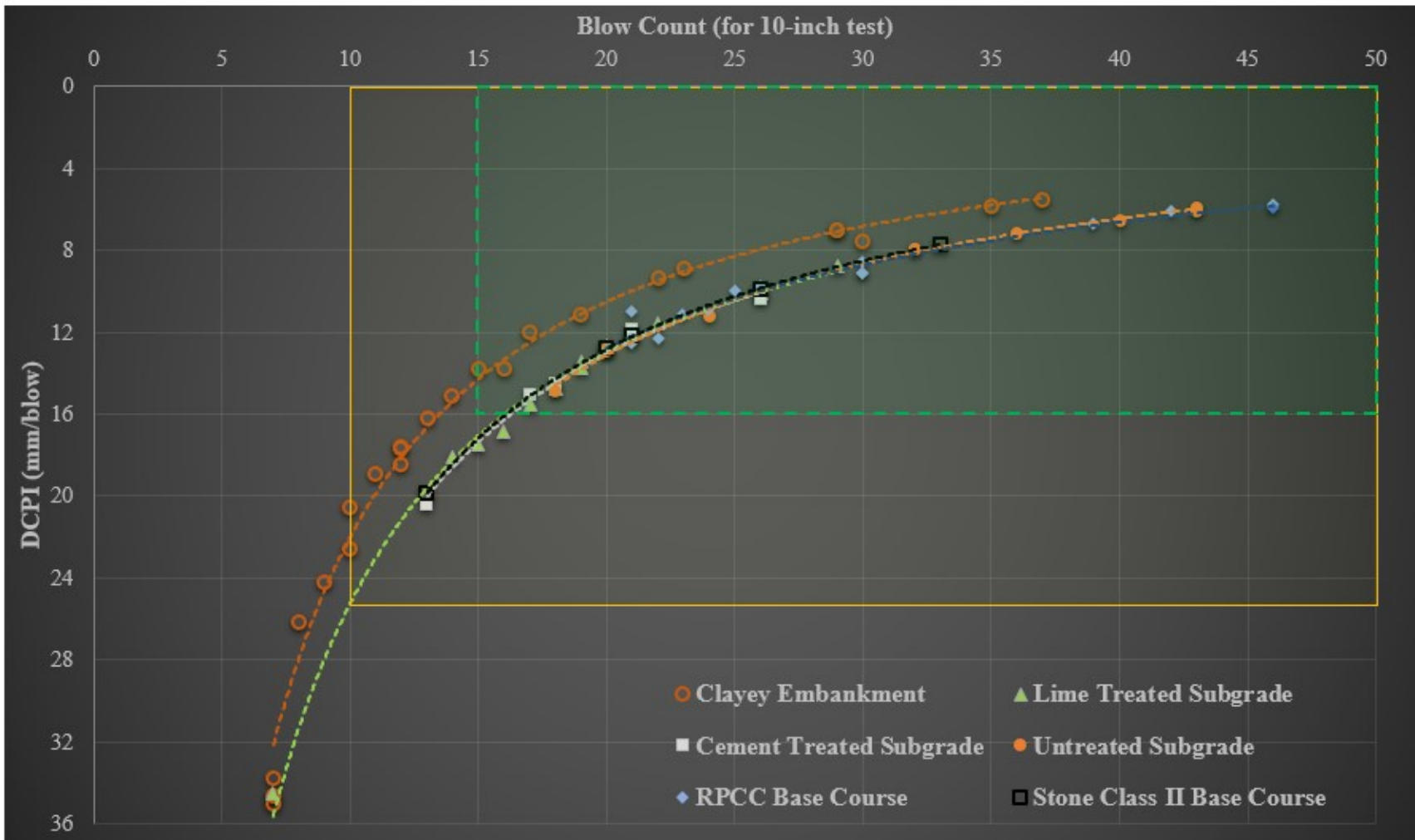
Determination of Possible DOTD DCP Acceptance Criteria for Embankment, Subgrade, Base Course Layers

Upon discussion amongst the LTRC researchers and the PRC, a DCP acceptance specification for Louisiana is possible. The data shows for multiple roadway layer types in relation to InDOT and MnDOT's already established DCP acceptance procedures. The proposed specification is attached in Appendix I and states that the DCP should be tested to 10 in., with the exception for an 8-in. DCP test for a 10-in. base course. A minimum blow count of 15 for a 10-in. DCP test (maximum DCPI of 16 mm/blow) is required for both subgrade and base course layers. In addition, the DCP test may be stopped if the first 6 in. of a tested layer does not exceed eight blows, as stated in InDOT standards [17]. A stone base course layer may have a stricter maximum DCPI of 10 mm/blow. A clay embankment can have a more lenient threshold with a minimum of 10 blows (maximum DCPI of 25.4 mm/blow) for a 10-in. DCP test.

Figure 19 shows the relationship of different layer types and our DCP test results. The layer types include: clay embankment, untreated subgrade layer, treated subgrade layers, recycled PCC base course layer, and a crushed stone base course layer. All the layers share a similar power trend line, where the "drop-off" from stiff soils occurs on the left (lower blow counts and higher DCPIs). All DCPI values (Y-axis) are normalized for a DCP test depth of 10-in.

The green (or smaller dash-lined) box in Figure 19 is a representation of the 16 mm/blow threshold for subgrade and base course layers, as mentioned before. The green box excludes the four lime-treated, one cement-treated, and one stone base course layer data points that InDOT's criteria would fail. The yellow (or bigger) acceptance box is the threshold for clay embankment data with a required blow count of 10 blows for a 10-in. DCP test. This acceptance box also excludes the three failings points according to InDOT and MnDOT's standards with an additional two points that would have passed. A DCPI of 25.4 mm/blow is currently drafted as the bar for DOTD DCP acceptance testing in embankments.

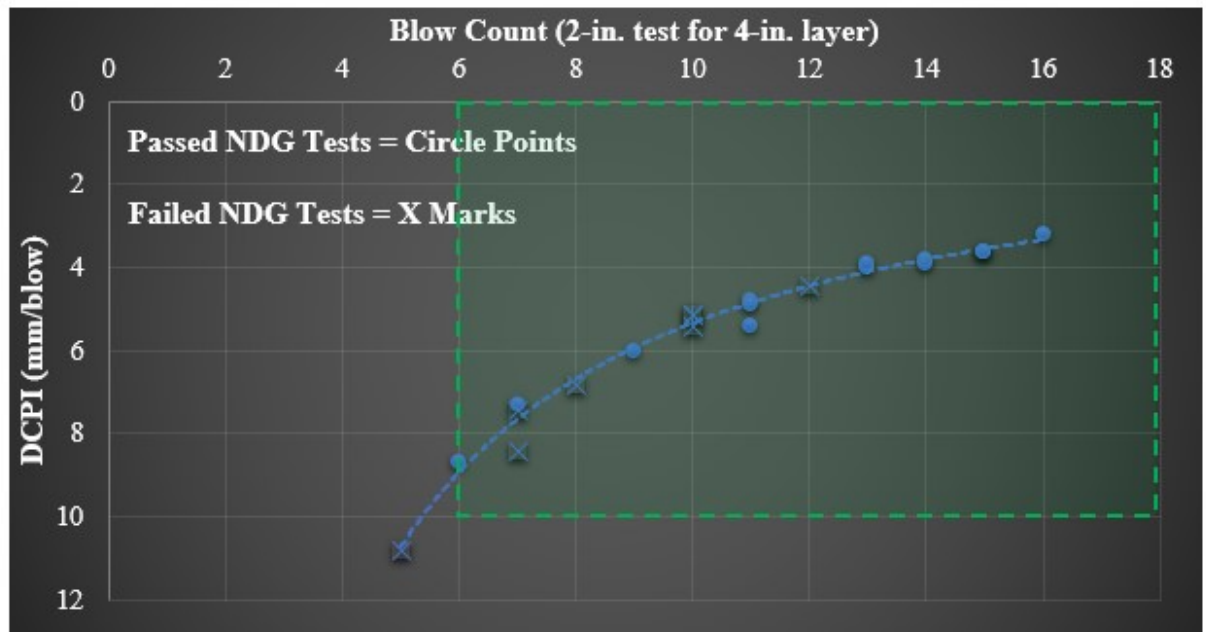
Figure 19. LTRC's DCP acceptance threshold for multiple layer types



LTRC's Acceptance Criteria for Stone Interlayer

Figure 20 shows the DCP data relationship of blow count and DCPI of the Arkansas road stone interlayer. One data point was left off the graph because it was an extreme outlier (two blows, 58.5 mm/blow). As before, the circle data points indicate that an NDG test has passed the percent compaction requirement, while the "X" data points indicate failed acceptance tests. There are multiple failed data points among the passing. This could have been caused by irregularities of the stone material, such as the angularity gradation issues. As mentioned before only one test location fails MnDOT procedure, and thus was excluded out of the dashed acceptance box in Figure 20. The green (dashed) acceptance box indicates possible requirements for a DCPI of 10 mm/blow or less and a blow count of at least six blows when performing a 2-in. test in a stone interlayer.

