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Soil quality —

Part 5: Physical methods —

Section 5.2 Determination of water content in the unsaturated zone — Neutron depth probe method

ICS 13.080

Committees responsible for this British Standard

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Association of Consulting Scientists
British Society of Soil Science
Cambridge University
Institute of Hydrology
Institution of Civil Engineers
Macaulay Land Use Research Institute
Soil Survey and Land Research Centre
University of Glasgow
University of Stirling
University of Ulster

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Contents

National foreword

This Section of BS 7755 has been prepared by Subcommittee EH/4/5 and is identical with ISO 10573:1995 *Soil quality — Determination of water content in the unsaturated zone — Neutron depth probe method*, published by the International Organization for Standardization (ISO).

ISO 10573 was prepared by Subcommittee 5, Physical methods, of Technical Committee ISO/TC 190, Soil quality, with the active participation and approval of the UK.

BS 7755 is being published in a series of Parts subdivided into Sections and Subsections that will generally correspond to particular International Standards. The Parts of BS 7755 are, or will be, as follows.

- — *Part 1: Terminology and classification*;
- — *Part 2: Sampling*;
- — *Part 3: Chemical methods*;
- — *Part 4: Biological methods*;
- — *Part 5: Physical methods*.

Cross-references. The Technical Committee has reviewed the provisions of the draft of ISO 11272 and ISO 11461, to which normative reference is made in the text, and has decided that they are acceptable for use in conjunction with this standard.

Textual errors. When adopting the text of the International Standard, the textual errors listed below were discovered. They have been marked in the text and have been reported to ISO in a proposal to amend the text of the International Standard.

In **6.2**, the second sentence of paragraph 5 should read “To meet the requirement for time invariant gradients, the calibration shall not be conducted after heavy rain or irrigation applications, or immediately after the sudden beginning of very warm weather.”

In **A.3**, the first sentence in item a) should read “This is characterized by a constant vertical distribution of water content (steady-state water content profile), for given soil water potential conditions in the unsaturated soil (pressure head, *h*) and a given depth *d* of the phreatic level (groundwater level), the so-called state variables.”

In **A.3**, paragraph 4 of item b), in lines 9 and 10 delete “hydrostatic pressure distribution”; in line 17, delete “Inversely” and substitute “Conversely”.

In **B.2**, the second sentence of paragraph 4, delete “depth probes calibration” and substitute “calibration procedures for neutron depth probes”. In paragraph 6, delete the last two sentences and substitute “A depth interval of less than 0.1 m is not usually useful because of overlapping of the measuring volume (the sphere of importance of the probe) as measurements are made”.

In **D.1**, line 3, delete “final result of” and substitute “resulting”.

NOTE *Typographical errors*
In **6.1** b), line 3, the reference to **6.1.1** should be to **6.1** a).
In **A.2.1**, in the first line of the paragraph below the list, “mentionned” should be “mentioned”.
In **A.3**, in the penultimate line of paragraph 1, “tab’s” should be “tables”; in the first sentence in paragraph 4 “corresponding” was misspelt.
In **D.3**, in the penultimate line of paragraph 4, “$s_e \approx s_1$” should be “$s\theta \approx s_1$”.
In Annex E, in reference [3], “GRAECEN” should be “GREACEN”.

Summary of pages

This document comprises a front cover, an inside front cover, pages i to iv, pages 1 to 12, an inside back cover and a back cover.

This standard has been updated (see copyright date) and may have had amendments incorporated. This will be indicated in the amendment table on the inside front cover.

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

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

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

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

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

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

NOTE 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.

NOTE 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.

NOTE 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.

NOTE 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;

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[1] To be published.

— 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.

NOTE 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.

NOTE 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. [2]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.

NOTE 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).

NOTE 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.

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

NOTE 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.

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[2] See national foreword for details of textual error.

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)

[3]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, corresponding 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 [3]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[3], 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.

