Field Measurements of Soil Moisture and Density with Radioactive Materials

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THE neutron-and-gamma-ray method for measurement of moisture and density was originally developed by D. J. Belcher, T. R. Cuykendall, and H. S. Sack of Cornell University. This paper deals with the application of this method for determining the moisture conditions under the paved areas at the San Francisco Airport. The measurement of moisture is based on the principle that when fast neutrons emitted from a radioactive source collide with hydrogen atoms they lose considerable energy and become "slow neutrons." These slow neutrons return to the vicinity of the source, are transformed by means of a silver foil on the probe to beta and gamma rays, which are in turn counted by a Geiger counter. Thus the number of slow neutrons is a measure of the number of hydrogen atoms present in the vicinity of the source. For density measurements, a source emitting gamma rays is used. When gamma rays are emitted, they are scattered by colliding with atoms in their path, the scattering being greater the higher the density of the surrounding medium. The greater the scattering the fewer rays return to the counter, hence, density is inversely proportional to the number of counts.

A total of nine 9-ft.-long metal tubes spaced approximately 40 ft. apart were placed across one of the runways at the airport. Probes containing a radioactive source and counter were lowered into the tubes and moisture and density measurements made at intervals of 1 ft. From these measurements a complete picture of the moisture condition under the pavement was developed.

This study shows that the longitudinal subdrains appear to be effective in lowering the moisture contents underneath the pavement. The paper shows that the neutron-and-gamma-ray method is relatively simple, rapid, inexpensive, and can be adapted to every day engineering use.

IN recent years the management of the San Francisco Airport has been concerned about the possibility of subsurface moisture endangering the stability of some paved areas of the airport. This has led to a program of investigation aimed at studying present moisture conditions, changes that may take place with time, and the reasons for the changes.

So far, the investigation has dealt only with the study of present moisture conditions. These conditions have been determined by the neutron and gamma-ray scattering method. The study has thus served to indicate the practicability of this method for field use.

APPARATUS

The determination of moisture contents and densities by the neutron and gamma-ray scattering method developed by Belcher, Cuykendall, and Sack, of Cornell University, has been described elsewhere.[1]

The basic principles underlying the method are somewhat as follows: When fast neutrons emitted from a source collide with hydrogen atoms they lose considerable energy and become "slow neutrons." Slow neutrons returning to the vicinity of the source are transformed by means of a silver foil to beta and gamma rays;

[1] Belcher, D. J., T. R. Cuykendall and H. S. Sack, "The Measurement of Soil Moisture and Density by Neutron and Gamma-Ray Scattering," *Technical Development Report No. 127*, U. S. Civil Aeronautics Administration, Government Printing Office, Washington, D. C.

which are counted by a Geiger counter and recorded automatically on a device known as a scaler. Thus the number of slow neutrons is a measure of the number of hydrogen atoms present in the vicinity of the source. These hydrogen atoms are measured whether they are bound chemically or not, hence moisture

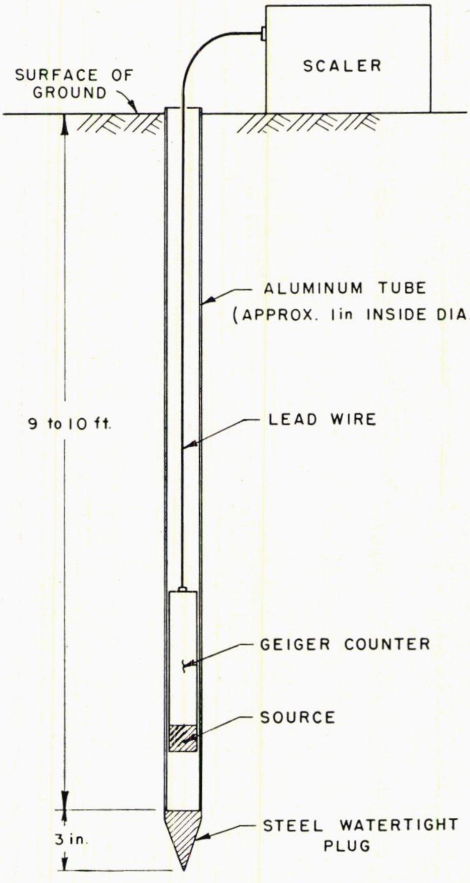

Figure 1. Sketch of moisture-and-density-measuring device.

is measured whether it is in the liquid, vapor, or solid state.

The procedure for measuring moisture content consists of lowering a probe containing a fast neutron source (polonium-beryllium) and a detector (Geiger counter) for counting slow neutrons into a small thin wall metal tube (1-in. dia.) driven into the soil. The probe it connected to a scaler which registers the couns in a specified period of time. The apparatus used in this project is shown in Figures 1 and 2.

The device for measuring density is very similar to the one used for the determination of moisture content. For density determinations a gamma-ray source is used (cobalt-60 in our case). When gamma rays are emitted from the source, they are scattered by collision with atoms in their path, the scattering being greater the higher the density of the

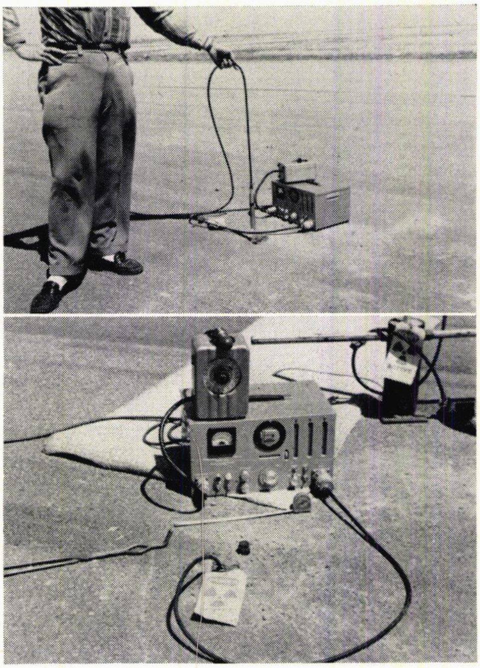

Figure 2. Equipment for moisture and density measurements.

surrounding medium. The greater the scattering the fewer rays return to the counter, hence density is inversely proportional to the number of counts. A probe is lowered into the metal tube, and the gamma rays which are scattered back to the vicinity of the source are counted on a Geiger counter and recorded on a scaler.

