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Optimization of Density and Moisture Content Measurements by Nuclear Methods

A staff digest of the essential findings from the final report on NCHRP Project 10-5A, "Optimization of Nuclear Density and Moisture Content Measurement Methods," by R. P. Gardner, W. L. Dunn, F. H. McDougal, and W. J. Lippold, North Carolina State University

THE PROBLEM AND ITS SOLUTION

The majority of acceptance specifications or quality assurance procedures for controlling the compaction of highway embankments, subgrades, and base courses involve the determination of densities and moisture contents of soil and aggregate materials during the construction process. Nuclear gauges for making these measurements first became available in the late 1950's. However, although the gauges seemed to answer a need for rapid and nondestructive testing, growth in their acceptance and use has been rather slow until the past few years, due largely to questions concerning measurement accuracy. Early experiences with regard to field reliability, economics, radiation, and licensing of operators also tended to discourage the use of nuclear equipment by highway departments, but these problems appear to have been overcome in recent years.

Density Gauges

Figure 1 shows the operational principles of gamma-ray nuclear density gauges. When gamma rays are emitted from a radiosotope source in proximity to a surface they interact with the material and are scattered or absorbed. The count of the gamma rays emerging from the surface at some point is influenced by the density and the composition of the material. A typical gauge consists of a gamma-ray source, a detector with associated counting electronics, and shielding between the two to prevent direct transmission of the gamma rays from the source to the detector. A wide variety of gauge configurations is possible, involving source energy and intensity, type and efficiency of detector, and source-detector separation. The most universally employed method of determining density with a gamma-ray gauge is by use of a calibration curve prepared from the empirically determined relationships between density and response for each individual instrument. The calibration curve for a particular instrument is originally obtained by plotting the response measured by the gauge for a set of calibration standards of known density.

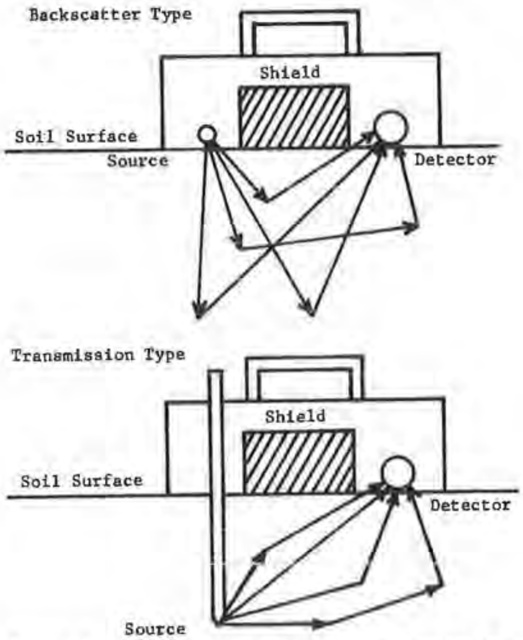

Figure 1. Representative gamma-ray paths for density gauges. *

NCHRP Report 43 describes the factors that influence the accuracy of nuclear density gauge measurements and methods that can be used for their reduction. The primary sources of error were identified as (1) inaccurate calibration techniques, (2) sensitivity to soil composition, and (3) sensitivity to surface roughness. The first two sources of error apply about equally to both direct transmission and backscatter-type gauges. The surface roughness problem is considerable for backscatter-type gauges and almost negligible for the transmission type. The report describes a mathematical model technique for preparation of calibration curves of suitable accuracy for highway construction control for identifiable soil types, thus making it possible to practically eliminate the first two sources of error. However, it was also found that a dual-gauge technique was equally effective and did not require knowledge of the soil composition. This dual-gauge technique consists of using two gauges, each with a different relative sensitivity to soil density and composition, and solving the calibrations models of each simultaneously. A nomograph solution of the air-gap calibration method, which employs the dual-gauge principle, is included in Appendix A of *NCHRP Report 43*. It is recommended as the most practical method for using existing nuclear density gauges.

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*Gardner, R. P., and Roberts, K. F., "Density and Moisture Content Measurements by Nuclear Methods," *NCHRP Report 43* (1967).

