Rock Correction Issues in Compaction Specifications for High Gravel Content Soil

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Construction control for engineered fills is usually provided by a specification requirement that the in-place dry density of the fill be at least a specified percentage of a reference dry density. The reference dry density is usually measured by a laboratory compaction test, such as the ASTM D698 (Standard Proctor) moisture-density relationship test. The use of laboratory determination of the reference dry density for construction control is based on the implicit assumption that the material compacted in the lab is substantially equivalent to the material compacted in the field. However, when the fill material contains gravel (material coarser than the No. 4 sieve), this assumption is generally not correct. Therefore the contractor and engineer must rely on experience with the performance of high gravel content fills at certain specified percentages of a reference dry density, selecting specification requirements appropriate to individual circumstances. Several methods are available to account for the effect of the coarse fraction on the reference dry density, including various rock correction equations and laboratory scalp-and-replace techniques. Each method may provide a different reference dry density. The impact of the rock-correction method on construction control is addressed. The results of a survey of several large construction companies in the southwestern United States revealed that contractors have a great deal of experience with scalp-and-replace rock correction methods and apparently not as much experience with rock correction equations, particularly in highway work. Although contractors may tend to have most of their experience with scalp-and-replace methods, many engineering testing firms tend toward the use of rock correction equations. Given the significant variation in computed relative compaction that can arise from the different rock correction methods, well-written compaction specifications for high gravel content soils, explicitly stating the technique for rock correction in compaction control, are a must. An understanding of the potential differences in rock correction methods, by contractors and engineers alike, should reduce conflicts and future problems with the compacted fill.

The use of laboratory determination of reference dry density for construction compaction control is based on the implicit assumption that the material compacted in the lab is substantially equivalent to the material compacted in the field. However, when the fill material contains gravel or rock (material coarser than the No. 4 sieve), this assumption is generally not correct. The laboratory molds place a physical restriction on the maximum particle size that can be conveniently tested. Fills containing material with large aggregate can be successfully constructed, but the effect of the coarse fraction on the reference dry density must be considered.

Because several methods are available to account for the effect of the coarse fraction on the reference dry density, the particular technique assumed (or preferred) by the engineer should be clearly stated in the compaction specifications to reduce the potential for conflict with the contractor. The method for accounting for the rock fraction may have a significant impact on the reference density. Because the required compacted fill density is expressed as a percentage of the reference dry density, the rock correction method selected can have a significant impact on the ease with which the contractor can meet a particular specification. Modifications to compaction standards, such as the new ASTM D698–91, could significantly affect compactive effort for soils with high rock content unless required relative compactions are adjusted to account for the differences in methods used to adjust the maximum dry density for rock. Therefore contractors, construction inspectors, and designers should be consistent in the method adopted for rock correction, following the procedure outlined as a part of a well-written specification. The technique for rock correction is often not clearly addressed in compaction specifications, leading to inconsistencies between rock correction techniques assumed for design and those adopted for construction.

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METHODS FOR OBTAINING A REFERENCE DRY DENSITY

Several methods are available to account for the effect of the coarse fraction on the reference dry density. The available methods may be categorized as rock correction equations and laboratory testing modifications. In rock correction equations, the maximum density of the fine (passing the No. 4 sieve) fraction, the percentage of the fill that is gravel sized, and perhaps the character of the fine fraction are used to produce a mathematical approximation of the maximum dry density of the total soil. In the laboratory, the maximum dry density of the field soil is usually estimated by testing a modified soil in which the gravel fraction is removed from the sample and replaced with material between the No. 4 and 19-mm (0.75-in.) screens (e.g., AASHTO T99, Method C, or the "scalp-and-replace" method). Only in specialized research applications is the maximum dry density obtained by laboratory or field compaction of large samples that include the entire gravel fraction.

