Developments in Radioisotope Measurement of Soil Moisture Content and Density

T. B. PARTRIDGE and P. J. RIGDEN, Respectively, Scientific Assistant and Director, National Institute for Road Research, South African Council for Scientific and Industrial Research, Pretoria

The paper describes research and development work carried out on the technique of determining the moisture content of soil by neutron irradiation and density by back-scattering of gamma rays. A new instrument is described that employs a single radium-berrylium source giving both neutrons and gamma rays. The source is used in a single probe for surface work or in a single depth probe for measurements at depth. Some new features in the apparatus include a means of controlling the effective depth to which density is measured and the use of special reflecting devices to increase the sensitivity in moisture determinations.

Extensive studies of the volume and depth of soil measured and of the problem of achieving accurate calibration of the instrument over the practical range of moisture content and density are described. Examples of different fields of application of the instrument are given.

●EFFECTIVE CONTROL of the compaction of soil or stone layers is an important factor in the construction of roads, airfields, and other types of foundations for civil engineering structures. This control involves the measurement of in-place densities and moisture contents. Of various tests commonly used for making these determinations, the sand-replacement density test and the moisture content determination by oven drying are perhaps the most generally used.

Work on a nondestructive technique by which the density and moisture content of soil can be tested in situ has been in progress for a number of years, principally in the U.S.A. and, to some extent, in Great Britain and some continental countries (1, 2, 3, 4, 5, 6).

The method that has shown most promise and on which most work has been done has used the radiation back-scatter technique. In this technique, soil density is determined by the amount of gamma radiation back-scattered and soil moisture is determined by the thermalization and scattering back of neutrons. Density measurements require radioactive sources emitting gamma radiation and moisture measurements require high energy or fast neutron radiation. In the instrument described in this paper, it has been found satisfactory and extremely convenient to use a single radium-beryllium source, emitting both gamma rays and fast neutrons.

Although considerable work had already been done on laboratory instruments overseas and, at least two commercial instruments were already available, it was felt that an instrument could be developed in South Africa that would include certain desirable and important features for field work, as well as general improvements in the instrumentation of the equipment, particularly in the reduction of electric power requirements with its consequent saving in weight. Accordingly, a development program was started, both in designing and field testing the necessary portable electronic counting equipment, as well as in developing field techniques for the use of the apparatus. The instrument now developed consists of a transistorized, battery-operated scaler and two types of combination probe: (a) a surface probe, and (b) a depth probe that can be lowered down a 2-in. (internal) diameter pipe to depths up to 100 ft (Figure 1).

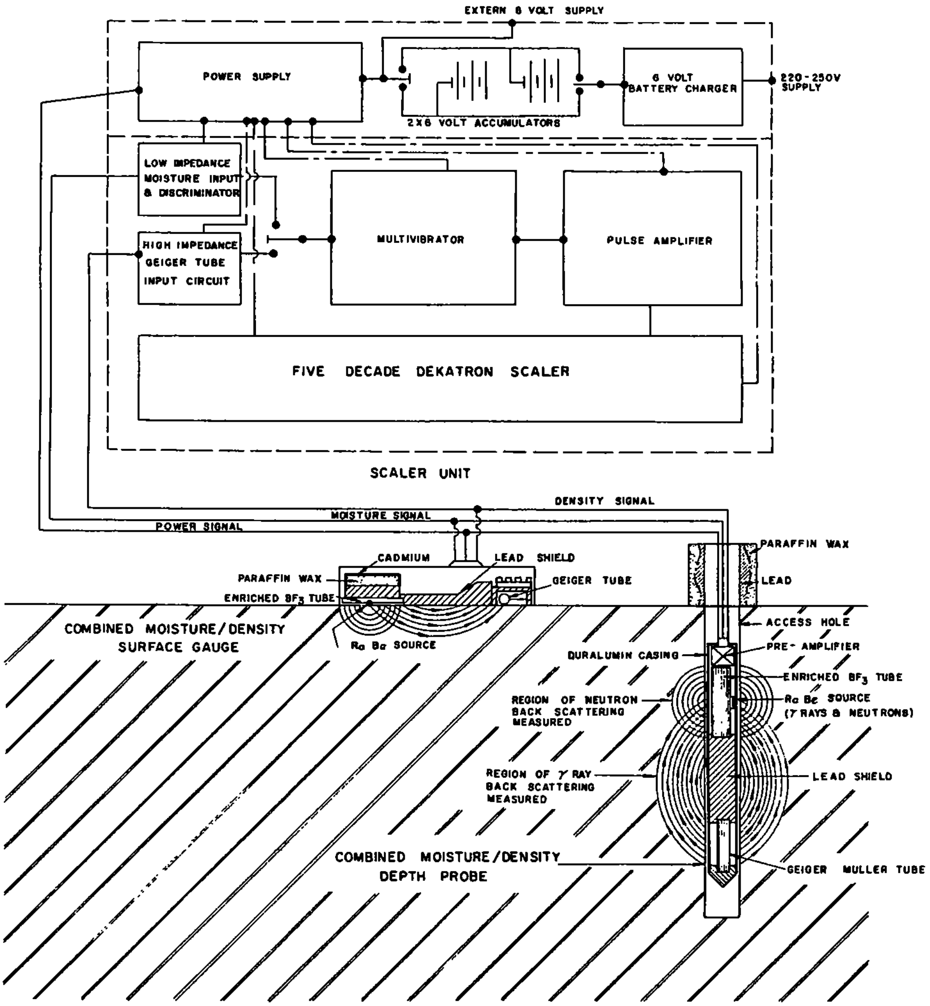

Figure 1. Diagrammatic sketch of moisture density apparatus.

PRINCIPLE OF OPERATION

The basic physical principles involved in this method are probably now so well known as to require only a brief mention here.

The surface probe contains at the bottom the radioactive source and suitable detector tubes protected from direct radiation by lead screening. When the probe is placed on the soil surface the gamma radiation from the source is emitted in all directions into the soil, where it is either absorbed or scattered back towards the Geiger-Müller detector tube by the Compton scattering process. The measured amount of radiation is indicated on a suitable counting unit. For the detector geometry employed, the quantity of back-scattered gamma radiation is inversely proportional to the total soil density (including water) in the range of about 70 to 170 pcf and is virtually independent of soil composition.

The fast neutrons from the source are also emitted into the soil in all directions and undergo collision with the nuclei of the different atoms present. If a nucleus is of the same order of mass as the neutron, the neutron undergoes an inelastic collision, loses a large proportion of its energy to the nucleus, and becomes a slow neutron. If, on the other hand, the nucleus is very much heavier than the neutron, collision is elastic; the neutron loses very little energy and remains a fast neutron. Inasmuch as the hydrogen nucleus has nearly the same mass as the neutron, hydrogen is the most effective element in slowing down or moderating the neutrons, whereas the nuclei of the other materials present in soil are generally much heavier than the neutron and so have comparatively very little moderating effect. After repeated collisions with hydrogen atoms, a proportion of the neutrons that have been slowed down are scattered back towards the probe. These are then detected by boron trifluoride tubes, which are sensitive only to slow neutrons, and the neutron count is again indicated on the counting unit. The count rate (i.e., the number of neutron pulses counted by the scaler per unit time) is then proportional to the number of hydrogen atoms in the soil and hence proportional to the moisture content of the soil. Organic matter also contains hydrogen, but this material is normally present in soils used in road construction only in very small amounts.

GENERAL DESCRIPTION OF INSTRUMENT

The general arrangement of the equipment is shown in Figure 1. Figure 2(a) shows a view of the equipment connected for use on the road. Figure 2(b) shows a set of replaceable plug-in units that make up the scaler circuits.

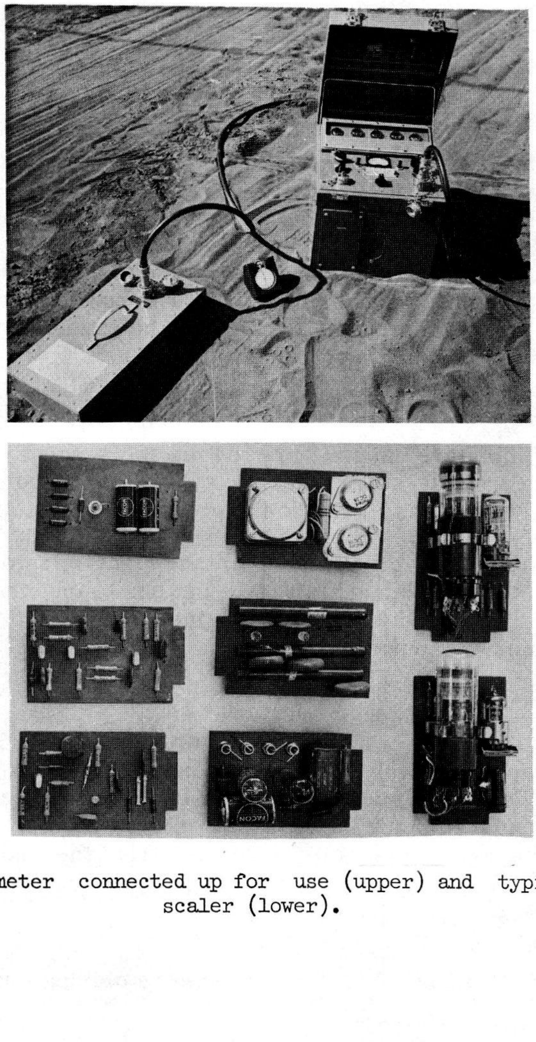

Figure 2. Hidrodensimeter connected up for use (upper) and typical plug-in units of scaler (lower).

Probe and Cable

The probe contains a 10 millicurie radium-beryllium source in a holder situated at one end. Screened for direct transmission from the source by 9½ in. of lead is the detector tube for gamma rays, an Anton, type 106C, halogen-quenched Geiger-Müller tube, operating at about 900 volts. Provision was also made to slide the Geiger-Müller tube horizontally so as to vary its distance from the source. In the "full-in" position referred to in this paper, the source-detector distance was 9½ in. In the "full-out" position this distance is increased to 13 in. At the "mid" position the distance is 11¼ in.

Also mounted in the probe are two boron trifluoride tubes (12EB40), copper-walled, operating at about 1800 volts. These two tubes lie at an angle, with the source between them.

Output pulses from the BF_3 detector tubes are fed to a four-stage transistorized pre-amplifier giving an overall gain of 150, with low impedance output into the probe socket. The signals from the Geiger-Müller detector tube are fed directly to the probe socket. A six-core cable, each core separately screened, carried all supply voltages and signals between the probe and scaler. The cable is terminated at each end with "Plessey" plugs mating into standard sockets. The six cores carry the following:

1. Moisture signal input from pre-amplifier in probe to scaler.
2. Up to 1,000 volts for the Geiger-Müller tube.
3. Negative 6 volts for pre-amplifier supply.
4. Earth.
5. Earth.
6. Up to 2,000 volts for the boron trifluoride tubes.

Reference Standard for Surface Probe

The surface probe has been designed with heavy top and side screening to protect the operator from stray radiation. The only emergent radiation is downwards. A special container has been designed for storage of the probe when not in use. In this container the probe rests on a 10-in. thickness of hard paraffin wax that absorbs neutrons. A block of lead is positioned in the wax under the source to absorb the gamma radiation. The wax also serves to provide reference counts for both "density" and "moisture." If the whole instrument remains in good working order, these reference counts will remain constant.

