Field Implications of Current Compaction Specification Design Practices

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Abstract: The engineering properties of compacted soils are of primary importance in fill performance. However, for economic reasons, the achievement of a given relative compaction and compaction water content has become an end in itself for field compaction control. Although the profession has developed an understanding of the relationships between properties and compaction density/water content, it has become routine practice to use some combination of precedence and code rather than desired material properties to establish compaction specifications. Because of the heavy emphasis placed on relative compaction, it is extremely important that geotechnical practitioners and earthwork contractors recognize the deviations in field density that can occur as a result of typical differences in the compaction processes and in the methods of compaction control encountered. Variations in both the field density and the laboratory-determined reference maximum dry density arise from numerous sources. A corresponding spatial variability of relative compaction should therefore be anticipated. This paper provides a comprehensive evaluation of potential problems in compaction control, and addresses the sources of field variability in relative compaction.

INTRODUCTION

The mechanical compaction of earthen materials is one of the oldest techniques for stabilizing fills and foundations, having been employed for centuries. Professionals and laypersons alike know that important material properties, such as compressibility, shear strength, and hydraulic conductivity, are improved by compaction to higher density.

It was not until the formalization of soil mechanics in the 1930s, and the mushrooming of laboratory soil testing during the following decades, that the relationships between the degree of soil compaction and the resulting soil properties were quantified. Laboratory testing programs have also shown that the compaction water content as well as the density strongly influence the final soil properties. The following is the general procedure that arose from these laboratory testing programs for designing fills and embankments.

For each representative soil type

1. Study the variation of the property(s) of interest (such as shear strength or compressibility) with compaction density and water content.
2. Select a set of compaction specifications that ensures property(s) that (1) are acceptable and practical for design; and (2) are reasonably obtainable in the field by the earthwork contractor.
3. Proceed with design, using properties consistent with the compaction specifications.

This procedure will be referred to hereafter as procedure I. A relevant aspect of this procedure that was discovered early on is that expressing density as a percentage of the maximum density by a standardized compaction test produced a normalizing effect. This percentage is termed the relative compaction. For example, suppose that the compressibility of a silty clay is found to have some particular value at 94% relative compaction, which corresponds to 17 kN/m^3. If this soil is compared to a different but similar soil, such as a sandy, gravelly clay, it would be found that the compressibility at 94% relative compaction would be close to, but not precisely equal to, the corresponding value for the first soil at 94% relative compaction. However, the agreement would be much better than if the two soils were compared at an equal density of 17 kN/m^3. Thus, the use of relative compaction is said to have a normalizing effect and has been generally used for compaction control.

Procedure I is unquestionably sound and represents good engineering. It was fairly widely adopted in the 1950s and 1960s, particularly in large institutions such as the U.S. Bureau of Reclamation (USBR) and the U.S. Army Corps of Engineers (USACE). However, its use has declined dramatically over the past three decades. It has been replaced with a much more empirically based approach that could even be described as a shortcut. This procedure, described in the following paragraphs, is currently used very widely. In the present paper, it will be referred to as procedure II.

For each general region of the country

1. Observe and/or gather statistics on (1) the minimum relative compaction specifications typically used in the area; and (2) the general performance of fills and embankments constructed under these specifications, particularly the number of failures or problems.
2. If the number of failures is judged to be too high, upgrade the relative compaction specifications. If the number of failures (problems) is acceptable, continue using that minimum relative compaction value as the compaction specification for future work.

The adoption of procedure II has been accompanied by a general trend toward less testing and analysis as part of geotechnical investigations, particularly the more sophisticated testing that could provide data for analyses and prediction of future performance. It is noteworthy that procedure II does not necessarily involve slope stability or settlement analyses. It seeks to establish a direct relationship between compaction specifications and performance. Perhaps the use of standard slopes for specific material types is implied in procedure II. Thus, the fact that the relationship between relative compaction and shear strength is not well-known is not particularly troublesome if no slope stability analysis is made.

It is of value to consider why procedure II has become so widely adopted. Probably the most relevant benefit of procedure II compared to procedure I is that it reduces the up-front

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costs of geotechnical investigations and testing. Pressure from owners and administrators to reduce design costs has had a pronounced effect. It is the opinion of the writers that the root cause of the trend toward decreased testing is the fact that geotechnical engineers have failed to establish a link between the amount of geotechnical testing and analyses and total life-cycle project costs (Houston et al. 1995). If such a link were established, it might be possible to demonstrate that the use of procedure I is typically less costly than the use of procedure II, relative to compacted fills.

Nevertheless, even though the use of procedure II in lieu of procedure I may arguably be a step backward in terms of engineering practice, it is firmly entrenched in both the private and public sectors. As a consequence, the achievement of a particular relative compaction has become an end in itself and, in many cases, without consideration of the accompanying performance of any specific fill [e.g., Schexnayder (1994)]. This situation is likely to persist until research showing the value of a more rigorous and complete approach is conducted and published. Because of the slow rate at which geotechnical engineering practice changes, it is likely that the heavy emphasis on relative compaction as an end in itself will persist for at least a decade or more. Furthermore, relative compaction is an important component of both procedures. The relative compaction is the ratio of the in-situ dry density to the reference dry density. Thus, a problem with either the determination of the in-situ density (in the field) or the reference density (in the laboratory) results in a problem with the relative compaction. The remainder of this paper is devoted to addressing these problems. A comprehensive evaluation of the potential pitfalls in compaction control in the United States as of this writing is provided. First, several sources of variation and ambiguity relative to the compaction control process are reviewed, followed by a discussion about the impact of these variations on the development of specifications, with a contrasting evaluation of common earthwork specification practice. Finally, these issues are considered in order to make some recommendations for practice and further study.

