TMS CALIBRATION HANDBOOK

Prepared by
Lukáš Jačka
Martin Kovář
Marta Kuželková

Translation by
Lucie Haase

Why calibrate the TMS?

The TMS enable an indirect electrical measurement of soil moisture. The device records the amount of high-frequency electromagnetic pulses (with an approximate frequency of 2,5 GHz) sent through the printed circuit board within a defined time interval. This amount is functionally dependent on the soil's relative permittivity (dielectric constant). The resulting signal of the sensor arises from inverting and scaling the number of pulses. When the moisture increases, so does the signal value. The approximate signal values are 350 for air and 3650 for demineralized water. While the relative permittivity (and therefore the signal value) heavily depends on the soil water content (soil moisture), its value is likewise affected by a range of soil properties such as mineralogical composition, bulk density, organic matter content, arrangement of solid particles (structure) and their relative content based on their size (soil texture).

In order to obtain the most accurate values of soil moisture possible (or, more precisely, the volumetric soil moisture [cm3/cm3]), it is necessary to calibrate the TMS, as with all other indirect methods of moisture measurements, to the specific soil measured. Thanks to the calibration, the original functional relationship between the TMS signal and the soil moisture, measured through the standard reference method, is obtained. As the reference method, the gravimetric method is used; it consists of weighing the wet and dried soil sample and subsequently directly determining the soil moisture. Below you may refer to examples of TMS calibration carried out in a laboratory on a disturbed soil sample and calibration carried out in the field using samples extracted directly in situ, close to the installed sensors.

1. Laboratory calibration of the TMS using a disturbed soil sample

The principle of laboratory calibration lies in determining the dependence of the signal on soil moisture. In order to uncover this dependence, it is necessary to measure at least five soil moisture conditions (for a reliable calibration, seven and more are recommended) and the corresponding signals from the TMS. These values are then plotted onto a graph with a regression curve fitted through them. Using the regression curve equation, it is then possible to convert the signal moisture value into volumetric soil moisture.

The equipment necessary for laboratory calibration:

- soil
- calibration container
- scale (A)
- stirrer
- weighing dishes (A)
- sieve (B)
- food foil
- sprayer (A)
- TMS dataloggers
- intact soil sampling kit: sampling head, steel cylinder with caps and a mallet (C)
- laboratory drying oven

Calibration procedure

It is necessary to obtain a sufficient amount of soil for the calibration (approximately 10l). First and foremost, the soil must be adjusted and homogenized. The soil sample should be left to air-dry, and then the large soil aggregates must be disturbed as they would otherwise hinder the mixing of soil and water. In case of gravel or solid organic material (e.g., roots) present, it is advisable to sift the soil through a sieve with a mesh diameter of 2 mm. Soil that has been treated in this manner is then ready for calibration.

The soil is poured into a calibration container (a bucket of known volume). During this step, a few samples of approximately 20g are taken out to help establish the mass moisture of the initial state of the soil (for the procedure for calculating mass moisture, see Appendix 1). The bulk density of the poured soil should be as close as possible to the bulk density of the natural deposit determined from the field survey (see Appendix 1). Based on the bulk density, the weight and volume of the soil in the container can be defined in order to achieve a bulk density corresponding to the natural deposition. We recommend marking a reference line on the calibration container to clearly indicate the initial volume, which we advise adhering to as precisely as possible in the following calibration steps. After pouring in the soil, it must then be compacted to the desired bulk density. It is possible to use dynamic or static compaction (tapping on the wall of the container, weighing the surface, or a combination of the two). It is essential to compact the soil gradually into several layers depending on its properties. After that, the dataloggers can be carefully placed into the container, with the basic setting of measurements every 15 minutes (see Figure 1). The dataloggers should be left like this for at least ten measurements (approx. 2,5h). At this point, the first soil moisture condition is measured (dry soil).

For subsequent moisture values, the amount of added water must be determined. To estimate the amount of added water, it is necessary to determine the porosity from an undisturbed soil sample. This porosity is practically equal to the maximum bulk density. Next, we multiply the volume of the entire soil sample in the calibration container by the soil porosity. The resulting value equals the maximum volume of water that could be added to the soil sample. This volume is then divided by the required number of moisture conditions (for the calibration curve), resulting in the volume of water that should be added to the sample with each step.

To prepare the second soil condition, pour the soil into a larger container and add the set volume of water. The goal is to mix the soil through as best as possible so that the water is evenly distributed and the moisture is the same throughout. The sprayer can serve well to achieve this. Once the sample is mixed, take out the samples to establish the mass moisture. The moistened soil can then be returned into the calibration container, granted it retained approximately the same volume and, if needed, can be compacted as with the first soil condition (dry soil). Afterward, carefully insert the dataloggers again. The containers should then be covered to avoid water evaporation (e.g. by using food foil, see Figure 2). The measurement duration should be adjusted to the properties of the soil, and the dataloggers should be kept in the sample until the signal values stabilize (the difference is in units), which is usually min. 24 hours.