Scaler

The "density" and "moisture" signals are fed via two separate input circuits, the density signals through a single-stage transistor to the moisture/density selector switch and start/stop buttons and thence to the grid of the first dekatron-triggering stage, a hard valve (type 6AK 5). The moisture signals are fed via a single-stage transistor and multi-vibrator to the variable voltage discriminator, and hence via the moisture/density selector switch and start/stop buttons to the first dekatron stage. The discriminator control can be adjusted under the dummy knob on the control panel to avoid unwanted gamma-ray input.

Dekatron Counting Circuits

The first-stage dekatron uses a hard valve, a 6AK 5, as its triggering stage, the resolution time being approximately 33 microseconds. The output of this stage is fed to the trigger tube of the second stage. The remaining three stages are fed in a similar way, the total count displayed being 99,999.

Power supply for the counting circuits is derived from the dekatron drive unit in the power supply section.

Power Supply Unit

This unit consists of two P. N. P. power transistors driving a pot core into saturation at a frequency of 1 kcs, producing a square wave of 20 volts amplitude peak to peak with an input of 6 volts D.C. A second transformer, also ferrox pot core, is fed from the 1-kcs transformer, the secondary being tapped to provide the necessary voltages for the complete equipment.

Battery Supply

The total power consumption of the equipment is only 9 watts. The battery used is a 6-volt Venner silver-zinc type, of capacity 15 ampere-hours. Due to the very flat discharge characteristics, at the normal current consumption of 1.5 amps, a fully charged battery should give a total operating time of about 10 hours. The battery voltage can be checked with the meter on the control panel by depressing the test button immediately to the left of the meter. Similarly, the high voltages for both the density and the moisture circuits can be checked by depressing the test button immediately to the right of the meter.

If the built-in battery voltage is low, a 6-volt external battery can be used by connecting into the socket on the scaler and switching the main control to the appropriate position.

Certain troubles have been experienced with the battery and voltage regulation and further work is in hand on this.

Charging Arrangements

For charging the internal battery from A.C. mains, a built-in battery charger is provided. The charger has a selector switch for 110, 200, 220, and 250 volts supply and regulates the current initially at 0.75 amp. This is reduced as the battery reaches the fully charged state. Charging is done by connecting the cable into the socket (as for the external battery) and switching the main control to the "charge" position.

The Depth Probe

The arrangement in the depth probe differs from that in the surface probe in that the Geiger-Müller tube lies along the axis of the probe (see Figure 1) and the single BF_3 tube lies along the probe axis with the source located against the center of the active portion. The change-over is made sinply by unplugging the cable from the surface probe and plugging the depth probe cable into the counting unit.

Counting Time

The emission of gamma rays and neutrons from the radioactive source is not absolutely constant with time but has a random distribution. Experience has shown that a minimum of 10,000 counts on the scaler is required in any particular measurement to ensure that the error from this source does not exceed 1 percent. Under average test conditions on roads, a count for 1 minute is usually sufficient to exceed the figure of 10,000. When necessary, however, the count can be taken for 2 minutes if the count rate is significantly below 10,000 per min.

INVESTIGATIONS INTO THE EFFECTIVE VOLUME AND DEPTH MEASURED

For the initial investigations into the effective volumes and depths of the "zones of influence" of the gamma and neutron radiation, a mold was required that would satisfy the requirements for depth determinations with the surface probe and also those for volume determinations with the depth probe.

Various tests were conducted to find (a) the best type of materials to be used, (b) the amount of compaction required, (c) the homogeneity of the mixture, and (d) its ability to be handled often. Finally, after repeated tests on a 6-in. diameter standard mold, the following materials were selected as components of the mixtures: river sand, blast-furnace slag, vermiculite, steel filings, paraffin wax, and tar. From these tests it was decided to make up five compositions by varying the proportions of the component materials to give the densities and simulated moisture contents shown in Table 1. The mixtures were prepared hot, and the wax and tar served as a binder to give a firm coherent material after compaction in the special ring molds to be described.

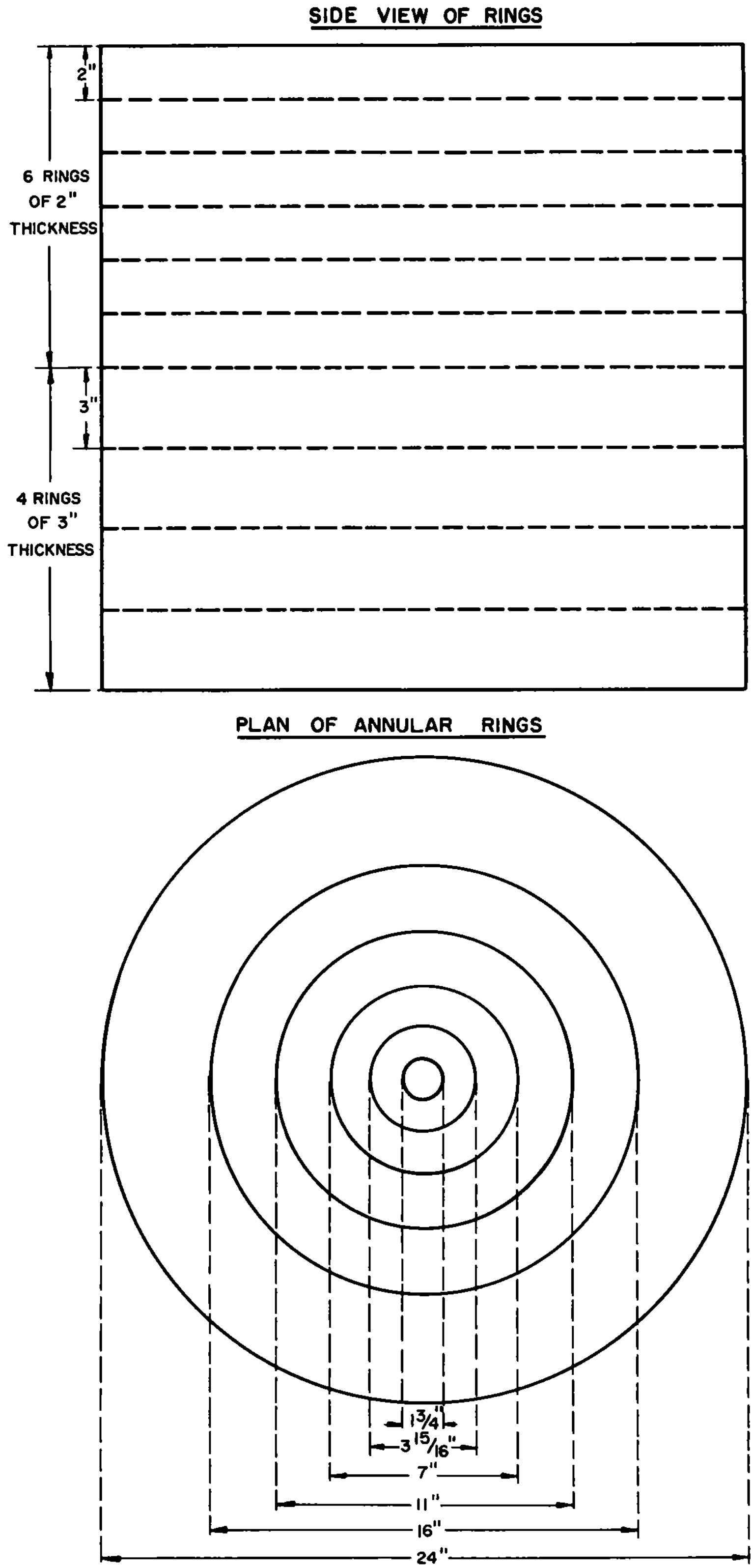

Figure 3. Annular ring molds.

Consideration was then given to the mold construction, and it was decided that each composition should be made up in annular rings reaching a final diameter of 24 in., with a centre core of $1\frac{3}{4}$-in. diameter that could be removed when using the depth probe. In all, 5 annular rings were made having diameters of $1\frac{3}{4}$ to $3\frac{15}{16}$ in, $3\frac{15}{16}$ to 7 in., 7 to 11 in., 11 to 16 in., and 16 to 24 in. Each completed mold also had to be 24 in. high and was made up of 4 rings of 3-in. thickness and 6 rings of 2-in. thickness. The final densities and simulated moisture contents were calculated from the weights and volumes of the molds and the percentages by weight of the wax and tar used. The exact hydrogen content of the wax and the tar was determined by chemical analysis. Figure 3 shows the details of a mold.

TABLE 1

Mold	Density (pcf)	Simulated Moisture Content (% dry wt)
1	78.2	30
2	86.4	23
3	106.7	16
4	125.4	9
5	145.2	4

Depth Investigation Using Surface Probe

It was first established that, for the surface probe to give its maximum count rate, the full 24-in. diameter mold was necessary (because the count rate fell after removing the outer ring). A 2-in. thick section (24 in. in diameter) was placed on the table and the surface probe positioned on the center of the mold. Readings of counts per minute were then taken for both moisture content and density, the distance between source and detector being varied for the density measurements in equal steps, a count being taken for each step. This section of the mold was then replaced by a 3-in. thick section and the tests repeated. Further thicknesses were then tested, increasing an inch at a time (i.e., 4 in., 5 in., 6 in., etc.) until it was observed that no change in count rate occurred with increase in mold thickness. This complete procedure was then repeated over the five compositions of varying density and moisture content. From the results obtained, curves were plotted to establish the following relationships:

(a) count rate against moisture content (Figure 4),
(b) count rate against wet density in pcf for various source-detector distances (Figure 5),
(c) counts per minute against mold thickness (Figure 6), and
(d) effective depth of measurement against wet density (Figure 7).

From these tests it was found that the effective depth measured by the radiation was a function of both the source-detector distance and the density. From the moisture investigations it was found that the effective depth measured was independent of both the density and the moisture content and that it remains constant at $4\frac{1}{4}$ in.

Volume Investigation Using the Depth Probe

For this work the full mold thickness of 24-in. was used throughout, the diameter being varied by adding annular rings as required. Initially the probe was lowered into the hole in the center of the mold and readings were taken at preset depths to ascertain the effect of the probe being used near the surface of the material. This was done for all positions of source-detector distance. Subsequent volume investigations were done with the radioactive source at the center of the mold, i.e., 12 in. from the top surface.

