Laboratory and Field Evaluation of Nuclear Surface Gages for Determining Soil Moisture and Density

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A laboratory evaluation of the nuclear surface gages for determining soil moisture and density was conducted using eight soils from various areas of California. A calibration curve was developed for each soil and all calibration curves were compared. The volume of soil being measured was determined. The reproducibility and other characteristics of the nuclear gages were studied. The nuclear gages were used on ten projects under construction and the nuclear readings were compared to conventional tests. The results of this evaluation program indicated that individual calibration curves would be required for the various soils encountered.

•THE ADVENT of the nuclear age has resulted in the application of radioactive materials to many new methods of nondestructive testing. In the late 1940's the petroleum industry was experimenting with the use of neutrons to measure the oil content of oil-bearing sands and the determination of the density of underground formations by gamma-ray backscatter. In 1949 to 1950 results of studies in measuring subsurface soil moisture and density with radioisotopes were reported by Cornell University. During the mid-1950's, work was done by various investigators which resulted in the development of the surface nuclear moisture and density gages discussed here.

The density gages used in this evaluation program employ the Compton backscatter-absorption principle. The Geiger-Müller tubes used in this equipment measure all energy levels of gamma radiation reaching them. Other available gages have a means of screening out the lower energy gamma rays and counting only a selected region of the gamma spectrum. Another type of gage uses the principle of transmission of gamma rays. The results of the work herein reported should only be applied to the Compton-absorption type gages that have pickup tubes to record all levels of gamma radiation.

From 1954 to 1958 the Materials and Research Department of the California Division of Highways made use of radioactive materials to determine change in moisture and density of foundation soils on several highway projects. From 1959 to 1961 attempts were made by the Department to use the gages, herein referred to as Instrument "A", on various highway projects. The densities indicated by the nuclear surface gages ranged from 0 to 15 pcf higher than those determined by sand volume tests when the manufacturer's calibration curve was used. At the manufacturer's suggestion, a new calibration curve was obtained in the laboratory using soil compacted in a large mold. This new calibration curve was about 5 pcf higher than the manufacturer's calibration curve and indicated that a deviation in density of more than ± 5 pcf could be expected with the nuclear density gages. The moisture gage indicated results within reasonable agreement with the conventional test methods.

Several operational studies made during this period were in general agreement with

Paper sponsored by Special Committee on Nuclear Principles and Applications.

the manufacturer's recommendations. The following two items were found to be of importance:

1. Seating of the gage so as to have complete contact between the soil and gage was found to be extremely critical. Seating the gage on a thin bed of sand was adopted as standard practice.

2. Calibration of the subsurface nuclear probes indicated that the density calibration was shifted about 15 pcf between dry soil and soil at a moisture content approaching 100 percent.

Because controversy existed over the use of these surface nuclear gages for fill compaction control, a carefully controlled study was undertaken in October 1961. This study consisted of two phases: a laboratory evaluation and a field evaluation. During the early portion of the laboratory evaluation another manufacturer's gage was purchased and is referred to as Instrument "B".

LABORATORY EVALUATION

Test Program

The laboratory testing program had the following objectives:

1. To obtain calibration curves for various California soils, to combine these calibration curves into one calibration curve, to determine the accuracy of the various calibration curves, to determine if the density calibrations are affected by the moisture content of the soil, and to obtain moisture calibration curves;
2. To determine how reproducible the nuclear results are from day to day on a standard;
3. To determine the effective volume of the soil being measured by the nuclear gages; and
4. To conduct special studies on performance of equipment.

Part 1.—The calibration curves were obtained by compacting each of eight soils (Table 1) in a steel mold 2 ft in diameter and 1 ft in depth. The soil was compacted in the mold by drop hammers and an electric compaction hammer.

The soil sample was air dried when received. A series of tests was run on this air-dried sample at two or more densities. Water was added to the soil to bring the soil moisture content to about one-half the optimum water content, and the soil was mixed and stored several days in sealed containers. Another series of tests was then performed with the soil at this moisture content at two or more different densities. Water was then added to bring the moisture content of the soil near the optimum and the procedure was repeated.

The nuclear moisture and density readings were obtained by setting the probes on the soil surface. A minimum of eight nuclear counts were obtained within 250 counts of each other. These counts were averaged and this value was used as the nuclear reading.

A sand volume test was performed in the area tested by the nuclear probes. On several occasions up to three sand volume tests each were made on the upper and

TABLE 1

PROPERTIES OF SOILS USED IN LABORATORY NUCLEAR STUDY

Soil No.	Description	Liquid Limit	Plastic Index	Sand Equiv.	Optimum Density	Optimum Moisture	Specific +4	Gravity -4	Grading (%)			
									Gravel	Sand	Silt	Clay
1	Sacramento freeway soil	24	4	12	121	13	--	2.64	--	41	38	21
2	American river sand	--	NP	97	104	16	--	2.71	--	96	3	1
3	Sacramento sand and gravel	--	NP	22	144	6	2.70	2.75	64	26	6	4
4	Vallejo base	46	36	21	106	18	--	2.56	56	25	11	8
5	Crushed rock	--	NP	80	134	7	2.79	2.80	71	25	3	1
6	Fresno soil	--	NP	20	129	10	--	2.69	12	49	31	8
7	San Diego soil	31	8	25	121	11	--	2.58	--	75	14	11
8	Eureka soil	26	11	10	125	12	--	2.65	1	47	22	30

lower ½ ft of the soil in the mold. This was done to determine the uniformity with which the soil was being compacted. A comparison of the sand volume and mold densities is shown in Figure 1.

Considerable difficulty was encountered in obtaining agreement between the densities as determined by the mold weight and volume of soil and the sand volume test. This resulted in a side study of the uniformity of the soil compacted in the mold and the accuracy of the sand volume test.

Oven-dry moistures were obtained from two or more samples of soil from the mold. The average moisture content of the total soil in the mold was then calculated in pounds of water per cubic foot of soil.

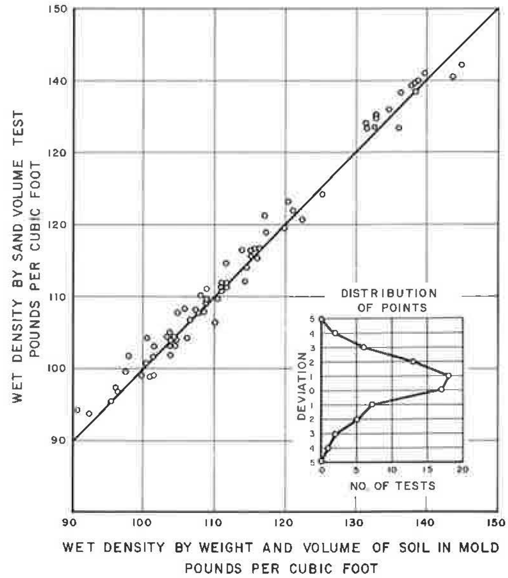

Figure 1. Mold vs sand volume densities.

Part 2.—To determine the reproducibility of the nuclear readings, two standards were established. One was on the concrete floor in the work area, and one was on a block of wood that was sealed to prevent loss of moisture. Readings were periodically taken on the surface of these standards throughout the test program. Marks were placed on the surface of these standards so that the probes were always placed at the same location. Three counts were then obtained that agreed within 2 percent.

Part 3.—The depth to which the density probes effectively measure the density of the soil was determined in two ways:

1. A 6-in. thick block of wood was attached to the bottom of the mold with a thin sheet of iron on top to protect the wood. A series of readings on the wood block was taken. Successive 1-in. layers of soil were compacted in the mold and nuclear readings obtained on each layer. The volume and weight of soil in each layer was determined to insure that a uniform density was being obtained.

2. Layers of concrete or soil 1- to 3-in. thick were constructed in 12- by 18-in. boxes. The nuclear density probe was suspended in air and a count rate was determined. Then each box of soil was placed on a pair of supports and a count rate determined.

Part 4.—Several miscellaneous studies are included in this program. The stability of the pickup tubes was studied by means of standard counts and plateau curves. The general performance of the equipment was also evaluated during this testing program.

The effect of the thickness of the sand used for seating of the probes was investigated. A count rate for a spot on the concrete floor was determined. Various thicknesses between ⅛ and ½ in. of sand were placed over this spot. Count rates were determined for each thickness of sand. The influence of objects near the probes was also studied. Count rates were determined with a clear space at 5 ft or more around the probes. Various objects were then placed near the probes and count rates determined without moving the probes.

Discussion of Results

Density Calibrations.—An important consideration in any calibration work is the accuracy of the standard used and the accuracy to which the equipment being calibrated will measure a change in the standard. In the density calibration program, two independent densities were determined: (a) the average density of the soil in the mold, and

(b) the density of the center portion of the soil in the mold by a sand volume test. They will be designated as mold density and sand volume density, respectively, in the remainder of this portion of this report.

A study of the density variation within the mold was made by performing several sand volume tests on the upper and lower halves of the soil in the mold and determining the density of chunk samples of the soil. Although the soil was compacted in equal soil weight lifts with equal compactive effort per lift, large variations were found between the density in the upper and lower half of the soil in the mold. The density of the two halves of the mold was then determined for all tests by two methods: (a) the volume of soil in the mold by measurement of its height and weight of soil, and (b) sand volume test. These tests indicated that side variations did occur between the top and bottom halves of the mold. Therefore, two series of readings were obtained each time the soil was compacted in the mold, one on the top half and one on the bottom half.

Figure 1 shows a comparison of sand volume and mold densities using one-half of the depth of the soil compacted in the mold. These comparisons are mainly on the moist soils because sand volume tests on the dry and/or loosely compacted soils could not be obtained. A distribution plot of the differences is included in the lower right-hand corner of Figure 1. The sand volume tests tended to indicate slightly higher densities than the mold. The average difference is ± 0.8 pcf and the standard deviation is 2.0 pcf.

