NUCLEAR METERS FOR MEASURING SOIL DENSITY AND MOISTURE IN THIN SURFACE LAYERS

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SUMMARY

The measurement of soil density and moisture at varying depths by means of nuclear instruments was described previously in Civil Aeronautics Administration Technical Development Report No 127. The present report describes the development of new meters that measure density and moisture of the surface layer of soil. Using the same radioactive sources and same counter tubes as used in the depth probes, but with a different geometric design, these preliminary models prove to be promising under both laboratory and field conditions. Further studies are being made to improve their operational characteristics, particularly that of sensitivity. When perfected, they can be used advantageously for compaction control and related purposes in all types of earth construction They are efficient, convenient, and economical It takes about fifteen minutes to take measurements and obtain the results on a complete set of density and moisture readings

INTRODUCTION

The scattering of gamma rays and of neutrons has been employed as the basis of a new method for the measurement of soil density and moisture at varying depths by means of instruments developed by Cornell University under contract with the CAA.[1] The same basic methods are incorporated in new designs of instruments in an attempt to measure the density and moisture of the surface layer as required in field construction In the present report, preliminary models and their performance are described. Studies are underway which have the objective of improving the performance of these initial models

The density meter previously described consists essentially of a short cylindrical probe containing a gamma-ray source and a detector This is lowered into an access tube, one inch in diameter, driven into the soil * Experiments show that the density determination is made over a volume of soil approximating a sphere 16 inches in diameter The sensitivity of this probe type of soil density meter is fully adequate for field investigations. Its operation is simple. However, along with the measurement of density at depth, there is a need of measuring density of the relatively thin surface layer, and usually it is desirable to avoid drilling holes in the surface Such measurements are important control procedures in earth fills for airport, road, and dam construction. Therefore, the development of an instrument that does not require penetration of the surface was undertaken.

Similarly, in addition to measurement of moisture at varying depths, which is satisfactorily accomplished by the moisture probe, the development of a moisture meter similar to the new density meter was attempted in order to meet the need of determining soil moisture of the surface layer

The surface meters and the probe meters use the same radioactive sources respectively, and the sources are interchangeable They are sister meters Individually, each set has its own specialized sphere of operation, collectively, they measure soils at all positions in the field

THE SURFACE DENSITY METER

Description

The design of the soil density unit for surface application is shown in Fig. 1, and the instrument itself is illustrated in Fig. 2 In external appearance, the unit resembles a flatiron attached to a thin aluminum plate The gamma-ray source and the Geiger-Mueller counter tube are positioned six inches apart and separated by a triangular-shaped sheet of lead 1 1/4 inches thick The source lies near the apex of the triangle, the counter tube lies parallel to the

[1] D J Belcher, T R Cuykendall, H S Sack, "The Measurement of Soil Moisture and Density by Neutron and Gamma-Ray Scattering," Technical Development Report No 127

* A satisfactory method has been developed for placing the access tube in intimate contact with the soil in stone-free, but very dense, dry clays. This is described in a forthcoming report on recent modifications of the probe instrument.