The depth probe was then lowered into the hole, using only the first annulus (i.e., $3\frac{15}{16}$-in. diam.) and counts per minute were taken for moisture and density. This procedure was then repeated, adding the annular rings until the full diameter was reached. Again this was done for the five compositions and curves were drawn to establish the following relationships:

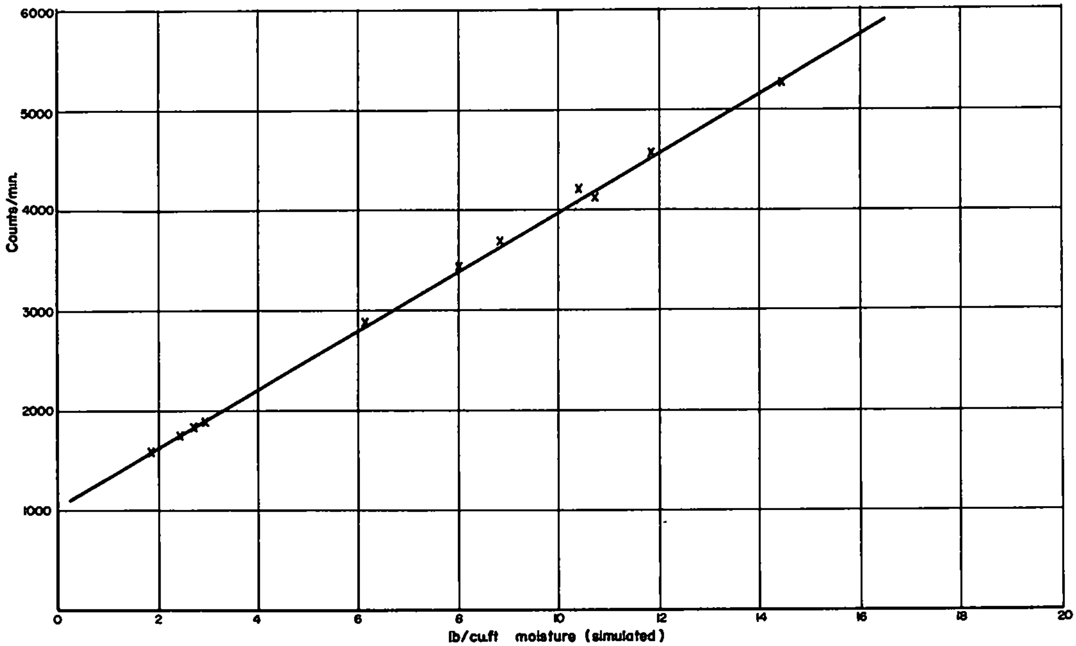

Figure 4. Relationship between moisture content and counts per minute.

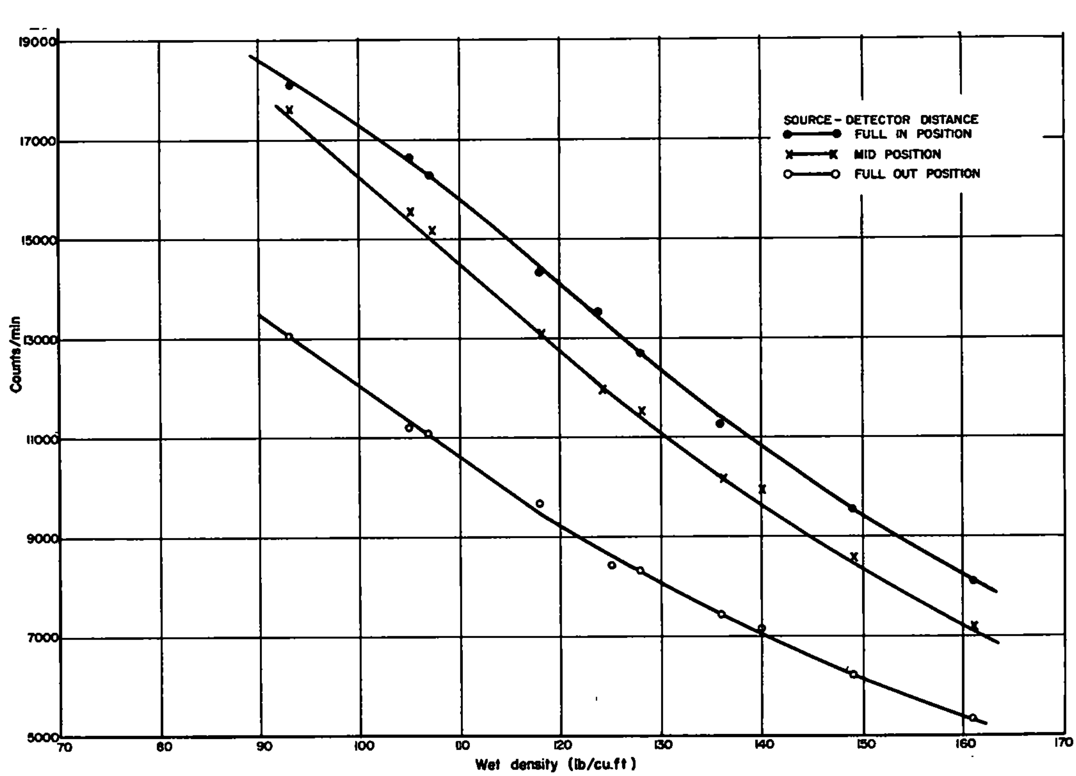

Figure 5. Relationship between wet density and counts per minute.

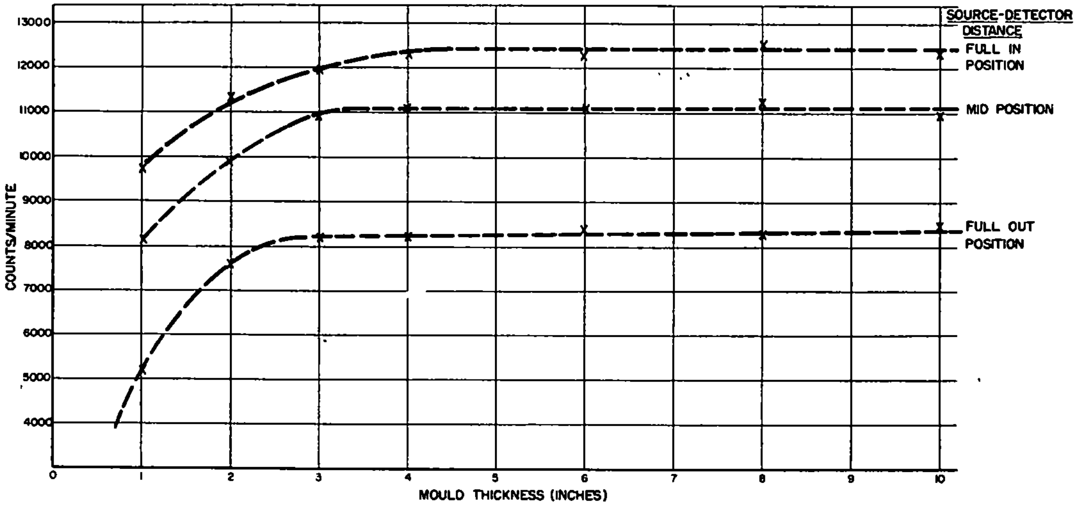

Figure 6. Counts per minute vs mold thickness for a density of 129.6 pcf.

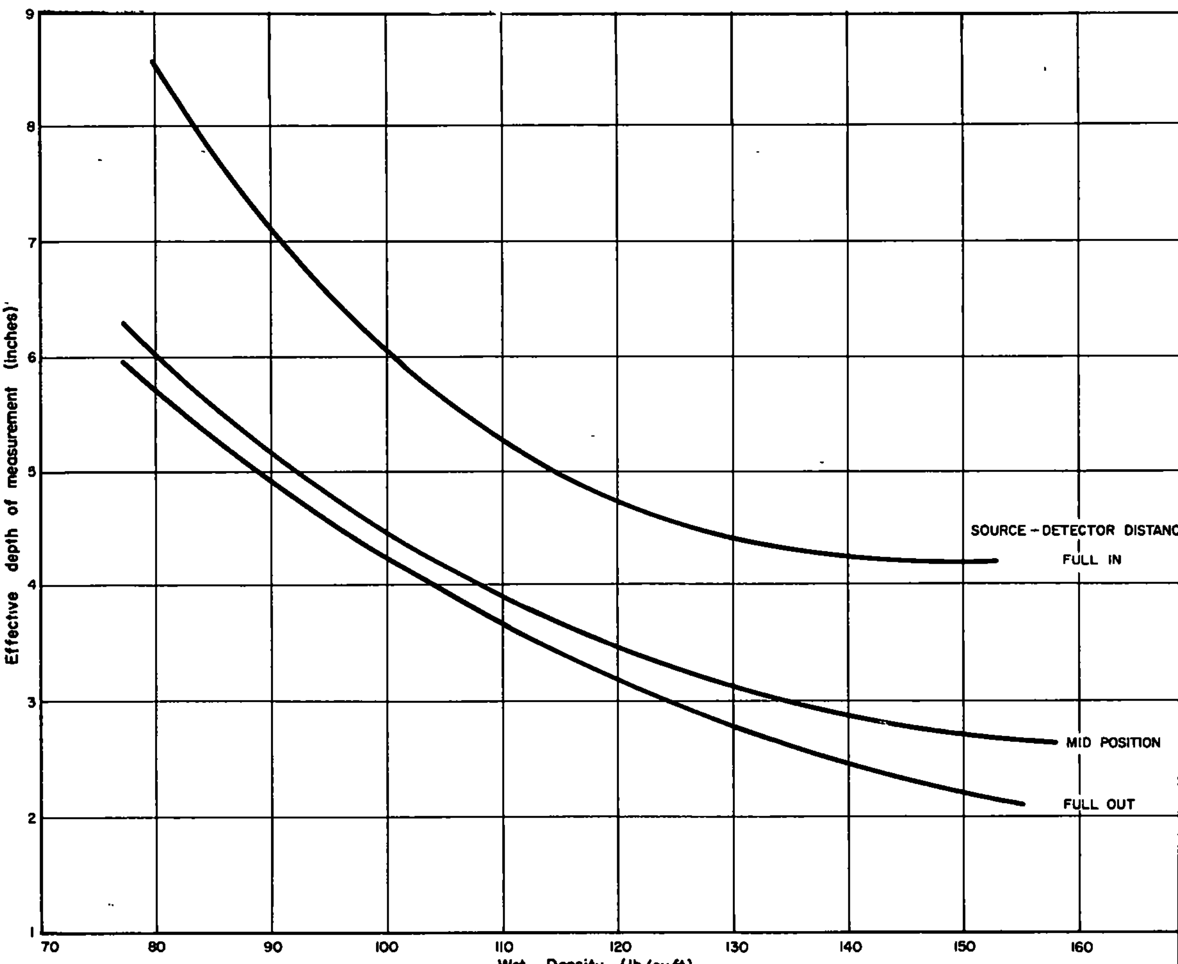

Figure 7. Relationship between effective depth of measurement and wet density.

(a) count rate vs moisture content on full diameter molds (Figure 8)
(b) count rate vs density on full diameter molds (Figure 9)
(c) counts per minute vs mold diameter (Figure 10, an example at one density), and
(d) effective radiation diameter vs wet density (Figure 11).

