Evaluation of Direct Transmission-Type Nuclear Density Gage for Measuring In-Place Densities of Soils

P. C. TODOR and WILLIAM GARTNER, JR.
Respectively, Assistant Research Engineer and Engineer of Research, Florida State Road Department

The direct transmission-type nuclear density gage has proved to be more accurate and faster than conventional methods. The use of the direct transmission principle seems to eliminate the necessity for several calibration curves. Density tests conducted by research personnel are usually made in areas where the contractor is having difficulty obtaining specified density. The nuclear equipment with its inherent speed has provided a means whereby the once time-consuming task of repeated density tests is considerably reduced. The equipment is also useful for setting up compaction equipment schedules and procedure. The amount of coverage required by a given type of compaction equipment to obtain specified density for an entire job can be determined quickly from one test section, provided extensive moisture or material changes are not encountered.

•THE TIME required to conduct conventional in-place density tests and the many possible sources or error (1) have made necessary a more dependable and less time-consuming method of test. Modern advancements in highway construction, especially in the speed of earthmoving equipment, and expanded construction programs, with emphasis on early completion, have increased the need for a faster method of test.

For these reasons, the Florida State Road Department's Division of Research initiated a comprehensive study of the available conventional and nuclear methods for determining in-place density. Results of the preliminary phases of this study have already been published (1, 2); this is a report on the continuation of the program.

The nuclear density equipment currently available commercially employs either of two principles, backscattering or direct transmission.

1. The backscatter gage (Fig. 1a) transmits gamma rays into the soil, and the rays that are reflected or scattered back by the interactions with electrons of the soil mass are counted.
2. With the direct transmission-type gage (Fig. 1b), the source is inserted into the soil and transmits gamma rays in all directions. The majority of the gamma rays counted have traveled in a relatively straight line from source to detector.

This report describes a laboratory and field evaluation of a direct transmission-type nuclear device manufactured by Troxler Electronic Laboratories of Raleigh, N.C. The purpose is the development of method of determining in-place density for routine control testing in base, subbase and embankment materials.

DESCRIPTION OF EQUIPMENT

The nuclear density-moisture measuring system used in this study consists of three units: (a) a surface density gage, (b) a convertible surface-depth moisture gage, and (c) a portable scaler.

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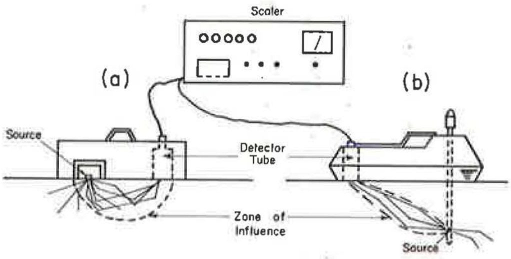

Figure 1. Commercially available nuclear density gages: (a) backscatter, and (b) direct transmission.

Surface Density Gage

The gamma source is radium-beryllium, double-sealed and double-encapsulated in type 304 stainless steel. The standard nominal activity is 3 millicuries, but other activities are available. The detector is a Geiger-Müller detection tube. The source is contained in a steel rod, ¾ in. in diameter, which can be lowered into the soil to a predetermined depth of 1 to 9 in. (Fig. 2).

Surface-Depth Moisture Gage

The fast neutron source is also radium-beryllium, double-sealed and double-encapsulated in type 304 stainless steel. The standard nominal activity is also 3 millicuries, but other activities are available. The detector, containing BF, enriched in the B-10 isotope, responds primarily to relatively slow or "thermal" neutrons and shows practically no response to fast neutrons.

The moisture gage was used as a surface gage in this report (Fig. 3); however, it can be used as a depth gage by removing the moisture probe from the surface gage and installing an adapter for the source (Fig. 4).

Scaler Model 200

The scaler, used for both the moisture and density measuring equipment, is transistorized and of modular construction (Fig. 5). Incorporated in the scaler is a mechanical 1-min timer and a rate meter. The selection of operation (moisture or density) is determined by the voltage setting, gain setting and circuit selection. The scaler is battery powered and is furnished with a charger operated from a conventional 115 volt, 60 cycle, a.c. current.

LABORATORY STUDY

The objectives of the laboratory study were (a) to determine whether one or several calibration curves would be required, as was the case in a previous study with a

Figure 2. Troxler surface density gage.