Any of the above methods could be used to write an acceptable specification for compaction of materials containing up to about 60 percent large aggregate. However, not all methods produce the same maximum dry density and optimum water content for use as the reference value (*1*). Furthermore the difference from one method to another varies depending on the characteristics, such as the Plasticity Index, of the material passing the No. 4 sieve (*2*).

New ASTM compaction procedures D698–91 and D1557–91 no longer include the scalp-and-replace option. The potential impact of compaction standard modifications on engineering and construction practice must be understood to avoid eventual conflict.

Commonly used rock correction equations are presented in detail in Table 1. These methods require laboratory testing to determine the maximum dry density of the minus No. 4 fraction. As an alter-

TABLE 1 Rock Correction Equations

Equation Designation	Reference	Equation*	Comments
AASHTO-1	AASHTO T224	$D = (1 - P_c)D_f + 0.9P_c(62.4)G_m$	D_f is determined using Method A or B, AASHTO T99 or T180
AASHTO-2	AASHTO T224	$D = \dfrac{62.4}{\dfrac{P_c}{G_m} + \dfrac{62.4(1 - P_c)}{r_a D_f}}$	D_f determined using Method A or B, AASHTO T99 or T180. r_a depends on rock content
ASTM-1	ASTM D4718	$D = \dfrac{62.4}{\dfrac{P_c}{G_m} + \dfrac{62.4(1 - P_c)}{D_f}}$	D_f determined using ASTM D698 or D1557
USBR-1	USBR 5515-89	$D = \dfrac{62.4}{\dfrac{P_c}{G_m} + \dfrac{62.4(1 - P_c)}{r_u D_f}}$	D_f determined using USBR Method 5500-89. r_u depends on rock content and plasticity of fines

*Definitions:

D_f = Maximum dry density of finer material (pcf)

D = Maximum dry density of finer soil (pcf)

P_c = Percent rock by weight (decimal)

G_m = Bulk specific gravity of rock

r_a = Correction factor in AASHTO equation to account for interference of large aggregate

r_u = Correction factor in USBR equation to account for interference of large aggregate

native to using one of the rock correction equations, small-scale compaction tests on material containing particle sizes up to 19 mm (0.75 in.) may be used to determine a reference dry density. The most common laboratory procedure is the scalp-and-replace method, sometimes referred to as the procedure for replacement of oversized aggregate. Scalp-and-replace methods involve the removal of all material larger than 19 mm and replacement with an equal weight of No. 4 to 19-mm material. Commonly used scalp-and-replace methods are ASTM procedure D698–78, Method D, and ASTM D1557–78, Method D, using a mold 15 cm (6 in.) in diameter; AASHTO T99, Method C, using a 10-cm (4-in.) mold; or AASHTO 180, using a mold 15 cm in diameter. The ASTM procedures for scalp-and-replace are no longer included in the ASTM D698–91 and D1557–91 standards, but have been used extensively in the recent past for compaction of fills.

COMPARISON OF REFERENCE DENSITIES

In general, the effect of increasing the rock content of a given soil is to increase the maximum dry density. This occurs because the specific gravity of the rock is usually much higher than that of the bulk material between the rock fragments. The percentage increase in maximum dry density (relative to zero rock content) as a function of percent rock is shown in Figure 1 (*2–4*). Several methods are available for determining maximum dry density of soils containing large aggregate.

The differences among the various methods for obtaining reference dry density have been found to be most significant for clayey soils (*2*). The rock correction equations presented in Table 1 were used to estimate the maximum dry density for five medium- to high-plasticity clayey soils. The maximum dry densities computed using the rock correction equations were compared to each other and to maximum dry densities obtained using the scalp-and-replace procedure (ASTM D698–78, Method D). Rock contents were varied in the laboratory from 10 to 60 percent, and the rock gradations consisted of material between the No. 4 and 19-mm sieves. When the rock contents were changed in the laboratory, the gradation of the minus No. 4 material was left unchanged, and the percentage by weight of the plus No. 4 material was increased or decreased as required.