The conclusions from this study were that the density variation within the mold was about 2 pcf from point to point from the average mold density. The indications are that the sand volume test was accurate to 1 to 2 pcf.

Calibration curves for each soil were determined using each of the two densities, sand volume and mold, as the standard density. Figure 2 shows a plot of the data using the mold density as the standard density. The equations of the curves were cal-

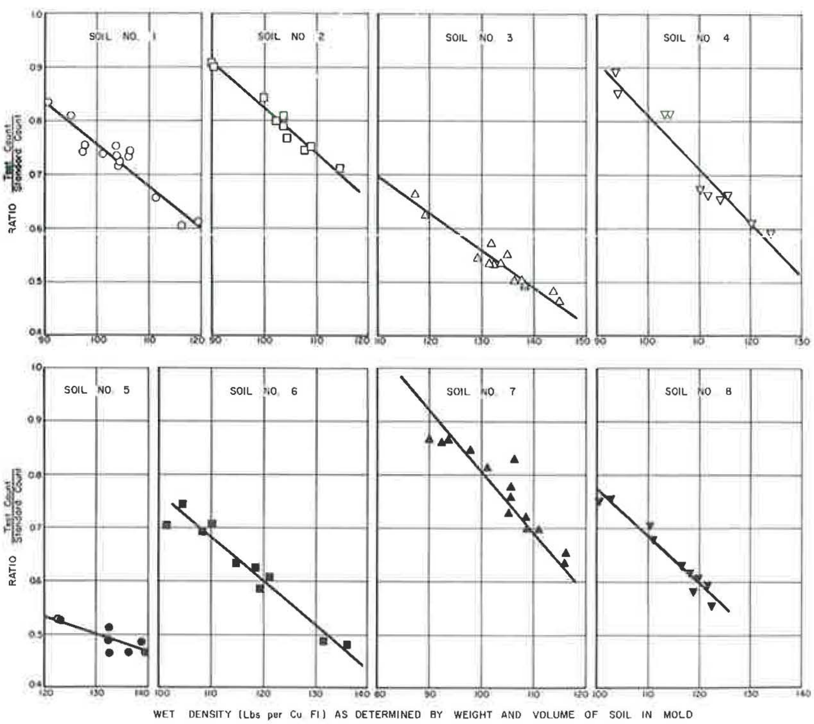

Figure 2. Density calibration curves for various soils using Instrument A surface density probe, mold density taken as standard.

TABLE 2

DENSITY CALIBRATIONS AND ERRORS

Soil No.	Sand Volume Test[a]			Mold Density[a]		
	Eq. Calibration Curve	Avg. Error	Std. Dev.	Eq. Calibration Curve	Avg. Error	Std. Dev.
			Instrument A			
1	R = 1.635 - 0.00857D	2.2	2.6	R = 1.543 - 0.00783D	2.0	2.9
2	R = 1.573 - 0.00758D	1.7	2.1	R = 1.660 - 0.00836D	1.2	1.5
3	R = 1.584 - 0.00780D	1.0	1.3	R = 1.467 - 0.00696D	1.6	1.9
4	R = 1.965 - 0.01151D	2.2	3.0	R = 1.963 - 0.01155D	2.0	2.3
5	R = 1.828 - 0.01009D	3.1	3.7	R = 1.823 - 0.01008D	2.8	3.3
6	R = 1.501 - 0.00751D	1.9	2.3	R = 1.572 - 0.00812D	2.2	2.6
7	R = 1.131 - 0.00467D	2.0	2.3	R = 0.935 - 0.00336D	3.5	4.5
8	R = 1.795 - 0.01003D	1.2	1.5	R = 1.680 - 0.00904D	1.3	3.0
All soils	R = 1.569 - 0.00786D	3.0	3.8	R = 1.619 - 0.00833D	3.2	4.0
			Instrument B			
4	C = 19740 - 69.52D	2.7	3.4	C = 21850 - 88.05D	1.6	2.0
5	C = 32910 - 163.61D	1.6	1.8	C = 15030 - 22.50D	—	—
6	C = 20000 - 75.59D	2.3	2.8	C = 20690 - 81.37D	2.7	3.2
7	C = 21490 - 82.27D	1.8	2.2	C = 22120 - 88.80D	1.6	2.0
8	C = 25070 - 116.43D	1.8	2.4	C = 23510 - 102.91D	1.8	2.8
All soils	C = 21940 - 90.00D	3.5	4.3	C = 20780 - 78.91D	4.1	5.0

[a]Used as standard density.

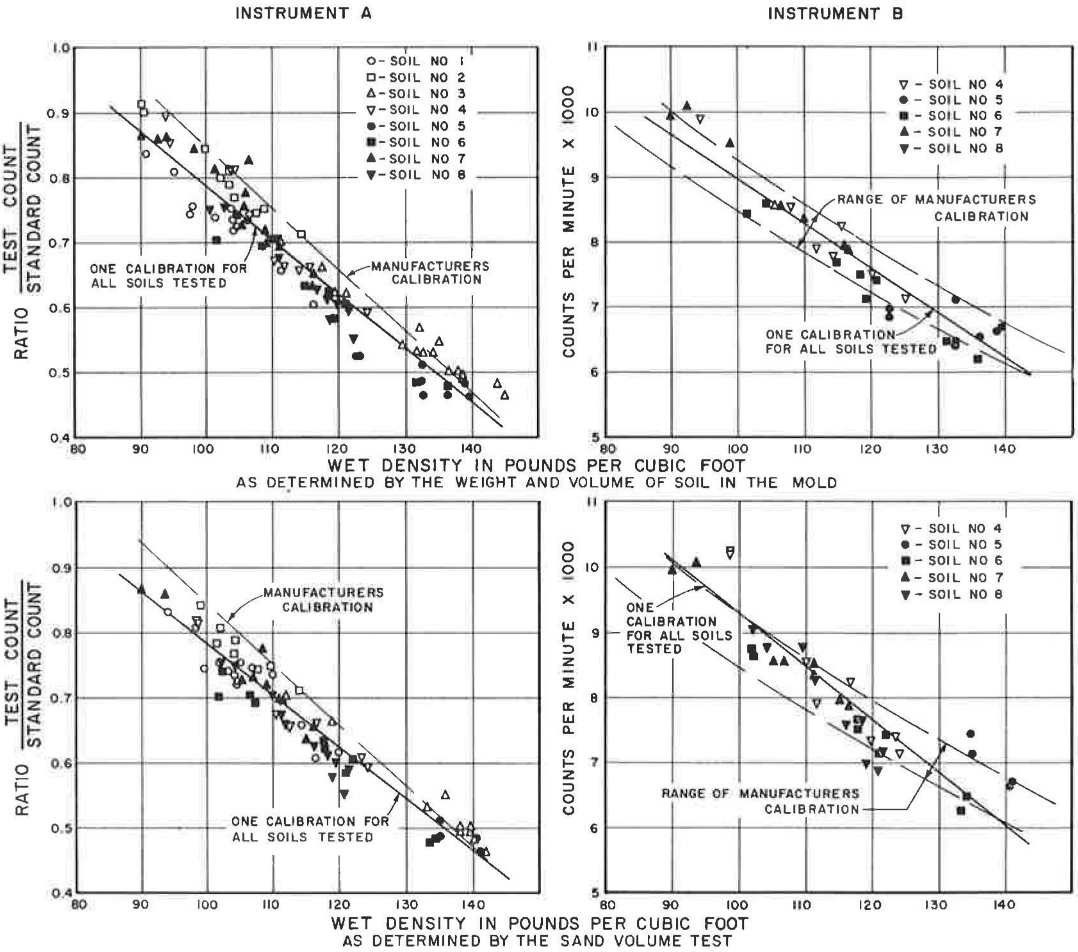

Figure 3. Density calibration curves for all soils tested.

culated and are given in Table 2 as well as average and standard deviations. For comparison, all of the points for different soils were plotted on one plot and a calibration curve was obtained (Fig. 3).

The data indicate that the standard deviation, where individual calibrations for various soils are used, will be 1 to 3 pcf. Using 1-min readings, the expected standard deviation from random radiation will be approximately 1.5 pcf. This would indicate that with both of the gages tested in this study, densities could be obtained to 2- to 3-pcf accuracy without difficulty, where individual calibrations are obtained for each soil tested.

The individual test points were within a band of 15 to 20 pcf when one calibration was used for all soils. The standard deviation when using one calibration curve for all soils tested was about 4 to 5 pcf for both instruments.

The distribution of the points using one calibration curve for all soils and a separate calibration for each soil are shown in Figure 4. Using the 90 percent criteria, 90 percent of the readings will be within 7 pcf when one calibration curve is used for all soils and within 3.5 pcf when separate calibration curves are used for each soil. The 90 percent criteria for a comparision of the mold and sand volume densities indicated that the results will be in agreement within ± 3 pcf 90 percent of the time. To obtain a reasonable accuracy with the density probes, a calibration is required for each soil encountered.