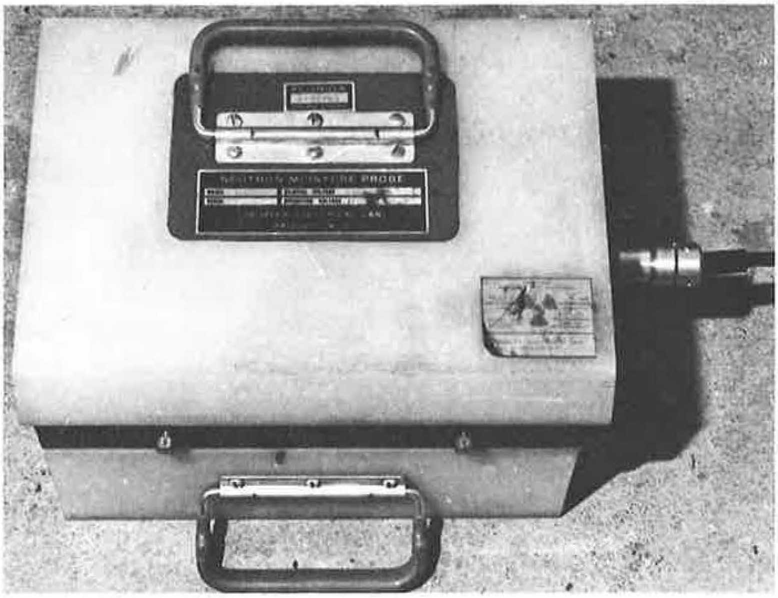

Figure 3. Moisture gage on paraffin standard.

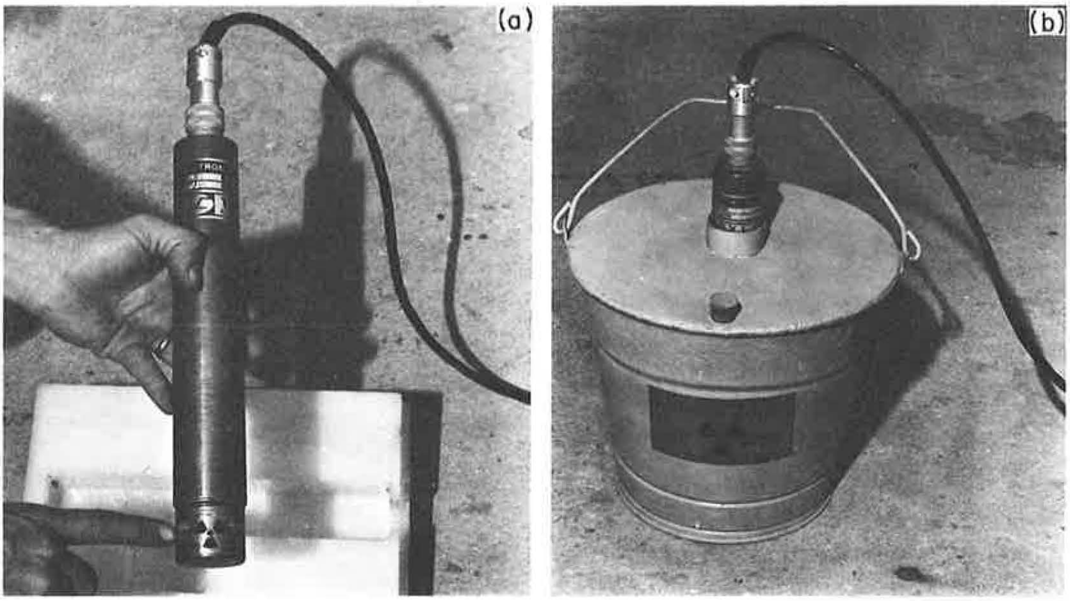

Figure 4. Probe Model 104: (a) removed from surface gage with special attachment, ready for use as a depth moisture probe; and (b) inserted in standard reference.

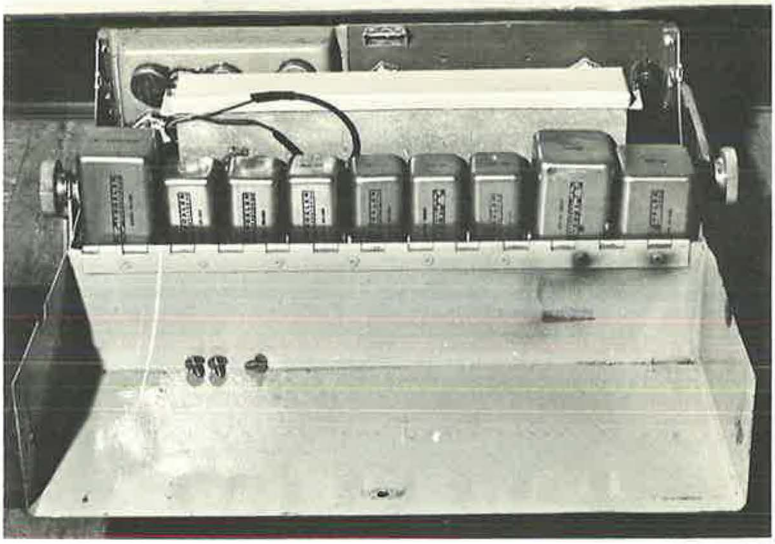

Figure 5. Interior of Model 200 scaler, showing modular type of construction.