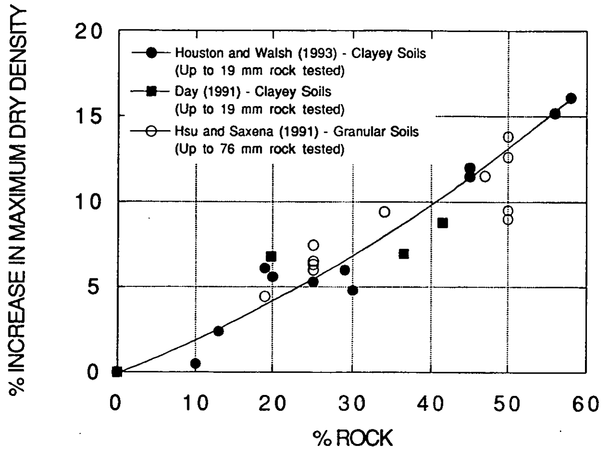

FIGURE 1 Effect of rock on maximum dry density.

In all cases the maximum dry density estimated from the rock correction equations was greater than the maximum dry density obtained from the scalp-and-replace compaction method. The percentage difference by which the rock correction equation exceeds the maximum dry density obtained from ASTM Method D increases with increasing rock content for equations AASHTO-1 and ASTM-1, as shown in Figure 2 and Figure 3. The AASHTO-2 equation incorporates a factor that provides a correction for the increased interference of the coarse aggregate on the compaction of the fine fraction as rock content increases. The AASHTO-2 equation estimates were 1.5 to 3.5 percent higher than the scalp-and-replace at all rock contents. The USBR-1 equation includes different correction factors based on the character of the minus No. 4 fraction. Estimates using the USBR-1 equation were higher than the scalp-and-replace estimates by about 3.0 to 6.5 percent at all rock contents.

The scalp-and-replace dry density was selected as a convenient basis for comparison. This selection should not be construed as an endorsement of the scalp-and-replace method over the other methods. The emphasis here is not on determining which value is the "correct" maximum density for a given fill soil containing large aggregate. In fact, it may well be that the whole question of the "correct" value is without meaning for such fills. The point of a compaction specification written in terms of a maximum density is to achieve a suitably dense fill, and not to achieve a given fraction of the maximum point on a curve developed with a testing method that arguably bears little resemblance to the actual compaction method in the field.

Specifications are written in terms of relative compaction instead of absolute density only because the performance of different soil types tends to be normalized by the maximum dry density. However, when considering the compaction of soils with large aggregate, selection of the rock correction method to establish maximum densities will likely be based on the experience of the designer with rock correction methods and related performance. Equally good specifications could be written with any rock correction method, as long as the differences between the results obtained with the differ-