VARIABILITY IN COMPACTION CONTROL

Reference Density

Torrey and Donaghe (1991) and Houston and Walsh (1993) have demonstrated that the maximum density is a complex function of many parameters. A partial list of relevant variables includes the soil type, the effort imparted, the equipment used in the test, the operator who performs the test, the size of the compaction mold, and the method used for accounting for material beyond the size that can be handled in the laboratory.

One way to account for the presence of many variables would be to rigidly control the test procedure and the value of these variables in the test. Although the maximum density test has been standardized, it has been standardized differently by different agencies. This is most clearly true for rock correction procedures, but secondarily true for the energy imparted to the sample, the maximum particle size that can be used in a given mold, and the mold size. The impact of differing standards can be a confusing array of experience-based expectations for performance among the contractor, the engineer, and the inspector, and the differences among these entities increase with geographic distance (Walsh et al. 1994).

To combat some of these issues, tightly written specifications should therefore include the rock correction method expected by the designer in the preparation of the design (Houston and Walsh 1993). Walsh et al. (1994) conducted a survey of contractors in the southeastern United States to evaluate the potential severity of the variability in rock correction procedures. While most contractors expressed that the American Association of State Highway and Transportation Officials (AASHTO) standard *T99* was the common control method, the contractors also indicated that they were accustomed to scalp-and-replace correction methods. Since the 1993 study, the scalp-and-replace procedure has fallen out of favor. In addition, the writers were surprised to find that many practicing geotechnical engineers felt the issue being raised was of little consequence, because of the perception that the common compaction control practices in the United States were uniform across the country.

The maximum density of a given fill or backfill material is generally treated as a quasi-fundamental property. Anyone who has reduced the raw data, or actually conducted the moisture-density relationship test, will report that the value of the maximum dry density is not precise. In the first place, each of the three to five points commonly used to draw the moisture-density relationship curve depends on a number of operator and process factors. If enough points were pounded at a given water content, one would find a distribution of values of density for any given water content (Fig. 1). One generally confronts this variation only when a point seems out of line from the others. Even assuming the moisture-density points are "right" according to some objective standard, the sketching of the moisture-density curve itself involves some subjective interpretation. Together, the point-by-point variability and the subjectivity of the curve imply a potential for different results, especially when the testing is performed by different technicians and/or labs.

Variability of this type is countenanced by the test procedure itself. The AASHTO test procedure for moisture-density relationships (AASHTO *T 99-94*) allows the same operator to test the same soil and obtain a different answer, as long as that answer is within about 2% of the maximum density and 10% of the optimum water content. Repeatability limits for the same soil by different laboratories are roughly twice as high. Very few rigorous and statistically significant tests of these limits have been conducted. Torrey and Donaghe (1991) provide an excellent summary of available evaluation of the multilaboratory and single-operator repeatability testing.

Fig. 2 shows the maximum densities and water contents for

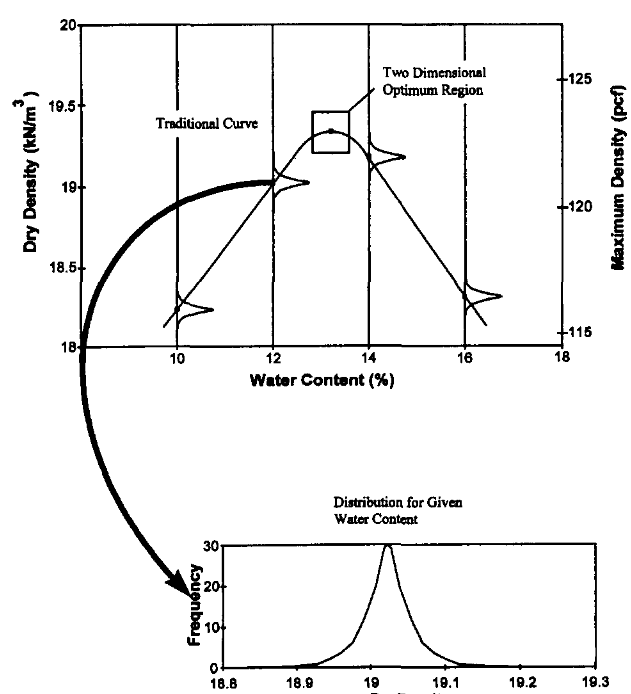

FIG. 1. Schematic Diagram Illustrating Variability of Measurement for Given Point

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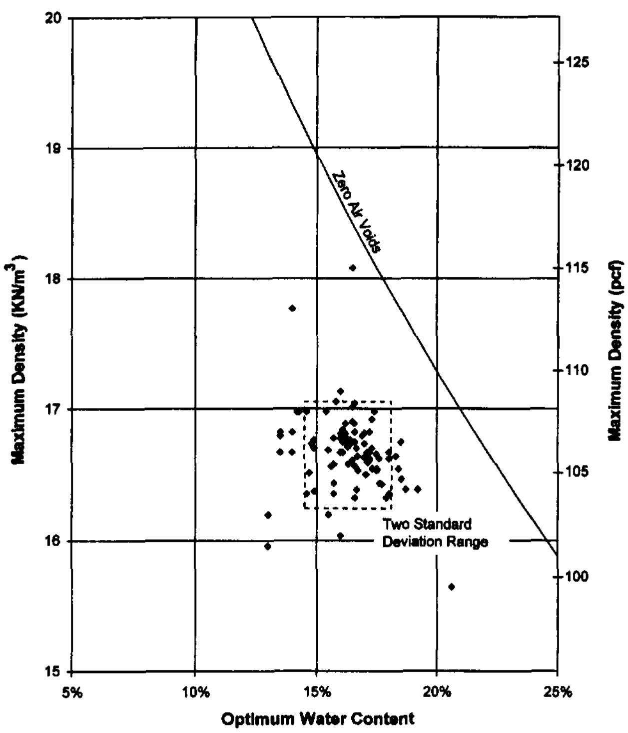