Figure 20. LTRC's DCP acceptance threshold for stone interlayers



Cost-Benefit Ratio

Table 27 shows the cost and comparisons of the NDG to the standard DCP and auto readers. Table 27 shows that the NDG roughly costs the department \$10K annually due to safety and licensing requirements, whereas the DCP and auto readers would have one-time costs for initial purchase plus additional disposable cone tips at roughly \$2 per cone tip [2].

Table 27. Cost & benefit comparisons

	Nuclear Moisture Density Gauge	Dynamic Cone Penetrometer		
		<i>standard DCP (w/o auto reader)</i>	<i>auto-readers</i>	
			<i>Smart DCP</i>	<i>Mag Ruler</i>
Measurement	Wet Density and Moisture	Stiffness		
Depth of Probe/Rod	Up to 12 in.	Up to 36 in. (900 mm) (Not including extension rod: approximately 6 ft.)		
Diameter	0.63 in.	Cone Tip = 0.79 in. Shaft = 0.63in.		
Radiation Source	Cesium 137	NA		
Device Life	Up to 30 years	Possible longer lifespan (wear & tear)		
Measurement Method	Gamma rays	Eye test/ruler	Laser sight	Sound
Badges/ Licensing/ Paperwork	Dosimeters Required	NA		
Leak Testing	Required every 6 months	NA		
Radiation Exposure	0.3 mrem at 1 meter (annual person limit = 5,000 mrems)	NA		
Storage Requirements	<ul style="list-style-type: none"> • Locked via transport • Locked in safety room 	<ul style="list-style-type: none"> • Normal equipment – no safety requirements • Carrying case provided 		
Safety Training	<ul style="list-style-type: none"> • Required by gov't. • Annual classes 	minimal		
Refresher Training	Current DOTD familiarity	Simple tool	Practice with smart application and transferring data	

COSTS				
Initial Cost	Roughly \$3,500 (\$2,500 trade-in)	\$1,300-\$1,780 (various kits)	\$1,700 alone	Roughly \$1,600 (\$2,900 DCP kit)
Disposal Cost	\$750	NA		
Thermoluminescent Dosimeters	\$7,860 per year	NA		
Licensing Certification	\$1,108 per year	NA		
Training classes	\$1,000 - \$2,000 per class (varies)	NA		
Battery Repairs	Less than \$500	NA	6 AAA	2 AAA
Other Additional Equipment Costs	Time required to complete paperwork and classes	Disposable Cones <ul style="list-style-type: none"> • Recommended; as oppose to permanent cone • Easier to take DCP out of the ground • Bulk of 100 cone tips: \$189 (under \$2 each cone) 		

NDG Monitoring and Safety

Nuclear moisture-density devices utilize a radioactive source, Cesium-137, which has a 30-year half-life. The NDG at LTRC has been operating since its purchase in 1987 and has only required a normal battery replacement for the display. However, due to the mass of the gamma source, there are classes and protocols for safety required to operate the NDG. A recent study, LTRC 17-2B, evaluated a lower nuclear source device as a possible alternative. The research report can be found at LTRC’s website [2].

It is crucial to monitor the amount of radioactivity that operators are exposed to while utilizing the NDG. DOTD utilizes two different dosimeter badges. One badge is kept at the operator’s desk and serves as a “control” badge. The second badge is worn while utilizing the NDG. These badges are collected and tested monthly. Radioactivity at DOTD is measured by millirems (mrem), and the allowable limits per code of federal regulations (CFR) can be seen in Table 28. However, it should be noted under proper utilization these mrem values are uncommon. The DOTD senior nuclear density gauge technician responsible for managing the devices commented on the safe nature of the NDG by stating, “With nearly 16 years of all day, nearly every gauge day use, my lifetime exposure report shows 738 mrem. A person is allowed 5,000 mrem per year.” [2].

Table 28. Annual radiation exposure limits (mrem)

Whole body, blood forming organs, gonads	5,000
Lens of eye	15,000
Extremities and skin	50,000
Fetal (Gestation period)	500
General Public	100

Based on the US NRC Regulations, Title 10, Part 20, Code of Federal Regulations and adopted by many states. Certain state and other regulatory agencies may adhere to different limits.

There are costs associated with these safety regulations that must be followed when utilizing the NDG. Thermoluminescent dosimeter badges are currently used by DOTD to detect the amount of radioactivity exposure amounts for operators. Landauer, Inc. provides radiation badges for monitoring using dosimeter technology to DOTD. The NDG requires an approximate annual cost of \$7,860 to Landauer for badge usage testing and reporting. In addition, NDG operators are required to have a license in order to track radioactive use. Even though it is relatively safe to utilize the NDG, radiation levels are high enough that require licensing. Licensing must be renewed every year at a price of \$1,108 annually [2].

Leak testing is required for all NDGs and is conducted twice a year. The leak test determines the integrity of the NDG. To determine if the NDG is suitable or needs to be replaced, researchers must send off a swab from the machine and wait for it to be analyzed. These leak tests do not cost the department any money, but it forces an employee to focus time on that leak test to collect samples and wait on the results vs. passing standards.

The NDG has been used for years within the department providing familiarity and ease of utilization. However, training classes can be costly. Table 29 shows an estimate of training classes' costs from the recent Troxler invoices per class. Each training class takes time from the technician's daily activities. For example, LTRC was charged a total of \$9,500 for 10 classes in the 2015-2016 fiscal year and \$24,450 for 18 classes in the 2016-2017 fiscal year. Training for each employee is on a 3-year cycle [2].

Table 29. NDG training cost per class

Nuclear gauge operator / Radiation safety training	\$1,625
Radiation safety officer training	\$2,025
Hazardous material refresher training	\$975

Note: These costs are for the 2015-2016 fiscal year and represent per class with a limit of 1-25 students.

Regarding storage and transportation of the devices, the NDG requires double lock security at all times. Ensuring the security of the NDG is essential and thus adds another tedious step in the process.

As with any operating system, there is always paperwork to be done. The NDG requires data collection, a license, dosimeter badges, operating training classes, and storage and transport documentation. All of this involves tedious paperwork that is necessary but takes time from the employee and department.

DCP Cost Benefits

The DCP lacks radioactivity use and thus requires no such license, dosimeter badges, leak testing, operating training classes, and storage and transport documentation. Annual costs to the department are at a minimum, if any at all.

The initial costs of the Kessler DCP (\$1,300 - \$1,780) cost approximately half of a new NDG (\$3,500). There is the possible addition of adding smart devices called auto-readers to help produce consistent results and reduce possible human error. The Mag Ruler and Smart DCP cost an additional \$1,700 but are highly recommended. The only other cost for the DCP is buying a bulk of disposable cones (Figure 21). Each DCP kit comes with a permanent DCP cone tip, however it can be troublesome and cause damage to the DCP when retrieving the DCP out of the ground. Disposable cones detach when the rod is removed upward and offers no resistance when lifting the DCP out of the ground. For example, 100 disposable cone tips from Kessler run at a price of only \$189 (approximately \$2 per cone).