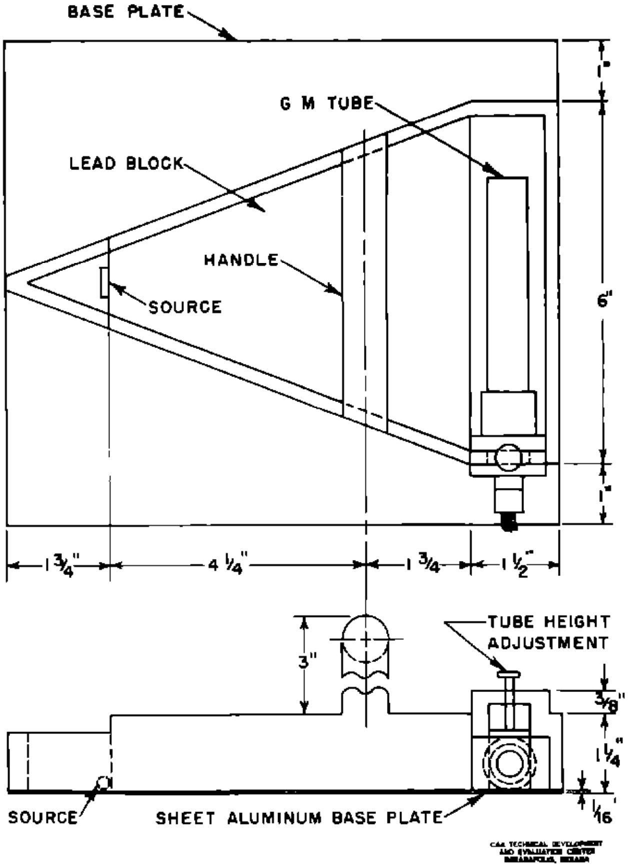

Fig 1 Surface Density Meter

Fig 2 Density of the Rolled Fill is Being Measured by the Surface Meter A Two- to Three-Minute Count is Necessary This Instrument, Together With the Electronic Scaler (Right Background) and the Standard (Left Background) can be Carried Conveniently in a Small Vehicle as a Mobile Unit to Make Measurements in Construction Fields

base A handle is provided for convenience in moving the unit from place to place The whole assembly weighs 14 pounds A Victoreen 1B85 thyrode counter tube and a 1-millicurie cobalt-60 source are installed in the unit

In use, the instrument is placed in close contact with the soil surface much as one might place a flatiron on a table The G-M tube is connected by suitable cable to a scaler and recorder such as described in the previous report[2] Gamma rays from the source are prevented from reaching the counter directly by the intervening lead triangle They do, however, penetrate the soil mass just under the base plate, are scattered in all directions by the soil, and those scattered toward the G-M tube are detected by that device The counting rate is a function of the density of the medium under the lead block and of several parameters that are fixed in any one design Unfortunately, this function is quite complex Attempts to predict, from theoretical considerations, the results of varying the parameters have not been successful.

Variations of Design Parameters

Laboratory studies were made employing techniques similar to those described previously Pits or bins, each 2 by 8 feet by 1 3 feet deep, were filled with soils compacted to approximately the desired densities Determination of the densities was made in two ways from the known

[2]Ibid

weight and volume of the soil, and by the conventional sand method After the work had progressed to the point where it was apparent that smaller samples could be used, they were prepared in wooden boxes 12 by 12 inches by 9 inches deep

Later, four concrete blocks of this size were cast, having densities of 86, 106, 120, and 123 pounds per cubic foot respectively These made very convenient density standards The lighter weight blocks were rather porous, therefore, attempts are now underway to procure a set of fine-grained permanent blocks to cover the desired range of density values It is contemplated that blocks of less porous and more uniform material would prove to be more helpful for calibration in future experiments

As pointed out in the previous report, the distance between the source and detector tubes is an important parameter because of its effect on the shape of the curve that shows the relationship between density and counting rate Curves of this relation were constructed for distance parameters of 4 1/2, 6, 6 1/2, and 7 inches. It was found that for all these values the slope of the calibration curve was not uniform For the smaller distance, the curve tended to become rather flat at low densities, while for the larger distances, a flattening was observed at high densities A value of 6 inches appeared to be the best compromise

Calibration curves also were made in which the G-M tube was moved vertically with respect to the base plate See Fig 1 for mode of adjustment A position close to the soil gave the best results

Sensitivity

Preliminary observations indicated that care must be taken to assure an intimate contact between the soil and the base plate of the instrument With such care, a number of laboratory measurements resulted in the calibration curve shown in Fig 3 It is seen that the counting rate varies with change of density in the manner to be expected and indicates the possibility that this method may be employed satisfactorily for the density determination of thin layers without the need of mechanically penetrating the layer Thus, a convenient control device for embankment construction may be provided

