Embankment Construction QC/QA using DCP and Moisture Control: Iowa Case History for Unsuitable Soils

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ABSTRACT

The Iowa Department of Transportation (Iowa DOT) has developed an end-result embankment construction specification, Quality Management Earthwork (QM-E), that utilizes the dynamic cone penetrometer (DCP) for quality control and quality assurance (QC/ QA) of fill compaction. The DCP measures the shear strength of a soil compaction layer by penetrating a conical tip attached to a shaft through the soil with successive drops of an eight kg mass. The QM-E specifies a maximum depth of penetration per blow of the DCP for acceptance of lift compaction for three different Iowa DOT soil grades: (1) select, (2) suitable, and (3) unsuitable. The current criteria for suitable and unsuitable soils is 70 mm/blow and was developed from a limited data set containing very few tests in unsuitable soils. In an attempt to better develop improved DCP acceptance criteria for unsuitable soils, a pilot project was selected. This paper presents the application of the QM-E to the construction of the US-34 bypass in Fairfield, IA. QC/QA testing was conducted throughout all phases of construction, including DCP, moisture, and density tests. The QM-E was successfully implemented at the pilot project. Modifications to the QM-E special provision based upon observations and experiences at this project are described in this paper.

Key words: compaction—dynamic cone penetrometer—embankment—moisture content—unsuitable soils

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INTRODUCTION

After a series of earthen embankment failures during the mid 1990s, the Iowa Department of Transportation (Iowa DOT) decided to investigate the possibility of improving their embankment construction practices. Research conducted by Iowa State University found that poor embankment quality was often linked to one or more of the following occurrences (Bergeson 1998):

- Inadequately trained personnel who, at times, misidentified the type of fill material, leading to fill misplacement
- Compaction of overly thick lifts
- Fill material placed and compacted at moisture contents well in excess of standard proctor optimum moisture content
- Field classification testing that had formerly relied too heavily on one-point proctor tests, while such tests are inadequate for certain soils for the determination of optimum moisture-density characteristics.

Based upon these findings and the results of two additional phases of research (White 1999; White 2000), the Quality Management Earthwork (QM-E) special provision was developed. The QM-E is unique in that it is an end-result specification that provides the contractor with greater flexibility in the methods and equipment used during construction, provided that the finished product meets the applicable acceptance criteria. This type of specification has the potential to reduce construction costs and time through contractor innovation.

PROBLEM STATEMENT

The Iowa DOT was interested in implementing a new embankment construction specification that would result in improved embankment quality. Though the QM-E special provision was seen as having great potential, it was largely untested, especially on projects in predominately “unsuitable” soil. Therefore, a full-scale pilot project was conducted to gain insight into the practicality of applying the special provision for these types of soils. The quality control and quality assurance (QC/QA) test data from the project were then used to refine the QC/QA testing requirements of the special provision.

QUALITY EARTHWORK MANAGEMENT PROGRAM

The QM-E aims at improving embankment quality by reducing or eliminating the problems, mentioned above, that are linked to poor performance. This is accomplished through three main components of the specification: inspector training/certification, QC/QA testing requirements, and test strip construction.

Inspector Training/Certification

The QM-E special provision required that all QC/QA personnel, both contractor and Iowa DOT, must first complete a five-day Certified Grading Technician Level I training course and examination. This training course sought to impart basic skills that aid in the field identification of soil and in properly conducting the required field and lab testing.

QC/QA Testing

The QC/QA requirements of the specification constituted the most significant changes in comparison to the former specification. Moisture content, lift thickness, density, stability, and uniformity are the key criteria used to evaluate embankment quality during the construction process. The QM-E requires that these tests be conducted at a minimum frequency and that necessary control limits are met, varying with the classification of the fill material.

Moisture Content

The moisture control limits specified by the QM-E for the pilot project were +/- 2.0% of standard Proctor optimum moisture content for all material, unless otherwise specified. These control limits could potentially be changed from project to project depending on the circumstance.

Density

The density control limits for fill material must not be less than 95% standard Proctor maximum dry density. Future versions of the QM-E specification may rely solely on moisture and in situ strength testing with the dynamic cone penetrometer (DCP).

Stability and Uniformity

The stability and uniformity of an embankment lift is measured by testing with the DCP (Figure 1). DCP tests are conducted by driving a 20 mm diameter, 60° cone into the ground under the force of an 8 kg hammer being dropped 575 mm (ASTM D 6951-03).