Figure 21. Disposable cone tips



Device Utilization Comparison

Table 30 shows the comparison of each device before and during testing. Test set up for the NDG requires a smooth surface and a pilot hole (hammered into the ground); whereas, the DCP test consists of penetrating a cone into the ground to a desired depth while measuring the DCPI along the way. NDG standard count times are necessary for the NDG and define how long the gauge measures and improves precision. Test procedure DOTD TR-401 for the NDG requires three measurements (moisture and density) in one hole with the NDG pivoting 120 degrees for three separate measurements. The DCP would just require one test at a location. Lastly, the amount of time required to test for each device are similar; both devices set up and performance could be completed in a span of 5-8 minutes. The only instance could be attaching the auto-readers on the DCP would require a learning curve.

Table 30. Utilization comparisons

	Nuclear Moisture Density Gauge	Dynamic Cone Penetrometer		
		<i>Kessler DC</i> <i>(w/o auto reader)</i>	<i>auto-readers</i>	
			<i>Smart DCP</i>	<i>Mag Ruler</i>
DOTD Specification	Current/Existing DOTD TR-401	Would need to develop or modify current DOTD TR-645		
Measurement Method and Sensitivity	Low (background radiation is negligible)	NA	Laser sight; avoid obstructions	Sound; background noises are negligible
Test Setup	<ul style="list-style-type: none"> • Smooth surface • Hammer pilot hole 	Smooth surface	Tools required to add attachments for both readers	
Device Setup Time	2-5 minutes for pilot hole and calibration	2 minutes for initial setup	Approximately 3-5 minutes for attachments to the DCP	
Standard Count Time	4 minutes (once a day)	NA		
Test Time	1 minute each (completed 3 times)	12 – 15 minutes	5 – 6 minutes	5 – 6 minutes
Ease of Use	<ul style="list-style-type: none"> • 1 licensed operator • DOTD familiar • One device for moisture and density 	<ul style="list-style-type: none"> • 2-3 operators to lift & record • Simple tool • Lifting hammer could fatigue 	<ul style="list-style-type: none"> • 1-2 operators to lift & record • Practice with auto-readers recommended • Lifting hammer could fatigue 	

Conclusions

This research focused on evaluating a non-nuclear acceptance method, the DCP, as an alternative to the NDG during QA/QC acceptance testing. The main motivation for this study was to eliminate existing safety concerns and reduce the costs of tedious requirements associated with the NDG.

A literature review was conducted to summarize other state DOTs' implementation of the DCP as a quality acceptance tool.

Field testing was performed at various south Louisiana construction sites, where the DCP was tested alongside (shadowing) the NDG, the current compaction acceptance test method.

LTRC compared and plotted multiple DCPI results against the NDG density and moisture readings to find effective relationships.

DCP stiffness in relation to the NDG's density and moisture levels were also analyzed for correlations.

Based on collected data, test results, and analysis the following conclusions are listed below:

- DOTD TR 645, a test method for utilizing the DCP, was modified to include a method (Method B) for compaction acceptance. The modification was developed in relation to other state DOTs specifications (MnDOT, InDOT, etc.) and based on field acceptance compaction test results from the NDG vs. DCP tests.
- Lime treated subgrade, cement treated subgrade, and recycled PCC DOTD acceptance and DCP results corresponded well (90% of all testing) with InDOT's established specification. To further improve on this, two DCP tests may be taken for verification.
- The DCP does not collect moisture or density; however, its results are stiffness based and relate to performance vs. materials property tests like density or moisture from the NDG.
- LTRC performed DCP tests at three clay/silty embankment sites, three subgrade sites, one interlayer site, and four base course sites to compile Table 31, as seen below. Table 31 is included in the proposed DOTD TR Method B, which indicates

the limiting DCP Index (mm/blow) parameter for the top 6-in. and full test layer depths for each of the tested types of soil layers in this research.

Table 31. LTRC DCP acceptance by layer type

DCPI ANALYSIS			
Layer Type	Material Properties	ACCEPTABLE DCPI	
		Top 6 in.	Full Layer
Clay/Silty Embankment	MDD < 105; OMC 19-24%	< 25 mm/blow	< 25 mm/blow
	MDD > 105; OMC 8-18%	< 22 mm/blow	< 25 mm/blow
Subgrade	Lime Treated	< 19 mm/blow	< 16 mm/blow
	Cement Treated		
	Untreated		
Interlayer (< 6-in)	Class II Stone	< 10 mm/blow	NA
Base Course	Recycled PCC	< 19 mm/blow	< 16 mm/blow
	Class II Stone	< 10 mm/blow	< 10 mm/blow

Recycled PCC corresponded well with the MnDOT established specification. However, the MnDOT DPI calculation only requires five DCP blows rather than testing the full layer thickness. The MnDOT’s procedure is fast in that it only requires several blows, but it does require a second test for verification. This may produce more confidence (two tests), while roughly equaling the time of a single test through the full layer thickness.

Performance, costs, and ease of utilization were a few of the parameters among others that were also evaluated for the comparison of the NDG and DCP. The following conclusions are listed below:

- The DCP can penetrate 36 in. in depth and can provide a full soil profile (multiple layers) compared to the NDG, which can only reach a maximum depth of 12 in.
- The NDG collects moisture contents. If field moisture is required with the DCP, follow DOTD TR 403: Determination of Moisture Content.
- The costs of DCP were significantly less than that of the NDG.
 - The NDG requires approximately \$9,000 per year for thermoluminescent dosimeters and licensing certifications, which are not required for the DCP.
 - Costs for NDG safety training class ranged from \$9,000 to roughly \$25,000 a year per 3-year training cycle, while the DCP wouldn't require such safety training classes.
- Additional testing was conducted to compare the DCP with and without an auto reader. Vertek's Smart DCP and Kessler's Mag Ruler were evaluated for correlation and ease of use.
 - Although the DCP with an auto reader adds a few minutes of setup time compared to the NDG, there is no required calibration, standard count times, or required safety storage/transporting rules with the DCP.
 - The Smart DCP was the more preferred auto reader due to its ease of utilization, instant data transferring, and visually appealing data interface smart phone application.
 - The Mag Ruler is also a quicker alternative than the standard DCP (without an auto reader), as test times were reduced by more than half.

Other state specifications (InDOT and MnDOT) are already established regarding the DCP as an acceptance tool for soil layers and recycled PCC base layers, and Louisiana field work correlates well with these existing specifications.

A transition to the DCP and auto readers will likely entail an overlap of devices to ensure continuity until a possible phase out of the older test procedure of utilizing the NDG.

Recommendations

Based on the research work and conclusions, the following items are recommended for implementation.

- The DCP may be utilized as an alternative to the current NDG acceptance testing.
- The DCP acceptance testing procedure is outlined in the modified specification (Appendix I): TR-645 Method B.
- Pilot projects should be selected to test and refine the draft specification. In this case, the project could utilize the DCP for acceptance and pay and have the NDG shadow the DCP for research purposes.

Acronyms, Abbreviations, and Symbols

Term	Description
ADD	Average Dry Density
CBR	California Bearing Ratio
CFR	Code of Federal Regulations
cm	centimeter(s)
DCP	Dynamic Cone Penetrometer
DCPI	Dynamic Cone penetration index (mm/blow)
DPI	Dynamic Penetration Index (MnDOT)
FHWA	Federal Highway Administration
DOTD	Louisiana Department of Transportation and Development
DOTD TR	DOTD test method
ft.	foot (feet)
GN	grading number
in.	inch(es)
LCD	liquid crystal display
LTRC	Louisiana Transportation Research Center
lb.	pound(s)
MDD	maximum dry density
mm/blow	millimeter per blow
mrem	millirems (measurement for radiation)
NDG	Nuclear Moisture-Density Gauge
OMC	optimum moisture content in percent
pcf	pounds per cubic foot (lb./ft ³)
PRF	Pavement Research Facility
RPCC	Recycled Portland Cement Concrete
%NPR	% Density (Dry Density/Maximum Dry Density)
PR	Maximum Dry Density (TR 416/TR418)
STA	Station

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Appendix I

DOTD TR 645-10
Adopted 06/10
Page 1 of 17
Method A

Method of Test for
**THE DETERMINATION OF IN-PLACE STIFFNESS BY THE
DYNAMIC CONE PENETROMETER (DCP)**
DOTD TR 645-10

INTRODUCTION

The locations of DCP testing shall be selected by the Engineer. In locations where the subgrade stiffness is being assessed, DCP testing should be conducted to at least 36 in. (914.4 mm) into the subgrade unless otherwise directed by the Engineer. In locations where the acceptance (Method B) is being assessed, DCP testing should be conducted to desired layer depth with the addition of five blows for time constraint purposes.

