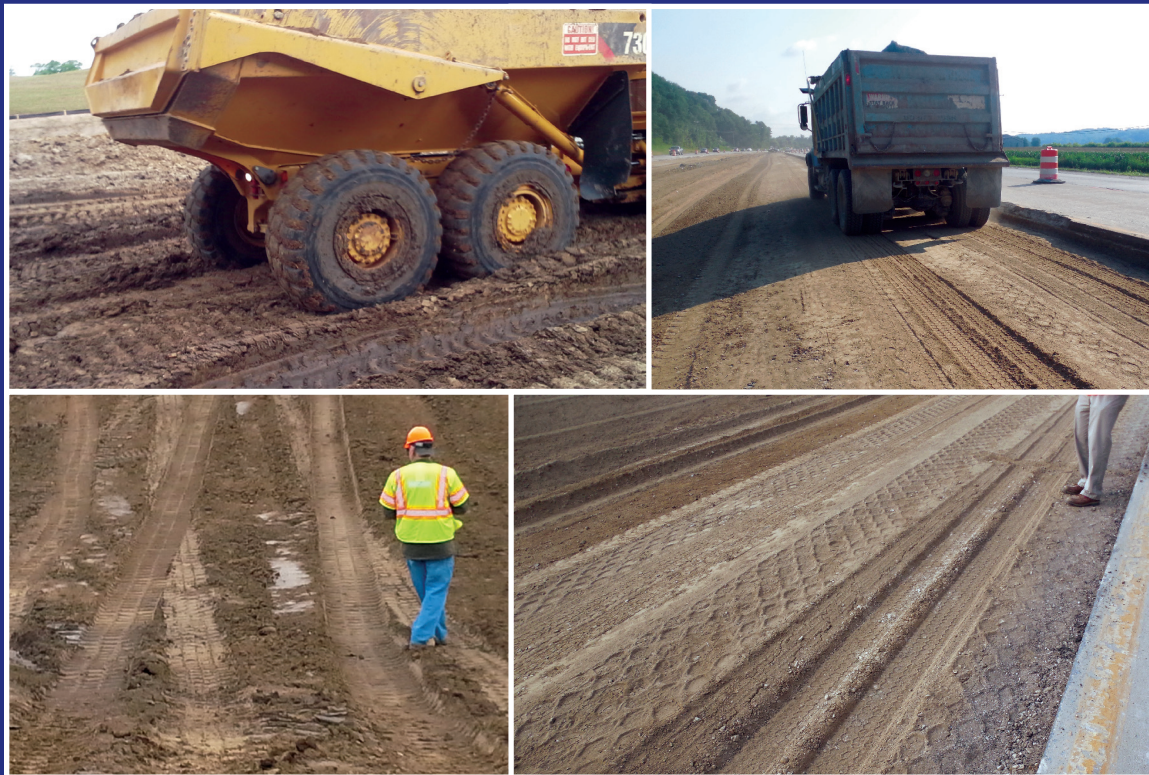


JOINT TRANSPORTATION RESEARCH PROGRAM

INDIANA DEPARTMENT OF TRANSPORTATION
AND PURDUE UNIVERSITY



Proof Rolling of Foundation Soil and Prepared Subgrade During Construction



Phillip S. Dunston, Antonio Bobet, Timothy B. McClure

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AUTHORS

Phillip S. Dunston, PhD

Professor of Civil Engineering
Lyles School of Civil Engineering
Purdue University
(765) 494-0640
dunston@purdue.edu
Corresponding Author

Antonio Bobet, PhD

Professor of Civil Engineering
Lyles School of Civil Engineering
Purdue University

Timothy B. McClure

Graduate Research Assistant
Lyles School of Civil Engineering
Purdue University

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16. Abstract <p>Proof rolling provides a method to examine the entire subgrade surface as a compliment to standard random acceptance testing. Proof rolling requires established criteria that account for the interplay of equipment parameters and soil characteristics, technique, and other specifics of the project to allow for proper interpretation. The researchers concluded that proof rolling is not appropriate for determining soil elastic properties, while it can reveal in situ strength properties. No information from state highway agencies (SHA) publications or interviews reports using proof rolling other than for the evaluation of the subgrade. Only eight SHA's have notable specifications or other supporting documents containing significant guidance or criteria. The requirements provided for use of either of two equipment types—tandem-axle rear dump trucks and chariot-style rollers—and a range of evaluation criteria based on soil type and whether the project is new construction or re-construction. Recommendations provided fall within parameters practiced by states that have the most well-developed specifications and practices for proof rolling. The recommendations include: evaluation is of the subgrade only and the equipment shall be either a tandem-axle rear dump truck or a tri-axle rear dump truck (with raised third axle) loaded to a minimum gross weight of 20 tons. The chariot-style roller loaded to a minimum gross weight of 40 tons could be alternatively specified. The test shall be a single pass in each traffic lane with the passing criteria of a 1" deflection for new construction and ½" deflection for re-constructed or stabilized subgrade, as well as the absence of pumping and cracking.</p>			
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EXECUTIVE SUMMARY

PROOF ROLLING OF FOUNDATION SOIL AND PREPARED SUBGRADE DURING CONSTRUCTION

Introduction

Proof rolling (also termed *test rolling*), a practice to examine the mass response of subgrade to vehicle-type loads before pavement layers are constructed, is performed by driving a selected heavy vehicle over designated areas of the soil surface. Proof rolling complements standard acceptance testing, which is typically randomly dispersed among spot locations, and it also has the potential to reveal issues with subgrade drainage. Proof rolling results can be properly interpreted only if criteria are established that account for the interplay of equipment parameters and soil characteristics, technique, and other specifics of the project. Indiana Department of Transportation (INDOT) Standard Specifications for proof rolling provide incomplete guidance to ensure consistency of implementation and therefore confidence in the results obtained. Some other states have more explicit standards and criteria for proof rolling, and establishing the same for INDOT projects will enable proof rolling to become a reliably informative QC/QA practice. Contractors and INDOT Construction Engineering staff need a standardized methodology, parameters, and criteria to ensure consistent quality outcomes. This study was conducted to collect and synthesize current knowledge regarding proof rolling and to propose a methodology that is suitable for implementation on INDOT projects.

Findings

The review of scholarly literature revealed limited research aimed at understanding the relationship of proof rolling to subgrade mechanistic properties. Researchers have concluded that while proof rolling can reveal the in situ strength properties of subgrade materials, it is not well suited for determining the soil elastic properties that would be key to predicting pavement performance. Review of state highway agency (SHA) standard specifications and

readily available supporting documents revealed only eight states to have notable proof rolling specifications. Interviews were conducted subsequently with personnel from four of these states—Illinois, Minnesota, New York, and Ohio—to gain further insight into their intent, practice, and experience with proof rolling implementation. Those interviews revealed a consensus practice of employing proof rolling exclusively for evaluation of the subgrade uniformity without any application to the natural soil foundation or intermediate layers of the constructed embankment. The SHAs interviewed specified primarily two equipment types—tandem-axle rear dump trucks and chariot-style rollers—and a range of evaluation criteria based on soil type and whether the project is new construction or reconstruction. The equipment, criteria, and associated procedures were suitable to frame a range of what appears to be acceptable practice. Observations made on INDOT sites also helped the investigators make their assessment of the practicality of recommendations to be derived from this compiled information.

Implementation

The investigators recommend, within the parameters of practice noted for the states that have the most well-developed specifications and practices for proof rolling, that INDOT limit its application of proof rolling to the evaluation of the subgrade. The recommended equipment includes a tandem-axle rear dump truck or a tri-axle rear dump truck (with raised third axle) loaded to a minimum gross weight of 20 tons. Another equipment option is the chariot-style roller loaded to a minimum gross weight of 40 tons. Proof rolling should be conducted by a single pass in each traffic lane and the passing criteria should be a 1" deflection (i.e., that includes both recoverable and non-recoverable deformation) for new construction and 1/2" deflection for reconstructed or stabilized subgrade, as well as the absence of pumping and cracking.

Although the investigators see no logical reason that proof rolling cannot also be implemented to evaluate the foundation or embankment lifts, the criteria recommended for the subgrade would be overly conservative. Different criteria would need to be established for those levels beneath the subgrade, and the absence of research results and any such practices by the other SHAs means that INDOT would need to pursue further research involving field data collection.

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1. INTRODUCTION

The performance of a pavement depends on all the tasks involved in the construction of the embankment that supports the pavement. This includes the foundation, fill, and most importantly the subgrade. Any advances in methods that provide efficient and cost effective assessment of the quality of all of these components are highly desirable. One such method is proof rolling (also termed *test rolling*) which is performed before proceeding with construction of the pavement structure. While standard acceptance testing is typically randomly dispersed among spot locations, proof rolling offers evidence of the mass response of the soil layers to vehicle-type loads and also has potential to reveal issues with subgrade drainage.

The Standard Specifications (INDOT, 2014) of the Indiana Department of Transportation (INDOT) call for proof rolling by the Contractor following compaction of foundation layers (i.e., natural subgrade and embankment) for the purpose of confirming layer strength before placing the next layer in the structure. In Section 203.26, a specific equipment type is stipulated, subject to criteria cited in 409.03(d)3, with substitutions allowed. Section 409.03(d)3 specifies minimum size and function requirements and a range of contact pressure for pneumatic rollers, but those equipment features have primarily to do with requirements for paving compaction rather than for proof rolling. Furthermore, these specifications do not explain how the Project Engineer should judge the suitability of an equipment substitution for proof rolling, and no concrete criteria are given for a satisfactory or failing proof rolling result. Section 207.03, for example, speaking with respect to proof rolling of the subgrade, only offers the criteria “Undue distortion...shall be avoided.” Thus, the relevant Standard Specification references do not provide adequate guidance to ensure consistency and therefore confidence in the results obtained from proof rolling. No standardized methodology, parameters, and criteria have been established for the reference of Contractors and INDOT Construction Engineering staff to ensure consistent quality outcomes.