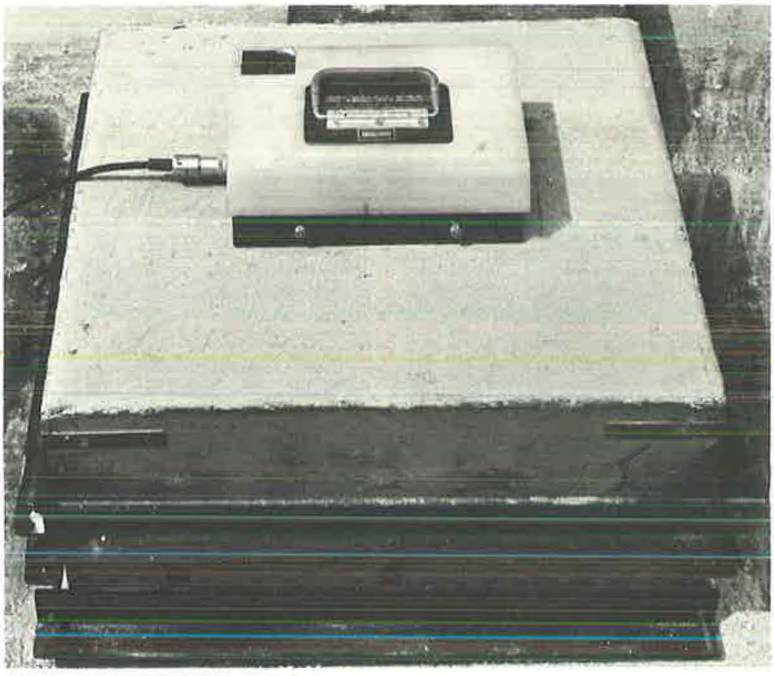

Figure 6. Moisture gage placed in center of sample to obtain moisture count for calibration curve.

backscatter-type device (2); and (b) to establish calibration curves to be used in the field evaluation study. Particular emphasis was placed on determining the extent of radiological safety precautions necessary when using this equipment. This emphasis was continued through the field evaluation.

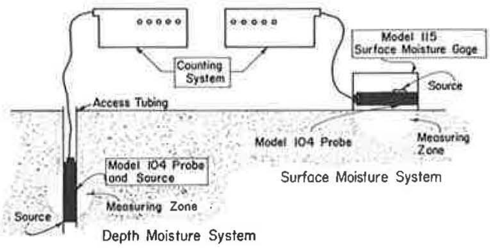

Figure 7. Moisture measuring systems.

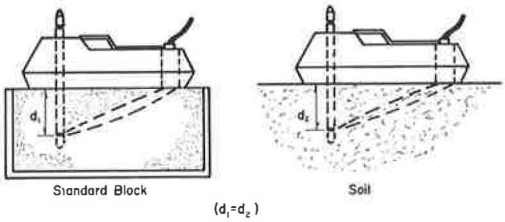

Figure 8. Test procedure using single calibration curve.

Procedure

The laboratory procedure used in this investigation was similar to that used in a previous study (2). Each soil was thoroughly mixed at predetermined moisture contents, covered with a plastic sheet to prevent surface drying, and left standing overnight to allow the moisture to reach a state of equilibrium. The soil was then compacted in boxes of known volume in approximately 2-in. layers to achieve a uniform density, both laterally and vertically, within the box. A collar was constructed which permitted the material to be compacted 2 to 3 in. above the top edge. The collar was then removed and the material was struck off in much the same manner as when preparing a Proctor sample. The entire box was weighed on a platform scale and the average wet density of the material was computed.

The nuclear moisture unit was next standardized (a method whereby the attitude and efficiency of the gage can be numerically evaluated) by taking a series of 60-sec counts on the standard reference paraffin block. The counts were taken until they reproduced themselves within $\pm \sqrt{N}$ (where N = 60-sec count) and then 10 counts were averaged for the standard count. The moisture gage was placed near the center of the sample and a 60-sec count was recorded. Four such counts were recorded with the gage rotated approximately 90 deg between each test (Fig. 6). Samples for ovendry comparison were taken after the density gage counts were recorded.

The nuclear counts resulting from the moisture tests were averaged to obtain a moisture count for the entire specimen. This was divided by the corresponding standard count to obtain the percent of standard. The nuclear moisture gage percent standard was plotted against the oven-dried samples to establish points for the calibration curve drawn as the line of best fit.

Figure 7 is a schematic of the moisture unit being used as a surface gage and as a depth gage. The data reported in this study include only that obtained using the moisture unit as a surface gage. In additional studies, the moisture unit was used as a depth probe and the tests showed favorable agreement with the manufacturer's curve. However, the data available at this time are limited and will not be included in this report.