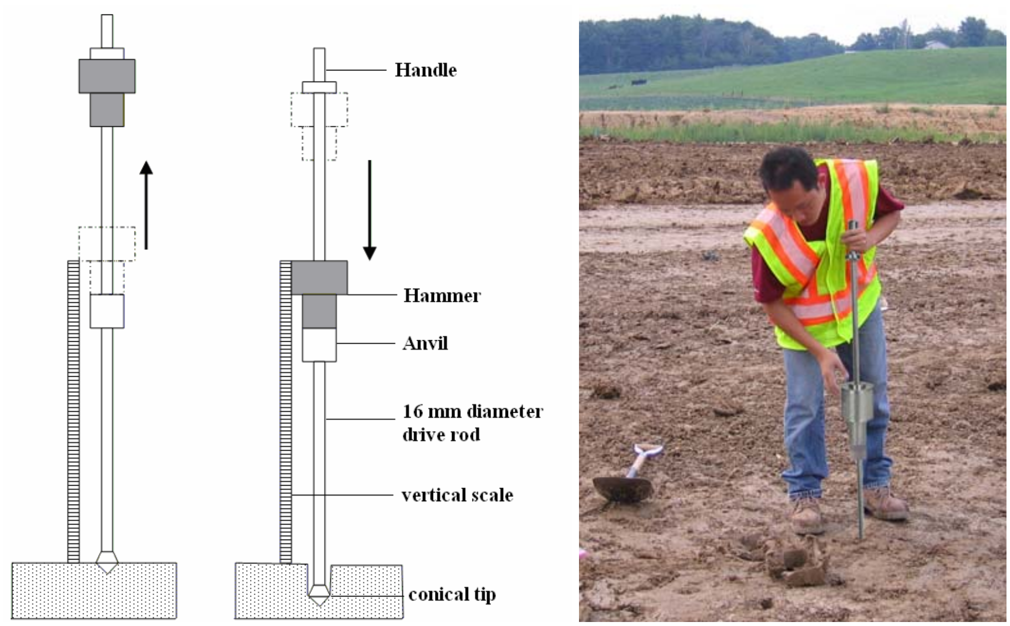

Figure 1. Dynamic cone penetrometer

DCP measurements are reported in millimeters of penetration divided by the number of hammer blows, and are referred to as DCP indices, recorded over a desired test depth. Figure 2 shows two plots of DCP index vs. depth for sets of hypothetical DCP readings. These plots give a lot of information about the soil profile. However, for convenience it is helpful to reduce this data to a single average DCP index value. There are various ways to attain an average DCP index for a given profile. The QM-E uses a weighted average method, calculated in accordance with Equation 1:

$$\text{Average DCP Index} = \frac{1}{H}\sum_{i=1}^{n} d_i^{\,2} \qquad (1)$$

where n is the total number of blows, d_i is the penetration distance for the i^{th} blow, and H is the depth of the desired test layer. Graphically, this is represented as the gray shaded areas in Figure 2B. A low DCP index, 25 mm/blow, is typical for stiff soils, and a high DCP index, 100 mm/blow, is typical for soft soils.

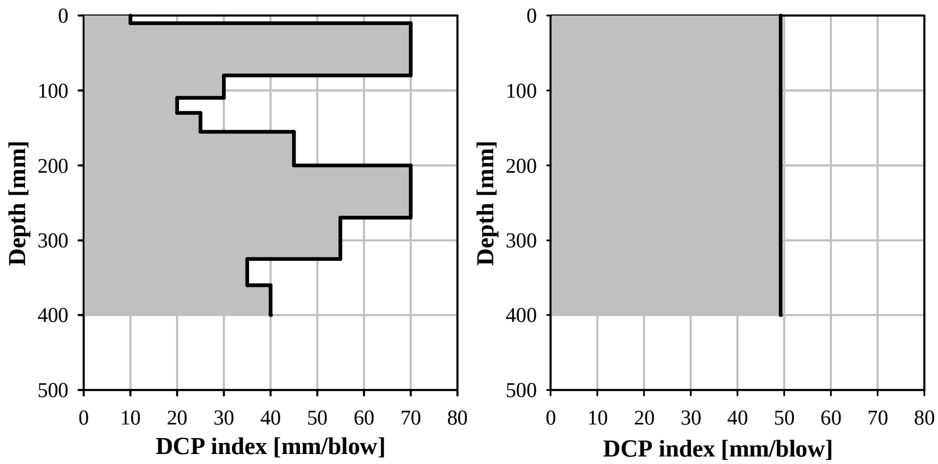

Figure 2 . DCP depth profile A (right) and B (left)