Engineering consideration makes it apparent that proof rolling results can only be properly interpreted if criteria are established that account for the interplay of equipment parameters (e.g., weight, tire pressure) and soil characteristics (e.g., soil type, moisture), technique (e.g., speed, number of passes), and other specifics of the project (e.g., new construction, rehabilitation). Some other states have more explicit standards and criteria for proof rolling, and establishing the same for INDOT projects is both desirable and feasible so that proof rolling can become a reliably informative QC/QA practice.

1.1 Problem Statement

Guidance in the INDOT Standard Specifications for proof rolling is inadequate to direct consistent practice

across the agency’s districts, resulting in a lack of confidence regarding the quality of prepared subgrade and its foundation upon which the pavement is constructed. While the Standard Specifications make it clear when to conduct proof rolling and what equipment is typically expected, but does not address such parameters as vehicle weight, tire inflation pressure, vehicle speed, depth of prepared subgrade, soil type, and soil moisture content. Failure and acceptance criteria must be relevant to soil type, conditions, and service expectations of the overlaying pavement. Some other state transportation agencies either have working standards or are conducting their own studies toward a standard. The results from this study to differentiate and standardize the use of proof rolling during construction are aimed to benefit both Contractors and INDOT Project Engineers by better equipping them with more informative and consistent methods and metrics to consistently achieve quality goals for INDOT projects.

1.2 Study Objectives

The initial objective of this study consisted of an extensive review of the standard proof rolling practices employed by other state highway agencies (SHAs) and of literature that informs an interpretation of proof rolling results. The breadth of variations in the behavior of natural and stabilized soils and the number of parameters deemed influential in proof rolling outcomes are of such a number that this first study has focused on a limited set of conditions. The second objective for this study was to provide to INDOT an initial set of recommendations for directing proof rolling and for interpreting the results for acceptance.

In addition to the review of SHA specifications, supporting documents, and scholarly publications on proof rolling, pursuit of the study objectives included field observations to gain an understanding of the current practices of Contractors as directed by INDOT Construction Engineers. Also, engineering staff from a short list of key SHAs were interviewed to round out the Investigators’ understanding of their specifications, practices, and experience with proof rolling. These information sources were synthesized to produce a set of recommendations to INDOT for the role and implementation of proof rolling on INDOT projects.

2. LITERATURE REVIEW

The literature review was divided into two stages. The first comprised review of the fifty state highway agencies’ (SHAs’) specifications and publically available supporting documentation. The second stage involved a review of the scholarly publications related to proof rolling. A summary of the literature review is presented as follows. The more detailed documentation is presented in Appendix B.

2.1 State Highway Agencies

2.1.1 Introduction

The review of the fifty SHAs' websites included searching the general specifications and for mentions of proof roll, test roll and all other variations of the terms. From the fifty states eight were found to provide enough detailed information for inclusion in the report. Four states (North Carolina, South Carolina, Texas and West Virginia) provide limited documentation but a relatively complete process for proof rolling. An additional four states (Illinois, Minnesota, New York and Ohio) provide substantial documentation regarding proof rolling. The definition of proof roll varied among the states with some utilizing or referencing the term 'test rolling' instead. Nevertheless, all describe a procedure that provides a qualitative assessment of the surface being evaluated.

2.1.2 Purpose

Each state presented slightly different reasoning for conducting the test but every state specifically associated the test to the subgrade. Reasons ranged from "locating soft areas" to "evaluate the adequacy of the subgrade" and to "distress the soil to conditions anticipated during construction."

2.1.3 Equipment

The states specified one of two types of equipment. The first option was a large "chariot-style" towed heavy pneumatic roller. This type of equipment typically ranges from 25 tons to 50 tons. The second type of specified equipment was a fully loaded tandem axle dump-truck. One state, Minnesota, has recently expanded their specifications to include the use of a tandem axle dump-truck. They now have specifications for both types of equipment with criteria for when to use each.

2.1.4 Procedure

The procedures also varied from state to state. Some states require as many as two coverages—a coverage referring to whatever trips are necessary for the tires of the test vehicle to have contact across the entire width of the test surface area—while Ohio only requires a single pass (trip). States typically specified the speed at which the test be performed between 2.3 to 5 miles per hour. One state simply specified "at walking speed" which appears to be the intent of all states which have formal procedures.

2.1.5 Pass/Fail Criteria

There is also a significant range noted in the pass/fail criteria employed by the states. The requirements range from a definitive measurement, to a typically acceptable defined depth of deflection, and to the ambiguous

"any deficiencies disclosed." Ohio and Minnesota also provide the depth to which they believe the test can identify deficiencies (i.e., the depth of influence). They state that the test targets soil up to five (5) feet below the subgrade surface. Both of these states utilize the large heavy chariot-style test vehicle.

2.2 Scholarly Publications

2.2.1 Introduction

The volume of scholarly publications directly addressing the topic of proof rolling is relatively low. This research included searches of "Google Scholar," "Engineering Village" and the Purdue University Library search engine. The searches included all variants of proof roll and test roll along with many associated terms such as "rutting," "pumping," "subgrade tests," etc.

2.2.2 Studies Emphasizing Proof Rolling

The earliest publication found in this review dates to 1960 by Turnbull and Foster (1960), published in the *Highway Research Board Bulletin*. They assigned the origination of the term proof rolling to the Corps of Engineers in a 1957 specification for graded crushed aggregates used for heavy duty pavements. The term originally carried a different meaning than typically understood today. The term referred to the process of applying thirty additional "coverages" with a fifty-ton roller to each lift after the tests results reported a hundred percent modified AASHO (renamed AASHTO since 1973) density.

Traylor and Thompson (1977) produced a report entitled *Sinkage Prediction—Subgrade Stability* as part of the Illinois Cooperative Highway and Transportation Research Program project number IHR-605. In the report, they included seven theoretical methods for predicting sinkage. They presented no testing support nor suggested that any actual findings were available for implementation.

Hambleton and Drescher (2008) introduced computer simulation into their predictions. They utilized some of the theoretical proposals (e.g. bearing capacity formula) from Traylor and Thompson (1977) to predict the soil strength. From the soil properties they used the computer simulation to estimate the associated deflection and rutting. As validation, they performed controlled laboratory tests. Their research incorporated the proof rolling procedures from the Minnesota Department of Transportation (MnDOT) using their heavy vehicle. They suggested that test rolling provides a continuous record of measurement, inspecting large areas and detecting inadequately compacted areas. They stated "test rolling is conceptually a good test for *in situ* characterization of the strength properties of subgrade materials. Test rolling is not well suited to determination of soil elastic properties, which are the properties commonly used to predict long-term pavement performance." Limited validation of the theoretical models

was accomplished through scaled lab tests. A later research report by Budge and Wilde (2011) utilized the findings in the Hambleton and Drescher report to develop an initial draft of the state of Minnesota's lighter weight test rolling specification (*MnDOT Standard Specifications for Construction*, Section 2.1.3). Their chosen apparatus used two ultrasonic sensors mounted on the front axle of a loaded tandem axle dump truck for deflection measurements. The procedure was implemented on several projects, and through their field testing they concluded the "new specification will be reasonable and applicable to the subgrade soils anticipated." They, like Hambleton and Drescher (2008), noted that the procedure results can be associated to strength but not to the elastic properties of the soil. They also proposed large-scale field studies to complete validation of the criteria. The actual implemented specification mentioned in Section 2.1.3 does not call for a precision deflection measuring apparatus as described in the related research, and per discussions with state personnel (Section 4.2.1), the state does not use the procedure for quantitative assessment.

Crovetti (2002) presented research findings of multiple research reports commissioned by the state of Wisconsin designed to develop specifications for accepting subgrades based on subgrade deflections. The research applied to a rolling wheel deflectometer (RWD) test to function as a portable deflection measuring device rather than proof rolling. The implementation of any RWD specification was not directly researched, and a search of the Wisconsin DOT's website returned no current proof rolling specifications.

2.2.3 Subgrade Undercut Criteria

In a report by Borden et al. (2010), the team developed a subgrade undercut criteria. The criteria developed considered soil modulus and strength values and associated them to Dynamic Cone Penetrometer (DCP) testing. The ultimate goal was that the final subgrade should meet the North Carolina state criteria of one-inch maximum rutting and pumping and provide a bearing resistance of two times the applied tire pressure. The research process utilized proof rolling as a means of evaluation of the subgrade and then additionally created a proof roll undercut criteria.

2.2.4 Intelligent Compaction as Alternative

Multiple reports presented findings on using intelligent compaction (IC). Vennapusa, Siekmeier, Johanson, White, and Gieselman (2009), and Mooney and Rinehart (2007) both suggested using IC as an alternative to heavy test rolling. Both of these research reports along with Tice and Knott (2000) discussed the advantage of IC over proof rolling to detect situations where a strong top soil layer covers an undetected weaker lower soil layer. Zambrano, Drnevich, and Bourdeau (2006) presented IC as the preferred method for evaluating subgrades but also recognized the need for proof rolling procedures to be

used as an evaluation method until IC is routinely utilized. Chen (2009), in his investigation into the premature structural failure of a specific road section on a Texas highway, noted that the specifications did not require proof rolling during the construction process. Quoting from his published findings "Although there are many different ways to minimize premature failures, an immediate action is to include proof rolling in construction quality control."

3. SITE VISITS

The Investigators visited and observed proof rolling at two construction sites during the 2015 construction season: (1) the SR 44 Curve Correction near Franklin, IN and (2) the Interstate 69 Extension near Martinsville, IN. Following are summary descriptions and observations from these site visits.

3.1 R-30599 SR 44 Curve Correction

3.1.1 Site Description

The first site visit took place on May 20, 2015 at the project located on Indiana SR 44 at the intersection of Centerline Road southwest of Franklin in the INDOT Seymour District. The project involved building a new roadway across native ground to partially eliminate the horizontal curvature of SR 44 and the addition of a concrete box culvert at a stream. The contractor on the project was Dave O'Mara Contractor, Inc. The test was performed under the supervision of the INDOT Project Supervisor Ed Unger. In addition to the Investigators, Nayyar Siddiki, Supervisor, Geotechnical Laboratory Services from INDOT was present as well as multiple contractor and engineering service representatives.