FIG. 2. 1964 American Council of Independent Laboratories Multilaboratory Variability Study of ASTM *D698-58* with ML Soil Duplicates [after Torrey and Donaghe (1991)]

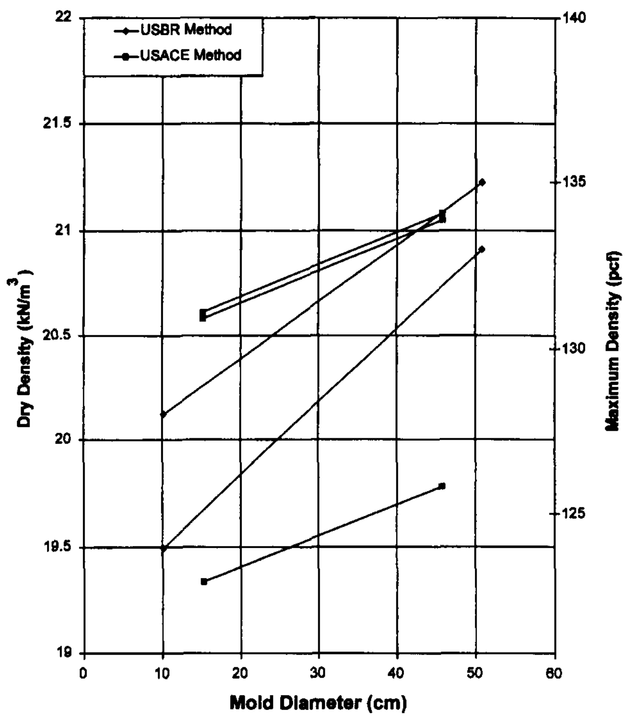

FIG. 3. Effect of Mold Diameter on Maximum Dry Density Using USBR and USACE Test Methods [Data Reported by Torrey and Donaghe (1991)]

"identical" soils as reported by 98 different laboratories. This figure shows that the optimum water content and maximum density, as determined by multiple laboratories, form a region in density-water content space. This result matches our expectation based on Fig. 1. One tends to think of the (usually singular) result from the laboratory that performed the test as "the" result. Clearly, different laboratories tend to yield different results, and similar, though smaller, variations could be demonstrated for a single operator in a given laboratory.

Another source of variability is the degree to which the material used to obtain the reference maximum density and optimum water content represents the material at the particular in-situ test. As will be discussed in more detail subsequently, a field technician typically must choose the reference density curve that was obtained for a material that most closely matches the material where a particular in-situ density test is performed. Approximations inherent in making this match represent a common source of error.

Furthermore, the equipment size impacts the result. A number of studies have shown a relationship between the size of the compaction mold and the location of the peak of the moisture-density relationship curve for a given soil and a given compactive effort (Fig. 3). In the case of a material with coarse-grained particles that cannot be tested in a standard-size mold, the relationship between mold size and curve position makes the determination of the "actual" maximum density even more ambiguous.

When a material contains particles too large to be tested in a standard-size mold, one must make a decision about how to proceed with the testing of the material. By way of definition, "too large" will be interpreted to mean any particle larger than about 1/6–1/8 of the diameter of the mold. In the writers' experience, this seems to be about the consensus for how large is "oversize." The writers are not aware of any rigorous testing of this rule, but most testing agencies and companies seem to use it (even though some agencies accept material as large as 1/4 of the mold diameter). For the purpose of this discussion, the actual boundary between acceptable and too large is not really important; in concept, one is faced with testing a material that will not fit in the mold. We will refer to the portion of the gradation that is judged to be too large as the "oversize material."

When the material to be tested includes an oversize fraction, one can proceed in about four directions, which we will discuss in no particular order (later in the paper, we will explore which avenues are most frequently used). Note that this discussion presumes a compaction test will be run; one could instead simply give up and adopt a method specification.

One option for handling the oversize material is to enlarge the compaction mold. The advantage of this approach is that the test procedure would then include the entire gradation. However, there are disadvantages to this approach. For one thing, the relationship between the position of the curve and the mold size (Fig. 3) would need to be addressed (Torrey and Donaghe 1991). Of considerably more practical importance is the increased difficulty of performing the test. Compactive effort is generally reported as work per volume of soil tested, meaning that as the mold diameter increases, the work required to perform the test increases dramatically. Here we are speaking simply of the work to physically compact the soil into the mold. The increased lab space, sample size, and handling difficulties that are imposed by large-scale testing are also significant concerns. Simply because of these issues, large-scale testing is rarely performed.