By reducing the test data to a single value, there is some degree of information lost. Figure 2 shows two different DCP profiles with the same average DCP index of 49.3 mm/blow for a test layer of 400 mm. However, both profiles are clearly very different: the first profile is more variable than the second profile. The uniformity value or variation in DCP index is used to represent this variability. The uniformity of a lift is calculated in accordance with Equation 2:

$$\text{Variation in DCP Index} = \frac{1}{H}\sum_{i=2}^{n} \left| d_i - d_{i-1} \right| \cdot d_{i-1} \qquad (2)$$

where, once again, n is the total number of blows, d_i is the penetration distance for the i^{th} blow, and H is the depth of the desired test layer. Figure 3 shows the plot of variation in DCP index for the DCP profile shown in Figure 2 with depth for the DCP index in Figure 2A. Thus, over a depth of 400 mm, the variation in DCP index or uniformity value is 26.3mm/blow. The uniformity value is most convenient for detecting the “Oreo cookie” effect, whereby lifts of soil alternate between hard and soft due to overly thick lift compaction. Ideally, the uniformity value for each lift would be as close to 0 mm/blow as possible; however, this is almost never the case, and it is fairly common to have uniformity values ranging from around 5–20 mm/blow for well-compacted fill.

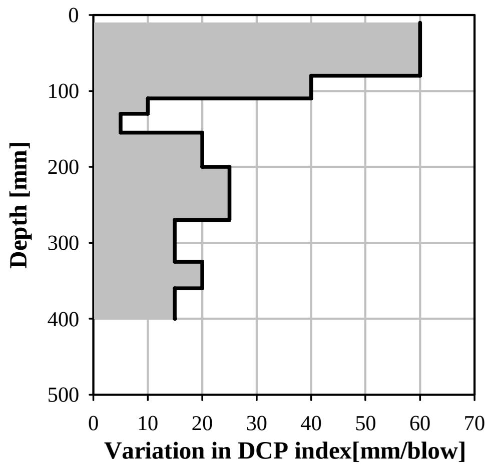

Figure 3. Uniformity or variation in DCP index for depth profile

The QM-E special provision sets the maximum stability and uniformity values acceptable for adequate lift compaction based upon the Iowa DOT borrow material soil type and grade classification (Iowa DOT Standard Specification 2102.06). See Table 1.

Table 1. QM-E stability and uniformity control limits for each soil type and grade

Soil Classification		**Average DCP Index (mm/blow)**	**Variation in DCP Index (mm/blow)**
Cohesive	Select	65	35
	Suitable	70	40
	Unsuitable	70	40
Cohesionless	Select	35	35
	Suitable	45	45

It is important to note that these control limits only apply explicitly for each test in test strip construction, as explained below, and to the four-point running average of all other QC/QA tests. This method is used to make the special provision more practical in the field to account for natural soil variability.

Test Frequency

The QC/QA testing for lift thickness, moisture content, and DCP tests are conducted at the same location and measured for each lift of embankment being placed. In addition, occasional material classification testing is conducted. The QM-E requires that all of the QC/QA testing maintain a minimum testing frequency, as shown in Table 2.

Table 2. QM-E required testing frequency

Test	Minimum Test Frequency
Lift Thickness Moisture Content DCP	Concurrently every 500 m^3
Determination of soil classification standard proctor maximum dry density, and optimum moisture content	Every 20,000 m^3

Iowa DOT Quality Assurance

Iowa DOT QA tests are conducted on a split sample at the exact location as the contractor's quality control test. In the event comparison test results are outside the above allowable differences, the engineer will investigate the reason immediately. The engineer's investigation may include testing other locations, reviewing observations of the contractor's testing procedures and equipment, and comparing test results obtained by the contractor with those obtained by the contract authority.

Iowa DOT QA testing will equal 10% of the testing conducted by the contractor. Testing will be acceptable if the QC and QA tests are within the acceptable ranges contained in Table 3.

Table 3. Acceptable range between QC/QA

Test	Acceptable difference between QC/QA
Moisture content	1.0%
Density	80 kg/m3 (0.8 kN/m3)
Optimum density and optimum moisture	80 kg/m3 and 1.5%

Control Charts

The QC/QA data is recorded in the form of control charts. Control charts contain data from a particular test versus a running test count for a particular area or soil type. These figures are convenient for visualizing QC and QA test data, as well as the failure criteria for the given parameter. In addition to containing each point measurement, these charts show the four-point running average of the test measurements, which is used as the acceptance/failure criterion for all testing. Control charts of data from the pilot project are discussed later.