You may then proceed in the same manner with all the other soil moisture conditions up to full saturation values. The dataloggers are very sensitive to contact with the soil, so it is essential to proceed cautiously during the manipulation to prevent dislocating them. The values of the mass moisture (sampled for each condition) must be converted to bulk density. The conversion is achieved by multiplying the mass moisture by the bulk density. Once the calibration is finished, the data can be downloaded from the dataloggers using the software provided by the manufacturer, and the signal values are assigned to the corresponding volume moistures (see Table 1).

The data obtained (volumetric water content and corresponding signal value) is then plotted on a graph. A regression curve, for example, the 2nd-grade polynomial, is fitted through the points (see Figure 3). For the resulting interpolation of points with a polynomial, it is advisable to omit the extreme soil conditions (dry soil, full saturation). The accuracy of the calibration increases with the number of soil conditions measured.

Figure 1: Placement of datalogger in sandy soil

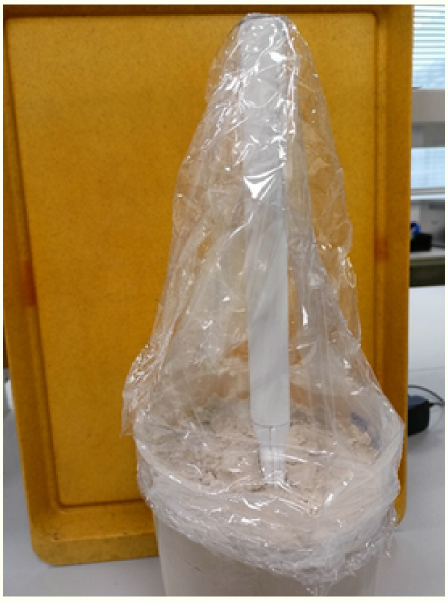

Figure 2: Food foil cover preventing water evaporation

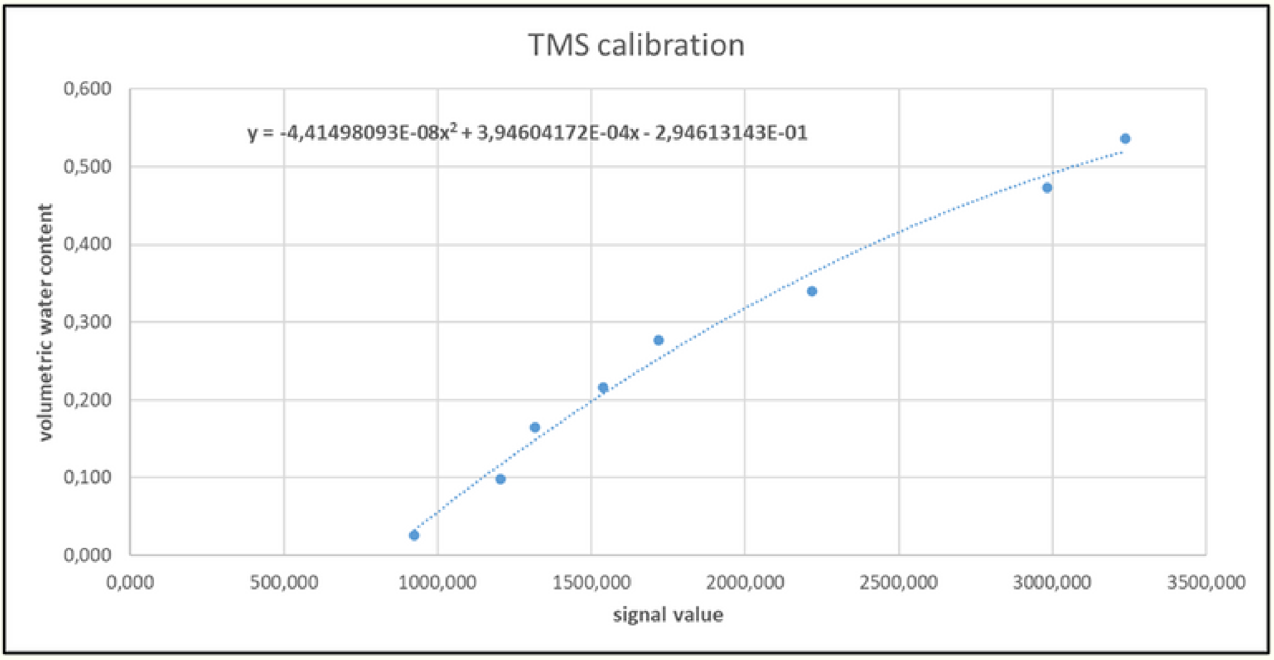

Figure 3: Points fitted with a curve of a 2nd-grade polynomial

Table 1: input data

signal value	**volumetric water content**
925	0,026
1203	0,098
1317	0,164
1539	0,217
1719	0,277
2219	0,340
2983	0,473
3235	0,537

2. TMS calibration carried out in the field using undisturbed soil samples, alternatively the TDR method

The key to calibrating in the field is determining the relation between the signal and the reference volumetric water content, which is defined for the naturally distributed soil located in close proximity to the installed TMS sensors.