3.1.2 Test Location

The proof roll test took place approximately between project stations 507+47 and 510+25. At the beginning station (507+47), there was an existing creek where a concrete box culvert was to be constructed. The elevation of the natural soil tested that day was below the future flow line and contained a very high water content near saturation. (See Appendix C, Figure C.1.) The existing ground was approximately 14 feet below the final subgrade centerline elevation. The test ending station was significantly higher in elevation and near the final subgrade. Furthermore, it was visibly apparent that the moisture condition of the soil at this location was much lower.

3.1.3 Equipment Used

The test vehicle was a Caterpillar 730 Articulated Dump Truck (Appendix C, Figure C.2). This truck was employed as an allowed substitute under INDOT specification Section 203.26 Proofrolling. Since no truck weight information was available from the Contractor,

a net vehicle weight of 26.6-ton was assumed per the Caterpillar website (http://www.cat.com/en_US/products/new/equipment/articulated-trucks/three-axle-articulated-trucks/18511058.html). The estimated payload was 19.5 tons, creating a gross weight of about 46 tons. The tires on the vehicle were Goodyear 23.5R25 with a specified overall width of 25.2 inches and diameter of 63.2 inches. Using information from the Goodyear website (<http://www.goodyearotr.com/cfm/web/otr/tire-selector/detailresults.cfm?tireid=939>), the tire inflation pressure was estimated to be 36–40 psi.

3.1.4 Procedure with Observations

The proof roll test began with the vehicle backing from station 510+25 towards 507+50. (Note: all stations are approximate.) There was three inch rutting at the beginning station (see Appendix C, Figure C.3). The test vehicle was leaving ruts of approximately four inches at station 509+00 (Appendix C, Figure C.4) and approximately eight inches at station 508+50 (Appendix C, Figure C.5). The final 60 feet of the test exhibited rutting in excess of two feet (Appendix C, Figures C.6 and C.7). The test consisted of three side-by-side passes of the equipment.

3.1.5 Results and Discussion

The Project Supervisor proposed a corrective action to be applied to the failing areas. The procedure consisted of removing two feet of the soft failing material followed by adding stone fill with a total of five feet of stone of multiple layers of decreasing size ranging from two feet to two inches in diameter. The ruts of eight inches at station 508+50 were accepted as passing in light of the fact that 14 feet of embankment was to be constructed at that location. The four-inch rutting at station 509+00, where the required fill was still more than ten feet, was also counted as passing. The soil at the higher elevation stations with three-inch ruts passed without additional consideration.

3.2 I69-DU5-B Interstate 69 Extension

3.2.1 Site Description

The second site visit took place on August 3, 2015, to the project located on Indiana SR 37 north of the intersection with Liberty Church Road southwest of Martinsville. The project was part of the extension of Interstate 69 between Indianapolis and Bloomington. The specific project identifier was I69-Design Unit 5B. At the test location, the future interstate followed the current SR 37. Crider & Crider Inc. was the contractor for the project. The Project Supervisor was Ted Sowders of HNTB; field staff from Professional Service Industries (PSI) administered the test. Also present were the Operations Director, Elliot Sturgeon; a QA observer from the project designer Isolux Corsan; two representatives from

the Indiana Finance Authority (IFA); and multiple Contractor representatives.

3.2.2 Test Location

The proof roll took place between project stations 1276+00 and 1288+00, approximately. The area to be proof rolled was the existing interior shoulder of the divided highway and the proposed interior paved shoulder (Appendix C, Figure C.8). With the test area being the shoulder of an existing highway, the native ground had been prepared during original construction creating conditions similar to a reconstruction project. In many locations of the proof rolled section there was an existing underdrain close to the existing road. This underdrain section contained granular fill instead of the clay material found in the remainder of the test area. The plans called for fourteen inches of chemical soil modification for the entire area after the proof rolling. No test results were reported, however visual inspection for the moisture condition of the soil created no concern.

3.2.3 Equipment Used

The test vehicle used under INDOT specification Section 203.26 Proofrolling was a 2009 Mack Granite tri-axle (Appendix C, Figure C.9) dump truck, acceptable as “other approved equipment.” The estimated payload was 22–23 tons, heavily loaded on the rear two axles, as the floating axle did not make contact with the ground (Appendix C, Figure C.10). The tires on the vehicle were Michelin 11R23.5 with a specified overall width of 11.3 inches and diameter of 44.0 inches quoted from the Michelin website (<http://www.michelintruck.com/tires-and-retreads/selector/>). The truck driver asserted the cold tire inflation pressure to be in the range of 100–105 psi.

3.2.4 Procedure with Observations

The proof roll began with the vehicle driving from station 1288+00 towards 1276+00 on the southbound side and then returning to the starting station on the northbound side. There was no rutting or pumping at the start station (Appendix C, Figure C.11). The overall test identified two locations where rutting exceeded one inch and they were between stations 1289+60 SB to 1289+40 SB and 1280+00 NB to 1277+00 NB (Appendix C, Figures C.12 and C.13). The proof roll at approximately station 1280+00 SB (Appendix C, Figure C.14) was adjacent to a replacement patch on the existing roadway and had rutting in excess of one inch. There was an unidentified location that exhibited surface cracking (Appendix C, Figure C.15). The areas with underdrain present had rutting greater than one inch (Appendix C, Figure C.16), however the project supervisor reported that the underdrain was to be removed and the rutting condition corrected.

3.2.5 Results and Discussion

The Project Supervisor expressed no concern related to the areas that failed the test because the design documents already specified fourteen inches of chemical soil modification. They noted that the typical remediation for a failing test was also fourteen inches of chemical soil modification. The Investigators engaged in discussions with multiple personnel regarding the criteria required for a passing test. The representatives agreed that rutting of one inch (or greater) or any signs of pumping would result in a failing test. The representatives also expressed that no rutting or pumping would be allowed on a proof roll of a treated subgrade. Pumping is being defined as elastic rebound. In a discussion with Elliot Sturgeon (a retired INDOT area engineer), he stated that he would not alter the passing criteria based on the amount of cover (i.e., embankment yet to be placed).

3.3 Summary of the Site Visits

The two sites presented fundamentally different situations. The R-30599 SR 44 Curve Correction (Site 1) presented un-worked native soil near a permanent water source with a planned fill of fifteen feet. The I69-DU5-B Interstate 69 Extension (Site 2) presented native soil that actually was part of an existing roadway, creating a situation similar to a reconstruct project. Neither site used the specified pneumatic tire roller listed in Section 203.26 of the INDOT specifications, but opted to employ “other approved equipment” as allowed in the specification. However, the equipment choices differed significantly with one site utilizing an off-the-road articulated dump truck and the other an on-highway dump truck. The differences of the equipment allow for no correlation of the existing soil conditions between the test sites. The SR 44 site engineer considered an eight-inch rut acceptable for soil fourteen feet below finished grade, while discussion with consultants at the I-69 site suggest their criteria would only allow a one-inch rut as a failing criterion. Decision makers at the former site also allowed a three-inch rut close to final grade to pass while those at the latter expressed that any soil exhibiting pumping failed the test but did not fail the areas with significant surface cracking, interpreting surface cracking to be a sign of sub-surface pumping. The Investigators also took note of rutting exceeding one inch beside the roadway restorative patch at the I-69 site, but not enough is known to assign a correlation between the patch and the rutting. The most significant conclusion that can be drawn from the site visits was the confirmation of the variety of conditions, equipment, and assessment criteria that are used in practice in the absence of more specific guidance.

4. INTERVIEWS WITH STA PERSONNEL

4.1 State Selections

The Investigators, with input from the Study Advisory Committee (SAC), chose to interview personnel

from four STA’s in regards to their state proof roll requirements and their development. The states were chosen based on proximity to Indiana (i.e., for similar soil types) or for having a greater quantity of detailed information available publicly to describe their proof rolling practices. Specifically, Illinois, Ohio, Minnesota and New York were chosen for the interviews. The intent of the interview was to confirm what was available in writing and to obtain information not available in the printed material such as insight from personal experience, motivations behind the development of their specifications, and other specifics of their procedures and intents. Table 4.1 lists details identifying the contacts made for the interviews.

4.2 Interview Summary

The Investigators, after completing interviews with DOT engineers in Ohio, New York, Illinois, and Minnesota subsequent to SAC recommendations, arrived at the following understanding regarding current proof rolling practice among these key states. Complete notes from the interviews are included in Appendix D.

4.2.1 Application

The states interviewed were unanimous in their aim for using proof rolling on their road projects. Proof rolling is used exclusively to assess the subgrade uniformity in supporting the pavement and to evaluate the ability of the subgrade to withstand the construction process. Toward that end, proof rolling is not conducted on the natural soil, nor on the various lifts of the embankment.

Furthermore, the proof rolling specification does not constitute an acceptance specification. Each state relies on other tests, such as DCPT or nuclear density, for acceptance. Relative to such tests, proof rolling serves as a complementary means to give engineers confidence that the accepted subgrade is without weak spots before constructing the pavement on top of it. The observation of a weak spot during a proof rolling pass can trigger an additional specified acceptance test.

Prior literature review had noted research that had been conducted to inform Minnesota’s use of proof rolling to confirm mechanistic properties of the subgrade. However, interview revealed that Minnesota has abandoned that aim in light of the MEPDG not treating the subgrade as part of the designed pavement structure.

4.2.2 Equipment

One of two equipment options are specified by the states interviewed. Ohio and New York both require contractors to use a large ‘chariot-style’ roller—a towed, single axle unit with large tires—with capacities ranging from 35–50 tons. The weight of the roller, as specified by the state, is meant to be low enough to avoid being a test of ‘failure’ of the subgrade. Minnesota specifies a similar large proof roller with similar loading, but also has a

TABLE 4.1
SHA Interview Information

State	Date	Name	Position
Illinois	April 13, 2016	Heather Shoup, P.E.	Central Office of Geotechnical Engineer
Ohio	April 1, 2016	Christopher Merklin, P.E.	Administrator of the Office of Geotechnical Engineering
Minnesota	April 22, 2016	Terry Beaudry, P.E. John Siekmeier, P.E.	Pavement reclamation, preservation (CIR), recycling, grading, base & aggregate engineer Senior Research Engineer, Materials and Road Research
New York	April 1, 2016	Brett Dening Robert Burnett, P.E.	NYS DOT Materials Bureau Chem Lab Engineering Division, Office of Technical Services, Geotechnical Engineering

‘fully loaded’ tandem axle dump truck option (with a 16-ton test axle load). Minnesota defines decision criteria for determining the proper equipment to use. Illinois specifies the use of a tandem axle dump truck loaded to a minimum gross vehicle weight of 20 tons. There appears to be no scarcity of these chariot-style rollers in the states where they are specified. One final detail of note is that Minnesota specifically examines the subgrade under the front tire of the tandem axle truck, and toward that end, is testing a laser-based system for automatically measuring the subgrade deflection under the tire load.