After completing the moisture counts, the density gage was standardized by taking a series of 60-sec counts on a standard reference concrete block at a 3-in. depth. The counts were taken until they reproduced themselves within $\pm \sqrt{N}$, and then 10 counts were averaged for the standard count. A hole was driven into the material near the center of the box with a hammer and pin. The nuclear density gage was positioned over the hole, the probe was lowered to the desired depth, and three 60-sec counts were recorded. Four such counts were recorded with the gage rotated approximately 90 deg between each test. Tests were conducted at probe settings of 3, 6 and 9 in.

With four locations tested, additional access holes were placed at each corner of the test specimen and tests were conducted with the detector toward the center. Without regard to magnitude, the eight tests were used for an analysis of uniformity. Standard deviations ranged from 0.58 to 2.5 pcf nuclear. Four balloon tests were conducted, one in each quadrant, with deviations ranging from 1.6 to 2.3 pcf.

The materials utilized in the calibration of the nuclear gage included two sources of limerock which varied in calcium content, two sand-clays that varied in iron content, and local sand.

The nuclear counts resulting from tests conducted at each depth were averaged to obtain a density count for the entire specimen. This count was divided by the corresponding standard count to obtain a count ratio for density. The resulting count ratio was plotted against box wet density for each soil tested to establish points for the calibration curve. A regression analysis was made using the method of least squares, assuming a linear relationship to establish a line of best fit for the density curve at each probe depth.

An exercise was conducted to determine the effective depth of test. The sample box was raised above the ground to achieve an air gap beneath the bottom of the box. Density tests were conducted starting at the top at 3-, 6- and 9-in. increments. A 1-in. layer of soil was then removed and the test series was repeated until the probe touched the bottom of the box.

At this point in the program, the field evaluation was initiated. It was soon evident that a calibration curve independent of depth would be very desirable. The equipment was brought back into the laboratory with the intent of establishing such a curve.

A uniform standard was constructed using a single grain-size aggregate, with an access hole that enabled the probe to be inserted to the full test depth of 9 in. in this case. A calibration curve was established, based on the assumption that if the standard count and the soil count were taken at the same depth, the resulting count ratio would be a near constant for all depths since the proportion of mass observed in the standard and in the soil would be the same (Fig. 8).

RESULTS OF LABORATORY STUDY

Utilizing the calibration curve established for the moisture gage, the nuclear moisture gage determinations were compared to the determinations obtained using a conventional Speedy Moisture Kit (3), and both methods were compared with ovendry tests. The results showed that the accuracy of both methods for the several soils tested was within ± 2 percent of the oven-dried samples. Since only one scaler was available, considerable time was saved when the Speedy Kit was used to determine the moisture content and the nuclear gage to determine the wet density.

Because of the sandy soil in Florida, the Speedy Moisture Kit can be used without any difficulty. If the gradation or clay content of a soil would not permit the use of a Speedy Kit, the nuclear moisture gage would be of great advantage since the material would otherwise have to be oven-dried.

The initial density calibration curve developed in the laboratory was satisfactory for all of the materials tested (Fig. 9). The accuracy obtained by using a single calibration curve for all materials was well within that obtained in earlier evaluation studies where the backscatter nuclear device was employed with a separate calibration curve for each material (2).

The results of the exercise to determine effective depth are given in Table 1. The tests were conducted beginning at the top and continuing to the bottom without any apparent influence from the air gap beneath the box. The results indicate that the density measured does not include any material below the bottom of the probe. Thus, one has an absolute control over the depth of test.

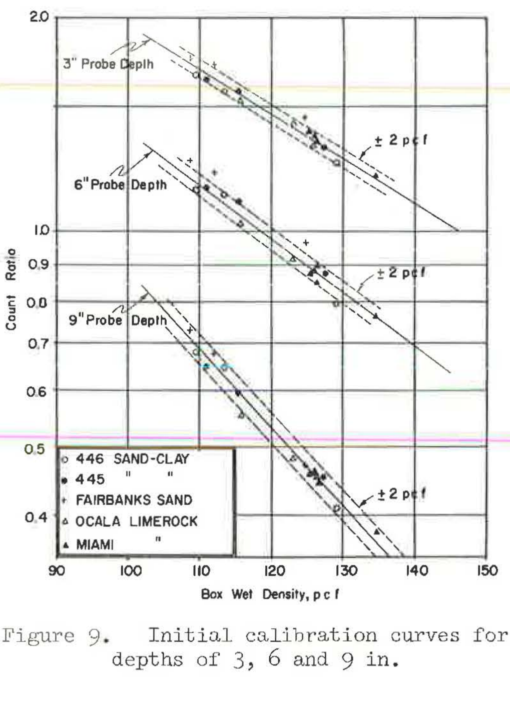

Figure 9. Initial calibration curves for depths of 3, 6 and 9 in.

