INTERNATIONAL STANDARD

ISO 10573

First edition
1995-12-15

Soil quality — Determination of water content in the unsaturated zone — Neutron depth probe method

Qualité du sol — Détermination de la teneur en eau de la zone non saturée — Méthode à la sonde à neutrons de profondeur

Reference number
ISO 10573:1995(E)

Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

Draft International Standards adopted by the technical committees are circulated to the member bodies for voting. Publication as an International Standard requires approval by at least 75 % of the member bodies casting a vote.

International Standard ISO 10573 was prepared by Technical Committee ISO/TC 190, *Soil quality*, Subcommittee SC 5, *Physical methods*.

Annexes A, B, C, D and E of this International Standard are for information only.

International Organization for Standardization
Case Postale 56 • CH-1211 Genève 20 • Switzerland

Printed in Switzerland

Soil quality — Determination of water content in the unsaturated zone — Neutron depth probe method

WARNING — Neutron depth probes contain radioactive sources which will present health and environmental hazards if a probe is improperly used, stored or disposed of. National and international legislation and regulations must be complied with.

1 Scope

This International Standard specifies an *in situ* method for the determination of water content in the unsaturated zone of soils using a neutron depth probe. It is applicable when investigations into the water storage, water balance and water distribution in the unsaturated zone of the soil are carried out. Because the method is non-destructive, it is particularly suitable for repeated measurements at fixed locations. Water content profiles can be obtained by measuring at a series of depths down to any depth within the range of the phreatic level at the site.

The advantage of the method compared with some others, for example the gamma probe method, is the rapidity with which measurements can be carried out. A disadvantage, however, is the relatively poor depth resolution of the measurements.

2 Normative references

The following standards contain provisions which, through reference in this text, constitute provisions of this International Standard. At the time of publication, the editions indicated were valid. All standards are subject to revision, and parties to agreements based on this International Standard are encouraged to investigate the possibility of applying the most recent editions of the standards indicated below. Members of IEC and ISO maintain registers of currently valid International Standards.

ISO 11272:—[1], *Soil quality — Determination of dry bulk density.*

ISO 11461:—[1], *Soil quality — Determination of soil water content calculated on a volume basis — Gravimetric method.*

3 Definitions

For the purposes of this International Standard, the following definition applies.

3.1 water content volume fraction, θ : The volume of water evaporating from soil when dried to constant mass at 105 °C, divided by the original bulk volume of the soil.

NOTES

1 The water content may be expressed as a percentage by volume or a volume fraction.

2 In this International Standard, water content as defined above may also be referred to as "free water".

---

[1] To be published.

3 The procedure for drying soil to constant mass at 105 °C is described in ISO 11461.

4 The procedure for determination of the bulk volume of soil is described in ISO 11272.

4 Principle

A neutron depth probe, consisting of a neutron source and detector, is lowered into a vertical access tube in the soil. The neutron source, usually of the ^{241}Am-Be type, emits neutrons of high kinetic energy. The neutrons lose part of their energy when they collide with atomic nuclei. After several collisions, their energy level is reduced to the thermal energy level corresponding to the prevailing temperature. This level is reached most rapidly when neutrons collide with hydrogen nuclei because their masses are almost equal.

The thermal neutrons form a stable cloud, the concentration of which is determined by the detector in the probe. The number of thermal neutrons registered by the detector per unit time (the count rate) is therefore a measure of the concentration of hydrogen nuclei in the soil around the probe. In general, the majority of those nuclei are in water molecules and therefore the count rate is also a measure of the soil water content. A calibration curve is used to convert the neutron count rate to soil water content.

NOTES

5 The neutron count rate obtained is influenced by the presence of all the atomic nuclei in the soil. However, the count rate at a given water content may be increased in some soils because of the thermalization of neutrons by collisions with nuclei of certain soil elements, or because much hydrogen is present in substances other than free water. However, the count rate may be decreased because of absorption of neutrons by nuclei with a large atomic absorption cross-section. See annex A.

6 The soil volume (measuring volume) to which the measurement refers approximates a sphere. For a given type of neutron probe, the radius of the sphere depends on the total density of atomic nuclei in the soil. For the majority of probes used in practice, the radius of the volume from which 95 % of the neutrons counted by the detector are generated ("the sphere of importance" [1]) can vary from 0,1 m to 0,2 m in wet soil to 0,8 m or more in dry (sandy) soil. Consequently, the measurement obtained at a given depth is influenced by the water content distribution within the measuring volume at that time, and by any other gradients in soil composition. Therefore, reproduction of the measurement of a given water content at a certain depth is only possible when the distributions of water content and of soil composition within the measuring volume are time-invariant. This requirement (local time-invariant gradients) is important for the calibration of the neutron depth probe. See annex A.