4.2.3 Criteria

These are the criteria that have been confirmed with the aforementioned states:

- Ohio uses generally applied criteria rather than strictly defined criteria. 1" deformation is allowed for new construction and ½" for reconstructed areas. Ohio specifies 100% coverage. One coverage of the proof roller is adequate to achieve proof rolling results.
- Minnesota has separate criteria for the different machines and different materials. For the larger machine, 3" is the passing limit for granular and 2" for non-granular soil. Minnesota requires one coverage for granular soils and two coverages for non-granular soils. For the tandem axle truck, 0.6" is the passing limit for granular and non-granular soils, 0.4" for full depth reclamation (as defined in Appendix A), and 0.3" for full depth stabilized reclamation with the same requirements for the number of passes.
- New York uses “good, reasonable judgment” without defining measurements. They require two complete passes over all areas (or two coverages).
- Illinois requires less than ½" rutting for passing with three to four passes minimum per lane.

As a final note, currently only Ohio has a separate pay item for proof rolling. Contractors in Minnesota have requested that proof rolling be covered under a separate pay item but the agency’s designers are not currently exercising this option.

4.2.4 Recommendations

The Research Investigators recommend that INDOT follow the philosophy adopted by the other states that

were interviewed. INDOT’s objective for proof rolling should be to assess the uniformity of the subgrade to support the subsequent pavement construction. Therefore, neither the natural soil nor the embankment lifts will be evaluated by proof rolling. However, the Investigators do not see a fundamental limitation of the method for evaluating the foundation or the embankment, but the formulation of any such procedures would require research to establish sound criteria and confirm the benefits. These proof rolling recommendations, while not constituting an acceptance test, may inform the need for additional standard acceptance testing as directed by the project engineer.

The proof rolling procedure recommendations made here (tabulated in Figure 4.1) are representative of procedures and specifications currently used by other SHA’s and not from original research. Therefore, the recommendations are offered as a starting point that should be subject to fine-tuning based upon INDOT’s experience. Further toward that end, the Investigators also recommend that INDOT conduct a review, after a minimum implementation of two years, to determine any need for further calibration of criteria and procedures. Appendix E contains a proof rolling daily report form used by the North Carolina Department of Transportation as their record of performance (of the proof rolling pay item). This form contains much of the data that would be pertinent for the implementation review and therefore could be used as a model for an official INDOT proof rolling form.

The Investigators recommend that INDOT specify the use of a tandem-axle dump truck loaded to a minimum gross vehicle weight of 24 tons for proof rolling. A similarly loaded tri-axle dump truck with the third axle raised or a chariot-style (i.e., towed) roller, loaded as described in Figure 4.1, may be used if available.

The Investigators recommend that proof rolling be conducted in a single pass (as defined in Appendix A) at walking speed in each traffic lane and that assessment be made based on inspection of the surface response to the rear axle load. Passing criteria should be no more than 1" deflection (i.e., including both elastic, i.e., recoverable, and non-recoverable deformation) for new construction and ½" deflection for reconstructed or stabilized subgrade and the absence of pumping and cracking.

Procedure	
Speed	Walking speed as determined by project engineer/supervisor
Passes	1 pass per travel lane
Vehicle	
Tandem Axle Truck	Tri-axle truck (only 2 rear axles w/surface contact allowed)
Weight	24 tons minimum gross vehicle weight
Tires	Per manufacturer's specification
Test axle	Rear axle
Evaluation Criteria	
New construction	1" deflection
	No pumping
	No surface cracking
Reconstruct or stabilized-subgrade	0.5" deflection
	No pumping
	No surface cracking
Vehicle	
Chariot Style Roller	
<i>Soils classified as A-3, A-4, A-6, or A-7-6</i>	
Weight	35 tons
Tires	18 x 24 or 18 x 25
Pressure	120 psi
<i>Granular soils, and soil, rock, and granular mixtures</i>	
Weight	50 tons
Tires	18 x 24 or 18 x 25
Pressure	120 psi
Evaluation Criteria	
New construction	1" deflection
	No pumping
	No surface cracking
Reconstruct or stabilized-subgrade	0.5" deflection
	No pumping
	No surface cracking

Deflection: vertical movement under load, including both elastic and plastic deformation
Pumping: recoverable vertical heave of the soil created by test load

Figure 4.1 Proposed procedure, vehicle and criteria.

5. SUMMARY

This study was conducted to establish recommendations for the practice of proof rolling based upon the collection of knowledge on SHA practices and engineering literature, tempered by practical considerations of resources and soil conditions on INDOT projects. After an extensive review of SHA specifications and supporting documents, review of scholarly publications, field observations, and interviews with engineering personnel in key SHAs, the Investigators have devised a set of recommendations for INDOT to consider for implementation. Because field testing and correlation with conventional engineering measurements was outside the scope of this study, these recommendations were carefully crafted to place INDOT's implementation within the boundaries of practices being implemented by the SHAs who have the most detailed specifications and

practices noted as being informed by engineering principles and research. Toward that end, the Investigators have proposed a set of specifications outlining equipment options, method, and unambiguous evaluation criteria, which are offered to INDOT as a sound beginning for detailed and uniform specifications and practice.

6. CONCLUSIONS AND FUTURE RESEARCH OPPORTUNITIES

All the data gathered during the research, as well as the analysis of proof rolling practices in Indiana and other States seem to indicate that there are no technical restrictions to extending the practice to other tasks such as inspection of embankment foundation or the body of the embankment. There are no data, however, or accepted practices to endorse such an extension. In other

words, there is no information at the present time to support the establishment of criteria for proof rolling applications to native soil foundation and fill assessments.

The recommendations put forward in this report apply to the proof rolling of the subgrade. If the same recommendations were extended to other parts of the embankment (fill) or to other tasks, they would be too restrictive, or even impractical, and incur unnecessary construction costs. There is an opportunity however for Indiana to move forward and use proof rolling for the embankment foundation and for the body of the fill. Establishing proper criteria will require additional work such that proof rolling yields results that are compatible with those obtained with current, acceptance practices. The following tentatively outlines the path of future research to accomplish the objective and calls for extensive field work where proof rolling is used in conjunction with current practices. Embankment foundation and the body of the embankment are discussed separately.

The foundation of an embankment (i.e., native soil supporting the fill) has to have the sufficient bearing capacity and stiffness such that no failure occurs and its deformations are not detrimental to the performance of the fill and, most importantly, of the pavement. Typically, areas where stabilization is required prior to construction are identified during the design phase of the project. It is imperative however to identify any additional zones that are not adequate or to assess that the stabilization performed, when necessary, is adequate. Current practices assess these issues based on field testing but by and large on engineering judgment. What is suggested is to identify a number of sites under construction and perform proof rolling, when access is possible, in parallel with current practices. The objective is to develop correlations between the response of the embankment foundation during proof rolling and the decision in the field of acceptance/not acceptance that ultimately will be used to provide recommendations for proof rolling of embankment foundations. Necessarily, data from a wide range of cases is desirable, including those where the foundation does not pass. This aspect of such a study is particularly important to ensure that proof rolling does not result in unnecessarily conservative results.

Proper quality control of the fill, as also with its foundation, is important to avoid failure or undesirable deformations. Quality assessment is based on the type of material used, placement and compaction operations, as well as on field testing, which may include density and moisture content measurements, LWD (light weight deflectometer), or DCPT (dynamic cone penetration test). The number of tests are necessarily limited and provide only information about the specific location where they are performed. It is suggested to identify construction projects using a wide range of soils and perform proof rolling concurrently with routine quality control tests. It is highly desirable to include cases that do not meet specifications to make sure that any recommendations for proof rolling are not excessively conservative.

As mentioned in this report, proof rolling has the distinct advantage over conventional tests that it examines quickly an entire surface at a small cost. Thus, it seems that extending this research to other tasks has the potential to improve the quality of construction and reduce cost of testing.

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APPENDIX A. DEFINITIONS

Full-depth reclamation is a pavement rehabilitation technique in which the full flexible pavement section and a predetermined portion of the underlying unbound layers (and possibly a portion of the subgrade) are uniformly pulverized and blended together to produce a homogeneous base course, ready to be surfaced with a new bound layer(s) or surface treatment. Full-depth stabilized reclamation follows the same procedure with the addition of a stabilizing agent to the blended materials to produce a stabilized base course.

Pass: a single trip in one direction

Deflection: vertical movement under load

Pumping: recoverable vertical heave of the soil created by test load

APPENDIX B. LITERATURE REVIEW

B.1 Review of State STAs' Proof Rolling Practices

B.1.1 Introduction

The review websites of the fifty state highway agencies (SHAs) found four states (Illinois, Minnesota, New York and Ohio) with substantial documentation regarding proof rolling. Four additional states (North Carolina, South Carolina, Texas and West Virginia) provide limited documentation but a relatively complete process for the proof rolling. The review found multiple stated goals for the performance of proof rolling and multiple types of equipment. This review begins with a presentation of the equipment used by the different authorities followed by the prescribed procedures. The final section presents a summary of the extended documentation from Illinois, Minnesota, New York and Ohio.

B.1.2 Equipment and Procedure

Four states (Minnesota, New York, North Carolina and Ohio) use a specially constructed towed equipment for proof rolling, sometimes referred to as a *chariot-style* roller. Minnesota also provides for using a tandem axle truck in a recently released special provision described separately below and discussed more in Section B.1.3.3. Each of these towed pieces of equipment contains a single axle with Minnesota requiring two tires and the others requiring four tires. The width of the test vehicle is not specified by any state, but by giving consideration to tire sizes, tire spacing, and evaluating photographs for scale, the width of the test vehicle appears to range roughly from five to eight feet. The required load ranges from 30 to 50 tons, which equates to 7.5 to 12.5 tons per tire. (See Table B.1 for details.) The specified tire pressures range from 40 psi to 150 psi. New York specifies the largest tire pressure range, from 40 psi to 130 psi, depending on the intended application of the test, which is discussed later.

