Embankment Compaction Variability—Control Techniques and Statistical Implications

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The development of a more effective method for field control of embankment compaction must be based on knowledge of the results being achieved using current inspection procedures. The purpose of this study was to determine the extent of compaction variability present in fill construction for typical Indiana construction projects and to identify the various factors that lead to this variation. Different techniques for measuring in-place density, including the sand cone replacement method, the water-filled balloon volume-measuring device, and the surface backscatter nuclear gage, were studied to prove variance estimates for use in the final statistical analysis.

The results indicate that widespread compaction variability is present in all field construction regardless of testing method, and that it is caused by a combination of many interrelated factors. This observed spread in compaction results indicates that current control procedures do not account for variability, and therefore an inspection program using statistical quality control procedures developed for these data is presented. The proposed technique is that of using a hypothesis decision theory that accounts for the compaction variability by using statistical parameters based on random sampling to make decisions as to overall compaction quality.

•THE PRESENT-DAY construction of highways is a high-speed, extremely complex operation. This is true whether it is a secondary road or a section of Interstate Highway. Because of this speed and complexity of construction, it is very important that adequate field control of the work be continually maintained to ensure that a quality product will be the end result.

One of the many important areas of construction over which this control must be maintained is the compaction of highway fills or embankments. For a fill to function as an adequate foundation for the structure it is to support, whether pavement or a bridge, the compaction must be controlled to ensure that the fill possesses given strength and stability characteristics and that these are uniform from one location to another.

To ensure that the finished fill is uniformly compacted to a specified level, it is necessary to establish a sampling and testing program that is related to the construction process and on which a realistic decision can be made with respect to the overall quality of the work. Historically, this control has been achieved by performing one or two control tests for a large quantity of material and accepting the entire volume of work as being satisfactory if the results of these isolated tests exceed some minimum specified value. The problem with this approach is that in most instances the sampling and testing program is not related to the true variability associated with the construction

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process and the decision thus made on the basis of these control tests is at best an educated guess of the actual quality of the work.

A solution to this problem encouraged by the Bureau of Public Roads (2) is that of applying statistical quality control. However, a great deal of research data is required to provide the necessary information with regard to what variability exists using present-day construction methods if a statistical quality control technique is to be developed for highway construction. This study is an attempt to provide such data.

PURPOSE

Based on this need for research data related to the variability associated with current construction practices, the primary purpose of this study was to measure the variability found in the compaction of soils used in highway embankments. The ultimate goal was then to use this information to establish future sampling and testing programs that allow for these inherent variations.

One of the factors that contributes significantly to the overall observed variability is the field testing method employed. This is true whether the measurement being made is for field density, field moisture content, or the maximum standard density, to which the field density is compared in establishing a relative compaction level. To establish estimates of variability for these important soil characteristics, several different testing methods were employed to measure each of these parameters to provide comparative data between test methods. The methods used in this study were either procedures that are currently in use or are proposed as possible future test methods for Indiana State Highway control testing.

SAMPLING AND TESTING PROGRAM

Sampling Procedures

The general field sampling and testing procedures used in this study were based on guidelines established by the Bureau of Public Roads and described in the publication "The Statistical Approach to Quality Control in Highway Construction" (3). Three projects were selected that contained over 400,000 cu yd of fill construction and each of these was divided into a series of 10 individual fills containing a minimum of 5,000 cu yd. A series of replicate tests including in-place density, in-place moisture, and laboratory standard maximum density were performed in each control fill. Based on previous work done by the Indiana State Highway Commission in this area of compaction control (10), it was decided that a minimum of seven replicate field tests should be performed per control section to establish variance estimates, and that more tests than this would be desirable if field conditions permitted.

With respect to the actual test locations, a table of random numbers was used to establish a longitudinal station and lateral offset for each field test. The vertical location of the control test was obtained by instructing the field crews to perform the assigned tests in any compacted lift that had been passed by the project grade inspector as meeting specifications and that fitted their overall testing schedule with the restriction that only one test per lift be allowed. Thus, the field crews could test the control fills as they were constructed and certified as meeting specifications, thereby allowing them freedom to test in the areas where work was progressing.

Large 25-lb bag samples and smaller 200-gram samples were taken from each test location and used in a laboratory testing sequence to establish maximum density values and classification data for the materials encountered on each project.

Testing Procedures

The actual testing program included performing the tests of importance—that is, in-place density, in-place moisture content, and standard maximum density-moisture content—using a series of test procedures currently applicable to the control of field compaction.

The in-place density tests used during this study were the sand cone replacement method, the water-filled rubber-balloon volume-measuring device, and the nuclear density surface backscatter approach. The sand cone method used followed AASHO T 191-64 test procedures, and the balloon method followed AASHO T 205-64 specifications except for the fact that a pressure gage was not used to ensure constant water pressure for all tests. Instead of using a pressure gage, the technicians would pump the pressure in the cylinder to a point where no further change in water level occurred and then would take their readings.

Three different models of nuclear gages were employed, with each being assigned to a specific project during the course of the testing program. All gages used are of the backscatter design and are commercially available units. Details of the actual calibration of these gages are presented in a paper by Williamson and Witczak (11).