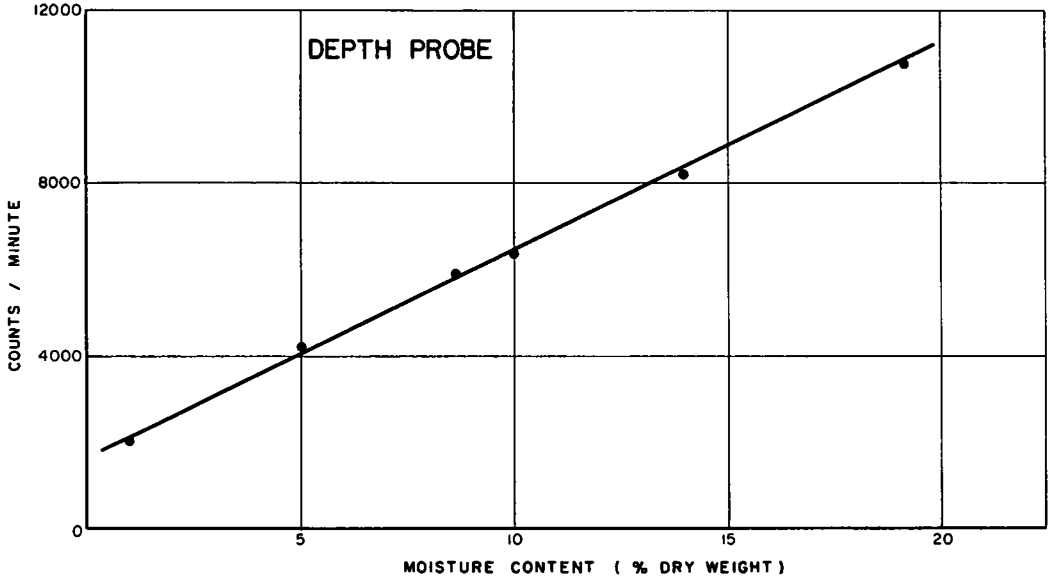

Figure 8. Counts per minute vs moisture content at one density.

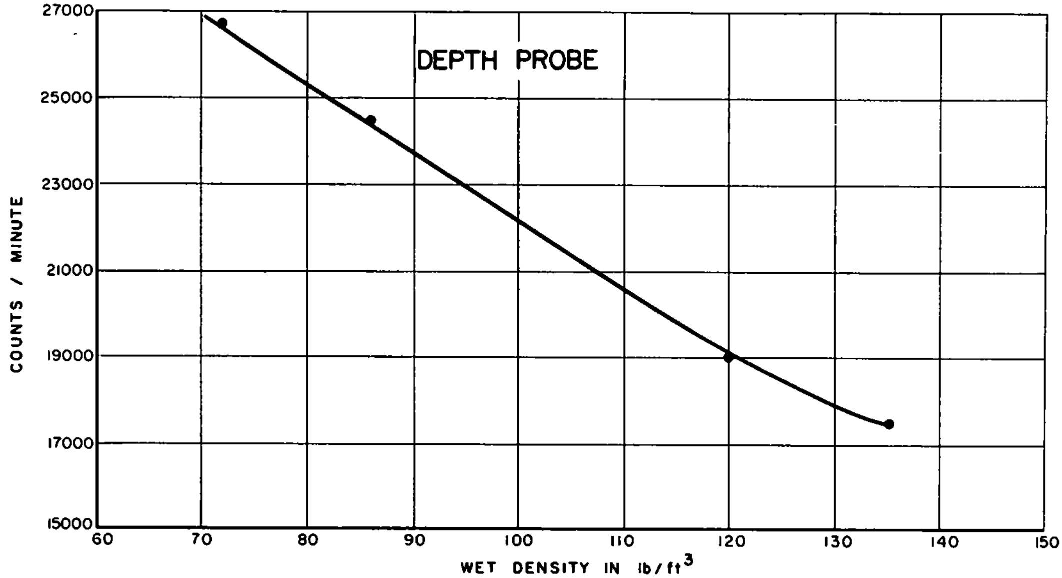

Figure 9. Counts per minute vs density.

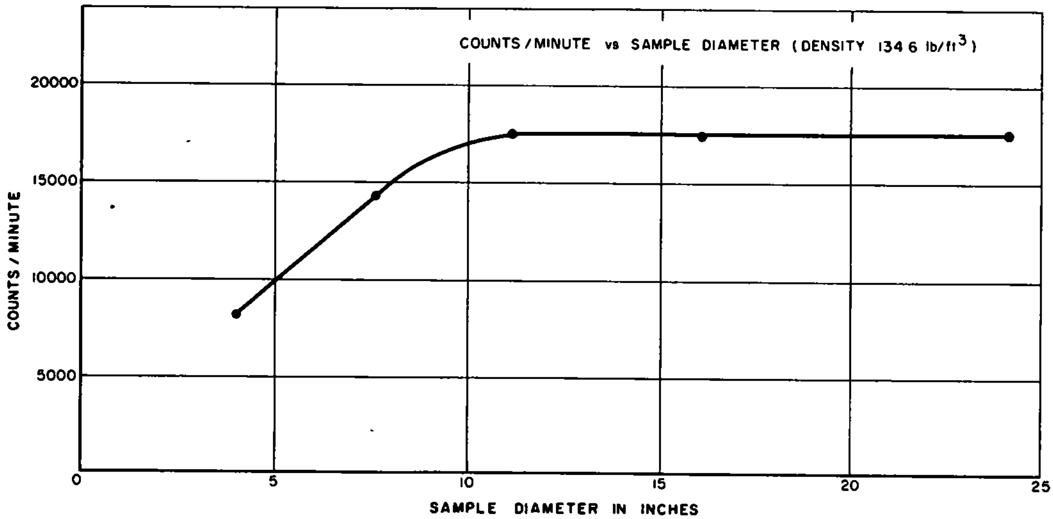

Figure 10. Counts per minute vs sample diameter at one density with the depth probe.

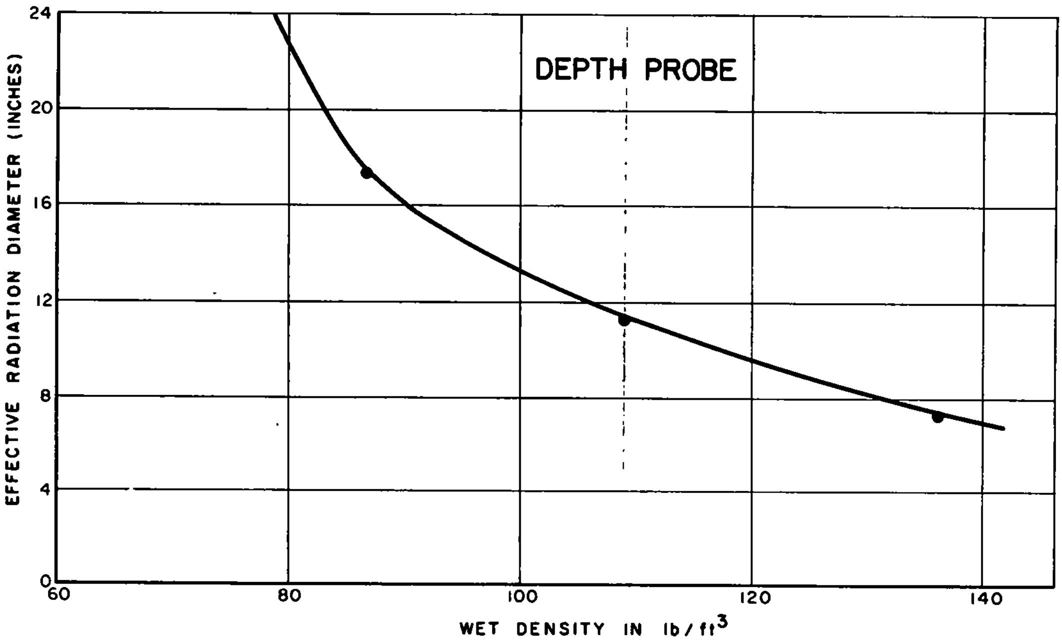

Figure 11. Effective radiation diameter vs wet density.

density measurement with the depth probe varies from about 7 in. at 140 pcf up to about 22 in. at a density of 80 pcf. For moisture content measurements, it was found that the effective volume measured by the depth probe was not influenced by either the moisture or the density.

In general, however, with both the surface probe and the depth probe the count rate for moisture measurement at a constant moisture content (percent moisture on dry weight) increased as density increased because at increasing density more water is enclosed by the fixed "influence volume." This implied the need for a family of moisture calibration curves over a range of densities. It was then found that a single moisture calibration curve can be used, independent of density, if the moisture content is expressed as pcf of water instead of the usual percent moisture on dry weight. This procedure also simplifies calculation of the results of measurements with the instrument. The gamma ray count gives wet density (cp cf) direct from the calibration curve, the neutron count gives water content (pcf) direct from the calibration curve and dry density is then given by the difference of these two quantities. The moisture (percent on dry weight) is then obtained by dividing the pcf of water by the dry density pcf).

FIRST SET OF STANDARD MOLDS

On completion of these investigations, it was decided to build a laboratory set of standard molds, again with a working range of density and simulated moisture content. The dimensions of these molds were to be based on results obtained with the annular ring molds for both surface and depth probes. The same type of composition was used as for the annular ring molds. Aluminum boxes were constructed of $^{3}/_{16}$-in. sheet into which the mixtures were to be compacted. In the center of each box a horizontal aluminum access tube of 2-in. outside diameter was welded to accomodate the depth probe. These molds were found to be more suitable in drawing up calibration curves for field work, inasmuch as the annular ring molds suffered from several disadvantages: small air gaps between the annular rings, slight changes in density between rings of the same size due to compaction difficulties, and superficial damage to the surfaces from repeated handling.

CALIBRATION OF SURFACE PROBE ON SOILS

Following the laboratory work, investigations with the surface probe were then carried out using four different types of soils, again to establish the effect of soil density on the effective depth of measurement and also to study the effects of different types of road building materials on the count rates obtained with the Hidrodensimeter.

A steel container, measuring 3 ft x 3 ft x 1 ft deep, was constructed for compaction of the material and lines were accurately scribed at 2-in. intervals around the sides for layer investigations. Six wet densities ranging from 70 to 145 pcf were selected. At each wet density, the moisture contents were varied from 2 to 20 percent on dry weight. Compaction was carried out in 2-in. layers and counts per minute for density and moisture were taken at each step for all three positions of source-detector distance until the count rates became constant with increasing depth of material. After each series of tests had been completed, sand-replacement tests were done and samples for oven drying taken to check Hidrodensimeter results. The results of this investigation, with its large number of combinations of density and moisture content, were used to establish the practical calibration curves. Figure 12 shows the density calibration curve obtained on the soils, with the points from the block molds included. Figure 13 shows the moisture calibration curve, also including block mold points. The effective depths of measurement found at the various densities, source-detector distances, and moisture contents verified the earlier results obtained on the annular ring molds. In fact, the results obtained with the four soils chosen did not effectively change the calibration curves already found (see Figures 12 and 13).

Referring to Figure 7, it will be seen that some control of depth of measurement is provided by varying the source-detector distance. At the high end of the practical range of wet density (150 pcf) the depth of measurement can be varied from $2\frac{1}{2}$ to $4\frac{1}{4}$ in. At the low end of density (e.g., 100 pcf) the depth of measurement can be adjusted from $4\frac{1}{4}$ to 6 in.

At present, a limitation on this range of adjustment is created by the physical size of the lead screen between the source and the Geiger-Müller tube. This screen governs the closest spacing of the source and detector and hence the greatest depth measured. Further work is in progress to find more efficient screening materials to enable this spacing to be reduced so as to increase the depth of measurement in the high density materials and, therefore, give the operator an increased degree of control over the depth of measurement.