TABLE 1

RESULTS OF DETERMINATION OF EFFECTIVE DEPTH

Test 1[a]				Test 2[b]				Test 3[c]			
Depth of Probe (in.)	Mat. Removed (in.)	In. Mat. Beneath Probe Tip	Density	Depth of Probe (in.)	Mat. Removed (in.)	In. Mat. Beneath Probe Tip	Density	Depth of Probe (in.)	Mat. Removed (in.)	In. Mat. Beneath Probe Tip	Density
3	0	7	111.5	3	0	7	110.5	3	0	7	105.5
6	0	4	112.0	6	0	4	110.0	6	0	4	105.0
9	0	1	111.0	9	0	1	109.5	9	0	1	106.5
3	1	6	111.8	3	1	6	109.8	3	1	6	105.8
6	1	3	112.5	6	1	3	108.5	6	1	3	106.0
9	1	0	110.8	9	1	0	108.5	9	1	0	105.5
3	2	5	111.0	3	2	5	109.0	3	2	5	104.8
6	2	2	112.8	6	2	2	110.7	6	2	2	106.5
3	3	4	111.5	3	3	4	108.9	3	3	4	105.0
6	3	1	112.0	6	3	1	109.8	6	3	1	106.0
3	4	3	112.5	3	4	3	110.5	3	4	3	105.5
6	4	0	113.0	6	4	0	109.0	6	4	0	104.0
3	5	2	111.0	3	5	2	109.5	3	5	2	106.0
3	6	1	112.5	3	6	1	110.0	3	6	1	105.5
3	7	0	111.8	3	7	0	110.5	3	7	0	105.0

[a]Box density, 111.0 pcf. [b]Box density, 109.0 pcf. [c]Box density, 105.0 pcf.

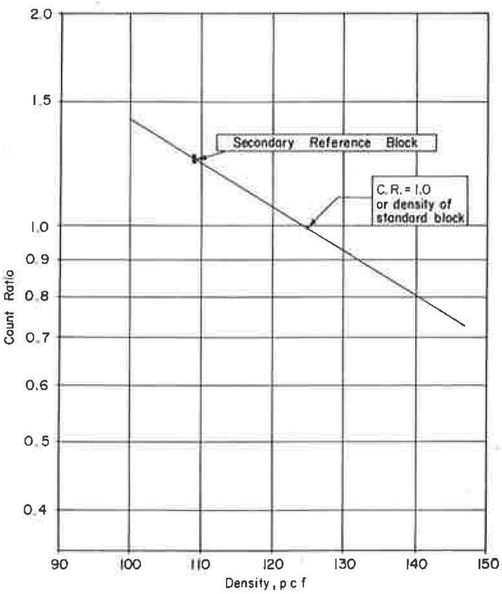

Figure 10. Single calibration curve established using two reference blocks.

Figure 10 shows the single calibration curve for any probe depth between 3 and 9 in. The curve was established by using two standard blocks, plotting the density of the heavier block at a count ratio of 1 and plotting the density of the second block at an average count ratio obtained by counts taken at depths of 1 to 9 in. The results of tests conducted utilizing the single calibration curve are presented in Table 2. The results were consistently within ± 2 pcf of the computed 109.0-pcf density of the secondary reference block, with the exception of the 1- and 2-in. depths.

Difficulty was previously encountered with these depth settings. The density determined at these depths was consistently greater than the computed density. The higher density at these depths may be attributed to the geometry of the source, shielding, and detector. As shown in Figure 11, the lead shielding intercepts a portion of the gamma rays at the 1- and 2-in. probe depths that are otherwise counted at probe settings of 3 in. or more. The reduction in the proportion of gamma rays counted invariably yields a higher density. Since the 1- and 2-in. depths are seldom used in density determinations of soils, the calibration curves for these depths are not presented here. However, future work in the measurement of asphaltic concrete densities will necessitate the establishment of these calibration curves.

Using the single calibration curve, initial tests on compacted samples indicated an apparent need to shift the curve approximately 2 pcf. This was probably caused by inaccuracy in computing the absolute density of the standards and possibly by a portion of the gamma rays escaping the perimeter of the standards. In the soil, these escaped