The field testing procedure involved first performing the necessary nondestructive nuclear counts using both the density and moisture probes on the selected test locations. The technicians then augered a hole for the balloon measurement in the exact location where the nuclear readings were taken and determined the density in this manner. Because the balloon method left the original hole intact, it was next possible to perform the sand cone test using the same hole or by augering it out to a slightly larger diameter to fit the sand cone plate being used. Both of these approaches were employed.

This testing procedure permitted a comparison to be made between the three methods on essentially the same material, although the influence of the nuclear gage was effective over a larger volume than the other two methods.

After the soil had been removed from each test hole, moisture determinations were made using both a Speedy carbide-gas moisture tester and the conventional laboratory oven-drying technique. These were in addition to the previous moisture determination as obtained by the nuclear equipment.

The portion of the sample from the density hole remaining after the moisture determinations had been made was used to perform a field one-point maximum density compaction test. This method is used by many agencies, and previous research by the Indiana State Highway Commission (10) has indicated the relative merit of such a test in establishing maximum density values for soils in the field. A unique feature of this test is that only one point of the standard AASHO T 99(A) compaction curve is established and this is accomplished under field conditions. The density and moisture content of this individual compaction test point are plotted on a set of typical compaction curves developed for Indiana soils and the maximum dry density and optimum moisture content are thus defined.

Because the one-point compaction test has not been approved for routine field use in Indiana, samples were taken from the vicinity of the replicate sand cone holes and subjected to a complete laboratory compaction test according to AASHO T 99(A). This provided data to compare these two approaches for determining maximum density and optimum moisture content.

Projects Tested

The three projects selected for this study were chosen to provide a wide degree of variation with respect to soil homogeneity and compaction technique used. All three projects were characterized as Interstate high-type rigid pavement construction. All of the projects are located in the glaciated till plains section of the Central Lowlands Province as defined by Lobeck (8).

Project 1 is located in central Indiana in an area of little topographic relief with the soil being geologically classified as a Tazewell stage, Wisconsin age glacial drift. The soils tested on this project were relatively homogeneous, consisting primarily of a low-plasticity silt classified by the HRB procedure as an A-4(5) with some isolated silty clays, A-6(7), also present. Compaction was achieved by the use of a towed sheepsfoot roller.

Project 2 is located in west central Indiana in an area of relatively dissected rolling topography. The soils are characterized as Illinoian age glacial till and are relatively heterogeneous, ranging from a low-plasticity silty clay, A-4(6), to a moderately plastic clay, A-6(9). Compaction on this project was achieved using a combination of a self-propelled sheepsfoot and a rubber-tired roller.

Project 3 is located in a very level area of northwestern Indiana in the Cary stage, Wisconsin age glacial drift region. This is a very young drift with the soil characterized as very heterogeneous, ranging from highly plastic lacustrian deposits, A-7-6(12), to granular beach sand deposits, A-2-4(0). Compaction equipment included towed sheepsfoot units, rubber-tired rollers, and steel wheel rollers, all used concurrently in a given control section.

CORRELATION TESTING RESULTS

Determination of Standard Maximum Density

The current Indiana State Highway Commission practice for establishing maximum density values for a given construction project is to obtain a series of representative soil samples from the project, and then to determine maximum density according to the standard AASHO T 99(A) compaction test at a central laboratory. The results of these tests are then sent to the project personnel and it is their responsibility to apply the correct values to the various field conditions. Because the soil varies widely from one location to another, this becomes an extremely difficult task for the field inspector. The results of the laboratory compaction tests for the samples collected during this study indicated that a range in maximum density values of about 20 pcf (pounds per cubic foot) existed for all three projects, thus emphasizing the importance of being able to determine the correct maximum density value to be used in computing relative compaction values for a given in-place field density test.

To avoid this problem of selecting a control density value, a field one-point compaction test as previously mentioned was performed for each field test location. The results of these field tests were used to determine the maximum density and optimum moisture content for each sample by comparing the observed density and moisture values with a set of typical Indiana curves as developed by Walter T. Spencer, Chief of the Indiana State Highway Commission Division of Materials and Tests.

The field one-point compaction test has several advantages over the present Indiana method of representative field sampling and laboratory testing. The test can be performed on the grade in about 10-15 minutes and requires only a minimum amount of additional equipment, thus resulting in a savings in time and money when compared to the prospect of extensive field sampling and laboratory testing. An additional advantage is that the one-point test establishes maximum density for the material from the in-place density test location itself and the density thus obtained can be used with more assurance that it is representative of the material.

A comparison of the laboratory and field one-point values obtained for standard maximum density indicates the one-point values average 2.5 pcf less than the laboratory data, based on 436 observations. A similar value of 3.1 pcf was obtained during a previous study (10) of subgrade compaction variability. Probably the major reason for this deviation is the fact that during the laboratory compaction test the sample is re-used for each subsequent test point on the compaction curve, whereas the field test involves the use of a new sample for each test point.

The discussion indicates the relative merit of the field one-point compaction test and the data obtained for this test compare favorably with the laboratory test results. On this basis, most percent compaction data presented in this study are based on these field one-point maximum density test values.