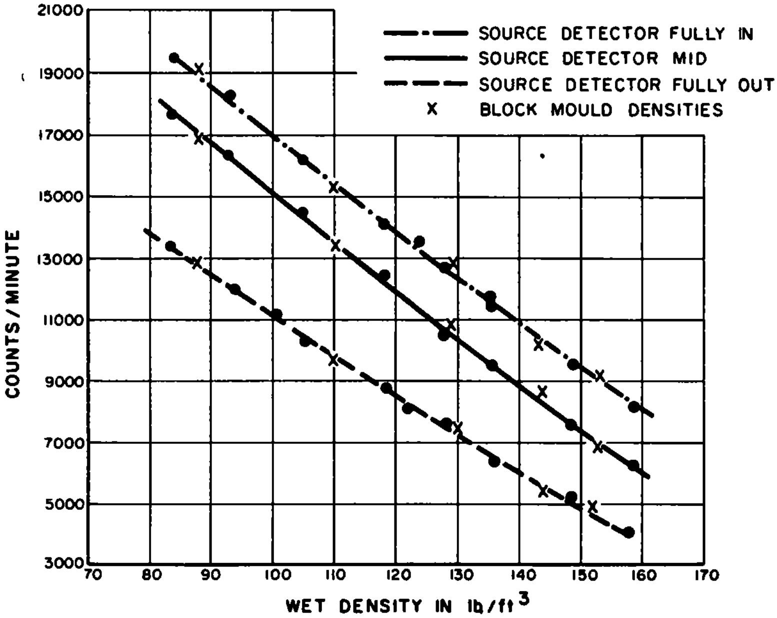

Figure 12. Density calibration curve.

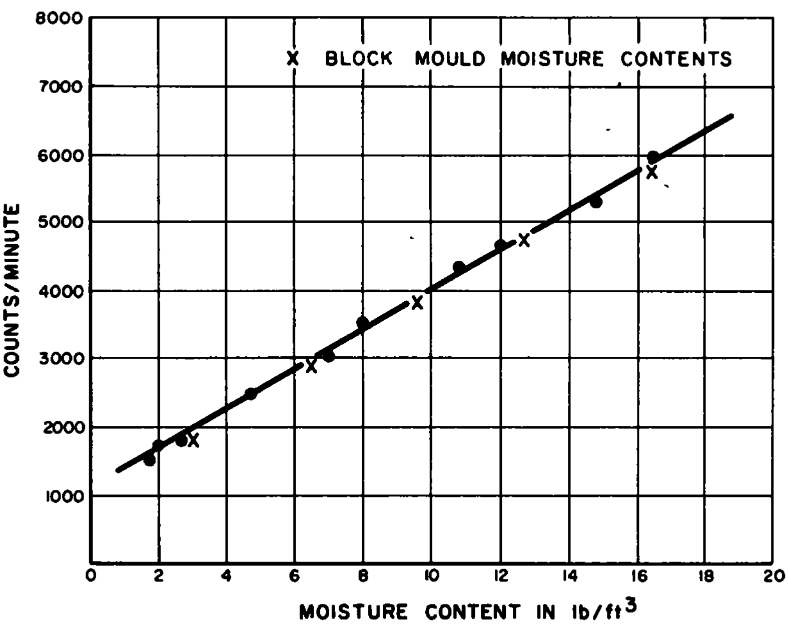

Figure 13. Moisture calibration curve.

Effect of Clay Content on Moisture Measurement

Holmes in Australia reported (7) that clay content of soils influenced the moisture count rate obtained by this method. Some preliminary work was done to examine this effect. Three materials were chosen: a heavy black clay, a medium clay, and a sandy soil of P.I. below 4. Each material was compacted into a large steel tray at three different moisture contents (the densities and moisture contents being verified by sand-replacement tests and oven drying). Readings were taken with the Hidrodensimeter surface probe and curves plotted from results obtained (Figure 14). From these results it was found that the type of material had no effect on the density count rate, but that the clay materials and sandy soil gave separate "moisture" curves. Figure 14 shows counts per minute against moisture content (percent dry weight) by oven drying.

The data obtained from the sandy soil agreed with the normal calibration curve to within ± 1 percent. Significant departures from the calibration curve were found with the two clays however. This was due to the bound hydrogen in the clay mineral structure giving a high background count. Materials normally used in constructing road foundation layers are nevertheless severely limited in clay content and experience in the field has shown this effect is negligible.

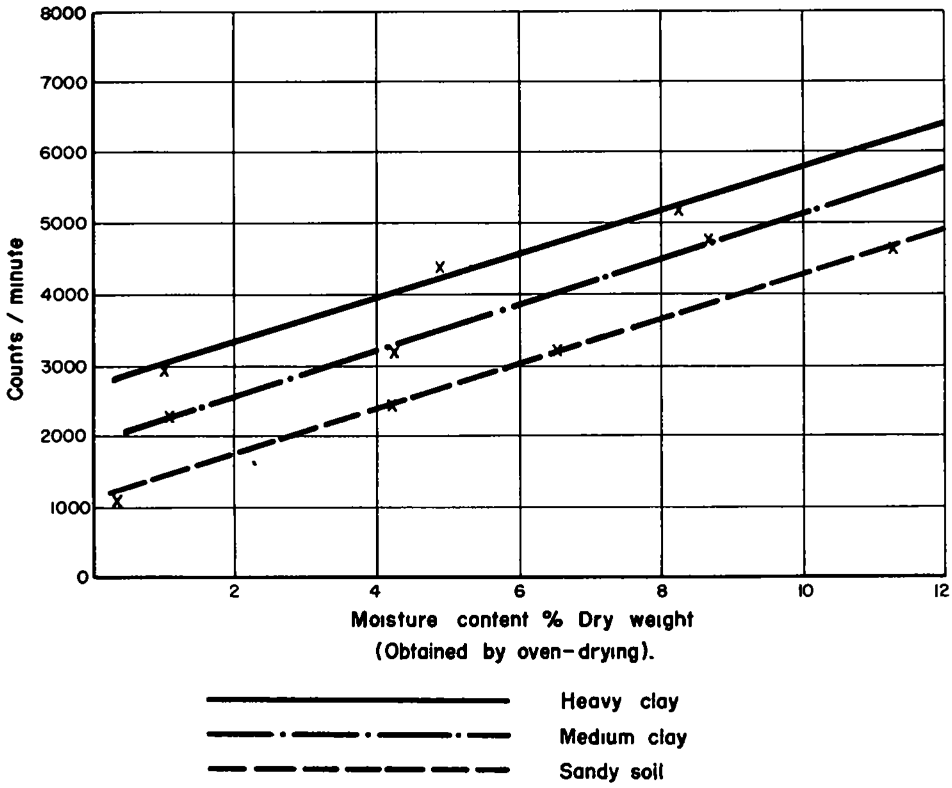

Figure 14. Effect of the clay content on moisture measurements using the Hidrodensimeter.

FIELD TRIALS WITH THE HIDRODENSIMETER

The next step after the laboratory calibration work was to take the instrument into the field and use it on road construction jobs alongside the normal sand-replacement method. This was done in all four Provinces of the Union of South Africa and a range of types of material was covered. The tour also gave an opportunity to demonstrate the speed of measurement in the field. Only the surface probe was used, as this provides the type of measurement of most interest to engineers in controlling compaction of soil layers.

To compare Hidrodensimeter results with those from the normal method, several series of tests were taken on a range of construction jobs with teams running sand-replacement tests alongside the operator with the Hidrodensimeter. Although it is commonly accepted that the sand-replacement test is itself liable to error, it was nevertheless felt that, if a good correlation between the two methods was found, the Hidrodensimeter could be used in the field with at least the same confidence as the present methods.

The results of about 95 tests obtained by both methods are discussed later. The detailed data is given in Table 2. These tests covered densities from about 100 to 150 pcf and moisture contents from about 1 to 12 percent. Each test consisted of a measurement with the Hidrodensimeter surface probe, followed by the sand-replacement method on precisely the same spot. The time required to make a determination at one point of both moisture content and density with the Hidrodensimeter is about three minutes. On the crusher-run materials, with their high density, the effective depth of measurement was about 4 in., while on most other materials tested the densities were lower and the effective depth of measurement was about 6 in. The sand-replacement tests were, in general, done to the same depths.

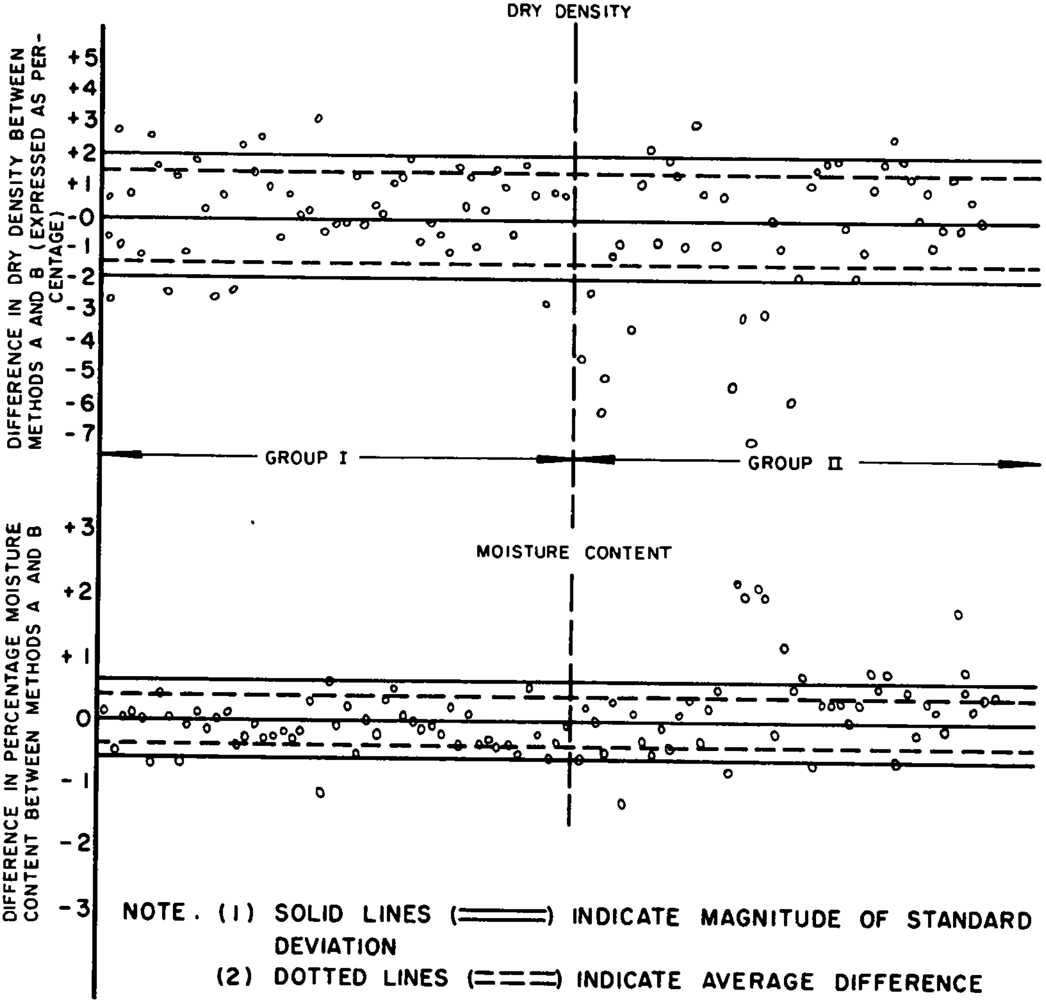

Figure 15. Graphical presentation of differences in results by the two methods.