Examination of Fig 3 shows that the sensitivity of this preliminary model of a surface density meter is only about one-half that of the probe type. This reduction of sensitivity is serious, principally because the G-M counter is not an instrument of high precision

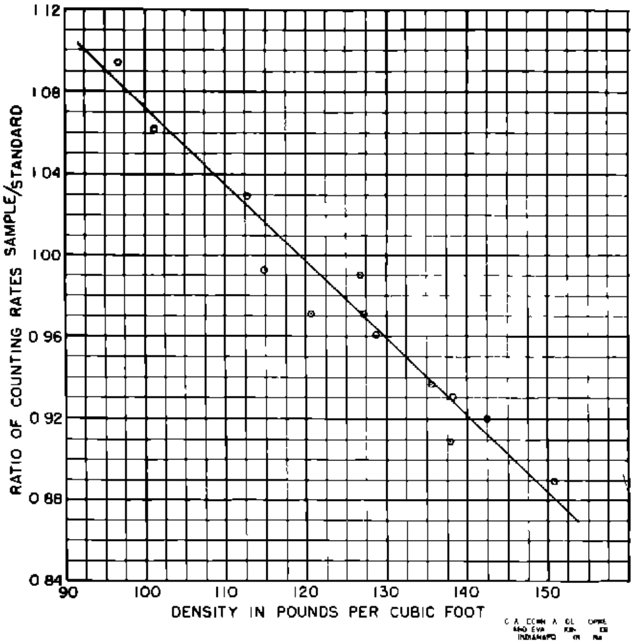

Fig 3 Ratio of Counting Rates Versus Wet Density of Soil (For Surface Density Meter)

By employing a source of suitable strength and counting for two- or three-minute intervals, it is possible to reduce the purely statistical error in the G-M tube readings to a satisfactorily small value However, other errors inherent in the counting system make it difficult in practical use to reduce the error of a given reading below 1 1/2 per cent This amounts to an uncertainty of about ± 4 pounds per cubic foot in the density observations It is concluded that the sensitivity of the preliminary design of the density meter is not so great as is desirable for a fully satisfactory instrument Modifications that may improve the sensitivity are described in a later section of this report

Effective Region

A measure of the effective depth of soil being surveyed by the surface-type meter was obtained by the following procedure A silt sample of about 110 pounds per cubic foot density was prepared in a suitable container which could be either suspended in air or placed on top of a block of sandstone Readings of the density meter were made with the container in each of the two positions and for various thicknesses of silt sample Changing the density of the material under the silt layer from practically 0 to 170 pounds per cubic foot produce a marked change in the counting rate if the silt layer was too thin to be wholly responsible for scattering gamma rays to the detector From these experiments it is concluded that, if the soil layer has a density of 90 pounds per cubic foot or more, marked changes in the density of the soil 6 inches or more below the density meter affect the reading less than 1/2 per cent, below 4 inches, less than 1 per cent, and below 2 inches, perhaps as much as 10 per cent For all practical considerations, the penetration of the present surface density meter is restricted to a 4-inch layer of soil

Experiments also were carried out to determine the area of surface surveyed by the instrument Silt of density about 118 pounds per cubic foot was prepared in a bin 2 by 4 feet by 1 foot deep, and the meter was placed at the center The soil was then cut away in vertical sections a little at a time so that the meter was successively 21, 18, 9, 7, 5, 4, and 2 inches from the edge of the soil mass Based on several experiments of this type, it is concluded that the meter does not survey the soil mass more than 2 inches beyond the base plate.

The fact should not be overlooked that the limited volume of soil surveyed is in some ways a disadvantage For example, a large stone nearly centered under the base plate and just under the surface would result in an excessively large density reading For this reason plans have been made for a new meter which, it is expected, will overcome this disadvantage Meanwhile, it also should be noted that all conventional methods are not measuring volumes much larger than the nuclear instrument which can be conveniently moved around to take as many readings as desirable Each reading takes only 2 to 3 minutes

Effect of Surface Irregularities

The effect of small surface irregularities, such as grooves, ridges, or pits resulting in air gaps between soil and base plate, is not well understood at present. From theoretical considerations, it is clear that abnormalities that lie just below the base plate give rise to very much greater discrepancies than equivalent factors deep in the soil layer.

