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Specifications for Embankment and Subgrade Compaction

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Supplementary Notes

Abstract

Six approaches were developed for specifying embankment and subgrade compaction and/or verifying compaction quality on Virginia Department of Transportation (VDOT) construction projects. These approaches, along with VDOT's current practices, were qualitatively evaluated for applicability considering the benefits and risks of each approach.

Based on the findings, the use of specifications based on embankment performance measurements is viable for large design-build or design-build-maintain projects. The use of these specifications permits greater innovation on the part of the contractor while shifting more of the overall project risk to the contractor. The contractor's increased stake in the post-construction performance of the embankment aims to promote high quality workmanship with reduced oversight by VDOT. The primary risks faced by VDOT through the use of performance specifications include: (1) disputes between VDOT and the contractor over deficient embankment performance during the warranty period; (2) the difficulty of repairing underlying embankments when finished roadway features, such as pavements, are already in place; and (3) the uncertainty that construction defects will be manifested in a measurable way during the finite term of the performance period.

There was considerable support, in both published sources and the responses generated from the survey of experts conducted for this project, for full time visual inspection of embankment construction. To the extent that is feasible considering fiscal and policy constraints, it is recommended that VDOT increase the number of experienced inspectors on embankment construction projects. Three approaches were considered to increase the number of inspectors. The first of these was simply for VDOT to hire more experienced inspectors; however, it is understood that this approach is very unlikely to be feasible. Another approach is for VDOT to outsource inspection work to a private engineering firm. The use of this approach allows for rapid adaptation of the inspection labor supply to changing construction demands. A potential shortcoming of this approach is that VDOT may see an increase in overall project costs compared to hiring its own inspectors. A third approach considered to increase the number of inspectors available on VDOT projects is to have the contractor contract with a private engineering firm to provide outside inspectors. This approach is not recommended based on extensive concerns expressed by the project focus group and the surveyed experts about the potential for a conflict of interest.

This study also considered the use of a pay factor for embankment construction to motivate the contractor to deliver high quality compaction. The pay factor developed for this project links the contractor's payment to the results of field density tests. A shortcoming of this approach is that it increases the potential for disputes between the contractor and VDOT because every density test has the potential to influence the contractors pay.

Another recommendation of this study is to significantly increase the minimum frequency of field density and compaction moisture content testing for embankment construction. It is important to highlight that an increased test frequency should not be considered as a replacement for observation by an experienced earthwork inspector.

FINAL CONTRACT REPORT

SPECIFICATIONS FOR EMBANKMENT AND SUBGRADE COMPACTION

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ABSTRACT

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Based on the findings, the use of specifications based on embankment performance measurements is viable for large design-build or design-build-maintain projects. The use of these specifications permits greater innovation on the part of the contractor while shifting more of the overall project risk to the contractor. The contractor's increased stake in the post-construction performance of the embankment aims to promote high quality workmanship with reduced oversight by VDOT. The primary risks faced by VDOT through the use of performance specifications include: (1) disputes between VDOT and the contractor over deficient embankment performance during the warranty period; (2) the difficulty of repairing underlying embankments when finished roadway features, such as pavements, are already in place; and (3) the uncertainty that construction defects will be manifested in a measurable way during the finite term of the performance period.

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INTRODUCTION

Embankments and subgrades are compacted to produce strong, stiff, and stable support for pavements and structures. Without adequate compaction, pavements fail prematurely, structures have inadequate support, and embankments can experience slope failures. Therefore, it is very important that adequate compaction be achieved on Virginia Department of Transportation (VDOT) construction projects. This can be done through a combination of (1) appropriate specifications in construction contract documents and (2) effective quality assurance measures during construction.

The typical approach to specifying compaction of soils is to require that the relative compaction exceed a specified minimum and the compaction water content be within a specified range. Quality assurance during construction is typically achieved by a combination of visual observations and limited field testing. The visual observations include such things as the type of fill material being placed, the compaction moisture content of the fill, the thickness of lifts, the equipment used to perform compaction, operation of the compaction equipment, deformations (such as rutting and pumping) of the fill under construction equipment, and any special operations near structures, side slopes, and material transitions. When an experienced inspector makes continuous observations of satisfactory earthwork operations, VDOT can have confidence that the intent of embankment and subgrade design is being achieved. In this approach, which has proven to be reliable through decades of experience, the purposes of limited field testing are to calibrate the inspector's observations, provide documentation for the project record, and provide means to enforce proper embankment construction if observations indicate this is not being done.

Prevailing opinion is that field testing cannot replace observations by an experienced inspector. Even with a very high testing frequency, only a minute fraction of the fill is tested, and testing alone cannot reliably assure that the entire fill is adequate. In contrast, full-time or nearly full-time observations by an experienced inspector in combination with limited field testing can provide this assurance.

The problem that VDOT faces is that full-time observation of earthwork is no longer being done due to budgetary restrictions, loss of experienced inspectors, and competing demands on the remaining inspectors' time. Despite this change, the previous practices of relatively infrequent field testing are still being used. Several instances on recent projects of uneven pavement settlement, as well as embankment and cut slope failures, have raised the question among VDOT engineers whether VDOT is receiving the embankment quality that is specified in construction contracts.

For these reasons, Virginia Tech was requested to investigate various approaches for specifying compaction and effectively assuring quality. Initially, the focus was on performance specifications for compaction, and this approach remained part of the research as the project evolved. However, it was also decided mutually among the Virginia Transportation Research Council (VTRC), VDOT, and the researchers that additional approaches would be developed and evaluated to provide flexibility so that VDOT could select approaches that would be most suitable for particular construction projects.

PURPOSE AND SCOPE

The purpose of this research was to develop approaches for (1) specifying compaction of embankments and subgrades and (2) providing VDOT with assurance that compaction quality is being achieved. Specifications and quality assurance are related, and both items must be considered when developing new specifications. Specific objectives included the following:

- Develop a suite of approaches that may be applicable to different types and sizes of construction projects, considering VDOT's staffing limitations.
- Provide an example of the reliability calculations that would be required of a design-build team working under performance specifications.
- Assess the approaches based on information in the published literature and discussions with VDOT personnel, VTRC personnel, and outside experts on compaction and performance specifications.
- Make recommendations to VDOT for compaction specifications and quality assurance.

The scope of this research was limited to conducting a literature review, developing approaches for compaction specifications and quality assurance, performing reliability calculations, discussing the approaches with knowledgeable experts, assessing the approaches for their applicability to VDOT projects, and making recommendations considering the risks and benefits of the various approaches. This research is policy oriented, and a qualitative risk-benefit analysis is provided, but a quantitative cost-benefit analysis is not possible under the present state of knowledge.

The focus of this research was on contract specifications and quality assurance using existing commonly used technology. New developments in continuous compaction control and intelligent compaction, as well as stiffness measurements and other testing technologies, show promise for directly affecting the issues addressed by this research. These emerging technologies should be studied for their applicability to VDOT projects; however, such technologies are not included in the scope of this research project.

METHODS

Literature Review

The published literature was reviewed to gain an understanding of the current state of practice and ongoing research in the fields of construction specifications, compaction technology, and compaction quality control.

Published material was obtained from a wide range of sources including: research sponsored by state departments of transportation (DOTs) and the Federal Highway Administration (FHWA), academic publications, conference proceedings, and professional journals. Electronic queries were conducted using databases such as The Comprehensive Engineering Index (COMPENDEX), the Transportation Research Information Service (TRIS), the ASCE database, and individual agency websites, such as the U.S. Army Corps of Engineers.

Single page summaries were prepared for published materials of value to this project. A total of 48 summaries were provided to the project focus group in electronic form in December 2004. An electronic copy of these summaries is available upon request to the authors.

Project Focus Group Discussions

A project focus group consisting of VDOT and VTRC personnel was formed to provide guidance for this project. The focus group consisted of Gale M. Dickerson, Thomas E. Freeman, Stanley L. Hite, Edward J. Hoppe, David T. Lee, Jose P. Gomez III, and Thomas E. Pelnik III. A series of meetings were held on January 7 and 9, 2005 with focus group members and other VDOT and VTRC personnel. As background for these discussions, a document was prepared outlining preliminary approaches developed for specifying and verifying the quality of embankment compaction. The discussions provided insight regarding the current state of embankment construction practices and quality in Virginia, as well as useful comments that guided further development of the approaches and recommendations for implementation. A copy of the meeting notes is contained in Appendix A.

Another meeting with members of the focus group was held in Charlottesville on April 25, 2005, to discuss the near final version of the approaches that had been developed.

Survey of Expert Opinions

We conducted a survey of experts between February and April of 2005. Over this period, a document describing the approaches was sent via email to a selection of individuals from agencies, private engineering firms, contractors, and academics. From the 24 recipients of the interview document, there were 14 responses, which is a response rate of nearly 60%. The responders represented backgrounds in state DOT work, private design-side engineering, academic research, construction, materials engineering, and project quality control.

The survey details are presented in Appendix B, which includes the document sent to the survey candidates, the names and affiliations of the responders, and their responses. The responses in Appendix B have been edited to enhance readability and provide for anonymity of the responders.

Development of Approaches for Specifications and Quality Verification of Embankment Compaction

After collecting information from the literature search, it became apparent that the scope of this project should be expanded to consider a range of different approaches, rather than to solely consider performance specifications. Consequently, seven different approaches were developed, as listed in Table 1. Some of the approaches in Table 1 can be combined. For example, Approaches 5 and 6 could be applied to Approaches 2 and 3. All seven approaches were reviewed and discussed by the focus group and the experts that were surveyed. Based on this input, and on information from the literature search, the approaches were revised to produce the versions presented in the Results section of this report.

Table 1. Approaches for Specifications and Quality Verification of Embankment Compaction

Approach	Final Order in Results Section	Original Order in Appendices
Specifications based on embankment performance measurements	1	7
VDOT hires experienced inspectors	2	2
VDOT outsources inspection work	3	3
Construction contractor provides third party inspection	4	4
Significantly increase testing frequency	5	5
Establish pay factors for compaction quality	6	6
Status quo	7	1

Based on a recommendation from the focus group, the order of the seven approaches listed in the Results section differs from that used in the discussions with the focus group and the experts that were surveyed. In the appendices, the various documents are presented as originally developed, using the original ordering of approaches. To facilitate comparisons, the correspondence between the final order and the original order is given in Table 1.

As part of the development of Approach 1, reliability calculations have been performed for a hypothetical embankment using the “first-order, second moment” Taylor-series expansion, as described and illustrated by Duncan (2000). The reliability analyses are mentioned in the Results section, and the example calculations are presented in Appendix E.

RESULTS

The following sections present concepts and details for seven approaches to specify embankment compaction and provide a level of assurance to VDOT that compaction quality is achieved.

Approach 1: Specifications Based on Embankment Performance Measurements

Introduction

This approach is applicable to projects delivered under the design-build or the design-build-operate frameworks. Projects using design-bid-build construction are not suitable candidates for specifications based on performance measurements as presented herein. A primary reason for this lies in the lack of a cost effective way to determine beyond doubt whether substandard performance is attributable to actions of the contractor. Only when a single design-build entity is responsible for complete project delivery (design and construction) can VDOT hold that entity responsible for embankment performance. The following sections detail requirements for design, construction, post-construction monitoring over a performance period, and warrantees.

Design Requirements

Finished embankments, slopes, ground improvement, foundations, and structures shall be designed to satisfy criteria established in the areas of stability, slope erosion, settlement, and rideability. The designs shall be developed to satisfy the criteria over the facility’s design life, as specified by VDOT. The stability, slope erosion, settlement, and rideability criteria are presented in the following subsections.

Stability

Cut slopes and embankments should be stable. Evaluate stability for interim construction stages, for the end of construction condition, and for design-life conditions. VDOT may designate particular cut slopes and/or embankments as being critical with the potential to impact private development, VDOT structures, or especially important traffic corridors

The minimum factor of safety against failure shall be 1.3. The minimum factor of safety against failure for critical embankments and cut slopes shall be 1.5. Stability shall be determined by appropriate limit equilibrium methods.

The maximum probability of failure shall be 1%. For critical embankments and cut slopes, the maximum probability of failure shall be 0.5%. Example reliability calculations are shown in Appendix E.

Slope Erosion

Measures shall be designed to prevent erosion of cut slopes and embankment slopes using vegetative cover or armoring.

Settlement

Total and differential settlement shall be of a magnitude that will not result in damage to adjacent or underlying structures, including utilities, and will not interfere with surface drainage. In addition, the tolerances for total and differential settlement will by the lesser of AASHTO requirements or the requirements of the structural engineer, as approved by VDOT.

Rideablility

The riding surface should remain smooth, as defined in the Special Provision for Rideability included as Appendix C to this report. Rideability criteria include minimizing the “bump at the bridge." Rideability is measured with a South Dakota type road profiling device, except that a 10-ft straight edge is used at connections with bridge decks, approach slabs, other structures and adjoining traffic lanes and shoulders.

Design Submittal

The project delivery team shall submit its designs to VDOT for review. The submittal shall include results of field investigations, laboratory test results, design assumptions, description of analysis methods, results of analyses, and presentation of the overall design and the design details.

Construction Requirements

During construction, the contractor should adhere to VDOT’s Special Provision for Density Control of Embankments and Backfill included as Appendix D.

Post-Construction Monitoring of Embankment and Cut Slope Performance

The overall performance of an embankment is related to slope erosion, slope stability, ride quality, and differential settlement. The performance of cut slopes is related to slope erosion and slope stability. The following subsections establish the methods and tolerances that should be applied to assess embankment and cut slope performance.

Slope Erosion

Erosion on exposed slopes will be assessed by evaluating the depth and extent of erosion. The extent of the erosion will be determined by taking visual cross sections of the slope in the direction of slope dip. If evidence of erosion is present along the cross section, then that portion of the slope is considered eroded. Erosion is defined as loss of ground due to precipitation or runoff to a depth of 6 inches or more compared to the adjacent uneroded slope. A survey of the extent of slope erosion should consist of dividing the overall slope length into blocks of 100 feet. If the slope is less than 100 feet long, a single survey block can be used. The extent of slope erosion (E_e) will be determined as the percentage of the slope face considered to be eroded:

$$E_e(\%) = \frac{cummulative\ eroded\ length}{length\ of\ the\ survey\ block}$$

As an example, the value of E_c for the slope shown in the Figure 1 is (A+B+C)/L expressed as a percentage.

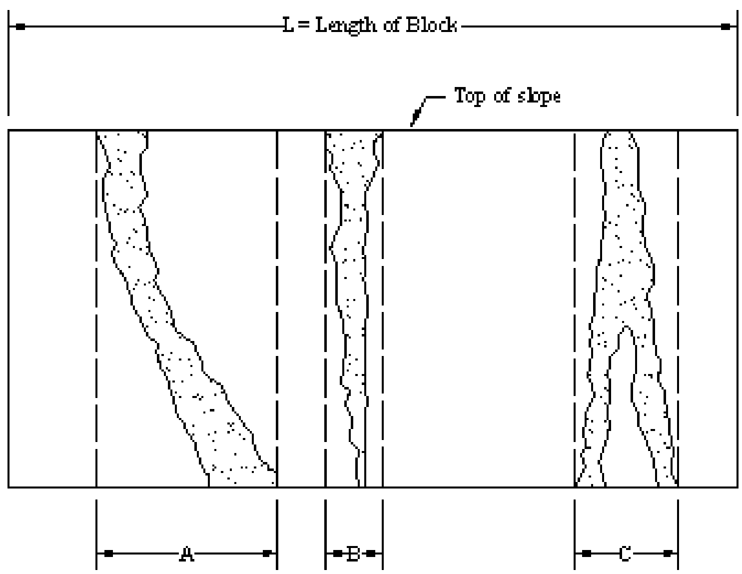

Figure 1. Example determination of extent of erosion

Tolerance for Erosion Extent: The maximum acceptable extent of erosion for a given survey block is E_e = 20%.

Tolerance for Erosion Severity: The maximum acceptable depth of any erosion channel present over a given survey block is 2 feet.

Post-Construction Slope Stability

The stability of the embankment will be evaluated by monitoring slopes for the presence of head scarps. Scarp formation at the top of slopes can be an indicator of the development of a failure surface within the slope.

Tolerance for Post-Construction Slope Stability: Head scarps with more than 3 inches of vertical displacement will be considered outside the range for acceptance.

Rideability

The Special Provision for Rideability is included as Appendix C. This provision replaces Section 315.07(a) of the 2002 VDOT Road and Bridge Specifications.

Tolerance for Rideability: The International Roughness Index (IRI) shall be measured in inches per mile for each 0.01-mile section for each travel lane of the surface course using the South Dakota type road-profiling device. Any section tested within 30 calendar days of completion with an IRI exceeding 70.0 inches per mile will be considered outside the range for acceptance. The maximum acceptable IRI for any section tested within 22 to 26 months of completion, or later, is 78.0 inches per mile. The beginning and end 0.01-mile sections of the surface course and tie-ins with bridges, approach slabs, other structures, and adjacent pavements and shoulders will not be subject to evaluation with the South Dakota type road-profiling device, and instead, a 10-foot straightedge will be used to measure the variation of the surface from the testing edge of the straightedge between any two contacts of the straightedge with the surface. The maximum tolerable gap between the straightedge and the surface is ¼ inch.

