Neutron and Gamma-Ray Methods for Measuring Moisture Content and Density to Control Field Compaction

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Several publications have described in detail the use of radioactive materials to determine the moisture content and density of soils in place. So far, most of the work has been confined to laboratory studies involving the development of instruments, and some small-scale experiments in the field. The results of these studies indicate that the method may develop into a useful tool for the practicing engineer.

One application of the nuclear method would be for control of compacted fills. The purpose of this investigation is to determine whether or not such an application is practical. It is planned to conduct tests with the nuclear equipment on various soils commonly used for fills and compare the results obtained by the nuclear method with those obtained through the use of the current field tests for moisture content and density. The material presented in this paper represents a small portion of the data it is planned to collect. The results of field tests upon a sandy loam only are given.

A brief description of the principles underlying the nuclear procedure is given to aid the reader in understanding the field procedures which are described in detail.

The effect of placing access tubes into the soil in different ways upon the results obtained by the nuclear method are included in the report, since these results served as the starting point for the development of a field procedure to check moisture content and density in a compacted fill. Four methods of placement were tried. Driving the access tubes yielded results which were the closest to the results obtained by the ordinary method of sampling.

The results of moisture and density tests at a site in Millbrae, California where several thousand yards of sandy loam are being placed each day are tabulated for comparison between the method now in use and the nuclear procedure.

It was found that the results obtained by the use of calibration curves developed on the job compared more favorably with the results obtained by the ordinary method of field sampling than did the results obtained by the use of calibration curves developed in the laboratory. When using calibration curves developed in the field the deviation between the nuclear procedure and the ordinary sampling method was slightly less than one percent water content in terms of dry weight and slightly less than three lb. per cu. ft. dry density. On the other hand the deviation between the two procedures was nearly 1½ percent water content in terms of dry weight and over 5 lb. per cu. ft. dry density when using laboratory calibration curves. A discussion of the personnel, equipment, and time required for each procedure is also included.

Finally, conclusions concerning the placement of access tubes for the nuclear procedure, and the use of the nuclear procedure for the control of compacted fills are set forth and discussed.

● THE determination of moisture content and density of soils by the use of radio-active materials has been adequately described in detail in a number of publications. Most of the work reported heretofore has concerned laboratory development of instruments and some small-scale experiments in the field. This work has indicated that the method has promise and may develop into a useful tool for the engineer wherever a knowledge