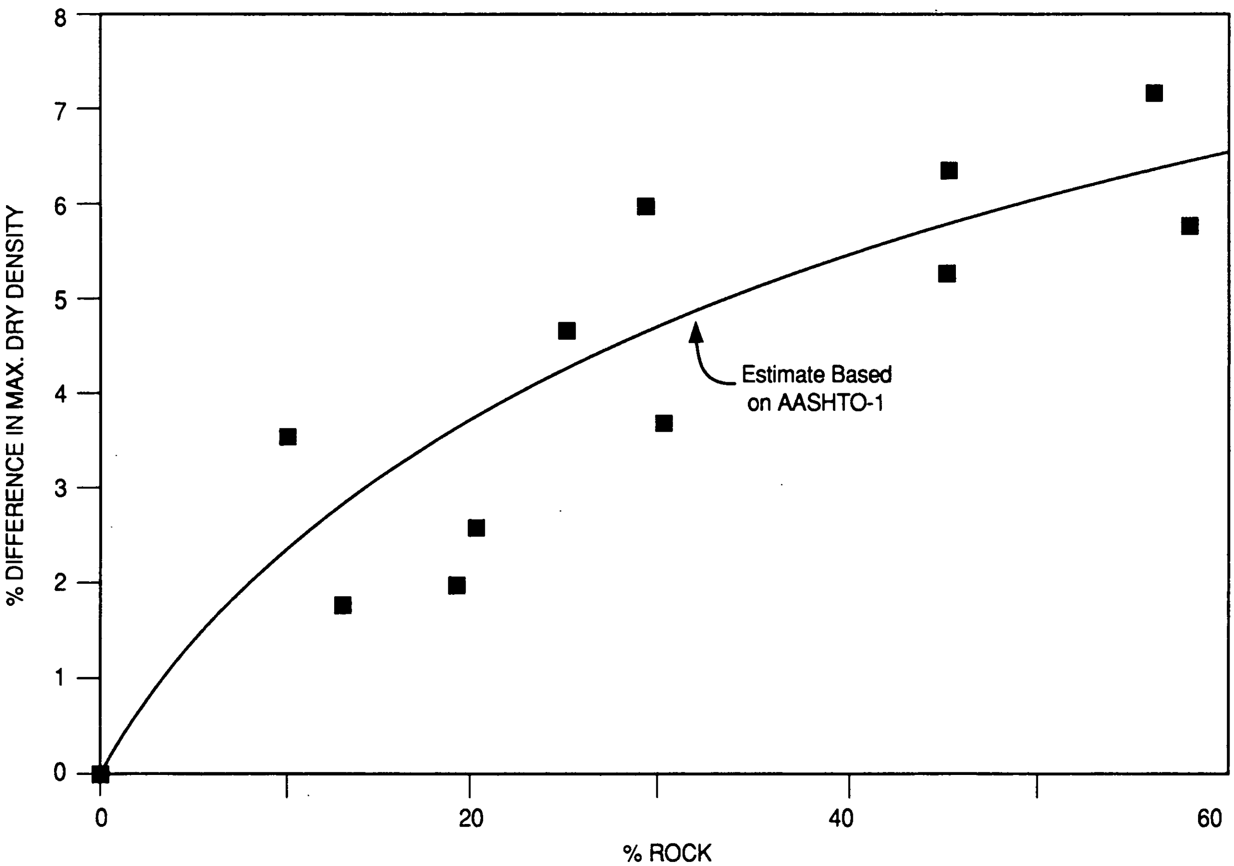

FIGURE 2 Comparison of maximum dry density estimates using scalp-and-replace method and AASHTO-1.