Moisture Calibration.—The moisture calibrations are shown in Figure 5 for all soils tested. Six of the soils are along one calibration curve and two along a different calibration curve parallel to the main calibration curve. Differential thermal analysis

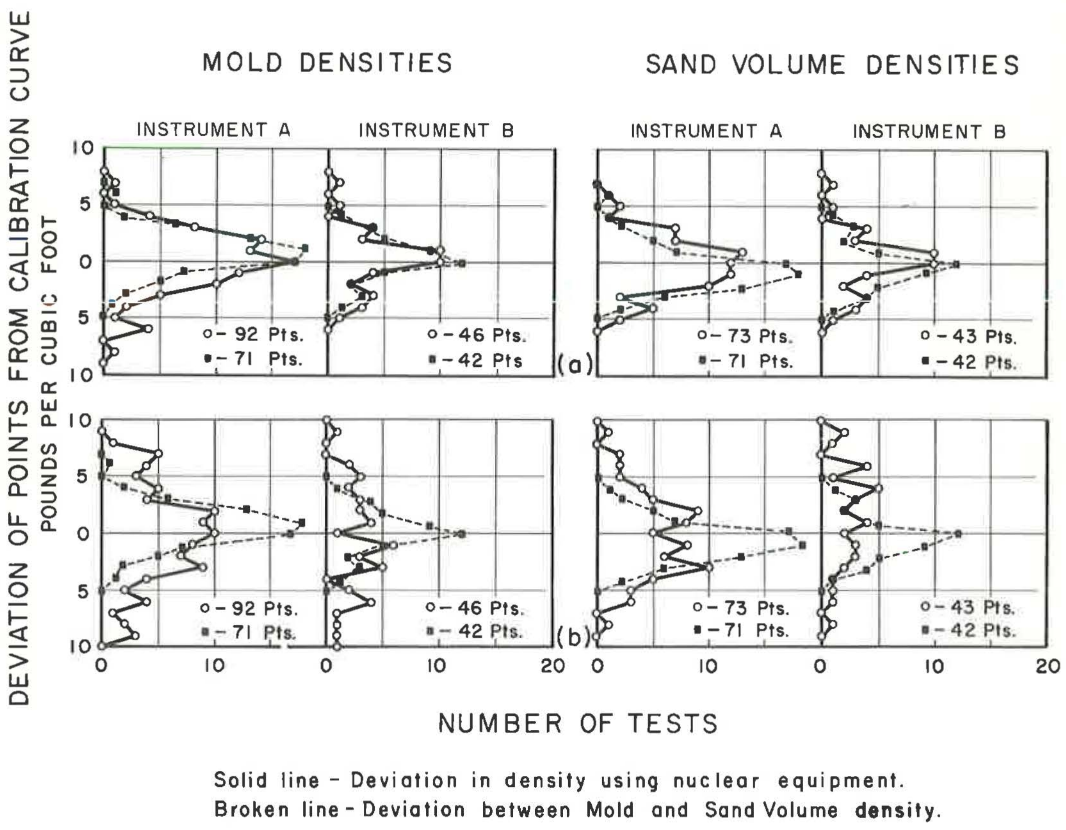

Figure 4. Distribution of points in density studies: (a) using individual calibration for each soil, and (b) using one calibration for all soils.

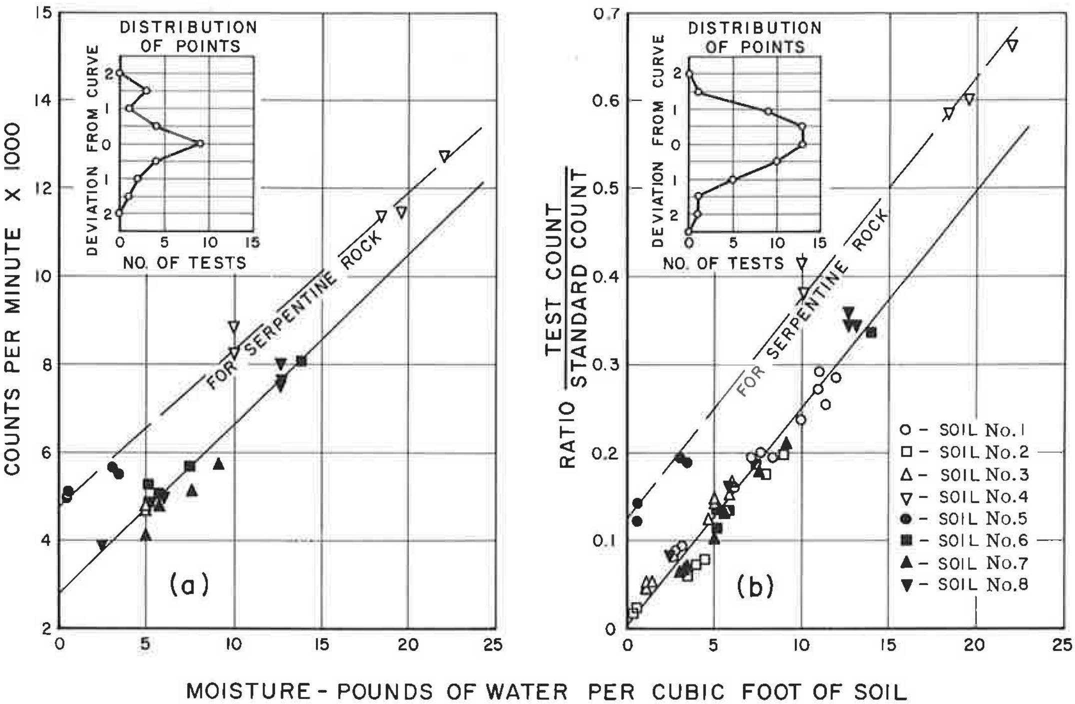

Figure 5. Moisture calibration curves: (a) using Instrument B surface probe, and (b) using Instrument A surface moisture probe.

was performed on the soils and soils 4 and 5 were found to be serpentine soils high in hydrous magnesium silicate. This high magnesium content is believed to be the cause of the many slow neutrons produced.

The moisture content determinations had an average error of 0.6 lb water per cubic foot, and the standard deviation was 0.8 lb water per cubic foot. The distribution of the points for the moisture determinations are shown in Figure 5. The data indicate that 90 percent of the readings are within 1 lb water per cubic foot of the moisture content indicated by the calibration curve. This variation will result in a 1 percent error in moisture at a dry density of 100 pcf and 0.8 percent error at a dry density of 125 pcf.

The moisture content of a soil can be accurately determined by the surface gage. One calibration curve will generally be accurate for most soils; however, checks must be made to determine that no elements are present to shift the curve as occurred with soils 4 and 5.

Effect of Moisture on the Density Calibration.—The previous work with the subsurface probes indicated that there is a shift in the density calibration curve from a dry soil to a soil at about 100 percent moisture content. It was not known if this effect on the density readings was significant at lower moisture contents.

A study of the data in this series of tests does not indicate that a measurable shift in the density calibration curve occurs with a change in moisture content. It was apparent that moisture contents below 20 percent do not affect the density calibration curves within the limits of accuracy of this testing program.

Reproducibility of Readings.—It was desired to determine how consistent the nuclear readings of a standard were over a period of time. There has been no difficulty in obtaining check count rates in a few hours; however, the Instrument A standard count had been previously observed to vary greatly over a period of a few weeks.

To determine how consistent the readings are, two standards were obtained and readings were taken on these standards two or three times a week over a 3-mo period.

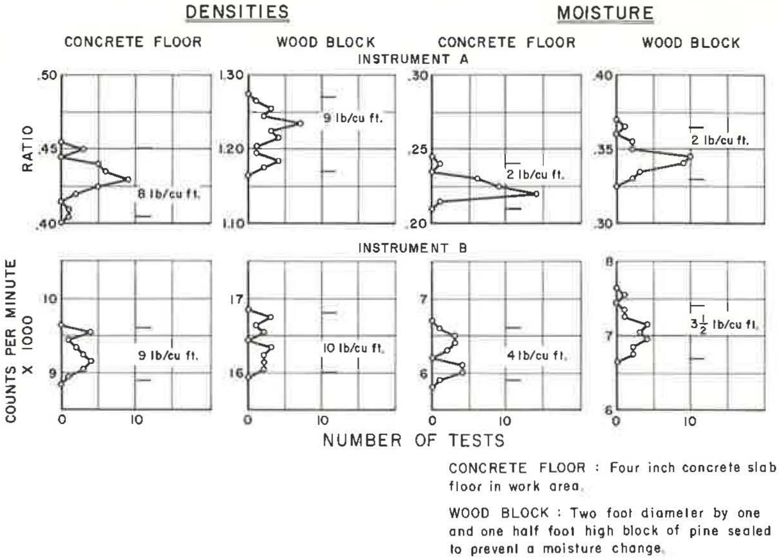

Figure 6. Reproducibility of nuclear readings.

The distribution of these readings is shown in Figure 6. The range in density or moisture represented by the range in readings is shown on each plot.

The range of readings obtained indicates a difference in density of about 9 pcf. This is a surprisingly large random variation in indicated density. Previous work had indicated that there was a large variation in standard count rates with the Instrument A density gage with time. It had been hoped that the use of the count ratio would correct these random variations; however, it does not appear to do so.

A statistical analysis considering random radiation indicates that the 1-min readings used in this study should be constant within about 150 counts or about 2 pcf. The standard varied less than 1 pcf in density. The seating of the probes was no problem and should have had no significant effect on the readings. The remaining 6-pcf variation in indicated density appears to be caused by elements within the equipment.

The moisture determinations indicate a spread of 2 to 4 lb water per cubic foot over the 3-mo period. This range is about what would be expected from statistical analysis.

To determine the short-time variations, where possible, readings were taken on the compacted soil samples in the late afternoon. The following morning check readings were taken before conducting the sand volume test. These readings all checked within 2 pcf in density and 1 lb water per cubic foot of moisture.

To evaluate the effect of this random variation in apparent density with time, check calibration points on soils 1, 3 and 7 were made after obtaining the original calibration curves for these soils. These check calibration points were within about 2 pcf of the calibration curves obtained 2 to 3 mo previously. As these check points were within the standard deviation for the calibration curves, it would appear that this random variation in indicated density will not affect the density readings obtained with the nuclear gages.

The significance of this random variation in indicated density of a standard is not clearly understood. There is no significant effect on the accuracy of the calibration curves obtained. This random variation may well explain the erratic readings occasionally obtained and indicates the need for obtaining check readings by rotating the gages.