Differential Settlement

Much of the monitoring for differential settlement is covered by the rideability monitoring. However, on particular projects, there may be other types of differential settlement not covered by rideability, such as differential settlement of structures and drainage systems.

Tolerance for Differential Settlement: For structures, differential settlements greater than the design values will be considered outside the range for acceptance. For drainage systems, differential settlements greater than design values or sufficient to interfere with necessary drainage will be considered outside the range for acceptance.

Post-Construction Performance Assessment Frequency

Post-construction assessment of embankment performance will occur on the minimum basis presented in the following subsections.

Slope Erosion

Embankment slopes and cut slopes should be inspected for erosion and evaluated according to the procedure described herein during the months of April, August, and November during the first year following project completion and during the month of April during the remainder of the assessment period.

Post-Construction Stability

The embankment slopes should be inspected for the presence of head scarps concurrent with the assessment of erosion.

Rideability

Assessment of rideability should be in accordance with the Special Provision for Rideability. The provision calls for testing by the developer within 30 calendar days of completion of the final surface course over the designated section, again within 22 to 26 months after completion of the final surface course over the designated section, and again at the end of the performance period.

Differential Settlement

Structures and drainage systems should be inspected concurrent with the assessment of erosion.

Performance Assessment Period

Embankment performance will be monitored for a period following construction as specified in the contract between the design-build contractor and VDOT. A study by Stephens et al. (2002) surveyed states that have experience with warranty contracts for pavement construction or rehabilitation. They found that the length of the warranty period for these contracts ranged from 3 to 20 years, with the majority spanning from 3 to 7 years. As such, it is reasonable for VDOT to consider a default warranty period of three to five years following opening the roadway to traffic. During this time, the contractor is responsible for abiding by the minimum assessment frequency for each of the performance measurements. The contractor's assessment will be periodically verified by measurements taken by VDOT or an independent testing agency retained by VDOT.

Warranty

Should, during the assessment period, one or more performance measurements fall outside the prescribed tolerance, the contractor must take corrective action to restore the embankment and dependant structures (e.g., pavements, drainage systems, signs, guard rails, and other structures) to the original design criteria and specifications.

Following corrective action, the assessment period for previously deficient areas and items will restart and remain in place for the original prescribed duration.

Upon completion of the assessment period with all performance measures within allowable tolerances, the contractor is released from responsibility for the project performance unless it is determined that contractor failed to perform under the obligations of the contract.

Approach 2: VDOT Hires Experienced Inspectors

In this approach, VDOT hires additional experienced inspectors and applies its current system for enforcing embankment construction quality. By this means, shortages of qualified inspectors are eliminated, and this would allow for full-time or nearly full-time visual inspection of construction activities combined with an appropriate frequency of in-place density tests.

Approach 3: VDOT Outsources Inspection Work

Introduction

The objective of Approach 3 is to supplement VDOT's inspection work force through the use of qualified inspectors provided by a private engineering firm. A contract for inspection services will include specific requirements established by VDOT outlining the number, skill level, qualifications, and responsibilities necessary for the inspection forces to be retained. These items are discussed in the following subsections.

Bidding and Contracts

A firm not under debarment by VDOT and meeting the requirements for eligibility will be permitted to bid on proposed work in accordance with specifications contained in Section 102 of the 2002 VDOT Road and Bridge Specifications. Conditions for the award and execution of a contract will fall under Section 103 of the 2002 VDOT Road and Bridge Specifications.

Responsibilities of the Private Firm

The private engineering firm will be responsible for assembling, managing, and compensating the inspection forces. The task of assembling the inspection force includes hiring, training, and verifying qualifications.

The private engineering firm will be responsible for verifying the qualifications of the inspectors and their performance on the project site. Inspector performance standards will be enforced through oversight by the private engineering firm and through spot checks conducted by VDOT. An inspector found to be negligent or otherwise deficient by VDOT or the private engineering firm may be given a warning or turned over to a review panel composed of one representative of the private engineering firm and two of VDOT. The review panel has the authority to take binding disciplinary action against the inspector, including but not limited to, mandatory training, forced leave of absence, or termination from the project. The private engineering firm must replace inspectors who voluntarily quit or are removed by the project review panel.

Laboratory services, including reference tests, will be executed under the agreement between VDOT and the private engineering firm. The minimum laboratory testing frequency should consist of one laboratory compaction test, one gradation test, and one Atterberg Limits test (VTM-1, -7, -25) on the borrow material at least weekly, and whenever there is a material change.

The private engineering firm is responsible for providing sufficient communication with VDOT. Communication includes prompt notification of issues that arise on the project, attendance at meetings requested by VDOT, and timely correspondence via written or electronic means. The private engineering firm is to provide VDOT periodic reports summarizing daily inspection reports, field testing, and laboratory results. These reports should be reviewed by the private firm's supervising engineer prior to submission to VDOT.

Modification to the Scope of Work

VDOT may specify additional testing and/or observation services. Provision for the alteration of the scope of work is covered in Section 104.02 of the 2002 VDOT Road and Bridge Specifications. Alterations constituting a "significant change" as defined in the provision will be paid at the unit rates supplied by the private engineering firm at the time the contract was awarded.

Responsibility and Authority of the Supervising Engineer

The services rendered by the private engineering firm should be performed under the direction of a supervising engineer employed by the private engineering firm. The supervising engineer is responsible for reviewing documents and test results submitted to VDOT. The supervising engineer is also to serve as the point of contact for the contractor for project related matters. The supervising engineer has the authority to conduct and orchestrate inspection of the contractor's work according to Section 105.12 of the 2002 VDOT Road and Bridge Specifications. The supervising engineer is not authorized, without VDOT's approval, to accept work that does not conform to the project plans and specifications. The supervising engineer is also barred from making changes to the plans or specifications, make final acceptance of the project, approve any of the contractor's operations or items, or act as foreman for the contractor.

Responsibility and Authority of Inspectors

The authority and duties of the inspector are consistent with those of inspectors employed by VDOT covered under Section 105.11 of the 2002 VDOT Road and Bridge Specifications. Inspectors will be responsible for observing, testing, and documenting whether the contractor's activities are in accordance with the project plans and specifications for embankment construction established in Section 303.04 (h) of the 2002 VDOT Road and Bridge Specifications.

The private engineering firm is to supply an inspection force of sufficient size to ensure full-time visual inspection of embankment construction activities. The inspectors will maintain daily field reports documenting their observations while on site. The inspector's observations should encompass all aspects pertinent to construction of the embankment. These include, but are not limited to, the subgrade condition and preparation, the type of fill material being placed, the compaction moisture content of the fill, the thickness of lifts, the equipment used to perform compaction, operation of the compaction equipment, deformations (such as rutting and pumping) of the fill under construction equipment, and any special operations near structures, side slopes, and material transitions. If embankment construction is a separate pay item in the contract, the inspector will be responsible for maintaining a daily record of the volume of embankment production. The suitability of the fill material used for embankment construction will be verified by visual inspection and by providing samples for laboratory testing as needed. Placement and compaction of fill will be inspected by observation and periodic field testing. Field tests should consist of density testing using either nuclear or sand cone methods performed on a scheduled minimum frequency of one test per 2,500 cubic yards of fill placed. A minimum testing frequency of one test per 500 cubic yards should be applied for the upper 5 feet of the fill. Moisture testing will be performed on the same basis. Test locations should be determined randomly. Locations should be staggered, so that the entire length, width, and depth of the fill are covered by tests. The top, bottom, and middle of fills, and any necessary points in between, shall be tested. Additional non-random spot test locations to investigate questionable areas of the fill will be withheld from statistical analysis (if used) to reduce the influence of bias.

Qualifications of Supervising Engineer

The supervising engineer must be a licensed professional engineer registered in Virginia. This individual must also have a minimum of 3 years experience observing and/or supervising earthwork construction.

Inspector Qualifications

Inspection personnel furnished by the private engineering firm must meet the requirements established in the project contract. Unless explicitly stated in the contract, all inspectors must have successfully completed VDOT's Soil and Aggregate Compaction Certification Program. All certifications must be current. In addition to the certifications, a lead inspector, designated by the supervising engineer, should be present on the project site whenever inspection activities are being performed. The lead inspector should have at least two years of earthwork inspection experience. On projects that require only one inspector, the lead inspector shall perform the inspection activities.

Provision for Coordination and Cooperation on Projects Using VDOT Personnel

VDOT may, at any time, conduct concurrent construction inspection with its own personnel. The private engineering firm should not impede or limit access to such work performed by VDOT personnel. When inspection of embankment construction is covered by both VDOT and the private engineering firm, one of the following management hierarchies will be adhered to as established in the contract between VDOT and the private engineering firm:

Hierarchy A

The private engineering firm will retain responsibility for quality and scheduling of their inspectors. The private engineering firm and VDOT will establish a joint schedule of inspection operations.

Hierarchy B

The private engineering firm will retain responsibility for quality of their inspection force but relinquish control of coordination of the inspector's activities to VDOT's supervisor of project inspection.

Provision to Prevent Conflict of Interest

Appropriate transparency will be maintained in the relationship between VDOT project supervisors and the private engineering firm. The activities performed under the terms of the agreement are subject to internal audit by VDOT according to Section 103.07 (b) of the 2002 VDOT Road and Bridge Specifications and/or verification by a qualified independent firm retained by VDOT.

Approach 4: Contractor Provides Third Party Inspection Services

Introduction

The objective of Approach 4 is to supplement VDOT's inspection work force through the use of qualified inspectors provided by a private engineering firm retained by the contractor. A contract for inspection will include specific requirements established by VDOT outlining the number, skill level, qualifications, and responsibilities necessary for the inspection force to be provided. These items are discussed in the following subsections. This approach is very similar to Approach 3, but modified to account for the contractor retaining the private engineering firm.

Responsibilities of the Private Firm

The private engineering firm will be responsible for assembling, managing, and compensating the inspection forces. The task of assembling the inspection force includes hiring, training, and verifying qualifications.

The private engineering firm will be responsible for verifying the qualifications of the inspectors and their performance on the project site. Inspector performance standards will be enforced through routine oversight by the private engineering firm and through spot checks conducted by VDOT. An inspector found to be negligent or otherwise deficient by VDOT or the private engineering firm may be given a warning or turned over to a review panel composed of one representative of the private engineering firm and two of VDOT. The review panel has the authority to take disciplinary action against the inspector, including but not limited to, mandatory training, forced leave of absence, or termination from the project. The private engineering firm must replace inspectors who voluntarily quit or are removed by the project review panel.

Laboratory services, including reference tests, will be included in the agreement between the contractor and the private engineering firm. The minimum laboratory testing frequency should consist of one laboratory compaction test, one gradation test, and one Atterberg Limits test (VTM-1, -7, -25) on the borrow material at least weekly, and whenever there is a material change.

The private engineering firm is responsible for providing sufficient communication with VDOT. Communication includes prompt notification of issues that arise on the project, attendance at meetings requested by VDOT, and timely correspondence via written or electronic means. The private engineering firm is to provide VDOT periodic reports summarizing daily inspection reports, field testing, and laboratory results. These reports should be reviewed by the private firm's supervising engineer prior to submission to VDOT.

Modification to the Scope of Work

VDOT may specify additional testing and/or observation services. Provision for the alteration of the scope of work is covered in Section 104.02 of the 2002 VDOT Road and Bridge Specifications. Alterations constituting a "significant change" as defined in the provision will be paid at the unit rates supplied by the private engineering firm at the time the contract was awarded.

Responsibility and Authority of the Supervising Engineer

The services rendered by the private engineering firm should be performed under the direction of a supervising engineer employed by the private engineering firm. The supervising engineer is responsible for reviewing documents and test results submitted to VDOT. The supervising engineer has the authority to conduct and orchestrate inspection of the contractor's work according to Section 105.12 of the 2002 VDOT Road and Bridge Specifications. The supervising engineer is not authorized, without VDOT's approval, to accept work that does not conform to the project plans and specifications. The supervising engineer is also barred from making changes to the plans or specifications, make final acceptance of the project, approve any of the contractor's operations or items, or act as foreman for the contractor.

Responsibility and Authority of Inspectors

The authority and duties of the inspector are consistent with those of inspectors employed by VDOT covered under Section 105.11 of the 2002 VDOT Road and Bridge Specifications. Inspectors will be responsible for observing, testing, and documenting whether the contractor's activities are in accordance with the project plans and specifications for embankment construction established in Section 303.04 (h) of the 2002 VDOT Road and Bridge Specifications.

The private engineering firm is to supply an inspection force of sufficient size to ensure full-time visual inspection of embankment construction activities. The inspectors will maintain daily field reports documenting their observations while on site. The inspector's observations should encompass all aspects pertinent to construction of the embankment. These include, but are not limited to, the subgrade condition and preparation, the type of fill material being placed, its compaction moisture content of the fill, the thickness of lifts, the equipment used to perform compaction, operation of the compaction equipment, deformations (such as rutting and pumping) of the fill under construction equipment, and any special operations near structures, side slopes, and material transitions. If embankment construction is a separate pay item in the contract, the inspector will be responsible for maintaining a daily record of the volume of embankment production. The suitability of the fill material used for embankment construction will be verified by visual inspection and by providing samples for laboratory testing as needed. Placement and compaction of fill will be inspected by observation and periodic field testing. Field tests should consist of density testing using either nuclear or sand cone methods performed on a scheduled minimum frequency of one test per 2,500 cubic yards of fill placed. A minimum testing frequency of one test per 500 cubic yards should be followed for the upper 5 feet of the fill. Moisture testing will be performed on the same basis. Test locations should be determined randomly. Locations should be staggered, so that the entire length, width, and depth of the fill are covered by tests. The top, bottom, and middle of fills, and any necessary points in between, shall be tested. Additional non-random spot test locations to investigate questionable areas of the fill will be withheld from statistical analysis (if used) to reduce the influence of bias.

Qualifications of Supervising Engineer

The supervising engineer must be a licensed professional engineer registered in Virginia. This individual must also have a minimum of 3 years experience observing and/or supervising earthwork construction.

Inspector Qualifications

Inspection personnel furnished by the private engineering firm must meet the requirements established in the project contract. Unless explicitly stated in the contract, all inspectors must have successfully completed VDOT's Soil and Aggregate Compaction Certification Program. All certifications must be current. In addition to the certifications, a lead inspector, designated by the supervising engineer, should be present on the project site whenever inspection activities are being performed. The lead inspector should have at least two years of earthwork inspection experience. On projects that require only one inspector, the lead inspector shall perform inspection activities.

Provision for Coordination and Cooperation on Projects Using VDOT Personnel

On projects where portions of the construction are overseen by VDOT personnel, VDOT will retain responsibility for their own inspection force. Third party inspection personnel provided by the contractor will be under the control of contractor and private engineering firm. Neither the contractor nor the private engineering firm should impede or limit access by VDOT personnel.

Provision to Prevent Conflict of Interest

At any point in the bidding phase or contract, VDOT has the authority to audit the contractor as granted in Section 103.07 of the 2002 VDOT Road and Bridge Specifications. All bidders must include as part of their proposal a list of resumes for all involved field staff, engineers, and laboratory staff. The private engineering firms are responsible for regular maintenance of all records. VDOT may challenge or reject any bidder that it feels is either unqualified or whose objectivity has come into question. An objective private engineering firm is one without financial obligation to the contractor, other than under terms of a formal contract, and without familial links (direct or by law) between the key members of the private engineering firm and the contractor. Key members on the part of the private engineering firm include the supervising engineer, lead inspector, and those otherwise involved managing the contract or reviewing the work performed. On the part of the contractor, key members include all management and foremen involved in the particular project. Bidders may retract their bids at any time with no penalty or prejudice on the part of VDOT. Contractors are obligated to provide assurance that there is no overlap of their staff between those responsible for production and those responsible for oversight of the third party inspection forces. Following award of the inspection contract, appropriate transparency will be maintained in the relationship between the contractor and the private engineering firm. The activities performed by the private engineering firm under the terms of the agreement are subject to audit by VDOT and/or verification by a qualified independent firm retained by VDOT. Transparency is defined as full disclosure of all documents and records as defined in Section 103.07 (b) of the 2002 VDOT Road and Bridge Specifications.

Provision for Inspection and Testing by VDOT

Testing and inspection will be performed by VDOT. VDOT reserves the right of full access to all test results and daily inspection reports. Statistical methods may be used to address discrepancies between test data generated by the private engineering firm's inspectors and VDOT personnel. VDOT has the right to challenge and investigate suspect discrepancies. Discrepancies found to be the result of negligent or deceitful actions of the part of the contractor or the private engineering firm will be subject to disciplinary and/or legal action.