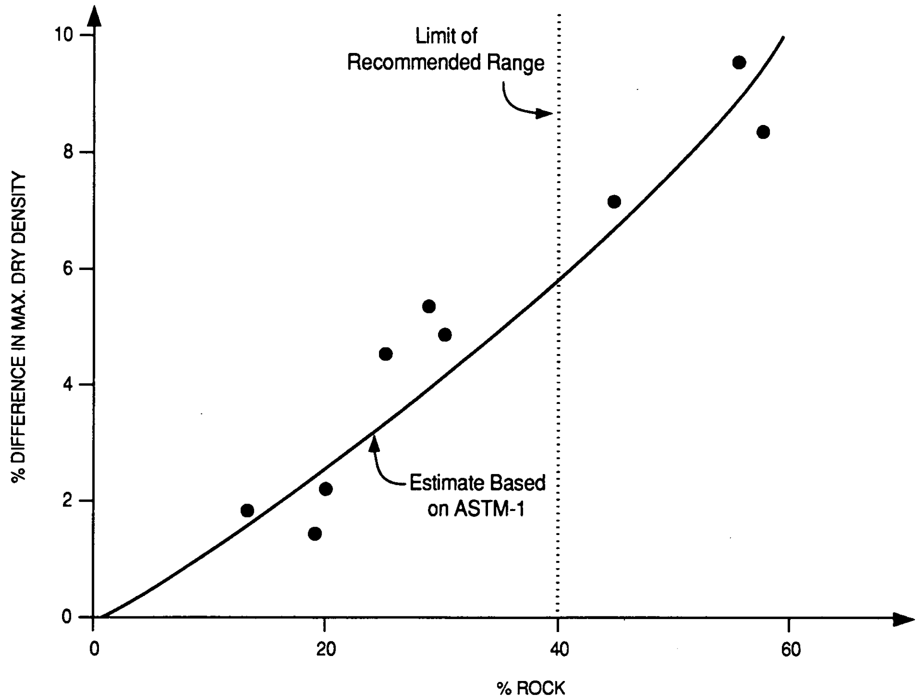

FIGURE 3 Comparison of maximum dry density using scalp-and-replace method and ASTM equation.

ent methods are understood. Therefore although arguments can be made about which method is better, this discussion is dedicated only to pointing out that the methods are different.

IMPLICATIONS FOR CONSTRUCTION

The maximum dry density of a clayey soil was determined at several rock contents, ranging from 0 to 60 percent, using several rock correction equations. The maximum dry density of this clayey soil was also determined using ASTM D698–78, Method D, scalp-and-replace. The clayey soil tested exhibited moderate expansive characteristics, having a plasticity index of 35. A compaction specification of 95 percent of the maximum dry density was selected for discussion purposes. This specification was applied to the maximum dry densities computed using the different rock correction methods to develop the actual required density to be accomplished in the field. The results are shown in Figure 4.

The actual required field density depends significantly on the rock correction method. At about 60 percent rock, for example, the required fill densities range from about 17.9 kN/m^3 (114 pcf) to about 19.6 kN/m^3 (125 pcf). These differences in required fill density amount to differences in the compactive effort that would be required to meet a specification. A contractor with experience with field control by scalp-and-replace methods would therefore experience greater than the expected difficulty in meeting specification requirements when completing a project to be controlled by AASHTO-1, for example. Therefore it is in the contractor's best interest to be aware of the differences and bid accordingly.

IMPLICATIONS FOR FORENSICS

Another area in which the differences between the various large aggregate correction methods can have an impact is in forensic investigations. In the case of fill failure, the issue of compliance with specification will almost certainly arise. It is likely that the in-place density of the fill will be evaluated and compared to the reference dry density to determine the relative compaction of the fill. If the method selected for rock correction in the forensic study is different from that used for construction control, very different conclusions could be reached regarding compliance with the specification.

The differences that could arise in a forensic study are shown in Table 2. The hypothetical 95 percent compaction specification for the clayey soil described in the previous section (Figure 3) was used to produce the estimate of maximum dry density required in situ for the various rock correction methods. The differences in relative compaction that would be attained if a different rock correction procedure were assumed are indicated for 40 percent rock and for 60 percent rock. Note that the entries along the diagonal of Table 2 are all 95 percent because the field control and forensic evaluation are performed with the same rock correction method.

Table 2 shows the differences in the various methods of rock correction. In the hypothetical case, the fill under consideration just reached the specified density by the control method used at the location of the test. Of course, only one actual field density exists for a given test sample. However, depending on the combination of field control and forensic investigation rock correction methods chosen, the computed relative compaction can vary from 89.6 to 100.7 percent at 40 percent rock. For the 60 percent rock case, the computed relative compaction can vary from 86.4 to 104.5 percent, although the actual dry density in situ has only one value. In real fills, sampling difficulties in coarse-grained materials and test scatter could easily widen the range.