Volume of Influence of Density Readings.—The data from the depth of influence readings are shown in Figure 7. The percentage of the total change in count rate is

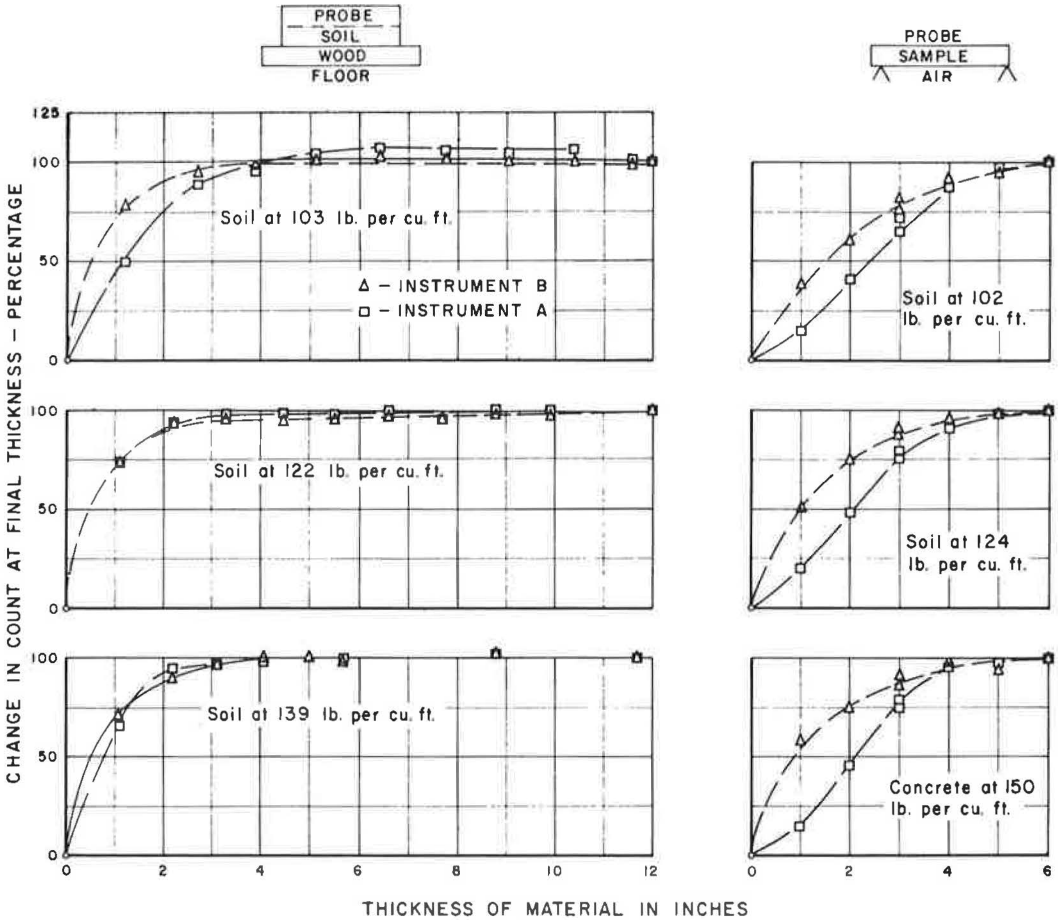

Figure 7. Depth of influence of nuclear density probes.

plotted against thickness of material. Where the difference in count rate between the wood block and the soil was used, the curves rise rapidly and show a 50 percent change in count rate at 0.5 to 1 in. and a 90 percent change in count rate at 2 to 3 in. The 100 percent count rate change was taken at the greatest thickness of soil tested. Where the difference in count rate between air and soil was used, the Instrument A and B gages gave slightly different results. The Instrument B gage indicated a 50 percent count rate change at 0.5 to 1.5 in. of soil and a 90 percent count rate change at 3 to 4 in. The Instrument A gage indicated a 50 percent count rate change at about 2 in. and 90 percent count rate change at about 3 to 4 in.

Theoretically, the effective depth of measurement should be a function of density of the medium being tested. The lower the density, the greater the depth of measurement. Although there is a slight tendency for the effective depth of measurement to be larger at lower densities, it does not appear to be a significant factor.

The two methods do not agree on the indicated depths of measurement. The effective depth of measurement was taken as that depth to which a density change of 5 pcf could be measured. The soil to wood block indicates about 2 to 3 in. is the effective depth of measurement, and the soil to air indicates 3 to 4 in. is the effective depth of measurement. In the previous field comparisons of nuclear and sand volume densities, the sand volume test was made to a depth of 6 to 7 in. In the field comparisons, included in this report, the sand volume test was made to a depth of 4 in. to obtain comparable volumes of soil.

Limited work was done to determine the width and length of the area of influence of the nuclear density gage. The measurements were made by placing a square basaltic stone in a soil having a density of 110 ± pcf. The top of the stone was about 1 in. below the surface of the soil. The zone of influence appears to be irregular in shape, with a width of about 8 in. at the pickup end and 3 to 4 in. at the source end. The length of the zone of influence appears to be approximately 10 in. These tests consisted of readings with the Instrument A density gage only and with the soil at one density only and with the stone at one depth. These measurements indicate that the zone of influence is on the order of 60 sq in. The volume of soil being measured by the nuclear gages is about 0.1 cu ft.

Standard Counts.—The Instrument A density standard counts varied from a high of 17,780 to a low of 15,520 counts per minute in the standardizing box provided for this purpose. This wide range of standard counts is believed to be due to the type of pickup tube used, and is the reason that the ratio system is used with the Instrument A equipment even though one more step is required in the obtaining of the density. The standard count of the moisture probe varied from 15,560 to 15,370 counts per minute. This was considered a stable range.

No difficulty was encountered with the Instrument B gage in obtaining standard counts within 170 counts per minute of the standard count supplied by the manufacturer.

Seating of Gages.—Seating of the gages was found to have a major effect on the readings obtained. The problem is to obtain a plane surface on which to place the gage. An air gap of $\frac{1}{16}$ in. was found to increase the counts recorded by about 1000 counts per minute. To overcome the difficulty of obtaining a plane surface on the soil, a thin layer of sand was used to seat the gages.

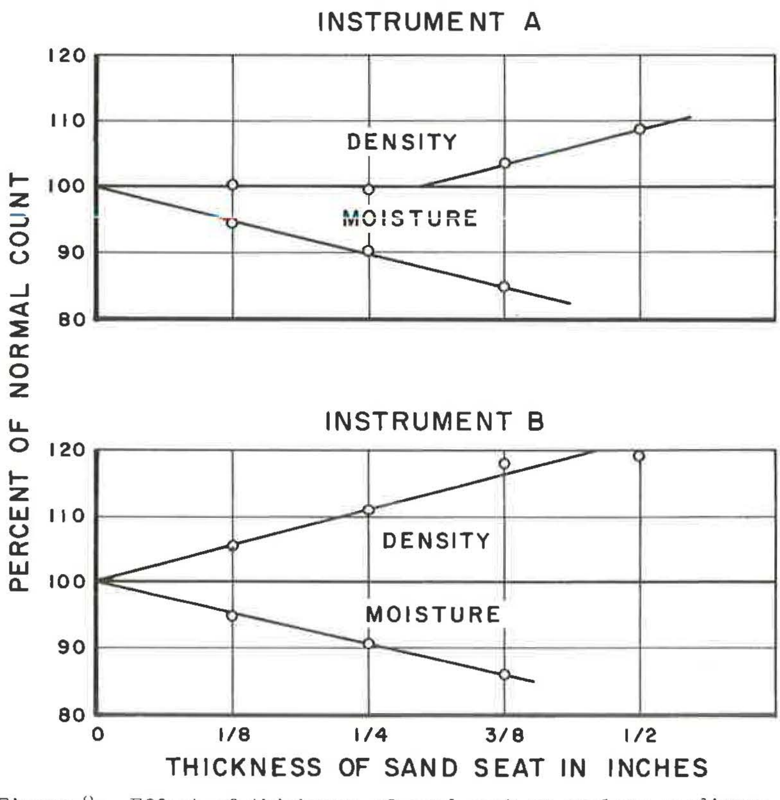

Figure 8. Effect of thickness of sand seat on nuclear readings.

The results of the studies to determine the effect of the thickness of the sand layer on the readings are shown in Figure 8. As the thickness of the sand used in seating the gages was increased, the count rate increased at a rate of about 5 percent per $\frac{1}{8}$-in. sand. The Instrument A density gage was least affected by the thickness of the sand seat to a thickness of $\frac{1}{4}$ in. This is believed due to the raised portions of the bottom of the gage with the built-in air gap.

These tests clearly indicate the necessity for having a plane surface on which to set the gage. The use of a thin layer of sand to level the surface will result in a small change in reading; however, a thick layer of sand will greatly alter the readings. The moisture gage readings will also be affected by the thickness of the sand seat.

Objects Near Gage.—The effect of objects near the gage on the count rates was studied. It was found that the objects had to be within 0.5 ft of the gage before a measurable increase in count rate could be detected.

The manufacturers recommend that no solid material that will reflect gamma rays should be within 5 ft of the gages, which would prevent their use in confined locations such as structural backfill. These tests indicate that the gages could be used in confined locations where a clear distance of one or more feet is available around the gage.

Conclusions

The following conclusions can be made from the laboratory work conducted in this report:

1. Using one calibration for each soil will result in 90 percent of the nuclear readings being within about 3.5 pcf, and using one calibration for all soils will result in 90 percent of the nuclear readings being within about 7 pcf. The use of a calibration curve for each soil will increase the accuracy of the readings by a factor of about two over using one calibration for all soils. Moisture determinations with the nuclear gage can be made with an accuracy of 1 lb water per cubic foot. Generally one calibration can be used for most soils; however, limited testing is necessary to determine that elements altering the calibration are not present.
2. The moisture content of the soil did not affect the density calibration curve in the low range (below 20 percent) of moistures used in this study.
3. The effective depth of the density determination is about 4 in. and the volume of soil being measured is about 0.1 cu ft.
4. The gages may be used in fairly confined locations without loss of accuracy.
5. Great care must be taken in obtaining a plane surface on which to set the gages. A thin sand layer can be used to aid in leveling the soil surface but must be kept less than $\frac{1}{16}$ in. thick.