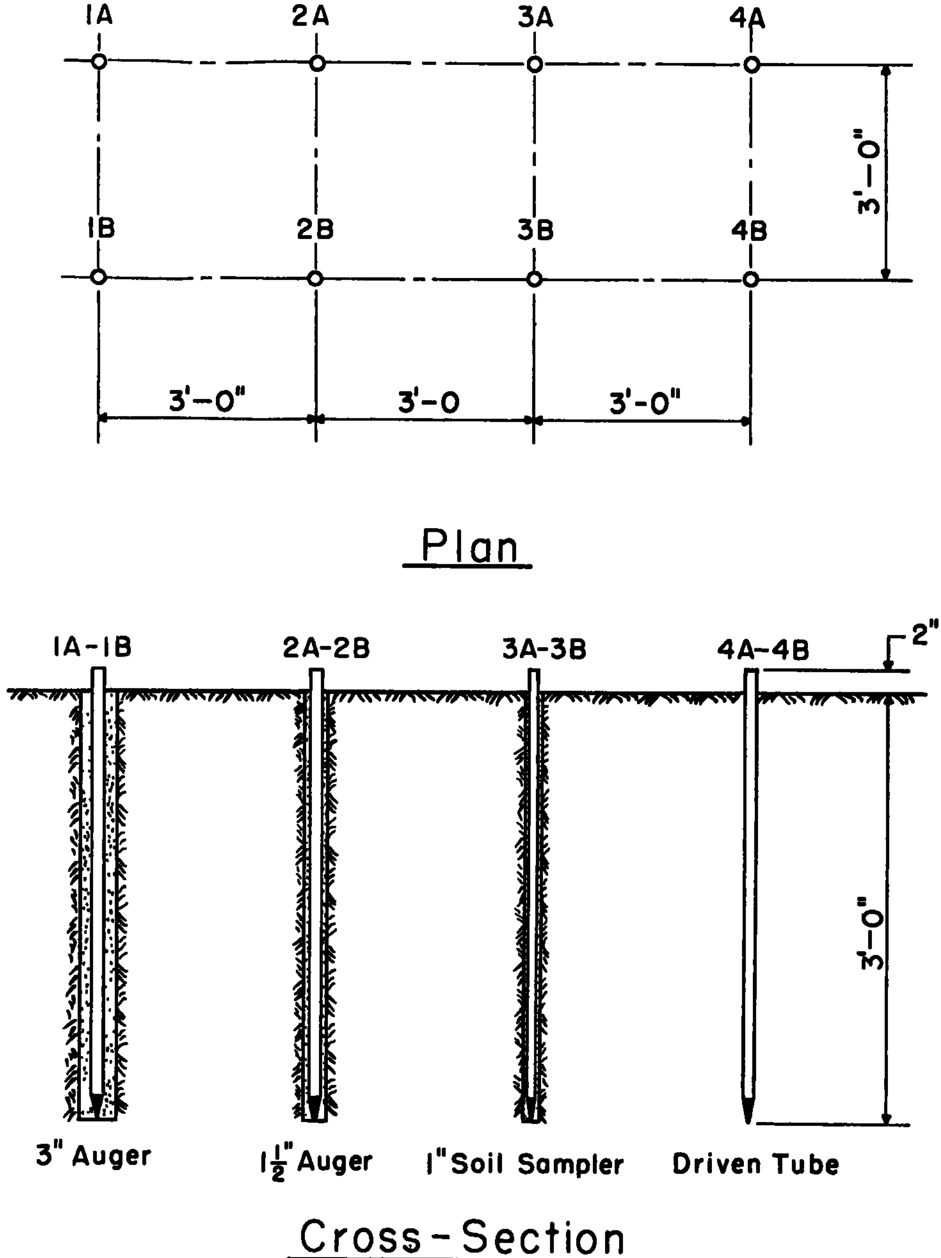

Figure 1. Arrangement and cross-section of access tubes in place.

of changing conditions in moisture content or density of soils is desired.

One application where the nuclear method might be used to advantage is in the control of density and moisture content of earth-fills during construction. The method requires no sampling, is more rapid than the procedures now in use, and requires no more personnel.

The purpose of the work reported here is to determine whether the nuclear method can be used to control soil compaction during construction. It is planned to conduct tests with the nuclear equipment on a variety of soils and compare the results with the results obtained by the use of current procedures for determining density and moisture content.

The material presented in this paper represents the results of field tests on only one type of soil, namely sandy loam.

In addition to the data on field compaction there are included some data as to how the placing of access tubes affects moisture and density determination by the nuclear procedure.

PHYSICAL BASES OF THE NUCLEAR METHOD

Readers interested in the theory of the nuclear method are referred to previously published work, especially to references 1,2,3,8, herein. A few fundamentals are, however, reviewed here because they bear on the interpretation of the procedures followed in this study and the results obtained.

TABLE 1

PLACEMENT OF ACCESS TUBES--
COMPARISON OF MOISTURE CONTENT
NUCLEAR METHOD VS. OVEN DRYING

Boring No	Difference in Moisture Content-Percent of Dry Weight			
	Maximum	Minimum	Average	Average for Method of Placement
1A	4 73	0.86	2 90	2.09
1B	3 08	0 07	1 29	
2A	1 37	0 03	0 69	1 68
2B	6 64	0 58	2 66	
3A	2.24	0.84	1.51	1.30
3B	2.08	0.27	1.09	
4A	1 48	0.09	0.54	0.57
4B	1 55	0 20	0 60	

Samples for oven-drying obtained with one-inch sampler

Water Content Determination

If a source of "fast" neutrons is placed in a soil, neutrons will scatter in a random manner from the source through the soil. These neutrons are particles of matter having a mass approximately equal to that of a hydrogen atom, high kinetic energy, and no change. As they move through the soil, they collide with atoms in the soil and rebound as objects do in an elastic collision. The neutrons lose some of their energy in these collisions. Since the hydrogen atom is the one atom in most soils with a mass nearly equal to that of the neutron, the neutrons which are scattered will lose more energy in collisions with hydrogen atoms (atomic wt. 1.008) than they will in collision with other atoms commonly found in soils (oxygen, atomic wt. 16,000). Some of the neutrons will return to the vicinity of the source after many collisions at a much lower energy level. If a counter capable of recording these "slow" neutrons is in close proximity the source of radiation, a count may be obtained which will reflect the quantity of hydrogen atoms in the soil. Fortunately, the principal source of hydrogen atoms in a soil is water, and therefore, such a count may be used to indicate the amount of water in the soil surrounding the source of "fast" neutrons.

Density Determination

If a source of gamma radiation is placed in a soil, gamma rays will be emitted from the source into the surrounding soil. These rays will be scattered by the electrons in the soil and lose energy in the process. Some of the scattered rays will return to a detector near the source and can be counted. The number of gamma rays counted will depend upon the average length of their path to the detector and their energy when they reach the detector. By properly shielding the gamma ray detector from the source of gamma radiation and placing the detector a specific distance from the source, an experimental curve may be drawn which will reflect the density of most common soils in terms of gamma rays counted during a time interval. For the common types of soil in which the engineer is interested, a low count of gamma rays will indicate high density; and a high count, low density. As the density of a soil increases, the electron density increases proportionally, and causes greater scattering and energy loss of the gamma rays. Thus the chance that gamma rays will be scattered back to the detector with great enough energy to be counted becomes smaller, and so the count rate drops.