There are generally five types of typical sections that will be assessed with the DCP as shown in Table 1. The Engineer shall provide specific instructions on the testing regime for each type.

Table 1

Case 1	Case 2	Case 3	Case 4	Case 5
Pavement	Pavement	Base course	Base course	Subgrade
Base course	Base course	Subgrade layer	Subgrade	
Subgrade layer	Subgrade	Subgrade		
Subgrade				

Only an Authorized DCP operator is to conduct the DCP tests. Completion of DCP training conducted by DOTD is required for authorization.

I. Scope

- A. The DCP can be used to measure the stiffness of cohesive and non-cohesive soils, base course aggregates, recycled asphalt pavement, recycled concrete pavement, blended calcium sulfate and in some instances chemically (cement or lime) stabilized or treated soils. Under no circumstance should the DCP be used to measure the stiffness of Concrete or Asphalt pavements as well as large size (> 1 in. diameter) aggregate.
- B. Reference Documents
 - 1. ASTM D6951-03, Standard Test Method for Use of Dynamic Cone Penetrometer in Shallow Pavement Applications
 - 2. DOTD TR 602M/602-96, Measuring Thicknesses and Widths of Base and Subbase Courses and Aggregate Type Surface Courses

II. Apparatus

- A. The schematic for the DCP is shown in Figure 1 (Source: ASTM D6951-03). The components of the DCP are typically constructed of stainless steel with the exception of the replacement tip, which is typically made of hardened tool steel or wear resistance material.
 - 1. Hammer: 17.6 lb. (8 kg) with a tolerance of 0.022 lb. (0.010 kg).
 - 2. Handle: Steel handle located at top of upper drive rod for proper hand placement.
 - 3. Upper Drive Rod: 5/8 in. (16 mm) diameter upper steel drive rod and handle. Fixed drop hammer height of 22.6 in. with a tolerance of 1 mm.
 - 4. Lower Drive Rod: 5/8 in. (16 mm) diameter lower steel drive rod.
 - 5. Coupler Assembly: 3 in. steel rod and quick connect pin that holds both drive rods in together (inserted just underneath anvil).
 - 6. Anvil: 2 in. (50 mm) diameter x 2.5 in. (62.5 mm) long (min).
 - a) Measuring rod or tape measure: The scale should have increments of 0.04 in. (1 mm) and a minimum length of 36 in. (914.4 mm).
 - b) Optional sliding attachment: An optional sliding attachment may be used to hold the scale vertical while conducting tests.
 - 7. Extension Rod: Length varies from 12 in. (304.8 mm) to 36 in. (914.4 mm).

8. Extraction Jack: Shown in Figure 4. (Source: ASTM D6951-03)
9. Rotary Hammer Drill: capable of drilling at least a 1 in. (25 mm) diameter hole through the pavement. Alternatively, augering with a coring rig is allowed (refer to TR 602M/602-98).
10. Cone tips: There are two types of cone tips as shown in Figures 2 and 3: Type I (reusable) and Type II (disposable). The Type I tip may be used repeatedly (up to 250 times) and has inclined angle of 60 degrees and base diameter of 0.787 in. (20 mm). Type II cone tips are used only once and its dimensions are similar to Type I cone tips. The tolerances for both types of cone tips are ± 1 degree for the tip angle and ± 0.010 in. (0.25 mm) for their diameter.

Note A-1: Wet coring is not allowed.

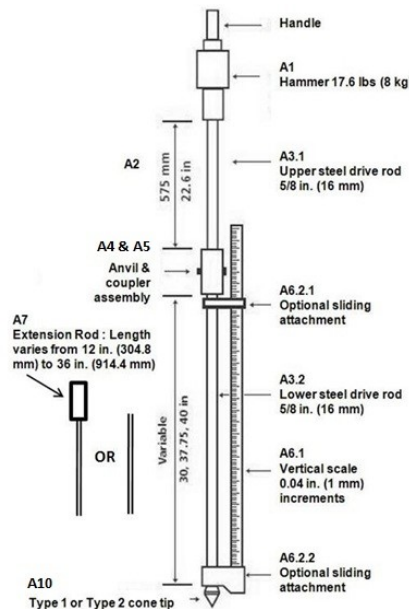


Figure 1. Schematic of DCP device

11. In addition to the DCP, DCP assembly tools as recommended by the manufacturer, lubricating oil, and a data recording sheet shown later may be required. Data may also be typed into an excel spreadsheet template, which is available to all DOTD personnel at <http://www.ltrc.lsu.edu/downloads.html>.

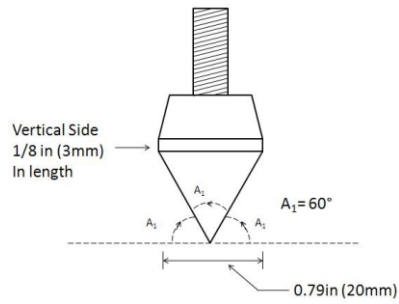


Figure 2. Type 1 Reusable Tip

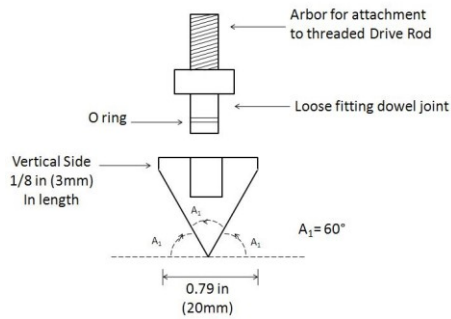


Figure 3. Type 2 Disposable Tip

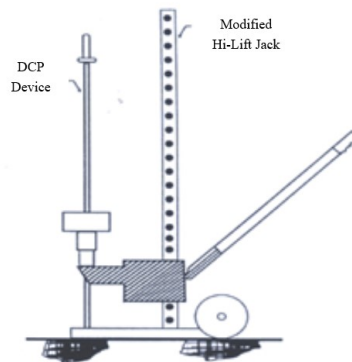


Figure 4. Extraction Jack

III. Health Precautions

Care must be taken with hand placement on the measuring scale, handle, or hammer during testing so as not to injure the hands or fingers.

IV. Samples, Test Specimens, Test Locations, etc.

The locations of DCP testing shall be selected by the Engineer. In locations where the subgrade is being assessed, DCP testing should be conducted to at least 36 in. (914.4 mm) into the subgrade unless otherwise directed by the Engineer.

V. Procedure

A. Equipment check: Inspect the DCP for damaged or fatigued parts and excessive wear of the drive rod or reusable cone tip if it is being used. Securely tighten or fasten all joints as well as the Type 1 or Type 2 tips on the drive rod. (See Figures 2 and 3).

B. Basic operation:

1. Operator

a) Hold the DCP in a vertical/plumb position.

i. On the pavement surface, take an initial reading.

ii. In a drilled hole (if applicable), take an additional reference reading.

b) Raise and release the hammer from the standard drop height.

2. Recorder

a) Read the scale at reference points and after each blow.

b) Record the measurements corresponding to the blow on the DCP data recording sheet included in this document (Appendix 1).

Note B-1: A measurement is recorded for each blow

C. Testing and recording procedures for Cases 1 and 2 sections as shown in Table 1.

1. Determine thickness needed to ensure that penetration will be at least 36 inches into the subgrade. Add extensions. The appropriate extensions should be added to the DCP assembly prior to beginning testing to account for the thickness of the pavement, base course, and subgrade layer.

2. Initial reading: Begin by placing the DCP and measuring scale vertically plumb on the surface and record the measurement (R1) (cm) on the data recording sheet as shown in Figures 5 and 6, respectively.
3. Pilot hole: Drill a vertically plumb 1 in. (25.4 mm) diameter hole (minimum) through the pavement layer as shown in Figure 7. Alternatively, the pilot hole may be created by auguring with a core rig. The pilot hole under no circumstance should be created by wet coring.
4. Record the reading prior to the first DCP blow: Place the DCP through the pilot hole and let the cone tip rest on top of the layer to be tested as shown in Figure 8. Record the reading (R2) (cm) in the location shown in Figure 6. This reading corresponds to blow count “0,” as shown in Figure 6.