FIELD EVALUATION

The second phase of this evaluation program was to use the nuclear gages on existing construction projects. Ten highway projects under construction during the summer of 1962, within 100 mi of Sacramento, were chosen for this study.

Object

Based on the results of the laboratory studies of the nuclear gages and the need for information on the field use of such gages the following objectives were decided on:

1. To compare the densities of soils as determined by the sand volume test and the nuclear gages;
2. To compare the moistures as determined by the oven-dry method and the nuclear gages;
3. To determine the relative compaction at each sand volume density location;
4. To determine the variation of soil density in the area of each comparison in No. 1; and
5. To make other minor side studies related to the problem of using nuclear devices in field control work.

Testing Program

A site was selected for each test and leveled off by digging 0.2 ft or more. Nuclear readings of the density were obtained at a given 1-sq ft area with both nuclear gages. The moisture content was measured with one of the nuclear gages at the same location as the density test. In all nuclear testing a 1-min reading was taken with the probe in one direction; then the probe was rotated 90°, maintaining the center of the gage over the same point, and a second 1-min reading was taken. If these two readings agreed within 200 counts, no further readings were taken. If these readings did not agree within 200 counts the probe was rotated 180° and 270° and 1-min readings taken at each position. If one count deviated greatly (over 300 counts from the average) it was disregarded and three readings were used in obtaining an average count rate for determining moisture or density.

Directly under the location of these nuclear readings, a sand volume test was made. The test hole was excavated to a depth of 4 in. and a diameter to give a minimum volume of 0.1 cu ft. In all other respects the sand volume test was performed according to California Test Method 216-E.

Before performing the sand volume test, four nuclear readings were taken 3 to 5 ft from the comparative test site, with both nuclear gages. These four tests were run about 90° apart with the comparative test site as a center. The purpose was to determine the variation of density around the comparative test site, over an area of about 100 sq ft.

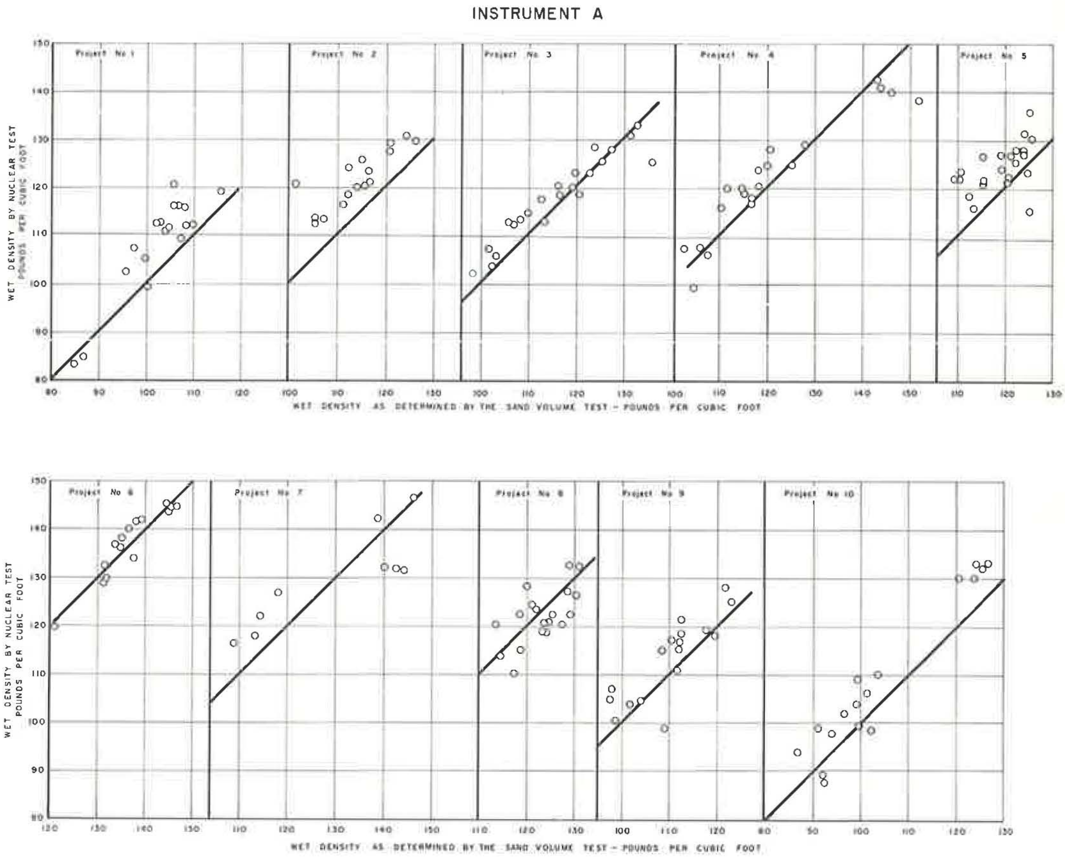

Figure 9. Comparison of nuclear and sand volume densities.

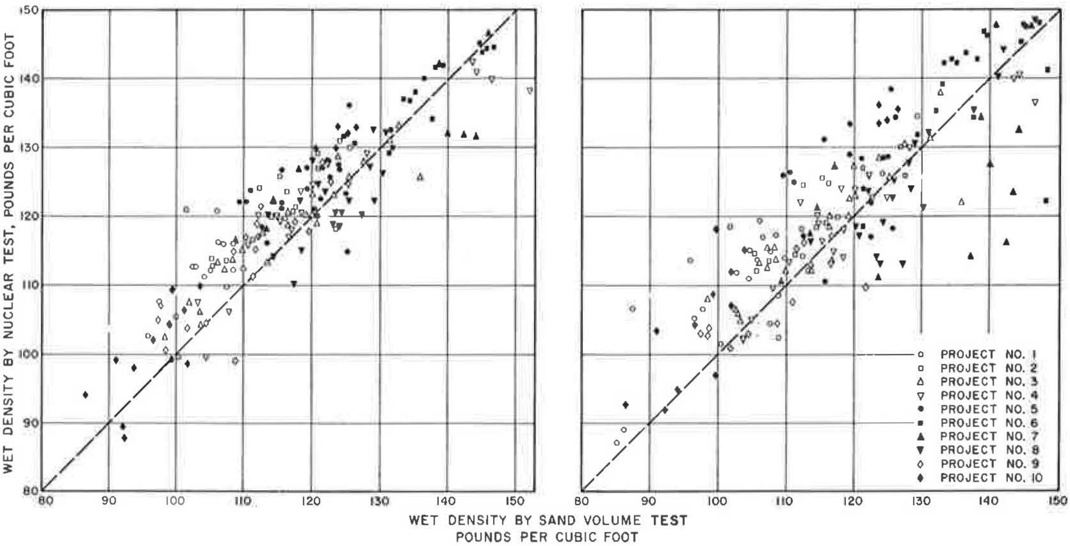

Figure 10. Comparative sand volume and nuclear density tests field surface nuclear studies.

The soil removed from the sand volume hole was placed in sealed cans and given to the field laboratory personnel on the project who then completed an oven-dried moisture test and an optimum density test on representative samples. At one location on each day a larger sample was obtained from the area of the comparative test. This sample was mixed on a canvas and two duplicate samples were obtained. One was given to the resident engineer for his crew to test in the normal manner and the other sample was sent to the Materials and Research Department for testing. Grading, plastic limits, sand equivalent, specific gravity and optimum density tests were then run on these samples. A pint sample was obtained from each test site with gradings and sand equivalent tests performed to aid in identifying the soils tested.

Discussion of Results

Nuclear Density Comparison.—The results of the nuclear density and sand volume density comparative tests for each project are shown in Figure 9 for one nuclear gage. The data from all ten projects are combined into one plot in Figure 10. In all these plots the calibration curves obtained in the laboratory nuclear study were used. The Instrument A density probe indicated a deviation range of ± 10 pcf from the sand volume test. The Instrument B showed a deviation range of ± 15 pcf from the sand volume test. When the density results were plotted for each project separately, the scatter was small on some projects and large on others (Fig. 9).

Test results for each soil type tended to be grouped along a trend line. A new calibration was assumed for each soil type to give the best fit for the points in each of the soil types. The average and standard deviations were calculated using one calibration for all soils and individual calibrations for each soil type, and are included in Table 3. The density comparison assuming a separate calibration for each soil type is shown for all projects in Figure 11. The range of variation of the nuclear density is about 7 pcf compared with the sand volume test when a separate calibration curve is assumed for each soil type.

TABLE 3

DEVIATIONS OF NUCLEAR DENSITIES FROM SAND VOLUME DENSITIES OF SOILS TESTED IN FIELD NUCLEAR STUDY

Project No.	One Calibration Curve for All Soils		Individual Calibration Curve for Each Soil	
	Avg. Dev.	Std. Dev.	Avg. Dev.	Std. Dev.
		Instrument A		
1	6	7	3.5	4.5
2	7	8	3	4
			1	1.5
3	3	4	2	2.5
4	3.5	4.5	2.5	3
			2.5	3.5
5	6	7	2	2.5
			4	5.5
6	2.5	2.5	1.5	2
			2	2.5
7	7	8.5	1.5	2.5
			1.5	2
8	4	4.5	2.5	4.5
9	4.5	6	1	1.5
			3.5	5
10	6	7	3	4
All Projects	5	6	2.5	3
		Instrument B		
1	6.5	7.5	3.5	4.5
2	5.5	7	3.5	4.5
			3	3.5
3	4.5	6	3	3.5
4	3.5	4.5	2.5	3.5
			2.5	3
5	8.5	10	7.5	8.5
			5.5	7.5
6	5.5	5.5	2.5	4
			5	6.5
7	13.5	17.5	5.5	6
			3	4.5
8	4	5.5	4	4.5
9	4	5.5	3.5	4
			3.5	5
10	8.5	10	4	5
All Projects	6	8	4	5

Using one calibration curve for all soils, there was a wide variation in standard deviation from project to project. Using the Instrument A gage, the standard deviation varied from 2.5 to 8.5 pcf, and using the Instrument B gage the standard deviation varied from 4.5 to 17.5 pcf. When individual calibration curves are used for each soil type encountered, the standard deviation is greatly reduced. Using the Instrument A gage the standard deviation varied from 1.5 to 5.5 pcf and using the Instrument B gage the standard deviation varied from 3 to 8.5 pcf.