The problem created by this variation is that different forensic investigators could come to very different conclusions regarding the degree to which the contractor met, or failed to meet, the specifications for a given project. What's more, these investigators would all

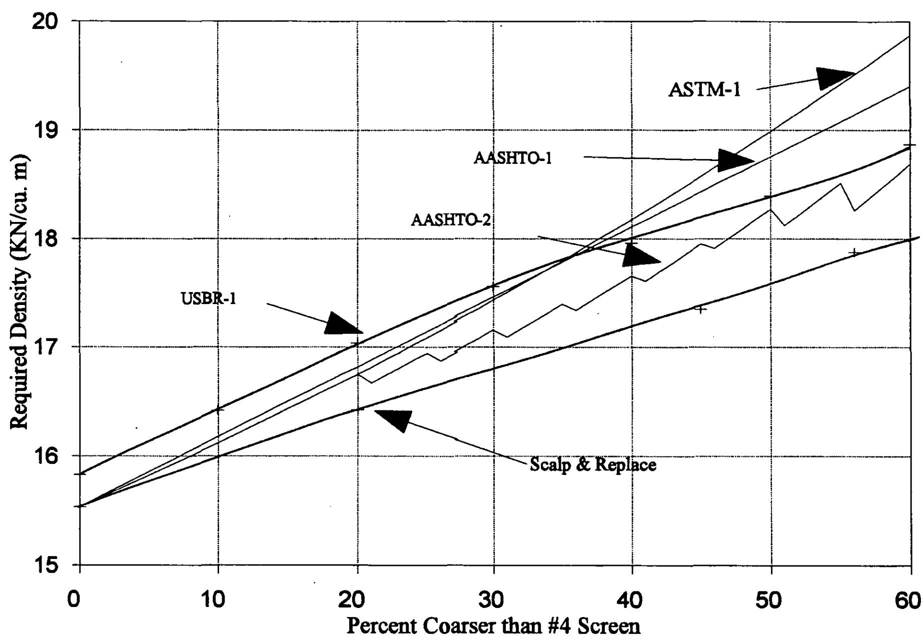

FIGURE 4 Maximum dry density estimates for various rock correction methods.

be considering a fill that passed the specification by the construction control method, at least in this hypothetical case.

As another example, consider a designer experienced with AASHTO-1 who produced a specification recommendation of 95 percent relative compaction and then discovered that the compaction control was monitored by others using the scalp-and-replace method. Because of the differences in the rock correction methods, the fill would be placed at only 88.5 percent relative compaction by AASHTO-1. The behavior of fill materials is closely related to the dry density, and therefore the discrepancy in dry density could have serious consequences with regard to the long-term fill behavior. In general, the use of rock correction equations for determining reference dry density will lead to denser compacted fills for a given specified relative compaction, as compared with scalp-and-replace. In addition, some rock correction equations produce higher reference values than other equations.

ROCK CORRECTIONS IN CONSTRUCTION PRACTICE

Several major construction companies, operating primarily in the southwestern United States, were surveyed to determine typical practices and specifications encountered by contractors dealing with soils containing large aggregate. Contractors surveyed reported that 20 to 90 percent of their compaction projects were on soils containing large aggregate. Thus the technique employed for handling rock correction may have a significant impact on their work.

According to contractors surveyed, compaction specifications often do not address the method to be used for rock correction. However, particularly in regions dominated by gravelly, high rock-content soils, the most common rock correction technique specified is the scalp-and-replace method. For highway applications, AASHTO T99, Method C, is typical, but most private-industry project specifications have used reference dry densities obtained using ASTM D698–78, Method D, scalp-and-replace. The authors have observed essentially no difference in reference dry densities obtained using the AASHTO and the ASTM scalp-and-replace methods for soils containing up to 19 mm (0.75 in.) particle size (*3*).

Contractors reported that the use of rock correction equations was infrequent compared with scalp-and-replace, particularly in highway work. Therefore much of the contractors' experience can be assumed to be with reference dry densities obtained using the laboratory scalp-and-replace method. Further, the rock correction technique (whether explicitly specified or assumed) did not affect the contractors' bids, implying that bidding is done primarily on the basis of experience with similar soils instead of in response to a particular specification. The required percent relative compaction (e.g., 90 versus 95 percent), or whether standard or modified compactive effort is specified, was more likely to affect bidding by contractors than the method specified for rock correction.