In order to correlate counts with the weight of water per cubic foot of soil, the apparatus used in this study was calibrated in the laboratory in the following manner: A 55-gallon drum was filled with six 6-in. layers of fine sand ranging from 1 to 30 percent moisture content, determined by oven drying. These layers were separated from each other by sheets of heavy building paper. A tube of the type used in field measurements was driven into the center of the drum, the probe lowered into the tube and the count recorded for each of the layers. The counts were then plotted against the known moisture contents and a calibration curve obtained.

The procedure for correlating counts with density was similar. By use of the 55-gallon drum and the density probe, a correlation with wet density was first obtained. Another drum was filled loosely with a known weight and volume of dry sand. A tube was driven into the center of this drum, a probe lowered, and the count recorded. The drum was then vibrated, increasing the density and the probe again lowered. This procedure was repeated several times. In this way the count was correlated with dry density. Having these two correlations, it was possible to determine the dry density from the measurements in the field.

TEST PROGRAM

San Francisco Airport is located on the western shore of San Francisco Bay about 7 mi. by existing highway south of the city limits, which is about 12 mi. by highway from the business center of the city. Most of the airport landing field was reclaimed from San Francisco Bay and rests on a soft, compressible clay foundation popularly known as bay mud. Prior to construction of the airport the surface of the mud varied from 0 to −5 ft. (airport datum) in the portions of the airport area that were reclaimed from the bay. The depth of the mud at these areas varies from about 30 to 80 ft. The mud is underlain by a firm residual clay and rock. The bulk of the airport fill is constructed of disintegrated sandstone obtained from the hills in the vicinity. The sandstone was dumped into the bay by means of trucks to an elevation of approximately 6 to 7 ft. From this level the material was spread in thin layers and compacted by means of sheepsfoot rollers, a 100-ton pneumatic-tired roller, and grid rollers. The surface is at an average elevation of about +11.5 ft. High tide at the airport averages 6.2 ft. Longitudinal subdrains were placed under the runways and taxiways, as shown in Figure 4, in order to lower the ground-water table in these areas. One purpose of this study was to determine the effectiveness of these drains.

Prior investigations indicated that the initial placing of the fill material could cause lateral displacement of the upper and softest layer of the bay mud. The placing of the fill was so controlled as to displace the upper 1 to 2 ft. of the soft mud and thus bring the contact surface between the fill material and the bay mud to an elevation of 1 to 2 ft. below the original surface of the bay mud. Later subsidence by compression of the underlying mud has lowered the contact plane to 2 to 4 ft. below the original mud surface.

In this study, nine 9-ft.-long metal tubes were placed across the north end of the north-south runway. A schematic diagram of the fill, the underlying bay mud, and the moisture tubes is shown on Figure 3. Four of the metal tubes were in the shoulder areas and five in the pavement. The locations of the tubes are shown in more detail in Figure 4.

Holes for the tubes were bored by driving a 1-in. sampling tube into the soil. Samples were taken at 1-ft. intervals, and moisture contents were determined by the ordinary method of oven drying. The holes were then loosely filled with the soil remaining from the sampling tube, and a 1-in. (inside diameter) aluminum tube with a steel point sealing it at the bottom was driven into the filled hole. This procecure gave good contact between the soil and the tube. The probes containing the radioactive source and detector were then lowered into the pipe and moisture and density measurements made at intervals of one foot.

RESULTS OF TESTS

It was stated earlier that when borings were made to install the moisture tubes, samples were obtained at 1-ft. intervals by means of a 1-in. soil sampler. These samples were taken into the laboratory and the moisture contents determined by oven drying. These moisture contents were then compared with the values obtained by the neutron method. In general, it was found that for the top 3 ft., the neutron method yielded consistently higher results, by about 25 percent; at greater depth the variation was not more than 10 percent and the neutron method did not always yield the higher value. The shapes of the moisture versus depth curves were very similar.