Approach 5: Significantly Increase Testing Frequency

An increase in the specified minimum field density and compaction moisture content testing frequency will produce more quantitative data than is generated using the currently applied testing frequency. Conceptually, this approach aims to improve construction quality by engaging the inspector more fully with the earthwork operation through the act of conducting more field density tests. In addition, the increased volume of data produced by these tests will provide the opportunity for more rigorous remote monitoring of compaction quality by VDOT engineers.

This approach was developed by revising the existing Section 314 prescribing field testing frequencies in VDOT's Manual of Instructions, which was prepared by the Materials

Division in March 2004. The revisions include significantly increasing the frequency of field tests for various locations within the fill, as well as the frequency of tests performed at the finished subgrade elevation. In addition, approval by the district materials engineer is required for waiver of compaction tests on special projects.

The focus group recommended that the minimum number of field density tests required will be one for each 2,500 cubic yards of embankment fill. It is recognized that this interval still far exceeds generally accepted norms for fill construction in the commercial sector. For the upper 5 feet of embankment fill, the recommended minimum frequency is one test per 500 cubic yards, which is closer to the rates often used in the private sector. The inspector may perform additional tests as necessary to confirm suitable compaction and to investigate areas of questionable compaction.

In the finished pavement subgrade in both cut and fill sections, the new minimum number of field density tests will be one test for each 10,000 square feet of subgrade. For the purposes of this subgrade testing, the subgrade area is defined as the full road width, including the shoulders, plus an additional 2 feet beyond the shoulders. Subgrade compaction and testing to 2 feet beyond the shoulders is necessary to ensure that full support is provided for the entire road and shoulders. The density test locations should be staggered to cover the entire subgrade area, including the road, shoulders, and the portion extending 2 feet beyond the shoulders.

A revised version of Section 314 of VDOT's Manual of Instructions is presented in Appendix F.

Approach 6: Establish Pay Factors for Compaction Quality

Introduction

This approach is structured around payment of a bonus as an incentive for good construction quality and imposition of a financial penalty as a disincentive for poor construction quality. The bonus or penalty would be imposed at the end of the project, after the volume of the completed embankment has been surveyed. The dollar value would equal the product of (1) the bonus or penalty percentage, (2) the unit bit price for embankment, and (3) the surveyed embankment volume.

The use of financial incentives provides VDOT with means to encourage the contractor to perform work that meets or exceeds the project specifications by linking construction quality to payment. VDOT can also track contractor performance over time by looking at records of bonus or penalty percentages.

Determination of the Bonus or Penalty Percentage

The bonus or penalty percentage is determined by using data from field density tests. The minimum frequency of density testing is one test per 2,500 cubic yards of material placed below the upper 5 feet of fill. Within the upper 5 feet of fill, the minimum testing frequency is one test per 500 cubic yards. Test locations should be determined randomly. Locations should be staggered, so that the entire length, width, and depth of the fill are covered by tests. The top, bottom, and middle of fills, and any necessary points in between, shall be tested. Additional spot test locations to investigate questionable areas of the fill will be withheld from computing the bonus or penalty percentage.

The bonus or penalty percentage associated with each density test is determined from Figure 2. For each density test, the relative compaction is calculated with respect to the maximum dry density determined according to VMT-1. For tests performed on embankment below the finished subgrade, Figure 2 shows that relative compactions of 92%, 95%, and 100% correspond to bonus or penalty percentages of -6%, 0%, and 5%, respectively. For tests performed on the finished subgrade, Figure 2 shows that relative compactions of 97%, 100%, and 105% correspond to bonus or penalty percentages of -6%, 0%, and 5%, respectively.

Density tests with relative compaction below 92% for embankment below the finished subgrade and below 97% for the subgrade are considered unacceptable. The contractor must rework the entire tributary area associated with each failing test until subsequent density tests show relative compaction values greater than or equal to 92% for embankment below finished subgrade and greater than or equal to 97% for the subgrade.

The final test results for successfully reworked areas, and not the earlier failed test results, will be used to determine the bonus or penalty percentage. Similarly, if the contractor voluntarily chooses to rework areas with low but passing test results, the reworked area will be retested, and the latest test results for that area will be used to determine the bonus or penalty percentage.

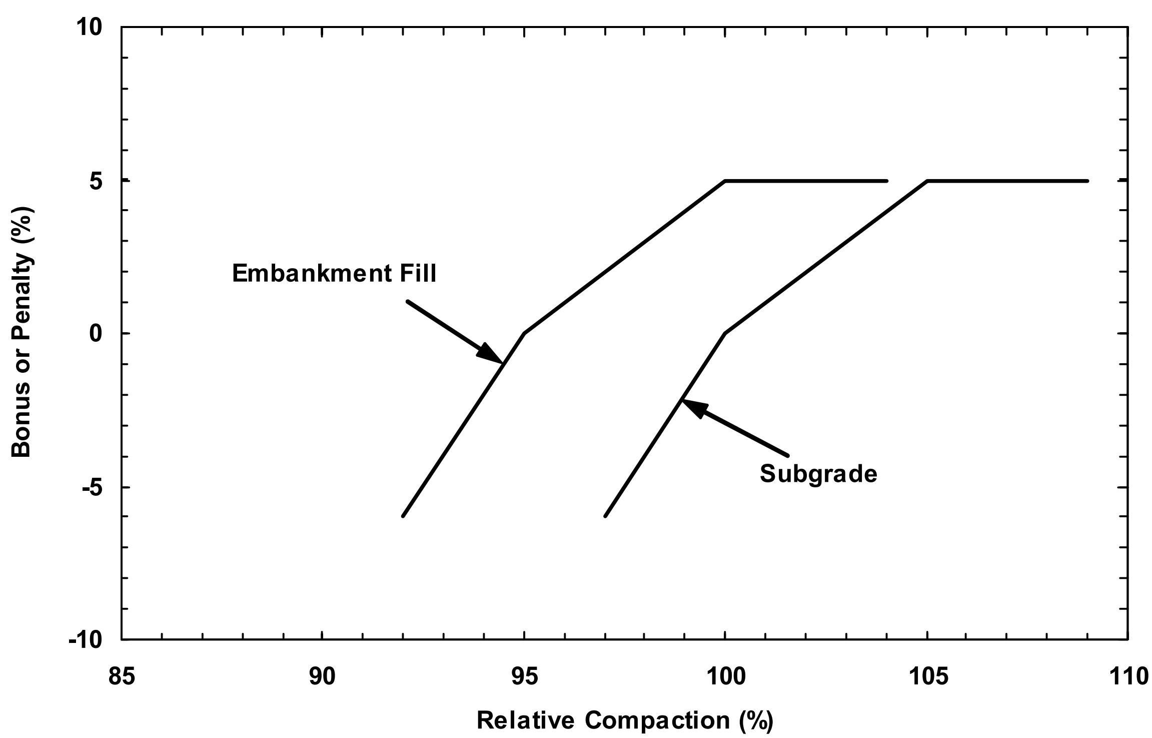

Figure 2. Bonus or Penalty versus Relative Compaction

The overall final bonus or penalty percentage is determined as the average of all the individual bonus or penalty percentages associated with the individual density tests. The following table shows an example calculation of the bonus percentage for a 21,000 cubic yard embankment with a unit price of $7 per cubic yard.

Table 2. Example Calculation of Final Bonus or Penalty Percentage

Relative Compaction (%)	Test Location	Bonus/Penalty (%)
97.6	Embankment	2.6
95.5	Embankment	0.5
101.2	Embankment	5.0
98.0	Embankment	3.0
97.4	Embankment	2.4
94.7	Embankment	-0.6
98.4	Embankment	3.4
96.3	Embankment	1.3
93.9	Embankment	-2.2
99.6	Embankment	4.6
100.5	Embankment	5.0
98.4	Embankment	3.4
95.1	Embankment	0.1
97.2	Embankment	2.2
101.7	Subgrade	1.7
100.8	Subgrade	0.8
102.9	Subgrade	2.9
99.2	Subgrade	-1.6
103.1	Subgrade	3.1
	Average	1.98

The resulting bonus is (0.0198)(21,000 yd^3)(7 $/$yd^3$) = $2,910.

Approach 7: Status Quo

This approach represents existing VDOT practices, and it is included here as a baseline for comparison with the other approaches described above. There is no mandate for VDOT to modify its current methods for specifying embankment fill compaction and verifying construction quality. VDOT's existing practices may be the most appropriate for certain projects.

DISCUSSION

The following subsections provide discussion of the applications, benefits, and risks of the seven approaches described in the Results section.

Approach 1: Specifications Based on Embankment Performance Measurements

Application

The use of performance measurements as a basis for embankment construction specifications would be applicable to the design-build mode of project delivery and its variants (e.g., design-build-maintain), and not to design-bid-build projects. This requirement stems from the degree of uncertainty that exists for construction of embankments composed of variable earth materials and founded on variable earth materials. As such, it is difficult, if not impossible, to determine beyond reasonable doubt that substandard performance of an embankment can be attributed to actions of the contractor and not the embankment designer. Thus, attempting to base specifications on performance for a design-bid-build project has the potential to create disputes that would be difficult, if not impossible, to resolve. An example of this would be if a particular embankment was suffering from inadequate surface drainage during heavy storms. This problem may be the result of design phase flaws such as an improperly designed drainage system or an error in the grading plan. The same problem could also be attributed to lapses in construction quality such as mistakes in the installation of the drainage system, poor grading, or excessive differential settlement of the embankment. A sufficient investment of time and money may be able to isolate the cause of the drainage problem to one or two of the factors listed above. However, if it is determined that embankment settlement is responsible for the problem, then an entirely new round of investigation would be needed to determine whether the settlement is related to design or construction. Design-build construction places the entire package of factors that are feasible to control into the hands of a single entity, thus eliminating the need to resolve disputes about the source of the settlement. Accordingly, if contract specifications place the responsibility for performance of the embankment on the contractor, it is essential that the contractor have control of the design decisions relating to foundation support, subgrade preparation, fill material selection, compaction requirements, and embankment geometry, although it is reasonable for the design to be subject to VDOT review.

Limiting the application of performance based specifications to design-build projects has some consequences. Firms capable of performing design-build work require significant physical, technical, and financial resources. The inclusion of a warranty period in the framework of this approach further raises the scale of firm needed to be a viable bidder. The high level of resources necessary for design-build work and its inherent risk would likely shut out many smaller firms. Reducing the pool of potential bidders could result in an increase in bid prices due to decreased competition. In consideration of these factors, the use performance specifications are more applicable to larger projects where design-build firms already have established positions in competitive markets.

Perceived Benefits

This approach is a significant deviation from the methods more commonly used by VDOT to enforce construction quality of embankments. The usage of this approach shifts a large portion of the overall project liability to the design-build contractor. This shift is advantageous from the standpoint of VDOT because it alleviates some degree of post-construction financial risk. Deficient performance of the embankment over the course of the performance period becomes the responsibility of the contractor. Depending on the structure of the construction warranty, VDOT may also be partially or fully relieved of maintenance costs while the embankment is under the contractor's care. If the contractor performs maintenance in a preventative mode, as opposed to simply getting the roadway through the warranty period, such maintenance could prolong the life of the roadway in a very cost-effective manner (Stephens et al., 2002).

The pressure of being responsible for embankment performance over the warranty period motivates the contractor to adhere to a high level of construction quality. Contractor initiated quality control would have the effect of less oversight required on the part of VDOT. In this way, performance specifications have the potential to reduce the amount of labor needed by VDOT during the construction phase of the project.

A prevailing view among supporters of performance based specifications expressed during the survey of experts conducted for this project and found in published sources is that performance specifications promote innovation and increased construction efficiency. The basis for this assertion is the increased freedom in the construction process granted to the contractor by use of such specifications (Pidwerbesky, 2003). In this way, performance specifications represent the antithesis of highly prescriptive, method-style specifications. Survey respondents mentioned that emerging quality control technologies, such as intelligent compaction and continuous compaction control, could meld nicely with a contractor's wishes to efficiently assess construction quality. A study by Stephens et al. (2002) suggested that the added cost of the warranty in the construction contract is sometimes overtaken by the reduction in construction costs due to more efficient practices. Wisconsin has reported net savings in paving costs and increased roadway performance using warranty contracts. Ohio has seen increased initial project costs using warranty contracting, however they expect these costs to be offset by reductions in long-term maintenance.

Potential Risks

The clearest risk to VDOT is an unwillingness or inability of the contractor to fulfill the conditions of the warranty, should an embankment be deemed unacceptable (Pidwerbesky, 2003). Disputes between VDOT and the contractor will likely consume considerable engineering time as well as legal effort. Building evidence for a case may require extensive geotechnical exploration, testing, and analysis. The process of dispute resolution can be guided by legal considerations that may stray from the best engineering, financial, environmental, and safety considerations. As a result, the outcome of legal dispute resolution processes may not be in the best interest of VDOT or the Commonwealth. This risk can be mitigated through a good relationship between VDOT and the contractor regarding the requirement of the contract and clear specification of performance criteria (Pidwerbesky, 2003). Furthermore, it is necessary for some mechanism to be included in the construction contract to guarantee the contractor's work during the performance period. Stephens et al. (2002) suggests either withholding a portion of the project costs until the warranty period ends, or requiring the contractor to purchase a warranty bond.

Another risk of this approach is the finite term of the warranty. Many construction defects require a triggering event to manifest the deficiency as physical damage to the embankment. The occurrence of triggering events, such as major storms or earthquakes, is essentially left to chance. It is possible that a contractor would engage in substandard construction activity based on a suspected low probability that the effects of the activity will manifest during the relatively short duration of the performance period.

The function of embankments as a roadway foundation inextricably links their performance to the overlying systems. Remediation of a deficient embankment, by either the contractor or VDOT, may require invasive demolition of otherwise functional roadway elements such as pavements to access the root of the problem. This aspect not only greatly increases repair costs but also can result in the loss of service of the roadway. The indirect costs absorbed by the public for loss of service may exceed the original construction cost of the embankment.

The use of performance specifications in transportation construction is a relatively new approach in this country. Application of the approach has been focused on types of construction with a relatively high degree of process control, such as pavements. Pavement construction has less uncertainty in material specification and product quality than earthwork. Furthermore, deficient pavements are often easily diagnosed and can be remedied without major demolition. Adoption of performance based specifications for embankment construction of VDOT projects is essentially navigating uncharted waters. The lack of an experience base contributes to the overall risk of using performance-based specifications.

Approach 2: VDOT Hires More Inspectors

Application

As described previously, the idea here is that VDOT would hire enough experienced inspectors to provide full-time or nearly full-time observation of embankment construction. This approach would be applicable to design-bid-build projects and to agency verification for design-build projects. This approach would be applicable to both large and small projects. VDOT's existing methods of specifying embankment compaction and verifying construction quality would be applicable to this approach, although the authors of this report feel this approach should be coupled with an increased testing frequency.

This approach is contingent on VDOT's fiscal constraints and ability to attraction a sufficient number of qualified job applicants. VDOT personnel have indicated that this is very unlikely.

Perceived Benefits

A principal benefit of this approach is that it has been used reliably for many years to provide assurance of embankment construction quality. In this approach, VDOT retains complete control of the construction inspection process using procedures that are already well established and understood by VDOT and construction contractors.

One of the outside experts that we contacted suggested that VDOT establish a mechanism whereby retired inspectors from the public or private sector could be hired part-time by VDOT. Maintenance of full training and certification of qualifications would be required of the part-time inspectors. The use of retired inspectors on a part-time basis could yield at least three benefits to VDOT. First, the approach provides additional experienced inspectors without some of the non-salary costs of hiring full-time personnel. Second, the use of inspectors with many years of experience provides a good opportunity for mentoring of less experienced VDOT inspectors. Third, this approach allows for flexibility to adjust staff levels to match seasonal fluctuations in earthwork construction activity. An important obstacle to hiring retired inspectors is that the private sector exerts a strong demand for experienced construction inspectors, which reduces the feasibility of this approach.

Potential Risks

The risks posed by this approach are those faced by VDOT any time there is a downturn in transportation construction. Logistically, it is very difficult to regulate the supply of full-time inspectors to the demand of construction. The lag time in response to fluctuations in demand leave inspectors either over or underutilized. If VDOT relies too heavily on layoffs to cap the size of its inspection force during times of low demand, it will become increasingly difficult to attract highly qualified candidates seeking job security.

Approach 3: VDOT Outsources Inspection Work

Application

This approach would be applicable to design-bid-build projects and to agency verification for design-build projects. This approach would be applicable to both large and small projects, although the contract administration time required to retain the services of an outside firm may make this approach less desirable for very small projects. VDOT's existing methods of specifying embankment compaction and verifying construction quality would be applicable to this approach, although the authors of this report feel this approach should be coupled with an increased testing frequency.