Test Strip Construction

Test sections are compacted fill areas that are incorporated into the embankment and measure 50 m long, 10 m wide, and one lift thickness deep. They serve to establish proper rolling patterns, number of roller passes, and lift thickness required to attain acceptable compaction. Upon completion of a test section, four random locations are tested for lift thickness, moisture content, density, DCP index, and variation of DCP index. The test section is acceptable if all moisture content tests are within the specified control limits, all density measurements are greater than 95% standard Proctor dry density, and the DCP index and variation of the DCP index are within the specified control limits. Provided that the test section meets these criteria, construction of subsequent lifts with the same fill material should utilize the same techniques determined from the construction of the test strip. Embankment quality is verified with random QC/QA testing throughout the construction process. New test sections are to be constructed if there is a change in soil type or soil compaction methods/equipment or if QC/QA testing reveals that embankment lifts are not meeting the necessary quality standards.

PILOT PROJECT

The pilot project NHSX-34-9(96)-3H-51 was one of the US-34 bypass construction projects near Fairfield, IA (Figure 4 and 5). This project involved construction of the eastern portion of the bypass and was awarded to CJ Moyna and Sons, Inc. of Elkader, IA.

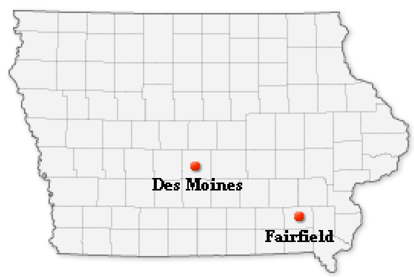

Figure 4. Map of Fairfield, Iowa

The construction spans approximately 4.6 km, and the plans call for the construction of three bridges, represented as gray rectangles; five bridge embankments; and four ramp sections, labeled A–D (Figure 5). This area of Iowa has an abundance of unsuitable soil in layers of weathered loess and Yarmouth Sangamon paleosol.

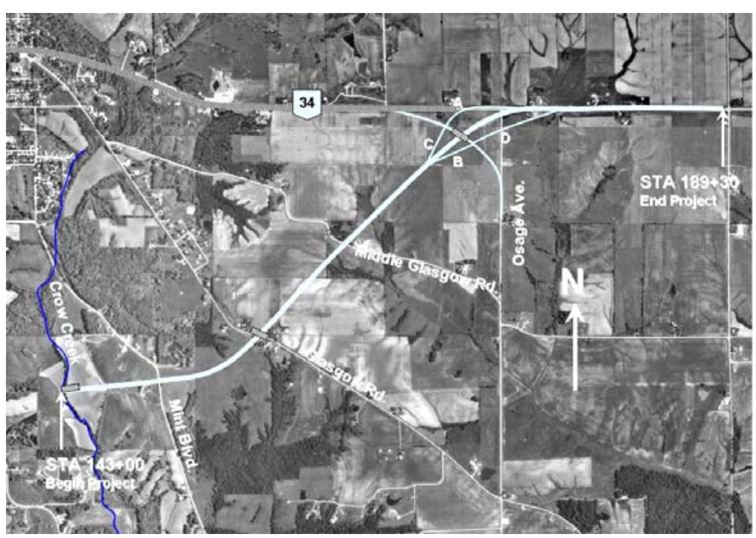

Figure 5. QM-E Pilot project, Iowa DOT project NHSX-34-8(96)-3H-51

Construction began in April of 2006 and halted in December 2006 for winter. QC/QA data was collected independently by the contractor, the Iowa DOT, and Iowa State University over this time.

ANALYSIS OF RESULTS AND KEY FINDINGS

The pilot project met the goals of providing a practical application for the QM-E provisions because considerable construction with unsuitable soil was required. Conditions throughout construction were very difficult due to relatively frequent rain and the poorly draining soils on the site. However, no significant delays were directly attributed to the QM-E provisions.

Figure 6 shows the stability, uniformity, unit weight, and moisture control charts from contractor and Iowa DOT data for an unsuitable soil at this project. There are many charts similar to this for other soils on the project; however, the general trends among them are similar.