Some simulated irregularities have been studied For example, a groove 1/4-inch deep and 1/4-inch wide was drawn across the soil surface, and the counting rate was determined for various positions of the density meter with respect to the groove Observed variations in counting rate were small, and because of the low sensitivity of the present design, the results were somewhat ambiguous

In other experiments, a very thin layer of fine dry material was dusted on the surface and the density meter was rubbed back and forth to make firm contact The results were inconclusive At present, the determination of the magnitude of error caused by surface irregularities remains a difficult problem.

Air-Gap Design

By inserting small spacers under the corners of the base plate, it was possible to study the effect of changes in this parameter Curves of air-gap thickness versus counting rate were obtained for several soil densities and for three different values of distance between the gamma-ray source and detector The variation of counting rate with thickness of air gap between base plate and soil surface was found to increase and then level off when the gap was about 7/16 inch Thus, irregularities in the air gap of approximately ± 1/16 inch should produce practically no effect on the readings at this elevated position

Optimum conditions were chosen for the design of a flatiron incorporating the air-gap principle This instrument was double-ended, in that two lead triangles with two sources were used with the counter tube located between them This design had a very large air background count and a low sensitivity Tests to ascertain the cause of the excessive scattered background count are incomplete, and it is generally felt that the promise of this design does not warrant more attention at this time

FIELD OBSERVATIONS WITH THE DENSITY METER

In order to observe the performance of the surface density meter under a typical set of field conditions, the equipment was taken to the site of a rolled-earth embankment during construction Personnel who were supervising construction of the embankment assisted in making a series of density measurements during a three-day interval

Because of gross irregularities caused by the penetration and withdrawal of the feet of the sheeps'-foot rollers, it was the practice of the personnel not to take density samples directly on the surface of the layer being compacted As a regular procedure, a bulldozer was called in to scrape away the loose fill on top in order to provide a working surface lying just below the penetration depth of the rollers Although this surface appeared smooth from a distance, the extreme rocky nature of the fill resulted in small pits and waviness in the surface left by the

TABLE I

Wet Density Measurements on a Rolled-Earth Embankment

Site	Density Meter (pounds per cubic foot)	Conventional Sand Method (pounds per cubic foot)	Remarks
A1	incomplete	137	1
A2	136 5	138 5	
A3	incomplete	137	2
B1	149	151	
B2	139.5	142 5	
B3	142.5	138	
B4	138	not taken	3
B5	135	135 5	
C1	147.5	134	
C2	varied	128.5	4
C3	incomplete	138 5	5
C4	128	129	
C5	128	132	

Remarks

1 Some difficulties were encountered with the counter tube

2 Only one reading was taken, the surface was too rough

3 A large stone was found very close to the surface, directly under the base plate, one dimension of its largest surface was approximately 3 inches, the other about 1 1/2 inches

4 Widely scattered readings were obtained, presumably caused by unrelieved surface irregularities

5. A stone somewhat larger than that of test B3 was found close to the surface

bulldozer blade The density meter was placed in turn in several positions within an area of about 6 by 6 feet. In each case, the surface in contact with the meter was given further treatment by patting down any upstanding hump, scraping with a steel straight edge, or dusting with fine material from the fill. Several such areas were worked throughout the embankment

Conventional density measurements were made by the sand method used routinely by many agencies The excavation for such measurements was made in most cases at the identical position previously occupied by the density meter in order to check density readings closely and to obtain information on any abnormalities which might have been present

Some idea of the roughness of the surface can be obtained from examination of the photograph, Fig 2 In nearly all cases, many stones of dimensions up to two inches were found upon examination of the soil under the density meter