TABLE 2

DATA USING SINGLE CALIBRATION CURVE ON STANDARD REFERENCE BLOCKS

Depth (in.)	Std. Block	Check Block	Density	Depth (in.)	Std. Block	Check Block	Density
1	25,699	30,450	111.0[a]	1	25,317	29,506	114.0[a]
2	31,262	37,186	111.0[a]	2	29,927	36,411	111.0[a]
3	31,826	39,878	109.0	3	31,009	38,300	110.0
4	29,404	38,068	107.0	4	28,514	35,359	109.0
5	25,640	31,544	110.5	5	25,210	31,612	108.9
6	21,310	26,914	108.9	6	21,184	26,904	110.0
7	17,600	22,405	108.0	7	17,245	22,491	106.5
8	14,570	18,835	107.0	8	14,741	18,978	108.0
9	12,214	15,535	108.0	9	12,213	15,737	108.0
1	44,603	51,272	114.5[a]	1	25,635	30,278	113.0[a]
2	53,018	62,965	112.0[a]	2	30,204	37,396	110.0[a]
3	53,823	67,482	108.9	3	31,726	39,828	109.0
4	50,521	62,979	109.0	4	29,762	37,341	108.5
5	43,674	54,320	109.0	5	26,244	33,148	109.0
6	36,366	46,236	107.5	6	22,078	28,009	109.5
7	30,192	39,038	106.5	7	18,410	23,682	107.5
8	24,670	31,755	108.0	8	15,295	19,499	108.0
9	20,278	26,004	107.0	9	12,456	16,160	107.5

[a]High readings at 1- and 2-in. probe depths result from shielding in gage and indicate that procedures used in this study are not applicable to these shallow depths. A special study is scheduled to establish a separate calibration curve for these probe settings.

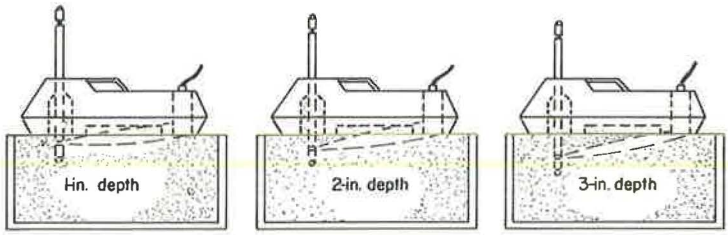

Figure 11. Schematic showing reduction of count due to geometry of source, shielding and detector at the 1- and 2-in. depths.

TABLE 3

RESULTS OF DENSITY TEST ON COMPACTED SAMPLES

Tolerance (pcf)	Prob. of Results Being Within Tol. (%)	
	Nuclear	Balloon
±2	68.2	56.3
±3	86.7	75.8
±4	95.4	88.3
Std. error of Est. (pcf)	1.95	2.33

gamma rays could be reflected back to the detector. A statistical analysis of data obtained with the corrected curve using five different soil types with the tests conducted at 3-, 6- and 9-in. depths is given in Table 3. An error of ±3 pcf would, in Florida materials, be equivalent to a variation of approximately ±2.5 percent in density.

FIELD STUDY

With the laboratory study completed and an equipment calibration curve established which would apparently hold true for

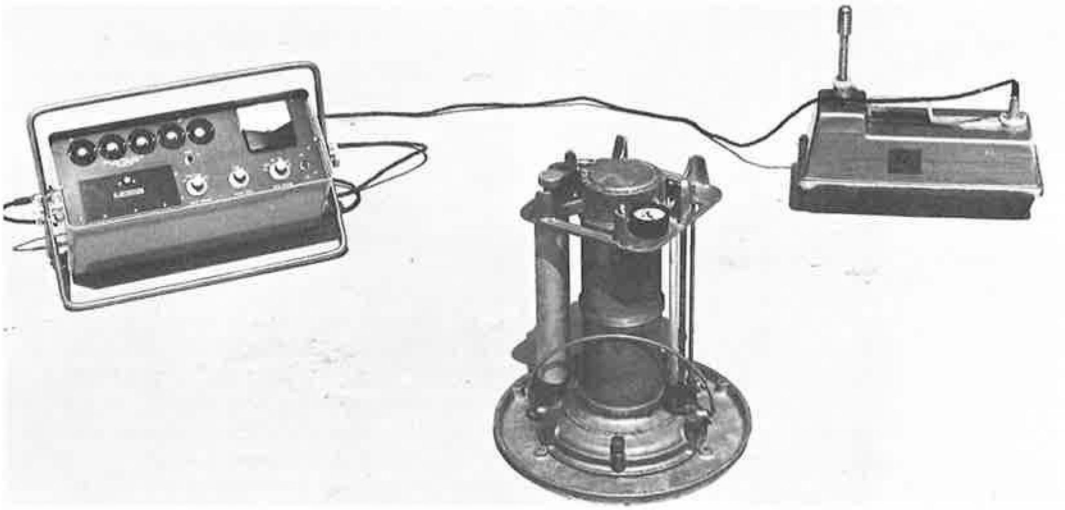

Figure 12. Rainhart Series 200 water balloon, used as comparison of test in field study.