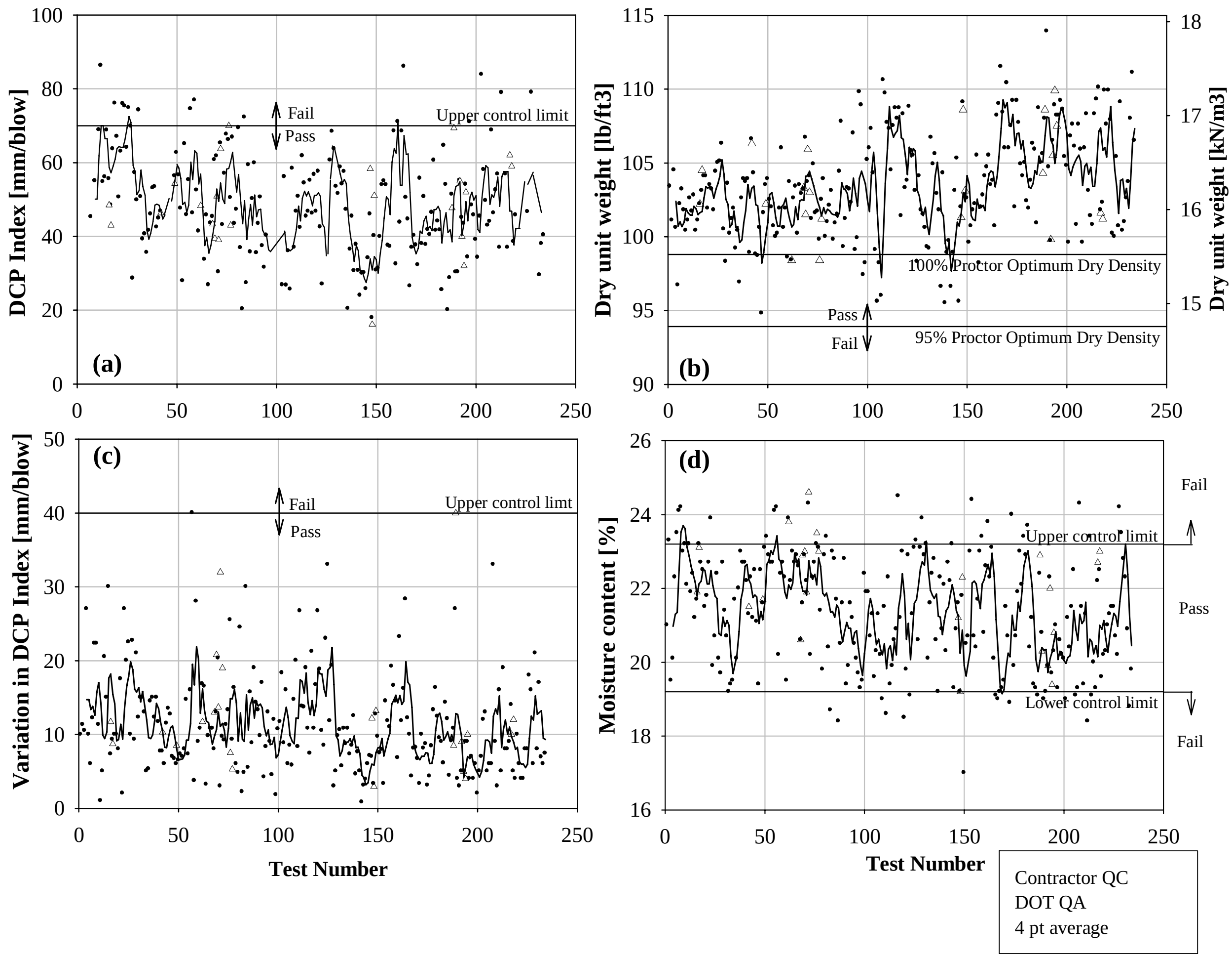

Figure 6. (a) Stability, (b) unit weight, (c) uniformity, and (d) moisture control charts for unsuitable soil

The DCP index control chart shows that observed DCP index values range from as high as 72 mm/blow to as low as 18 mm/blow, with an average DCP index of 49.3 mm/blow for all the testing. The four-point running average of DCP index did not exceeded the upper control limit of 70 mm/blow, and only a handful of single tests exceeded this limit. These observations show that at least the control limit of 70 mm/blow is not overly restrictive in unsuitable soil. In fact, if anything the control limit may be overly conservative. Regardless, the DCP test still provides records of fill strength after compaction placement, information that is not attained with density or moisture testing alone. Furthermore, density and moisture control QC/QA practices rely heavily on the results of Proctor tests. DCP test data alone are very useful for detecting fill instability that results from undercompaction, overly thick lifts, and compaction of soil well in excess of optimum moisture. Even more importantly, this information is available the instant the test is finished.