Measurement of In-Place Wet Density

The current method preferred by the Indiana State Highway Commission for measuring in-place density is the sand cone. This method has been in use for many years and is a proven field technique. However, there has recently been some dissatisfaction with this method because of (a) the amount of time required to perform the entire test, (b) the possibility of making an error at any one of the many steps associated with the test, and (c) the necessity of making a series of detailed computations to arrive at the final density value. Based on this, two alternate approaches, the balloon volume-

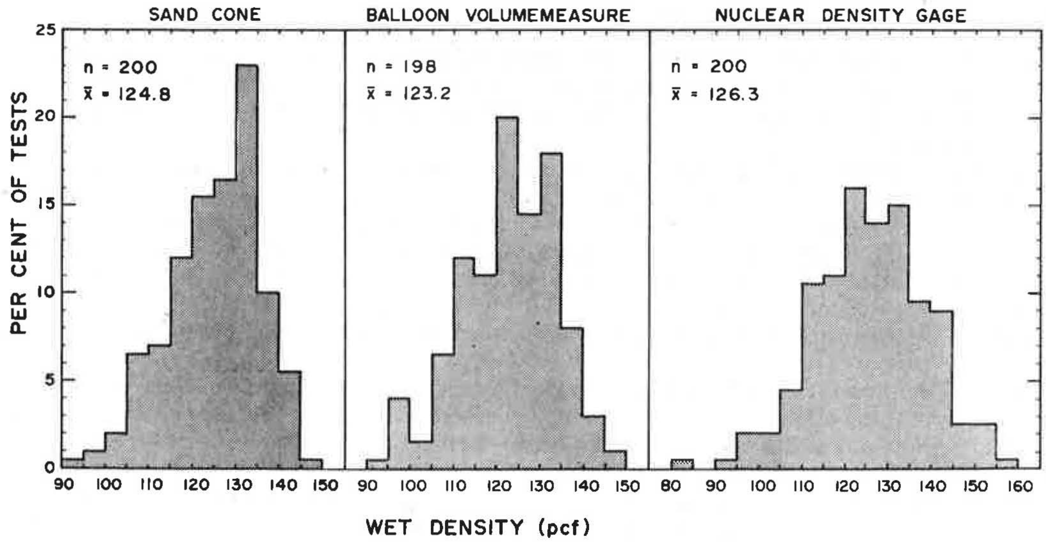

Figure 1. Variation of in-place wet density values for Project 1.

measuring method and the nuclear backscatter method, were also employed to measure field density.

The balloon device is used by many agencies and the use of nuclear equipment is rapidly gaining favor among highway engineers. Both have the advantages of simplicity with respect to computations involved and relative speed of operation in comparison with the sand cone technique.

The subject of developing appropriate calibration curves for nuclear moisture-density gages has been dealt with by many authors, with several different methods proposed (5, 11). The calibration technique used by the Indiana State Highway Commission is based on the work done by Williamson and Witczak (11) and basically involves using a statistical hypothesis testing approach. Three different brands of nuclear gages were used of which only one performed satisfactorily. A series of electronic failures that were not easily corrected made it impossible to collect sufficient field data for the nuclear density units assigned to Projects 2 and 3.

The results of performing all three tests on Project 1 are shown in Figure 1, which shows the variations in field wet density values. These data indicate that the methods all resulted in similar values of density, as shown by the average values ranging from 123.2 pcf for the balloon device to 126.3 pcf for the nuclear gage. Also, the overall range in values, from 90 to 150 pcf, was approximately the same for all three techniques.

Comparative results for the balloon and sand cone data obtained on Projects 2 and 3 indicated similar results, although for Project 2 the balloon values were approximately 5 pcf lower than the sand cone values, whereas the average values for Project 3 were almost identical for the two methods. A possible explanation is that, on Project 3, the field operators used exactly the same density hole for both sand cone and balloon tests, whereas on the other two projects the technicians enlarged the density hole to fit the sand cone apparatus after taking their balloon test. The enlarged sand cone test hole was approximately 0.05 cu ft, compared to about 0.03 cu ft for the balloon density test.

The overall close similarity of results obtained for these three field density tests indicates that any of them could be used in the field with equal reliability. The decision as to which method to use would then depend on which particular advantage or disadvantage associated with the tests was felt to be most critical or important. The nuclear gage would be best suited for performing an extensive series of tests, as might be required for a statistical quality control program, because of its speed of operation.

Determination of Moisture Content

The computation of dry density, which is used as the basis for computing percent compaction in this study, depends on the accurate determination of the moisture content of the wet density sample. This is true for both the in-place field and standard laboratory density tests.

The two common methods presently used for field measurement of moisture content in Indiana are the field stove-drying method and the Speedy carbide-gas moisture tester. The stove-drying method has been in use for many years and a previous study conducted by the Indiana State Highway Commission (10) indicated a high degree of correlation with standard laboratory oven-drying results. The Speedy moisture test is relatively new and no significant amount of documented correlation data for its results had been obtained by Indiana State Highway Commission field personnel prior to this study.

A third method for determining field moisture content being used in Indiana on a trial basis employs the nuclear surface backscatter moisture gage. Based on the need for data to determine the applicability of these methods, moisture data obtained using both units were compared with standard laboratory oven-drying results. The desire to use either of these methods for field control is based on the speed at which the test can be performed in comparison with oven-drying or field stove-dryings methods, and the simplicity of the computations associated with both methods.