Perceived Benefits

This approach solves the problem of VDOT's inability to hire a sufficient number of inspectors to provide full time or nearly full time visual inspection of earthwork construction. VDOT can apply this approach as needed, and thereby adjust the level of inspection forces to satisfy construction demand. This solves the problem of staff utilization that would be created by Approach 2. In addition, VDOT will not need to own and maintain as many work vehicles or as much test equipment.

Potential Risks

The risk of substandard inspection due to low quality inspectors provided by a private engineering firm can be mitigated by strict qualification requirements for the outside inspection team and supervising engineer. Firms looking to build a working relationship with VDOT will be motivated to meet or exceed project requirements for inspection. This is, however, only true if VDOT engages in selection of engineering firms in a way that does not foster an atmosphere conducive to “low-ball” bidders.

Another potential pitfall of this approach is that there may be little appreciable savings to VDOT for outsourcing inspection work. The markup in labor rates charged by the private engineering firm, assurance testing by VDOT, and the cost of administering the contract with the outside party could result in higher overall costs for VDOT than if inspection was performed in-house. One survey respondent mentioned that California has had some experience with this approach and that the total costs were higher than when using state employees for inspection.

As with any third party oversight, there is some risk that the objectivity of the independent private engineering firm can be compromised. The firm’s aforementioned desire to build a working relationship with VDOT, which is interested in fair assessment of construction quality, should reduce any potential for bias.

Approach 4: Contractor Provides Third Party Inspection Services

Application

This approach would be applicable to design-bid-build projects and to design-build projects. This approach would be applicable to both large and small projects, although the added contract complexity may make this approach less desirable for very small projects. VDOT’s existing methods of specifying embankment compaction and verifying construction quality would be applicable to this approach, although the authors of this report feel this approach should be coupled with an increased testing frequency.

Perceived Benefits

The use of this approach provides benefits to VDOT that are similar to those of Approach 3 with one addition. Holding the contractor responsible for payment of the services provided by the private engineering firm adds an additional level of self-interest to perform work in a manner that doesn’t require extra inspection time. If the contractor frequently needs to rework compacted lifts, there will be an increased amount of oversight needed before acceptance is achieved. This arrangement also places more burden on the contractor to troubleshoot problems without unnecessary input from VDOT personnel.

Iowa and West Virginia have some experience with contractor quality control (CQC) programs verified by quality assurance testing by DOT personnel. The U.S. Army Corps of Engineers has also used a similar approach for the past twenty years on its projects. The results of the Corps experience have been mixed. The method has worked adequately for military type construction, but it has not worked as well on civil earthwork projects. One survey responder mentioned that there is no difference in outcome if the contractor is performing quality control testing with internal forces or using an independent third party.

Potential Risks

The prevailing opinion of the survey responders was that this approach is putting "the proverbial fox in the chicken coop." Some of the strongest opinions were expressed in opposition to this approach. One responder felt that objectivity cannot be obtained as long as the contractor holds "the power of the purse" over the inspectors. The potential for conflict of interest for this approach in unarguably greater than for Approach 3. VDOT has only limited means by which to investigate and monitor the relationship between the contractor and the private engineering firm for lapses in objectivity. Bias would likely be very subtle and not involve a paper trail that VDOT could use to prove its existence. A conflict of interest may simply be the engineering firm's desire to maintain working relationships with local contractors.

Approach 5: Significantly Increase Testing Frequency

Application

This approach would be applicable to design-bid-build projects and to design-build projects, and it would be applicable to both large and small projects. This approach is limited only by the time available for inspectors to perform the increased number of tests. For projects with full-time inspection, the test frequency is still low enough that additional inspectors would not be needed, but for projects with only part-time inspection, the additional testing may require an overall larger inspection work force. This approach could be applied to Approaches 2 through 4, and even more frequent testing is already incorporated in Approach 1.

Perceived Benefits

Benefits of this approach are that an increased testing frequency will promote vigilant visual observation by the inspector, provide the contractor with the understanding that construction operations are being closely monitored, and provide quantitative data for remote evaluation of construction quality. In addition, an increased number of tests will improve the degree to which meaningful statistical conclusions can be drawn from the data.

Potential Risks

As one survey responder put it, it is easy to "fall in love" with test results. At first glance, nothing appears more definitive than quantitative data. If fill placement moisture contents are within tolerance and relative compaction is meeting or exceeding the specification, then it is tempting to believe that the construction is satisfactory. However, experienced engineers know that, even with very high testing frequency, a miniscule portion of the overall volume of fill will be tested. Furthermore, density and compaction moisture content testing do not answer the important questions of lift thickness and whether the fill material has the necessary index properties, gradation, and quality. For this reason, there was overwhelming emphasis from the survey respondents that there is "just no substitute for a good set of eyes connected to a calibrated brain."

Reliance on this approach to assess compaction quality is also subjected to sampling and testing error as well as the inherent variability of the laboratory Proctor Test and the field nuclear density test. For example, sampling locations can unintentionally be selected in a way that induces bias into the data set. Such bias can occur if an inspector selects test locations only in suspected problem locations or if the contractor can anticipate the time and locations of the testing. Testing error may occur if the inspector mistakenly uses the wrong laboratory compaction reference test or improperly performs the test.

Studies by Torrey and Donaghe (1991) and Houston and Walsh (1993) have demonstrated that testing variability induced by the methods used to assess compaction moisture content and density both in the lab and the field can be significant (Walsh et al., 1997). One survey responder highlighted the AASHTO tolerances for testing variability. AASHTO T-99 prescribes a maximum single operator repeatability using the same laboratory equipment of ±10 percent optimum moisture and 2.2 pounds per cubic foot density. Between different operators and laboratories, the prescribed allowed repeatability is ±15 percent optimum moisture and 4.5 pounds per cubic foot maximum density. Measurement of in-place density and moisture content are associated with comparable uncertainty. Based on AASHTO method T310 (nuclear method), acceptable single operator spread for two measurements is ±1.0 to 1.3 pcf and double that for multiple operators. For water content, acceptable spread can add an additional 1 to 2 pcf uncertainty. With this type of uncertainty in the reference Standard Proctor and in-place density measurements, calculated percent of maximum density is not as reliable an indicator of compaction quality as it might at first appear. For this reason, engineers who are experienced with embankment construction understand the importance of visual observations, and they use density tests as a supplement to their observations and to provide necessary data for enforcement and acceptance.

Approach 6: Establish Pay Factors for Compaction Quality

Application

This approach would be applicable to both mid-size and large design-bid-build projects where embankment is a separate pay item in the contract. This approach would not be suited to small projects because there would not be enough data to reasonably apply the method and the cost factors would not warrant the effort. This approach could be applied to Approaches 2 through 4. The increased testing frequency of Approach 5 is necessary to generate the data required of this approach.

Perceived Benefits

Conceptually, the objective of this approach is to motivate the contractor to maintain a consistent high level of construction quality by linking relative density of the fill to payment. The desired outcome for VDOT would be that a contractor, motivated by financial self-interest, would construct a high quality embankment with less oversight.

Based on the maximum bonus or penalty percentages, VDOT could potentially be required to pay an additional five percent above the contract value for embankment construction. This added up-front cost might result in lower long-term maintenance costs if the embankment is significantly higher than average quality. In the same way, there is the possibility that VDOT will save up to 5% on the up-front cost of embankment construction if the contractor delivers marginal compaction quality. This extra money can be applied to offset the maintenance costs of the embankment, which may be higher due to a lower than average quality of construction.

Potential Risks

This approach may generate conflict between the contractor and VDOT. Currently, no conflict arises for the test results within the allowable range. However, if the results of every test have an influence on the contractor's pay, then it is realistic to imagine that the contractor may dispute every test, and an adversarial relationship could develop between testing personnel and the contractor. Weed (1984) suggested that the use of continuously variable pay factors, as applied in Approach 6, is preferable to a system of incremental stepped pay scales because their use reduces the potential for conflict by eliminating the instance where test results are close to an interval boundary. This approach is also limited by the accuracy and precision of density tests. This limitation could lead to further conflicts.

Basing compaction quality on the value of relative compaction obtained from a series of field density tests is not a complete assessment of the contractors actions. This method provides no pressure to limit lift thickness, verify that the fill material is within the specification, or that compaction water content is appropriate. Thus, other procedures, such as visual inspections and water content specifications, will have to be applied

It is expected that this method will increase administration costs, but not by much because the record keeping and calculations are relatively simple.

Approach 7: Status Quo

VDOT's guidelines for embankment construction mention in-place density testing at a frequency as low as one test per 10,000 yd^3 of embankment. When these guidelines were developed, testing was accompanied by full-time or nearly full-time observation by experienced earthwork inspectors. Now, due to retirements and fiscal constraints, full-time observation by experienced inspectors is not occurring, yet the in-place density testing frequency is still low. The result has been several instances of embankments with slope stability problems and overlying pavements with low ride quality. For these reasons, VDOT engineers believe that the status-quo is not acceptable.

According to the focus group, another current procedure that is not working is “phased inspection,” in which the inspector is free to choose which construction activities to inspect. An undesirable outcome of phased inspection is that earthwork inspection tends to be left out in this process.

CONCLUSIONS

Approach 1: Specifications Based on Embankment Performance Measurements

- The use of performance based specifications permits greater innovation on the part of the contractor while shifting more of the overall project risk to the contractor.
- A desired outcome of this approach is to motivate the contractor to deliver a high quality product with reduced oversight by VDOT.
- This approach is suited to larger projects delivered using the design-build framework.
- Smaller construction companies may not be able to mobilize the necessary expertise, equipment, personnel, and financing to be competitive on such work.
- The use of post-construction warranties provides VDOT a period within which to assess performance of the embankment and require the contractor to take corrective action on deficiencies. The benefit of the warranty is limited by uncertainty that construction defects will be manifested in a measurable way during the finite term of the warranty.
- VDOT faces two major issues with respect to correcting deficiencies: (1) the potential for costly and time consuming dispute resolution and (2) the difficulty of repairing underlying embankments when finished roadway features, such as pavements, are already in place.

Approach 2: VDOT Hires Experienced Inspectors

- VDOT is familiar with this approach and has had many years of success with it.
- The consensus of survey respondents is that full time visual inspection of earthwork construction by experienced inspectors provides the highest level of assurance that VDOT is receiving the intended end product.
- The likelihood of VDOT applying this approach is small because of fiscal and policy constraints.

Approach 3: VDOT Outsources Inspection Work

- This approach alleviates the shortage of inspection personnel on VDOT projects. Use of inspectors provided by private engineering firms provides VDOT with the ability to quickly adapt to changing construction demands.

- There is some evidence that this approach would not reduce VDOT's overall costs compared to hiring its own inspectors.

Approach 4: Contractor Provides Third Party Inspection Services

- As with Approach 3, this approach also alleviates the shortage of inspection personnel on VDOT projects.

- This approach has an inherent potential for conflict of interest because the contractor is paying for the engineering services that determine acceptance of payment for construction work.

Approach 5: Significantly Increase Testing Frequency

- The existing field testing frequency specified in VDOT's Manual of Instructions is far below that used in private practice. It is expected that an increased testing frequency would motivate the contractor to improve construction quality.

- Increased testing frequency should not be considered as a replacement for observations by an experienced earthwork inspector. It is unreasonable to rely solely on test results for oversight of embankment construction.

Approach 6: Establish Pay Factors for Compaction Quality

- This approach motives the contractor to achieve compaction quality by linking the degree of compaction tested in the field with VDOT's payment for embankment construction.

- Application of this approach requires a frequency of field testing significantly higher than what is currently in place.

- A shortcoming of this approach is that it increases the potential for disputes between the contractor and VDOT because every test has the potential to influence the contractor's pay.

Approach 7: Status Quo

- The current system used by VDOT to provide assurance of construction quality is not as effective today as when there was full-time or nearly full-time visual inspection of construction activities.

- The practice of "phased inspection," in which the inspector is free to choose which construction activities to inspect, is not effective for earthwork.

RECOMMENDATIONS

Approach 1: Specifications Based on Embankment Performance Measurements

- This approach is only recommended for large design-build or design-build-maintain projects.

- The first few times that this approach is implemented, it should be closely monitored by VDOT to gain experience with the method.

Approach 2: VDOT Hires Experienced Inspectors

- To the extent feasible considering fiscal and policy constraints, this approach is recommended.

- This approach is recommended for design-bid-build projects of all sizes and for limited VDOT monitoring of Approach 1 on design-build and design-build-maintain projects.

Approach 3: VDOT Outsources Inspection Work

- This approach is recommended for use in the same ways as Approach 2.

- The costs of this approach should be monitored and compared with the costs of Approach 2 to provide a rational basis for deciding which approach should be used in the long-term.

Approach 4: Contractor Provides Third Party Inspection Services

- Based on the extensive concerns expressed by the focus group and the surveyed experts, this approach is not recommended.

- If this approach is applied, it should be carefully monitored using Approach 2 or 3.

Approach 5: Significantly Increase Testing Frequency

- This approach is recommended.

- For the portion of the embankment below depth 5 feet, consideration should be given to further increasing the testing frequency to one test per 1,000 yd^3 or one test per 500 yd^3.

Approach 6: Establish Pay Factors for Compaction Quality

- If this approach is attempted, special care should be given to test quality and documentation to help prevent disputes.

- As for Approach 5, consideration should be given to further increasing the testing frequency to one test per 1,000 yd^3 or one test per 500 yd^3.

Approach 7: Status Quo

- The practice of "phased inspection" as it applies to earthwork should be abandoned.

- Based on concerns that have been expressed about embankment quality under existing practices, it is recommended that improvements to the status quo be made by adopting one or more of the recommended approaches.

Recommended Specification Review

Whenever new construction specifications are being considered for implementation, they should be reviewed by legal, construction, and earthwork experts prior to inclusion in bid documents.

Recommendations for Further Research

- There is a growing trend toward continuous compaction control and intelligent compaction processes for earthwork. These technologies are being developed in Europe and, more recently, in the United States. Related new technologies for verifying compaction quality, such as stiffness measurements, also show potential. It will be important for VDOT personnel to stay abreast of these developments and consider the extent to which such technologies can be applied VDOT projects.

- Certain soils in Virginia have caused more problems than have others. These soils should be investigated to provide a database of engineering property values for use in design. Field data sets of compaction of such soils should also be analyzed statistically, as illustrated in Appendix E, to provide the necessary information for reliability analyses.

COSTS AND BENEFITS ASSESSMENT

Because this is policy-oriented research, quantitative assessments of costs and benefits are not feasible. However, risks and benefits can be presented qualitatively. The potential benefits of the recommended approaches include:

- Fewer embankment slope failures, improved ride quality, longer pavement life, and lower maintenance costs are potential benefits for Approaches 1, 2, 3, and 5.
- Lower VDOT manpower requirements for Approaches 1 and 3.
- Opportunity for contractor innovation in return for increased contractor responsibility in Approach 1.
- Reduced potential for construction claims in Approach 1 because the contractor "owns" the problems that may arise.

The risks of the various approaches include:

- Unintended outcomes associated with the innovative nature of Approach 1.
- Because Approach 1 places primary reliance on measurement during the warranty period, VDOT is exposed to long-term risk in this approach.
- Increased VDOT labor and equipment costs for Approach 2.
- Increased VDOT costs for professional services in Approach 3.
- Conflict of interest and increased construction contract costs for Approach 4.
- Increased disputes over field testing data for Approach 6.
- Continued problems with slope failures, ride quality, and high maintenance costs in Approach 7.

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APPENDIX A

MINUTES FROM JANUARY 2005 MEETINGS WITH PROJECT FOCUS GROUP MEMBERS

Performance Specifications for Embankment Construction

Summary of Conversations with VDOT and VTRC Personnel on January 7 and 9, 2005

David Lee and Wade Pence (January 7):

- Appendix III
  - The draft performance-based earthwork specs that were considered for the Route 58 PPTA project contain some very good aspects.
  - VDOT's standard earthwork specs are being used at the Route 58 PPTA project.
- Appendix IV
  - Item 1. Status quo.
    - The status quo is generally unable to provide an acceptable level of quality assurance.
    - When the work load is high, there are not enough inspectors to go around.
    - Testing frequency is not adequate.
  - Item 2. VDOT hires additional experienced inspectors.
    - Even with more inspectors, other issues would need to be addressed.
    - Inspectors often perceive compaction control as unimportant. Instead, they focus on project completion time, cost, environmental issues, and documentation.
    - Often, problems don't show up until after construction is complete.
    - At Route 460 Bypass, there were enough inspectors, but not enough emphasis on compaction. The results included surficial landslides and poor ride quality due to uneven settlement.
    - VDOT has a certification/training program for inspectors.
    - VDOT also has a Construction Quality Improvement Program (CQIP). Russell Whitworth is in CQIP and would be a good contact.
    - VDOT inspectors do focus on compaction of the upper few feet of embankment fill because there is a perception that this affects pavement support. However, compaction within the bulk of the embankment and at the side slopes is often considered relatively unimportant.
    - Embankment side slopes can be effectively compacted by either operating a compactor on the slope, which may require use of another piece of equipment at the crest with a cable down to the compactor, or by overbuilding and trimming back.
    - In addition to the problems at Route 460 Bypass, there have been problems with shale/siltstone slopes on Route 100.
    - Embankment stability problems are shallow slope failures. Not aware of any deep seated embankment landslides. However, ride quality is also an issue, which calls for compaction within the central portion of the embankment.