TABLE 2

PLACEMENT OF ACCESS TUBES--
COMPARISON OF MOISTURE CONTENT,
NUCLEAR METHOD VS OVEN DRYING

Method of Placement	Percent of Nuclear Measurements Within Indicated Percent of Dry Weight Determined by Oven Drying		
	5	3	1½
1 (A & B)	100	70	40
2 (A & B)	90	80	60
3 (A & B)	100	100	70
4 (A & B)	100	100	90

APPARATUS USED IN STUDY

The principal items of equipment used in this investigation were two probes containing radioactive sources; an electronic instrument capable of recording the pulses from the detectors in the probes caused by radiation; an electric timer; and access tubes. In the field measurements, a gasoline generator provided current which was fed through a voltage regulator and a variable resistance in order to reproduce the 60-cycle, 115-volt current normally available in the laboratory. A continuous check upon the current cycle was obtained by means of a Frahm Frequency Meter.

TABLE 3

COMPARISON OF NUCLEAR MEASUREMENTS OBTAINED BY USE OF CALIBRATION CURVES DEVELOPED IN THE FIELD WITH MEASUREMENTS MADE BY EXTRACTING SAMPLES

	Deviation Between the Two Procedures			
	Water Content		Density	
	lb per cu ft	% of Dry Wt	Wet lb./cu ft.	Dry lb /cu ft
Maximum	2 70	3 20	6 30	7 80
Minimum	0 00	0 00	0 20	0 00
Average	1 08	0 97	3 18	2 80
	41% of measure-ments were within 0 5 lb	41% of measure-ments were within 0 5 %	50% of measure-ments were within 3 0 lb	64% of measure-ments were within 3.0 lb

Moisture Probe

This probe, which was similar to that used by the Civil Aeronautics, Administration, consisted of a thin-walled brass cylinder with an outside diameter of approximately 1 inch and a length of 7 inches. The neutron source, which in this study was a $Po^{210}Be$ (half-life 140 days), was held in a brass cap fastened to the end of the probe. A short lead plug separated the source from the Geiger-Mueller tube which was enclosed in a thin silver foil 3 mils thick. "Slow" neutrons returning to the probe react with the silver foil to form isotopes of silver. These isotopes decay very rapidly and emit, as one of the products of this decay, gamma rays which are counted by the Geiger tube. Details of this probe are shown in References 6 and 7.

Density Probe

This probe is the same as that used by the Civil Aeronautics Administration. The density probe is about 6 inches longer than the Moisture Probe although it is approximately the same diameter. The source, which was Co^{60} (half-life 5.3 years), is held in an aluminum probe. A much greater amount of lead is needed to shield the Geiger tube detector from gamma radiation directly from the source. This accounts for the greater over-all length of the probe. Details of this probe are shown in References 6 and 7.

Access Tubes

The access tubes were fabricated from aluminum. The inside diameter of the tube was approximately one inch and the wall of the tube was $^1/_{32}$ in. thick.

Auxiliary Equipment

The recording unit used with the probes was a Model 2000 manufactured by the Berkley Scientific Company. This unit electronically records counts from 0 to 999 and has a mechanical counter which records from 1,000 to 100,000,000. The unit has a regulated high-voltage supply ranging from 0 to 2,500 volts, read on a scale with 50 volt increments.

A timer was connected to the recording unit so that at the end of a preset time, (200 seconds in this study) the counting was stopped automatically. A photograph of the scaler and timer are shown in Reference 6.

A spherical container of aluminum in which was inserted a lead sphere surrounded by paraffine was used to house the moisture probe during transit to and from the job. The container also served as a standard for checking the equipment in the field.

TABLE 4

COMPARISON OF NUCLEAR MEASUREMENTS OBTAINED BY USE OF CALIBRATION CURVES DEVELOPED IN THE LABORATORY WITH MEASUREMENTS MADE BY EXTRACTING SAMPLES

	Deviation Between the Two Procedures			
	Water Content		Density	
	lb per cu. ft	% of Dry Wt	Wet lb./cu ft	Dry lb /cu. ft.
Maximum	3 50	2 70	13 00	12 70
Minimum	0 00	0 00	0 30	0 20
Average	±1 44	±1 09	± 6 75	± 5 63
	10% of measure-ments were within 0 5 lb	25% of measure ments were within 0 5 %	20% of measure-ments were within 3 0 lb	28% of measure-ments were within 3.0 lb

FIELD PROCEDURES USED IN STUDY

Description of Test Sites

Prior to initiating the tests on control of compaction in the field, some exploratory

