TRANSPORTATION RESEARCH CIRCULAR

Number 195, April 1978
ISSN 0097-8515

Transportation Research Board, National Academy of Sciences, 2101 Constitution Avenue, Washington, D.C. 20418

STATE OF THE ART IN TRANSPORTATION APPLICATIONS OF SUBSURFACE NUCLEAR MOISTURE AND DENSITY MEASUREMENTS

subject areas
34 general materials
35 mineral aggregates

INTRODUCTION

Several times during the last 15 years, most recently in 1973, the Transportation Research Board has surveyed the 50 state highway agencies, the Canadian provinces, and counties, cities, and others to obtain the latest information on their use of nuclear moisture and density gages. Most of the information gathered in those surveys has been concerned with the procedures and specifications for use of surface gages, i.e., equipment which measures moisture and/or density at depths no greater than 12 inches (0.3 m) from the surface.

This report is concerned with the state-of-the-art in transportation agency use of subsurface nuclear moisture and density gages. The measurement range considered is from one foot (0.3 m) to 150 feet (50 m) below the surface, although few agencies reported attempting to obtain data beyond 20 feet (6 m).

The report consists of a summary of the results of a survey on subsurface gage usage made by the Transportation Research Board in February 1976; a brief bibliography of relevant general information and of recent gage applications; and discussion, including recommended practices, based on the survey questionnaire and the literature.

As the results of the survey will show, transportation agencies at present make relatively little use of subsurface nuclear noisture and density gages. No effort was made in the present survey to obtain responses from a larger group of users, the agencies which use gages primarily for hydrologic or agricultural purposes.

SURVEY RESULTS

Forty-six states responded to the survey questionnaire, as did eight Canadian provinces, five local governments and 22 offices of federal agencies included the Federal Aviation Administration, the Forest Service, the Bureau of Mines and the Geological Survey. One province, one county, 19 state transportation departments, and three federal agencies reported having used subsurface nuclear moisture/density gages.

The following items are summarized in this report from the questionnaires of those respondents who reported using the gages.

1. Extent of Equipment Usage
2. Types of Use
3. Test Procedures
4. Calibration Procedures
5. Problems

Because answers were not always given to all questions and some agencies reported multiple answers to some questions, totals will not always be 24 or 100 percent of the respondent users.

1. Extent of Equipment Usage.

The table below lists those agencies which indicated that they have owned or leased subsurface moisture and/or density gages and distinguishes which are currently using or planning to use them from those which have used them in the past.

	Equipment		Use	
	Moisture	Density	Past	Current or Planned
Arizona	X		X	X
California	X	X	X	X
Colorado	X	X	X	
Illinois	X	X	X	X
Kansas	X	X	X	
Louisiana	X	X	X	X
Maine	X	X	X	
Maryland	X	X		X
Michigan	X	X	X	X
Mississippi	X	X	X	
Montana	X	X	X	X
New Jersey	X			X
North Dakota	X	X	X	X
Oklahoma	X	X	X	
Pennsylvania	X	X	X	X
South Dakota	X	X	X	
Texas	X	X	X	X
Utah	X	X	X	
Virginia	X	X	X	
Saskatchewan	X	X	X	

	Equipment Type Moisture	Equipment Type Density	Use Past	Use Current or Planned
U.S. Forest Service (Region 6; Portland, OR)	X	X	X	X
U.S. Bureau of Mines (Spokane Mining Research Center)	X	X	X	
U.S. Geological Survey	X	X	X	
San Diego County DOT	X	X	X	

Of the 24 agencies which reported gage usage, only five owned or leased more than a single system, i.e., one density probe and one moisture probe. None owned more than three. Twenty-six of the 48 probes listed were produced by either of two manufacturers, although there are several other companies currently selling the devices. Only 15 of the 48 probes can be classified as belonging to the latest generation of equipment, while many of the others are regarded as obsolete by their owners.

In addition to the above, one state (North Dakota) reported using a two-probe density gage; i.e., one probe containing the source, the other the detector. They indicated they had considerable difficulty getting good results from the system because of problems in establishing and maintaining equal distances (12 in. or 0.30 m) between each pair of access tubes.

2. Types of Use.

Twenty-two of the 24 respondents indicated using the subsurface gages only as tools for field research or for trouble-shooting. No agency reported using subsurface gages routinely for quality control of subgrade materials.