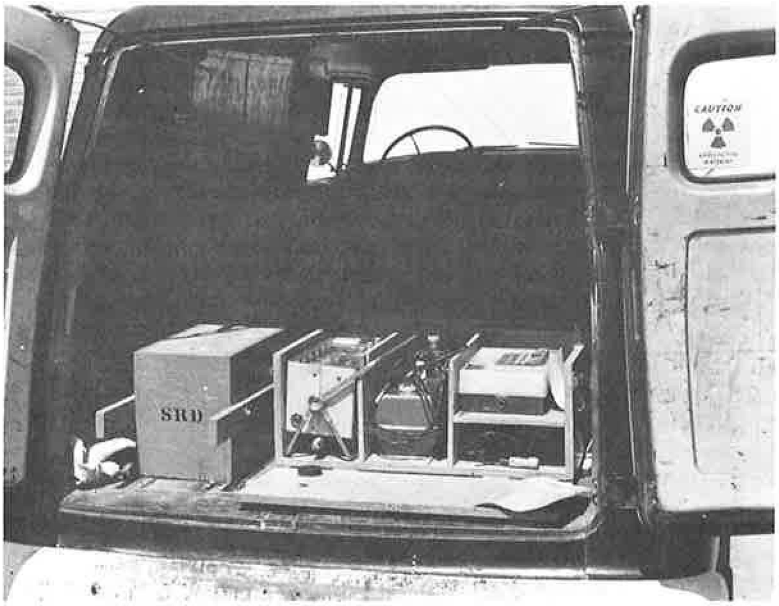

Figure 13. Transportation of equipment for field study.

the wide variation of soil types encountered in the field, the main objectives remaining were to determine the feasibility of using this equipment in the field as a standard control testing device and to determine the ability of the nuclear equipment to function under field conditions. The program also included a study to determine the time required to conduct a conventional destructive-type test and a nuclear test. For this purpose and also to provide a direct comparison of results, a conventional balloon test was conducted at the location of each nuclear test (Fig. 12). The choice of the balloon for the comparison tests was based on previous data obtained (1).

Figure 14. Location of construction sites for field evaluation.

Procedure

Most of the field testing took place on newly constructed subbase and base materials. The equipment was usually transported by a panel truck (Fig. 13). No special care was taken, except to avoid reckless handling of the equipment. The equipment was transported over construction areas throughout the entire state (Fig. 14).

A standard count was taken before each test in the field. The initial field procedure was to standardize the gage before each test. The procedure finally adopted was to standardize the gage before the start of a day's run, and to take a single count on the standard block before each test series. If the single count was within $\pm\sqrt{S.C.}$ (original standard count), it was used. If it was not, another 10-count standard was conducted. It was found necessary to run a standard count in the morning and in the afternoon. A new standard would generally be required for a 20 to 30 deg change in temperature.

After standardization of the equipment, a hole was drilled with a hand auger and the probe was inserted to the desired depth. After satisfactorily seating the gage, three 1-min counts were taken and averaged. The standard count was divided into the average count for the respective count ratio. The calibration curve was then used to determine the wet density.

As mentioned previously, the moisture gage was not used extensively. Instead, the percent of moisture of the material removed with the hand auger was determined by a Speedy Moisture Kit.

At each location, the nuclear tests were conducted first, followed by a Rainhart balloon test conducted between the access hole and the point of the detector at a depth equal to the probe depth.

Time Study

Throughout the field study, a log was kept of the time required to conduct and record a density test by both the nuclear and conventional methods. One phase of the field study included the assigning of a density man equipped with the nuclear gage to several construction projects on which density tests were conducted in limerock base, A-3 and A-2-4 subgrade materials, embankment, pipe backfill, etc. The purpose of this exercise was to determine if one man with nuclear equipment could replace several density crews working on several separate projects.

RESULTS OF FIELD STUDY

Figure 15 represents the relationship determined between the nuclear density gage and the Rainhart water-balloon. For the data shown in Figure 15, 73 percent of the test results agree within ± 2 pcf. There is a little more scattering of results than experienced in the laboratory when both methods were compared to box density; however, an analysis of variance indicated that the amount of scatter would be statistically expected if the standard error of estimate for each device (±1.95 nuclear and 2.33 balloon, as obtained from data shown in Figure 16 taken from a previous study (1) for the convenience of the reader) are considered in the calculations. The total estimate of error in calculations is equal to:

$$S_t^2 = S_n^2 + S_b^2 \qquad (1)$$

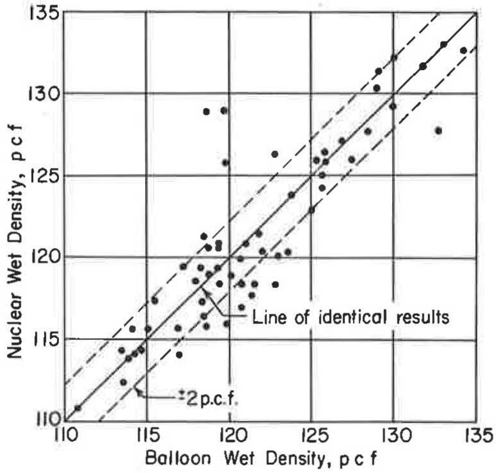

Figure 15. Results of field study, showing relationship between densities obtained by nuclear gage and by Rainhart balloon.