The results obtained during this study indicate that both methods provide results that compare very closely to laboratory oven-drying data. A linear correlation analysis was performed for the data, and correlation coefficients from 0.81 to 0.85 were obtained for the nuclear gages, indicating the validity of using this type of equipment. It should be pointed out that the nuclear gage is affected by the total hydrogen (moisture) in the soil, whereas the laboratory oven-drying method accounts for only the moisture that can be driven out of the sample at a temperature of 105 C. Also, the nuclear gage measures the average moisture content of a relatively large volume of material, whereas the oven-dry samples represent only 150 to 200 grams of soil. These differences are assumed to account for the major portion of the observed variations when comparing moisture contents determined by these methods.

Results obtained comparing moisture content determined by the Speedy device with oven-drying results also indicated excellent correlations. The data for this phase of the study are based on obtaining moisture samples from two different test sources, the actual in-place density test material and the material extracted from the one-point compaction test sample. Also, two different sizes of Speedy moisture units, one with a 6-gram sample capacity and the other using a 26-gram sample, were tested. One of the major criticisms of the Speedy method is that the relatively small size of sample used does not provide representative results and this use of two sample sizes allowed a comparison to be made with respect to the results achieved by each unit.

The data indicate that very high linear regression correlation coefficients were achieved when using the 26-gram sample size Speedy moisture tester for all field test data. These ranged from 0.84 to 0.93 and appeared to be independent of sample sources, i.e., in-place material or one-point compaction test sample. The results for the smaller 6-gram sample tests were not as encouraging, especially for the in-place density material, which had a correlation coefficient of only 0.48 compared with 0.88 for the one-point compaction test material. A possible explanation lies in the relatively uniform moisture content present in a one-point compaction test sample as prepared by the grade inspector vs the possible nonuniformity of moisture content that may be present in the in-place density material.

Thus, based on the preceding correlations between the field methods tested and laboratory oven-drying values, it is suggested that either the larger (26-gram) Speedy moisture tester or the nuclear technique can be used to establish reliably estimates of moisture content. Both methods can be performed in a very short period of time, so that either would be applicable to a statistical quality control testing program that places an emphasis on speed because of the number of tests required.

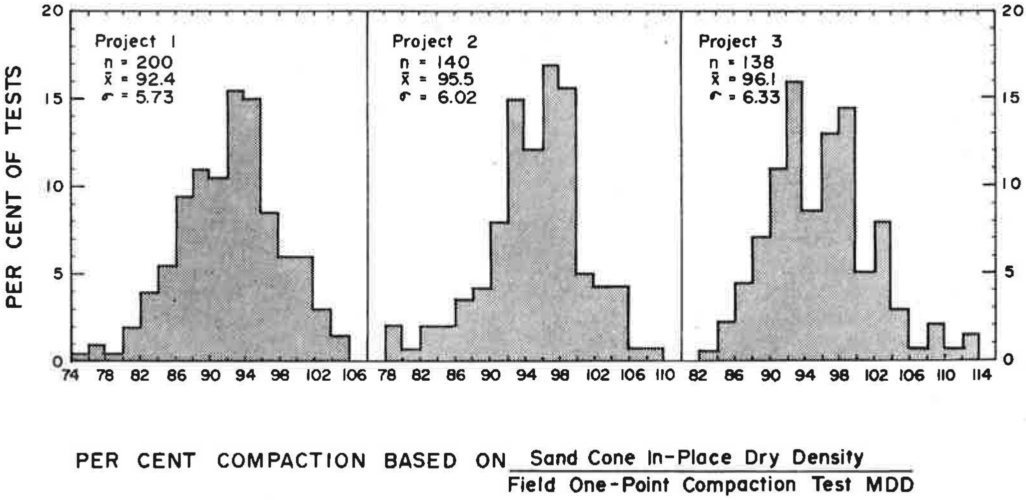

Figure 2. Variation of field compaction for study projects.

PERCENT COMPACTION RESULTS

Current Indiana State Highway Commission specifications (6) require that all fill material be compacted to a minimum of 95 percent of AASHO T 99(A) maximum density. This latter density value is obtained by testing representative field samples obtained for typical project soils. Because this approach permits some area of doubt with respect to whether or not the soil from the field test hole actually exhibits the compaction characteristics of these representative samples, the alternate method of using the field one-point compaction test to determine maximum density was used for determining percent compaction levels for this study.

Using the dry density data obtained from the sand cone test, which is the method currently used by field personnel, and the corresponding one-point maximum dry density values, the distributions of relative compaction for the projects studied are shown in Figure 2. The first values of interest are those for mean relative compaction. These are observed to be 92.4, 95.5, and 96.1 for Projects 1, 2, and 3, respectively. These indicate that for Projects 2 and 3, the contractor met specifications based on the average of the tests, whereas the average compaction level of Project 1 was well below minimum specifications.

The second values of interest are the overall ranges in compaction that were observed. In general, the data for all projects showed a similar trend in variability with low values of from 74 to 82 percent compaction up to maximum values of 106 to 114 percent compaction depending on the test method involved. This indicates a general range of almost 30 percent relative compaction values for all three projects, illustrating the extreme variations that must be accounted for in a realistic control program.

A third value that expresses a characteristic of the distribution of the data is the standard deviation. The standard deviation is a statistical expression that provides an indication of the variation of the data about the overall mean of the distribution. This is to say that if the data points are close to the average, the standard deviation will be small in magnitude. The standard deviations indicated by Figure 2 are 5.73, 6.02, and 6.33. These values indicate that, while the mean compaction level for Project 1 was lower than for the other two, the compaction was slightly more uniform. Because it is a combination of two parameters—actual relative compaction level and uniformity of compaction—that determines whether a volume of soil has been compacted satisfactorily, it is difficult to establish which of the three combinations observed in this study actually represented the best overall compaction.