The various uses to which the gages are put can be categorized as follows:

	Number of Respondents
Long-term monitoring of subpavement moistures and densities	7
One-time analysis of problem areas	6
Long-term monitoring of problem fills	3
Other	5

Long-term monitoring of moisture in subpavements is being used by one State to develop an environmental factor for use in pavement design. The others report using the devices to monitor subbase and subgrade moistures and densities under either experimental base and pavement sections or under standard sections. Readings for this application typically are made at depths of 1/2 to 10 ft. (0.15 to 3 m).

The moisture and density gages have proven useful in diagnostic efforts in problem areas such as:

a. Possibly unstable sand fills in marshland areas;
b. "Moving" embankments;
c. Warping pavements, where the condition is believed to be caused by moisture movement in shale cuts and embankments;
d. Expansive clays in subgrades.

The gages also have enabled researchers to assess how the load-carrying capacity of drilled shafts (for piles) is affected by moisture content and to establish moistures and densities in landslides and natural slopes, in existing granular fills, and in compressive silts undergoing consolidation.

Long-term diagnostic efforts with moisture-density probes appear to be useful on problem fills--one state's researchers are completing a study in which they are attempting to correlate moisture and density monitor changes in hydraulic backfills in underground mines. Diagnostic tests are typically made to 20 or 25 ft. (6 or 7 m), although four of the agencies reported taking measurements, with considerable difficulty, at 40 ft. (12 m) or more.

Other applications outlined in the responses include using the nuclear gages to check the utility of moisture membranes, to test for voids in cat-in-place concrete piles during construction (up to 150 ft. [45 m] down), and to assess rock quality in rock pits.

3. Test Proceudres.

Only one of the 24 user agencies reported having a standard test method for either of the subsurface devices. Four stated that they rely on the methods presented in the manufacturers' operating manuals, and this is probably common practice for these devices which are used primarily as field research tools. Neither ASTM nor AASHTO have test methods for these devices in their latest compilations of standard procedures. ASTM Committee D-18 on Soil and Rock for Engineering Purposes has been considering a tentative version of "A Standard Method for Subsurface Measurement of the Moisture Content of Soil by Nuclear Techniques" for several years.

Users were asked to make estimates of gage accuracy and of the size of the soil volume measured and to list factors which influence the performance of their nuclear systems. Only seven of the survey subjects responded to the request for accuracy estimates. The values stated for the two standard deviation accuracy of moisture measurements ranged from $\pm$ 0.3 to 8.0 pcf ($\pm$ 5 to 128 kg/m^3) over a range typically of 0 to 30 pcf (0 to 480 kg/m^3). The median value was $\pm$ 2 pcf ($\approx$ 32 kg/m^3). The density accuracy estimates ranged from $\pm$ 0.35 to 7.6 pcf ($\pm$ 6 to 122 kg/m^3) over a range typically of 80 to 150 pcf (1280 and 2400 kg/m^3). The median value for this accuracy estimate was also $\pm$ 2 pcf ($\approx$ 32 kg/m^3).

Estimates of the size of the soil volume "seen" by the subsurface moisture gage (by 11 respondents) ranged from 0.02 to 4 ft.^{3} (0.0006 to 0.11 m^3). Several noted that the volume seen is a strong function of the moisture content of the soil. The median value was 1 ft.^{3} (0.03 m^3). The subsurface density gage estimated volumes (by eight respondents) ranged from 0.06 to 4 ft.^{3} (0.002 to 0.11 m^3), with a median value again of 1 ft.^{3} (0.03 m^3).

Parameters which were stated to affect the responses of the probes are tabulated below:

	Number of Respondents Moisture Probe	Number of Respondents Density Probe
Soil Composition	8	6
Temperature	5	5
Density	5	-
Moisture	-	2
Voids Around Access Tube	2	2
Others	4	1

All of the respondents who reported temperature effects are owners of early model moisture and density gages; manufacturers claim that these effects have been eliminated from the latest generation of gages.

The other influences listed were automobile ignition interference, moisture in the access tube, particle size, and electronic drift.

4. Calibration Procedures. Eighteen of the users' replies included information about calibration procedures

	Number of Respondents
Used manufacturers' calibrations	11
Established calibration in laboratory with permanent standards or with local material compacted into molds	7
Calibrated by comparison with conventional oven-drying tests on field samples	4

Some of the respondents used combinations of these methods, e.g., using oven-drying tests to verify or to adjust a manufacturer's calibration curve.