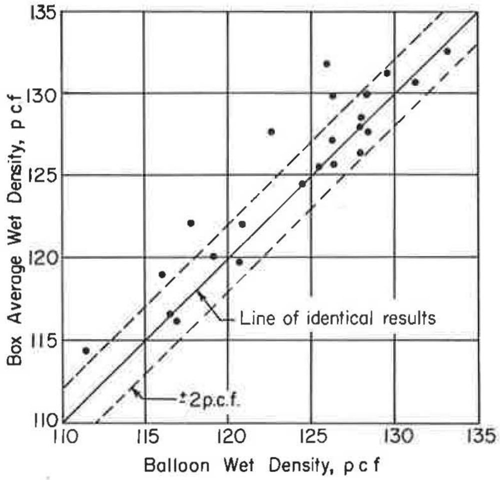

Figure 16. Results of previous study (1) in which density tests were conducted using Rainhart balloon on compacted samples.

TABLE 4

TIME COMPARISON STUDY

Test Method	Time (min)
Oil	28-30
Balloon	19-20
Nuclear	9-12

In this case S_t = ±3.04 pcf, and the computed total estimate of error using the data in Figure 15 is ±2.76 pcf. Since any variation greater than that determined from Eq. 1 would be attributed to soil type, the soils encountered on the 12 field projects did not appear to influence the results.

Throughout this study, a limited amount of minor difficulties were encountered with the equipment. However, with the use of the operational manual, the simplicity of the modular construction made it possible to perform all necessary maintenance. A problem was encountered with the timing system and a great deal of the calibration and initial field work had to be done with the aid of a stopwatch. The timer on the scaler used in this study is mechanical. This scaler has since been replaced with one having an electromechanical timer. Thus far, no difficulty has been encountered with the newer timer.

Time Study

Table 4 gives the average time required to conduct an in-place density test by the conventional procedure and with the nuclear equipment.

Table 5 gives a time comparison of the nuclear equipment and the balloon method. Instead of using the standard procedure of digging the density hole, a coring device was used with the balloon device. This speeded up the balloon tests considerably.

The time study points out that the nuclear equipment does have an unquestionably great advantage of speed. To illustrate further, one technician was as-

TABLE 5

TIME COMPARISON STUDY

Location	No. Tests	Device	Time (min)
Proj. 1	13	Balloon[a]	165
	13	Nuclear	120
Proj. 2	17	Balloon[a]	185
	17	Nuclear	125
Proj. 3	10	Balloon[a]	95
	10	Nuclear	65

[a]Motorized coring device used to dig density holes.

signed to four construction projects with the nuclear equipment. The normal assignment would be a minimum of three density men. For a period of 1 wk, the technician maintained the density tests required for all four projects. The construction sites were not a great distance apart; nevertheless, a nuclear-equipped density man did replace three density men equipped with conventional equipment, including three pickup trucks.

Radiological Safety

A radiological survey indicated a need for additional lead shielding during storage and transportation of the equipment. Even though the radium-beryllium source is not under the control of the Atomic Energy Commission (AEC), the source should be treated with the same respect as cesium or cobalt. The equipment should be "leak tested" at least twice a year and survey meters are readily available. Film badges should always be worn by personnel using the equipment.

During this study, only one of the personnel film badges recorded any radiation exposure. The film badge was used over a period of 4 wk with an accumulation of 80 mr, which is only 20 percent of the allowable AEC dosage of 100 mr/wk.

This study indicates that the equipment, if used conscientiously and monitored by a good radiological safety program (leak test, survey meters and film badges), can be used without any radiological health hazard.

CONCLUSIONS

1. Throughout this study, the direct transmission-type nuclear density gage has proven to be more accurate and much faster than conventional methods.

2. Use of the direct transmission principle in a nuclear density gage seems to eliminate the necessity for several calibration curves. As shown in Figure 11, the final calibration of the density gage is a single calibration curve which is suitable for the various soils tested and independent of depth for depths of 3 in. or more.

3. The nuclear equipment has been an asset to the Division of Research. The density tests conducted by research personnel are usually made in troublesome areas where the contractor is having difficulty in obtaining the specified density and where conditions necessitate repeated density tests. The nuclear equipment with its inherent speed has provided a means whereby the once time-consuming task of repeated density tests is considerably reduced.

4. The data obtained in this study indicate that the direct transmission-type nuclear density gage is an answer to the present need for a method of test which will keep pace with the advancements made in the capacities and speed of earthmoving equipment and with the expanded construction program.

The nuclear equipment is not only an asset in controlling density testing, but also a useful tool for setting up compaction equipment schedules and procedures. The amount of coverage required by a given type of compaction equipment to obtain specified density for an entire job can be determined quickly from one test section, provided extensive moisture or material changes were not encountered.

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