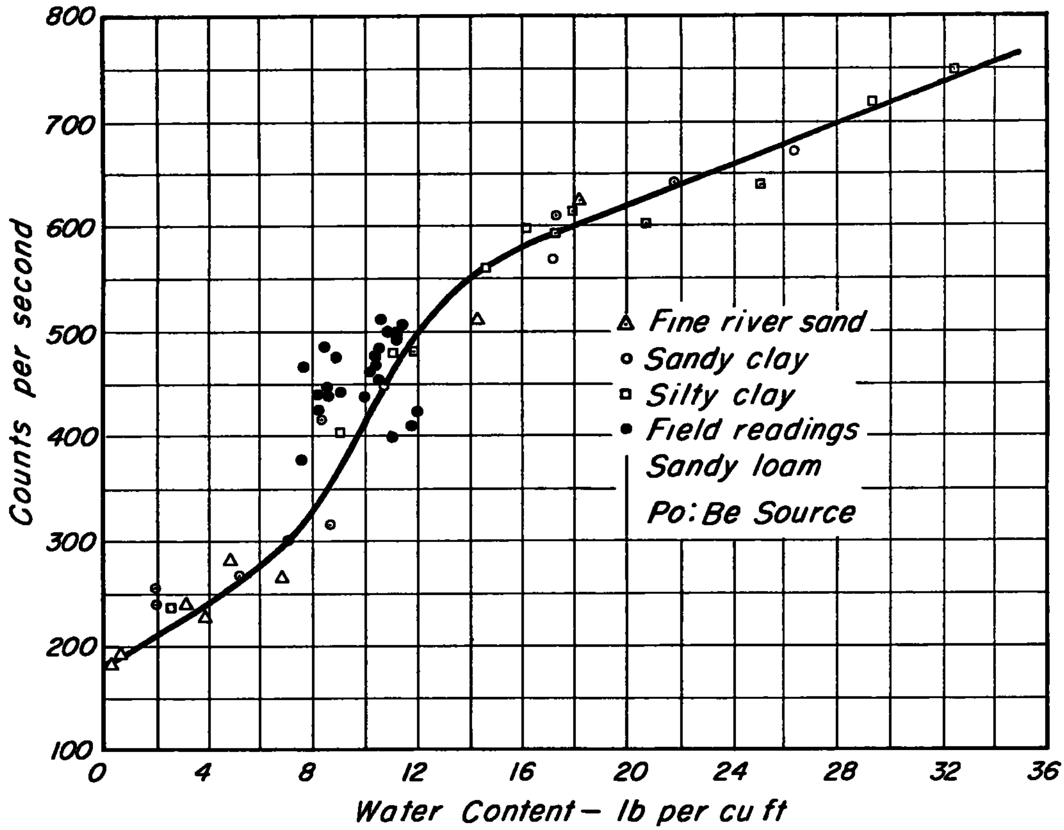

Figure 2. Water content, results of readings in the field superimposed on calibration chart developed in the laboratory.

tests to determine the effect of placement of access tubes on the results obtained by the nuclear procedure were conducted. These tests were carried out at the Engineering Field Station of the University of California in Richmond, California, and in Orinda, California, at the intersection of State Highway 24 and the San Pablo-Moraga Highway. At the Engineering Field Station, the tests were conducted at two different locations, while in Orinda, only one location was utilized. At Richmond, the upper 1½ ft. of soil consisted of loam while the underlying stratum was sandy clay. At Orinda the material consisted of a mixture of sandy clay and black shale.

For the control of field compaction a sandy loam fill being constructed in connection with the development of the Mills Estate near Millbrae, California was utilized.

Placement of Access Tubes.

For the exploratory tests at Richmond and Orinda four methods of placing access tubes were investigated. These methods were as follows: (1) A hole was made with a 3-in. soil auger, the soil removed being placed in a covered pan. When the hole had been drilled to a depth of 3 ft. the soil was returned to the hole, and rodded with the access tube to avoid large voids. The access tube was then driven into the center of the hole. This method of placement is referred to as 1A and 1B in Tables 1 and 2. (2) The same as in Case 1, except that a 1½-in. soil auger was used to bore the hole. This method of placement is referred to as 2A and 2B in Tables 1 and 2. (3) The access tube was driven into a hole made by a 1-in. soil sampler after the soil removed from the hole by the sample had been replaced loosely. This method of placement is referred to as 3A and 3B in Tables 1 and 2. (4) The access tube was driven directly into the ground. This method of placement is referred to as 4A and 4B, in Tables 1 and 2.

A sketch of the access tubes in place is shown in Figure 1. It was felt that this arrangement of access tubes would keep the test holes close enough so that similar conditions of moisture and density could be expected, and yet far enough apart so that the readings at a particular hole would not be influenced by the close proximity of the other access tubes.

In the tests at Millbrae the access tubes were driven directly into the ground, since, as will be seen later in this report, this method proved to give the best results.

Depths at Which Nuclear Measurements Were Made

In the case of the exploratory tests at Orinda and Richmond the access tubes were driven approximately 3 ft. into the soil (see Fig. 1) and readings taken at a depth of 2 ft. from the surface.