TABLE 2

COMPARATIVE DATA OBTAINED WITH HIDRODENSIMETER AND SAND-REPLACEMENT METHODS

Type of Soil	Group I				Group II				Type of Soil
	Hidrodensimeter[a]		Sand Replacement[b]		Hidrodensimeter[a]		Sand Replacement[c]		
	Dry Dens. (pcf)	Moist. Cont. (%)	Dry Dens. (pcf)	Moist. Cont. (%)	Dry Dens. (pcf)	Moist. Cont. (%)	Dry Dens. (pcf)	Moist. Cont. (%)	
Crusher	147.1	1.6	146.2	1.7	125.1	6.2	125.2	5.6	
Run	146.4	2.2	150.4	1.7	116.0	4.9	111.0	5.1	Decom-
(Primed	148.2	1.8	146.9	1.8	113.7	7.3	111.0	7.3	posed
surface)	144.1	1.7	145.1	1.8	112.0	7.5	106.5	7.0	granite
	145.8	1.1	147.3	1.1	112.2	7.9	111.0	8.2	
	147.0	2.2	150.9	1.5	112.2	10.1	111.3	8.8	
	142.5	2.4	144.8	2.8	111.8	8.3	108.0	8.75	
	147.7	1.1	144.2	1.1	135.8	3.5	137.3	3.2	Subbase
	141.0	2.1	142.8	1.4	134.0	3.0	137.0	2.5	Granite
	145.2	2.1	143.5	2.0	138.9	2.8	138.8	2.7	and
	149.7	1.1	152.4	1.2	143.1	3.4	145.8	3.0	Sand-
	144.5	1.8	144.9	1.6	131.2	2.7	133.0	2.8	stone
	145.8	1.1	142.2	1.1	131.4	3.4	130.2	3.7	
	143.8	2.3	144.8	2.4	133.8	3.0	137.9	2.7	
	145.7	0.9	142.3	0.5	125.2	3.1	126.2	3.3	
	149.8	2.4	153.3	2.1	126.0	5.5	125.0	6.0	Base
	143.6	2.6	145.7	2.5	148.0	3.1	149.1	2.3	Crusher-run
	144.5	1.9	148.2	1.6	119.0	6.1	113.0	8.3	Sand-
Base	133.0	9.9	133.1	9.7	117.9	6.3	114.2	8.3	stone
Course	134.7	9.8	135.0	10.1	117.8	6.9	110.0	9.0	
	129.4	11.8	133.5	10.7	119.4	5.6	115.8	7.6	
	136.0	8.3	135.4	8.9	115.8	5.9	115.8	5.7	
	127.8	10.8	127.6	10.7	115.9	7.8	114.9	9.0	
	135.0	10.1	134.9	10.3	119.1	6.7	112.6	7.2	
	142.0	8.1	143.8	7.6	96.2	12.7	94.4	13.4	Decom-
	137.8	9.6	137.5	9.6	99.8	9.4	101.0	8.7	posed
	133.0	9.6	133.4	9.4	101.3	8.9	102.8	9.2	granite
Sandy	115.7	7.6	115.8	7.9	99.2	11.1	101.0	11.4	
soil	102.1	11.1	103.2	11.6	101.9	10.3	103.9	10.6	
	107.7	12.2	110.1	12.3	102.2	10.6	102.0	10.6	
	112.1	11.5	114.3	11.5	109.0	8.7	107.0	9.0	
	109.4	10.4	108.6	10.3	102.4	9.9	101.4	10.7	
	112.9	9.1	112.8	9.0	104.1	9.9	105.1	10.5	
	107.0	12.2	106.5	12.0	108.6	9.8	108.8	10.6	Medium
	123.0	10.9	121.7	11.1	115.3	8.2	118.3	7.6	clay
	119.5	12.0	121.4	11.6	101.5	10.1	103.5	10.6	
	116.2	11.9	116.6	12.0	108.0	10.8	109.5	10.6	
	121.9	12.3	120.8	11.9	113.6	8.4	113.6	8.7	
	120.4	12.0	120.6	11.7	113.0	7.4		7.1	
	118.9	11.9	120.7	11.5	134.2	3.3	135.4	3.5	Crusher
	113.4	12.2	114.5	11.8	136.0	3.8	134.9	3.7	run
5-in.	130.3	4.2	131.6	3.9	136.4	3.5	136.0	5.3	base
gravel	130.4	3.3	129.5	3.1	131.3	4.5	133.0	5.0	course
layer	132.6	2.7	133.6	2.4	137.9	4.4	137.6	4.6	
Natural	111.0	7.9	110.5	7.4	137.7	4.4	138.5	4.8	
shoulder	116.5	8.1	118.5	8.6	135.0	4.4	135.0	4.8	
material	122.3	7.0	123.2	6.8					
	111.4	7.9	108.5	7.3					
	109.1	9.5	110.0	9.1					
	109.2	9.7	110.0	9.6					

[a]Results obtained by National Institute for Road Research.
[b]Results obtained by experienced teams.
[c]Results obtained by less experienced teams.

Because the results of the sand-replacement method are, in general, subject to a significant but unknown error, they do not really provide a satisfactory reference against which to compare the Hidrodensimeter results (8). This point must be borne in mind in considering the results discussed herein. As a first attempt to compare the two sets of results, the differences between the individual results obtained by the two methods were plotted for all the determinations relative to a line signifying zero difference. In other words, differences between the test results by the two methods were examined, considering either set as reference. Figure 15 shows the differences in dry density (expressed as a percentage) and the differences in percent moisture content.

Three quantities were calculated from these results: the mean arithmetical difference (A), the mean of the modulus of the difference (B), and the standard deviation of the differences (C). These are given in Table 3 and shown graphically in Figure 15.

TABLE 3

QUANTITIES A, B, AND C FOR RESULTS OBTAINED IN FIELD TESTS

Results	Differences in Dry Density (%)			Differences in Moisture Content (%)		
	A	B	C	A	B	C
Group I	+0.4	1.3	1.4	+0.13	0.28	0.36
Group II	-0.5	1.7	2.4	-0.3	0.6	0.88
All	-0.05	1.44	2.0	+0.08	0.4	0.62

In Table 3, the results in Group I were obtained by field teams having considerable experience in using the sand-replacement test method, while the Group II results were obtained by less experienced teams. It will be seen in Figure 15 that the Group I differences show only a moderate and consistent scatter, while in Group II a number of the differences are well outside the standard deviation. This is reflected in the figures given in Table 3. Because the standard deviations for Group II are about twice those for Group I, it was concluded that most of the differences between individual results from the two methods could be ascribed to operational errors in the sand-replacement test.

Further analysis of the data was carried out, using more conventional statistical methods, to compare the results given by the two methods. Two points were examined:

1. The correlation coefficient between the two sets of results. The dry density results were grouped into data obtained on crusher-run bases and on other bases. For crusher-run material a value of the correlation coefficient (r) of 0.96 (26 observations) were obtained. The 95 percent confidence limits for r were 0.91 and 0.98. For other bases a value for r of 0.95 was found (69 observations). The 95 percent confidence limits were 0.92 and 0.97. Regression equations were calculated for both the crusher-run and the other data and it was found that the slopes of the two lines did not differ significantly. For all 95 results taken together a value of r of 0.98 was obtained with 95 percent confidence limits of 0.97 and 0.99. For moisture content the correlation coefficient for all 95 results was 0.83 with 95 percent confidence limits of 0.76 and 0.88.

2. The significance of the differences in the results by the two methods. The "Wilcoxon matched-pairs signed ranks" test was then carried out. No significant difference in the results obtained by the two test methods was found (probability level a = 0.05, two-tailed test). This applied to both the density and moisture content data.

When these correlation tests were carried out, no consideration was given to the possibility of density gradients occurring in the layers measured, a factor that only came to light from later field work. Because, however, the effective volume of soil measured by the radiation method differs from the volume involved in the sand-replacement method, it becomes necessary to take this factor into account when making comparative measurements by the two methods on layers through which a density gradient exists. A procedure for the identification of density gradients and for carrying out density tests in such cases was worked out.

DETERMINATION OF THE WET DENSITY OF A SOIL LAYER WHEN A DENSITY GRADIENT EXISTS

To find whether a density gradient exists in the compacted soil layer being tested, use is made of the fact that, by changing the source-detector distance on the surface probe, the effective depth of measurement of density can be varied.

Density determinations are made at the same spot with the source-detector distance in the "full-in" position and then in the "full-out" position. If there is no difference in the densities read off from the respective calibration curves, no density gradient exists and further determinations on the same material can be made with the source-detector distance in the "full-in" position. Under these conditions, the results obtained with the Hidrodensimeter can be compared directly with those found by the sand-replacement test. It is advisable to repeat this procedure whenever there is a change in type of soil or compaction plant being used.

If, on the other hand, the two densities differ, a density gradient exists and it is normally found, that the density increases with an increase in source-detector distance (i.e., with a decrease in the effective depth of measurement). In other words, the density is usually greatest near the top of the layer.

The following procedure should then be used. Let the wet densities obtained with the detector in the "full-in" and "full-out" positions be respectively d_1 and d_2 as read off the appropriate calibration curves, and let the corresponding effective depths of measurement be h_1 and h_2, as found from the curves shown in Figure 7. Plot a curve of wet density (d) against $^3/_8$ times the effective depth (h) as shown in Figure 16 and draw a straight line through the points. This line represents the density gradient in the soil layer.

The average density as determined with the Hidrodensimeter for any depth h' in between h_1 and h_2 can now be read off opposite $^3/_8$ h' (i.e., d'). Similarly, the average

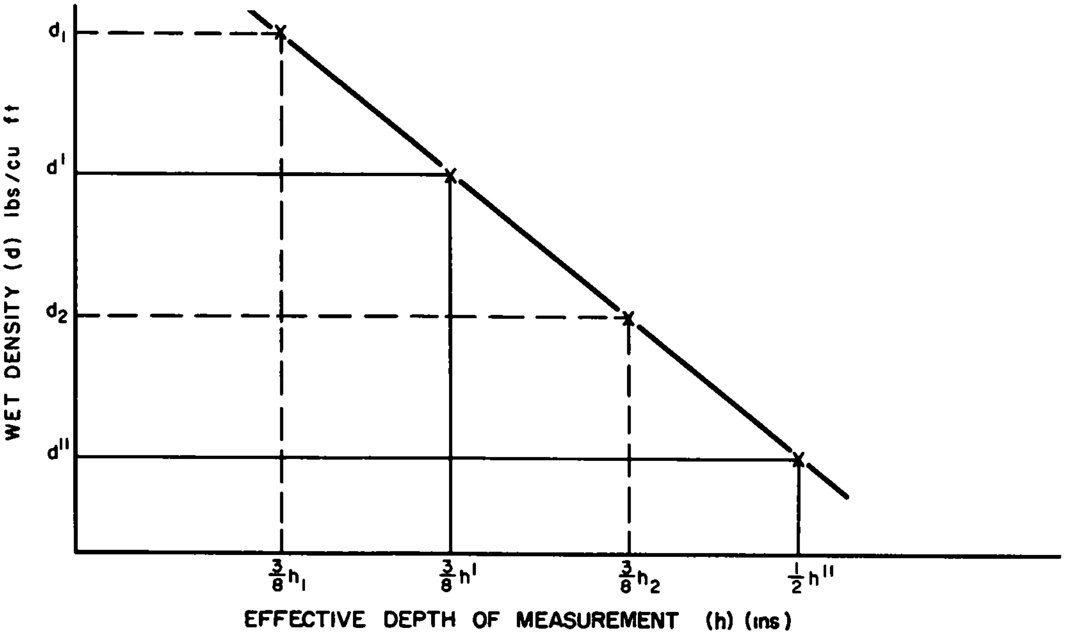

Figure 16. Procedure for dealing with density gradient.

density as determined by a sand-replacement test at a depth h" can be read off opposite ½ times h" (i.e., d"). When the depths h' and h" are the same, there may still be a small difference between the densities as determined by the two methods due to the different shapes of the volumes measured in each case.