TABLE 1

SUMMARY OF PERCENT COMPACTION RESULTS FOR STUDY PRODUCTS

$\left(\text{Percent Compaction Based on } \dfrac{\text{Indicated Test In-Place Dry Density}}{\text{Field One-Point Compaction Test MDD}}\right)$

Category	Project 1			Project 2		Project 3	
	Sand Cone	Balloon	Nuclear	Sand Cone	Balloon	Sand Cone	Balloon
Number of sampling locations	100	99	99	70	70	69	67
Number of compaction determinations	200	197	198	140	140	138	134
Range of percent compaction data	74 to 106	70 to 108	74 to 118	78 to 110	70 to 108	76 to 116	78 to 116
Average percent compaction	92.40	90.80	93.48	95.46	90.92	96.05	96.80
Standard deviation	5.73	6.63	7.48	6.02	7.25	6.33	6.13
Percent of tests less than specification limit of 95 percent compaction	67.0	74.5	57.5	43.5	70.7	50.0	46.2

The fourth important characteristic of these distributions is that they are all normal. The Kolmogorov-Smirnov test (9) for normality was applied to the three projects and they were all found to be normally distributed at the 95 percent significance level. This was also true for all percent compaction data obtained during this study regardless of the test methods used.

It should be noted that the data for Projects 2 and 3 were obtained by performing the specified seven replicate density tests in each of the ten control sections. A larger number of data values was obtained for Project 1, because a favorable construction schedule made it possible to perform ten replicate tests in each control section. Thus, the distribution of data for this project represents a larger random sample from the total infinite population than for the other two projects. A summary of the overall compaction data obtained during this study is given in Table 1.

For Project 1 the range in percent compaction data is observed to be approximately the same for all three methods, varying from 75 to 108 percent, but the standard deviations of the data are quite different. These values range from 5.73 for the sand cone to 7.48 for the nuclear gage, with a value of 6.63 for the balloon tests. These data indicate that, although the results for the nuclear gage show the highest average level of compaction, they also have the largest degree of variability around their mean. It is noted that average compaction levels are below specifications for all three methods of measuring in-place density. The compaction results for Project 1 are also shown graphically in Figure 3 with the normal distribution curves superimposed on the frequency histograms.

The Project 2 mean compaction level of 95.5 percent for the sand cone data exceeded the specification limit and was significantly higher than the average compaction level of 90.9 percent recorded for the balloon data. Also, of the total number of tests performed, 56.5 percent of the results based on the sand cone test exceeded specifications, whereas this value was only 29.3 percent for the balloon test data. The standard deviation of 6.02 for the sand cone was much lower than the balloon value of 7.25, indicating the sand cone data resulted not only in a higher average level of compaction but also in a more uniform situation. However, because the true density at each test location was not established, it is impossible to say which of these sets of data is the most representative of the true compaction level.

The overall results obtained for Project 3 indicated close agreement between the sand cone and balloon data, with mean compaction values of 96.1 and 96.8 percent respectively. Also, the standard deviation values are almost identical, being 6.33 for the sand cone and 6.13 for the balloon data. The percent of total tests that exceeded the minimum specification limit was slightly over 50 percent for both methods.

It should be noted that for the field testing on this project, the sand in-place density test hole was used for both methods, indicating that either one will be satisfactory when applied to identical field conditions.

A summary of compaction results for the individual control sections of Project 1 is given in Table 2. The average compaction levels vary considerably from one section to another regardless of the in-place density test involved. A similar variation is also observed for the standard deviation values, with the sand cone data exhibiting the most consistent results for both average compaction and uniformity, the latter as given by the standard deviation estimates. Similar variations in compaction data were also obtained for the other two projects when comparing individual control sections.

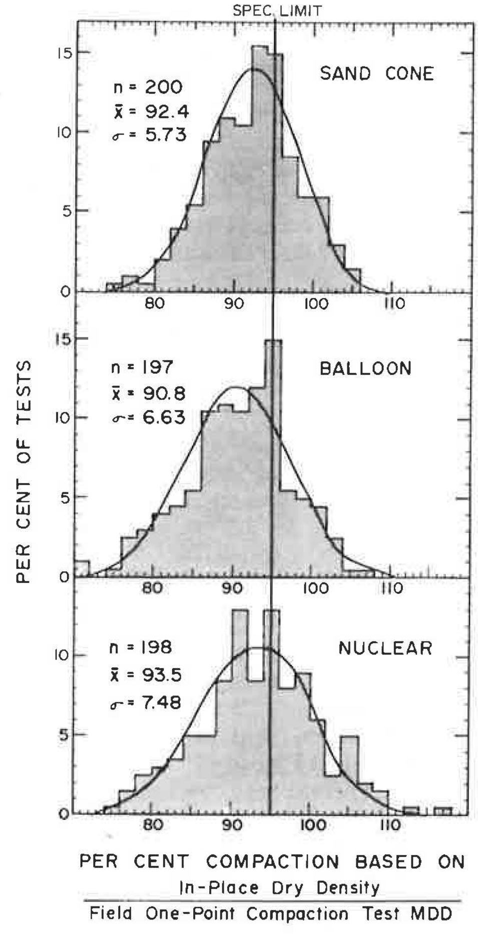

Figure 3. Variation of field compaction for Project 1.