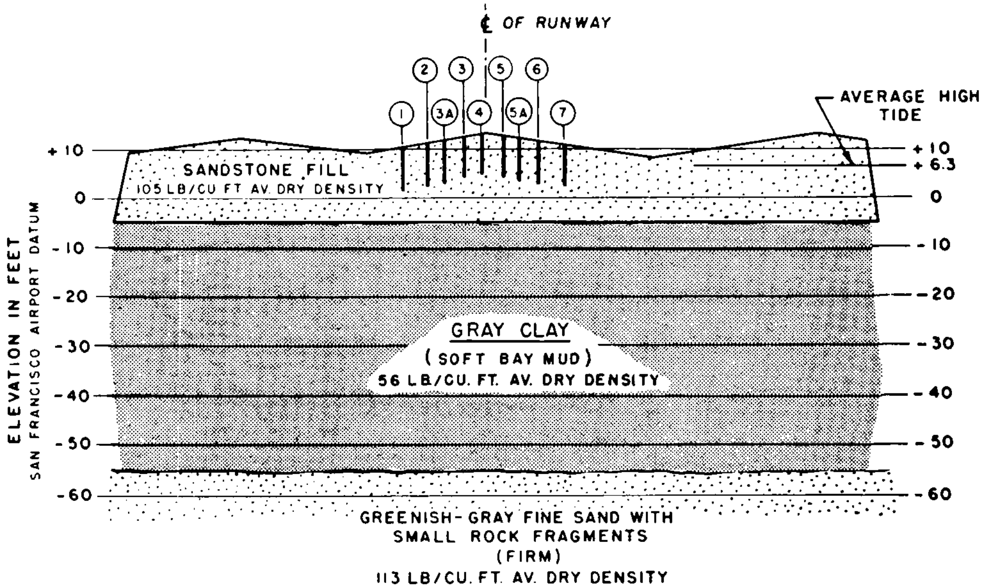

Figure 3. San Francisco Airport: Sectional view of fill.

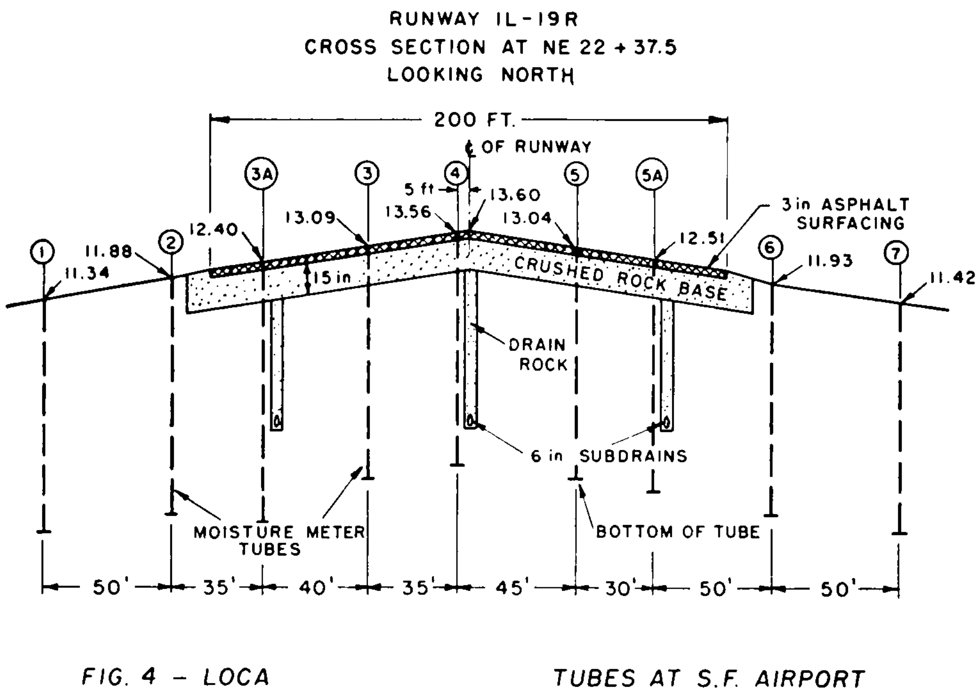

Figure 4. Location of moisture tubes at San Francisco Airport.

Variation in moisture content with depth at Tube 1, determined by the neutron method, is shown on Figure 5. Tube 1 is located in the shoulder area. The dry densities determined by the gamma-ray procedure are also shown on this chart. For any particular elevation the plotted value of density represents the average of several determinations. The spread at a particular elevation was never larger than 2 lb. per cu. ft. An examination of the data in Figure 5 reveals that there is a marked increase in moisture content with depth to an elevation of approximately 6 ft.; thereafter the moisture content remains fairly constant as the depth increases. From these measurements it was suspected that below elevation 6 ft. the soil was fully saturated. In order to check this assumption a perforated aluminum pipe (1-in. dia.) was driven about 10 ft. from Tube 1 and the ground water level noted about one week after placement. The level of the ground water as determined by this

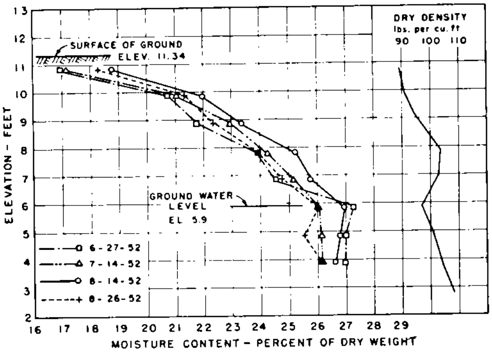

Figure 5. Moisture contents at Tube 1.

procedure is also shown in Figure 5 and lies approximately at elevation 6 ft. Note that the moisture contents at any particular depth do not vary more than about 1.5 percent, which is well within the degree of accuracy of the method, and indicates how closely one can reproduce the results with this procedure.

Figure 6 shows the variation of moisture content and density with depth at Tube 4, located at approximately the centerline of the runway (see Fig. 4). Note that at this location the moisture content increases rapidly from the surface down to about elevation 8 ft.; thereafter the increase with depth is considerably smaller. A perforated pipe was driven close to Tube 4 and the level of the ground water recorded at elevation 6.3 ft. It will be noted that the ground-water level at this location is approximately at the same elevation as at Tube 1. A comparison of the moisture contents at Tube 1 with the moisture contents at Tube 4 indicates that at the same elevation the moisture contents at Tube 4 are from two to three per cent lower than at Tube 1.