Table I presents the complete set of observations made

A second field trip was made to investigate the behavior of the modified meter containing an air gap as previously described The density measurements gave very inconsistent values, and therefore the air-gap design is considered unsatisfactory

As a whole the initial design (as shown in Fig. 1) gave reasonably good results under field conditions, although further improvements are necessary The tests made on the embankment provided a good opportunity to evaluate the merits and defects of the device The convenience and economy in operating the instrument under field conditions were generally recognized, the major objective to be achieved is to increase its sensitivity

The rocky nature of the embankment represented about the worst possible condition and, hence, provided a most crucial test for the instrument It is believed that the device will perform better in less stony soils

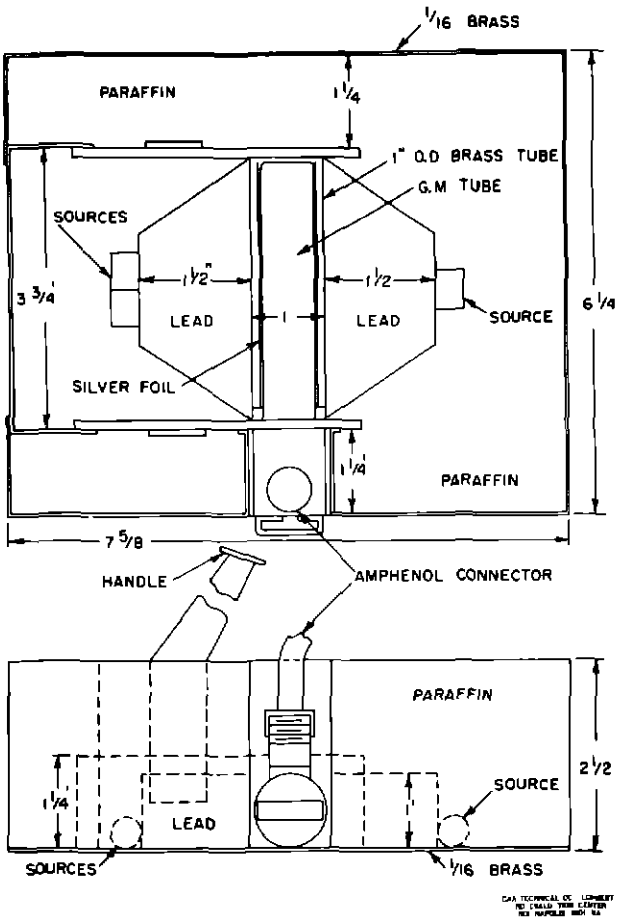

Fig 4 Surface Moisture Meter

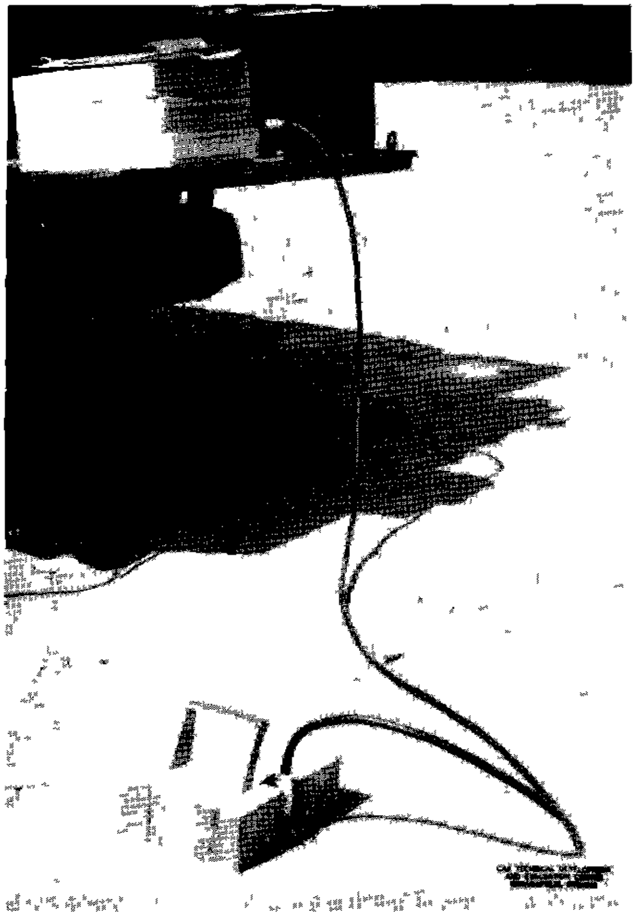

Fig 5 Measuring Soil Moisture in the Surface Layer of an Earth Dam With the Double-Source Instrument A Section and an Elevation View of This Moisture Meter are Shown in Figure 4 A Three-Minute Count is Required After Equilibrium is Reached

THE SURFACE MOISTURE METER

Description

A drawing of the surface instrument for the determination of moisture content is shown in Fig 4, and the instrument itself is pictured in Fig 5 A Geiger counter tube lies between two neutron sources (RaD plus Be) separated from them by sufficient lead to form a shield against the weak residual gamma rays emitted by any impurities in the sources A silver foil surrounding the counter is selectively sensitive to slow neutrons, capture of the slow neutrons by the silver makes it radioactive, and the beta decay of the foil is measured by the Geiger counter About five minutes waiting time is required for equilibrium to occur