Moisture Content Gauges

Determination of the dry density of the soil or aggregate materials being placed, which is necessary for computing percent compaction, depends on a reasonably accurate method for measurement of moisture content. When nuclear equipment is used to determine total density, the same equipment is normally used to measure the moisture content of the soil. A neutron moisture gauge essentially consists of a fast-neutron source and a slow-neutron detector with associated counting electronics. When the gauge is exposed to a surface the number of slow neutrons in the vicinity of the detector is determined mainly by the hydrogen content of the surface material. If most of the hydrogen is present in the form of water, the gauge, with proper calibration, can be used to measure the moisture content.

According to *NCHRP Report 43*, nuclear moisture content gauges are sensitive to variations in soil density and to soil composition. However, the accuracy of these gauges has not been questioned to the same extent as that of density gauges, probably for the reason that a greater percent error of moisture content can be tolerated. When the moisture content of the soil is about 10 percent, 10 percent deviation from the mean will result in a possible error of only 1 pcf.

Research Approach

The objective of Project 10-5A was to minimize the errors identified with measurement of density and moisture content of soils using nuclear gauges. The North Carolina State University researchers approached this over-all objective by detailing four somewhat independent research efforts as follows:

1. Optimization of the dual-gauge principle to compensate for soil composition effects of gamma-ray density gauge measurements.

2. Optimization of the energy discrimination method to compensate for soil composition effects of gamma-ray density gauge measurements.

3. Study of techniques for minimizing errors due to surface effects of gamma-ray density gauge measurements.

4. Optimization of the model method for calibrating neutron gauges for measurement of moisture content in soils.

In approaching the problem of optimization of density gauges the North Carolina State University researchers recognized the need to consider the interaction of all possible errors. For example, the best gauge configuration or technique for minimizing surface roughness errors might result in an increase in errors influenced by composition. To provide a reasonable basis for optimization, the errors were combined to yield a single criterion, the Quality Factor, which can be used to evaluate the over-all performance of a nuclear density gauge. Research aimed at minimizing moisture content measurement errors involved using the Monte Carlo or random walk method to simulate gauge response, checking the results of the simulation against experimental studies, and attempting to generalize the Monte Carlo results.

The results of this study have been evaluated sufficiently to permit immediate application and, combined with previous research and experience such as that contained in *NCHRP Report 43*, provide a valid basis for adequate calibration and the practical field use of nuclear density and moisture content gauges. The Quality Factor concept is defined explicitly and presented in a form that can be used by practicing engineers for evaluating different types of gauges.

FINDINGS

Three significant findings or conclusions of the phases of the study pertaining to density measurements are:

1. The Quality Factor concept provides an excellent method for evaluating over-all gauge performance.

   The Quality Factor concept is an attempt to combine all of the identified errors to form one parameter that can be used as an indication of the performance of a nuclear density gauge. Although initially developed as a research tool, the concept can be used effectively to improve gauge configuration and design and, in simplified form, for the evaluation of existing gauges and for use in nuclear equipment specifications as described herein.

2. Commercially available transmission-type nuclear gauges and backscatter-type nuclear gauges employing the air-gap calibration method can be used for determining soil density with adequate accuracy for the control of compaction during highway construction.

   A number of studies completed in recent years have made it apparent that many current acceptance programs for control of compaction of highway components based on measurement of density of representative samples are unrealistic. The percent compaction degree of variability is such that statistical concepts including random sampling must be used to provide an unbiased estimate of actual field density. Effective compaction specifications should recognize the heterogeneity of the material and incorporate the variability in the over-all acceptance program. It is in the context of such a program that nuclear testing can provide a more reliable measure of actual field density than the gravimetric method. For example, when the variability of percent compaction of an embankment varies by as much as ±20 percent, a large number of random tests with a possible individual error of ±5 percent will result in a more reliable indication of actual field density than a small number of tests with a possible individual error of only ±2 percent.