D. Testing sequence

1. Dropping the hammer: Hold the DCP assembly vertically plumb. Lift and drop the hammer and from the standard height as shown in Figure 1. The person recording the data records the blow count and reading from the vertical scale corresponding to each blow as the DCP penetrates through the layer as shown in Figure 6. Alternatively, the data may be recorded directly into the excel template as mentioned in Section II.A.10.

Note D-1: A reading must be recorded for each blow.

2. Depth of penetration: The depth of penetration should be to at least 36 inches into the subgrade as shown in Figure 9 unless otherwise directed by the Engineer. For example, if the total thickness of the pavement, base course, and subgrade layer is 24 in. (609.6 mm) then a 24 in. (609.6 mm) extension should be added to the assembly.
3. Refusal: In some instances, the DCP may not penetrate very stiff material or may perform at a slow rate where it will damage the DCP. If after 10 blows, the device has not advanced more than 1 mm, testing shall cease on that layer. When refusal occurs, the DCP is removed from the hole and the rotary drill is used to drill through that layer as shown in Figure 10. The DCP is then carefully placed vertically plumb through the hole and allowed to rest on top of the layer to be tested. Record that reading (R2) (cm) and re-label that blow as 0 as shown in Figures 11 and 12. Testing is resumed as before as outlined in V.D.1.

4. Extraction: Once testing is complete, use the extraction jack to remove the DCP from the testing hole.

Note D-2: Do not reverse impact the handle to extract the DCP. Damage/breakage will occur.

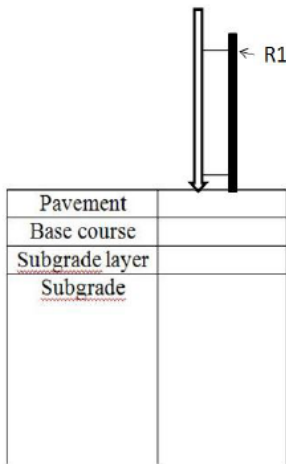


Figure 5

Project		
Date		
Location (CSLM / STA.)		
Location (Lane direction)		
Location (Outside / Inside Lane)		
Location (Distance from centerline)		
Initial reading on Surface	R1 = 42.1	
Pilot hole depth	R2-R1 = 56.8-42.1=14.7	
Reading after pilot hole	R2 = 56.8	
Comments		
Number (A) Of Blows	Rod (B) Reading (cm)	Comments
0	56.8	
1	61.7	
2	62.6	
3	63.1	
4	63.5	
5	64.0	
"	"	

(A) Number of Hammer blows between test reading
 (B) Scale reading corresponding to blow in cm

Figure 6

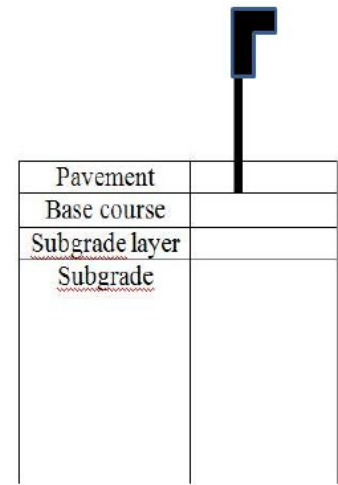


Figure 7

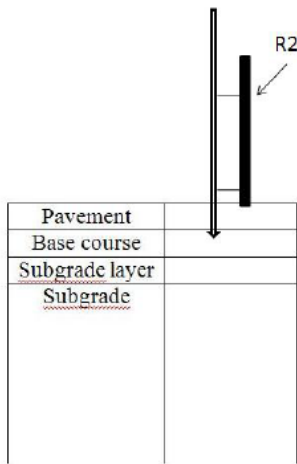


Figure 8

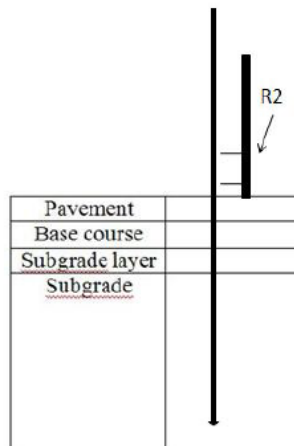


Figure 9

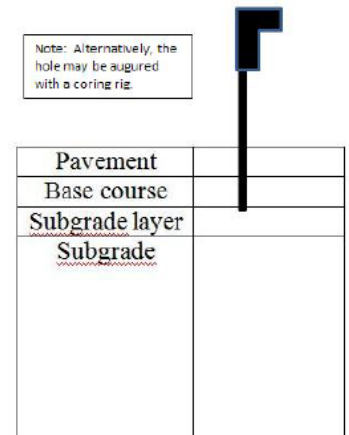


Figure 10

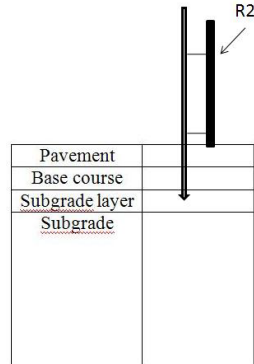


Figure 11

Project		
Date		
Location (CSLM / STA.)		
Location (Lane direction)		
Location (Outside / Inside Lane)		
Location (Distance from centerline)		
Initial reading on Surface	R1=30.2	
Pilot hole depth	R2-R1=26.6	
Reading after pilot hole	R2=56.8	
Comments		
Prior to refusal		
Number (A) Of Blows	Rod (B) Reading (cm)	Comments
0	46.3	
1	46.8	
2	49.9	
3	47.0	
4	47.0	
5	47.0	
6	47.0	
7	47.0	
8	47.0	
9	47.0	
10	47.0	
11	47.0	
12	47.0	
13	47.0	
0	56.8	
1	61.7	
2	62.6	
3	63.1	
4	63.5	
5	64.0	
"		

(RF) Refusal occurred from Blows 3 to 13 & drilled through layer
 (A) Number of Hammer blows between test reading
 (B) Scale reading corresponding to blow in cm

Figure 12

5. Data recording: Use the form shown in Appendix 1 to record field data from DCP testing or the Excel template mentioned in A10 to record the data in a lap top computer. Form can be downloaded from <http://www.ltrc.lsu.edu/downloads.html>.

VI. Calculation and Interpretation of Results

Refer to field measurements

VII. Report

If the field data was recorded on the form in Appendix 1, then it will be transcribed into the Excel template mentioned in Section II. A10 and given to the Engineer. If the field data was recorded into the excel template in the field, that shall be delivered to the Engineer as the report.

VIII. Normal Test Reporting Time

DCP testing time varies from 5 to 30 minutes depending upon site conditions.

IX. Illustrations and Tables, etc.

Appendix 1
DCP field measurements

Sheet _____ of _____

Project Number (1)	456-99-0562	Date	12-21-2009
CSLM (1)	1.356	Lane Direction	NB
Lane (Outside/Inside)	Out	Distance from Centerline	9
Reading on Surface (cm)	10.0	Reading after pilot hole (cm)	30.0
Pilot hole depth (cm)	20.0		
Comments	La 1, Avoyelles Parish (DCP tests in right wheel path)		

DOTD Designation TR 645-Method B

(Proposed Draft)

**THE DETERMINATION OF IN-PLACE STIFFNESS BY THE DYNAMIC CONE
PENETROMETER (DCP) FOR ACCEPTANCE TESTING**

I. Scope

The DCP can be used to measure the stiffness for acceptance when initially mixed and compacted. Test layers include cohesive and non-cohesive soils, base course aggregates, recycled asphalt pavement, recycled concrete pavement, blended calcium sulfate and in some instances chemically (cement or lime) stabilized or treated soils. DCP testing should be conducted at a depth of five blows exceeding the desired test layer (unless unable to due to impenetrable underlain soil cement).

II. Apparatus

Refer to the Apparatus section in Method A.