7 The shape and parameters of the calibration curve depend on the following (see [2] in annex E):

- the chemical composition of the soil horizon considered and its bulk density;
- the gradients in this composition that occur within the measuring volume;
- the gradients in soil water content that occur within the measuring volume;
- the method of access tube installation;
- the characteristics of the access tubing;
- the specifications of the apparatus used.

The calibration curve usually differs for each soil layer. In homogeneous layers that are thicker than the measuring volume, calibration curves are generally linear, their parameters depending on the soil composition. In the case of thin or non-homogeneous soil layers, however, calibration curves will often be non-linear due to the different effects of gradients in soil composition and water content under wet and dry conditions.

5 Apparatus

5.1 Neutron depth probe, consisting of a fast neutron source and a thermal neutron detector combined with a read-out unit.

5.2 Thin-walled access tubing, with an inner diameter slightly larger than that of the neutron probe. The tubing shall consist of material that is very "transparent" to fast and thermal neutrons (e.g. aluminium, aluminium alloy) and which is resistant to chemical corrosion and to deformation due to installation activities. Stainless steel, galvanized iron and plastics (polyethylene) are also suitable, though less transparent to neutrons.

5.3 Equipment for installing access tubes.

5.4 Equipment for drying and cleaning the access tubes, if necessary, a dummy probe for testing the tubing performance.

5.5 Calibration curves, for conversion of count rate to water content.

5.6 Usual apparatus for taking soil samples, for carrying out a field calibration to determine the volumetric water content θ gravimetrically according to ISO 11461.

6 Procedure

6.1 Installation of access tubes

The location shall be representative of the immediate surroundings and care shall be taken to avoid surface water from concentrating on the spot. Use a platform to prevent damage to surrounding vegetation and compaction of the soil surface whilst installing a tube. Ensure that radial soil compaction around the tube, compaction below it and the creation of voids adjacent to it are prevented as far as possible.

Install access tubes by either of the following methods.

a) Push the tube into the soil using a hammer and empty it using an auger. It is recommended that the lower end of the tube be closed with quick drying cement or a stopper, to prevent infiltration of ground water.

b) Push the tube into a prepared hole of the same or slightly smaller diameter and of the required depth, then seal the lower end as in 6.1.1. Alternatively, the lower end of the tube may be sealed before insertion.

Holes can be prepared using a guide tube or an auger or by a combination of these two methods. Close the top of the tube with a tight rubber stopper to keep out rain or surface water. The tubing shall always be dry inside.

NOTES

8 It is recommended that access tubes be cut to protrude above the soil surface as little as the apparatus permits, so as to minimize the radiation dose received by the operator when lowering the probe.

9 More specific guidelines for installation are given in [3] and [4] in annex E.

After installation, take great care to minimize disturbance of the soil and vegetation at the site whilst conducting measurements in the access tube.

6.2 Calibration

In most cases, calibration curves supplied by neutron probe manufacturers, and those published in the literature, give only a rough indication of the absolute soil water content, because no or insufficient recognition can be given to the specific influences of the site mentioned in note 7 in clause 4 (see also annex A).

The influence of chemical composition and bulk density (see A.2) is accounted for in calibrations derived theoretically from the macroscopic neutron-interaction cross-section of the soil concerned (see [1], [4], [9] in annex E).

The combined influence of gradients in water content, chemical composition and bulk density is only accounted for by a field calibration. Therefore an *in situ* field calibration is necessary for accurate measurements of absolute water content.

The field calibration is based on simultaneous determination of the neutron count rate and sampling for the determination of the volumetric water content of each soil layer in accordance with ISO 11461, under several different hydrological conditions, to derive a calibration curve for each layer.

NOTE 10 The subdivision of the soil profile into layers is determined initially by differences in soil composition, but the form of soil water content gradients that systematically recur should also be considered. Further divisions may be necessary to meet the objectives of the investigation.

The hydrological conditions under which the calibration is conducted shall differ as much as possible so that the calibration curves are representative of the range of conditions which occur at the site. To meet the requirement for time invariant gradients that do not vary with time as much as possible, the calibration shall not be conducted after heavy rain or irrigation applications, or immediately after the sudden beginning of extremely warm weather.