   Some typical errors and Quality Factors computed during this study for commercially available backscatter-type and transmission-type nuclear density gauges are:

Gauge Type	Error (pcf)			Quality Factor
	Composition	Surface Roughness	Counting Rate	
Backscatter	2.0 - 5.0	6.7 - 13.0	0.7 - 1.2	0.17 - 0.33
Transmission	1.7 - 4.0	1.4 - 2.1	0.5 - 0.8	0.36 - 0.56

3. New backscatter-type nuclear gauges with significantly higher Quality Factors can be built.

As described earlier, transmission-type nuclear gauges currently available have a higher Quality Factor range than backscatter-type gauges, but they require the punching or drilling of a hole in the surface to be tested. An objective of this study was to optimize the dual-gauge principle for backscatter-type gauges to the extent that they would be at least as accurate as the transmission type and would require little or no preparation of the surface to be tested, thus being truly nondestructive.

The optimization program was carried out by searching through 826 dual-gauge combinations using the calibration model described in *NCHRP Report 43* and various values for each of the four variables--source energy, source-detector distance, counter types, and source collimation. The optimum dual-gauge design identified during the research has a QF of 1.34 and 19 dual gauges were identified with a QF of more than 1.0, which is considerably better than any current backscatter or transmission-type gauge. It was found that the design parameters are not particularly critical except that the source-detector separation of one should be small and the other large and one Geiger-Mueller counter should have a relatively low efficiency while the other should have a relatively high efficiency for low-energy gamma rays. Twelve of the best 25 dual-gauge designs had surface roughness errors of less than 0.35 pcf, compared to the lowest of 6.1 pcf for current backscatter-type gauges. Thus, the bulk of the surface preparation time could be essentially eliminated when dual gauges of the designs developed become available.

The significant findings of the moisture content measurement phase of the study are:

1. The Monte Carlo simulation of nuclear moisture content gauges is accurate but requires a large amount of computer time.

2. Attempts at a complete generalization of the simulation have not been successful to date.

3. A less complete and empirical generalization of the simulation appears quite promising and a tentative calibration method for a specific gauge configuration has been developed.

The formula developed during the study will serve as a tentative calibration model for neutron gauges of the general type that use a BF_3 proportional counter, any alpha-particle emitting radioisotope with berylium neutron source, and an approximate source-to-detector center distance of 1 inch. It probably should not be used with neutron gauges that contain neutron moderators such as polyethylene and have a large background response when no moisture is present in the sample.

The calibration procedure involves (1) the preparation of four to six laboratory standard samples with representative ranges of hydrogen, total density, and iron content, (2) obtaining gauge responses on the prepared standards, (3) determination of best least-squares analysis of the data, and (4) preparation of a family of calibration curves for various densities and iron equivalent contents. In the field, the particular curve that is closest to the density and equivalent iron content of the soil being tested should be used to determine the moisture content in pounds per cubic foot. This tentative calibration model was checked for four commercial gauges on 15 prepared soil and aggregate samples with density as the only variable. A standard deviation of 1.2 pcf for all gauges was obtained. This would have probably been reduced with incorporation of calibration for composition. The standard deviation was 2.2 pcf when the single calibration curves of the manufacturers were used.

APPLICATIONS

The Quality Factor concept developed during this study appears to be an excellent method for evaluating the over-all performance of all types of nuclear density gauges. The development of the concept is summarized as follows:

The soil composition standard error of a nuclear density gauge is defined as

$$\sigma_c = \left[\sum_{i=1}^{4} \frac{(\bar{\rho}_i - \rho_i)^2}{4} \right]^{1/2} \quad (1)$$

where $\bar{\rho}_i$ is the known density of the i^{th} one of the four standard samples and ρ_i is the measured density of the same standard sample.

Uncertainty in the detection of radiation can be obtained from the slope of the calibration curve and the standard deviation of the counting rate measurement. This counting rate standard error is defined as

$$\sigma_s = \frac{\partial \rho}{\partial R} \sigma_R \quad (2)$$

where

$\frac{\partial \rho}{\partial R}$ = Slope of calibration curve

σ_R = Standard deviation of counting rate

If at least 10,000 counts are accumulated to ascertain the counting rate and if the ratio of the sample counting rate to the counting rate of a standard is taken as the gauge response, R, a good rule of thumb is to take σ_R as 1 percent of the gauge response, R.