In the tests at Millbrae the access tubes were driven 14 in. into the soil and readings taken 12 in. below the surface of the ground. Since the principal objective at the Millbrae site was to control compaction it was desirable to obtain a reading as close to the surface of the soil as possible since the contractor was placing the fill in layers approximately 8 in. thick.

Procurement of Soil Samples for Moisture and Density Determination for Comparison with Nuclear Method

At Orinda and Richmond, soil samples for moisture content determination by oven drying were obtained at a depth of 2 ft. by means of a 1-in. soil sampler. Except for the access tubes which were driven directly into the ground these samples were taken in the identical location as the tubes. In the case of the driven tubes the samples were taken about a foot away. No density determinations by sampling were made at these two sites.

At Millbrae, AASHO Test Procedure T 147-49 utilizing sand was used to determine the density and moisture content of the fill. The test holes were about 6 in. in diameter

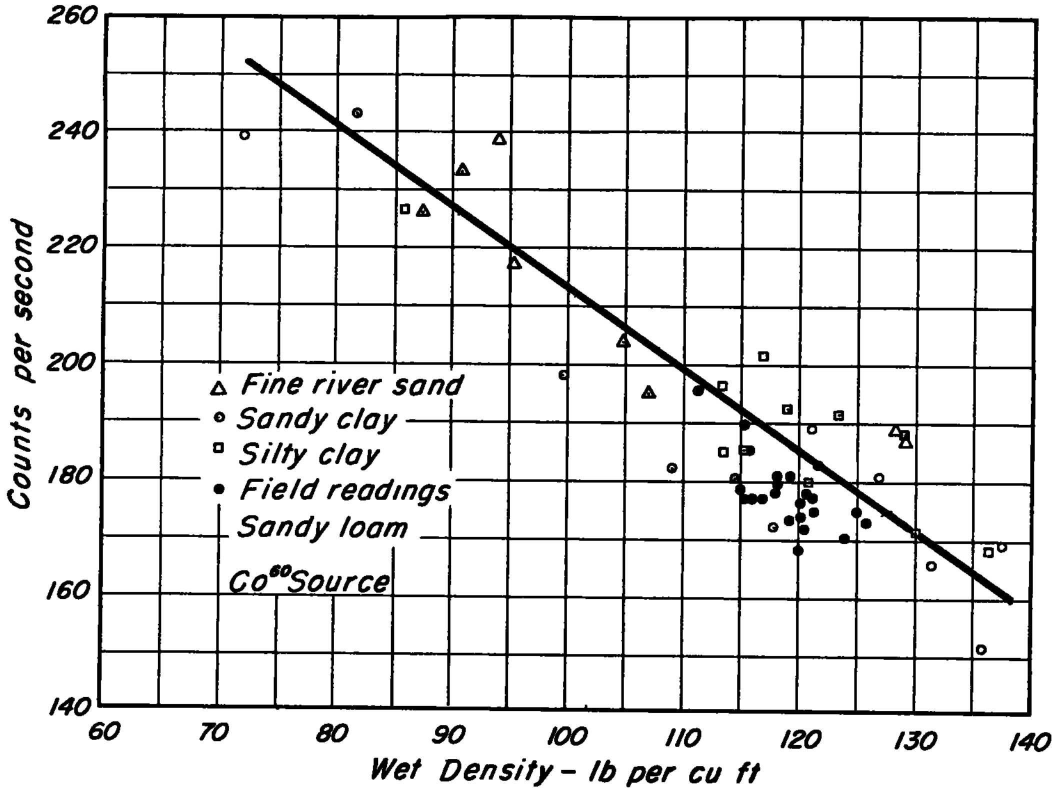

Figure 3. Wet density, results of readings in the field superimposed on calibration chart developed in the laboratory.