Illinois, South Carolina and Minnesota specify loaded tandem axle dump trucks while Texas and West Virginia specify rollers. In Indiana, the specifications define a roller as the approved vehicle but allow alternates to be approved and provide the example of a fully loaded tri-axle truck. In these states specifying dump trucks and rollers, the specified weights range from 20 to 50 tons

and the tire pressures range from 50 psi to 150 psi. The specification details listed by state are shown in Table B.2.

The actual procedural description (i.e., performance) of the test for all nine states in their respective general specifications is quite limited and non-descriptive. However, many of the procedures that are defined are quite similar. The states that specify a speed for the procedure range from 2.3 mph to 6 mph. Illinois calls for the test to be completed at walking speeds which appears to be the general unstated goal of the states that define a numerical value. Two states, Ohio and South Carolina, define the completion of the procedure according to the number of passes by the equipment. Ohio requires one while South Carolina requires five passes. The other states use coverage to define the completion of the test. One coverage is a pass over every portion of the surface. The states require either one or two coverages. The complete summary appears in Table B.3.

In the different states' documentation only two, Minnesota and Illinois, provide quantitative failure criteria. (See Table B.5.) Minnesota's failure criteria range from two to three inches depending on soil type. Ohio provides guideline numerical values that apply "under most circumstances," referring to typical soil conditions within the state. Ohio's criteria range from 1/2 to 1 inch depending on type of construction, while Illinois only allows 1/2-inch rutting. Ohio and Illinois also address elastic rebound in the criteria. The remaining states provide qualitative criteria such as failures, irregularities and non-uniform in their documentation. As stated, Ohio provides a numerical guideline but the actual criteria is more descriptive and is very specific to the individual location's soil type. Quoted from the Ohio *Construction Inspection Manual of Procedures*, "the maximum allowable rutting or elastic movement of the subgrade is the amount that allows the subgrade soil to maintain the specified density throughout the construction process."

B.1.3 Procedural Description by State

The differences in the proof rolling testing becomes apparent in the more specific testing parameters provided in the extended documentation. This section provides a summary of the differentiating details.

B.1.3.1 New York New York defines two separate purposes for proof rolling depending on the location at depth of the material to be tested. The following is copied from the New York geotechnical design manual: "The purpose of proof rolling embankments is to find areas of non-uniformity of compaction, and in cuts, areas of the subgrade which will not satisfactorily support the proof roller."

First, for embankment, the soil type of the subgrade determines the load for the testing equipment. With the guidance of the regional geotechnical engineer, the soil type is assessed. The correct loading is determined based on the soil assessment. If the proof rolling creates "consistent lateral displacement of soil out of the wheel paths" during the initial stages of the test, then the loading of the test vehicle is adjusted to the next lower stress level (see Figure B.1). The process continues until the correct loading is determined. Figure B.1 presents the stress level table from the NY Standard Specifications. The criteria call for the proof rolling to take place "after the appropriate stress level is determined." The specifications define no failure criteria and simply require that all "deficiencies" be addressed.

TABLE B.1
Trailer Specifications

State	Trailer		Tire			
	Weight	Axles	Tire Pressure	Separation	Quantity	Size
Ohio	35–50 ton	1	120–150 psi	32 in max	4	
New York	30–50 ton	1	40–130 psi		4	18.00 × 24 or 18.00 × 25 (24 ply tires)
Minnesota	29.8–30.2 ton	1	95 psi	6 ft min	2	18 × 24 or 18 × 25
North Carolina	48–50 ton	1	68–72 psi	32 in max	4	

TABLE B.2
Vehicle Specifications

State	Vehicle	Specified Equipment				
		Equipment		Tire		
		Weight	Axles	Tire Pressure	Quantity	Size
Illinois	Tandem-axle truck, or similar	20 tons min				
Indiana	Pneumatic roller 5.5 ft min overall width			50–90 psi contact		7:50 by 15* min
S. Carolina	Fully loaded tandem axle dump truck			70–90 psi		
Texas	Roller	25–50 tons	2	150 max psi contact	4 min	
W. Virginia	Pneumatic tire roller	50 tons				
Minnesota	Tandem-axle truck	25 tons min 8 tons min	Front axle	80 min psi		11–17" wide

*From Indiana Standards and Specifications 409.03(d)3.

TABLE B.3
Test Procedure by State

State	Passes	Speed
Ohio	1 Pass	2.5–5 mph
New York	2 coverage*	
Minnesota	1 coverage* 2 coverages*	2.5–5 mph
Illinois	Should be a minimum of three to four truck passes. Proof rolling shall consist of 40 passes in each lane of the completed aggregate base course	Usually performed at walking speed
North Carolina	1 coverage*	2.6–3.4 mph
Indiana	1 or 2 coverages*	
South Carolina	5 passes	2.3–3.4 mph
Texas	2 coverages*	2–6 mph
West Virginia	2 or more coverages*	≤5 mph

*Coverage is described as passing the test vehicle over the entire surface area.

The function of the test is completely different in areas of cut. Determining sufficient bearing capacity of the soil in cut sections is the goal. The requirements call for the evaluation test loading based on the least acceptable soil type. From Figure B.1, the poor classification is the least acceptable subgrade support with an associated loading, of 30-ton and a tire pressure of 40 psi. The specifications call for the test to be performed immediately prior to the final trimming of the subgrade. This portion of the specifications, like those for embankment, also provide no defined failure criteria.

B.1.3.2 Ohio The state of Ohio states the reason for proof rolling to be “to locate soft areas, check the subgrade compaction, to carry out the intent of the design, and to provide uniform support for the pavement structure.” The Ohio construction inspection manual recognizes the problem water creates for soil bearing capacity and addresses the need for properly draining the subgrade. It also requires the inspectors to be proactive and to address problems as evidenced by the following “When rutting and deflection under heavy equipment indicates soft subgrade, the Engineer should authorize the correction.”

The specifications require the top 12 inches of the subgrade be compacted and for the proof roll to take place immediately after compaction, when the moisture content is near optimum. The required equipment varies based on the material to proof roll. For soil types A-3, A-4, A-6, and A-7 the specifications require a 30-ton roller with 120 psi tire pressure. For granular soils, and soil, rock and granular mixtures, the specifications require a 50-ton roller with 120 psi tire pressure. The construction inspection

manual requires a tire pressure of 150 psi for the granular material, which creates disagreement of 30 psi between the specifications and the construction inspection manual. The applied definition for “granular soils” is also unclear as the documentation recognizes A-3 is a granular soil while it is included in the list of other soil types.

The proof rolling is used to trigger further investigation and not as the defining test for subgrade acceptance. The official proof rolling failure criteria is as follows: “the maximum allowable rutting or elastic movement of the subgrade is the amount that allows the subgrade soil to maintain the specified density throughout the construction process.” They also provide maximum numerical values to the ruts from proof rolling as a guide that “apply to the vast majority of projects.” For new construction a permanent rut deeper than one inch is failing and for reconstruction that value is only one half inch. The specification also limits the amount of elastic rebound to the same values if there is also substantial cracking or substantial lateral movement. Commentary in the specifications asserts that the elastic rebound with cracking could signal soft soil conditions as much as five feet below the subgrade.

The construction inspection manual notes that the occasional or nominal failure should not create concern. They note that the proof rolling load is ten times the final in-place stresses once the pavement is constructed.

B.1.3.3 Minnesota Minnesota uses two terms, *test rolling* and *proof rolling*. Test rolling is addressed in both the pavement design manual and the materials lab supplement. The information for proof rolling references a special provision. A special provision

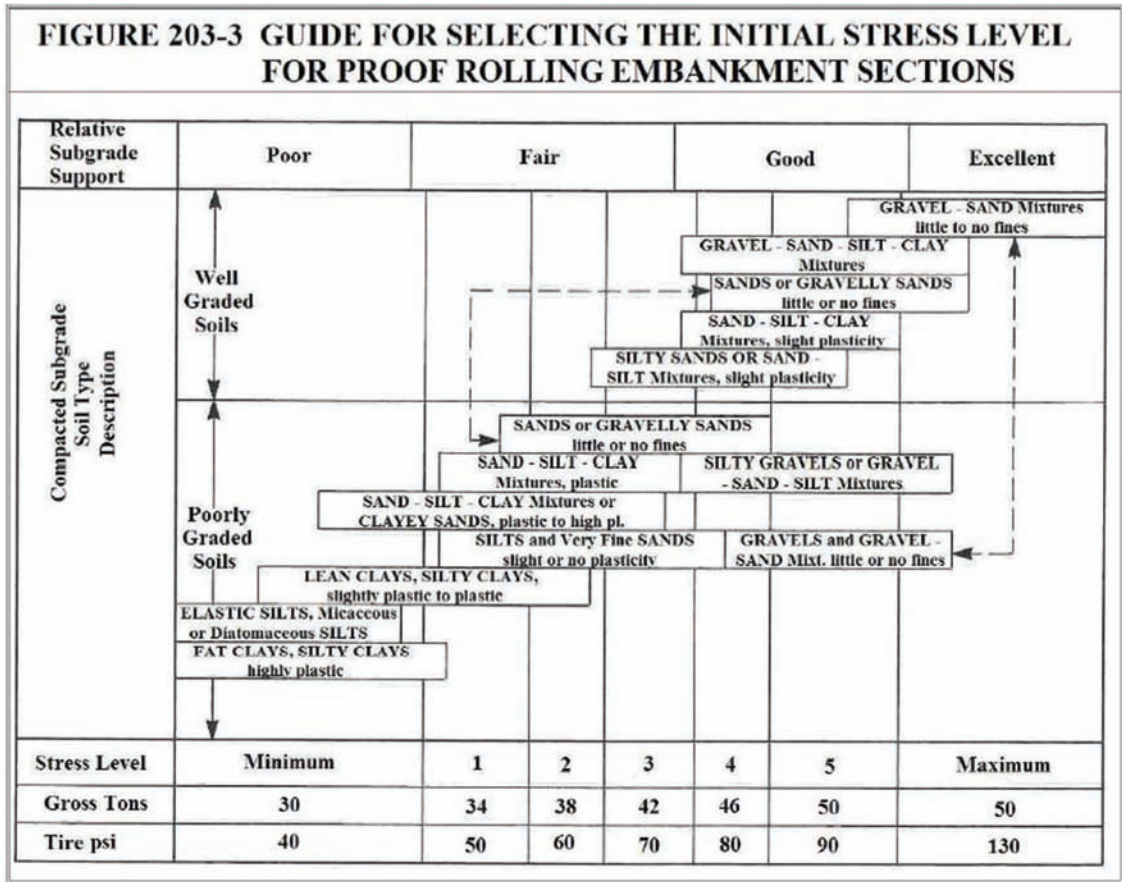


Figure B.1 Reprinted from NY Standard Specifications. (Source: NYSDOT, 2015.)