The unit weight control chart shows that the dry unit weight values ranged from as low as 14.9 kN/m^3 to as high as 18.0 kN/m^3, with an average dry unit weight of 16.2 kN/m^3 and optimum dry unit weight being 15.5 kN/m^3. The dry unit weight measurements almost always exceeded 100% Proctor optimum dry unit weight, and in some cases the measurements exceeded 110% proctor optimum dry unit weight. This may be the result of a change in the material properties that occurred after the classification tests were conducted. However, considering the trend in the DCP index was to decrease, indicating higher stability, it is of less concern.

The variation in the DCP index control chart shows that all but two of the tests were well below the control limits. One reason that these values tended to be so low is that the uniformity parameter was created to detect the "Oreo cookie" effect. This effect is more noticeable over multiple lift layers; however, the QM-E only requires the DCP test to be conducted for a single lift, and thus the variation in DCP index values tend to be low.

In general, the contractor focused most on conditioning the soil to within the proper moisture control limits. The contractor felt that as long as the soil was compacted within the proper moisture range the dry unit weight and DCP testing would pass the acceptance criteria. The moisture control limits were only exceeded twice near the beginning of construction, and the problem seems to have been corrected.

Comparisons of contractor QC and Iowa DOT QA testing reveal that the average differences between measurements at the same location for DCP index, variation in DCP index, moisture content, and dry unit weight were 7.6 mm/blow, 6.4 mm/blow, 0.8%, and 0.17 kN/m^3, respectively. These differences are within the range of acceptable variation specified by the QM-E.

Figure 6 also seems to show some trends with time. The DCP and unit weight control charts seem to show that the unsuitable soil got stiffer and denser as the project proceeded. Even the moisture and uniformity charts seem to show that the soil became more uniform and tended to have slightly lower moisture content later in the project. It is difficult to explain all of these occurrences; however, it seems probable that the fill materials properties changed at some point, especially considering that the dry unit weight measurements regularly began to exceed 105% relative compaction. This example illustrates two very important points regarding the QM-E. First, the control limits for moisture and dry unit weight are solely dependent on the results of Proctor testing. While the QM-E sets guidelines regarding the frequency of this type of testing, it is the engineer's and quality control technician's responsibility to determine whether or not additional testing is required. Finally, the control charts are very helpful tools for deciding when additional testing may be required. If the control charts show a systematic change in the values on any or all of the charts, it likely indicates that some sort of change has occurred, whether this is in soil properties or the moisture content of the soil at compaction. These changes may not always be detrimental, but the engineer must make a judgment call based upon the available data as to whether some sort of corrective measure is required.

Figure 7 shows the distributions of the contractor data. This data is the same as the data shown in Figure 6. The distributions are useful for looking at the frequency of each measurement.