Figure 7 shows the variation of moisture content with depth at Tube 3A, in the paved

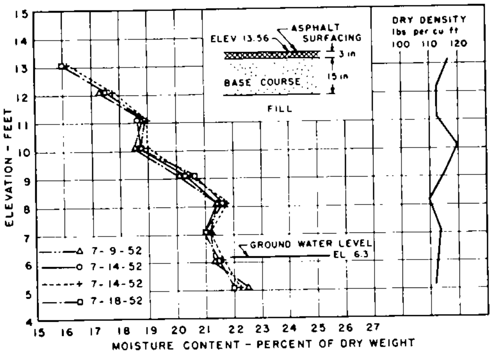

Figure 6. Moisture contents at Tube 4.

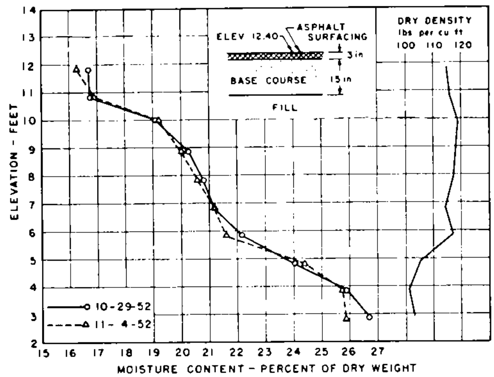

Figure 7. Moisture contents at Tube 3A.

area very near a drain. Although not shown in this paper, moisture versus depth data were developed for the other six locations (Tubes 2, 3, 5, 5A, 6, and 7). The moisture contents at the different elevations (12, 11, 10, etc.) at all of the nine locations were averaged and a contour map of moisture content developed as shown in Figure 8. For convenience, straight lines were drawn connecting the points of known moisture content. The contour map clearly portrays the draw-down effect of the three subdrains.

that the tide apparently has little effect on the moisture content.

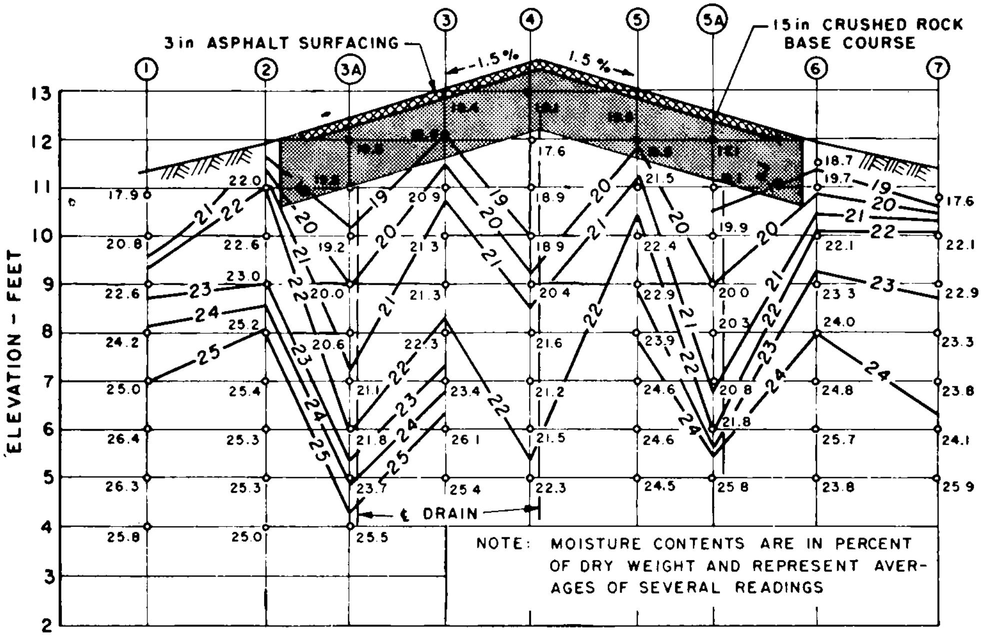

Figure 8. Moisture conditions at Station 22 + 37.5, NE-SW Runway, San Francisco Airport.

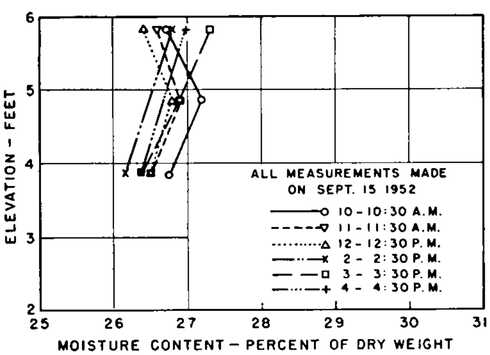

Figure 9. Selected moisture measurements at Tube 1.

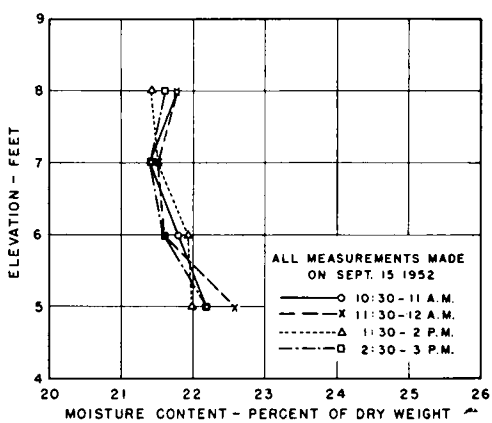

Figure 10. Selected moisture measurements at Tube 4.