It is again advisable to repeat this procedure whenever there is a change in soil type or in the compaction equipment being used.

FURTHER DENSITY CHECKS AND INVESTIGATION OF EFFECTIVE VOLUMES MEASURED

In addition to the systematic calibration work already described in this paper, it was felt desirable to make one or two spot checks on the absolute accuracy of the instrument by using materials of known density, and also to determine more closely the effective shape and volume of the "zone of influence" of the radiation. This work is not yet completed, so only a few preliminary results can be given here.

Three concrete blocks measuring 2½ ft square and 1 ft thick were made up with approximate densities of 157; 135, and 104 pcf. The lower densities were obtainend by using "no fines" concrete and an ash aggregate. After using the Hidrodensimeter to test completely both top and bottom surfaces for density, 5-in. diameter holes were drilled in each block at selected spots and the average density of the extracted core was determined. The cores were then cut into slices and densities were determined for each slice.

The first block, made from a conventional dense concrete mix, was found to be reasonably uniform in density and suitable for the purpose. Unfortunately, the second block of "no fines" concrete and the third block containing an ash aggregate were not sufficiently uniform in density to provide useful checks for the Hidrodensimeter. The results obtained with the first block are given in Table 4, which shows the minimum and maximum densities found anywhere on the top face and again on the bottom face using the Hidrodensimeter, the respective mean densities and effective depth of measurement, and the density results obtained directly from weight and volume of the core and its slices. Although

TABLE 4

COMPARATIVE MEASUREMENTS ON A CONCRETE BLOCK

Surface of Block	Hidrodensimeter Readings (pcf)				Densities Found on Cores (pcf)							
						Densities on Individual Slices						
	Minimum Density Measured	Maximum Density Measured	Average Density for Block	Effective Depth of Measurement (in.)	Average Density for 12-in. Core	0-2 in. (Top Slice)	2-4 in.	4-8 in.	8-10 in.	10-12 in. (Bottom Slice)	Mean for Top 4 in.	Mean for Bottom 4 in.
Top	154.2	157.0	155.6	4.2	156.2	154.1	154.9	161.4	152.2	156.0	154.5	-
Bottom	156.4	159.2	157.8	4.1	-	-	-	-	-	-	-	154.1

some variation in density occurred over both faces, the agreement is reasonably good. Work along these lines however, is, being continued.

By moving the surface probe near to the edges of this square block and by observing the distances to the edge at which the count rate just began to fall off, it was possible to define fairly closely the shape in plan of the effective "zone of influence" of the gamma radiation. This is shown in Figure 17. As would be expected, this is a distorted or egg-shaped ellipse due to the finite length of the gamma-ray detector tube.

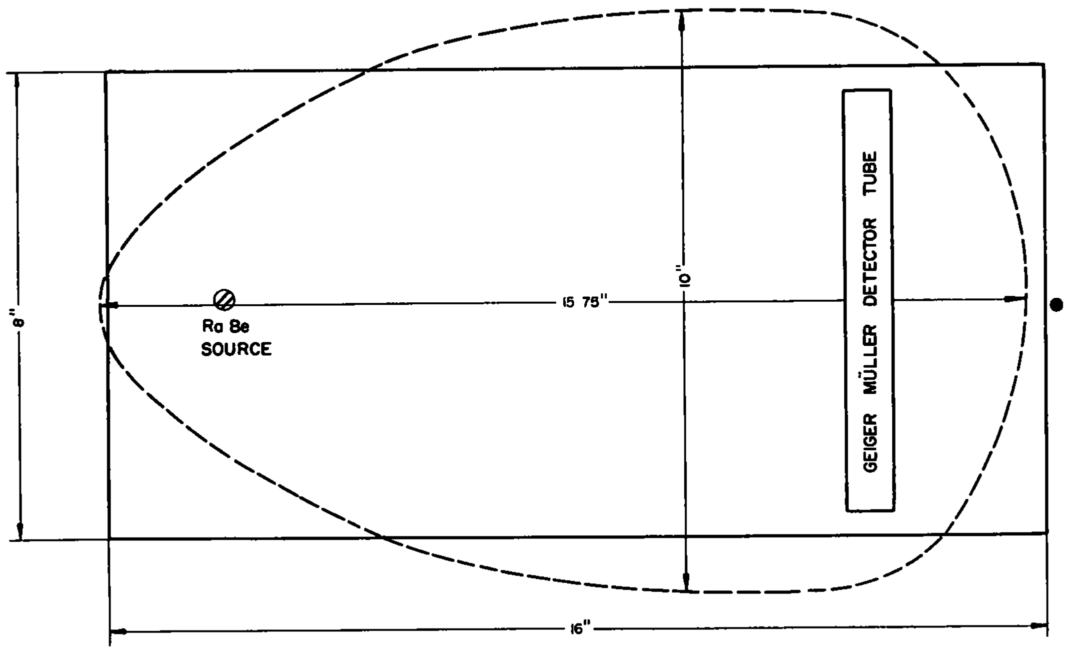

Figure 17. Diagram of surface radiation sphere around probe.

A new system of molds is at present being constructed to investigate accurately the volumes and depth measured and also to study in more detail the effects of density gradients in soil layers. Seven separate sets of molds are being made, each mold consisting of 12 separate slabs, 1 in. thick and 2½ ft square. Again the densities will be varied throughout the working range from 75 to 150 pcf and simulated moisture contents from 2 to 16 percent of dry weight. New types of special materials are being used to give very accurate dimensions and finished surfaces highly resistant to repeated handling. From this work it is hoped that the true shapes of the "zones of influence" can be determined and the effect of different types of density gradient studied.

FACTORY CALIBRATION OF COMMERCIAL INSTRUMENTS

It was considered necessary, in view of the fact that the Hidrodensimeter was to be manufactured commercially, to have a set of standard molds made that would be compacted to known densities and simulated moisture contents. Twenty-three of these molds, each a 3-ft cube, were constructed on the premises of the manufacturers, the wet densities ranging from 80 to 160 pcf and simulated moisture contents from 1 to 15 percent dry weight. The molds were made of granular materials, including sand, vermiculite, and powdered iron ore, the simulated moisture contents being introduced by addition of a hard paraffin wax and tar, which also served to bind the mixtures together.

FIELD APPLICATIONS

More recently, the Hidrodensimeter has been used in the field on a number of road construction jobs in various parts of the country to demonstrate its application in compaction control or to assist in the solution of particular compaction problems that have arisen. A few of the more interesting points that have come to light in this work may be mentioned.

Density Checking

In one case a 3-mi length of new crushed-stone base had to be checked quickly before being used for a major surfacing experiment. In two days the whole length was scanned with the instrument and only one short "low spot" was shown up. The limits of this spot were accurately defined. In all, some 250 density measurements were made.

The value of obtaining a more general picture of the compaction of a particular length, rather than density values from only one or two check points, has been emphasized. In practice, layers are rarely uniform over a few 100-ft lengths, even under well-controlled conditions. As an example Figure 18 shows the results of a compaction study

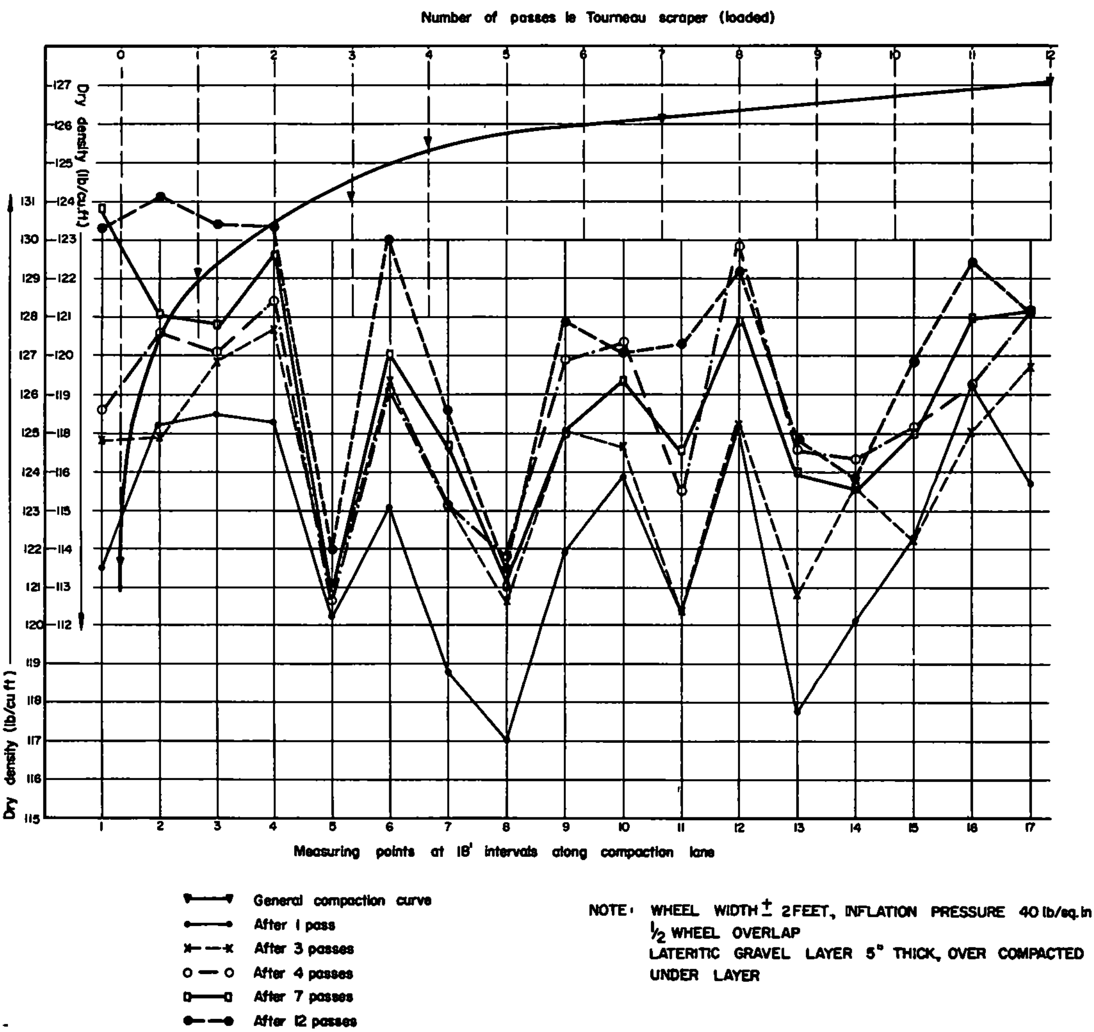

Figure 18. Compaction study with loaded le Tourneau scraper.

using the Hidrodensimeter along a compaction lane in nominally uniform material (a lateritic gravel subbase). After 12 passes there was still a range of density from 121.5 to 130 pcf at different points.