ANALYSIS OF VARIANCE RESULTS

General Variance Terms

The basic mathematical technique known as the analysis of variance, denoted as ANOV, used in this study was a one-way Model II, equal number of observations per treatment approach. This ANOV was applied to relative compaction expressed as a ratio of field dry density to one-point compaction test maximum dry density.

It should be pointed out that to apply the ANOV technique, the data must first satisfy the criteria of being normally distributed with homogeneity of variances. The Kolmogorov-Smirnov test for goodness of fit (9) was used to test for normality, and results indicated that the percent compaction data for all projects was normally distributed at the 0.05 confidence level. The Foster-Burr test for homogeneity of variance (4) was applied to the ten control sections within each project and the results of this analysis indicated that the percent compaction variances were homogeneous at the 0.05 confidence level.

TABLE 2

SUMMARY OF PERCENT COMPACTION DATA FOR PROJECT 1

$\left(\text{Percent Compaction Based on } \frac{\text{In-Place Dry Density}}{\text{Field One-Point Compaction Test MDD}}\right)$

Control Section	No. of Tests	Sand Cone		No. of Tests	Balloon		No. of Tests	Nuclear	
		Mean	Std. Dev.		Mean	Std. Dev.		Mean	Std. Dev.
1	20	89.91	7.45	18	85.92	8.12	20	92.33	7.84
2	20	94.02	6.76	20	91.67	8.53	20	90.65	6.78
3	20	92.64	4.47	19	92.71	4.66	20	95.10	7.57
4	20	90.79	5.85	20	88.92	7.72	20	96.83	6.67
5	20	92.05	5.76	20	89.50	5.13	20	91.56	5.87
6	20	93.78	4.82	20	92.78	6.43	20	94.61	8.87
7	20	93.07	5.89	20	91.72	6.17	20	92.11	8.19
8	20	93.85	5.73	20	92.77	6.12	20	95.20	5.08
9	20	91.17	5.43	20	90.60	5.28	18	95.40	7.00
10	20	92.69	3.97	20	90.36	4.98	20	91.22	8.78
OVERALL	200	92.40	5.73	197	90.80	6.63	198	93.48	7.48

The analysis of variance establishes values for three important terms. These are the within-treatment variance, the between-treatment variance, and the standard deviation estimate based on the combination of the preceding variances.

The within-treatment variance, denoted as σ_{ω}^2, represents the variation in compaction between replicate tests. The magnitude of this variability is basically a function of (a) "testing error" including the inherent inconsistencies in the field tests themselves and the error introduced by the individual technician performing the test, (b) material variations within a relatively small testing area, and (c) variability associated with the compaction process.

The between-treatment variance denoted by σ_{β}^2 represents variations in compaction between treatments along the project with a treatment defined as a pair of replicate tests performed at essentially the same location. Again, as for the within-treatment variance, the factors primarily influencing the magnitude of the between-treatment variance are (a) soil type variations, (b) variations associated with the actual compaction process used, and (c) technician or testing variability, arranged in order of importance.

The standard deviation estimate accounts for both variability within small test areas and the variability between these test areas throughout the fill. This value is computed by using the following relationship for the overall variance estimate (σ_{ϵ}^2):

$$\sigma_{\epsilon}^2 = \sigma_{\omega}^2 + \sigma_{\beta}^2 \tag{1}$$

Overall Project Variances

Because each contractor was required to achieve the same minimum level of compaction for all of the fill earthwork, the ANOV was first performed on the total data for each project. Using the sand cone data for comparative purposes, the results show that the within-treatment variance term is relatively constant, ranging from 13.07 for Project 3 to 16.91 for Project 1. Because this term basically represents the testing error, it would be expected to be constant, assuming the field technicians all performed the tests by following carefully prescribed procedures.

The between-treatment variance terms vary widely from a minimum value of 15.97 for Project 1 to 21.81 for Project 2, and finally to a maximum of 27.24 for Project 3. These between-treatment variance results for the three projects emphasize the importance of the effects of soil variability and compaction process variations in analyzing compaction variability. This is evidenced by referring to the previous section describing project selection, which indicated the relative homogeneity of soil characteristics and construction techniques for Project 1 in comparison to the very heterogeneous nature of Project 3.

Variances Associated With Field Density Tests

The ANOV was also performed on the data obtained for each individual fill control section using results for each field density test method used. These results provide an indication of the compaction variability for individual fill areas while also providing a comparison of the various field testing techniques. An example of this variance data is given in Table 3.

Examining these results for Project 1, the within-treatment variance varied considerably from section to section and method to method. In particular, this variance term appeared to be very high for control section 1, especially for the balloon and sand cone compaction results. This is explained by the fact that the initial field tests performed by the personnel assigned to this project were all in this section because the contractor concentrated on this fill volume at the beginning of the testing phase. The fact that the technicians had not yet sufficiently developed their testing techniques obviously contributed significantly to the occurrence of these large within-treatment variances. As testing experience was gained, these variances decreased considerably, as shown by Table 3.