Neutrons penetrate the soil mass, are scattered by the nuclei therin, and in collisions with hydrogen nuclei lose energy very rapidly The relative number having low energy, as determined by the silver foil and Geiger counter, are proportional to the number of hydrogen atoms (mostly in the form of water) present in the soil The sensitivity of the system is increased by covering the tube and sources with paraffin, as indicated in Fig 5, which reflects many neutrons that otherwise escape into the air

Calibration

The ratio of counting rate, obtained when the meter was placed on the surface of a sample of known moisture content, to the rate determined for a standard block as a function of the moisture content is shown in Fig 6 Either two- or three- minute counts were taken as they were in moisture probe observations The soil samples were prepared in boxes in the laboratory in the con-

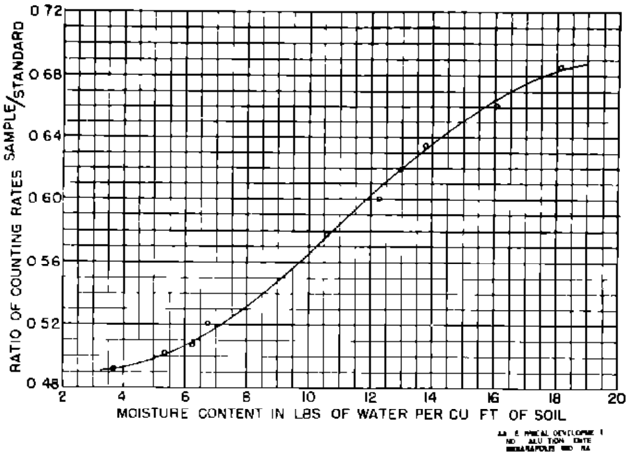

Fig 6 Ratio of Counting Rates Versus Moisture Content (For Surface Moisture Meter)

ventional manner, Memphis silt being the principal material used A thick slab of paraffin forms a most satisfactory reference standard

As is the case for the moisture probe, the sensitivity decreases markedly at very low moistures It is expected that when measurements of moisture above 18 pounds per cubic foot are available, a slight flattening at higher moisture content also will be found However, from an examination of this curve, it would appear that an accuracy of ± 1 pound of water per cubic foot is possible Confirmation of this, however, must await the results of further studies on the performance of this preliminary model