Determine the calibration curves by analysing the various combinations of neutron count rate and water content for each soil layer by regression analysis. The count rate is considered as the independent variable (x) and the water content as the dependent variable (y). Calibration curves so derived are specific to the neutron probe used. Use of reference counts to normalize the count rate measurements used in the regression allows calibrations to be used with different probes of the same geometry (see annex C).

Further guidelines for carrying out a field calibration are given in [2], [3], [4] in annex E and in annex B.

NOTES

11 The calibration curves may change in time due to the following processes:

- changes in the chemical composition of the soil including that of the soil water, and changes in bulk density. This can be corrected for, to a certain extent, on the basis of known (chemical) properties (see [3] in annex E);
- decrease of the source strength of the probe due to radioactive decay, and/or decrease in the sensitivity of the detector. This can be corrected for by the use of reference counts made in a medium with invariant characteristics (see annex C).

12 The guidelines given here apply to the measurement of absolute water content. When only relative measurements (i.e. changes of water content in time) are to be assessed, the requirements for calibration and demands on accuracy may be less stringent.

6.3 Measurements

The neutron depth probe shall be used in accordance with the manufacturer's instructions as much as possible, and particularly with respect to technical handling and safety.

Lower the probe in the access-tube to the depth at which it is required to make the measurement.

Conduct the counts according to one of the following methods:

a) with a fixed counting time; in this case the number of thermal neutrons detected is recorded;

b) with a fixed number of detected thermal neutrons; in this case the counting time is recorded.

NOTES

13 When changes of water content in time are to be determined, precise positioning of the probe at a specified depth is important.

14 The second method mentioned for taking the counts has the advantage that the accuracy of the measurement is relatively constant (i.e. precision of the count rate), whereas the accuracy depends on the water content in the first method.

Instead of conducting a single count for a long time, it can be advantageous to make a number of counts for a short time because this provides quantitative information about the spread of the measurements. This information allows detection of certain types of failure in the apparatus.

It is recommended that reference counts in a medium with invariant characteristics, such as a large water barrel (see C.3.1), be made at frequent intervals to check the overall performance of the instrument. For example, a reference count might be carried out before and after each series of measurements in a specific access tube. A certain amount of drift in the reference count is to be expected. However, a sudden change from the general pattern almost certainly indicates a failure of the apparatus, which should be repaired or replaced.

6.4 Safety and maintenance

SAFETY PRECAUTIONS — The radioactive source within a neutron depth probe is a potential hazard to the operator, the public and the environment. Most governments and organizations have legally enforceable regulations concerning the acquisition, operation, transport, storage and disposal of radioactive devices, which must be adhered to. In the absence of specific radiological safety regulations, the guidelines of the International Atomic Energy Agency [6], [7] and of the International Commission on Radiological Protection [8] should be consulted.

The half-life (458 years) of the americium commonly used in neutron depth probes is longer than the time over which the integrity of the source container (e.g. about 30 years) can be expected to last. When a neutron depth probe is no longer required, the radioactive source must be disposed of at a repository for radioactive waste.

Neutron depth probes shall only be used by suitably trained operators. Maintenance shall only be conducted by appropriately skilled persons. Periodic checks to test for leakage from the sealed source shall be carried out by a competent agency.

7 Expression of results

Calculate the count rate R, which is the number of detected thermal neutrons per unit of time, using the following equation:

$$R = \frac{N}{t}$$

where

R is the count rate, in counts per minute;

N is the number of counted thermal neutrons;

t is the counting time, in minutes.

Calculate the water content θ, using the equation:

$$\theta = f(R, p)$$

where

θ is the water content, expressed as a volume fraction;

f is the calibration function (calibration curve) calculated by regression analysis;

R is the count rate, in counts per minute;

p represents the parameters of the calibration curve.

When necessary, the count rate can be corrected for the difference between the actual reference count rate (R_s) and the expected reference count rate (R_{se}). In most cases, a correction of the type $R' = R(R_{se}/R_s)$ may apply, where R' is the corrected count rate. For further explanations, see annex C.

8 Accuracy

8.1 The accuracy of the water content determined with the neutron probe is influenced principally by the following error sources.

a) The scatter in individual counts or count times as a result of the random variation in the number of neutrons emitted by the neutron source.