The within-treatment variances for the nuclear gage did not exhibit this pehnomenon, probably because of the minimal influence that the operator has on this type of density

TABLE 3

SUMMARY OF ANOV RESULTS FOR RELATIVE COMPACTION DATA OF PROJECT 1

$\left(\text{Percent Compaction Based on } \frac{\text{In-Place Dry Density}}{\text{Field One-Point Compaction Test MDD}}\right)$

Control Section	Sand Cone			Balloon			Nuclear		
	σ^2_ω	σ^2_β	σ_ϵ	σ^2_ω	σ^2_β	σ_ϵ	σ^2_ω	σ^2_β	σ_ϵ
1	56.96	–	7.56	64.33	3.28	8.20	62.76	–	7.90
2	25.17	21.72	6.85	35.24	39.62	8.62	40.88	5.38	6.79
3	11.69	8.78	4.51	15.70	26.14	6.46	15.37	44.31	7.71
4	16.63	18.64	5.93	29.36	32.40	7.84	28.12	17.26	6.72
5	7.21	27.46	5.89	20.68	5.96	5.16	11.19	24.50	5.96
6	16.05	7.61	4.86	13.19	29.78	6.53	61.80	17.86	8.90
7	6.02	30.25	6.02	23.16	16.20	6.26	20.85	48.75	8.32
8	12.24	26.76	6.24	14.83	23.92	6.21	9.07	17.67	5.16
9	6.96	23.75	5.54	11.24	17.57	5.36	43.20	6.18	7.01
10	10.13	5.96	4.02	17.00	8.27	5.02	48.08	30.71	8.85
OVERALL	16.91	15.97	5.71	24.15	19.67	6.60	34.04	21.99	7.48

test, but the variances were more widely scattered than for the sand cone and balloon data. A comparison of the within-treatment values obtained for different density tests for all test projects indicates that in general the lowest values are obtained for the sand cone.

The between-treatment variances for all three projects appear random in nature and vary widely from section to section within each project studied. The highest values were found for Project 3, which has been described previously as characterized by variable soil conditions and compaction techniques.

PRACTICAL APPLICATION OF A STATISTICAL QUALITY CONTROL PROGRAM

Basic Concepts

Most current highway specifications imply a form of quality control. A sampling and testing program is usually applied to the finished product, and a decision is made concerning the quality of the construction on the basis of these tests. Unfortunately, the number of compaction tests involved is usually only one or two and the results of these are taken as being representative of a relatively large volume of material. To be sure that the true compaction level of a given enbankment or fill had been established would require performing an infinite or at least an extremely large number of field tests and this would not be realistic. The use of a statistical control program is then a compromise between these two situations. Statistical control of a construction process involves using some statistical technique to make a decision about overall quality based on results of a random sample.

Before considering which statistical technique might be most applicable to embankment compaction control, a decision must be made with respect to the size of the control section in which the specified random sample tests are to be performed. A comparison of the variances obtained from the ANOV for each fill with the corresponding volume of the fill, which ranged from 7,500 to over 100,000 cu yd, indicated little or no correlation between these parameters. This agrees with previous data collected during a study of subgrade and subbase compaction (10).

Several approaches can be used in selecting the size of the control section. One method is to establish a fixed volume (or area) of material to be used as the control section, thereby ensuring equal control testing of all materials involved. However, it is difficult to estimate an optimum volume or area to be used as a control section based on the relative independence that seems to exist between observed variability and the corresponding testing area within which the variation is recorded.

An alternate approach is to base the size of the control section on the individual fills or construction units within the project, as was done in this study. Before construction begins, the different construction areas can be established by their stationing and each of these would then constitute a control section. However, it is suggested that for larger fills, say over 2,000 ft in length, the fills should be subdivided and these smaller units then used as the control sections. This approach generally coincides with the contractor's schedule in that he will usually construct a fill by placing and compacting a given lift over the length of the fill unless it is relatively long. If it is too long, it may be more feasible to build up several lifts over a portion of the fill and then proceed with the construction of the remainder of the fill.

There are many statistical techniques available that can be applied to this problem of relating a sample mean to the true mean of a normal population. One approach that can be practically applied to the control of compaction and that is recommended by this author is that of a hypothesis testing procedure based on a t statistic. An example of the use of this type of analysis applied to the fill compaction data from this study is presented in the following section.

Statistical Control Based on Hypothesis Testing

A statistical hypothesis is a statement about the value of some population parameter such as the mean or standard deviation. The parameter of interest in this study is that of the true mean value of relative compaction for a specified fill lift or population.

The hypothesis to be tested in the case of embankment compaction control is H_0 : $\mu \geq \mu_0$ where μ represents the true population mean and μ_0 is a specified acceptable compaction level. Because it is impossible to test the entire population, the decision to accept or reject the null hypothesis, H_0, must be based on the statistics of a randomly selected sample. Thus, based on the mean, $\bar{X}$, of a specified number of test samples, n, a decision is made relative to whether or not the true population mean, μ, from which these samples were randomly selected exceeds some specified value, μ_0.

Two values that must be established in any hypothesis test are the probability of making a Type I error, which is the rejection of the hypothesis when it is really true, and the probability of making a Type II error, or accepting a false hypothesis. The probabilities are denoted by α and β respectively, and a value of 0.05 was assumed for both of these parameters, thus compromising between the risk accepted by the highway department, β, and that accepted by the contractor, α.