The surface roughness error, E_{se}, is defined as that error introduced by comparing the density measured 1/16 in. above a smooth surface with the density measured flush with the same surface.

The volume factor, VF, is taken as a measure of the error due to sample heterogeneity, and is defined as

$$VF = 0.1 \frac{xwd}{288} + 0.9 \quad (3)$$

where x if the effective sample depth, in inches; w is the sample width, in inches; and d is the source-to-detector distance, in inches. The factors 0.1, 288, and 0.9 are used to force the VF to vary from 0.9 to 1.0 so that it is not given appreciable weight in comparison to other sources of error.

The Quality Factor was developed by first combining the soil composition and counting rate errors to form a total normal error, as follows:

$$\sigma_n = \sqrt{\sigma_c^2 + \sigma_s^2} \quad (4)$$

The total normal error may either be added to or subtracted from the surface roughness error to determine the error level, L, and error range, D.

Lowest most probable error = $E_{se} - \sigma_n$

Highest most probable error = $E_{se} + \sigma_n$

$$L = E_{se} - \sigma_n \tag{5}$$

$$D = (E_{se} + \sigma_n) - (E_{se} - \sigma_n) = 2\sigma_n \tag{6}$$

A good indication of the total of the three errors is obtained by taking the square root of the sum of the squares of the level and range of the errors. The total error is defined as

$$E_t = \sqrt{D^2 \pm L^2} \tag{7}$$

with the positive sign used when L is positive and the negative sign used when L is negative ($\sigma_n > E_{se}$).

The Quality Factor, QF, is then described as

$$QF = \frac{2VF}{E_t} = \frac{2VF}{\sqrt{D^2 \pm L^2}} \tag{8}$$

Although a Quality Factor of greater than one is possible, it is normalized to a value of 1.0 when VF is 1.0, E_{se} is 1 pcf, and σ_n is 1 pcf.

The Quality Factor concept for evaluation of nuclear density gauges may be undertaken by performing the following steps:

1. Prepare calibration curves using measurements on the four standard materials and the methods described in *NCHRP Report 43*. Calibration should be in accordance with the method used in the field (such as single calibration curve, multiple calibration curves for identified soil types, or air-gap dual-gauge method).

2. Calculate the soil composition error, σ_c , using Equation 1.

3. Calculate the counting rate error, σ_s , using Equation 2.

4. Calculate the total normal error, σ_n , using Equation 4.

5. Measure the surface roughness error, E_{se}, by determining the average of the errors on each of the four standards. The surface roughness error for each standard is the difference between the measured density flush with the surface and the measured density 1/16 in. above the surface.

6. Assume a volume factor (VF) of 1.0. This is valid for existing commercial gauges or if similar gauges are to be compared.

7. Calculate the Quality Factor (QF) using Equation 8.

Early investigations of nuclear gauge accuracy were primarily concerned with comparisons between the measured densities of individual samples consisting of very small volumes of an embankment or base course using a nuclear gauge and one or more conventional tests, such as the sand cone or water balloon method. This type of comparison failed to recognize that (1) gravimetric methods of measurement are not without errors, (2) nuclear gauges usually measure a larger volume than gravimetric methods, and (3) accuracy should be evaluated in relation to the total acceptance program rather than be limited to comparisons between test methods.

This study has verified that, with proper calibration, currently available nuclear equipment for measurement of density and moisture content provides satisfactory accuracy for the control of compaction of highway embankments and base courses when used within the concept of random sampling and statistically based quality assurance programs. It has also provided the Quality Factor as a means for evaluating the performance of existing nuclear gauges and methods to refine the calibration of gauges when improved accuracy is desired. In addition, the research provides the necessary technical and investigative background for the production of the next generation of nuclear density and moisture content measurement equipment, which should be even more accurate and require less surface preparation than current models. Thus, the results will provide highway agencies with both immediate and long-range benefits.

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