A second approach to the oversize material would be to remove it from the sample and test the fraction of the material that remains. The procedure for removing the upper portion of the gradation curve is often called scalping. When the relative weight of oversize material is extremely small, this procedure can be expected to yield approximately comparable moisture-density relationship curves as would result from full-scale testing. However, when the percentage of oversize material is large, scalping clearly produces a major change to the properties of the material being tested and can therefore yield changed results (Torrey and Donaghe 1991).

A commonly used procedure to ameliorate the change in the gradation described earlier is to replace the weight of material

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removed with an equal weight of almost oversize material. For example, if the 19 mm (3/4 in.) screen is chosen as the maximum permissible size, a new material might be created in which the weight of material removed by scalping with the 19 mm sieve is replaced with an equal weight of material that passes through the 19 mm sieve but is retained on the #4 screen (#4 × 19 mm). In effect, one would test a material with a similar percentage of gravel by weight but with a more uniform gradation of the gravel. This procedure, often referred to as scalp-and-replace, has been removed from the ASTM standard but is still allowed under AASHTO test methods (*Method C*). Critics of the scalp-and-replace procedure argue that the change in the shape of the gradation curve is typically too great, as are the corresponding changes in material properties, including the maximum density.

The last solution is to run the compaction test with a scalped gradation and then use an equation to correct the resulting maximum density and optimum water content to those that would have been obtained if the full gradation had been tested. There are a number of such so-called rock correction equations in use. The advantage of the rock correction equation approach is that the test itself is only complicated to the extent that scalping must be performed, which is a relatively simple procedure in the laboratory. The field application of the method is also relatively straightforward. By scalping the field sample to determine its percentage of oversize, one can obtain a maximum density specific to that particular location simply by evaluating the equation at that location. The disadvantage to the rock correction equation arises in the confidence, or lack of it, that one has in the corrected result.

The scalp-and-replace method and the rock correction method are the most common oversize correction methods in use today, with equation-based methods by far the more popular of the two. For simplicity, we will confine our treatment of these two methods to the maximum density that results, although obviously a similar discussion could be conducted for optimum water content. In the context of this discussion, it is important to keep in mind the following two key issues: (1) The maximum dry density that results from the laboratory test itself contains inherent variability such as that depicted in

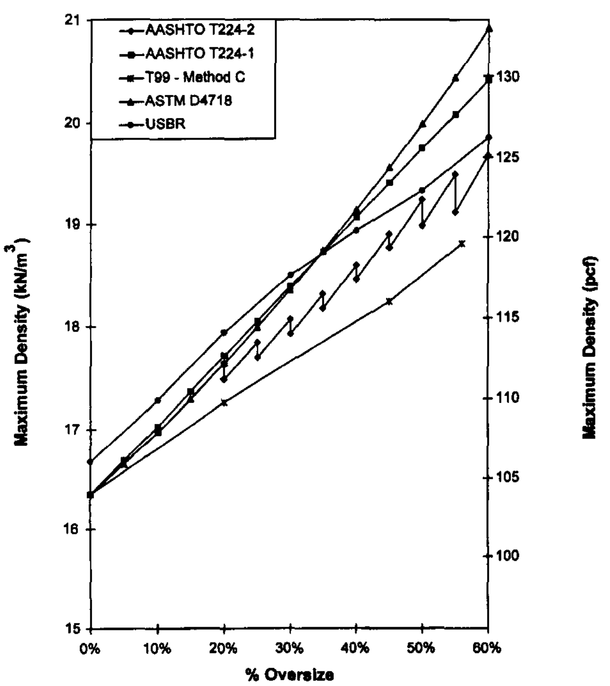

FIG. 4. Predicted Maximum Density versus Oversize Content for Several Common Methods [Data from SC Soil after Houston and Walsh (1993)]

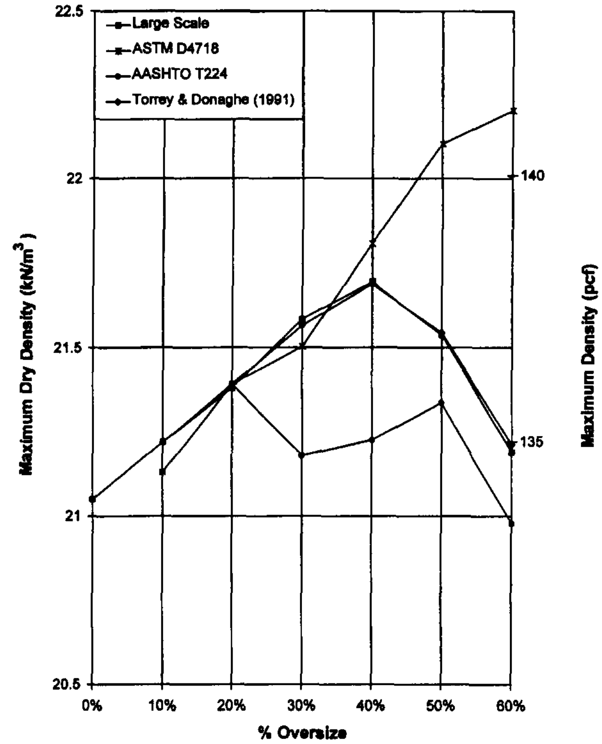

FIG. 5. Comparison of Rock Correction Methods of ASTM, AASHTO, and Torrey and Donaghe (1991) to Large-Scale Results [after Torrey and Donaghe (1991)]

Fig. 2; and (2) The treatment of the oversize material has been shown to have a significant effect on the maximum dry density obtained, an effect that increases with increasing quantities of oversize materials. Fig. 4 is an example of this effect for several important rock correction equations applied to a clayey sand and gravel sample from central Arizona.