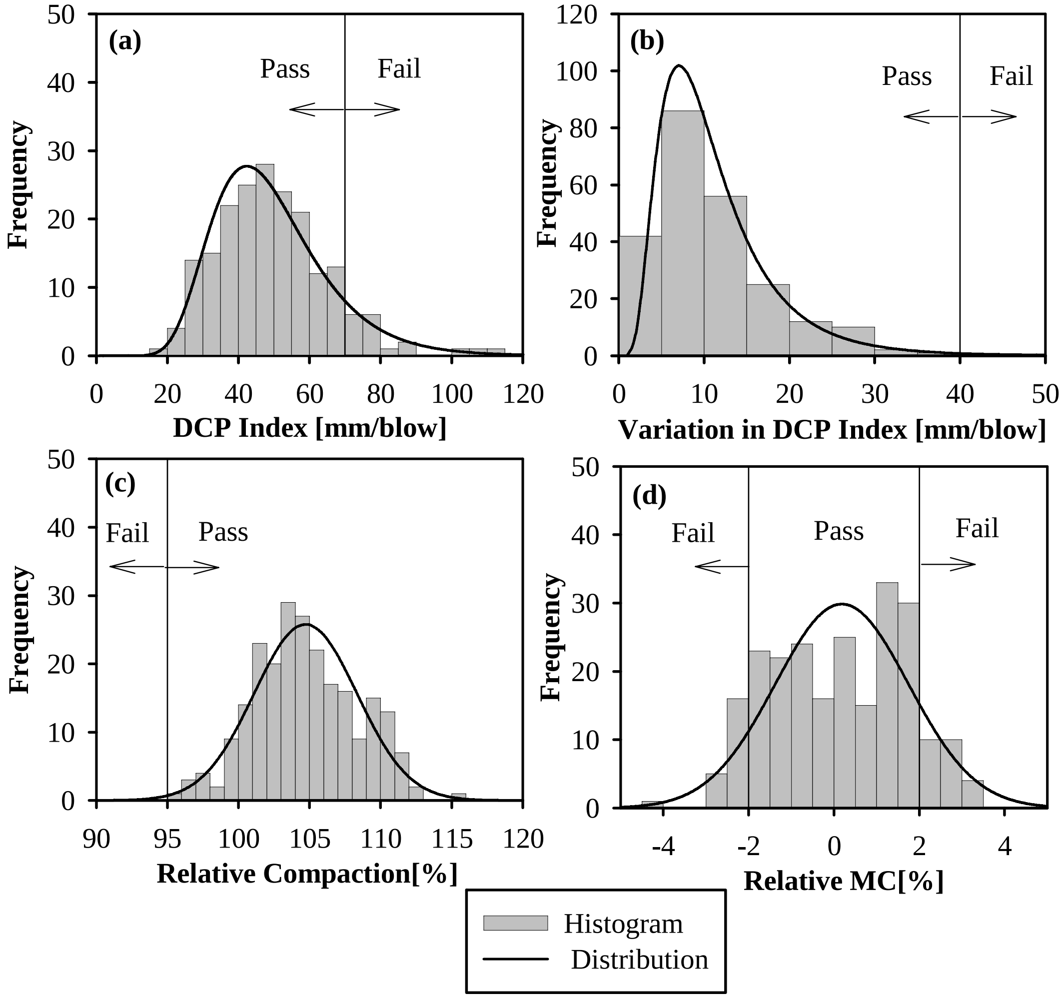

Figure 7. (a) DCP index, (b) variation in DCP index, (c) relative compaction, and (d) relative moisture distribution

The distribution of DCP index values shows that 12.7% of the testing exceeded the DCP index control limit of 70 mm/blow. While this may seem high, since the four-point running average of tests is used for the failure criteria, very few, if any, failures would occur. Additional distributions of DCP index data for varying soil types would be helpful for examining the probability of failures and potentially justify raising or lowering the control limits accordingly.

The distributions of variation in DCP index seem to reiterate the conclusions from earlier. None of the contractor tests exceed the control limit of 40 mm/blow, with only 17% even exceeding 20 mm/blow. One of the biggest problems that was identified with the uniformity parameter was that it is extremely rare and nearly impossible for a DCP test to pass the DCP index control limit for a single lift and fail the variation in DCP index control limit. This makes the test slightly redundant and seems to indicate that the control limit for variation in DCP index may be overly conservative as well. Additional research is necessary to develop this concept, and perhaps a new method of calculation is required.

The distributions for relative compaction and relative moisture content both appear to have a bimodal distribution. The highest peaks are at 103% relative compaction and 1.5% relative moisture content, while the smaller peaks are at 110% relative compaction and -1.5% relative moisture content. These peaks seem to suggest that the data contains two different soil types, supporting the prior assertion that fill properties may have changed at some point during construction.

Iowa State University also conducted independent classification and QA testing based out of the Iowa State University Geotechnical Mobile Lab throughout the project (Figure 8). Testing was conducted to monitor the Iowa DOT and contractor QC/QA testing. Figure 9 shows the results of testing conducted on August 17, 2006, between STA 143–145 of the project and comparisons to contractor QC test data. The fill material at the time of these tests was classified as the same unsuitable material from the above figures.

The DCP index and variation in DCP index control charts show that the Iowa State University and contractor testing seem to fall within similar ranges. The moisture and dry unit weight control charts show greater differences between Iowa State University and contractor data. Iowa State University moisture tests ranged from 19.8%–25.6 %, while contractor tests ranged from 19.2%–21.0%. The dry unit weight tests also ranged from 17.4–18.7 kN/m^3 and 16.4–17.2 kN/m^3 for Iowa State University and contractor tests, respectively. The Iowa State University classification tests resulted in a higher optimum dry unit weight and lower optimum moisture content in comparison to the values that were being used by the contractor at the time. Interestingly, even using the modified control limits, all of the contractor's QC testing would have passed. While all of these discrepancies potentially represent some degree of bias in either the QC or QA testing, it is more likely that they are the result of natural variability within the sample, illustrating one of the fundamental challenges of all earthwork QC/QA programs.