- Item 3. VDOT requires the contractor to hire a third party inspector.
    - This is tricky because it puts pressure on the third party inspector to please the contractor. Route 58 PPTA has this issue. Contact Joe Hamed (375-3595). Joe has worked for a contractor and a consultant in the past, and he is now with VDOT, so he has a broad perspective.
    - Alternatively, VDOT hires the third party inspector. This may be a much better choice.
- Item 4. Provide financial incentives for good performance.
    - A problem with price adjustments is that there would be pressure applied to VDOT and/or third party inspectors.
    - Price adjustments also require plenty of data and time for VDOT engineers to evaluate the data.
    - This approach requires good quality field test data, as well as laboratory reference tests on the correct materials.
    - An appeals process is necessary.
    - This type of approach is successful for paving materials, and it could also be applied to good effect for earthwork. It might be a good approach for particular projects, given sufficient data and VDOT engineer time.
- Item 5. Base specifications on embankment performance measurements like settlement and stability.
    - Some problems don't show up for years. Longer performance periods will increase bid prices.
    - Who does the long-term measurements? Might not be enforced.
    - This approach sounds good, but the details (e.g., items 5a through 5d) may be very difficult to address.
    - This approach may be appropriate for some specialized projects.

Tom Freeman, Jose Gomez, and Ed Hoppe (January 7):

- What are suitable means for shifting liability from VDOT to the contractor?
- Construction quality has suffered as a result of VDOT focus on time and budget.
- There is a road in Chesterfield County that has had several slope failure problems. Stan Hite is familiar with this.
- It will likely be possible to come up with reasonable measures of embankment performance, e.g., settlement criteria and limitations on slope failures. However, contractors may claim that outside forces, such as unusual weather and/or human activity, are responsible for failure to meet such criteria.
- A good approach may be to combine density testing and earthwork observation with the more direct measures of embankment performance.
- There was discussion of the performance period that would be appropriate. As the performance period increases, it seems more difficult to enforce the specifications because the likelihood increases for unforeseen outside forces, loss of data, new construction (e.g., overlays) that would interfere with data interpretation, change in personnel, change in VDOT policies, etc. Also, the longer the performance period, the higher the construction cost. One approach that was suggested would be to have a relatively short performance period combined with relatively tight criteria. For example,

if the differential settlement over one year is held to a small value, then the long term differential settlement might not be excessive.

- Earthwork contractors would be receptive to the approach in Item 5 of Appendix IV.
- Tom Freeman will send names and contact information for earthwork contractors that we could contact.
- Any new specifications that are generated will have to be reviewed for their legality before they are applied.

Stan Hite and Tom Pelnik (January 7):

- There is some frustration with quality of new earthwork construction. One example is Walthal Road, for which poor earthwork quality produced settlements even before the road opened. CPT testing in the embankment disclosed spikes in the cone resistance at two-foot intervals suggesting that the fill lifts were about two feet thick.
- An important issue is defining unsuitable fill materials. Can these be defined in terms of PI, organic content, water content, particle size, and deleterious inclusions?
- Quality suffers not because of lack of emphasis by VDOT's top management, but because schedule and budget are easier to measure than quality.
- The current specified density testing frequency is as infrequent as one test per 10,000 cu. yd. of fill, with modifications for various aspects of embankment geometry. At the time this frequency was established, the level of earthwork observation by inspectors was much higher.
- The CQIP group has documented that fill density is a problem.
- This research project can't solve possible organizational problems within VDOT, and the focus should be on technical issues. Nevertheless, there is widespread agreement that earthwork compaction is a problem, and organizational issues are a contributing factor.
- If the contractor is required to hire a third party inspector, a high testing frequency would have to be specified because the contractor won't call out the inspector any more often than needed to perform the required tests.
- VDOT experience so far is that design-build projects incorporate high-quality engineering firms. Also, the contract documents for design-build projects can incorporate quality requirements for construction monitoring services. A key element is that the person responsible for quality must be different from the person responsible for production.
- For design-build projects, how should values of safety factor and reliability be specified?
- One advantage of requiring that the contractor, instead of VDOT, hire a third party engineering firm for monitoring construction quality is that the contractor then "owns" any problems that may arise, rather than being able to blame them on VDOT or VDOT's engineer.
- Stan will contact Wilford King who is with VDOT and who has an earthwork specification of interest.
- Virginia Tech should contact Koch Construction about design-build issues.
- Providing financial incentives (Item 4 in Appendix IV) is a good idea. The upper pay limit should be 105%. Instead of having a 0% pay level, require that the contractor rework and get the material into an acceptable pay zone.

- For federally funded projects, VDOT is required to do some of their own testing.
- For asphaltic concrete, VDOT requires the contractor to do their own testing, and VDOT does some of its own check tests.
- Give consideration to using a random number generator to determine test locations. VDOT could provide test locations (based on a random process) immediately after a lift is placed.
- For performance specifications (Item 5 in Appendix IV), the following details were suggested:
    - A warranty period of 3 years.
    - Make measurements every 6 months.
    - Set the slope erosion limit to 10% of the exposed slope.
    - Limit head scarps to 3 inches.
    - Other criteria, including differential settlement, would also be necessary.
    - For anything that fails to satisfy the criteria during the 3-year warrantee period, the contractor should be required to fix the problem, and the 3-year warrantee period for that problem would restart as soon as the problem is fixed.
- A combined approach including elements of Items 2 through 5 of Appendix IV may be appropriate.

Tom Pelnik and Kord Wissmann (January 9):

- Currently, VDOT requires a 5-year performance bond on all construction.
- Does rideability cover all differential settlement concerns?
- Most VDOT work will remain design-bid-build.
- When things go wrong, contractors will try to place the blame on outside causes, e.g., differing site conditions, weather, VDOT, etc.

APPENDIX B

SUMMARY OF INTERVIEW RESPONSES, DOCUMENT SENT TO SURVEY CANDIDATES, AND NAMES AND AFFILIATIONS OF RESPONDERS

SUMMARY OF INTERVIEW RESPONSES

An important component of the research conducted for this project consisted of expert feedback on the alternative approaches being explored. During February and March, 2005, a document describing the alternatives was sent via email to a selection of individuals from agencies, private engineering firms, contractors, and academics. Of the twenty-four recipients of the interview document there were fourteen responses. The responders represented backgrounds in state DOT work, private design-side engineering, academic research, construction, materials engineering, and project quality control. As a whole, the responses often expressed strong opinions for and against various alternatives. The opinions varied and no single alternative was universally championed. However, there was general consensus that visual inspection of earthwork should be an important component of any construction specification.

The following sections present summaries of the replies we received, sorted by alternative. We are not identifying individual responses in this document in order to protect anonymity.

Alternatives 1 (Status Quo) & 2 (VDOT hires more inspectors)

The respondents that commented on the status quo felt that the traditional system of near full time visual inspection and periodic field testing was successful in promoting high as-constructed quality. In this sense, Alternative 1 (the Status Quo) is generally considered conceptually satisfactory, but in its current condition, it lacks the labor resources for proper execution. Five respondents considered Alternative 2 to be the preferred course of action among the alternatives being explored. There was considerable emphasis on the importance of visual inspection, and two respondents stated that there should be more value placed on inspection when considering direct and indirect project costs.

Presented below are edited comments summarizing the responses to Alternatives 1 and 2:

- From a technical standpoint, the most preferable alternative is the Department hiring more experienced inspectors. If budget limitations prevent this approach from being implemented, then alternatives nos. 3, 4, and 5 would also be negated. VDOT would be better served by making modifications to the traditional approach to fit their limitations than to implement any of the other alternatives. Professor Peck commented in one of his papers in reference to earthwork construction control: “There is no substitute for a good set of eyes connected to a calibrated brain.”
- Effective quality control of any earthwork project has one essential component, and that is the experienced person who is in the field full time watching the work. There is just no acceptable substitute for this person. The QC testing that is normally performed (in-place density and moisture, Proctor curves, etc) is a valuable supplement to full-time inspection

and serves to document the quality that was achieved and the properties of the fill. However, if given the choice between eliminating the QC testing or the full-time experienced inspector, the preference would be to retain the inspector.

- The problems with budget to hire additional personnel and utilization from season to season are not insurmountable. One possibility is to hire experienced people on a temporary basis who have retired or wish to retire. This way has definite financial as well as technical benefits. First, the payroll burden for a temporary employee is maybe 15% as opposed to 30%-40% for a permanent employee. Second, the person has many years of experience and the quality of his work is known (or is discoverable through careful reference checking). Third, younger people working under them or with them will have the benefit of their experience.
- With regard to seasonal fluctuation in workload, VDOT faces the same problem shared by other state employers as well as private firms. In order to provide continuous observation of the construction means and methods, VDOT should retain a core of trained inspectors with a floating group to work under their supervision.
- Alternative nos. 2 through 5 all require more spending on the part of the Department. If the Department's objective is to improve construction quality under a reduced budget, then these options are unhelpful.
- The current method to control earthwork has been generally satisfactory over the past 50 to 60 years.

Alternatives 3 (VDOT provides third party inspection and testing) & 4 (Contractor provides third party inspection and testing)

Four respondents considered Alternative no. 3 to be a viable method of enforcing construction quality using the traditional approach of full time inspection and periodic testing. One respondent considered this the best option. More than one respondent considered Alternative no. 3 to have the potential for conflict of interest, but none found this issue to be insurmountable. Three respondents made a special point to stress that the qualifications and experience level of the personnel provided by the outside party are key to the success of this approach. Two of the respondents highlighted that VDOT needs to specify the minimum qualifications for inspection personnel in the contract and one felt that VDOT should provide the training.

There was not a single respondent who stated support for Alternative no. 4. The primary reason was the strong potential for conflict of interest between the Contractor and the inspection team.

Three responders mentioned QC testing by the Contractor and QA testing by the Authority for verification/validation as a desirable option to improve construction quality.

Presented below are edited comments summarizing the responses to Alternatives 3 and 4:

- Approach no. 3 is the preferred approach under the current budget limitations. An outside inspection firm can provide the resources needed for full-time visual inspection and periodic testing on VDOT projects. VDOT personnel can perform random Independent Assurance Testing for verification.

- Approach no. 3 is a viable option. The risk of conflict of interest is not a show stopper for this alternative. There are already safeguards in place when using VDOT personnel for inspection. An outside inspection firm retained by VDOT ultimately has to answer to VDOT. The need for a benchmark of quality and expertise among firms can be addressed by making the appropriate training available and requiring the third party firm to send their inspection personnel.
- Approach no. 4 is not viable. When the Contractor has the "power of the purse" over the inspector, the risk of conflict of interest is overwhelming. It will be difficult, if not impossible, for VDOT to investigate and police the relationship between the Contractor and his retained inspection firm. Furthermore, in the interest of cutting project cost, the Contractor may attempt to stretch the output of each inspector. An overworked inspector is likely to be less vigilant.
- The Iowa DOT is moving toward a contractor quality control (CQC) program verified with 10% quality assurance (QA) reference testing by DOT personnel. Quality control (QC) tests are performed every 1000 m^3 and include moisture, density lift thickness, and soil classification. A four point moving average is being used for acceptance.
- Consideration should be given to QC by Contractor and QA by Authority. Statistical measures can then be used for validation/verification. Because the Contractor is responsible for operation control, he can base the QC testing frequency upon the quality of the equipment, operations, and site work.
- Approach no. 3 has been used in the past with some success. There should be no conflict of interest if the third party is under contract to and reports only to VDOT. This is the method used by the State of California for control of their earthwork operations. Variations in practice standards from firm to firm should likewise not be a problem if the contract is properly written so as to require not only services to be furnished, but the time frame in which they must be provided and the minimum qualifications of personnel performing the required services. This method will require QA by VDOT. One disadvantage of this approach is the cost. Past experience has shown these contracts to be expensive. This approach is second in preference to full-time inspection by VDOT personnel.
- Approach No. 4 is used by the Corps of Engineers. Experience with this system has shown it to work adequately with military type construction projects (buildings, site work, utilities, etc.) but not as well on large earthwork projects. This approach if fraught with potential conflict of interest problems and requires extensive QA by the owner. For the type of projects VDOT usually constructs, this approach is not recommended.
- The contractor has a built-in conflict of interest when it comes to QC work. The best contractors will perform adequately, and average (i.e., most) contractors will turn in mixed performances. If the job is a difficult one and he expects that he may not meet his profit goals, the quality will probably suffer.
- An outside consultant's goal is to provide an adequate service consistent with the average standard of care in his area and maximize his profit. Based on the current state of inspection and testing on most VDOT projects, this will result in the consultant putting his lower paid, therefore less experienced, people on a project. In regards to the variation of the standard of practice from firm to firm, the quality of the person that the firm puts on the project, and that person's qualifications and experience should be the paramount selection criterion. The only apparent way to address these issues is for VDOT to specify

the level and type of experience required, make a qualifications-based selection, and then negotiate the fees.

- Approach no. 4 is putting the proverbial fox in the chicken coop. The Corps of Engineers has been using contractor QC in all of its contracts for the past 20+ years, and the results are predictable. It doesn't matter whether the contractor is performing these services with his own forces or with "independent" third parties.

Alternative 5 (Significantly increase VDOT's requirements for the frequency of density and water content testing)

Two respondents found this alternative to be a good idea when used in conjunction with some degree of visual inspection. Three respondents emphasized that testing should in no way be considered a substitute for visual inspection.

Two respondents expressed dislike for this approach primarily due to variability in the testing data and added cost.

Presented below are edited comments summarizing the responses to Alternative 5:

- Test frequencies for earthwork construction are typically limited (e.g., VA's one test in 10,000 yd^3). In the past, rather than requiring a much stiffer testing regimen, everyone went the route of full-time inspection. Over time, the "inspection world" has changed, so we (states and private) are all revisiting this issue again. The most practical approach is to use experienced, highly motivated inspectors on a full-time basis rather than introduce sampling and testing error issues through the use of more frequent Proctor testing (moisture content and density) as a substitute. Statistical methods can be used to some degree to address variability, bias, and error in tests results, but this requires large data sets to fairly protect the interests of the Contractor and the Department. Testing frequencies necessary for this approach could heavily influence the project budget not only to cover the costs of the tests but the added contingency to cover unfamiliar site conditions.
- Even with a high frequency of testing, the volume of soil actually tested is miniscule compared to the volume placed. As such, observation is needed to reveal that something is wrong. The moisture and density tests simply verify the source of what is wrong. A rare test at a location based on random selection leads to no confidence that the overall fill meets the specified requirements. Testing should be applied most frequently at the beginning of the work as a guide to observation. Thereafter, testing can be applied less frequently as consistent means and measures are adopted and confirmed.
- Experience has shown that control of earthwork operations solely by the use of density and water content testing along with laboratory compaction testing, is an inadequate means of control, even for an end-result specification.
- Even with careful laboratory testing, the precision of Proctor tests is only fair. AASHTO T-99 prescribes a maximum single operator repeatability using the same laboratory equipment of ±10 percent optimum moisture and 2.2 pounds per cubic foot density. Between different operators and laboratories, the prescribed allowed repeatability is ±15

percent optimum moisture and 4.5 pounds per cubic foot maximum density. Measurement of in-place density and moisture content are associated with comparable uncertainty. Based on AASHTO method T310 (nuclear method), acceptable single operator spread for two measurements is ±1.0 to 1.3 pcf and double that for multiple operators. For water content, acceptable spread can add an additional 1 to 2 pcf uncertainty. With this type of uncertainty in the reference Standard Proctor and in-place density measurements, calculated percent of maximum density is a questionable parameter to monitor compaction quality.

- Test locations can easily be designated in areas that will bias the results.
- The time element between the time tests are taken and a percent compaction is computed and related back to the field is often too long to be of use when construction is proceeding at a normal rate. This is especially true in areas where the embankment is rising vertically at a rapid rate.
- Because of the nature of earthwork (compacted lifts placed upon compacted lifts) coupled with the aforementioned time problem, it is very difficult to implement corrective action when required.
- Determination of percent compaction requires an accurate determination of maximum dry density. This is particularly difficult and time consuming in variable soils and earth-rock mixtures, both of which are common in VDOT projects.
- High-lifting (excessive lift thickness) is one of the most common problems in earthwork construction and will result in a density gradient in the lift with the lower portion being less dense than the upper portion. It is unlikely this condition will be detected by in-situ density testing.
- It is very easy for one to “fall in love” with test results and, since test results are so definitive, think that visual inspection may be minimized.
- In earthwork construction it is always preferable to assess the work as it is being performed rather than after the fact.

Alternative 6 (Provide financial incentives for good performance)

Two responders mentioned that this approach was viable while two expressed dislike.