Torrey and Donaghe (1991) reviewed the important common correction methods (including the ASTM, AASHTO, USACE, Naval Facilities Engineering Command [NAVFAC], and USBR methods) and found them to correlate poorly with the results of large-scale tests. This poor correlation was found to extend even to the more sophisticated methods such as the AASHTO and USBR methods, which include a factor to account for the decreasing compaction of the finer-grained fraction of the material as the percentage of oversize material increases. Because these correction factors are very soil specific and thus standard relationships cannot be expected to precisely describe a wide range of soil types, Torrey and Donaghe recommend an approach for the development of soil-specific correction factors. While this approach can yield extremely good agreement with large-scale testing (Fig. 5), it is very unlikely that such an approach will be used, except for projects involving extremely large quanities of fill.

In-Situ Density

In current practice, the as-compacted, in-situ density and water content are the properties of most interest for monitoring compaction. Monitoring requires that the density and water content of the fill under evaluation be measured, and that the results be compared to the appropriate laboratory reference value. The comparison, which generally consists of a computation of the field density as a percentage of the laboratory maximum (relative compaction) and the difference between the field water content and the laboratory optimum, must be within the tolerances described by the compaction specification. For very granular materials, a relative density approach is often adopted (Monahan 1986). The compaction testing,

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computation of relative compaction, and comparison to specification are generally performed by a field technician.

The tests are typically performed under pressure to obtain results quickly, so that construction of the fill can continue. As a consequence, over the last decade or so, rapid methods of obtaining the field result are preferred to the more traditional sand cone test. Today, nuclear density gauges and chemical moisture tests are the rule for field testing because the results are essentially instantaneous. As compaction proceeds, the technician is required to compare the borrow soil tested to the soil used to develop the curve or curves available, and to select the most representative curve. The selection of the most representative curve is primarily based on visual evaluation and knowledge of the borrow source, although sometimes indicator tests are performed in the field to aid in the selection of a proper curve. When a new soil is encountered for which no available moisture-density test is deemed appropriate, the technician is required to obtain a new curve for evaluation of the new soil. In short, the technician supporting the engineer's specification is charged to make many decisions in a very limited time.

The process of performing the compaction does not lead to highly spatially uniform densities. When a significant amount of fill is to be placed, the compaction will be primarily handled with large-scale equipment. The density and water content of the fill at any one point will be dependent on a number of factors, such as the number of times the equipment passed over that point and the degree to which the soil was sufficiently or insufficiently wetted. Therefore, there will be spatial variation in the density within the fill, and a corresponding distribution of relative compaction, for reasons quite apart from the issues described for the test itself or for the evaluation of the reference density.

Fig. 6 shows a frequency distribution of compaction test results for a large fill project in Arizona, representing over 240 tests. The specification called for compaction to at least 95% of the maximum dry density resulting from Arizona Department of Transportation (ADOT) *Test 225* (a slightly modified version of AASHTO *T99*). The points shown are from the first test at a given point, meaning that the results of retests after rework to improve the density at locations where the specification was not met are not shown. Clearly, the preponderance of results are above the specification limit, with some well above and a few well below.

The figure reveals a few important issues. First, the compaction specification is developed and the compaction process is monitored to ensure that the relative compaction will be equal to or higher than some minimum value. For example, the minimum allowable value may correspond to a minimum value in shear strength. The fact that parts of the fill will have relative compactions in excess of the minimum value is rarely taken into consideration in the design and analysis of fill performance. The influence of the distribution of fill properties on fill behavior has received little attention, and the improvement that results in scattered locations within the fill is generally used as a sort of unstated factor of safety.

Using Figs. 6 and 7, one can evaluate the potential impact of being subjected to a rock correction method outside one's experience. Imagine that a contractor has developed experience over a long period of time in compacting gravelly fills with compaction controlled using a rock correction method such as scalp-and-replace, that tends to result in lower corrected reference values. This experience has led to the development of estimating tools and construction practices geared to meeting that specification. During compaction, a distribution of relative compaction values similar to that shown in Fig. 6 might be developed. These relative compactions could be multiplied by the maximum density achieved using the scalp-and-replace method to develop a distribution of absolute densities having the same shape.

Now, imagine that this contractor embarks on a new job in which compaction will be controlled with a more aggressive rock correction procedure, such as the factored AASHTO method (*T224 Equation* 2). If the contractor is unaware of the significance of the change in rock correction methods, the company may well develop its bid and perform its compaction using the methods that worked in its experience. However, the densities developed using these methods, which were acceptable under scalp-and-replace rock correction, would now more frequently fall short of the target relative compaction. Fig. 7 was developed by transforming the relative compaction data of Fig. 6 to absolute densities using the value of maximum density predicted by scalp-and-replace (*T99 Method C*) in Fig. 4 at 30% rock content, and then evaluating the relative compaction by the AASHTO density from Fig. 4 at 30% rock content. The percentage of failing tests increases from 10% to 56% as a result of this change.