The accuracy of the sand volume test is of concern due to its use as the standard in this test program. The laboratory study indicated that the sand volume test has a standard deviation of about 2 pcf. The equipment used in performing the field density tests was the same as that used in the laboratory testing, so the standard deviation of the field sand volume tests would probably be of the same order of magnitude as was obtained in the laboratory study.

Considering that the sand volume test is accurate to ± 2 pcf and with this variation subtracted from the nuclear variation the following accuracies are obtained from the standard deviations. Using one calibration for all soils and separate calibrations for each soil type ± 5 and ± 2 pcf accuracies, respectively, are indicated. This would indicate that comparable densities can be obtained with the nuclear probes compared to the sand volume test when a separate and individual calibration is used for each soil type encountered.

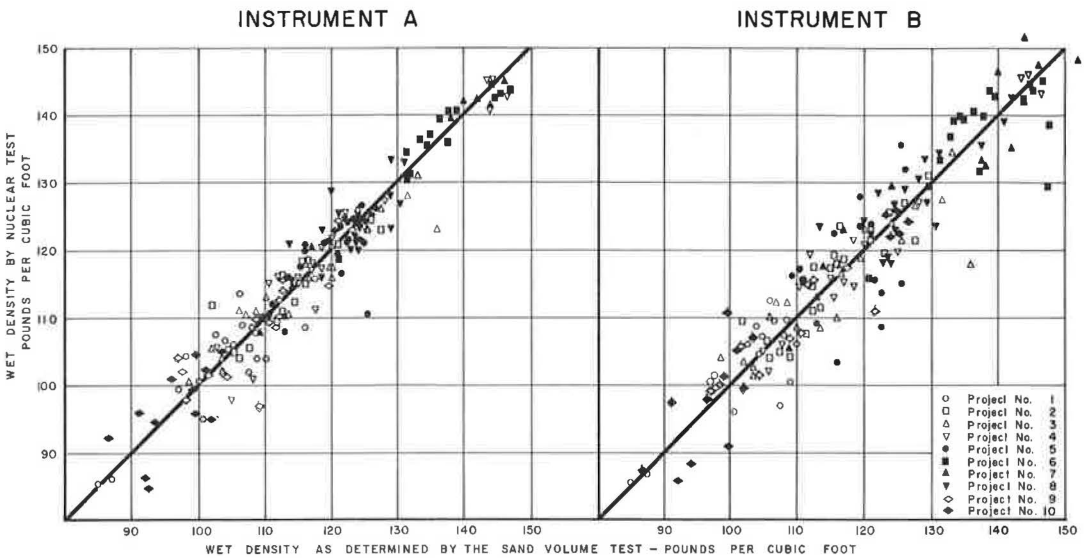

Figure 11. Comparative sand volume and nuclear density tests using individual calibration curve for each soil type.

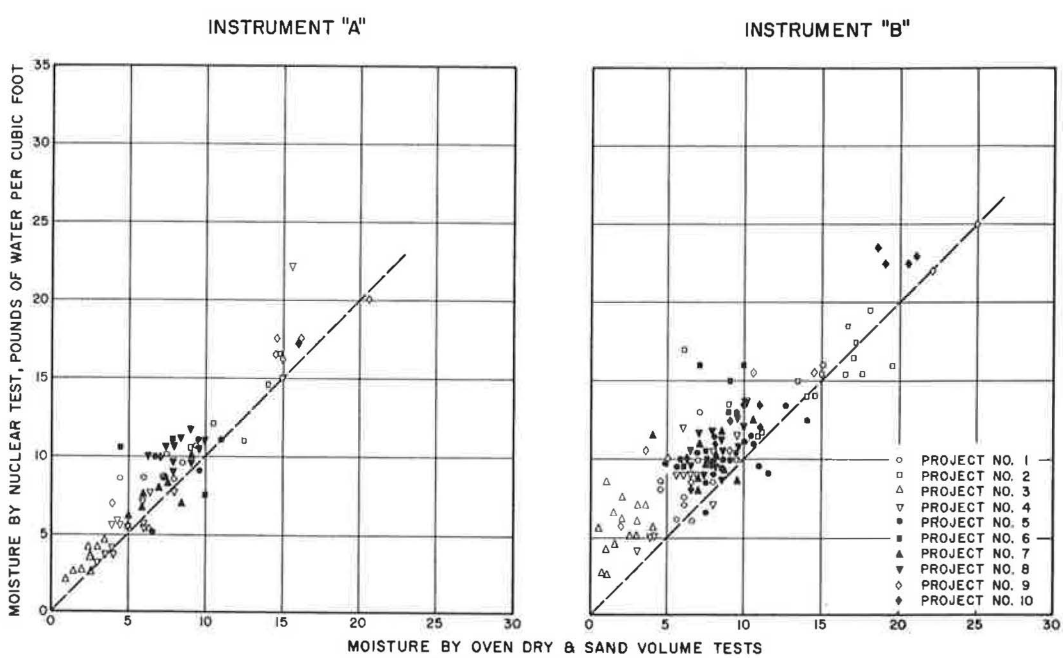

Figure 12. Comparative oven-dry and nuclear moisture tests using one calibration curve for all soils.

Nuclear Moisture Comparison.—The comparison of nuclear and oven-dry moistures for all projects are combined in Figure 12. The nuclear moistures tend to be about 1 pcf water higher than the oven-dry moistures. The moisture as determined by nuclear probes ranges from -1 to +5 lb water per cubic foot compared to the oven-dry moistures. The average and standard deviations for the moisture determinations are shown in Table 4.

The moisture data indicate that moistures of soils can be obtained by surface nuclear probes to within 2.5 pcf using one calibration curve for all soils. Obtaining individual calibration curves for various projects would reduce this range about 1 lb water per cubic foot. However, considering the accuracy of the density gages it is felt that this was not necessary in this study.

Variation of Soil Density in a Limited Area.—The central control point at each site was chosen arbitrarily by the operators; generally tending to be where the best instrument "seating" conditions prevailed. The sites for the radial readings could not be chosen arbitrarily as they were controlled by the central point; therefore, the best conditions could not always be selected for instrument seating, etc. Furthermore, since sand volume densities were determined at the central site, the subsurface conditions were known only at that point. At the locations of the radial readings, however, no such tests were made so that it was not known if density-changing factors, such as large rocks, wood, debris, or air voids, existed below the surface.

In the analysis of the data, the center nuclear densities were taken as the standard and the deviation of the surrounding densities was determined. The deviations were analyzed statistically for each of the ten projects and individually for both types of nuclear equipment. Although there are not enough points on the individual projects to be entirely significant, the curves generally show a normal distribution. The exceptions to this are found in Project 7, which shows no tendency toward a normal distribution curve. It was reported by the operators that the field conditions on this project indicated extreme non-uniformity of soil density.

The distribution curves for the nuclear equipment show a generally good comparison with each other for most of the projects. The data from all projects were combined separately for the Instrument A and Instrument B equipment and the resulting distribution curves are shown in Figure 13. Normal distribution curves are formed and the curves for the two types of equipment are reasonably comparable.

The values for the combined projects show for the Instrument A determined densities an average deviation of ± 3.5 pcf, a standard deviation of 5 pcf, and a 90 percent limit of 8.5 pcf. Those determined by the Instrument B equipment show an average deviation of ± 4.5 pcf, standard deviation of 6.5 pcf, and 90 percent limits of 10 pcf. These sets of values, although they differ about 1 to 2 pcf, show the wide range of in-place densities encountered in a supposedly uniformly compacted soil.

TABLE 4

AVERAGE DEVIATION OF MOISTURE OF SOILS TESTED IN FIELD NUCLEAR STUDY[a]

Proj. No.	Avg. Dev.	
	Instrument A	Instrument B
1	1.5	2
2	1.5	2
3	1	3.5
4	1	2
5	1	2
6	4	3
7	1	2
8	2	2.5
9	1.5	2.5
10	2	3
All Projects	1.5	2.5

[a]Deviation of nuclear from oven-dry moisture.

Comparative Maximum Density and Moisture Tests

A total of 36 comparative maximum density and moisture tests were obtained during this study. Compaction tests were made by both project and Materials and Research Department personnel on duplicate samples. The results of the Materials and Research Department compaction test were taken as standard in these studies and the deviation of the project tests was calculated.