Presented below are edited comments summarizing the responses to Alternative 6:

- This is not a good approach. Most contractors are not likely to argue about the results of a nuclear density test. By adding a financial incentive, the compaction quality would become a battleground issue between the Contractor and the Authority.
- This approach is used throughout the industry for such things as pavement smoothness and to determine partial payments for non-conforming work that will be allowed to remain in place. This seems to be a viable change, although it would likely require increased testing frequency to be fair.
- This approach eliminates the option of the Contractor providing some or all of the quality control data.
- This approach is reasonable, however the incentive should not be based solely on density but reflect overall compaction quality.

- This approach would be very difficult to manage, is subject to error, and would likely require a significant amount of processing time. There is also the issue of deciding how to tie the payment structure to the minimum design requirements.
- This approach does not have a significant experience base to rely upon and will require extensive training of the inspection personnel. There will likely be considerable inertia to efficient use of this approach both on the part of the Department and the Contractor.
- It is doubtful that performance can be quantitatively measured. On a particular job, there were Proctor curves with maximum dry densities that varied from 90 pcf to 115 pcf; and it was impossible to identify the correct curve to use by visual inspection of the material.

Alternative 7 (Performance Specifications)

Three responders spoke favorably of this approach, while four expressed serious doubts. The primary doubt was whether there was a viable framework under which performance could be efficiently and fairly assessed.

Presented below are edited comments summarizing the responses to Alternative 6:

- This is a viable option for certain projects. This approach is not suited for small projects and small contractors. Inclusion of a performance warranty and/or provision for collection of liquidated damages is required for enforcement of the performance standards established in the spec.
- Performance specifications can be used in tandem with density testing.
- Measuring performance indicators post-construction has the same potential as field testing during construction for error, variability, and bias.
- This approach has potential. Feedback from contractors indicates a high level of interest (especially with larger contractors). Further, recent advances in Continuous Compaction Control (CCC) and Intelligent Compaction (IC) systems could provide a nice framework for performance based evaluation because they provide 100 percent coverage and generate a robust data set for statistical analysis.
- The use of performance indicators to evaluate construction quality has been used for pavement construction in pilot studies with reasonable success. To implement this approach for embankment construction, the performance indicators have to first be identified. Allowable tolerances for the indicators have to be established and whether certain indicators are considered more critical and weighed accordingly. It is advantageous if the indicators can be normalized and combined. There is also the question of the practicality of monitoring and assessing the indicators within the constraints of VDOT's resources. Furthermore, it may be a good idea to combine Alternative no. 6 to some or all of the selected performance indicators.
- VDOT typically makes the decisions regarding when certain materials need to be undercut and replaced with higher quality embankment material. If a contractor is going to be responsible for the performance of an embankment over a multi-year period, then the contractor needs to be in control of undercut decisions. To reduce financial risk, a contractor would tend to error on the conservative side and perform more undercut and

replacement than VDOT typically would. This would possibly result in a significant increase in the up front project costs.

- The use of multi-year warranties and the associated cost to maintain a warranty bond over the time period may present problems in today's insurance market. Smaller firms, especially, may find it difficult to obtain this type of coverage, given that there will be no loss history.
- The performance factors should be based on traditional performance indicators (i.e. compaction density and placement moisture content). Using criteria such as maximum allowable differential settlement and slope area subject to instability presumes that some baseline level of these problems is permissible. With the foundation of any structural feature being the most critical, why would any settlement or instability be tolerated? The use of full time visual inspection and periodic testing minimizes the undesirable conditions of settlement and instability. For a project using performance specification, the owner is inherently willing to accept some risk of failure in lieu of up front inspection and testing. This approach is not sound because, if the foundation fails, all dependant overlying structures fail as well. This is contrary to cases where performance specifications are used for pavement construction because the failures are at the surface, making them easy to detect, address, and isolate from damaging other structural elements.
- Transportation agencies exploring the use of performance specifications for various types of construction are overlooking the administration cost of post-construction inspection of the performance indicators, the user delay costs for repairs, and possible litigation. The Michigan DOT uses warranty specifications based on performance indicators for asphalt and concrete pavement construction.
- Is any slope instability acceptable or would some minor sloughing be acceptable? What does slope "area" have to do with a slide that takes out a road? It would appear that a slide involving 1,000 sf of surface area which impacts the highway is just as bad as one that involves 5,000 sf of surface area.
- Once the embankment is complete and the pavement is constructed, it is too late to catch defects without costly consequences. The Department cannot afford to delay or interrupt public access to the roadway to repair defects that are the result of poor construction. The length of time for a performance period is innately arbitrary because performance of the fill will be significantly affected by the weather following completion of the earthwork. Virginia saw many slopes this past year that revealed low quality construction years and decades after completion.
- The legal ramifications and how the contract would be structured are major challenges to the use of performance specifications. Even if the contractor is willing to affect repairs two or three years down the line, VDOT would still have a construction project on their hands with road closures, detours, etc. Would these embankments have to be heavily instrumented? It seems that, if the deficiencies themselves are used to judge whether a contractor must perform remedial measures, he would still have to know the source of the problem in order to properly remediate it. In the end, would the use of performance specifications be any better or cheaper than conventional methods? There is legitimate concern over the use of any method of specification that requires more input from lawyers than from engineers.

Additional General Comments by the Responders

- Method specifications are a means to achieve a certain level of uniformity of the fill. With a specified compaction effort, the resulting density will be determined by placement water content. It is impractical to perform a statistically significant frequency of end result testing (density and water content). Therefore, there must be an approach to give the engineer a level of reliability of how representative the limited tests results are of a broad area of fill. The approach is to specify means and methods in terms of maximum lift thickness and minimum number of passes. If there is no regularity in the thickness of the lifts and the number of passes of a given compactor, the test results of density cannot be relied upon to provide meaningful results of overall fill quality.
- The maximum Proctor density is highly susceptible to small changes in gradation. A small increase in fines content can significantly raise maximum density. With this sensitivity, how can one accurately correlate lab results to a test in the field?
- It is very difficult to get through to people that control of earthwork construction is every bit as important as the design itself. The best and most sophisticated design can be totally negated by construction that does not meet minimum design requirements. Costs for proper construction control should be as much a part of the project as the construction itself.
- None of the proposed alternatives represent the direction that VDOT should be heading to improve construction quality. Technologies are becoming available that allow for practical use of stiffness measurements to indicate compaction quality. Continuous Compaction Control (CCC) and Intelligent Compaction (IC) are examples of such an approach. This technology provides near 100% monitoring of compaction performance while accommodating VDOT's reduced inspection staff.
- The as-constructed quality of embankments could largely be improved by focusing on challenging soils that are specific to various regions in the Commonwealth. These soils should be studied using demonstration projects to hone in on compaction methods that yield consistent, high quality results. Furthermore, these soils should be evaluated over a period following construction to study their long-term behavior and influence on embankment performance.

DOCUMENT SENT TO SURVEY CANDIDATES

The following document was prepared on February 18, 2005, and was sent to the survey candidates via email.

Some Alternative Approaches for Embankment Construction Specifications

<u>Background:</u>
The Virginia Department of Transportation (VDOT) spends hundreds of millions of dollars each year on earthwork, and much of that is spent on embankment construction. Roadway embankments that are stable against vertical and lateral deformations provide good ride quality, remain safe, and require only limited maintenance expenditures over time. The traditional approach to providing quality assurance for earthwork operations is to combine limited field

testing with full-time observation by an experienced inspector. Inspection by experienced personnel provides verification of the fill material quality, water content, lift thickness, compaction equipment type, compaction equipment operation, and quality of the finished product. This approach has been used effectively by VDOT to control the construction quality of embankments that have performed very well over many years of service. However, because of recent reductions in the number and experience level of VDOT inspectors, it is becoming increasingly difficult to implement this approach. Much VDOT earthwork is now observed only part-time by inspectors who may be relatively inexperienced. Even though oversight by VDOT inspectors has decreased, field density testing is still performed at an infrequent rate. The current specified density testing frequency is as infrequent as one test per 10,000 cu. yd. of fill, with modifications for various aspects of embankment geometry. The result is that VDOT has not been able to adequately verify that it is receiving the quality it is purchasing, and slope failures and excessive settlements have occurred. VDOT would like to improve this situation.

Definitions:
For purposes of this discussion, we are starting with the following definitions of method, end result, and performance specifications applicable to embankment construction:

> Method Specification: A method specification establishes requirements for such items as the water content of the fill material, the lift thickness, the type of compaction equipment, the compactor operating speed, and the number of compactor passes per lift. The final relative compaction or relative density is not specified.
>
> End-Result Specification: An end-result specification establishes the water content and relative compaction or relative density that must be achieved without specifying the compaction equipment or its operation. Most often, the maximum lift thickness is also specified.
>
> Performance Specification: Embankment performance indicators, such as maximum allowable differential settlement and maximum allowable slope area subject to instability, are specified without detailing requirements for equipment, methods, water content, relative compaction, or relative density.

We welcome any comments and suggestions for improving these definitions, as well as information about any existing standards for such definitions.

Some Alternative Approaches:

> 1. Status quo. Use existing VDOT specifications (end-result specifications with density and water content testing on an infrequent basis) without full-time inspection by experienced personnel.
>
> 2. VDOT hires more experienced inspectors. Use existing VDOT specifications (density and water content testing on an infrequent basis) and provide full-time or nearly full time inspection by experienced personnel.
> Issues:

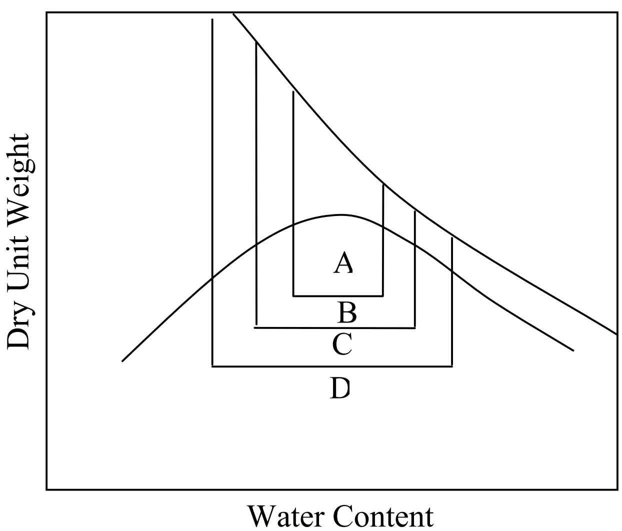
a. Budget limitations may prevent VDOT from hiring additional personnel.
b. Can staff be fully utilized considering variations in work load from season to season and year to year?

3. VDOT hires a third party, e.g., a private engineering firm, to provide the services of Item2. Use spot checking by VDOT personnel.
Issues:
a. Potential conflict of interest.
b. Variations in practice standards from firm to firm.

4. Require the contractor to hire a third party, e.g., a private engineering firm, to provide the services of Item 2. Use spot checking by VDOT personnel.
Issues:
a. Potential conflict of interest.
b. Variations in practice standards from firm to firm.

5. Significantly increase VDOT's requirements for the frequency of density and water content testing. This approach could be well integrated with approaches 2 through 4.

6. Provide financial incentives for good performance. For example, pay according to zones:



A => 105% pay
B => 100% pay
C => 90% pay
D => Contractor must re-work the material until it reaches at least zone C

Issues:
a. Such an approach could be applied to 1 through 5 above.
b. Continuous variation (versus the discrete zones shown above) may reduce conflict by eliminating abrupt jumps in pay at zone boundaries.
c. Establishing the zones (discrete or continuous variation) and accompanying pay scales could be determined by experience and judgment or by testing and analysis.
d. Need to determine suitable lot sizes and testing frequency.

e. What roles should the mean and standard deviation play in such an incentivized specification?
f. How much data and how much engineering time are required to apply this approach?

7. Base specifications on embankment performance indicators such as embankment settlement, percent area subject to slope failures, and pavement support quality.

Issues:

a. Length of performance period
b. Type of performance period. One example would be that construction must produce three continuous years without defects, and if a defect occurs, the performance period restarts after repair. A less demanding requirement would be that the contractor fixes any defects that occur within the performance period without restarting the performance period.
c. Method and frequency of measurements of performance indicators.
d. Types of incentives and penalties. These could include financial consequences and/or removal from pre-qualification lists.
e. Methods for excluding factors out of the contractor's control.
f. Methods for appeal and dispute resolution.

8. Combine two or more of the above approaches 2 through 7.

NAMES AND AFFILIATIONS OF RESPONDERS

Name	Affiliation
Joe Hamed	VDOT
Russell Whitworth	VDOT
Curtis Bleech	Michigan DOT
Victor Gallivan	FHWA
David Hammer	US Army Corps of Engineers
Wael Bekheet	Stantec Consulting
Rick Simon	Virginia Geotechnical Services
Tom Cooling	URS
Richard Bird	URS
David White	Iowa State University
Patrick Lang	Koch Performance Roads
James Schmidt	Koch Performance Roads
Rich May	Koch Performance Roads
Richard Hertzer	Vecellio & Grogan, Inc

APPENDIX C

VIRGINIA DEPARTMENT OF TRANSPORTATION
SPECIAL PROVISION FOR
RIDEABILITY

September 3, 2003

SECTION 315 – ASPHALT CONCRETE PAVEMENT of the Specifications is amended as follows:

Section 315.07(a) Surface Tolerance is replaced by the following:

Determine pavement smoothness with a profiler on designated lanes having a posted speed of 35 miles per hour or higher as specified herein. Test intersections and transition lanes with a straightedge.

Except as noted herein, the surface course ride quality acceptance will be based on the lowest average International Roughness Index (IRI) for each 0.01-mile section produced by a minimum of two test runs, using a South Dakota type road profiling device and reported for each travel lane. The device shall measure both wheel paths with laser height sensing instruments. The Developer shall conduct the testing within 30 calendar days of completion of the final surface course over the designated section, and again within 22 to 26 months after completion of the final surface course over the designated section. Conduct testing in accordance with the requirements of VTM – 106.

Acceptance

Establish an IRI number in inches per mile for each 0.01-mile section for each travel lane of the surface course. Any section tested within 30 calendar days of completion with an IRI exceeding 70.0 inches per mile will be subject to correction by the Developer. Any section tested within 22 to 26 months of completion with an IRI exceeding 78.0 inches per mile will be subject to correction by the Developer. The beginning and end 0.01-mile sections of the surface course for the project will not be subject to evaluation with the South Dakota type road-profiling device.

Areas excluded from testing by the profiler, as noted herein, shall be tested using a 10-foot straightedge. The variation of the surface from the testing edge of the straightedge between any two contacts with the surface shall not be more than + 1/4-inch to -1/8-inch at structures and +/- ¼-inch at project tie-ins. Humps and depressions exceeding the specified tolerance will be subject to correction by the Developer.

When corrections to the pavement surface are required, the Developer shall submit its method of correction for review and approval by the Department. In order to produce a uniform cross section, the Department may require correction to the adjoining traffic lanes or shoulders. The Developer shall make corrections to the pavement surface and/or the adjoining traffic lanes and shoulders at no cost to the Department. Methods of correction shall be limited to diamond grinding, remove and replace, and AC overlay.

Where corrections are made after the official test, the Developer shall retest the pavement to verify that corrections have produced an IRI less than or equal to 70.0 inches per mile for initial testing, and 78.0 inches per mile for the test period 22 to 26 months following completion, for each segment subject to the South Dakota type profiling device.

APPENDIX D

VIRGINIA DEPARTMENT OF TRANSPORTATION
SPECIAL PROVISION FOR
DENSITY CONTROL OF EMBANKMENTS AND BACKFILL

September 6, 2002 (Revised April 18, 2005 by Virginia Tech)

The following requirements supersede Section 303 of the Road and Bridge Specifications and Section 314.01 Density Control, Materials Division "Manual of Instructions" (d) Frequency of Field Density Tests (1) Embankments and Finished Subgrades, (5) Backfill for Pipes and Box Culverts, (6) Backfill for Abutments, Gravity and Cantilever Retaining Walls, (7) Mechanical Stabilized Earth (MSE) Walls, and (8) Backfill for Minor Structures:

The Contractor shall employ a full-time, Construction Quality Control Engineer. Qualified representatives of the Construction Quality Control Engineer shall observe and test all placements of fill. Do not place fill if a qualified representative of the Construction Quality Control Engineer is not present and prepared to complete the necessary tests. The Contractor shall remove any fill that is not tested at the specified frequency or is not compacted to the specified density, and replace it in accordance with the specifications, at no additional cost to the Department.