addressing proof rolling was not found by searching the Minnesota DOT’s website. From the description, the proof rolling special provision provided for testing the adequacy of subgrade compaction using a lighter test vehicle and targeting a more shallow test area. A recently released test rolling special provision refers to lighter weight test rolling equipment, which appears to be similar to the referenced “proof rolling” special provision. The test rolling procedure using the lighter weight vehicle is not discussed in DOT documents but was created in coordination with the research report “Development of New Test Roller Equipment and Construction Specifications for Subgrade Compaction Acceptance” which is discussed in Section 2.2.2 (Budge & Wilde, 2011).

The pavement design manual provides the following description for test rolling. Minnesota defines test rolling as “an evaluation of a subgrade or subbase with a heavy roller to evaluate the adequacy of the roadbed construction relative to uniformity and consistency of the subgrade support in terms of strength, stiffness, stability, density and moisture content. The test roller will detect weak/unstable subgrade areas due to inadequate compaction (both in terms of moisture content and density), and/or unstable soils to a depth of about 5 feet.” A draft of a document providing decision guidelines for the two testing procedures makes distinctions to use the heavy equipment in the situations meeting the following criteria and the lightweight equipment when the situation is otherwise:

- New construction \geq 2-lane miles.
- Layer thickness is \geq 30 in.
- No utilities within 30 in of testing surface.
- No geotextiles within 60 in of testing surface.

The materials lab supplement applies test rolling to embankments. Minnesota represents the only state to use a heavy towed

vehicle with only two wheels. While the load per tire remains comparable to the other states, the location of the load application differs significantly. They specify the failure criteria as a three-inch deflection for granular and two inch for non-granular soils. The lab manual also describes the method of measuring the deflection. The requirements specify the use of a measuring device attached to the center of the axle extending 12 inches outside of the tire. Therefore, the failure criteria are associated with total deflection, or sinkage, rather than permanent rutting.

B.1.3.4 Illinois Illinois does not provide criteria for state-wide use, but a review of information of proof rolling from around the state. Apparently, due to the collection of information from different locations some of the information presents conflicting data. The primary source for the information is the subgrade stability manual. As defined in the manual, the subgrade is the top material below the pavement structure.

They provide the following description: “Proof rolling involves driving a loaded truck, or heavy construction equipment, repeatedly over the subgrade (especially in cut areas) and observing the surface deflections and the development of rutting. “The difference between this quoted definition and definitions from other states lies in the term repeatedly. One reported reason for the repeated passes is that “repeated passes of truck loads cause moisture to move up from high ground water, soften or remold the moisture-sensitive silty soils.”

Noting that proof rolling is not a test for directly evaluating the strength of the subgrade, proof rolling is recommended as a field procedure to be utilized prior to running DCP or SCP tests. However, some districts find the procedure too time consuming and prefer to proof roll areas identified by other testing. Still other districts perform proof rolling by observing the effects of the construction equipment and haul trucks as they travel over the

subgrade. The wording suggests that the process is not an “official” test but the application of observation to typical job processes.

The passing criteria in Illinois differ based on the vertical location of the lift. These criteria are not a true pass/fail criteria but signal requirement for additional testing. For proof rolling tests performed on a non-surface layer, rutting of 1.25 inches triggers more testing. High deflection rebound (pumping) also signals the need for more investigation. However, for the finished subgrade the failure criteria are much more stringent and reduced to one half inch.

All of the different states’ failure criteria are tabulated in Table B.4. The descriptions from the different states of when the tests are to be performed are presented in Table B.5. Information from the different state’s publications on the purpose for proof rolling is also found in Table B.5.

B.2 Review of Published Proof Rolling Literature

B.2.1 Introduction

The volume of scholarly publications directly addressing the topic of proof rolling is relatively low. This research included searches of “Google Scholar,” “Engineering Village” and the Purdue University Library search engine. The searches included all variants of proof roll and test roll along with many associated terms such as “rutting,” “pumping,” “subgrade tests” etc. Of the

publications found, one directly addresses the test equipment and procedures for proof rolling. Five publications address proof rolling as a significant portion of the report with others addressing the proof rolling topic indirectly. This section reviews the published research reports and peer reviewed journal articles found.

B.2.2 Early Publication

The earliest publication found in this review dates to 1960 by Turnbull and Foster (1960), published in the *Highway Research Board Bulletin*. They assign the origination of the term proof rolling to the Corps of Engineers in a 1957 specification for graded crushed aggregates used for heavy duty pavements. The term originally carried a different meaning than typically understood today. The term referred to the process of applying thirty additional “coverages” with a 50-ton roller to each lift after the tests results reported a hundred percent modified AASHO (former name for AASHTO) density. Turnbull and Foster (1960) altered the number of required coverages in their description of proof rolling to “a few” coverages. They also defined the purpose of proof rolling as to “check the adequacy of normal compaction and to correct any deficiencies that may exist.” This definition differs from the common current definition in that proof rolling corrected the deficiencies and not simply identified them.

Turnbull and Foster (1960) identified factors that affected proof rolling as a method to increase the in-place density. The moisture content of the compacted layer was the primary variable.

TABLE B.4
States’ Failure Criteria

State	Vertical Target Depth	Condition	Failure Criteria
Ohio	3 to 5 feet		The maximum allowable rutting or elastic movement of the subgrade is the amount that allows the subgrade soil to maintain the specified density throughout the construction process
		New	Generally applied criteria Rutting 1 inch (25 mm), or the same in elastic (rebound) movement with substantial cracking or substantial lateral movement
		Reconstruct	½ inch (13 mm) replaces “1 inch (25 mm)” from above
New York		Embankment	“Any deficiencies disclosed...”
		Cut	“...fails to provide a satisfactory support for the proof rolling operation...”
Minnesota	Up to 5 feet (heavy vehicle) (tandem axle)	Embankments granular	3”
		Embankments non-granular	2”
		Granular and non-granular materials	0.6 inches
		Aggregate surfacing, full-depth reclamation, aggregate base, shoulder base aggregate	0.4 inches
Illinois		Stabilized full depth reclamation	0.3 inches
		Non-finished subgrade	1.25” or areas of high rebound deflections (pumping)
		Finished subgrade	0.5” or areas of high rebound deflections (pumping)
North Carolina			
Indiana			Roller marks, irregularities, or failures
South Carolina			Unstable or non-uniform
Texas			Unstable or non-uniform
West Virginia			Unstable areas or soft spots

TABLE B.5
States' Purpose and Timing

State	Timing	Purpose
Ohio	Immediately after the subgrade compaction, with moisture content near the optimum	<p>“The primary purposes of proof rolling are to locate soft areas, check the subgrade compaction, to carry out the intent of the design, and to provide uniform support for the pavement structure.”</p> <p>“The goal of proof rolling is to maximize the load to locate soft subgrade. These soft soils could be 3 to 5 feet (1 to 2 m) deep. In rare cases, the soft soil may be deeper than 5 feet (2 m).”</p>
New York	<p>Embankment: After an acceptable stress level is established</p> <p>Cut: Immediately prior to final trimming of the subgrade surface and placement of subbase materials in cut sections</p>	<p>“Proof rolling is not designed or intended to fail an embankment, but to point out areas of non-uniform compaction.”</p> <p>“The purpose is to determine the location and extent of areas below the subgrade surface that require corrective undercutting”</p>
Minnesota		<p>“Proof rolling is a method, similar to test rolling, to evaluate the adequacy of subgrade compaction. The weight of the testing equipment (a loaded truck) is substantially lower with proof rolling and therefore the depth that is being tested is less.”</p>
Illinois		<p>“It is intended to distress the soil to conditions anticipated during construction.” “It is an economical method of identifying unstable/unsuitable soils during construction”</p>
North Carolina	Within 0.5 ft of final grade	
Indiana		
South Carolina	5 ft or less below finished grade	
Texas		
West Virginia		

They also reported that both the increase in the number of coverages and the increase in the tire pressure increased the density. In contrast, they noted that an increase in the load of the roller vehicle did not increase the density of the layer. Their final observation recognized that the excessive over rolling caused damage to the layer and lowered density. The reviewed literature provided no insight into the transition of the original definition into the current understanding of evaluation only, with no expectation of compaction.

Multiple research reports attempt to predict the rutting and deflection. The reports explore different predictive methods while considering different soil properties. Those reports are reviewed next.

B.2.3 Correlating Proof Rolling and Soil Properties

Traylor and Thompson (1977) produced a report entitled *Sinkage Prediction—Subgrade Stability* as part of the Illinois Cooperative Highway and Transportation Research Program project number IHR-605. In the report, they present seven methods for predicting sinkage. Depending on the method, different factors contribute to the calculations. Shear strength, California bearing ratio, cohesion, load, tire pressure, and contact area are all used in at least one method. They note that some of the methods are somewhat involved and not practical for field applications. The prediction methods discussed are presented in the following list:

1. Load-flow theory
2. Load-flow theory to pneumatic tires (not field practical)
3. Rodin's sinkage theory
4. The road research laboratory's sinkage prediction (chart based)
5. Kraft-analysis (50% accuracy)
6. WES flotation requirements (nomograph)
7. Track sinkage prediction

Crovetti (2002) presents research findings in an executive summary of multiple research reports commissioned by the state of Wisconsin designed to develop specifications for accepting subgrades based on subgrade deflections. The implementation of any developed specification was not directly researched. However, a search of the Wisconsin DOT's website returned no current proof rolling specifications. In the research, Crovetti's team develops a rolling wheel deflectometer (RWD) to function as a portable deflection measuring device. The RWD used the steering wheels of a quad axle dump truck as a model. The research concluded that, within constructed subgrades, deflections might be appropriate for detecting poor in-place stability. They noted that the moisture density conditions greatly affect the deflections. Due to that moisture-density effect, they also acknowledge that deflection testing alone may not detect differences between acceptable and unacceptable subgrade stabilities. However, Crovetti reports that the primary objective of determining useful correlations between subgrade deflections and in-place subgrade stability had been achieved.