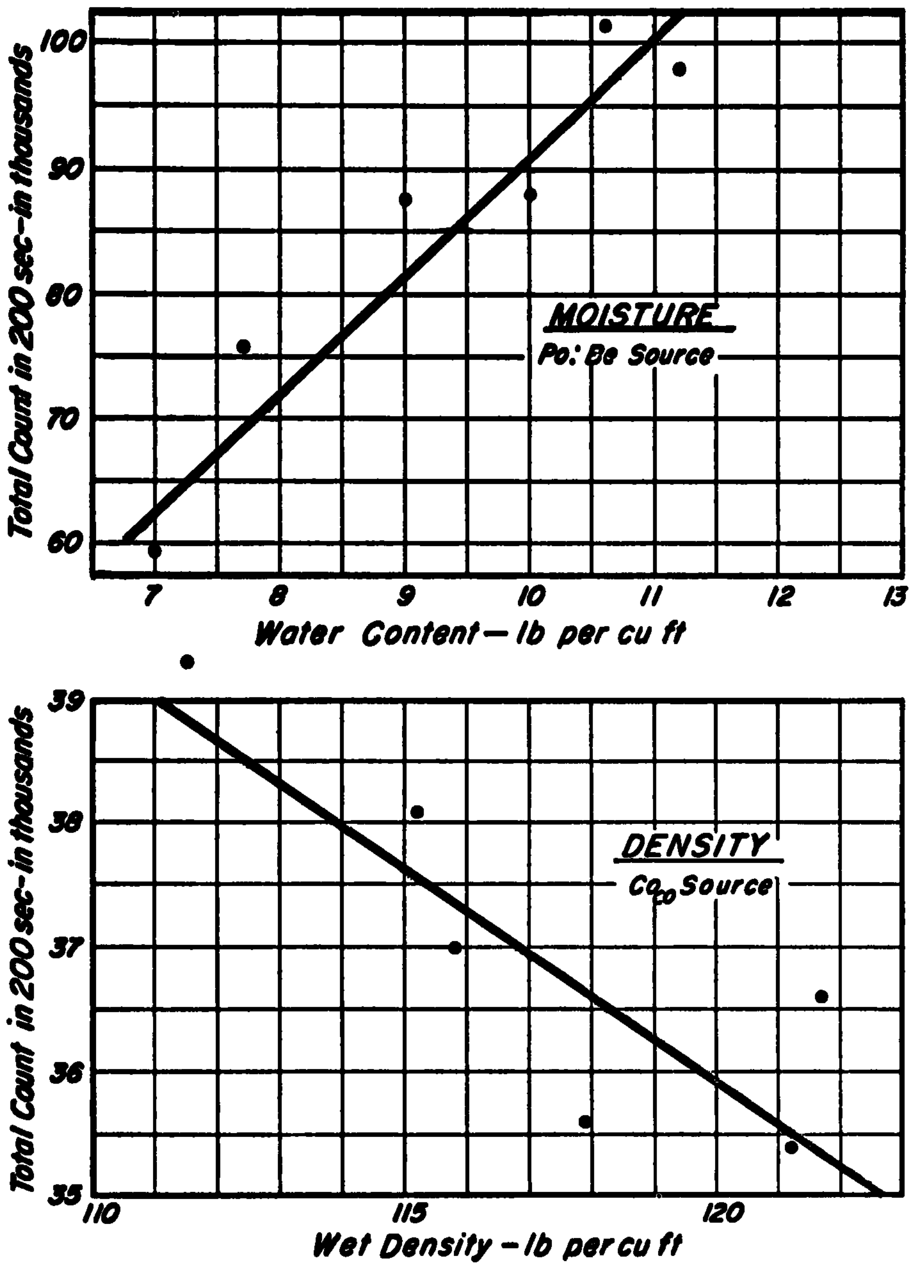

Figure 4. Mills estate, field calibration curves, nuclear procedure.

and the depth likewise was about 6 in. below the prepared surface. The prepared surface was about 2 in. below the surface of the ground. This was done to eliminate the loose material near the surface from being included in the test.

Procedure for Use of Nuclear Apparatus in the Field

Upon arrival at a test location, the gasoline generator was started and the recording apparatus set up near the test holes. A period of about 20 minutes was allowed for the tubes in the scaler to warm up. Then the moisture probe was attached by means of a cable to the recording unit and the probe lowered into the access tubes to the desired depth below the surface of the ground. A period of five minutes was allowed for the moisture probe to come to equilibrium at the level a reading was desired and then the count in a period of 200 seconds was recorded. Generally, two and no more than three counting periods were sufficient to obtain readings within one percent of each other. The average of the counts was used as the final count at a particular access tube, for the determination of water content.

After the moisture determinations were completed, the density probe was attached to the scaler and the probe again placed in the access tubes. A 200-second period was also used for the density determination and the average of two or three consecutive readings within one percent of each other taken as the density count. No time is necessary for the density probe to come to equilibrium and counting can be started at once.

In order to avoid waiting several minutes for the moisture probe to come into equilibrium at each access tube, the following procedure was used. When the moisture content determination at one access tube was completed, the probe was immediately taken to the next access tube and allowed to remain in the tube while the density measurements were being made at the first tube.

Before beginning each day's field tests and at the end of the day, the moisture probe was taken into the laboratory and lowered into an access tube placed in the center of a barrel of water. This access tube was identical with those used in the field tests. The counts obtained in the barrel were used to calculate a correction factor which could be applied to all the readings for moisture content obtained in the field on that day. This factor includes the decay of the source and any changes in the sensitivity of the electronic equipment. Similarly, a correction factor for density readings was determined. These correction factors, in effect, transposed the readings for Moisture Content and Density back to a reference date. It was necessary to do this since the calibration curves on Figures 2 and 3 are also based on the same reference date. The count obtained in the sphere was used to establish a ratio in count between the water and the sphere. In the field, every so often counts were obtained in the sphere to ascertain whether the equipment was in proper working condition. If the counts in the sphere were, at any time, different materially from the initial reading in the laboratory, this would indicate that the equipment was not performing properly.