Construction Quality Control of earthwork shall:

(a) Locate tests randomly throughout each work area.
(b) Complete a one-point Proctor test and one sand cone or drive cylinder density test at least daily to calibrate the nuclear test data with the site family of compaction curves.
(c) Complete one laboratory compaction test, gradation and Atterberg Limits tests (VTM-1, -7, -25) on the borrow material at least weekly, and whenever there is a material change.
(d) Correlate daily field density test results to the appropriate lab test and adjust construction methods to achieve specifications.
(e) The CQC Engineer, who shall be a Professional Engineer, registered in the Commonwealth of Virginia, shall review, sign and submit Daily CQA/QC field density test reports. At minimum, the report shall indicate the amount of fill placed, including starting and ending elevations, station and offset limits, number of lifts, lift thickness, number of tests required and completed, comparison to laboratory compaction test results, field density test results and compliance or non-compliance with specifications, and actions taken at areas that are not in compliance with specifications.
(f) The CQC Engineer shall submit summary reports of embankment and backfill density corresponding to requests for payment.

Section 314.01 Density Control, Frequency of Field Density Tests:

<u>(1) Embankments and Finished Subgrade</u> Complete a minimum of one field density test for every 500 cubic yards of material placed for embankment construction. Complete a minimum of one field density test at 500-foot intervals for every lift of fill placed, and whenever there is a material change. Complete a minimum of one field density test for each work shift at each embankment fill location, and whenever there is a material change.

<u>(5) Backfill for Pipes and Box Culverts, (6) Backfill for Abutments, Gravity and Cantilever Retaining Walls, (7) Mechanical Stabilized Earth (MSE) Walls, and (8) Backfill for Minor Structures</u> Complete a minimum of one field density test for every 150 cubic yards of material placed below, around, or above a specific structure, minor structure, pipe, riser, manhole or wall location, etc. Complete a minimum of one field density test at 100-foot intervals for every lift of fill placed, and whenever there is a material change. Complete a minimum of one field density test for each work shift at each fill location, and whenever there is a material change.

Perform tests behind abutments or walls at a minimum distance of eight feet away from the back wall, and at least three feet away from the back edge of the zone of the select fill area.

Section 303.05 – Tolerances

(c) Quality Control of Density of Embankments and Backfill

a. The Contractor shall measure the field density and submit reports at the frequencies noted above. Report all test results. If a substandard area is repaired and retested, then include the measurements obtained following the repair in the calculations for acceptable tolerances.
b. The average of all field density measurements shall be equal to or greater than 95-percent of the pertinent Laboratory Determination of Theoretical Maximum Density per VTM-001.
    i. 95-percent of all field density measurements shall be greater than 90-percent of the pertinent Theoretical Maximum Density.
    ii. 100-percent of field density measurements shall be greater than 87-percent of the pertinent Laboratory Determination of Theoretical Maximum Density per VTM-001.

Section 303.06 – Measurement and Payment

(a) Excavation, (b) Embankments and (d) Backfill:
If the pay item does not satisfy the Tolerances noted above, and in the event that it is accepted by VDOT, the CQC Engineer will document the basis of acceptance. The Design Build Contractor and VDOT will negotiate an appropriate adjustment in the Contract price or other specific requirements or adjustments that are appropriate.

APPENDIX E

EXAMPLE RELIABILITY CALCULATIONS FOR EMBANKMENT STABILITY

Introduction

In addition to deterministic analyses of the factor of safety, reliability analyses also provide a useful tool to assess the stability of embankment slopes. Approach 1 in the Results section of this report requires that design-build teams perform reliability analyses to demonstrate that their designs provide embankments with probability of failure not more than 1% in all cases and not more than 0.5% for critical embankments.

This appendix provides example reliability calculations for a hypothetical embankment with dimensions recommended by the project focus group. The embankment is 140 feet high with a crest width of 200 feet. A surcharge pressure of 250 psf is applied at the embankment crest, but this surcharge pressure is held back 10 feet from the edge of the crest. The example embankment is placed on a strong foundation.

The soil property values used for the embankment were taken from a report (Scarborough et al. 1998) prepared for the U.S. 29 Bypass embankments at Madison Heights near Lynchburg, Virginia. We did not have access to field density test data from construction of these embankments. Instead, we used data provided by Schnabel Engineering, Inc. for a private-sector project that used soils from the same physiographic province and with similar index property values. We used this field data to establish values of the mean, standard deviation, and coefficient of variation for the engineering property values of the compacted soils in the example embankment.

Soil Property Values and Variability

The brown silty sand described in the Madison Heights report (Scarborough et al. 1998) was selected for use in these analyses. This soil has approximately 30% passing the U.S. No. 200 sieve, and is non-plastic. Its symbol in the Unified Soil Classification System is SM. The maximum dry unit weight is 98.2 pcf and the optimum water content is 19.5% according to the standard Proctor compaction test, VTM-1. This is a residual soil that is derived from phyllite, which is a metamorphosed mudstone similar to shale.

As part of the Madison Heights study, unconsolidated-undrained (UU) triaxial compression tests were performed on laboratory compacted samples of the brown silty sand. The test results were interpreted for the current research to obtain values of cohesion intercept, c, and friction angle, ϕ, based on total normal stresses. A wide range of compaction conditions were tested, which permitted developing the contour plots of c and ϕ shown in Figures E-1 and E-2. It can be seen in these figures that the values of c increase with increasing dry unit weight and the values of ϕ increase with decreasing compaction water content. These trends are similar to the trends for UU test results for other compacted soils as shown by Duncan and Wong (1999).

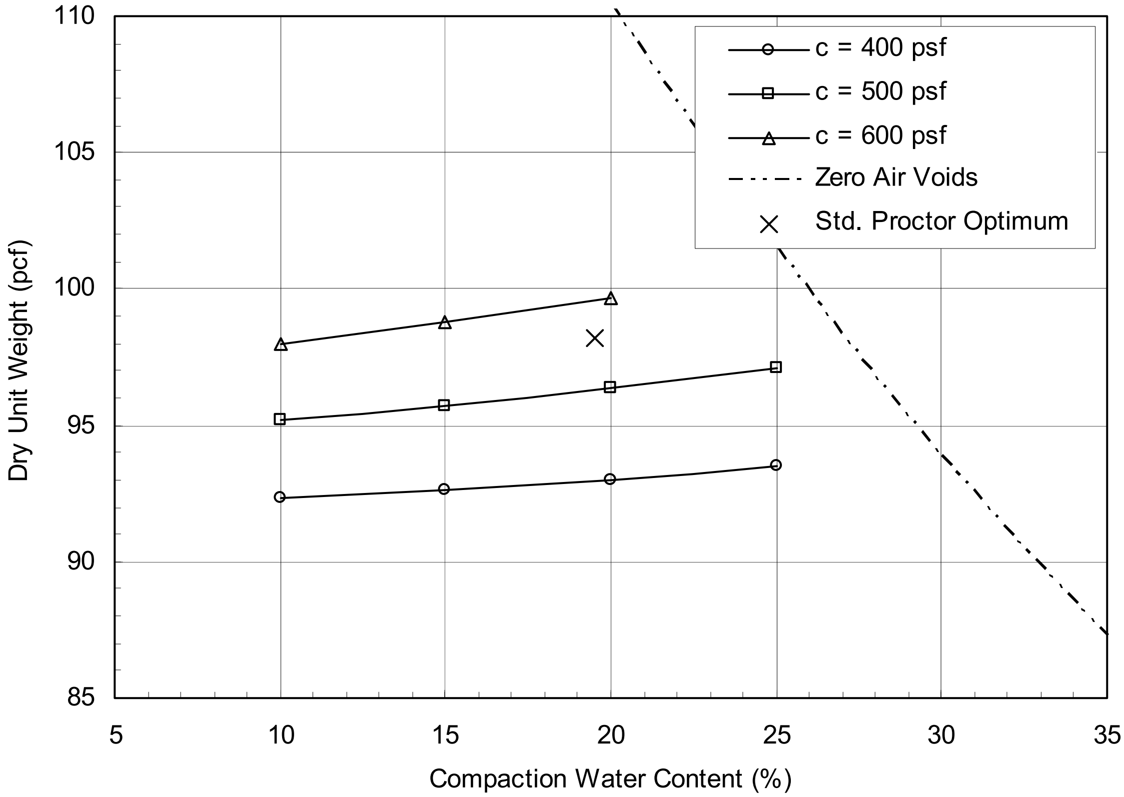


Figure E-1. Contours of cohesion intercept for the silty sand soil from Madison Heights.

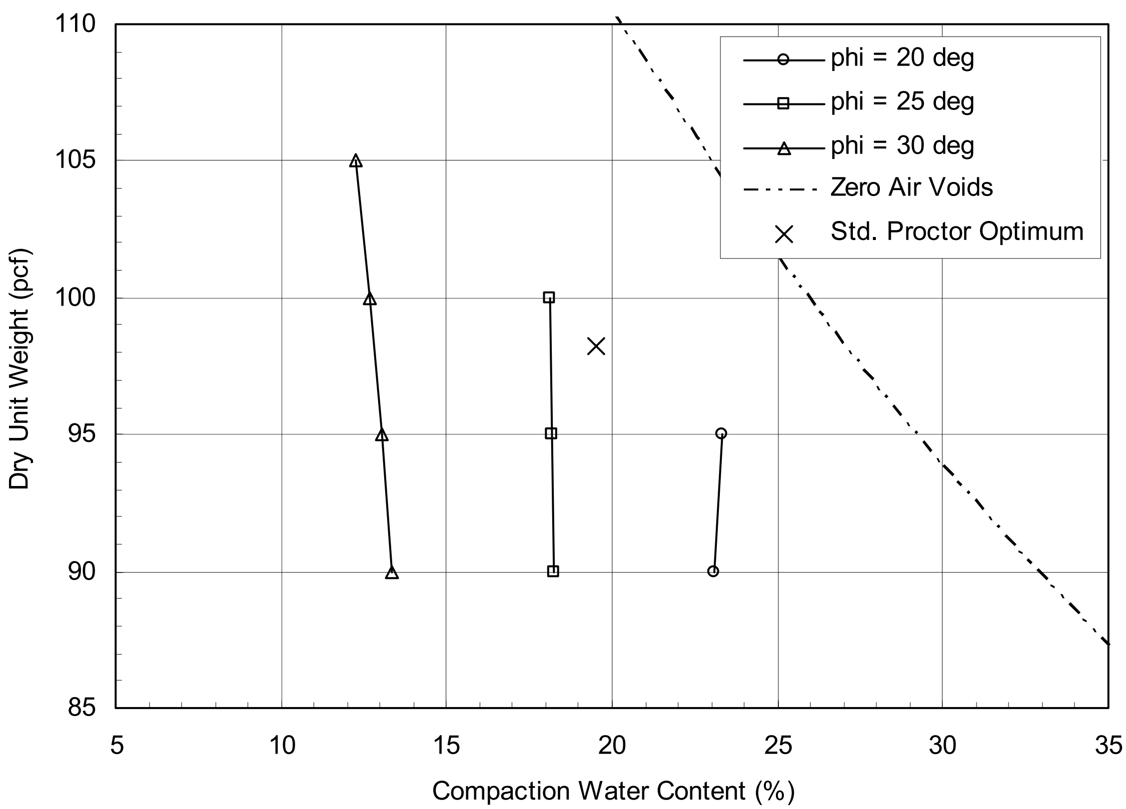


Figure E-2. Contours of friction angle for the silty sand soil from Madison Heights.

Equations that generate the contours in Figures E-1 and E-2 are:

$$c = 560 - 100\left(\frac{w}{w_{opt}} - 1\right) + 3000\left(\frac{\gamma_d}{\gamma_{d,max}} - 1\right) - 1000\left(\frac{w}{w_{opt}} - 1\right)\left(\frac{\gamma_d}{\gamma_{d,max}} - 1\right) \qquad \text{(E.1)}$$

$$\phi = 24 - 18\left(\frac{w}{w_{opt}} - 1\right) + 20\left(\frac{w}{w_{opt}} - 1\right)\left(\frac{\gamma_d}{\gamma_{d,max}} - 1\right) \qquad \text{(E.2)}$$

where w = the soil water content = the weight of water divided by the weight of dry soil solids
w_{opt} = the optimum water content determined according to VTM-1
γ_d = the in-place dry unit weight
$\gamma_{d,max}$ = the dry unit weight determined according to VTM-1

The value of c is in psf units in Eqn. E.1, and the value of ϕ is in degrees in Eqn. E.2

The field compaction data provided by Schnabel Engineering, Inc. is also for a non-plastic silty sand (SM). This soil has 41% passing the U.S. No. 200 sieve. The maximum dry unit weight is 99 pcf and the optimum water content is 21% according to the standard Proctor compaction test, VTM-1. Thus, this soil is very similar to the brown silty sand from the Madison Heights report. The field compaction data is listed in Table E-1, which also lists values of c and ϕ for each data point. These strength parameter values were obtained by applying Eqns. E.1 and E.2 to the field compaction data.

The soil property values needed for these stability analyses are c, ϕ, and the total unit weight, γ. Table E-1 provides the mean values and the standard deviations for the soil property values c, ϕ, and γ. These are the inputs needed for the reliability analyses. Table E-1 also lists the values of the coefficient of variation, V, for c, ϕ, and γ. The values of V are in reasonable agreement with published values of the coefficient of variation for soil properties (Duncan 2000).

The Schnabel data used for this analysis is for soil compacted under a specification that required 95% relative compaction determined using the standard Proctor compactive effort. This is the same relative compaction required by VDOT in its standard specification. However, construction conditions on VDOT projects are not the same as on private sector work. It would be useful to perform similar statistical analyses using data from typical VDOT projects to determine the extent of variation in compacted soil property values on those projects.

Table E-1. Field compaction data from a private sector construction project.

Test No.	w (%)	w/wopt - 1	γd (pcf)	γd/γdmax - 1	ϕ from E.1 (deg)	c from E.2 (psf)	γ (pcf)
10	23.2	0.105	96.8	-0.022	22.1	485	119.3
11	23.9	0.138	101.6	0.026	21.6	621	125.9
12	23.7	0.129	99.2	0.002	21.7	553	122.7
13	23.6	0.124	97.3	-0.017	21.7	498	120.3
14	24.3	0.157	97.1	-0.019	21.1	490	120.7
15	22.6	0.076	99.3	0.003	22.6	561	121.7

Test No.	w (%)	w/wopt - 1	γd (pcf)	γd/γdmax - 1	ϕ from E.1 (deg)	c from E.2 (psf)	γ (pcf)
18	24.4	0.162	94.2	-0.048	20.9	406	117.2
28	25.3	0.205	94.4	-0.046	20.1	410	118.3
31	24.5	0.167	100.2	0.012	21.0	578	124.7
37	23.4	0.114	94.1	-0.049	21.8	406	116.1
41	23.4	0.114	98.3	-0.007	21.9	528	121.3
42	24.6	0.171	96.7	-0.023	20.8	477	120.5
53	21.8	0.038	88.4	-0.107	23.2	239	107.7
54	19.5	-0.071	98.4	-0.006	25.3	549	117.6
64	15.7	-0.252	89.7	-0.094	29.0	280	103.8
65	21.1	0.005	99.1	0.001	23.9	563	120.0
66	14.3	-0.319	97.6	-0.014	29.8	545	111.6
67	14.0	-0.333	99.0	0.000	30.0	593	112.9
67a	25.4	0.210	95.0	-0.040	20.1	426	119.1
71	27.4	0.305	99.8	0.008	18.6	551	127.1
79	22.1	0.052	95.7	-0.033	23.0	457	116.8
80	20.8	-0.010	97.1	-0.019	24.2	503	117.3
81	28.9	0.376	94.8	-0.042	16.9	411	122.2
82	17.2	-0.181	94.0	-0.051	27.4	417	110.2
83	18.1	-0.138	96.7	-0.023	26.5	501	114.2
84	19.4	-0.076	97.8	-0.012	25.4	530	116.8
88	19.0	-0.095	96.2	-0.028	25.8	482	114.5
89	17.2	-0.181	96.7	-0.023	27.3	504	113.3
90	24.2	0.152	98.1	-0.009	21.2	519	121.8
101	20.1	-0.043	95.5	-0.035	24.8	457	114.7
103	17.2	-0.181	97.4	-0.016	27.3	527	114.2
110	20.3	-0.033	99.8	0.008	24.6	588	120.1
113	23.9	0.138	99.4	0.004	21.5	558	123.2
114	15.9	-0.243	97.8	-0.012	28.4	545	113.4
118	20.4	-0.029	96.8	-0.022	24.5	496	116.5
119	23.3	0.110	99.9	0.009	22.0	575	123.2
122	24.8	0.181	100.4	0.014	20.8	582	125.3
123	23.2	0.105	100.1	0.011	22.1	582	123.3
129	25.4	0.210	98.0	-0.010	20.2	511	122.9
141	21.0	0.000	98.8	-0.002	24.0	554	119.5
188	25.8	0.229	100.7	0.017	20.0	585	126.7
190	21.0	0.000	96.7	-0.023	24.0	490	117.0
199	22.0	0.048	95.3	-0.037	23.1	445	116.3
200	22.6	0.076	94.0	-0.051	22.6	405	115.2
201	22.7	0.081	94.4	-0.046	22.5	416	115.8
202	24.0	0.143	99.8	0.008	21.5	569	123.8
203	23.0	0.095	95.0	-0.040	22.2	433	116.9
210	24.4	0.162	96.4	-0.026	21.0	469	119.9
211	24.9	0.186	93.7	-0.054	20.5	391	117.0
				Mean Values	23.1	495	118
				Standard Deviation	2.9	79	5
				Coefficient of Variation	0.125	0.160	0.041

Reliability Analysis Method

The method used here for reliability analyses is the first order, second moment Taylor series method, as described by Duncan (2000). In this approach, the factor of safety calculated using the mean values of the parameters is designated F_{MLV}, which indicates the most likely value of the factor of safety. Then, the impact of the variation in parameter values on factor of safety is analyzed one parameter at a time by varying each parameter value one standard deviation above and below its mean value. The difference between the two values of factor of safety for variation of the first parameter is designated ΔF_1. The process is repeated for each parameter, and the standard deviation of the factor of safety, σ_F, considering variation of all parameters 1 through N is calculated according to:

$$\sigma_F = \tfrac{1}{2}\sqrt{\Delta F_1^2 + \Delta F_2^2 + \cdots + \Delta F_N^2} \qquad \text{(E.3)}$$

The coefficient of variation of the factor of safety, V_F, is given by:

$$V_F = \frac{\sigma_F}{F_{MLV}} \qquad \text{(E.4)}$$

The probability of failure, p(f), is given by using the standard normal distribution function, which is designated by NORMDIST in Microsoft Excel and in the following equation:

$$p(f) = 1 - \mathrm{NORMDIST}\left(\frac{\ln\left(F_{MLV} \big/ \sqrt{1+V_F^2}\right)}{\sqrt{\ln\left(1+V_F^2\right)}}\right) \qquad \text{(E.5)}$$

Reliability Based Design of the Example Embankment Slopes

The computer program Slope/W (Geo-Slope International 2004) was used to perform slope stability analyses for the example embankment using Spencer's method with circular failure surfaces. A tension crack depth of 7 feet was specified, and the program was allowed to search for the critical circle that produced the lowest value of the factor of safety. The procedures described above and represented in Eqns. E.3 through E.5 were used to calculate values of the probability of failure. For the case of embankment slopes at an inclination of 2.2H:1V, the reliability calculations are presented in Table E-2.