In the final reviewed report linking soil properties and proof rolling, Hambleton and Drescher (2008) introduce computer simulation into their predictions. In addition to the simulation, they also present an analytical approach based on the bearing capacity formula. As validation, they performed controlled laboratory tests. Their research incorporates the proof rolling procedures from the Minnesota DOT. A summary of their conclusions follows.

1. Test rolling provides a method for providing a continuous record of measurement, inspecting large areas and detecting inadequately compacted areas. However, no quantitative record is produced.
2. The research utilized ABAQUS finite element software for the simulation and an analytical approach based on the bearing capacity formula. The analytical method provided a universal and easily applied method, although the results are

more approximate. The analytical expressions relate to strength and are solvable with any standard computational software. The numerical simulations support the analytical expressions; however, they provide no direct method for evaluating soil strength parameters.

3. Given a load and wheel geometry, the models provide a means to predict penetration given a soil with known material properties. "The theoretical predictions appear to be fairly accurate for sinkage-to-diameter ratios $0.01 < s/d < 0.08$."
4. Graphs relating soil strength parameters, wheel geometry, weight, and sinkage are presented as an alternative to the analytic expressions.
5. The soil deformations are primarily permanent, thus associated with soil yield and soil strength properties of friction angle and cohesion. This observation implies test rolling evaluates the soil strength rather than elastic properties of the soil.
6. The theoretical models are affected indirectly by the properties of unit weight and moisture content. The compaction of sand increases the friction angle and the increased density and decreased moisture of cohesive soils increase cohesion.
7. The type of soil directly affects the ability to infer soil strength parameters. If the soil is not homogeneous parameters (e.g. sand and fines), then the evaluation will require more than one wheel with different characteristics.
8. Soil type, layer position, relative strength, wheel force and wheel geometry affect the influence depth of the rolling wheel. From the analytic method, influence depth is strongly affected by the wheel weight and moderately affected by wheel size.
9. Large wheel weights create a greater sensitivity to underlying weak layers. Also a slight change in soil strength creates a large change in sinkage under large weights as opposed to smaller weights.
10. Wheel flexibility affects sinkage substantially in both methods. The theoretical prediction accounting for tire flexibility predict sinkage half of a rigid wheel.
11. For rigid wheels:
 - a. For granular soils, the relationship between sinkage and wheel weight is linear.
 - b. For granular soils, the relationship between sinkage and wheel width is inversely proportional. The relationship is to the width squared for cohesive soils.
 - c. For both soil types, the relationship between sinkage and wheel diameter is inversely proportional.

Validation of the theoretical models was accomplished through scaled lab tests.

The research report by Budge and Wilde (2011) utilizes the findings in the Hambleton and Drescher (2008) report to develop an initial draft of the state of Minnesota's lighter weight test rolling specification presented in Section 2.2.2. The chosen apparatus uses two ultrasonic sensors mounted on the front axle for deflection measurements. The location of the vehicle is continuously recorded using GPS technology. The researchers recognized the capacity of the GPS technology to provide sub-centimeter x, y, and z coordinates but chose to use the ultrasonic method for the z component based on system cost. The procedure was implemented

on several projects and through their field testing they concluded the "new specification will be reasonable and applicable to the subgrade soils anticipated." They also proposed additional field studies to complete validation of the criteria.

B.2.4 Subgrade Undercut Criteria

In a report by Borden et al. (2010), the team developed a subgrade undercut criteria. The criteria developed considered soil modulus and strength values and associated them to Dynamic Cone Penetrometer (DCP) testing. The ultimate goal was that the final subgrade should meet the North Carolina state criteria of one-inch maximum rutting and pumping and provide a bearing resistance of two times the applied tire pressure. The research process utilizes proof rolling as a means of evaluation of the subgrade and then additionally creates a proof roll undercut criteria. The undercut criteria refer to determining the amount of inadequate soil to remove and replace with acceptable fill.

With proof rolling used as an evaluation tool, specific proof rolling insights were generated. The researchers noted that the North Carolina proof rolling equipment applied a plane strain type loading while typical construction traffic applied axisymmetric loading. The structure of the proof rolling equipment specified as a single axle with four wheels created the plane strain loading. This plane strain loading configuration evaluated deeper levels of the embankment. The researchers concluded that rutting was primarily associated with shear deformation in shallow layers, while pumping was mainly a function of stiffness parameters which may reside in deeper layers. The research team established undercut criteria based on both axisymmetric and plane strain modes. The developed proof rolling undercut criteria is a 2.0 ratio for bearing capacity and one-inch settlement for pumping.

B.2.5 Proof Rolling as Complement to other Soil Acceptance Tests

Multiple reports present findings on using intelligent compaction (IC). Vennapusa et al. (2009), and Mooney and Rinehart (2007) both suggest using IC as an alternative to heavy test rolling. However, the Mooney and Rinehart (2007) procedure for proof rolling included a week delay between compaction and proof rolling creating a low moisture content top layer in which soft deeper failing soil was not detected. This finding agrees with similar statements in both (Croveti, 2002) and Borden et al. (2010). That same basic situation of the strong top layer with undetected weaker lower layers is also presented by Tice and Knott (2000) in their discussion of relocating the Cape Hatteras lighthouse. Zambrano et al. (2006) presents IC as the preferred method for evaluating subgrades but also recognizes the need for proof rolling procedures to be used as an evaluation method until IC is routinely utilized. Chen (2009) in his investigation into the premature structural failure of a specific road section on a Texas highway notes that the specifications did not require proof rolling during the construction process. Quoting from his published findings "Although there are many different ways to minimize premature failures, an immediate action is to include proof rolling in construction quality control."

APPENDIX C. SITE VISIT FIGURES



Figure C.1 Moisture condition near stream.



Figure C.2 Test vehicle.



Figure C.3 No rutting at starting station.



Figure C.4 Four-inch rutting @ approximately 509+00.



Figure C.5 Eight-inch rutting @ approximately 508+50.



Figure C.6 Deep rutting near stream.



Figure C.7 Test vehicle near stream.



Figure C.8 Test site (typical).



Figure C.9 Another test vehicle.



Figure C.10 No contact by floating axle.



Figure C.11 Beginning of proof roll with no rutting.



Figure C.12 SB failing test area.



Figure C.13 NB failing area.



Figure C.14 Next to roadway patch area.



Figure C.15 Surface cracking.



Figure C.16 Underdrain.

APPENDIX D. STATE INTERVIEW NOTES

Illinois

1. Foundation is not proof rolled.
2. Only sub-grade proof rolled, not embankment during construction.
3. In Illinois, the subgrade is not considered in the design of the pavement section; it is only engineered for uniformity of support.
4. Intent of proof rolling.
 - a. To evaluate for consistency in compaction.
 - b. Not to evaluate “structural” design.
 - c. Used as a method to identify areas for additional testing (unless rutting is significant eliminating the need for additional tests).
5. The only specification is associated with specific aggregate base. This spec is the only application requiring 40 passes.
6. Normal proof rolling is 1–2 passes.
7. Passing is rutting < 1/2”.
8. Illinois uses DCP and nuclear density gauge for embankment control.
9. Existing documents outside the standard specs are only guidelines with the exception of one district that uses a special provision to make proof rolling a pay item.

Ohio

1. Foundation is not proof rolled.
2. Only sub-grade is proof rolled, not embankment during construction.
3. Intent of proof rolling.
 - a. To evaluate for consistency in compaction.
 - b. Overload to evaluate for subgrade’s ability to withstand construction.
 - c. Not to evaluate “structural” design.
4. Importance of large machine.
 - a. Ability to overload subgrade.
 - b. Forces standardization of testing equipment.
5. Tires are fluid filled.
6. Proof rolling is a pay item (as of approx. 2006).
7. Ohio monitors embankment construction with observation and compaction tests (primarily nuke gauge) Typical failure criteria are 1” deformation.
8. Reconstruction projects have more physical constraints creating the different passing criteria.
9. In a few isolated cases proof rolling is used on MSE wall foundation and MSE rockwall berm (exception to policy on not proof rolling foundation).
10. Ohio uses DCP rather than proof rolling in low CBR soils.
11. Ohio accepts readings from portable scales for weight measurement.
12. DCP and proof rolling can contradict each other.
13. A 35-ton machine was typically adequate.
14. Granular subgrades typically do not cause concern.

New York

1. “Uniformity is more important” [than strict achievement of a certain subgrade strength/stiffness].
2. Foundation is not proof rolled in embankment sections.