III. Optional Attachments

- A. Smart DCP auto reader: Device utilizing a smart phone application to record results instantaneously. Requires a smart phone (iPhone, Android, etc.) device with a Bluetooth connection and access to the Vertek Smart DCP application through the App store or Google Play store. Vertek CPT has YouTube videos showing how to download the app, as well as how the device works. Link can be found here: https://www.youtube.com/watch?v=-j1Ow7-5tUU&list=PLYWKjbbOuWP1Jvq09H_UXmmA8D-z1cGhI

The laser target top plate with level guide is fastened to the top of the lower shaft underneath the anvil. The laser sight extensometer requires two AAA batteries and is attached to the bottom plate that, which is set on top of the soil layer. The Smart DCP provides a graphical view of the results as soon as the operator completes the test.

- B. Mag Ruler auto reader: The device works with sound and magnetics by recording the depth at each hammer impact on the anvil and provides a liquid crystal display (LCD) interface.

IV. Testing with the Standard DCP (without an auto reader)

- A. Record location number, soil test layer type, and initial measurement prior to the first blow.
- B. Record each depth in millimeters after each blow. The operator lifts the hammer and releases at the handle to allow impact with the anvil. Other staff read and record from a ruler adjacent to the DCP on a table, as seen in Appendix 2.
- C. Follow this process until five blows past the desired depth has been reach. For example, record five blows past the 1-ft. (300-mm) mark for a 12-in. soil layer.

V. Testing with an Auto Reader

- A. If utilizing the Smart DCP or Mag Ruler auto readers, Name the DCP test (i.e., Site location_Date_Test #) and wait for the device/application to search for an initial measurement. The device will indicate when to start with a “beep”; make sure smart phone device volume is on and loud enough to hear. (The Mag ruler will only be indicated visually on the LCD display).
- B. Repeat by lifting the hammer and waiting for the auto reader to record a measurement on the smart device. Again, a beeping sound will be indicating that each measurement has been recorded. If an error measurement is recorded, just swipe to the left to delete last measurement.
- C. After desired depth is reached, stop the test and hit “Yes” to save the test. You can also pause the test, if needed (i.e., rotating the DCP, rotating personnel, quick break for water, etc.).

VI. Sampling and Test Depth

- A. The locations of DCP testing shall be selected by the Engineer. DCP acceptance testing should be conducted to at least five blows beyond the indicated test layer, unless otherwise directed by the Engineer. The following represents metric equivalents:

2 in. = 50 mm
4 in. = 100 mm
6 in. = 150 mm
8 in. = 200 mm
10 in. = 250 mm
12 in. = 300 mm

B. DCP Acceptance Testing shall be performed within 4 hours of compaction.

VII. Procedure

A. Basic Operation (i.e., dropping the hammer, refusal, extraction)
Refer to Procedure section in Method A.

B. Depth of penetration: The depth of penetration should be the indicated test layer, followed by five blows for verification (i.e., DCP testing shall be concluded at five blows beyond the 12-in. (300-mm) benchmark of a 12-in. subgrade layer).

C. Testing sequence without auto reader:

- i. Refer to the Procedure section in Method A.
- ii. Record the measurements corresponding to the blow on the DCP data recording sheet found in the appendix of Method B.

D. Testing sequence with an auto reader:

- i. The recorder shall inform the operator when to lift and drop the hammer after each sound from the device indicating that the depth has been recorded.
- ii. The recorder may pause the test by hitting “pause” on the Smart DCP application or Mag Ruler.
- iii. To delete an undesirable reading/mishap:
 1. Smart DCP: Swipe left on the most recent point on the smart device application and select “Delete.”
 2. Mag Ruler: write down on a separate sheet of paper and change once you transfer the data to excel via a flash drive.
 3. Import DCP data from smart phone application (or flash drive if utilizing the Mag Ruler) automatically to excel.

E. Calculate the average DCP Index (mm/blow) by dividing the depth immediately surpassing the predetermined test layer depth by the number of blows the DCP test took to reach this depth.

Note E: Example of this calculation can be found in Appendix 2.

VIII. Acceptance Criteria

- A. The contractor often utilizes the moisture-density nuclear gauge towards acceptance requirements for Quality Control (QC). Quality Assurance (QA) tests are conducted after QC efforts with DCP tests.
- B. Perform DCP tests on each desired test layer for acceptance per 1000 ft. of lateral distance of job site.
- C. Two passing DCP tests are required based on the standards listed below. Table 2 shows the acceptance criteria based on the average DCPI (mm/blow) of one DCP test.

Table 2. Acceptable DCPI criteria for layer types

DCPI ANALYSIS			
Layer Type	Material Properties	ACCEPTABLE DCPI	
		Top 6-in	Full Layer
Clay/Silty Embankment	MDD < 105; OMC 19-24%	< 25 mm/blow	< 25 mm/blow
	MDD > 105; OMC 8-18%	< 22 mm/blow	< 25 mm/blow
Subgrade	Lime Treated	< 19 mm/blow	< 16 mm/blow
	Cement Treated		
	Untreated		
Interlayer (< 6-in)	Class II Stone	< 10 mm/blow	NA
Base Course	Recycled PCC	< 19 mm/blow	< 16 mm/blow
	Class II Stone	< 10 mm/blow	< 10 mm/blow

Note C: Two DCP tests should be taken in one location for verification.

D. Table 3 is an additional acceptance benchmark that can be utilized based on minimum blow counts for a given layer thickness. If the minimum value is not reached for a given depth/layer thickness, the layer is weak and will likely fail acceptance. The operator should stop tests and test at another location or have QC compact soil further.

Table 3. Blow Count Criteria per layer type

BLOW COUNT ANALYSIS		
Layer Type	Layer Depth	Minimum Blow Count
Clay/Silty Embankment	6 in.	7
	8 in.	8
	10 in.	10
	12 in.	12
Subgrade	6 in.	8
	8 in.	11
	10 in.	15
	12 in.	19
Interlayer (Stone)	2 in.	6
	4 in.	10
Base Course	6 in.	8
	8 in.	11
	10 in.	15
	12 in.	19
Base Course (Stone)	6 in.	15
	8 in.	20
	10 in.	25
	12 in.	30

- E. If the above acceptance criteria are not met, then one of the following must happen:
- i. Additional DCP testing has to occur until two pass the acceptance criteria in Table 2.
 - ii. The soil layer is worked by the contractor (QC) to meet the requirement.
 - iii. The contractor may ask for QA acceptance testing utilizing the nuclear moisture-density gauge following DOTD's TR 401 test procedure.

IX. Report

A. **DCP Index (DCPI) [mm/blow]:** Report the number of blows and depths to obtain the required stiffness of the DCPI for the predetermined test layer depth. Calculate DCPI of test layer. Refer to Table 2 for acceptance criteria.

B. Datasheet:

- i. If utilizing standard DCP: Record data (use Appendix 2 as an example) and convert to Excel which shall then be given to the Engineer as the report.
- ii. If utilizing an auto-reader: Record the number of blows and depth that surpasses the predetermined test layer depth (i.e., 10 or 12-in. layer). Then, calculate the DCPI (mm/blow).