5. Problems

a. Access Tube Installation

Developing a method for installing access tibes which will not add to the statistical and other errors inherent in the nuclear methods has been a problem for almost every user. The techniques used depend on the drilling equipment the user has available and on the material in which the tube is to be installed.

Method	Number of Respondents
Drive split spoon sampler or Shelby tube in, remove, then insert access tube	6
Power auger hold of approximately access tube diameter, then insert access tube	4
Power auger hole of larger diameter, insert access tube, then backfill	2
Drive access tube itself, without predrilling	3
Hand auger hole, then insert tube	2

The users reported that the driven samplers produce a good fit between the access tube and the soil and also noted that they yield good samples for calibration purposes. Power auger users who use augers the same diameter as the access tube indicated they had considerable difficulty in getting the same size hold over a range of soils. Their responses state that exact size holes were feasible in heavy clays, but oversize holes were the result in loamy materials and in tough silts. Thus, in some materials there would be error-producing voids around the access tube.

Augering a hole approximately two inches larger than the access tube, installing the tube, and then backfilling with either cuttings from the original hole or fine gravel was reported to produce only small errors. This method was found to be very suitable when either rock or very dry materials were encountered. Driving access tubes themselves (to as deep as 20 ft. [6 m]) was reported to be successful by two users, but the third warned that tubes cannot be driven very far in most materials before they bend or distort. Hand augering was reported to be feasible for shallow installations.

The most widely used access tubing (five responses) was Class 150 aluminum irrigation tubing (2-inch O.D. [50.8], 1.90 inch I.D. [48.3 mm]). Five additional respondents reported using aluminum tubing, but did not specify the size. Three agencies indicated they used thin wall steel tubing. One agency's researchers who were looking for data down to 40 ft. (12 m), said they had to shift from aluminum to thin wall steel drill casing. However, this change resulted in a considerable loss of probe sensitivity. The agency using a density probe to test for voids in borehole concrete piles constructed its access tubes from sections of 2-inch (50.8 mm) diameter PVC pipe. The pipe was tied to the reinforcing steel before the concrete was poured and reportedly worked well.

b. Other Problems

Twelve of the agencies which have used gages in the past now have no plans for future use. The problems which these agencies encountered and which contributed to the decision to discontinue are listed below:

	Number of Respondents
Frequent instrument breakdown	2
Equipment drift with temperature	2
Erratic or erroneous results	5
Equipment obsolete	4
Access tube problems	6
No further need	4

The primary problems reported by current users were in installing access tubes and in minimizing any errors due to the presence of voids around the tubes. Two users indicated they got poor results when they compared moistures and densities determined from calibration curves constructed on laboratory standards with the results of conventional field tests, e.g., oven-drying. Another cited the manufacturer's calibration curve as being inadequate. A fourth reported still having problems with temperature effects on the response of the equipment.

DISCUSSION

From the survey results, it is apparent that subsurface nuclear moisture and density gages have proven useful to highway engineers in a number of field research and trouble-shooting studies. Their future usefulness to transportation agencies will depend on continued improvement of the instruments by the manufacturers, the development of standard test methods, and the elimination of user's problems in installing access tubes and in establishing appropriate calibration procedures. The internal problems, e.g., drift with temperature and unreliability and the status of test procedure development were discussed earlier in this report. The following paragraphs, which are based on the survey results and the literature, are intended to serve as discussion of the state-of-the-art in resolving some of the continuing problems associated with subsurface gage usage.

1. Access Tube Installation

The survey results and the literautre indicate that there is, at present, no installation method clearly superior for all materials and for all depths. However, depth gage users and researchers agree that it is important to get as tight a fit as possible between access tube and soil. Data indicates that each increase of 1/16 inch (1.6 mm) in the air gap between the tube and the soil results in an additional error of 0.3 percent in moisture determinations (at 13 to 15 percent moisture).

Continuous air-gap voids are produced because a single auger will yield different size holes in different soil materials, while the access tube diameter remains the same. Voids are also produced locally in granular materials when pieces of rock are dislodged during drilling and during tube installation. These voids produce errors in gage readings both when they are air-filled and at later times when many become water-filled. In certain materials, such as rocky or very dry soils, augering a hole twice as large as the access tube and then backfilling around the tube with either sand or cuttings from the hole works well. It is particularly important with this method, however, to adjust calibration curves by comparing gage responses with data from field samples (oven-dried for moisture determinations).