3. Foundation proof rolled in cut sections, where surface acts as subgrade.
 - a. Cuts rarely more than 1 foot.
4. Only sub-grade proof rolled not embankment during construction.
5. Intent of proof rolling.
 - a. Evaluate for consistency in compaction, i.e., look for weak areas.
 - b. Overload to evaluate for subgrade’s ability to withstand construction.
 - c. Intent is not to evaluate “structural” design.
6. Importance of large machine.
 - a. Ability to overload subgrade.
 - b. Forces standardization of testing equipment.
 - c. Roller has been used for 50+ years.
7. NY monitors embankment construction with observation and compaction tests (nuke gauge and standard metrics).
8. Typical failure criteria (no specific number given; said simply to apply ‘good, reasonable, judgment’).
 - a. Compaction
 - b. Rutting
 - c. Weaving (pumping)

Minnesota

1. Foundation is not proof rolled.
2. Only sub-grade proof rolled and not embankment during construction.
 - a. Considering halving the number of compaction tests required if embankment is proof rolled (professors confirm my interpretation).
3. Intent of proof rolling.
 - a. Evaluate for consistency in compaction.
 - b. Intent is not to evaluate “structural” design.
4. First year requiring proof roll using new smaller proof roller (TR10).
5. Lighter vehicle needed because parts for larger proof roller are becoming obsolete (large in use for 20+ years).
6. Not used on foundation.
7. Used on subgrade only now—next year will include 2 additional uses/locations.
 - a. Top of base.
 - b. Non-stabilized full depth reclamation.
8. Original plan was to eventually tie proof rolling to design criteria through published and future research. A change in design procedure (not considering resilience modulus) negated the need.
9. Dubbed proof rolling “poor man’s intelligent compaction.”
10. Currently proof rolling is incidental to other contract items; it is mandatory for QC/QA as a no-cost item. While designers have the option to include it as a pay item, it is not done in current practice.
11. Contractors want to return to the practice of having proof rolling as a pay item.
12. Agency is testing an accurate (laser-based) deflection measurement device.
13. Pointed out Iowa State did proof rolling as part of IC research project and followed up with article.
14. A big test roller only recommended after 30” of embankment placed.

APPENDIX E. NORTH CAROLINA PROOF ROLLING FORM

Following is a form and procedure for documenting the performance of proof rolling, taken verbatim from the North Carolina State Department of Transportation. The form is shown here only as a potential model from which INDOT might develop their own reporting format, as referenced in Section 4.2.4.

PROOF ROLLING DAILY REPORT

The Proof Rolling Daily Report (M&T Form 507) documents proof rolling operations and serves as a pay record that supports the final payment for proof rolling. Since the form serves as a source document for payment, proof rolling need not be recorded in a pay record book. M&T Form 507 can be obtained from the Materials & Tests Unit stockroom.

The report should be completed daily for each proof rolling operation. It should be signed by the Resident Engineer after being reviewed to indicate concurrence with the contents and to signify acceptance of the report as a source document for payment purposes. **The Inspector should not place the Resident Engineer's name on the report in lieu of the Resident Engineer reviewing the report.**

The **Proof Rolling Daily Report** should contain the following information:

- Date:** The date the work is performed. A separate report must be completed for each crew, each day, and/or each work order.
1. **Project No.:** The project contract number or WBS Number. In the case of multi-WBS Numbers, use the WBS Number applicable to the location of the work being performed.
 2. **ID No.:** The Transportation Improvement Plan (TIP) number for the project.
 3. **Report No.:** The number of the report. Each WBS Number should have its own sequentially numbered set of reports.
 4. **County:** The county or counties where the project is located.
 5. **Make of Roller:** The make of roller used for proof rolling, including the model number.
 6. **Tire Size and No. Plies:** The size of the tires and the number of plies the tires have, such as 20 × 28 (36 ply). All tires should be the same manufacturer and size.
 7. **Weight:** This should be the gross weight of the proof roller in tons.
 8. **Air Pressure:** This is the air pressure of each tire, checked on a daily basis. Incorrect tire air pressure can cause the weight of the proof roller to be unequally distributed during the proof rolling process. This may prevent the proof roller from detecting unstable areas. The recommended tire pressure is **68–72 psi**.
 9. **Time:** The Inspector should record the time started and stopped in this section of the report to the nearest minute. The number of Hours Rolled should be determined by dividing the total number of minutes included in the start and stop times by **60**. This number should be recorded to the nearest **0.1 hour**. The Contractor is paid for all initial proof rolling. In the event of failure due to the Contractor's negligence or weather, the Contractor is required to perform corrective measures and proof roll the failed area at no cost to the Department. Proof rolling hours for which payment is not to be made as provided by Section 260 of the specifications will be kept separate from proof rolling hours for which payment is to be made (see Failures below).

10. **Area Rolled:** Areas that have passed proof rolling requirements of the contract should be recorded by specific station number in this section of the form along with the number of coverages performed. Proof rolling is typically performed on all areas of a project. Special emphasis should be placed on grade points, undercuts, or other questionable areas.
11. **Failures:** The areas that failed proof rolling should be recorded by specific station number in this section of the form. Each failure should be noted by identifiable asterisks. Sufficient information to document the failure should be provided as listed below:
12. **Cause of Failure:** Document the reason the subgrade failed the proof rolling and any conditions at the specific location.
13. **Method of Correction:** Document what corrective measures were performed by the Contractor to correct the section. Do not allow the Contractor to wait several days and proof roll again without performing corrective measures. A second coverage on a previous failure area should be noted as such. A definition of coverage is shown at the bottom of the form.
14. **Remarks:** Any remarks regarding payment for work and the Contractor's performance should be recorded in this section of the report for each area.
15. **Signature:** The Technician who observed the operation should sign the report. The Resident Engineer should also review and sign the report.

A copy of each report should be sent to the Division Engineer and Geotechnical Unit for review. The original report remains in the Resident Engineer's project file until completion of the project. Original proof rolling daily reports are submitted with the final estimate assembly as source documentation.

Proof rolling reports should be numbered consecutively, except when failures occur. If a section that has been proof rolled fails, the next report that covers that section should have a letter designation that continues progressively with each report until it passes. For example, if a section on report 1 fails, that area should be shown on report 1A the next time it is rolled. If it does not pass on that report, it will next be shown on report 1B. This will better enable project personnel to ensure all failing areas are re-rolled.

The correct proof rolling procedure is accomplished by operating the proof roller in the following manner:

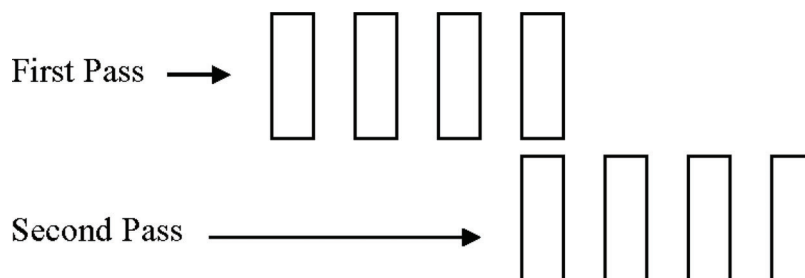


Figure E.1 Proof roll wheel placement.

NORTH CAROLINA DEPARTMENT OF TRANSPORTATION
DIVISION OF HIGHWAYS

PROOF ROLLING DAILY REPORT

Date: _____ (1)

Project No.: _____ (2) ID No.: _____ (3) Report No.: _____ (4)

County: _____ (5) Make of Roller: _____ (6)

Tire Size and No. Plies: _____ (7) Weight (Tons Gross): _____ (8)
Use 43-46 Metric Tons (48-50 Tons)

Air Pressure (Checked Daily): _____ (9) MPa. (PSI)
Use 480-500 Mpa (68-72 psi)

Time: Started: _____ (10) Stopped: _____ (10) Hours Rolled: _____ (10)
(Units, Decimals)

Started: _____ Stopped: _____

Started: _____ Stopped: _____

Area Rolled: Sta. _____ (11) to Sta. _____ (11) Coverages:^a _____ (11)

Sta. _____ to Sta. _____ Coverages:^a _____

Sta. _____ to Sta. _____ Coverages:^a _____

Failures: ** Sta. _____ (12) to Sta. _____ (12)

*** Sta. _____ to Sta. _____

Sta. _____ to Sta. _____

Cause of Failure: ** _____ (13)

Method of Correction: ** _____ (14)

Remarks: ** _____ (15)

*A coverage is considered that stage in the rolling procedure when the entire width of the section designated has been in contact with the pneumatic tires of the roller.

Inspector: _____ (16)

SIGNED

Resident Engineer: _____ (16)

c: Geotechnical Unit
Division Engineer
File

Figure E.2 North Carolina blank proof roll form.

Example

**NORTH CAROLINA DEPARTMENT OF TRANSPORTATION
DIVISION OF HIGHWAYS
PROOF ROLLING
Daily Report**

Date: 7-12-98

Project No.: 8.1234567 ID No.: R-12344 Report No.: 5

County: Person Make of Roller: Ferguson

Tire Size and No. Plies: 18.00 x 25 (52 Ply) Weight (Tons Gross): 49.2 Tons
Use 43-46 Metric Tons (48-50 Tons)

Air Pressure (Checked Daily): 70, 70, 69, 71 MPa.
 (PSI)
Use 460-500 Mpa (68-72 psi)

Time: Started: 7:51 a.m. Stopped: 8:21 a.m. Hours Rolled: 1.5
(Units, Decimals)

Started: 8:50 a.m. Stopped: 9:08 a.m.

Started: 10:04 a.m. Stopped: 10:36 a.m.

Area Rolled: Sta. 11+00 Rt -L- to Sta. 16+50 Rt -L- Coverages:^a 1

Sta. 16+50 Rt -L- to Sta. 21+75 Rt -L- Coverages:^a 1

Sta. 21+75 Lt -L- to Sta. 30+00 Lt -L- Coverages:^a 1

Failures: ** Sta. 17+25 Rt -L- to Sta. 18+75 Rt -L-

*** Sta. 22+00 Lt -L- to Sta. 26+50 Lt -L-

Sta. _____ to Sta. _____

Cause of Failure: ** Excessive moisture due to improper drainage (standing water on subgrade).

*** Unsuitable material was encountered one foot below subgrade in cut section.

Method of Correction: ** Contractor aerated, recompacted, and re-rolled subgrade.

*** Contractor undercut unsuitable material and replaced with approved borrow material, recompacted, and re-rolled material.

Remarks: ** All work at Contractor's expense.

*** All work performed at state's expense including re-proof rolling (see Report #2)

*A coverage is considered that stage in the rolling procedure when the entire width of the section designated has been in contact with the pneumatic tires of the roller.

SIGNED

Inspector: Q. M. Insulator

Resident: Q. M. Resident

Engineer: _____

c Geotechnical Unit
Division Engineer
File

Figure E.3 North Carolina completed example proof roll form.

About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,600 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at: <http://docs.lib.purdue.edu/jtrp>

Further information about JTRP and its current research program is available at: <http://www.purdue.edu/jtrp>

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