Another critical value involved in hypothesis testing is the estimate of the population variance or standard deviation. Because it is impossible to establish a value for the true population variance, an estimate must be used. For this study project, standard deviation values ranged from a minimum of 5.7 for the sand cone data of Project 1 to a maximum of 7.5 for the nuclear data of that project. To account for the range in values obtained for the different test methods and projects studied, the following values are proposed for this type of construction: sand cone, $\sigma_\epsilon = 6.0$; balloon, $\sigma_\epsilon = 6.7$; nuclear, $\sigma_\epsilon = 7.5$. These estimates represent three-dimensional variability rather than variability for a given lift, and comparative data obtained from a previous study (10) involving two-dimensional sampling indicated a relative compaction standard deviation estimate of approximately 5.0 as being realistic for sand cone testing.

The decision as to the value to be assigned for μ_0 or the specified compaction control level is subject to question. Current specifications require that all field compaction exceed 95 percent of standard AASHO maximum density. However, the results of this study, obtained by performing tests only in areas that had previously been passed as meeting the 95 percent compaction specification based on the field inspectors' tests, show that a considerable percentage of the tests fell below this level.

As previously noted, the relative compaction data were observed to be normally distributed, thus indicating that approximately 68 percent of the total data points are between the mean and plus or minus one standard deviation. Based on this concept, and using the means and corresponding standard deviation estimates for the three study projects, it can be shown that approximately 16 percent of all field data fell below 88 percent compaction. By changing the specification limit to 102 percent by increasing it by one standard deviation, this would result in 16 percent of the total data falling below only 95 percent compaction, which would be a more desirable situation. However, whether this is necessary or not is debatable because construction quality obtained by using the current 95 percent specification appears to be satisfactory.

Based on the indicated values of α, β, and σ_ϵ for each density test method, it is possible to determine the number of field tests that would be required for this approach based on a t test for the significance of means. This is accomplished using Appendix 9 of "Statistics in Research" (9). In using this table, a value of 7.0 was selected for δ, which represents the minimum level at which the hypothesis test is to be detected.

Based on these data, the number of field control tests required using the different field density testing methods is 10 with the sand cone, 11 with the balloon, and 14 with the nuclear gage used in this study.

TABLE 4

TYPICAL COMPUTATIONS FOR STATISTICAL DECISION THEORY USING PSEUDO t STATISTIC

Field Relative Compaction Data:

$X_1 = 104.2$	$X_6 = 97.7$
$X_2 = 96.6$	$X_7 = 98.6$
$X_3 = 89.4$	$X_8 = 94.9$
$X_4 = 92.3$	$X_9 = 90.8$
$X_5 = 93.0$	$X_{10} = 101.4$

Computations:

$H_0: \mu \geq \mu_0$ with $p = 0.95$, $n = 10$, $\mu_0 = 95.0$

$X_{max} = 104.2$

$X_{min} = 89.4$

$R = 104.2 - 89.4 = 14.8$

$$\tau = \frac{\frac{(104.2 + 89.4)}{2} - 95.0}{14.8} = \frac{96.8 - 95.0}{14.8}$$

$$\tau = \frac{1.8}{14.8} = 0.121$$

τ tabular = -0.22

$\tau > \tau$ tabular

Therefore, the embankment compaction does meet specifications.

The routine control procedure would be to perform the above number of tests for each lift and then compute a test statistic t using

$$t = \frac{(\bar{X} - \mu_0)\sqrt{n}}{s} \tag{2}$$

The decision would then be made to accept the hypothesis $\mu \geq \mu_0$ if the calculated t value equaled or exceeded a negative tabular t value as obtained from a cumulative t distribution table.

Unfortunately, using from 10 to 14 test points would make the computation of the mean and standard deviation relatively time-consuming, thus unnecessarily slowing construction. To simplify field computations, it is proposed that a pseudo t statistic denoted as τ be used. This value is computed by the relationship

$$\tau = \frac{\left(\frac{X_{max} + X_{min}}{2} - \mu_0\right)}{R} \tag{3}$$

where X_{min} and X_{max} represent the minimum and maximum relative compaction values for a random sample of n tests, and R is the range between these values. This calculated τ value is then compared to a tabular critical value as given by Appendix 17, Table 3 of "Statistics in Research" (9). The hypothesis is then accepted if τ calculated $\geq -\tau$ tabular. It must be noted that a random sample from a normal population is assumed. An example illustrating this approach is given in Table 4.

CONCLUSIONS

The results of this study and other similar quality control investigations clearly illustrate the importance of adopting a more realistic field sampling and tesing program if adequate control of compaction construction is to be gained. The sophisticated procedures now being applied to highway design coupled with the speed of current highway construction have antiquated the inspection control now being enforced.

The overall wide variations in relative compaction results observed in this study indicate the need for more extensive field testing coupled with a statistical technique for making a rational decision concerning overall compaction quality. This compaction variability is a combination of many interrelated factors including material variations, testing error, and compaction methods, and can only be accounted for by applying a sampling and testing program that accounts for this variability.

The approach suggested in this paper is the use of a hypothesis test using a pseudo t statistic for making the decision to accept or reject the work. This technique allows a rational decision to be made concerning the overall quality of compaction based on the results of a series of random tests rather than trying to judge the quality on the basis of one or two isolated test results.

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