Determination of Moisture Content and Density by the Nuclear Procedure

For the tests at Richmond and Orinda the moisture content (in pounds per cubic foot of soil) and wet densities (in pounds per cubic foot) were established by the use of calibration charts developed previously in the laboratory (Figures 2 and 3).

For the tests at Millbrae field calibration charts for moisture and density shown on Figure 4 were developed. On the first day of the tests the counts corresponding to the moisture contents and densities determined by the ordinary sampling procedure were plotted against the counts obtained by the nuclear procedure and curves drawn. Thereafter these field calibration charts were used to determine the moisture contents and densities at Millbrae.

ANALYSIS OF RESULTS

Comparison of Water Content Measurements by Various Methods of Placing Access Tubes

The effect of various methods of placing access tubes upon water content determinations by the nuclear procedure can be shown by comparing the nuclear measurements with the water contents found by oven drying soil samples. In Table 1 there are tabulated the differences in water content between the nuclear and oven-drying procedures for each method of placement. The data indicate that driving the access tubes directly into the ground (Boring 4A, 4B) yields the least difference between the two procedures (in terms of percent of dry weight), while the use of a 3-in. soil auger (Boring 1A, 1B) yields the greatest difference. The other two methods fall in between these two extremes. It will also be noted that placing the access tube into the hole made by a 1-in. soil sampler yields results that are slightly closer to oven drying moisture contents than placing the tube in a hole made by a $1\frac{1}{2}$-in. soil auger.

Another way of indicating the effect of access tube placement on nuclear moisture measurements is to indicate for each method of placement the proportion of the nuclear measurements which differ no more than specified amounts (5, 3, 1½ percent) of the water contents determined by sampling. This comparison is shown in Table 2. It will be noted that almost all of the nuclear measurements, regardless of the method of placement differed not more than 5 percent (dry weight) with the measurements made by oven drying soil samples. On the other hand, only 40 percent of the measurements made using the 3-in. auger (1A, 1B) were within 1½ percent water content determined by oven drying, while for the driven tubes (4A, 4B) 90 percent of the measurements were within 1½ percent.

Effect Upon Wet Density of Method of Placing Access Tubes

In the exploratory tests at Richmond and Orinda densities were not measured by sampling, nevertheless a few observations concerning density measurements by the nuclear procedure are worthy of mention. The following was observed: (1) the wet densities in the 3-in. auger hole were lower than for any other method of placement; (2) the wet densities in the 1½-in. auger hole were slightly less on the average than those for the driven tube and for the tube placed in the hole bored by the 1-inch soil sampler; and (3) the wet densities obtained in the access tubes driven directly into the ground were not significantly different from the wet densities in the access tubes placed in holes bored by the 1-inch soil sampler.

Results of Tests on Field Compaction

A total of 26 measurements of moisture and density were made at the Millbrae site. These measurements are tabulated in Table 4A. The nuclear moistures and densities obtained by the use of calibration curves developed in the field (Figure 4) are compared with the measurements made by the sand method (AASHO Test Method T147-49) in Table 3. The data in this table indicate the amount of deviation between the two methods. The average difference for moisture is approximately one percent (in terms of dry weight) and for dry density it is approximately three lb. pcf.

It has been the thinking that calibration charts developed in the laboratory could be used for field measurements provided the same types of radioactive sources and access tubes were used for the field measurements. In Table 4 the nuclear moistures and densities obtained by the use of calibration curves previously developed in the laboratory (Figs. 2 and 3) are compared with the moisture and densities obtained by the ordinary procedure of sampling.

It will be noted that the difference in moisture content between the two procedures is a little greater than in the case where a field calibration chart was used; for density the average differences between the two procedures is considerably greater, indicating that for this particular soil, greater accuracy was obtained by the use of calibration curves developed in the field than in the laboratory. Graphically, these differences are shown by plotting on the laboratory calibration charts (Figs. 2 and 3), for a particular test position, the counts obtained in the field by the nuclear procedure against the corresponding moisture and density obtained by the usual sampling procedure. An examination of Figures 2 and 3 indicates that, for a particular moisture content the count in the field is higher than the count shown by the laboratory calibration chart. This means that in most cases, if the laboratory chart were used for the field readings, the moisture contents determined by the nuclear procedure would be higher than the moisture contents determined by sampling. On the other hand, for a particular wet density the count is lower than shown by the laboratory calibration chart. If the laboratory chart were used for the field readings most of the wet densities determined by the nuclear procedure would be higher than the corresponding densities determined.

Manpower and Time Required for Field Compaction Tests

It was found that on the average 20 minutes were required to make one moisture and one density determination by the nuclear procedure. In an eight-hour work day about 16 moisture and density measurements can be made with the nuclear equipment. A certain amount of time is required for moving from one test position to another, driving access tubes, and checking the performance of the equipment by obtaining counts in the sphere.