Note B: *Stop recording field measurements if the amount of blow counts do not meet or exceed the set limits for a certain depth, as shown in Table 3.*

Appendix 2
DCP field measurements

Sheet ____ of ____

Project	H. 000000	
Date	MM/DD/YY	
Location (Zone/STA)	STA 00 + 00	
Lane Direction	EB	
Initial Reading <i>(Non-zero, if drilled pilot hole)</i>	0.0	cm

Blow Count	Depth (cm)	Blow Count	Depth (cm)	Blow Count	Depth (cm)
0	0.0	16	17.5	31	23.2
1	1.4	17	18	32	23.6
2	2.3	18	18.5	33	23.8
3	3.2	19	19.1	34	24.4
4	4.2	20	19.5	35	24.7
5	4.9	21	19.7	36	25.0
6	6.0	22	20.2	37	25.5
7	6.9	23	20.5	38	30.3
8	8.1	24	20.9	39	31.5
9	9.4	25	21.2	40	33.3
10	10.4	26	21.7	41	
11	11.8	27	22.0	42	
12	13.2	28	22.1	43	
13	14.9	29	22.7	44	
14	16.2	30	23.0	45	
15	16.9				

DCPI = blow count at test layer depth divided by test layer depth	6.9	mm/blow
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*Note: test layer was 10 in (25.4cm) Example: [(25.5*10)/37]*

Appendix II

InDOT and MnDOT's Specifications and DCP Procedure

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203.23 Embankment other than Rock, with Strength or Density Control

The compaction will be determined by dynamic cone penetrometer, DCP, testing in accordance with ITM 509 and the moisture content in accordance with ITM 506. Soil classification will be performed in accordance with the ITM 512 and the following DCP blow counts will be used for compaction control:

Textural Classification	Maximum Dry Density (pcf)	Optimum Moisture Content Range (%)	Acceptable Minimum DCP value for 6 in. for 95% compaction	Acceptable Minimum DCP value for 12 in. for 95% compaction	Acceptable Minimum DCP value for 6 or 12 in. for 100% compaction
CLAY SOILS					
Clay	< 105	19 - 24	6		*
Clay	105 - 110	16 - 18	7		*
Clay	111 - 114	14 - 15	8		*
SILTY SOILS					
Silty	115 - 116	13 - 14		9	*
Silty	117 - 120			11	*
SANDY SOILS					
Sandy	121 - 125	8 - 12		12	*
Sandy	> 125			15	*
GRANULAR SOILS - STRUCTURE BACKFILL and A-1, A-2, A-3 SOILS					
No. 30				6	9
No. 4				7	10
1/2 in.				11	14
1 in.				16	19
Note: * Test section required in accordance with ITM 513.					

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Unless otherwise specified, all material directed to be compacted in accordance with 203.23 shall meet the acceptable minimum DCP value for 95% compaction. Subgrade shall meet the acceptable minimum DCP value for 100% compaction when required.

SOILS DRYING WITH CHEMICAL MODIFIERS (SECTION 217)

For drying soils having moisture over 2% above optimum moisture content, fly ash or lime is allowed to be used. Soils containing greater than 6% by dry weight calcium, magnesium carbonate or organic material, or having a maximum dry density of less than 95 pcf, or with soluble sulfate content greater than 1000 ppm shall not be used.

The moisture content of the mixture shall be at the optimum moisture content or above the optimum moisture content as determined by the mix design in accordance with 215.03. The Contractor is required to perform moisture tests during the day to verify the spread rate application of the flyash or lime.

Acceptance of chemically modified soils will be performed on the finished grade with the DCP, gradation tests and moisture tests and will meet the following requirements:

1. A minimum DCP blow count of 20 for 12 in. and a minimum DCP blow count of 8 for the top 6 in.
2. A minimum of one passing DCP test for each 1000 lft for each 2-lane pavement section
3. A minimum of one gradation test for every 2500 lft for each 2-lane pavement section
4. A minimum of one moisture test for every 4h of lime soils mixing

Construction traffic is allowed after the minimum DCP blow count is obtained and shall be routed in one direction so that the chemically modified soil does not pump or rut.

ONE POINT PROCTOR – CLAY, SILTY, OR SANDY SOILS

All soils are required to be compacted to not less than the specified strength based on the DCP or the minimum percent of maximum dry density. The moisture content is required to be in the specified range of the optimum moisture content. To determine the compliance with these requirements, samples representing each soil type on the contract are required to be tested in a laboratory for maximum dry density and optimum moisture content in accordance with

MnDOT Specifications Grading and Base Manual

C.1 Procedure – Base Aggregate and Granular materials.

1. Locate a level and undisturbed area (test site) that is representative of the material to be tested.
2. Place the **DCP** device on the base aggregate test site. To properly seat the **DCP** (coned tip), two hammer blows are required. Therefore, carefully raise the sliding weighted hammer until it meets the handle, then release the hammer under its own weight. Repeat this process one more time for a total of two complete blows. If seating penetration exceeds the allowable value (base only), then the test fails. Recompact the area.
3. There is no seating requirement for granular materials, however seat the **DCP** using two blows, before the DPI is calculated.
4. Record the penetration measurement after seating using the graduated rule on the **DCP**. The measurement is taken to the nearest mm. (Use form G&B-204, Figure 24).

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5. Carefully raise the hammer until it meets the handle, then release the hammer under its own weight. Repeat this process two more times for a total of three times.
6. Record the final penetration measurement using the graduated rule on the **DCP**. The measurement is taken to the nearest mm.
7. Subtract the measurement in step 3 from the measurement in step 5 and then divide the difference of the measurements by the number of blows (3) required for testing. If necessary, follow the formula on the test form to convert from inches to mm. Round off all test results to the nearest mm or one tenth of an inch, see section, "5-692.705 "Procedures for "Rounding Off".
8. No moisture test required if the hardest penetration requirement is meet.

Figure 22. Penetration index method example (Form G&B-204)

(Table 2211-3) DCP Penetration Index Method		G&B-204 (10/29/2019)																																																																																				
SP	Highway	Inspector																																																																																				
Material	Date	Engineer Notes																																																																																				
Procedure																																																																																						
<ul style="list-style-type: none"> Enter Project info and Gradation Data. Calculate the Grading Number (GN) (electronic version calculated automatically) When bitumen content is $\geq 2.5\%$, compact to achieve a penetration index value of 10mm and a seat value of 40mm. $Seating = Reading\ after\ 2\ blows - Initial\ Reading$ $DPI = \frac{Reading\ after\ 5\ blows - Reading\ after\ 2\ blows}{3}$ 																																																																																						
Electronic Version <ul style="list-style-type: none"> Determine the test location and conduct the DCP test. Measure the moisture content (MC) at the DCP test location. Enter the Test Information and DCP Data in table. Establish the allowable values for SEAT and DPI based on GN and MC. Compute SEAT and DPI test results. Compare SEAT and DPI to Maximum Requirements. Both must pass to accept test. 																																																																																						
No moisture test is required when DPI is met for a given GN. I.E., if GN is 4.8 and DPI is 14, no moisture test is required.																																																																																						
Gradation Data (use % passing in formulas)																																																																																						
$GN = \frac{1^{\#} + \frac{3^{\#}}{4} + \frac{2^{\#}}{8} + 4^{\#} + 10^{\#} + 40^{\#} + 200^{\#}}{100}$																																																																																						
Sieve	% Passing	Grading Number	Approx. Test Layer (inch)																																																																																			
1 inch	100	< 3.1	4 - 6																																																																																			
3/4 inch		< 5.0	4 - 6																																																																																			
3/8 inch		3.1 - 3.5	4 - 6																																																																																			
# 4		> 8.0																																																																																				
# 10		< 5.0																																																																																				
# 40		3.6 - 4.0																																																																																				
# 200		> 8.0																																																																																				
GN =		4.1 - 4.5	5 - 6																																																																																			
		> 8.0																																																																																				
DCP Data																																																																																						
<table border="1" style="width:100%; border-collapse: collapse;"> <thead> <tr> <th colspan="2">Test Information</th> <th colspan="2">Requirements</th> <th colspan="2">DCP Data (mm)</th> <th colspan="2">Test Results</th> </tr> <tr> <th>Test #</th> <th>Date</th> <th>Station</th> <th>Offset</th> <th>Test Layer Depth (mm)</th> <th>MC (%)</th> <th>GN</th> <th>Maximum Allowable SEAT (mm)</th> <th>Maximum Allowable DPI (mm/blow)</th> <th>Reading after seating (2 Blows)</th> <th>Reading after 5 blows</th> <th>SEAT Pass or Fail</th> <th>DPI Pass or Fail</th> <th>DPI: (1) Adequate Layer?</th> <th>TEST: Pass or Fail</th> </tr> </thead> <tbody> <tr> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> </tr> <tr> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> </tr> <tr> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> </tr> <tr> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> <td></td> </tr> </tbody> </table>				Test Information		Requirements		DCP Data (mm)		Test Results		Test #	Date	Station	Offset	Test Layer Depth (mm)	MC (%)	GN	Maximum Allowable SEAT (mm)	Maximum Allowable DPI (mm/blow)	Reading after seating (2 Blows)	Reading after 5 blows	SEAT Pass or Fail	DPI Pass or Fail	DPI: (1) Adequate Layer?	TEST: Pass or Fail																																																												
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Appendix III

This section shows results of an embankment repair project (I-55 Slope Repair - H.013260) underneath the I-55 bridges over the Illinois Central Railroad in District 62 in Tangipahoa Parish near US-190 in Hammond, LA. The research team visited the project site three times from March 09 - March 13, 2020. Figure 23 shows an aerial view of US 190 and Interstate 55; the embankment project can be seen around the Illinois Central Railroad.