The magnitude of this error is usually expressed as the standard deviation of the number of neutrons counted. As the emission process follows a Poisson distribution, the resulting standard deviation in the number of detected neutrons is

$$s_N = \sqrt{N}$$

b) The inaccuracy of the calibration curve used.

This can be determined from the results of the regression analysis used to derive the curve. Within the field calibration, the following sources of errors can be distinguished:

- horizontal spatial variability in soil water content during the field calibration;
- small fluctuations in the shape of the water content profile during the field calibration, due to non-stationary flow conditions (see also annex A).

Together, these influences determine the residual standard deviation of the regression curve, i.e. the calibration curve (standard error of the regression).

c) Inaccuracy in the depth of placement of the probe with respect to the calibration depth, particularly when steep water content gradients occur.

8.2 When large variations in the shape of the water content profile occur, e.g. as a result of strong wetting or evaporation fronts, the calibration curves are less reliable and accuracy decreases accordingly.

8.3 When field calibration and measurements are carried out under the conditions mentioned in this International Standard, the accuracy of the calculated water content will also be determined by the number of counts taken for each measurement [see 8.1 a)], the number of samples for gravimetric determination that are taken for each soil layer and/or sampling location [see 8.1 b)] and the number and range of different hydrological conditions sampled. For sandy soil profiles of reasonable spatial homogeneity, an accuracy of 0,005 m^3/m^3 to 0,01 m^3/m^3, or 0,5 % (V/V) to 1,0 % (V/V) in the calculated individual water content can be reached, with moderate effort (see [2] in annex E). For soils that are more spatially variable with respect to water content (particularly clay, alluvium and peat soils), a greater effort is necessary to reach that accuracy. Further details with respect to conducting measurements and determination of accuracy are given in annex D.

8.4 The accuracy of the relative or differential water content (i.e. the change in water content with time) will always be better than that of absolute values, because some systematic errors (e.g. in the positioning of the calibration curve) are eliminated. To calculate the accuracy of the differential water content, the error sources listed in 8.1 a), b) and c) can be taken as a starting point for the analysis of the propagation of errors through the relevant equations (i.e. the calibration curve and the equation for calculating the differential water content).

9 Test report

The test report shall include the following information:

a) a reference to this International Standard;

b) an accurate site description of the sampling location and characterization of the soil profile;

c) a description of the procedure used to install access tubes;

d) a reference to an accurate description of the apparatus used, with all necessary performance characteristics;

e) data on the calibration curves used;

f) the water content for various depths, in cubic metres of water per cubic metre of soil;

g) all observations that are important to the interpretation of the results, such as the hydrological and meteorological conditions before and during the measurements.

Annex A
(informative)

Background information for the calibration of the neutron depth probe

A.1 Introduction

This annex elaborates upon the theoretical problems associated with neutron probe calibration under practical circumstances.

A.2 Fundamental influences on measurements made with a neutron depth probe

Several factors influence the count rate measured at a given soil water content. Distinction can be made between so-called homogeneous effects and non-homogeneous effects. The first group refers to effects that are present when taking measurements in a homogeneous medium, i.e. in which the (chemical) soil composition as well as the water content are uniform. The second group refers specifically to the effects caused by gradients in these parameters within the measuring volume.

A.2.1 Homogeneous effects

When measurements are carried out with a neutron depth probe in a homogeneous medium, the count rate at a given (free) water content is influenced by the following processes.

a) Thermalization due to collisions with atomic nuclei other than hydrogen nuclei in the soil measuring volume.

   Because they are such significant components of soils, oxygen and silicon nuclei are the most important. However, whereas an average of 17 collisions with a hydrogen nucleus are necessary to bring a neutron with an initial energy of 1 MeV to a thermal energy level of 1/40 eV, this requires 136 collisions with an oxygen nucleus and 240 collisions with a silicon nucleus (see [10] in annex E). The hydrogen present therefore dominates the thermalization process.

b) Collisions with hydrogen nuclei present in

   1) non-free water (H_2O); or

   2) those present in other compounds containing hydrogen.

   Category 1) refers to water that does not evaporate when soil is dried according to the prescribed procedure (see ISO 11461).

   Categories 1) and 2) include

   - water present in confined pores;
   - intercrystalline water, such as water between clay plates;
   - intracrystalline water, i.e. water of crystallization;
   - hydrogen present in aluminium hydroxides (bauxite laterite soils) or in organic compounds (peat soils).