There was some feeling that the fluctuations in tide might affect the ground water level and hence the moisture contents. In order to ascertain the effect of the tide, a number of measurements were made at the lower elevations at Tubes 1 and 4. The results of these measurements are shown in Figures 9 and 10. From these measurements it is clearly seen

COMMENTS

It was found that the neutron and gamma-ray method was very satisfactory for determination of moisture contents and densities at the San Francisco Airport. The method offers the advantage of speed, as witnessed by the large number of measurements made at Tubes 1 and 4 on September 15. The equipment is compact and easy to handle. Precautions must be taken to prevent injury from radiation, but these present no serious problem, being largely confined to observing routine procedures in the handling of radioactive material. The neutron source may be stored in a portable container filled with water or paraffin. The gamma-ray source must be stored in a lead container having a wall thickness of about 2 in. The cost of the equipment is not excessive. On the basis of present day costs the probe, scaler, source and accessory equipment can be obtained for approximately $2,000.

Probably the greatest disadvantage of the equipment so far developed is the shallow depth at which measurements can be made (not over 10 ft.). A single probe which will measure both moisture and density at much greater depths is now being developed. Additional advantages of such an instrument are the greater speeds at which measurements can be made, and greater safety because the radioactive strength of the single source need not be as great as in the existing setup.

It is important, as has been implied, to precede field measurements with careful calibration in the laboratory. Another important consideration is the manner in which the tubes are placed in the soil. It is essential that the soil be in close contact with the tubes, otherwise the readings will be in error. One way to install a tube is to drive it directly into the soil. Another way is to bore a hole slightly larger than the tube, fill the hole with loose soil from the boring, and then drive the tube into the filled hole. It is recognized that both methods disturb the soil adjacent to the tube to a small extent.

An encouraging feature of the method is the consistency of results. Nowhere was the spread in moisture content readings at the same elevation more than about 2 percent. The density measurements were even more consistent.

Because the tubes will last indefinitely and are not a hazard in paved areas the neutron and gamma-ray method appears to be advantageous for the study of long-range trends in moisture conditions under highway and airport pavements. It can also be adapted for the determination of moisture conditions in earth-fill dams and other earth structures.

All of the current measurements at the San Francisco Airport were made during the dry season (0.04 in. of rain during the period measurements were taken). Measurements will be continued through the winter season to ascertain the effect of the rains on the moisture contents and the ground-water level.

It was mentioned previously that in the top 3 ft. the neutron method yielded consistently higher moisture contents than the ordinary oven-drying method. It is believed that this discrepancy in part is due to the method of calibration. For lower moisture contents where the number of hydrogen atoms is low the effective volume in which neutrons are scattered is larger than for higher moisture contents. It is believed that the diameter of the drum used for calibrating the instrument was not large enough to contain the scattering for the low moisture content. Preliminary trials indicate that a higher count would have been registered in a larger diameter barrel. This would have the effect of decreasing the moisture content in the top drier layer.

CONCLUSIONS

As far as the specific findings at San Francisco Airport go, this study has served to show that the longitudinal subdrains along the runway investigated appear to be effective in lowering the moisture contents underneath the pavement. The following conclusions with regard to the method of taking measurements are indicated:

1. Moisture contents obtained by the neutron method agreed fairly well with those obtained by the ordinary method of sampling and over drying, except for the top 2 to 3 ft.
2. Application of the neutron and gamma-ray methods is relatively simple, rapid, and inexpensive, and can be adapted for everyday engineering use.
3. The method is particularly suited to long-time studies of moisture and density under highway and airport pavements, although it can be adapted for other uses in earth structures.

ACKNOWLEDGMENTS

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particularly George Burr, senior engineer for the commission, and F. V. Philpot, maintenance engineer at the airport.

On the Institute staff, Alexander Klein and Louis J. Tresconv, of the Basic Research Laboratory, under whose guidance much of the development work in instruments took place, and Harry B. Seed made valuable suggestions throughout the investigation.

DISCUSSION

Paul F. Carlton, *Civil Engineer*, and Raymond C. Herner, *Chief, Airport Division, CAA, Technical Development and Evaluation Center*—Although the development of suitable equipment employing radioactive materials for the measurement of soil moisture and density has been under way for several years, the field study at the San Francisco Airport, by Horonjeff and Goldberg, represents one of the first successful applications of the nuclear method in the investigation and analysis of subgrade moisture problems. From that standpoint, we feel that it is a very worthwhile contribution.

Unfortunately, the authors did not present any test data obtained as a result of direct sampling of the subgrade. They stated, however, that moisture values obtained by the nuclear method varied as much as 25 percent from moisture contents obtained by oven drying. From the description of the methods used, it may be assumed that errors of that magnitude could have been introduced during the calibration of the probes. Laboratory tests conducted at Cornell University and at the Civil Aeronautics Administration's Technical Development and Evaluation Center have shown that both the moisture and density probes survey a bulb of soil having a radius of 6 to 15 in. depending upon soil conditions. The size of this bulb of soil would preclude the use of 6-in. layers of soil as calibrating mediums, and might explain the consistently higher moisture results obtained in the top 3 ft. of soil by the nuclear method.

The use of the two density calibration curves for both wet and dry density is not fully explained, and seems somewhat complicated. Perhaps this could be covered more fully in the author's closure, or by a revision of text.