The distribution of the differences in densities of the compaction results is shown in Figure 14. The average difference was 2.5 pcf and the standard devia-

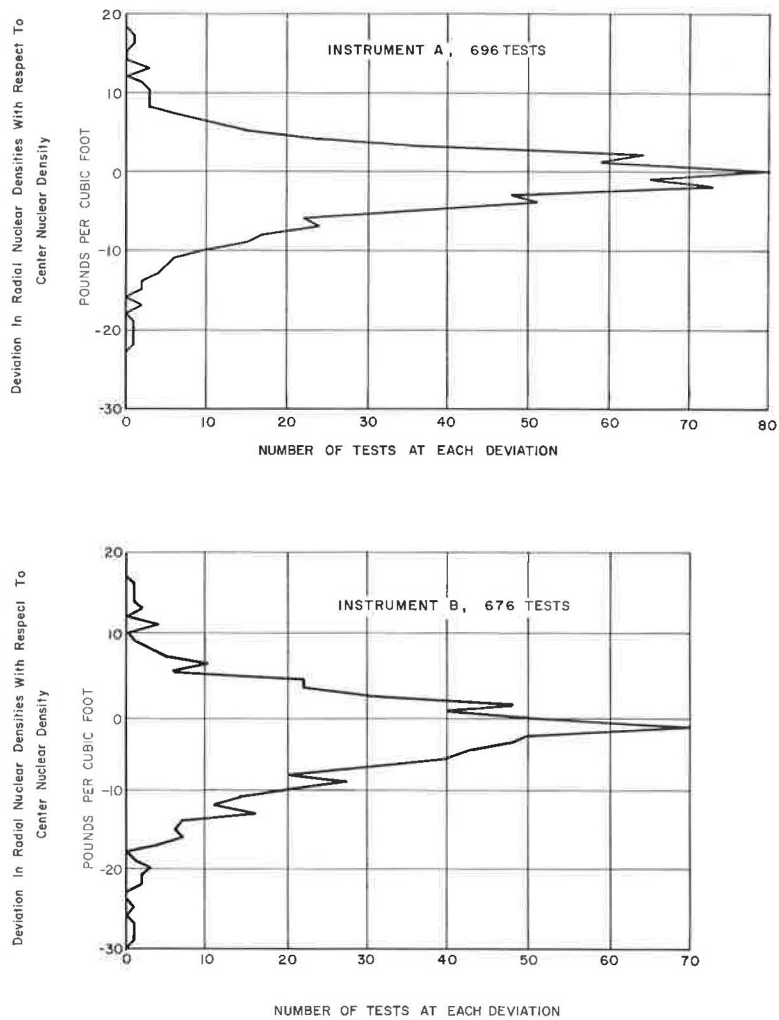

Figure 13. Deviation of radial densities from center density, all projects combined.

tion 3.5 pcf. The 90 percent confidence limit was 6 pcf. This is an unexpectedly large difference in results. During construction this represents the standard to which a contractor is expected to compact a soil. This large variation in the standard would result in a 4 percent variation in the value of the relative compaction.

The optimum moisture deviations showed an average deviation of 1.2 percent water and a 90 percent confidence limit of 2 percent moisture. These results are of a random nature. The optimum moisture variations are within the normal limits expected for a compaction test.

Maximum Densities on Each Project

The maximum densities obtained with each sand volume test were compared to determine feasibility of using one maximum density for each soil type as defined by the nuclear calibration curves. The average and standard deviations were calculated using the average density for each soil (Table 5).

The standard deviations varied from 2 to 12 pcf from the average maximum density. This standard deviation could be partially due to the normal variations occurring in the test for determining the maximum density. A value of 3 pcf was assumed as a reason-

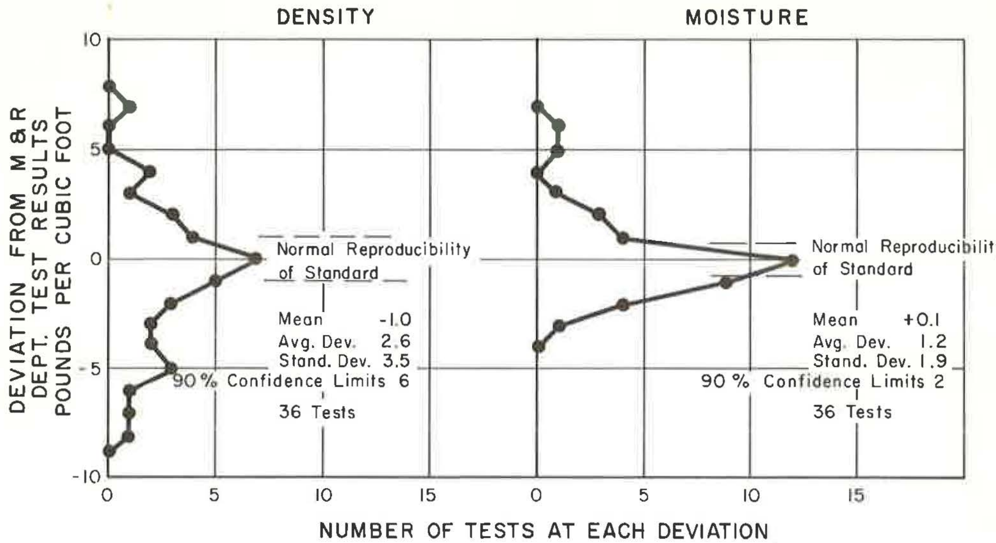

Figure 14. Deviation of optimum densities and moistures as determined by nuclear field studies.

TABLE 5

DEVIATION OF MAXIMUM DENSITIES FROM AVERAGE MAXIMUM DENSITY[a]

Project No.	Avg. Max. Density	Avg. Dev.	Std. Dev.	90% Confidence Limits	Soil Type
1	113	3	5	6	Silty clay
2	111.5	4.5	5.5	7	Silty clay
	116.5	4.5	6.5	7	Silty sand
3	124.5	4.5	5	6.5	Silty sand
4	130.5	2.5	3.5	3.5	Sandy silt
	133.5	2.5	4	4.5	Sand w/gravel
5	124.5	2	2	2	Sand w/rocks
	122.5	3	4.5	5.5	Clay w/rocks
6	124.5	1.5	2	2	Silty clay w/rocks
	134	3	4	4	Sand w/gravel
7	140.5	2	2.5	3	Sand
	124.5	5	7.5	7.5	Clay
8	128	2	2.5	4.5	Silty sand
9	120	3.5	4	5	Silty sand w/gravel
	107	10.5	12	13	Silty clay w/rocks
10	112.5	3.5	5	8	Silty clay

[a]As determined by California Test Method 216-E.

able allowable standard deviation in the maximum density for a soil to be considered uniform in regards to density. This 3 pcf will result in about a 2 percent deviation in relative compaction. Twenty-five percent of the soils studied in this report had standard deviations in maximum density of less than 3 pcf.

Several of the projects contain two soil types. The standard deviation of one soil type may be less than 3 pcf and the other much larger than 3 pcf. The use of a single standard maximum density for one soil, and a maximum density test for each field density test for the other soil, would be confusing. There was only one project where a single standard maximum density could have been used throughout the project. It does not appear from this study that the use of one standard maximum density for each soil type on a project is practical.

Conclusions From Field Data

The data clearly indicate that when nuclear equipment is used for soil moisture and density measurements, a calibration curve is required for each soil and that more than one calibration curve generally will be required for each construction project. Any hope of speeding up control testing by use of the nuclear surface gages would be seriously handicapped by this limitation. By the use of calibration curves with the nuclear gages for the various soils encountered, densities comparable to those obtained by the sand volume test can be obtained. However, the difficulty would be in knowing when the calibration should change. The grading and physical appearance of a soil may not be reliable indications of the need for changes in the calibration for the nuclear probes.

The manufacturer and various users recommend field calibrations; that is, the calibration of nuclear gages against field density and moisture tests. This means periodically performing field sand volume tests to check the nuclear densities. It appears that this method of using the nuclear gages would still mean using the sand volume test for control and adding a few nuclear tests to obtain a larger number of tests. It is strongly felt that if the nuclear gages are to be used for construction control they should "stand on their own results." This would mean calibrating the gage in the field laboratory and then being able to use the nuclear gages to obtain the relative density directly without further checking. This is possible at the present time on only a limited number of projects.

It appears that the nuclear moisture gages will indicate reasonably accurate moistures at the present time.

Use of Nuclear Density Surface Probe for Compactor Studies

During the past years several attempts have been made to use the surface probes in construction operations. One of these studies was to determine the compaction of a soil after various numbers of passes of the roller.

The testing consisted of taking nuclear density tests at the same location on a soil after increasing numbers of passes of a roller. The count rate would decrease as the roller compacted the soil. Making a plot of the nuclear counts vs the passes of the

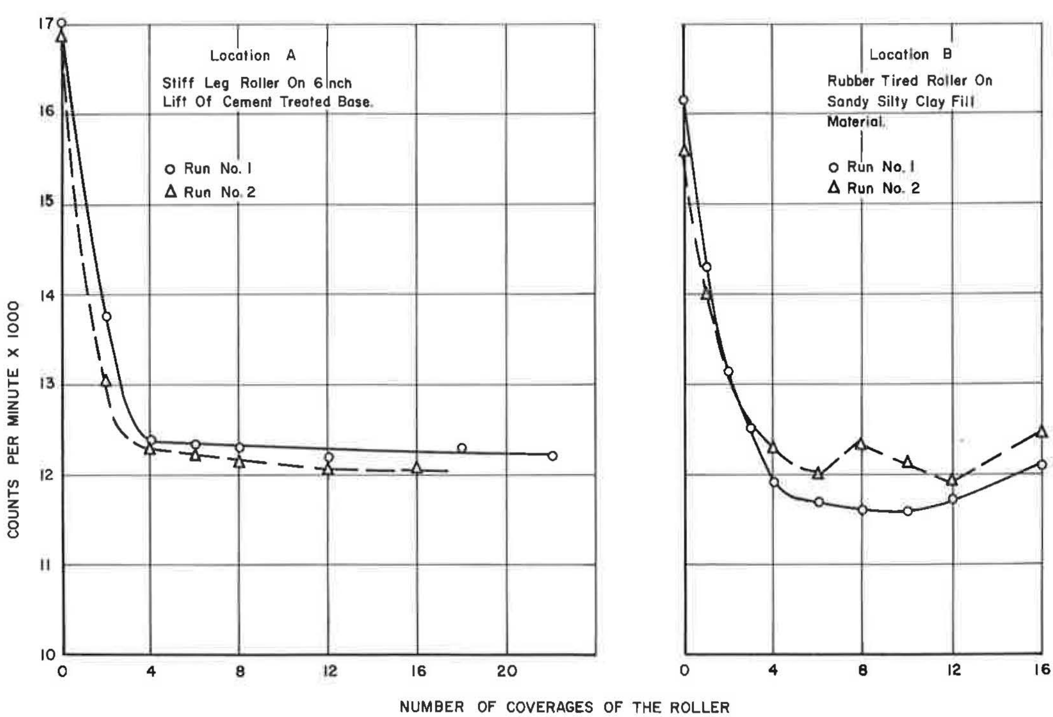

Figure 15. Use of nuclear surface density probe in compaction study.

roller, the required number of passes of the roller for compaction of the soil could be determined. The results of two such studies are shown in Figure 15.