Density gradients

The Hidrodensimeter has indicated in compacted layers the presence of density gradients not previously suspected when using the sand-replacement method. As an example, Figure 19 shows results obtained on a 6-in subbase layer of natural course gravel of P. I. about 7. The trouble was found to be due to wrong moisture contents during compaction. It was, in fact, demonstrated on this job that "on-site" studies with this instrument can give valuable information on the applicability of laboratory compaction data to field conditions, particularly concerning the choice of optimum moisture content for compaction in the field.

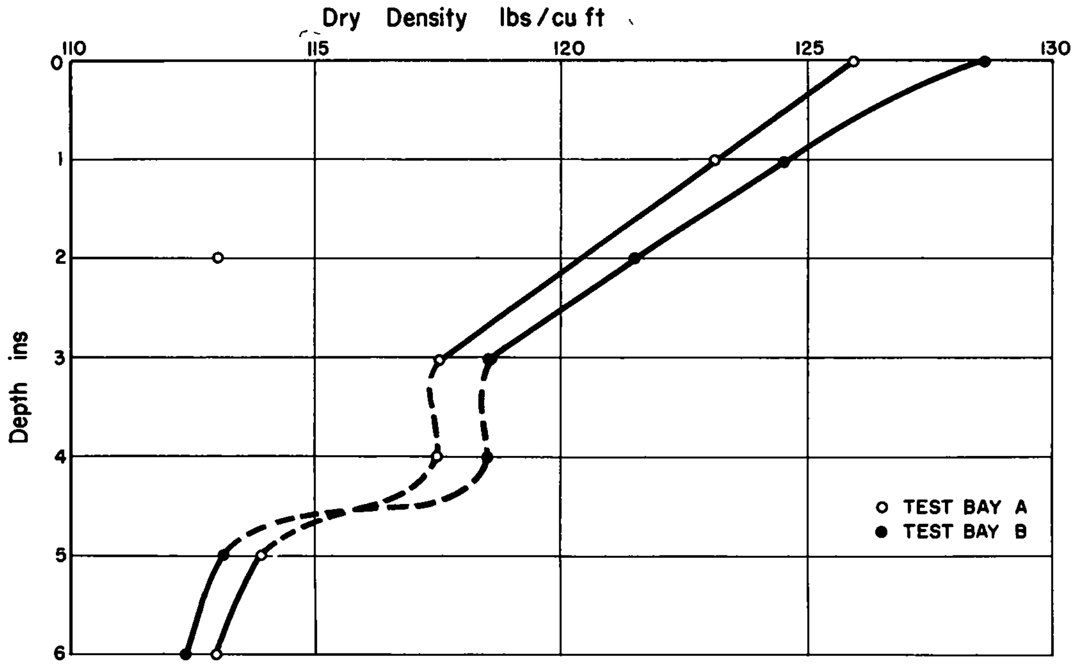

Figure 19. Relationship between dry density and depth on a length compacted with a 3.3-ton vibrating roller.

The whole approach to the probelm of specifying the density and control of density of compacted foundation layers needs some fresh thinking. A more thorough statistical approach that recognizes the inherent variations present would appear to be called for. The radioisotope method with its high speed of measurement provides the engineer with a new tool with which such an approach can become feasible. However, further discussion of this point is beyond the scope of the present paper.

Performance of Compaction Equipment

The instrument has been used on several jobs to assist road authorities with the problem of finding the best type or combination of compaction equipment to achieve required compaction in the most economic manner. As an example, Figures 20 and 21 show results from a study in the Orange Free State to find the optimum plant usage for compacting a cement-stabilized silty-sand layer, a type of material commonly used in that Province. Figure 20 shows density against number of passes of a 50-ton

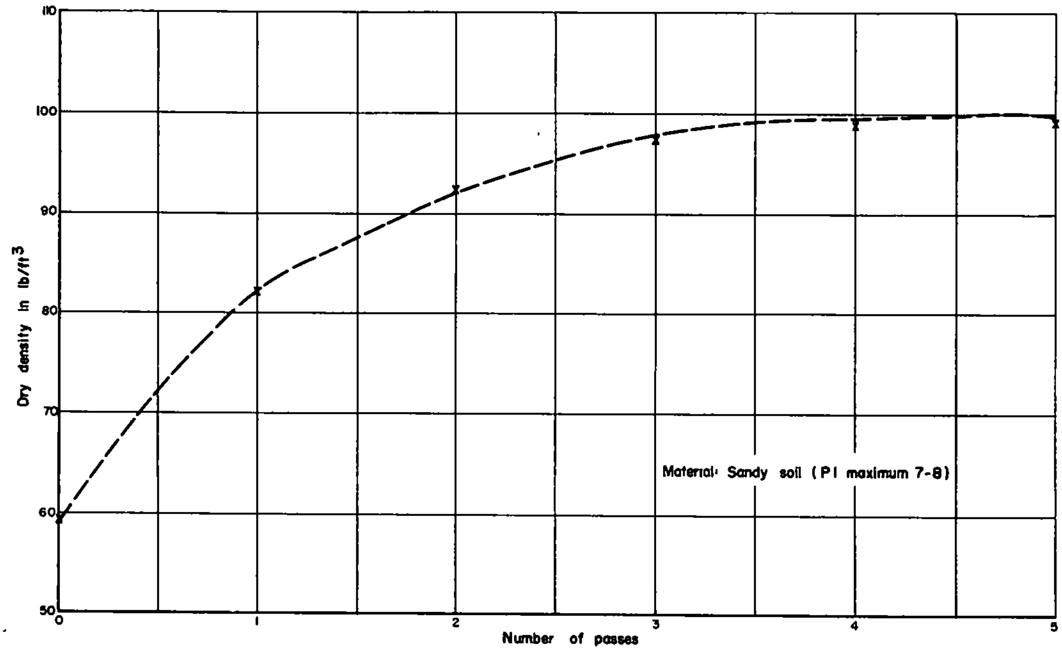

Figure 20. Dry density vs number of passes with 50-ton pneumatic roller, Heilbron-Petrus Steyn (O.F.S.).

pneumatic compactor. Several different compactors were available on this job and a study was made in two or three days to find the best combination of equipment and number of passes to achieve the required density. An example of the type of results obtained is given in Figure 21.

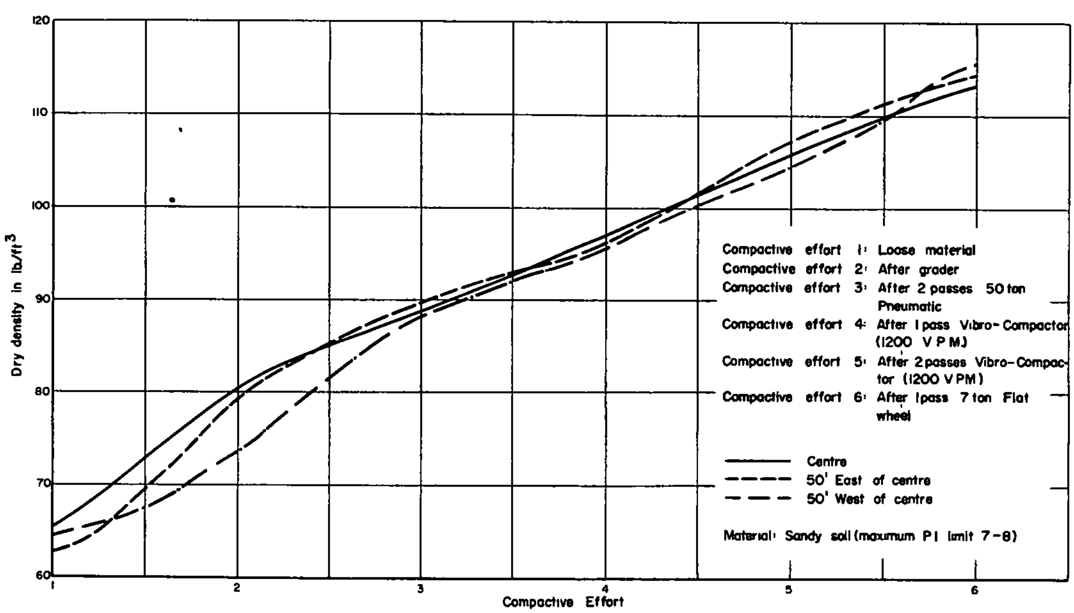

Figure 21. Compactive effort vs dry density, Heilbron-Petrus Steyn (O.F.S.).

Other Applications

Other applications of the instrument include density and moisture studies at depth (using the depth probe) on earth dams, large fills, and building foundations. In Natal, the depth probe was used successfully to establish density/depth profiles in river beds for investigations into scour depth following heavy floods. In these investigations the depth probe was specially waterproofed for working under water down to a 100-ft depth. In the National Institute for Road Research, the depth probe is also being used to follow long-term trends in the moisture profile under roads to certain selected sites where permanent aluminum access tubes (2 in. in diameter) have been sunk beneath the road surface. Agricultural authorities have also experimented with the moisture probes.

CONCLUSIONS

In conclusion, the more obvious advantages of the radioisotope method can be given:

1. The test is nondestructive, i.e., for all normal purposes using the surface probe.
2. Results for moisture content and density at a single point can be obtained in 2 to 3 minutes.
3. The method is accurate and easy to perform, minimizing the human error.
4. Apart from routine density control, its speed of working gives it a number of other important uses, particularly in studying compaction problems on site.
5. It provides a method of density control that is sometimes difficult with the sand-replacement method, e.g., on crushed stone bases and concretes.
6. It can be used under adverse weather conditions.

ACKNOWLEDGMENT

The work described has been carried out as part of the research program of the National Institute for Road Research and is published by permission of the South African Council for Scientific and Industrial Research. The authors wish to thank Mr. D. J. Smit for assisting with the statistical analysis referred to in the paper.

REFERENCES

1. Belcher, D. J., Cuykendall, T. R., and Sack, H. S., "The Measurement of Soil Moisture and Density by Neutron and Gamma-ray Scattering." U. S. Civil Aeronautics Admin. Tech. Development Report No. 127 (1950).
2. Gardner, Wilford, and Kirkham, "Determination of Soil Moisture by Neutron Scattering." Soil Science, 73: 391-401 (1952).
3. U. S. Army, Corps of Engineers, "Measurements of Soil Moisture and Density." (March 1955).
4. Stewart, G. L., and Taylor, S. A., "Field Experience with the Neutron Scattering Method of Measuring Soil Moisture." Utah State Agricultural College (1956).
5. Huet, J., "Application des Techniques Radioactives aux Problèmes Routiers." La Technique Routière, 2: No. 3 (1957).
6. Cameron, J. F., and Bourne, M. S., "A Gamma Scattering Soil Density Gauge for Sub-surface Measurements." Internat. Jour. of Applied Radiation and Isotopes, 3: 15-19 (1958).
7. Holmes, J. W., and Jenkinson, A. F., "Techniques for Using the Neutron Moisture Meter." Jour. of Agricultural Engineering Research, 4: No. 2 (1959).
8. Meisher, M. B., "Performing and Interpreting the Field Density Test." Civil Engineering, 29: 65 (1959).