Extensive evaluation tests made by the CAA, using equipment similar to that employed by Horonjeff and Goldberg, have shown that average accuracies of plus or minus $\frac{3}{4}$ lb. of water per cubic foot of soil can be obtained with the moisture probe, and plus or minus $3\frac{1}{2}$ pcf. with the density probe An analysis of test data obtained during the past two years has shown that the moisture content of the soil has a slight effect on the determination of wet density. Soils having high moisture contents give slightly higher counting rates than do low moisture content soils having the same wet density. By adjusting density test results in such a manner that the effect of moisture content was eliminated, it has been possible to reduce the average error to plus or minus 2 pcf.

Although the results obtained at the San Francisco Airport may not be quantitatively precise, the general agreement in relative moisture content among the nine access tubes, as well as the excellent reproducibility exhibited, is extremely encouraging. The authors are to be complimented for pointing the way to one of the many possible uses of the nuclear method in obtaining reliable soil moisture and density data rapidly and at nominal cost.

Robert Horonjeff and Irving Goldberg, *Closure*—The authors are indebted to Carlton and Herner for their constructive suggestions. The presentation by the authors was primarily intended as a progress report in a long-range study of moisture conditions at the San Francisco Airport by the use of radioactive materials.

It was evident at the time the paper was prepared that there were some unexplainably large differences in moisture contents in the top 3 ft. of soil, between the neutron scattering and the oven-drying methods of measurement. Since that time, further studies have in part explained the cause for these differences. It is hoped that within the year a complete report on the investigation, including the basic data collected can be made available to those interested in this field.

It was suggested that the large difference (25 percent) in moisture content between the neutron and the oven-drying methods in the top 3 ft. could be due to errors in laboratory calibration. The authors are in agreement with this statement. Some preliminary tests in a 6- by 10-ft. box, filled with sand at various low moisture contents resulted in counts ranging from 6 to 14 percent higher than those obtained for the corresponding moisture contents in the 3-ft.-diameter drum. This difference in counts occurred when the moisture content was below about 15 pcf. The corrected calibration curve, Figure A, would tend to lower by approximately the same percentage the moisture measurements in the field, and would therefore agree more closely with the oven-dry moisture contents, though they would still be somewhat higher.

At the present time, there is a great necessity for determining the exact configuration of the area of soil surrounding the access tube in which the moisture affects the counting rate. The variables which affect the scattering of neutrons in a nonhomogeneous medium such as soil are numerous and extremely complex. Consideration of the theoretical area of influence in the soil would seem to indicate a considerably distorted "bulb." Methods for experimentally determining this area are being studied at the present time.

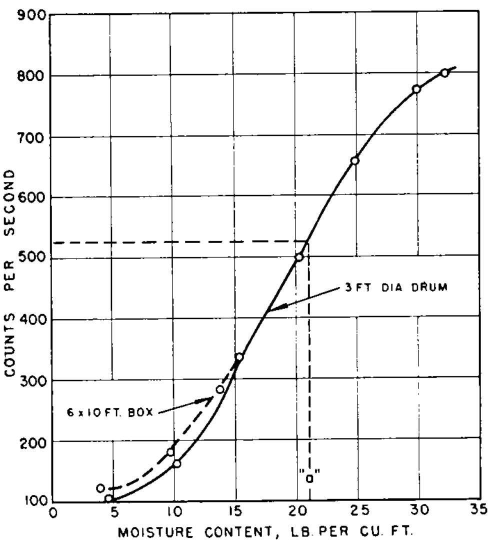

Figure A. Moisture content versus counts.

The comments concerning the method used for density determinations requires a clarification of this procedure. This method is based upon the observation that the scattering of gamma rays is different in a pound of soil than in a pound of water. The wet density count obtained in the field is a combination of water and soil in different proportions. Simply subtracting the moisture content obtained by the neutron method from this wet density will result in an erroneous dry density,

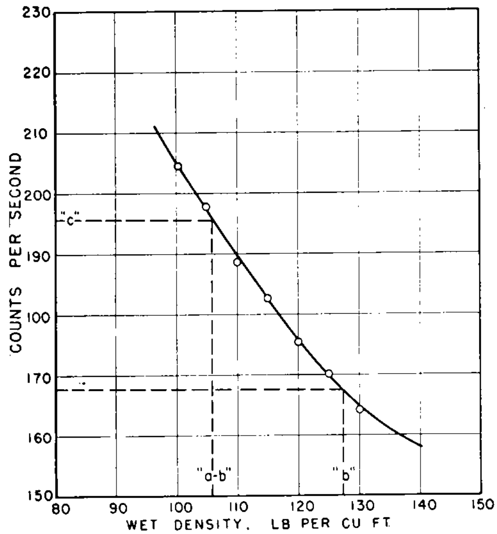

Figure B. Wet density versus counts.

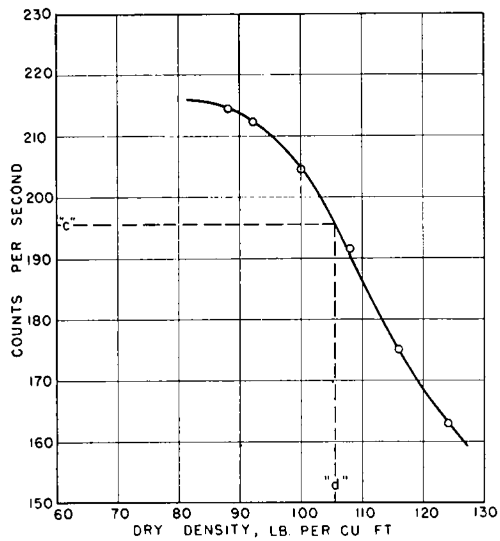

Figure C. Dry density versus counts.

the error increasing in magnitude with increase in moisture content. Figure B demonstrates the effect of moisture content upon the counting rate, using a soil of a constant dry density. Figure C shows the effect of dry density on the counting rate. Combining these curves in the manner described below provides a correction for the effect of moisture on the wet density readings:

In the field, the moisture probe is lowered into the access tube, and the moisture content in pounds per cubic foot, *a*, obtained from Figure A. The density probe is then lowered into the access tube and the wet density in pounds per cubic foot, *b*, determined from Figure B. Subtracting the moisture content from the wet density and entering Figure B with the new weight, *a–b* as abscissa, the corresponding count, *c* is read. Entering Figure C with count *c*, the corrected dry density, *d*, in pounds per cubic foot is obtained. Because the dry density does not change appreciably in the short intervals of time between readings, it is not necessary to determine it each time a moisture reading is made.