Annex B (informative) Field calibration

B.1 Introduction

This annex gives background information on the actual field calibration of the neutron depth probe and elaborates upon the procedures to be followed when carrying out a field calibration.

B.2 Field calibration procedures

In view of the information given in Annex A, it is important when conducting calibrations that

a) the calibration field work should be carried out under stationary flow conditions as far as possible;

b) if possible, the time of calibration should be chosen so that typical hydrological conditions for that time of year exist.

This permits derivation of calibration curves which are representative for all subsequent measurements, made under similar conditions.

Field calibration is based on simultaneous determination of count rates and gravimetric sampling in a given soil layer.

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[3] See national foreword for details of textual error.

There are several alternative approaches to field calibration. Useful reviews of depth probes [4)]calibration procedures for neutron are provided by [3] and [4] in Annex E. The objectives of the investigation determine what degree of accuracy is desirable for the water content measurements and these (external) requirements should be considered when designing the calibration procedure.

Whichever method is applied, it is first necessary to distinguish the layering in the soil profile and to determine at what depths calibration data are to be collected. These are usually apparent from the constitution of the soil profile itself, because the strongest gradients in water content will be present at transitions in texture and soil composition. Depending on the objectives of the investigation, supplementary distinctions may be made. In principle, there is no limitation, for calibration purposes, to the minimum distance between two depths where measurements are carried out.

However, the relative accuracy of the differences in the water content measurements made will decrease because of the decrease in the differences as such. [4)]Therefore, a differentiation in the vertical that is too important will be less meaningful.

There are two main approaches to field calibration as described in **B.2.1** and **B.2.2**, and combinations of these may also be used.

B.2.1 *Permanent access tube; fixed-site calibration method*

Counts are made at selected depths in an access tube and samples for the gravimetric determination of water content as a volume fraction (according to ISO 11461) are collected at those depths from positions around the access tube, but at a distance of at least 1 m from it. This exercise is repeated several times so that the data are representative of the full range of soil hydrological conditions at the site. The calibrations so obtained are specific to the access tube at the site. It is reasonable to assume that, for a point measurement within a homogeneous soil, the spatial variability generally is "saturated" within a few metres (i.e. within that distance the full amount of short-distance variability is reached) and sampling points should be distributed within a circle with a radius of about 2 m. Usually, this also gives enough room for repeated sampling without altering the hydrology of the area around the access tube significantly.

B.2.2 *Temporary access tube; walking-site calibration method*

One or more temporary access tube(s) is (are) installed near the measurement site. Counts are made in each at the selected depths and then samples are taken from the area immediately adjacent to each tube (i.e. from within the measuring volume of the probe) at the same depths, by excavating around it. The tube is then removed. This exercise is repeated several times so that the data are representative of the full range of soil hydrological conditions. The locations where the temporary tubes are installed should be seperated by at least 2 m. The calibrations so obtained are representative of the layers that have been defined.

B.3 Design of the field calibration

For the design of the calibration and sampling (by either **B.2.1** or **B.2.2**), the following procedure may be used. On the basis of an estimate of the spatial variability of the water content in the relevant layers, it is possible to define

a) the number of soil samples to be taken in each soil layer for each sampling date;

b) the number of hydrological situations that should be sampled (i.e. sampling dates).

For this, the formula given in **D.3** can be used.

For site-specific calibrations, the distribution of sampling, in a horizontal direction about the permanent access tube, should be representative of the area which the calibration is intended to represent. So, in the case of near-site representativity, a small area is sampled, while a larger area is sampled in the case of far-site representativity; according to the purposes of the investigation.

It is always preferable to aim to sample a large range of soil hydrological conditions, even when the focus is only on a part of the calibration curve. This is because the accuracy of the slope of the calibration curve is very sensitive to the range of water contents sampled.