With the nuclear equipment the construction work is always under observation of the inspector. With the ordinary procedure of sampling the inspector must do his work in a field laboratory usually located away from the actual construction operations.

Discussion

It is believed that a number of factors entered into the observed differences between the results obtained with the nuclear procedure and those obtained by the ordinary method. One such factor is related to the volumes of soil measured by the two procedures. The nuclear procedure measures moisture content and density in a soil by a process of integration over the volume of a bulb of soil with the radioactive source as the centroid of the bulb. The effective radius of the bulb varies but is generally from 15 to 18 inches and decreases as moisture content and density increase. In contrast to this method, the sampling procedure uses the volume of soil taken from a hole 6 inches in diameter and approximately 6 inches deep. The moisture content determination is made by using a portion of this soil (generally from 100 to 150 grams) as a representative sample.

In the studies conducted by the Civil Aeronautics Administration, the moisture contents and densities were plotted against count-ratios rather than total counts or counts per second. The count-ratio is the ratio of the count in the soil to the count in a so-called standard material such as water (for moisture) and concrete (for density). The advantage of the count-ratio is that any variation in counts due to decay of the source and to performance of scaler and probe are automatically taken care of. On the other hand the count-ratio requires that every time a reading is made in the soil, a reading must also be made in the standard material. This increases the time necessary to make an individual measurement. It has been observed that the counts in the standard materials vary to some extent even in an 8-hour period. It was therefore thought to be pertinent to study the magnitude of these variations in order to ascertain whether there would be a large advantage gained in obtaining counts in the standard each time a measurement in the soil was made.

Readings were made in the field and in the laboratory over periods of several hours to observe the magnitude of these variations. The standard used for this purpose was the sphere filled with paraffine. With the equipment and sources used in this study the count in the standard remained relatively steady (within 1.5 percent) in an 8-hour work day. However, it is advisable to keep the power source and the electronic counter continously in operation in order to minimize the variations in the count in the standards. Therefore, the best procedure to follow would be to take the readings in the standard in the field immediately before starting to work and on several occasions during the working day. The counter and power generator should remain in operation at all times, even during the lunch hour.

The final factor which may have entered into the observed variations between the two methods is the "dead time" of the Geiger tube used in the nuclear apparatus. It is known that in the particular model of tube used in these studies there is a "dead time" of 100 micro-seconds. This means that if two gamma rays arrive at the tube within 100 micro-seconds of each other the tube will only count one of them. This occurrence leads to loss of counts and introduces errors into the results in a random manner. However, for practical purposes, if the count rate is high, the error may be considered negligible in comparison to the other factors which influence the results.

It was found in this study that the results obtained using a calibration curve developed in the field for the particular soil investigated were superior to those obtained using a previously developed laboratory curve. From a practical standpoint, the results obtained using the laboratory curve were not close enough to the results obtained by the ordinary method to allow accurate control of filling operations. Up to now it appears that in using the nuclear method for compaction control it is better to rely on calibration curves developed in the field than on those developed in the laboratory.

A few final observations may be made regarding the field equipment used in this study. Since this investigation was in the nature of a pilot study, no attempt was made to construct equipment which would serve for a long period of time in the field. Laboratory equipment was merely adapted to field conditions. The equipment proved to be cumbersome and unwieldy at times, but stood up remarkably well under the rough conditions encountered in the field. However, it was the concensus of those engaged in this study that in applying the nuclear procedure to the control of a compacted fill over a long period of time, modifications would have to be made in the equipment and its arrangement. The scaler, timer, and voltage stabilizer, as well as the frequency meter should be contained in one unit which is provided with a dust cover. This unit should be mounted on shock absorbers. It would also be desirable to replace the gasoline generator with a vibrator pack similar to that used with the Army Signal Corps ANGRC 9 radio. Such changes in the apparatus would definitely improve the speed and ease, and reduce the cost, of taking nuclear readings under field conditions.

CONCLUSIONS

Placement of Access Tubes

1. In this investigation driving the access tube directly into the ground yielded results which were the closest to the results obtained by sampling.
2. The results obtained by placing the access tubes in a 1-in. diameter hole were very similar to the results obtained by driving the tubes.

Field Compaction

The following conclusions are related only to the soil so far investigated:

1. The nuclear procedure can be used for the control of field compaction provided the depth at which measurements are made is not less than 8 in.
2. Calibration curves developed on the job yielded results in closer agreement with the moisture and density measurements by sampling than did the use of calibration curves developed in the laboratory. This was particularly true for density.
3. The moisture contents by the nuclear procedure were in fairly close agreement with the sampling procedure; the average of all measurements by the two procedures being within one percent (dry weight) of each other.
4. The densities obtained by the nuclear procedure did not compare as favorably with the densities by sampling as did the moisture contents; the average of all measurements by the two procedures (using field calibration charts for the nuclear procedure) being about three lb. apart.

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