Each failure will require that the contractor do some rework, either a few extra passes with the equipment if the result is close to the specification, or potentially more significant rework if the result is far short. In any case, the experience developed with the scalp-and-replace method will not serve the contractor well under a change in rock correction methods. In all likelihood, the contractor will change methodologies once the failures start occurring more frequently early in the job. However, the estimating tools used to determine the cost

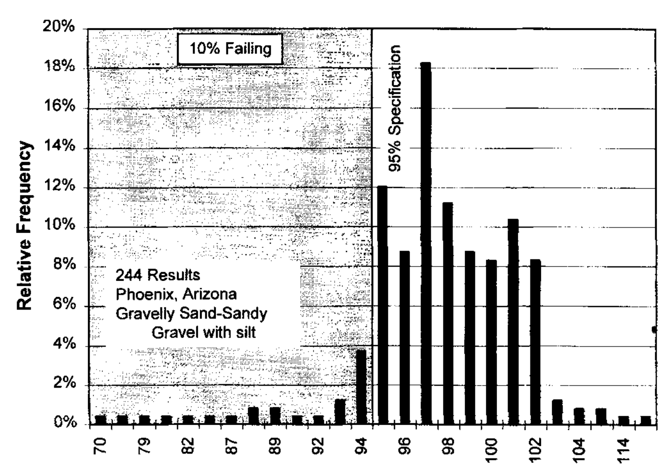

FIG. 6. Distribution of First Compaction Test Results for Large Earth Fill Project

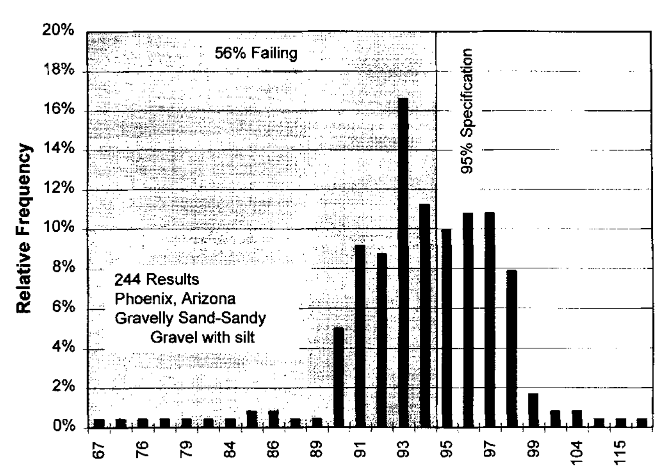

FIG. 7. Change in Frequency Distribution under Different Oversize Correction Procedure

of applying appropriate compactive effort are still important to the contractor, whether the correction occurs before or after the density test results are obtained.

SPECIFICATION PRACTICE

Specifications for compaction control in use in the United States today do, in fact, vary widely across the country. Using procedure I, the specification would be developed by developing contours of the property of interest in moisture-density space, and then selecting a specification so that this property has the desired value (Daniel and Benson 1990). However, for the vast majority of transportation projects, this kind of effort is rarely expended. Instead, compaction control specifications are most likely developed by precedence (procedure II). A particular specification finds its way into a standard specification or a consulting office and is only rarely changed. While this practice is acceptable as long as the resulting fills perform satisfactorily, overdesign may occur from time to time. The potential is created for compaction specifications to vary from place to place, not due to technical issues but, rather, due to jurisdictional issues.

To evaluate the extent of these variations, the writers conducted a state-by-state survey of typical compaction specification practices in state departments of transportation (DOTs) across the United States. All 50 states plus the District of Columbia were contacted, and information was obtained from 49 jurisdictions. The results are summarized in Tables 1 and 2. Table 1 summarizes the number of states that reported using the indicated test method for the moisture-density relationship curve for roadway fill, exclusive of base or subbase materials. The most common test method is *T99*, commonly referred to as the standard Proctor, with the balance of the states reporting modified effort with the use of *T180*. Some states use both methods, and so are double counted. In one state, compaction is routinely controlled by specification of method rather than by control of density. More than half of the states have modified the AASHTO standards, some significantly; but all methods were grouped together into *T99* or *T180*, according to the compactive effort used. Reported major changes included different mold sizes, partial segregation of fines, scalping requirements (#10 to 12 mm were reported), different maximum particle sizes (up to 45 mm in the 152 mm mold), use of the ASTM procedures, and use of the Harvard miniature procedure.

TABLE 1. Number of State DOTs Using Indicated Standard Test Method

Test designation (1)	Number of DOTs reporting (2)
AASHTO *T99*	41
AASHTO *T180*	10
ASTM *D698*	1
Method specification	1

TABLE 2. Minimum Limit Specifications for Relative Compaction Reported by State DOTs for Upper Portion of Embankment Fill

Relative compaction limit (1)	Standard proctor (2)	Modified proctor (3)
85%	0	1
90%	2	1
92%	2	1
95%	30	5
96%	1	0
97%	1	0
98%	0	1
100%	5	1

The specification limit in common use for the upper portion of an embankment fill can be found in Table 2. The most common specification limit for density is 95% of the *T99* maximum density. Through the course of the development of this table, it was clear that some states will typically use *T99*, but might sometimes specify *T180* with roughly a 5% reduction in the specification limit. While this rule of thumb may result in a similar density, the water content difference that arises from the increased effort of *T180* must also be considered. In general, the lowest specification limits (85% of *T180* or 90%–92% of *T99*) were reported by states with significant quantities of expansive materials. Geographically, the use of *T180* is more common in the South than in any other region.