For mathematical reasons (regression analysis) it is important that the independent variable (in this case the count rate) has a negligible error. When conducting calibrations, it is recommended that a count rate accuracy that is an order of magnitude higher than the expected accuracy in the water content values is obtained, either by making repeated counts, or by using longer count times.

[4)] See national foreword for details of textual error.

When only temporal changes in water content (e.g. relative water content changes) are to be determined, more simplified calibration procedures may be applied, such as soil — specific calibration, neglecting all non-homogeneous effects.

If a neutron reflector is used in order to diminish the neutron loss near the soil surface, a different calibration curve will result.

Annex C (informative) Reference counts

C.1 Introduction

This annex gives background information on the performance of reference counts and elaborates upon the necessity for and use of reference counts.

C.2 Procedures

Reference counts should be made so that any defects and variations in the neutron depth probe can be detected. For older equipment, regular correction of water content measurements by means of the reference count is sometimes unavoidable because of persistent drift in the count.

As long as the variation in the reference count is systematic, it can be used as a basis for correction of counts that have been made in the field. Where the variations in the reference count rate are proportional to the magnitude of the count rate, the following formula can be used for correction:

$$R' = R \times \frac{R_{se}}{R_s}$$

where

R is the actual count rate, in counts per minute;

R' is the corrected count rate, in counts per minute;

R_{se} is the reference (i.e. expected) count rate in the reference medium, in counts per minute;

R_s is the actual count rate in the reference medium at the time of measurement, in counts per minute.

In principle, any arbitrary value for R_{se} can be used, as long as the same value is used during calibration and all measurements carried out thereafter.

Similarly, if reference counts are routinely made, different neutron depth probes of the same design can be used at the field site, the reference count being used to normalize the count rate. See also [11] in Annex E.

A sudden change in the reference count generally indicates that the instrument is faulty and that it should be checked before further use.

After repair, the reference count of a probe may have changed, in which case the new reference should be used to correct field counts.

C.3 Reference medium

Possible options for the reference medium are described in **C.3.1** to **C.3.3**.

C.3.1 Measurement in a reservoir filled with water or any other compound with time-invariant characteristics.

The reservoir should be large enough for the difference between the count rate obtained within it and that which would be obtained in an infinite volume, to be negligible. A water-filled barrel, at least 0,5 m in diameter and 0,6 m deep, with a watertight access tube fitted axially is suitable for most types of probe.

C.3.2 Measurement in so-called reference layers.

These are layers in the soil profile at the measurement location that are always below the phreatic surface. It can therefore be assumed that the water content is constant in time. This method requires that the access tube extends to below the deepest phreatic level that may occur at the site. Control of the reliability of reference layers is possible by selecting more than one layer and comparing the variations mutually. The advantage of this method is that the reference measurements are part of the ordinary measurement scheme and do not require further effort.

C.3.3 Measurement within the shielding of the measuring apparatus in a fixed position, for example by always placing it on the box in which the apparatus is transported.

Great care is required with this approach because the readings will be sensitive to changes in the surroundings, including temperature, and the position/proximity of the operator. This method is not suitable for certain types of older equipment. It is not recommended unless other methods are impracticable.

Annex D (informative) Precision and applicability of field calibration curves

D.1 Introduction

This annex elaborates on the precision and applicability of field calibration curves and the propagation of errors in the [5]final result of neutron depth probe measurements.

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[5] See national foreword for details of textual error.

D.2 Error sources

Even when the requirements mentioned in **A.3** for calibration and measurement of stationary water content profiles are met, the physical sources of error described in **D.2.1** to **D.2.3** can be distinguished.

D.2.1 *Error sources during calibration in the field*

a) The distribution of horizontal spatial variability in the water content of the soil layer under consideration at the time of calibration.

The relevant variable for this type of error is the standard deviation s_1 of the horizontal spatial distribution of the water content. This includes the inaccuracy of the gravimetric water content of the soil samples used for the field calibration.

b) Small variations between the real shape of the water content profile and the "ideal" stationary profile (see **A.3**) and variations in the profile as a result of hysteresis in physical characteristics of soil.