The authors concur with Carlton and Herner in the observation that soils having high moisture contents give slightly higher counting rates than do low moisture content soils having the same wet density. It is true that the dry densities obtained by the use of the curves shown on Figures B and C are accurate only for soils having a dry density equal to that of the soil used in preparing Figure B (100 lb. per cu. ft.). In the range of dry densities used in this investigation, however, the error falls within the limits of the overall accuracy of the method.

Finally, we are encouraged by the results obtained thus far in this investigation, and agree that this method for determination of soil moisture and density has possibilities for wide application in many aspects of engineering work.

D. J. Belcher, T. R. Cuykendall, T. Liang, H. S. Sack, *Cornell University*—The authors have indeed presented a clear illustration of the possibilities of practical applications of the nuclear moisture-and-density meter developed at Cornell University under the sponsorship of the Civil Aeronautics Administration. The Cornell group has also used the instrument, in its present state of development, for several other practical applications which it may be useful to mention here briefly.

In a study of landslides in the vicinity of Ithaca, New York, the probe-type moisture instrument was used to locate, successfully, the seepage lines associated with this phenomena. Also, seepage during a spring thaw was followed along its position under the pavement in a road cut. A quite different type of application, principally to assess the practicality of a slightly modified unit, was a few measurements made of the moisture content of a concrete mix. In a general study of the gamma-ray scattering related to probe design, density-probe observations were made in coal piles and in bins of cereal grains. "Bread board" models have been used to determine the moisture contents of aggregates and sands and these, in turn, suggest many other field and laboratory uses related to bituminous materials and pavement mixes.

In a beach project supported by the Office of Naval Research, the fluctuations of moisture content of beach sand with tide and location on the beach were detected by the probe-type moisture instrument. Figure E shows a profile of the beach and the location of the different access tubes. The letters A to F indicate positions of the probe at which moisture readings were made. The tide was 3 ft. The moisture content, read from the laboratory calibration curve, and expressed in pounds of water per cubic foot, is given in Figure D as a function of time and, hence, of the tide cycle. Small arrows on the abscissa indicate the time of high tide. The interpretation of these curves permits interesting conclusions about the motion of the water in the sand during the tide cycles. For instance, Position A is so far above the high tide level that the moisture content is small and scarcely varies with time. Although Position B, slightly below the high tide level, shows the increase of moisture during the high tide, the peak lags an hour or more behind the high tide mark. Also, the fluctuations between high and low tide are very great since practically all the water is able to drain away as the tide decreases. The peaks are very narrow since the drawdown is rapid. As one approaches the ocean (Holes 3 and 4), the time lag becomes less and the fluctuations become smaller and the peaks broader since the drawdown is less rapid at those points. The difference between the lower and higher positions in the same access tube can also be interpreted in these terms.

An exploratory use of the surface-type density-and-moisture instruments for compaction control purposes in earthen-dam construction (assisted by the Pittsburgh office

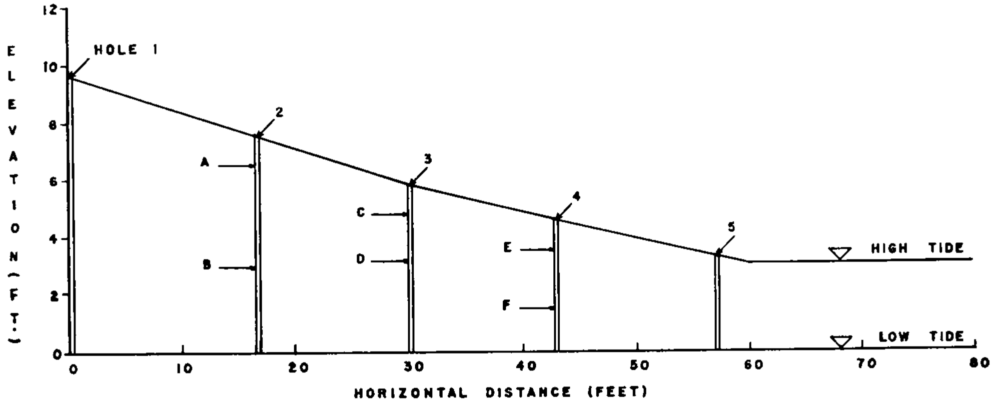

Figure D.