A number of rock correction procedures appear to be in current use by state DOTs (Table 3). While a significant number of states (six) reported that oversize correction was never needed, most reported the use of some form of oversize correction practice. The majority of the states (34) appear to be using rock correction equations, most commonly AASHTO *T224*. Three of the four states listed under "Other" have their own equation, two of which are identical to *T224* with modified correction factors. Six states reported that they use a scalp-and-replace procedure, with scalping reported on screens ranging from the 12.5 mm to the 25 mm screen. Three states indicated that gravelly materials are handled by changing the compaction control procedure. When gravelly soils are being compacted, these states use a method specification augmented by the judgment of the site engineer/technician. It should be noted that those states that encounter occasional, very gravelly fills reported that a method/judgment procedure was used when the oversize percentage exceeds 30%–50% (roughly the limit of applicability for *T224*).

Consulting geotechnical engineers have also developed their own experience base for compaction specifications. These specifications, which may be loosely based on a county or municipality code, are typically used for commercial and industrial projects. A survey of geotechnical firms in the arid to semiarid regions of the Southwest United States was recently completed by the writers. The results of this survey show that procedure II is widely adopted in practice, as indicated by the fact that 21 of the 24 firms involved reported that they used precedent as a primary guide for selection of relative compaction specifications, particularly when significant large aggregate was present in the soils. City or county code was also cited as a controlling factor in compaction specification selection. Rock correction equations were found to be very common, with 21 of the 24 firms adopting rock correction equations for dealing with soils containing large aggregate.

Approximately one-third of the firms indicated that they did perform laboratory tests on compacted soils to assess performance with respect to hydrocompression or swell. The reason for the relatively recent increase in laboratory response-to-wet-

TABLE 3. Number of State DOTs Using Indicated Oversize Correction Procedures

Correction procedure (1)	Number of DOTs reporting (2)
None[a]	6
AASHTO *T224*	24
ASTM *D4718*	6
Other[b]	4
Scalp	1
Scalp-and-replace	6
Method specification	3

[a]Gravelly materials not present in DOT fills.
[b]Two states report modifications of correction factors used in *T224* (*Equation* 2); two states report radically different approaches not discussed herein.

ting testing is likely due to numerous cases of poor fill performance and litigation in the Southwest regions of the United States, particularly southern California. Thus, procedure II has led to a general increased stringency in the relative compaction specifications of Southwest region firms. While a decade ago it was common practice to routinely call for relative compaction of fill materials to densities greater than or equal to 90% of ASTM *D1557*, approximately one-half of the firms surveyed indicated that a typical compaction specification for deep fills is now greater than or equal to 95% of ASTM *D1557*. Additionally, when expansive soils are present, lower densities and higher water contents are often specified to control swell. Procedure II can lead to a general improvement of practice over time, as evidenced by the upgraded compaction specifications beginning to emerge in arid regions of the United States due to poor fill performance in response to wetting (Kropp et al. 1994; W. N. Houston, unpublished survey, 1996). Typically, the upgrading of practice is a slow process. Further, procedure II still bypasses the fundamental issue of tying field compaction practices to properties once the new practice, based on performance, is established.

All of the preceding information indicates that the assignment of minimum compaction limits in compaction specifications varies significantly based on geographic and experiential factors. The obvious question that therefore arises is whether the resulting fills have sufficient density. Again, the density itself is of comparatively little interest. What is of interest is another property that can be indicated by the density. In the case of transportation infrastructure, the shear strength and settlement properties are usually of the greatest concern. Although systematic studies of these factors with changing compaction specifications and particle size are somewhat rare, some general comments can be offered.

The specifications shown in Table 2 were not developed entirely by accident. The state departments of transportation and consultants would not continue to use these specifications if the resulting fills consistently performed poorly. The specifications have been tested by the tincture of time, consistent with procedure II. However, Torrey and Donaghe (1991) report significant development of pore-water pressures for several rocky fills at 95% of the standard maximum density. The indication of this result is that, even at this density, the fill is quite contractive and is therefore in a relatively loose state. Kropp et al. (1995) report significant hydrocompression of fills compacted to 90%–95% of the modified maximum density. It has also been observed that the response to wetting of compacted fills depends on the compaction water content (Kropp et al. 1994; Brandon and Duncan 1990; Noorany and Stanley 1994).

Procedure II, which represents an attempt to correlate compaction specifications with the performance of the compacted materials, has a number of inherent shortcomings, as implied in the introduction. First, the correlation between specifications and performance could never be expected to be strong, because available technology is not being utilized. Thus, when a failure occurs, the cause may not be limited to insufficiently stringent compaction specifications. Other causes could include (1) failure to enforce specifications that were actually adequate; (2) failure to choose properties for analyses that are consistent with the specifications; (3) failure to perform properly a stability or settlement analysis—or failure to perform these analyses at all; (4) failure to account for the effects of wetting; and (5) unanticipated loading. A report from a survey of geotechnical firms (Kropp et al. 1994) shows that designers fully recognize that stringent compaction specifications alone will not alleviate all of the problems with fill performance. Therefore, increases in compaction specifications in response to several failures will very often result in overly conservative designs. Procedure II in its simplest form does not facilitate a "balanced" design of deep fills, whereby a very stringent specification is used for the bottom third of the fill, a less stringent specification for the middle third of the fill, and a still less stringent specification for the top third. To achieve the savings inherent in a balanced design of this type requires more rigorous analyses, which certainly require that compaction specifications be related to properties. One serious shortcoming of procedure II is that it can result in an overly conservative design. A fill may be constructed without a study of the variation in properties with compaction specification, and without analyses, and still perform satisfactorily. However, in this case, the margin of safety is unknown and may sometimes be very large and costly.