Contractors reported that in-place densities were normally determined by nuclear gauge or sand cone methods. Although several government agencies require sand cone tests, the majority of field compaction control is performed using nuclear density determinations. One contractor noted that when scalp-and-replace rock corrections are used, often there is insufficient laboratory testing for determining reference maximum dry density when there are radically changing soil conditions on a given project. The problem arises when numerous soil-type changes occur and there are insufficient laboratory compaction tests (scalp-and-replace) to provide appropriate reference values for all soil types. An inappropriate reference dry density may lead to problems in meeting specifications.

Based on the authors' studies, the scalp-and-replace method has been found to provide lower reference dry densities than any of the rock correction equations evaluated. Therefore contractors accustomed to field control on the basis of scalp-and-replace would likely find it more difficult to meet the specified relative compaction when the reference dry density is based on rock correction equations, such as those called for in the new ASTM D698 and D1557 standard procedures. The more clayey the fine fraction of material, the greater the differences in rock correction methods are likely to be.

There is a trend with engineering testing firms away from scalp-and-replace rock correction methods in favor of rock correction equations. One advantage to using rock correction equations is that, for a given specified relative compaction, a denser fill tends to be achieved compared to scalp-and-replace methods. However, contractors must recognize the potential differences in compactive effort that may arise from changes in rock correction specifications. In addition, the various rock correction equations lead to different reference dry densities. Ultimately the relative compaction specification specified for any reference dry density should be related to field performance.

The use of nuclear density testing for compaction control is quite prevalent. When nuclear gauges are used to determine in situ densities, it is good practice to calibrate the results with occasional sand cone density tests. In addition, when a nuclear gauge is used to obtain density, the percent rock (e.g., material retained on the No. 4 sieve) should be measured at each density test location so that an appropriate reference dry density (by the selected rock correction method) can be determined. Percent rock at field density test locations is not always measured. Failure to adjust the reference dry density for the appropriate rock content could lead to problems in fill performance if the reference dry density is too low (rock content underestimated), or it may make compaction specifications difficult for the contractor to meet if the reference density is too high (rock content overestimated).

Failure to directly address rock correction in compaction specifications, or failure to apply rock corrections to laboratory determination reference dry density during field inspection, can lead to poor field performance. The density of a compacted fill increases with increasing rock content. Therefore the use of a reference dry density determined at a lower-than-average rock content may result in loose compacted fill with poor engineering performance.

A case history of a rocky compacted fill that experienced hydrocollapse is presented by Kropp, McMahon, and Houston (*5*). The compacted fill contained a high percentage of rock and gravel-sized fragments, with the fine-grained portion of the soil consisting primarily of granular materials with some clayey fines. The compaction specifications were based on laboratory testing using ASTM D1557–78 (Modified Proctor), requiring 90 percent relative compaction. Although the rock contents (plus No. 4) varied widely in situ from 10 to 80 percent, only three soil types were identified for reference dry density. The three soils were described by the project engineer as brown silty, sandy, broken rock (GM); brown, silty, with broken rock (SM); and brown, silty, sandy gravel (GM), having maximum dry densities by ASTM D1557–78 of 20.4 kN/m^3 (130 pcf), 20 kN/m^3 (127 pcf), and 20.8 kN/m^3 (132 pcf). Field den-

TABLE 2 Hypothetical Forensic Results

Forensic Study with Rock Corrections Below for Relative Compaction	a) Field Control at 95% of the maximum density corrected for 40% oversize aggregate using:				
	Scalp & Replace	AASHTO-2	USBR-1	AASHTO-1	ASTM-1
Scalp & Replace	95.0%	97.8%	99.5%	100.3%	100.7%
AASHTO-2	92.1%	95.0%	96.5%	97.4%	97.7%
USBR-1	90.6%	93.3%	95.0%	95.8%	96.1%
AASHTO-1	89.9%	92.6%	94.1%	95.0%	95.3%
ASTM-1	89.6%	92.3%	93.8%	94.7%	95.0%