The most extensive tube installation program, that by Oklahoma (see Bibliography), indicated success over a wide range of materials using a 1 7/8-inch (47.6 mm) O.D. auger with a small diameter stem to drill holes for 2-inch (50.8 mm) O.D. access tubes. The same researchers reported that expansive soils generally produced a very tight fit around access tubes within 60 days of installation.

Aluminum is the material of choise for access tubing because it is not a strong neutron absorber. Aluminum access tubes thus allow probes to show the maximum sensitivity to variations in moisture content. Steel is more suitable when data is to be taken at greater depths, and it may be desirable to use stainless steel if the soil environment is corrosive. Iron is a strong neutron absorber,so there will be a considerable loss of sensitivity of the moisture probe. Plastic tubing is cheap and corrosion resistant, but it reduces probe sensitivity to moisture changes even more than does steel tubing. Tubes for long-term soil testing should be capped at the bottom end to prevent water rise inside.

2. Calibration

Although many of the respondents to the survey indicated they rely on manufacturer's calibration curves, this practice is not to be recommended. Variations in chemical composition and density between the user's soils and the manufacturer's standards will often produce significant errors in moisture content determinations. As a very minimum, a manufacturer's curve should be corrected by comparing several oven-dried moisture contents with the gage responses.

For long-term use, a single composite calibration curve developed by the user may be adequate for a state's range of soils. However, IAEA Report 112, cited in the Bibliography, states that using a single calibration curve for a variety of soil compositions and densities will limit accuracies of moisture content determinations to about $\pm$ 0.1g/cm^3 ($\pm$ 6.2 pcf). The composite curve may be constructed from readings on laboratory primary (local materials compacted at various moisture contents in drums or barrels) or secondary (limestone, concrete, alum) standards. Calibration curves may also be constructed from field test comparisons with results of gravimetric procedures, e.g., oven-drying, or from combonations of the laboratory and field methods.

Calibration curves produced from primary laboratory standards are the most desirable, but it is difficult to get homogeneity and to maintain constant moisture in the standards. Also, calibration curves constructed from laboratory standards are valid in the field only when used with access tubes of the same material and wall thickness as were incorporated in the standards. Care must be taken with laboratory standards to make sure that they are large enough to represent an "infinite" sample to the probe. (Correspondingly, measurements must not be taken too near to the surface, i.e., centered less than 1 ft. (0.3 m) down, or to structures.) Field gravimetric tests are subject to criticism as standards of comparison because the nuclear moisture gage looks at a much larger soil volume than does a standard oven-drying determination.

For greatest accuracy, it is necessary to construct a moisture calibration curve for each material and density being encountered. The IAEA report estimates that this calibration procedure will allow accuracies up to $\pm$ 0.01 g/cm^3 ($\pm$ 0.6 pcf).

3. Accuracy

The users claimed nuclear moisture content measurements were accurate to within $\pm$ 0.3 to 8 pcf ($\pm$ 5 to 128 kg/m^3) of "true" values and densities were accurate to within $\pm$ 0.35 to 7.6 pcf ($\pm$ 6 to 122 kg/m^3).

These compare with the results of the 1967 ASTM survey of gage manufacturers which reported the corresponding ranges as $\pm$ 0.3 to 1.5 pcf ($\pm$ 5 to 24 kg/m^3) and $\pm$ 2.0 to 4.0 pct ($\pm$ 32 to 64 kg.m^3) respectively. One state reported that nuclear moisture contents were generally within 2 percent of the gravimetric value and never more than 4 percent away. For a given user and soil sample, the accuracies of nuclear density and moisture determinations are limited by:

a. The quality of the calibration curves;
b. Local chemical composition and density variations;
c. Gage precision;
d. Voids or other distortions in the sample which arise during access tube installation; and
e. The inaccuracy of the results of conventional tests to which they are compared.

CONCLUSION

There has been little evident growth in the use of subsurface nuclear moisture and density gages by transportation agencies in the past decade. Problems with unreliable first generation equipment, questionable results, and lack of apparent need have slowed the spread of their use. Nevertheless, as the present survey results indicate, the nuclear gages remail useful tools for obtaining subsurface moisture and density information for a variety of research and trouble-shooting needs.

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