CONCLUSIONS AND RECOMMENDATIONS

Although the shear strength and volume change characteristics of earth fills are critical factors in controlling performance, compaction control is generally achieved through monitoring the dry density and water content of the fill as it is placed. However, in most cases compaction specifications are based on precedence, not on compacted fill properties. The connection between the relative compaction and the properties of interest, while understood in a general way, is rarely investigated in particular for any given soil or any given project.

Compaction control represents a daunting challenge. The reference density values are based on results of laboratory testing. The results are dependent to some extent on the laboratory and the operator performing the test. Rock correction issues and different methodologies for handling oversize materials increase potential variability. The methods that different agencies and different design engineers use for measuring the reference density and correcting for oversize materials can vary significantly. The variations resulting from these differing procedures can have measurable production and dollar consequences for the earthwork contractor, even when the specifications look the same.

As the current practice for compaction control will probably continue for the indefinite future, owners, geotechnical engineers, and earthwork contractors need to be aware of the variability in the field product that results from the numerous sources of variation in dry density and water content. Differences in methods of controlling field compaction, particularly when large aggregate is present, can affect construction cost and embankment performance. Several specific recommendations are presented in the following paragraphs.

Because compaction processes, soil and rock characteristics, field variations in water content, and the methodology for compaction control are often region-dependent, it is unwise to translate experience gained from a specification in a particular region to another region. It is therefore recommended that earthwork contractors entering the bidding process insist on precise and complete descriptions of (1) the method to be used for obtaining the reference density, including the handling of oversize materials; (2) the method to be used for assessing the field density, including testing frequency; and (3) the method to be used in defining a failure to pass compaction specifications. If any of these elements/procedures are outside the realm of the bidder's experience, appropriate adjustments to the experience database should be made.

It is necessary for the engineer to evaluate the "average" condition of the fill based on projected field compaction results. The projection of field results is necessarily based on data from similar soils that are compacted using similar specifications and control methods. There are, unfortunately, little data available in the literature addressing the actual field product, particularly the variability in density and water content. Therefore, geotechnical professionals need to become diligent

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in collecting this information and reporting it in the technical literature. Whenever possible, and particularly when dealing with unfamiliar soils or specifications, laboratory tests on compacted specimens should be performed to assess properties. For example, laboratory response-to-wetting tests on compacted specimens can be very useful for the selection of compaction specifications to ensure adequate fill performance upon future wetting. When preparing lab specimens, the engineer should take into consideration the water content and density specifications that will be given to the contractor. Specimen preparation should also take into consideration the probable range in placement water content and density that will occur, given the particular specification and soil conditions.

Because historical performance, rather than the specific properties of a given material, governs specification practice in many cases, it is very difficult to gauge the degree of underdesign or overdesign for any given project. Methods for more fundamental design practice are available; the concept of contouring properties to select fill specifications is well known to practicing engineers and is sometimes used for large projects. The writers are sensitive to the general concern that increased testing drives up the cost of geotechnical design. However, one wonders whether a life-cycle evaluation of the costs would show that the overall savings to the project in right-size specifications or avoided failures would not exceed the design budget. This is especially true when one considers that the geotechnical design is a markedly small fraction of the design cost, to say nothing of the first cost of the structure. When one adds maintenance and operations costs over the lifetime of a structure, the costs for careful specification design are hard to find in the larger number. More detailed evaluations of life-cycle costs in relation to geotechnical design are generally needed.

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APPENDIX. REFERENCES

Brandon, T., and Duncan, J. M. (1990). "Hydrocompression settlement of deep fills." *J. Geotech. Engrg.*, ASCE, 116(10), 1536–1548.

Daniel, D. E., and Benson, C. H. (1990). "Water content-density criteria for compacted soil liners." *J. Geotech. Engrg.*, ASCE, 116(12), 1811–1830.

Houston, S. L., and Walsh, K. D. (1993). "Comparison of rock correction methods for compaction of clayey soils." *J. Geotech. Engrg.*, ASCE, 119(4), 763–778.

Houston, W. N., Walsh, K. D., and Houston, S. L. (1995). "Earthwork design and construction issues for arid regions." *Infrastruct.*, 1(2), 24–33.

Kropp, A. K., McMahon, D., and Houston, S. L. (1994). "Case history of a collapsible soilfill." *Vertical and horizontal deformation of foundations and embankments*, A. Yeung and G. Felio, eds., ASCE Special Publ. No. 40, ASCE, Reston, Va., 2, 1531–1542.

Monahan, E. J. (1986). *Construction of and on compacted fills*. John Wiley & Sons, Inc., New York, N.Y.

Noorany, I., and Stanley, J. V. (1990). "Settlement of compacted fills caused by wetting." *Vertical and horizontal deformation of foundations and embankments*, A. Yeung and G. Felio, eds., ASCE Special Publ. No. 40, ASCE, Reston, Va., 2, 1516–1530.

Schexnayder, C. J. (1994). "Compaction specifications for low hydraulic conductivity clay embankments." *Transp. Res. Rec.*, 1462, 10–16.

Torrey, V. H., and Donaghe, R. T. (1991). "Compaction control of earth-rock mixtures." *Tech. Rep. GL-91-16*, U.S. Army Corps of Engrs., Waterways Experiment Station, Vicksburg, Miss.

Walsh, K. D., Houston, S. L., and Wilson, G. P. (1994). "Rock correction issues in compaction specifications for high gravel content soil." *Transp. Res. Rec.*, 1462, 3–9.

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