The count rate decreased rapidly as the first four coverages were placed on the soil. Additional coverages then only slightly decreased the count rate. Since density increases as the count rate decreases, the data indicate that the optimum number of passes of these rollers on a soil would be about four.

This demonstrates a possible practical application of the nuclear probes. The increase in density of a given soil mass can be determined as additional compactive effort is applied. If the same soil is tested each time and calibration of the nuclear probe is not required, rapid testing can be performed on the same soil mass with only minor delays to the contractor. Testing of the same soil mass each time is possible due to the nondestructive nature of the nuclear testing.

ACKNOWLEDGMENTS

The work contained in this report was performed at the Materials and Research Department of the California Division of Highways. The author wishes to thank John Campbell and Joe Puleo who conducted the testing and T. W. Smith and F. N. Hveem for their advice and guidance.

Discussion

PATRICK J. CAMPBELL, Western Regional Engineer, Nuclear-Chicago Corp.—In February 1963, the small compaction mold illustrated in Figure 16 was developed by Whitman, Requardt and Associates and the Nuclear-Chicago Corporation to provide a faster, more homogeneous, and simpler method for field checking of nuclear soil gages. In March 1963, limited numbers of four of the soils in Mr. Weber's paper were prepared in this new mold in the California Division of Highways (CDH) Sacramento laboratory. The results predicted a single calibration curve; however, they apparently

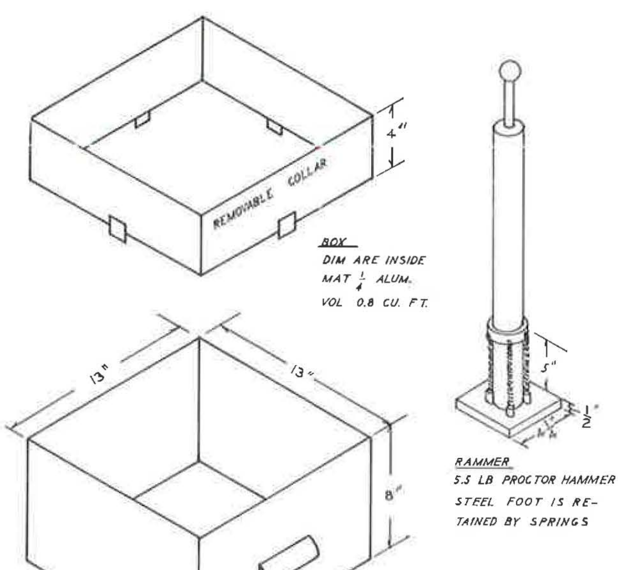

Figure 16. Special mold and rammer used by California Division of Highways and Nuclear-Chicago Corp. during 1964 calibration study.

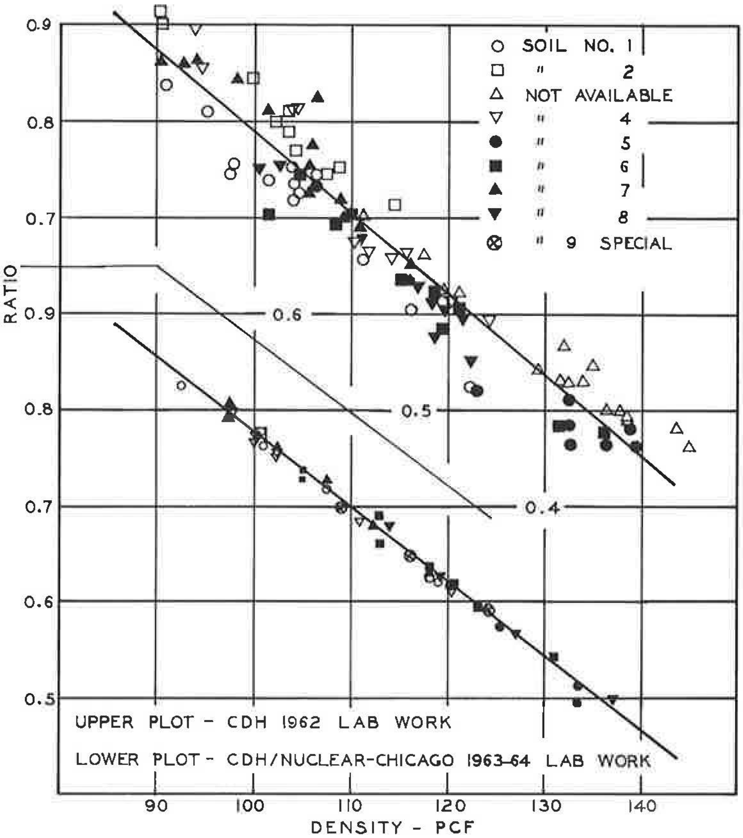

Figure 17. Calibration plots.

were deemed inconclusive because further investigation was not carried out.

In December 1963, an intensive cooperative effort was undertaken to verify the results of the earlier work with the small mold with the results to be published as an addition to Mr. Weber's paper. The work described herein was performed by a team of engineers from the California Division of Highways and the Nuclear-Chicago Corp. at the CDH Sacramento laboratory. Seven of the original eight soils used in Mr. Weber's 1962 laboratory work were used. In addition, a "special soil" consisting of 20 lb each of the other seven was prepared and included. In all, 51 samples were prepared. Of these, 39 were deemed valid for consideration regarding the initial purpose of the investigation, 6 were discarded because of operator errors in preparation of the samples,

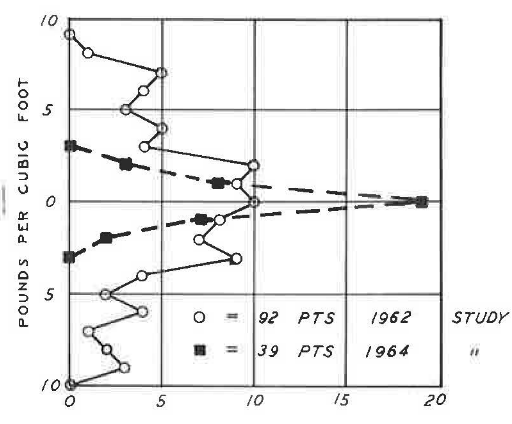

Figure 18. Distribution of points using one calibration curve for all soils.

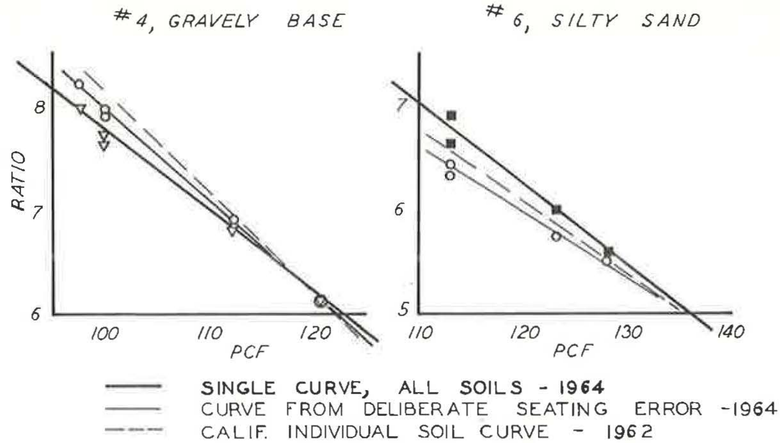

Figure 19. Deliberate seating errors reproduce 962 results.

and 6 were deliberately prepared in error to carry out a side investigation. Any questionable data may be quickly verified with the mold with approximately one hour required per sample.

It became obvious at the start that the manufacturer's engineer used a seating technique different from that used by the CDH engineer. This turned out to be the major reason for the calibration error in the earlier work. Figure 17 illustrates the calibration plots, on the same scale, of the earlier CDH laboratory work and this 1964 work. A single calibration curve can be used on these soils described by Mr. Weber as being typical in types and geographical locations of construction soils generally found in California. Complete descriptions are in Mr. Weber's paper. Figure 18 illustrates the error distribution of the two studies. The 1964 work has a standard deviation of approximately 0.75 pcf as opposed to the earlier deviation of several pounds. Figure 19 illustrates the results obtained when the d/M gage was seated incorrectly using the procedures followed in the CDH earlier work. The two soils vary widely in surface characteristics and illustrate the fact that improper seating, even though consistent in technique, can produce opposing errors, depending on soil type. It is significant that the team was able to approximate the earlier special calibration curves. Field measurements using the same poor techniques will produce similar results.

In summary, only one calibration curve is required for use with backscatter-type nuclear gages, provided correct operating techniques are used. Improper seating techniques probably account for the major source of trouble among users of nuclear soil gages who experience unsatisfactory results.

WILLIAM G. WEBER, JR., Closure—The work performed by Mr. Campbell at the Materials and Research Department has been carefully reviewed by the author. It is evident that two different interpretations of the data exist. The author's interpretation of the data from the work performed in both studies is that a separate calibration curve would probably be required for various soil types.

The seating problem is evident with all work performed at the Materials and Research Department. With the soil samples compacted to a smooth surface in Mr. Campbell's work, this effect was minimized. In the work that the author reported, the soil surface in the laboratory was compacted rough and then smoothed as would normally be done in the field. It is felt that this is a realistic approach to use in a laboratory study. It is recognized that the seating of the gage on the soil surface is a major variable in the use of the nuclear gages.