This error source cannot be determined independently, but manifests itself in the spreading of the calibration points around the calibration curve (regression analysis), together with the influence of other errors.

c) Deviations due to installation (e.g. compaction, holes, variations in access-tube geometry) represent an error source only in the case of the walking-site calibration method (see **B.2.2**).

Quantitatively, these errors express themselves in the residual standard deviation of the regression line representing the calibration curve.

D.2.2 *Error sources in the normal measurements* (normal measurement errors)

a) Variations in the individual counts as a result, in the first place, of variations in the emittance of neutrons by the neutron source. As a consequence of this, the standard deviation in the detected number (N) of neutrons equals the square root of that number ($\sqrt{N}$).

b) Inaccuracy of the positioning of the probe.

c) Inaccuracy of the correction based on reference countings, if applied.

These normal measurement errors also apply to the field calibration. It is assumed, however, that a careful field calibration reduces these errors so as to be negligible compared to other types of error.

D.2.3 *Incidental error sources*

In addition to the sources of error mentioned in **D.2.1** and **D.2.2**, incidental errors can occur: for example, reading errors, mistakes in the positioning of the probe, etc. They cannot be estimated, however, and should be eliminated by screening the results (analysis of outlying values). These errors fall outside the scope of this annex.

D.3 Propagation of errors

With respect to the propagation of errors into the final uncertainty of the water content values obtained with the neutron probe, the following conditions apply:

- the errors in the field calibration are systematic in time for each soil layer;
- the normal measurement errors are of variable or random nature in time and space.

The influence of the errors during calibration in the field (i.e. the uncertainty of the calibration curve), can be approximated as follows:

$$s_\theta = \sqrt{\left(\frac{s_1^2}{n_1} + s_2^2\right) \times \frac{1}{n_2}}$$

where

s_θ	is the standard deviation of the water content (volume fraction) of the average calibration point;
s_1	is the standard deviation of the horizontal spatial variability in the water content (volume fraction) of the soil layer considered at the time of sampling;
s_2	is the standard deviation resulting from all other error sources (see **D.2.1**);
n_1	is the number of samples taken at a specific sampling date in the horizontal plane;
n_2	is the number of sampling dates.

The term $(s_1^2/n_1 + s_2^2)$ corresponds to the spreading of the individual calibration points around the regression line and therefore equals the residual standard deviation (s_e) of the calibration curve.

For known values of s_1 (spatial variability) the extent to which the calibration meets the requirements concerning hydrological stationarity during the calibration can be tested (i.e. if s_2 is acceptably small). When $s_e \approx s_1$, these requirements are fulfilled to a reasonable extent.

With the approximation given above and assuming that $s_2 = 0$, the number of samples required per layer (n_1) and the number of sampling dates (n_2) can be evaluated so as to meet the requirements concerning the accuracy of the final water content, s_θ. The accuracy criterion itself should follow independently from the objectives of the investigations carried out.

As a guide, the following values for spatial variability (s_1), which are representative of conditions in the Netherlands, are provided:

— sandy horizons: 2 % (*V*/*V*) to 5 % (*V*/*V*);

— peaty horizons: 5 % (*V*/*V*) to 10 % (*V*/*V*);

— loamy horizons: 5 % (*V*/*V*) to 15 % (*V*/*V*).

D.4 Applicability of field calibration curves

As stated in **D.2.1** a), it can be assumed that the inaccuracy in the gravimetric determination of the water content, carried out according to ISO 11461, is accounted for in these values.

The accuracy assessed in this way only applies to measurements under the following conditions:

— stationary unsaturated flow conditions in the soil;

— time invariant soil structure, chemical composition and physical properties of the soil profile and soil water.

Where these conditions are not met, the calibration curves will not represent the true distribution of water content so well.

Annex E (informative)
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