   In all cases, the presence of hydrogen in such compounds may have a significant effect on the thermalization process.

c) Absorption of thermal neutrons by nuclei with a large cross-sectional area of absorption. The most important elements in the context of soils are boron, chlorine, iron and nitrogen because they occur in abundance in certain situations.

The factors mentionned under categories a) and b) increase the measured count rate for a given water content. Absorption of thermal neutrons [category c)], however, decreases the count rate. The influence of all these factors can vary with time because of changes in the concentration of the compounds involved. This applies particularly to organic matter (oxidation), iron and other metals and minerals (leaching influenced by soils genesis), chlorine (in the case of saline soils) and nitrogen (fertilization and leaching).

Changes in soil bulk density due, for example, to cultivation, alter the concentration of all the compounds present in the soil and so modify the effects of the factors mentioned under a), b) and c).

A.2.2 Non-homogeneous effects

Non-homogeneous effects arise when gradients in soil composition and/or water content are present within the measuring volume. For a given water content at a certain depth, the probe count rate reflects the integrated water content distribution within the measuring volume. This is also influenced by the generally bell-shaped impulse-response function (i.e. sensitivity distribution) of the detector. For the same water content at that depth, but with a different water content distribution around it, the probe will give another result. Thus, for reproducible measurements, the water content distribution for a given water content at a certain depth should be time-invariant. This condition can be regarded as the basic requirement for the field calibration of the neutron depth probe.

Another factor is the non-symmetric averaging within the measuring volume, because the radius of the measuring volume depends on the total atomic nuclei density [2]. This results in a net underestimation of the average water content within the measuring volume when a gradient of water content is present, irrespective of its direction. This effect is also referred to as the interface effect in the literature.

In practice, the most severe examples of the interface effect occur at the soil surface (soil/air interface) and commonly also in the interface present between a humus-rich topsoil and the subsoil or bedrock.

A.3 Hydrological state of the soil water

Time-invariant gradients of water content occur under certain hydrological conditions. At any point in time, the vertical distribution of water content is governed by the type of flow occurring in the unsaturated zone. In soils with shallow water tab's, two types of flow can be distinguished.

a) **Stationary flow** (equilibrium conditions)

This is characterized by a constant vertical distribution of water content (steady — state water content profile), for given conditions in the topsoil (pressure head h) and a given depth d of the phreatic level (groundwater level), the so-called state variables. This results in spatial-(depth-)invariant and time-invariant capillary flux. Each time that this combination of state variables occurs, the same local gradients will occur. In this explanation, the influence of hysteresis of soil physical properties is neglected.

b) **Non-stationary flow** (non-equilibrium conditions)

This is characterized by a varying vertical distribution of water content for a given combination of the state variables, h and d. Therefore, for a given water content at a certain depth and a given combination of state variables, different local water content distributions can occur within the measuring volume. Non-stationary flow conditions occur mostly after severe rainstorms (wetting fronts) or after any other sudden change in hydrological conditions, hence also after the onset of a period of severe drought (evaporation fronts).

In practice, there is a fairly consistent seasonal course to the hydrological changes in the unsaturated zone, correspondig to a sequence of fixed combinations of h and d. At any one time, this combination will vary around the average combination. This results in slight divergences in water content measurements. The effect of hysteresis is similar. In field calibration, these divergences manifest themselves in spreading of calibration points around the calibration curve and thus in the accuracy of this curve.

For sites with a shallow water table, the following applies.

Satisfying the requirement of time-invariant (local) gradients is only possible when the state variables can be determined, and when stationary flow is taking place. In practice, the depth of the phreatic level is the more sensitive of the state variables. The reason for this is the steep gradient $d\theta/dh$ of the water retention curve in that area (i.e. h is approximately zero), from which it follows that the gradient in the water content is large at high water potentials hydrostatic pressure distribution (slightly negative to zero), and small at low water potentials (large negative values). So, for a given depth of the phreatic level, the biggest change in the water content profile due to changing conditions in the topsoil, will occur near the phreatic level. But, under such wet conditions, the radius of the measuring volume, and thus the interface effect, is minimal. Inversely, the radius of the measured volume will be larger near the topsoil, but the gradient in the water content profile will be smaller. Hence the conditions in the topsoil are less sensitive with respect to the requirement of time-invariant gradients.

Where no permanent shallow water table exists, non-stationary flow conditions will be prevalent. For calibration purposes, conditions occurring when marked wetting or drying fronts are moving through the soil should be avoided.