Effective Region

To understand the effective sphere of the instrument, observations were made in the changing of counts as affected by the changing of the volume of soil Only rather sketchy experiments have been made to the present time The moisture meter was placed on the surface of a mass of soil about 2 by 4 feet by 1 foot deep The soil was trimmed away so that the edge of the soil mass approached the edge of the meter frame, and it was found that when this distance became 3 inches a very slight change in counting rate occurred For a 1-inch distance, the change was more than 5 per cent

Studies of effective depth were made by placing the moisture meter on a layer of moist soil contained in a large aluminum tray The counting rate was determined for two cases, the tray suspended in air or resting on top of a thick slab of paraffin A marked difference in counting rates was found for a soil thickness of 2 inches, about 5 per cent difference for 4 inches, and no effect for a soil layer 6 inches thick

The effective volume of soil measured by the moisture meter varies slightly with the moisture content, becoming larger for drier soils Experiments of the above type have not yet been made for very dry samples However, from results obtained in the subsurface studies, it is believed that the effective soil mass measured is not over six inches thick and one square foot in area

FIELD OBSERVATIONS WITH THE MOISTURE METER

Although still in a preliminary development stage, the surface model of the moisture meter was included in the equipment taken on a field trip and was used in a series of measurements made on sandy beaches A few readings also were taken during the second trip to the embankment site

A real test of the performance was not obtained, since the locations surveyed in beach areas tended to be either very wet or very dry and required extrapolation of the calibration curve at the high moisture end However, estimating an extrapolation, the moisture meter read well within the experimental error as compared to conventional oven-dried samples Exact agreement was obtained for samples in the 3 to 5 per cent moisture range This is believed fortuitous since the calibration curve does not admit a respectable precision in this region Four observations were made in the 5 to 8 per cent range, three of which were within experimental error

The moisture contents in the rolled fill fell in the normal range, and the few measurements made by the meter generally agreed with the oven-dried results However, an exact comparison of these readings with the laboratory values that were expressed in percentage of soil weight is rather difficult because, as explained previously, the density measurement during the second trip was made with the air-gap meter which gave irregular readings It is evident that more field observations in soils containing moistures of normal range are necessary

In general, the moisture meter performed quite well, and it is believed that, after further modifications, it will be a fully satisfactory instrument

PROGRAM FOR FURTHER DEVELOPMENT

As indicated previously, the performance of the density meter is not considered fully satisfactory, and lately it has been found to be highly sensitive to certain design parameters

Recent tests show that the Geiger counter is not fully shielded from scattered rays which have not entered the soil mass Reduction of this unwanted background is expected to increase the sensitivity Some modification of the source system, in order to partially direct the gamma rays into the soil mass, may be shown to be desirable from studies in which the shape of the lead block is varied at the region of the source.

In the preliminary model, the source is not adequately secured in a fixed position with respect to the base plate, and small changes have caused irregular results Redesign of the source holder is planned so that the position of the capsule is fixed, but the assembly can be easily removed for storage purposes

It is believed that the wing-like portions of the base plate serve no useful purpose and should be removed

To overcome the limitation of small volume of soil surveyed, it is planned to incorporate in a new design two sources equally spaced on either side of the Geiger counter, as is done in the moisture meter Somewhat deeper penetration of the radiation may be secured, where desirable, by modification of source holder and counter shielding

The previous discussion indicates certain of the major modifications which it is believed desirable to study in the design of a more satisfactory instrument for surface density measurements

Concrete plans for further improvement of the surface model of the moisture meter must await the results of more extensive performance tests

ACKNOWLEDGEMENTS

Much of the construction of the two instruments, the measurements of counting rates, and preparation of soil samples required in this work were carried out by Messrs W E Jahsman, T Liang, R J Rosa, and T W J Wong From the engineering viewpoint, Dr Ta Liang has carried much of the responsibility for field testing of the instrument in keeping with construction requirements

Special acknowledgment is made to engineers of the CAA for suggestions for this instrument and to the Pittsburgh District Office, Corps of Engineers, for co-operation and assistance in the field studies