Forensic Study with Rock Corrections Below for Relative Compaction	b) Field Control at 95% of the maximum density corrected for 60% oversize aggregate using:				
	Scalp & Replace	AASHTO-2	USBR-1	AASHTO-1	ASTM-1*
Scalp & Replace	95.0%	98.3%	99.2%	102.1%	104.5%
AASHTO-2	91.8%	95.0%	95.8%	98.6%	101.0%
USBR-1	91.0%	94.2%	95.0%	97.8%	100.2%
AASHTO-1	88.5%	91.5%	92.3%	95.0%	97.3%
ASTM-1*	86.4%	89.4%	90.2%	92.8%	95.0%

* Beyond Recommended Range

sities were determined using a nuclear gauge. In all field tests, the contractor met or exceeded the required 90 percent relative compaction, averaging about 93 to 94 percent, but typically below optimum water content. Because percent rock was not determined in the field to correct reference dry densities, there was no way to determine whether the reference dry density was consistent with engineering expectations. Given the apparent ease with which the contractor met specification on this project, it is likely that the percent rock in the laboratory specimens was lower, on average, than that in the field. The fill material that resulted in this case was loose, and significant building damage resulted from the wetting-induced differential settlements. In general, any compacted fill, whether rocky or not, may collapse on wetting when compacted to 90 percent of Modified Proctor, particularly when compacted dry of optimum. However, fills containing high rock content may be particularly susceptible to poor performance when inappropriate specifications and field control (relative to the rock content) are used.

CONCLUSIONS AND RECOMMENDATIONS

The method used to account for the coarse fraction (material larger than 19 mm) in a fill can have a significant impact on the reference dry density used to evaluate a fill. The presence of the coarse fraction can be accounted for by

- The scalp-and-replace method where the material greater than 19 mm is replaced by an equal weight of material between the No. 4 and 19-mm sieves; or
- The use of a rock correction equation and compaction test results, usually on the fine fraction (material passing the No. 4 sieve) only, although ASTM D698–91 and 1557–91 call for testing of particles up to 19 mm (0.75 in.) to obtain densities to be corrected by equation for large aggregate.

The rock correction equation methods generally give higher estimates of the maximum dry density than the scalp-and-replace method.

Differences between the maximum dry densities determined from the various rock correction methods have been observed. The required density to pass a compaction specification (as a function of rock content) was determined for one clayey soil, and a significant variation depending on the rock correction method selected was obtained. Because the density achieved for a given fill soil is related to the compactive effort expended, the rock correction method used for field control can have a significant effect on the difficulty in complying with a given specification. This effect should be clearly understood by the contractor producing a bid to complete earthwork.

Further, the differences in rock correction methods were shown to create a range of conclusions regarding the adequacy of fill in a forensic study. Because of the possible range in computed relative compaction using different rock correction methods, the forensic engineer could conceivably arrive at almost any conclusion, depending on the combination of methods employed for correcting for the effects of large aggregate in construction control and forensic study. Such a possibility is clearly not desirable for achieving an understanding of the problem being studied.

Because of the potential variation implicit in the application of different rock correction techniques, recommendations for fill compaction and well-written specifications should include the intended rock correction method. Based on a survey of contractors, the practice of specifying the rock correction method is apparently not consistently used. Further, the rock correction method to be used does not appear to affect contractor bids.

A well-written compaction specification should include the desired percent compaction for different classes of fill material and the intended rock correction method. The effect of the rock correction method on compactive effort and performance of compacted soils must be recognized by engineers and contractors alike to avoid conflict.

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Publication of this paper sponsored by Committee on Transportation Earthworks.