Reliability analyses were repeated for slopes of 2.0H:1V and 2.5H:1V. The results are presented in Figure E-3, which shows that the value of the deterministic factor of safety, F_{MLV}, increases and the probability of failure decreases as the slope inclination decreases. The design criteria for Approach 1 in the Results section are that F_{MLV} should be at least 1.3 and p(f) should not exceed 1% for non-critical embankments and F_{MLV} should be at least 1.5 and p(f) should not exceed 0.5% for critical embankments. Therefore, according to Figure E-3, the slopes for the example embankment should not be steeper than 2H:1V if this is a non-critical embankment, in which case the reliability criterion just barely controls over the factor-of-safety criterion. The slopes should not be steeper than 2.4H:1V if this is a critical embankment, in which case the factor-of-safety criterion controls over the reliability criterion.

Table E-2. Reliability calculation for the example embankment with 2.2H:1V slopes.

	Mean Value	Coefficient of Variation	Mean minus one standard dev. Value	Mean minus one standard dev. Factor of Safety	Mean plus one standard dev. Value	Mean plus one standard dev. Factor of Safety	ΔF
Unit Weight	118 pcf	0.041	113 pcf	1.427	123 pcf	1.398	-0.029
Cohesion	495 psf	0.160	416 psf	1.358	574 psf	1.466	0.108
Friction	23.1 deg	0.125	20.2 deg	1.255	26.0 deg	1.566	0.311

$F_{MLV} = 1.412$

$\sigma_F = \frac{1}{2}\sqrt{0.029^2 + 0.108^2 + 0.311^2} = 0.165$

$V_F = 0.165/1.412 = 0.117$

$$p(f) = 1 - \mathrm{NORMDIST}\left(\frac{\ln\left(1.412/\sqrt{1+0.117^2}\right)}{\sqrt{\ln\left(1+0.117^2\right)}}\right) = 0.002 = 0.2\%$$

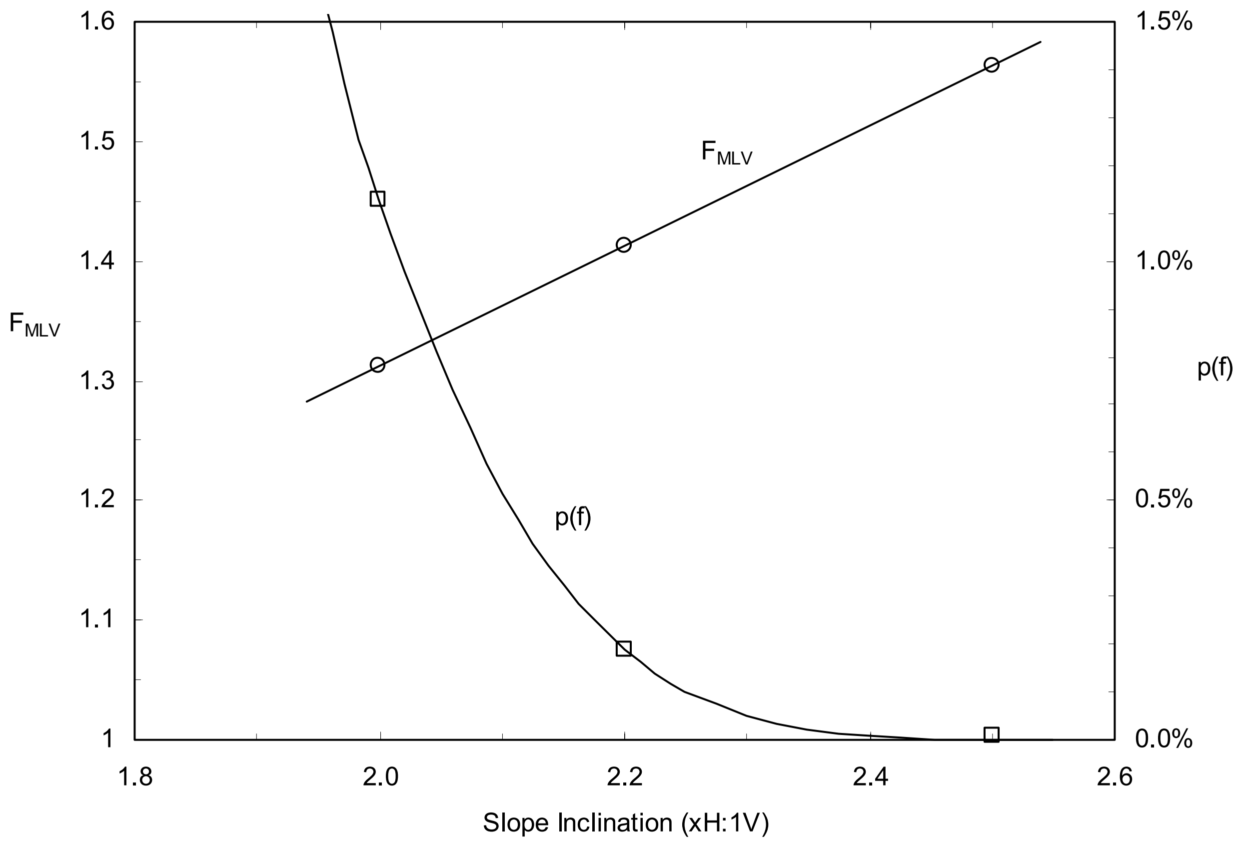


Figure E-3. Factor of safety and probability of failure versus slope inclination.

APPENDIX F

SECTION 314 OF VDOT MANUAL OF INSTRUCTIONS (MARCH 2004) REVISED BY VIRGINIA TECH (MARCH 2005)

The following material is modified from VDOT's Manual of Instructions prepared by the Materials Division in March, 2004.

REVISED SECTION 314 ROAD SAMPLING, TESTING, AND INSPECTION

The following section contains instructions for the density and depth control of compacted embankments and finished subgrades (density), cement or lime stabilized subgrade, consisting of material in-place or imported material other than aggregate base, subbase, or select material, treated or untreated aggregate base, subbase, and select material, and aggregate shoulder materials.

Sec. 314.01 Density Control

(a) General

(Reference Secs. 303.04, 304, 305.03, 306.03, 307.05, 308.03, and 309.05, Road and Bridge Specifications.) See Sec. 206 herein for Independent Assurance sampling requirements. See Sec. 207 herein for possible waiver of compaction tests on special projects. Waiver of compaction tests can only occur after review and concurrence by the District Materials Engineer.

Compaction is defined as "the process by which a soil mass is reduced in volume by the application of loads, such as rolling, tamping, or other means." Since compaction and settlement each bring about a closer arrangement of soil particles, it is evident that proper compaction will prevent subsequent ~~natural~~ settlement of an embankment or pavement layer under its own weight and the effects of traffic.

It is, therefore, essential that proper control be exercised to ensure that the correct amount of moisture and compactive effort are applied when constructing an embankment or densifying a subgrade or pavement layer.

The density of a soil is defined as the weight per unit volume (lbs. per cu. ft.) in a oven-dry condition.

Optimum moisture is that moisture content of a soil at which maximum density can be obtained under the standard compaction procedure.

The percentage compaction is the ratio of the dry weight of the soil (density), as placed by mechanical means, to the maximum dry weight (density) of the same soil compacted in the Laboratory under a standard procedure (AASHTO T99, Method A), or as modified. This ratio may also be determined using the One-Point Proctor Method, VTM-12, in lieu of AASHTO T99. However, in case of determining field density by the nuclear method, the percentage compaction is determined in a somewhat different manner, as outlined in Sec. 314.01(c)(1) herein.

Before field control of compaction can be exercised, it is necessary that the Laboratory maximum density and optimum moisture content for each type soil or aggregate (pavement base or subbase materials) be determined in advance of the compaction operation.

In addition to information available on soil survey reports, it may be necessary to submit representative samples of the soil to be compacted to the District Laboratory, unless the One-Point Proctor Method is used for this determination in the field. Samples submitted to the District Laboratory should be from 30 to 50 lbs., or one full bag. If C.B.R. tests are to be performed, 2 full sample bags are required. The following information shall supplement that normally given on Form TL-11 which accompanies the sample:

(1) Horizontal limits (by station number) represented by the sample.
(2) Vertical limits (in feet) represented by the sample.
(3) Visual description of material (Example: a highly micaceous silty sand).

(b) Compaction and Determination of Field Density
(1) Use of Laboratory and One-Point Proctor Density - As noted above, in computing the percent of compaction in the field, it will be necessary to compare the density, as determined in the field, to either a standard laboratory density, as determined by AASHTO T99 (VTM-1), or by the One-Point Proctor density, as determined by VTM-12, unless otherwise noted herein.

(2) Equipment Needed for Field Density Test - The equipment necessary for performing field density tests is available through the District Materials Engineer. To provide instruction and assistance to the Project Inspectors who operate nuclear gauges for measurement of density of soils, aggregates, and other paving materials, a Materials Technician is available in each District for this purpose. See Secs. 105.02, 105.03, and 105.04 herein for details and safety precautions for the use of nuclear equipment.

(3) Control of Moisture - Control of moisture is most important in obtaining proper compaction of soils and granular materials. Too little moisture will require more compactive effort to obtain the desired density. If there is too much moisture, the maximum density cannot be reached regardless of how much the soil is rolled. The Inspector should perform frequent moisture tests, in order to be sure that the soil has correct moisture content.

Materials having a moisture content above optimum by more that 30 percent of optimum are not to be placed on a previously placed layer for drying, unless it is shown that the previously placed layers will not become saturated by downward migration of moisture in the material. If moisture is not within the specified tolerances, then the lift will have to be aerated or moisture added, as the case may be. All moisture tests taken are to be recorded and become a permanent part of the record of the project.

It is suggested that the "Speedy" Moisture Tester be used for expediency in conducting these tests, except when the soils are heavy clays, in which case the field stove method should be used. The above instructions apply primarily when conducting field density tests by one of the methods other than the nuclear density method. When using the nuclear density method, moisture will be determined, as outlined in Paragraph (c)(1) below.

(c) Methods of Field Density Determination

(1) Nuclear Moisture-Density Method

The nuclear moisture-density method of field density determination, when specified, will be conducted in accordance with VTM-10 and Secs. 303 and 304 of the Road and Bridge Specifications. The entire scope of nuclear testing is also outlined in detail in the Department's Nuclear Moisture-Density Testing Procedure Manual, and will not be repeated here.

Nuclear density tests of embankments, subgrade, cement or lime stabilized subgrade, and backfill for pipes and culverts will be conducted using the Direct Transmission Method of testing. The nuclear density obtained is compared with either the Laboratory density, AASHTO T99 (VTM-1), or the One-Point Proctor density, VTM-12, to determine the percentage compaction.

Nuclear density tests of aggregate base, subbase, and select materials, both untreated and treated with cement or lime, for pavement as well as shoulder material, will be conducted using the Backscatter, Control Strip Method of testing. The nuclear density obtained in the test sections is compared with that of the corresponding control strip. In this case, the Laboratory density (VTM-1) or the One-Point Proctor density (VTM-12) is not normally used. On some small projects, such as turning lanes, crossovers, bridge approaches, etc., the District Materials Engineer may waive the Control Strip Method in favor of the Direct Transmission Method of testing, and compare the density obtained with the Laboratory (VTM-1) or One-Point Proctor (VTM-12) density.

Moisture tests of soils will be made directly using the nuclear device, rather than as outlined in Paragraph (b)(3) above.

If there is a breakdown in the nuclear testing equipment, then the Inspector should continue checking density using other conventional methods.

(2) Sand-Cone Method

When specified, field density tests by the Sand-Cone Method will be conducted in accordance with AASHTO T191. Next to the nuclear method, this is probably the most widely used method of determining field density. Briefly, it involves finding the weight of a sample and measuring the volume occupied by the sample prior to removal. This volume may be measured by filling the space with a material of predetermined weight per unit volume, in this case sand. The percentage compaction will be determined by comparing the field density obtained with the Laboratory, AASHTO T99 (VTM-1), or the One-Point Proctor, VTM-12, density.

(3) Other Methods

Other approved methods may occasionally be adopted for use in determining field density. The procedures outlined in pertinent instructions will be followed.

(d) Frequency of Field Density Tests

The frequency of field density testing shall be as outlined herein. Again, it should be emphasized that the rates given for testing are the minimums considered desirable to provide effective control of material under ideal conditions, and more testing than that specified should be done, if deemed necessary by the Engineer.

(1) Embankments and Finished Subgrades
The minimum number of field density tests required will be one for each 2,500 cu. yds. of embankment fill. For the upper 5 ft of embankment fill, the minimum frequency is one test per 500 cu. yds. The inspector may perform additional tests as necessary to confirm suitable compaction and to investigate areas of questionable compaction.

Test locations should be staggered, so that the entire length, width, and depth of the fill is covered by tests. The top, bottom, and middle of fills, and any necessary points in between, shall each be tested. When testing is not being conducted, the Inspector is to visually observe lifts being placed to ensure that proper placement and compaction procedures are being used. These observations include, but are not limited to: subgrade condition and preparation, the type of fill material being placed, its compaction moisture content, the thickness of lifts, the equipment used to perform compaction, operation of the compaction equipment, deformations (such as rutting and pumping) of the fill under construction equipment, and any special operations near structures, side slopes, and material transitions.

In the finished pavement subgrade in both cut and fill sections, a minimum of one test shall be made for each 10,000 square feet of subgrade. For the purposes of this subgrade testing, the subgrade area is defined as the full road width, including the shoulders, plus an additional 2 feet beyond the shoulders. Subgrade compaction and testing to 2 feet beyond the shoulders is necessary to ensure that full support is provided for the entire road and shoulders. The locations should be staggered to cover the entire subgrade area, including the road, shoulders, and the portion extending 2 feet beyond the shoulders.

If the embankment fill contains a high percentage of large particles, like rock fragments, it may not be possible to conduct meaningful in-place density tests of the compacted fill. However, if at all possible, a density test should be conducted. The amount of rock that will preclude meaningful density test should be determined by the Project Inspector. If the Project Inspector determines that a density test cannot be performed, the compaction observations described above should still be made and recorded in the inspector's daily report.

The District Nuclear Technician will conduct a continuous program of instruction for project personnel in running density tests and will inspect all density testing equipment used by Project Inspectors, to ascertain that it is kept clean and properly calibrated.

The District Nuclear Technician should observe the Project Inspector conduct a density test, and should make such corrections as are necessary. An initial inspection should be made as soon as possible after a project starts, and as often thereafter as necessary. The Technician should also inspect density test reports prepared by the Inspectors, to determine if sufficient tests and proper coverage have been made, that reports are properly prepared and completed, and that all pertinent information has been included on the test reports.