Figure 8. Geotechnical Mobile Lab (left) and Iowa State University Q/A testing at the Crow Creek embankment on August 17, 2006 (right)

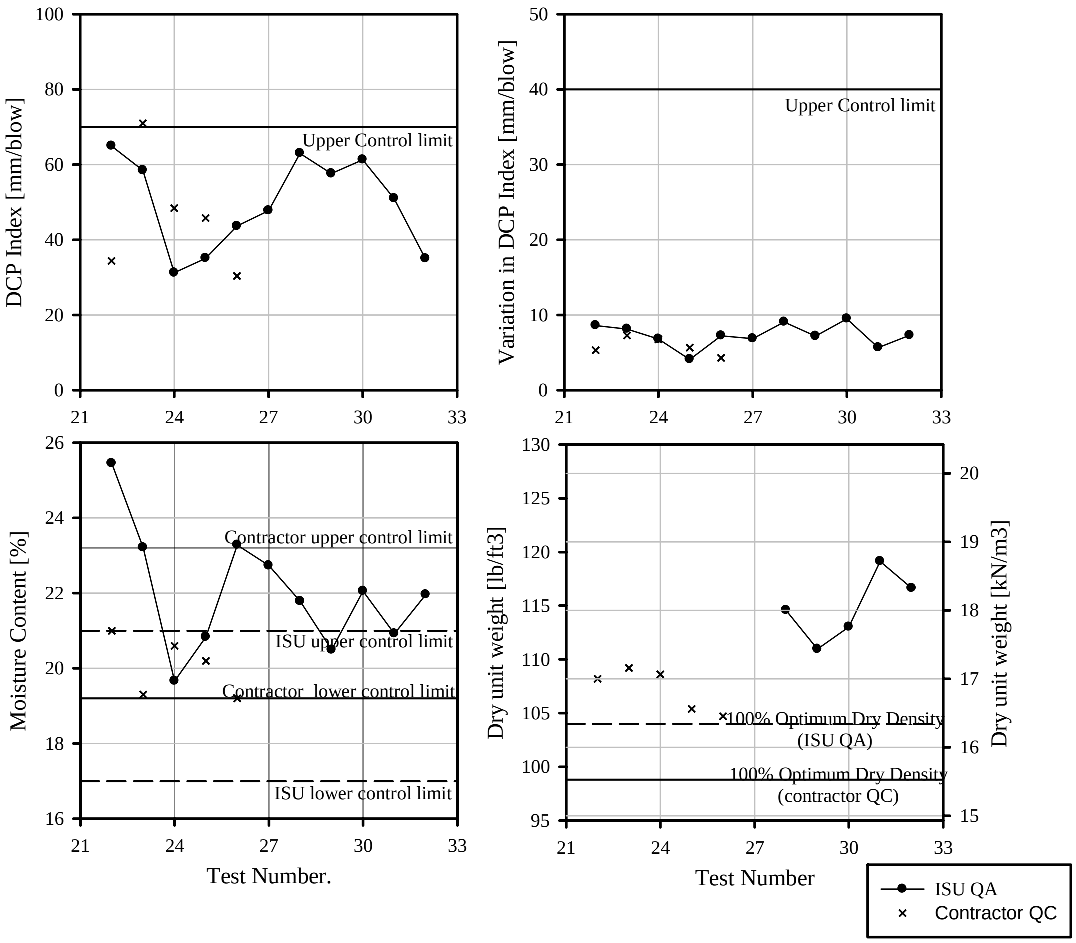

Figure 9. ISU QA testing data taken on August 17, 2006 between STA 143–145

CONCLUSIONS

The QM-E was successfully implemented for a pilot project that involved predominately unsuitable soil. Although the implementation was generally successful, a few areas of improvement were identified. First, the required DCP testing depth needs to be modified to be at least two lift thicknesses to improve the usefulness of the uniformity parameter, which was originally developed based upon testing over many lifts. The DCP index will still be reported for only the top lift; however, the variation in DCP index will be reported for the full depth of the test. While this change addresses some immediate concerns, additional research is required to further develop the understanding of the uniformity parameter, and a new calculation method may need to be developed. Secondly, a new provision must be added to require additional classification testing in the event that the four-point average of dry unit weight testing exceeds 105% optimum dry unit weight. This requirement will attempt to correct some of the issues that were observed at the pilot project with improper soil classification. Finally, though the DCP index control limit for unsuitable soil appears to be overly conservative, additional laboratory testing would be required to justify lowering the limits. It is the authors' opinion that an overly conservative DCP index is not necessarily a bad thing. The moisture control limits should be the controlling factor in embankment construction until research provides a better understanding of the relationship between strength-moisture-density. For now, the DCP testing should be supplemental to verify that the fill material is meeting a minimal strength requirement.

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