Figure 23. Aerial photo of H.013260



The sand embankment was classified as an A-3 Fine Sand and was compacted in a series of 1-ft. lifts. Each lift tested was with the NDG in accordance with Section 203 in *Louisiana Standard Specifications for Roads and Bridges* [12]. The sand had Proctor

values of 107.3 pcf for MDD and 6.0% for OMC. The layer requires 95% compaction. DOTD district personnel conducted QA NDG tests to depth of 10 in., while only 8-in. tests were taken by the contractor (QC).

Researchers conducted Smart DCP tests to a depth of approximately 20 in. (500-550 mm) through each of the sand lifts, twice the depth of the NDG tests. The surface of the compacted layer was unconfined and often loose. The DCP's weight alone would penetrate into the loose surface sand a few inches. This unintentional penetration from the DCP's weight was recorded as "blow zero" for lifts 5 and 6 were found; however, these values were neglected for layers 1 and 2 because the depth of "blow zero" was much smaller. Below in Figure 24, there is a street view showing the site without the new retaining walls in January 2020. Figure 25 consists of two photos taken of the south and north wall embankments walls after lift 2. Figure 25 (a) shows lift 2 of the south retaining wall during compaction, and Figure 25 (b) represents lift 2 of the north retaining wall after compaction. Figure 26 shows a picture from June 2020 of the embankment walls after completion.

Figure 24. I-55 slope repair site prior to construction



Figure 25. I-55 south and north wall retaining walls



a. South retaining wall



b. North retaining wall

Figure 26. I-55 embankment wall completion



Table 32 shows the results of the NDG and DCP for lifts 1, 2, 5, and 6. The MDD prior to NDG testing was 107.3 pcf for all lifts with the exception for lift 1 (105.7 pcf). The results from the NDG are shaded in *blue*, and DCP results are shaded in *yellow*. The *red* numbers indicate failed NDG acceptance tests.

Table 32. I-55 slope repair NDG and DCP data

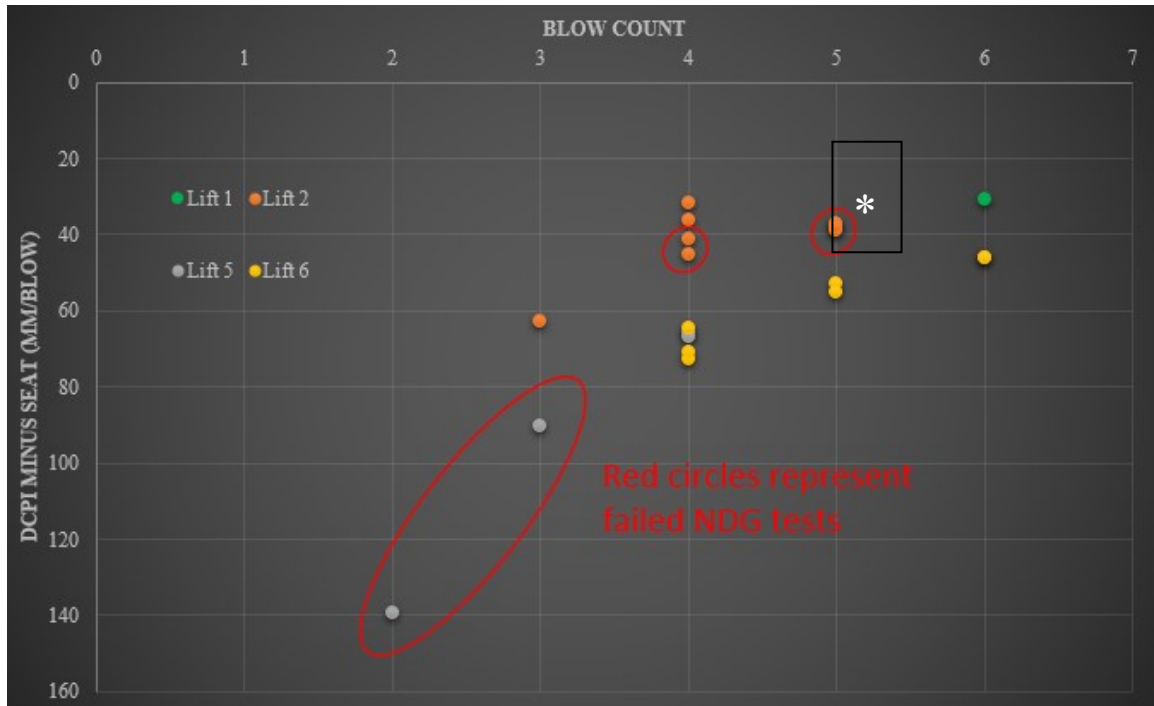
Lift No.	Depth of NDG (in)	%NPR (%)	ADD (pcf)	Blow Zero (in)	Average DCPI of Test Layer: minus Blow Zero (mm/blow)	Number of Blows (#)		
Lift 1	10	97.6	103.2	NA	30.6	6		
Lift 2		94.5	101.4		41.0	4		
		10	93.2		100.0	45.1	4	
			38.8		5			
			37.2		5			
			31.6		4			
		8	99.2		106.4	36.1	4	
Lift 5		10	96.0		103.0	38.2	5	
	93.0		99.8	4.5	139.2	2		
	95.2		102.2	3.5	90.3	3		
					66.1	4		
Lift 6	10	97.9	105.0	67.0	4			
				52.8	5			
	8	97.4	104.5	3.5	46.3	6		
				55.2	5			
	10	97.3	104.4	4	46.0	6		
					96.6	103.6	3.3	72.9
70.8								4
8					97.9	105.1	64.8	4

As mentioned before, the DCP weight alone penetrates through the top few inches of sand unlike the NDG, where a pilot hole is created. This loose sand at the top of the layer may indicate that lower layers are also loose, so these first few inches of penetration through a lift should be measured separately (blow zero). This first placement and penetration of the DCP varied throughout the site tests and lifts.

Figure 27 shows the graphing representation of I-55 DCP slope repair data. Each lift is separated by colors: lift 1 (green), lift 2 (orange), lift 5 (gray), lift 6 (yellow). The red circles indicate failed acceptance tests performed by the NDG. Just relying on this data, the researchers have composed of possible requirements for the DCP when testing on

sand embankments. For 10-in. DCP tests, a blow count of at least four is required to pass for compaction acceptance. The DCPI should be less than 40 mm/blow for lift 1, 40 mm/blow for lift 2, 70 mm/blow for lift 5, and 80 mm/blow for lift 6. In addition, “blow zero” (the penetration of the DCP weight alone) should not exceed a depth of 3.25-3.5 inches.

Figure 27. I-55 DCP graphing by lift



Note: The white asterisk is to clarify that there are three data points for Lift 2 (colored orange), and one of the three passed NDG acceptance.

Comparison with InDOT and MnDOT standard did not show consistency with the DOTD NDG acceptance tests. Out of 12 nuclear density tests taken, 75% passed NDG acceptance. However, InDOT’s DCP acceptance would have only passed 40% of the locations/lifts. InDOT’s minimum requirement from Table 17 for an A-3 soil (or coarse sand) was six blows for a 12-in. layer (approximately five blows for a 10-in. test layer). MnDOT’s DCP acceptance was even more strict in only passing one location based on the gradation number of 5.6 for the coarse sand. The one location that passed MnDOT’s stiffness criteria had a DPI of 28 mm/blow, which matches the limit as seen before in Table 19. All other locations had a DPI of 33 mm/blow or more. Further testing on coarse sand embankment would be required to recommend the DCP as an alternative for QA/QC acceptance testing.

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