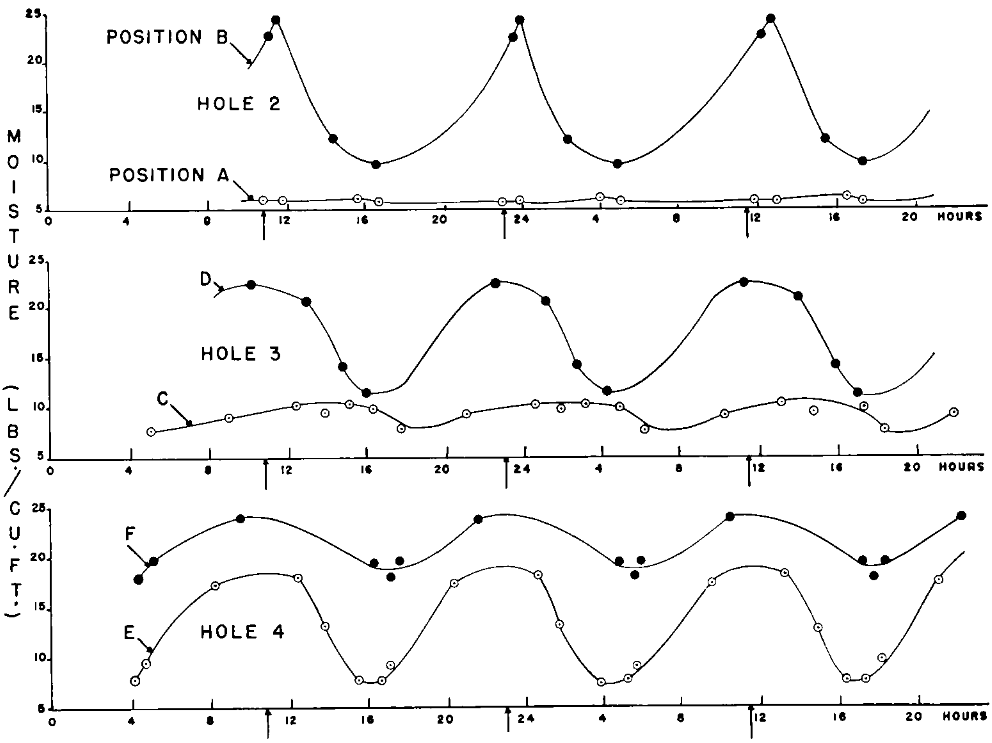

Figure E.

of the Corps of Engineers) is described in the CAA Technical Development Report No. 161, February, 1952.

In reviewing critically the present state of development of the instrument, it is the opinion of this group that it may be used successfully in measurements concerned primarily with the observation of relative variations of moisture or density with respect to time, or the observation of such variations with respect to position within a region which can be considered homogeneous in soil type and structure. The moisture instrument is particularly useful and accurate if knowledge of the absolute moisture content (pounds of water per cubic foot) is sufficient, and its conversion to percent dry weight is not essential in the use of the information. With regard to absolute measurements, certain difficulties are still to be overcome, some of which are discussed by Herner and Carlton of the Technical Development and Evaluation Center of the CAA. However, it is believed that in its present form the accuracy of the instrument compares favorably with other means of measuring soil moisture and density, and is adequate for many purposes.

Since the components used in the instrument are still essentially of laboratory research type, it is expected that, at times, difficulties and perhaps erroneous readings may occur. Such situations are immediately recognized by operators familiar with this type of equipment. Consideration of designs leading to a rugged field instrument is an important future step. One improvement would avoid the waiting time for equilibrium by using a boron-filled counter, or a scintillation counter, etc. Work in this direction is being conducted at present at Cornell and at Indianapolis.

To use the probe instruments in deep holes, the Cornell group has constructed in a small cylinder a cathode follower type of impedance matching device which is connected to the probe by means of a short flexible cable and is introduced into the access tube together with the probe. Only two additional wires (not coaxial cable) leading from the scaler to the probe are required. With this arrangement, 100 ft. of cable have been used without changing the number of counts per minute or the precision of the instrument. This type of probe was prepared for the investigation of fluctuation of soil moisture and density with time in an earth-filled dam which the Cornell group intends to undertake in the near future.

The influence of chemically bound water, organic matter, or salts, has been studied to some extent by the Cornell group and has been reported in earlier reports or theses.[1]

Finally, it should be noticed that the scattering phenomena of gamma rays that forms the basis for the density determination is not quite as simple as explained by the authors. In fact, the intensity of the gamma rays recorded by the counter tube does not monotonously decrease as the density is increased. First, there is an increase of the intensity as densities in the low ranges are increased, then the intensity reaches a maximum, and only from then on does it decrease with further increases in density (and this relation is not really inversely proportional). The density at which the maximum intensity occurs depends upon the energy of the gamma rays and on the distance between the counter tube and the source. With the particular design used at Cornell, which differs little from the one used by the authors, this maximum occurs at a density of about 65 lb. per cu. ft.

R. Horonjeff and I. Goldberg, *Closure*—The authors express their appreciation for the interesting and informative discussion by Sack and his colleagues, especially the description of the various practical applications of the procedure to engineering problems. Mention is made that the density is not always inversely proportional to the count rate. The authors were aware that this relation is valid only if the density is not less than a certain value (in our case approximately 70 lb. per cu. ft). Below this value the density is directly proportioned to the count rate. The density at which this reversal takes place is dependent not only on the type of source used and its position with respect to the detector but also on the atomic weight of the surrounding medium. It was felt that an explanation of the complex nature of the factors contributing to this reversal was beyond the scope of this paper.

[1] These are: (1) CAA Technical Development Report #127, October 1950; (2) CAA Technical Development Report (same series as 1) to be published in March, 1953, where references to Cornell Theses are given; and (3) Belcher, Herner, Cuykendall & Sack, "Use of Radioactive Material to Measure Soil Moisture and Density", paper delivered at the meeting of the Committee D-18, ASTM, held at Cleveland, Ohio on March 5, 1952, being published in ASTM Special Technical Publication No. 134.