The equipment necessary for field calibration:

- installed TMS
- kit for undisturbed soil sampling (see laboratory method, Fig. C)
- laboratory scale with a precision of at least 0,1g (see laboratory method, Fig. A)
- laboratory drying oven with the option of temperature regulation
- optional: accurate indirect moisture measurement method, e.g. TDR

Calibration procedure

In order to determine the relationship between the signal and the referential volumetric water content, it is necessary to collect undisturbed soil samples close to the installed TMS and into cylinders of known volume (see Appendix 2) and define their volumetric water content (see Appendix 3). Make sure to collect the sample at the same depths reached by your installed TMS sensors. It is important to collect the samples at different soil moisture conditions, especially at their driest and dampest during the data-collection period. It is useful to detect several soil moisture conditions for the initial calibration. For long-period monitoring (several years), we recommend collecting at least five various soil moisture conditions due to the potential nonlinearity of the relation between the signal and moisture. This will mean at least five field trips dedicated to collecting the small cylinders (undisturbed soil samples) when different soil moisture conditions are expected.

At the same time as the soil was sampled, data from TMS sensors should be downloaded using the software provided by the manufacturer. We recommend checking the TMS signal progress approximately in a period from 1 hour prior to extracting the first sample up to the last sample extraction and evaluating the signal variability accordingly. The signal should only change in the order of units. The change in humidity is then negligible, and it is recommended to calculate the arithmetic mean of the signal over the specified time interval. If the changes are larger, you will need to evaluate the signal individually based on the specific conditions. When downloading the TMS signal, always proceed cautiously to avoid disrupting the contact between the sensor and the soil. During data download, you can also check whether the signal has changed significantly (in the order of tens of units or more).

Average signal values shall be assigned to corresponding reference volumetric water content. The reference soil volumetric water content is determined by the moisture average of all the sampled depths (see below). As in the case of laboratory calibration, the TMS signal values are then plotted against the reference volumetric water content onto a graph (see Figure 3). The points obtained from all sample collections are then interleaved with the regression curve. Using the equation of the regression curve, it is possible to convert the signal value into soil volumetric water content.

The undisturbed soil sample must be collected close enough to the TMS sensor but far enough at the same time (approximately 50 cm for the majority of soils) so that 1) you avoid disturbing the soil at the point of contact with the sensor and 2) you do not change the hydrological soil behaviour around the sensor compared to the natural soil deposition. It is likewise advisable to collect the soil sample from multiple depths depending on how the sensors are installed.

For example, if the sensor is placed vertically, reaching a depth of 15 cm, we would recommend extracting three small cylinders beneath one another (with the cylinder height being 4 or 5 cm) from a middle depth of approximately 2,5cm, 7,5 cm, and 12,5 cm. The number of depths sampled will generally depend on how you installed the TMS sensor. For instance, one cylinder extraction will suffice for horizontal installation, i.e. one middle depth sampled. The middle depth is defined as half of the sampled depth range; for example, for a depth of 5-10 cm, this would be 7,5cm. When sampling, the vertical centre of the cylinder should correspond to the middle depth as closely as possible.

The advised distance of the cylinder from the sensor might not always be sufficient to establish the volumetric water content right beside the sensor, especially in case of high soil heterogeneity. For this reason, for field calibration, it is also possible to use an additional precision portable moisture sensor calibrated for the studied soil. For example, with the TDR-type sensor, the soil disturbance is significantly lower (it only has two openings of a diameter of approx. 0,5cm for transmission rods) than when extracting the cylinders, which therefore enables you to collect the sample considerably closer to the TMS (minimum distance approx. 15cm). The sampled soil thickness should be as similar as possible for both the TMS as well as the portable moisture sensor. For example, the length of the transmission rods of the TDR should at least approximately correspond to the 14cm length of the TMS soil moisture sensor (green section). For accurate determination of volumetric water content, the calibrated portable moisture sensor allows sampling in 2 or more positions for each TMS sensor. By averaging the values, you can thus retrieve a more precise estimate of reference moisture, which is notably advantageous for heterogenous soils with naturally high variability. However, the disadvantage of using an additional portable moisture sensor is the need to calibrate it to the soil studied.

Choosing your calibration method

The two calibration methods described, field and laboratory calibration, have advantages and disadvantages.

Laboratory calibration

Advantages

The main advantages of the laboratory method are 1) the ability to adjust the number of calibration points to the required accuracy and time possibilities, 2) the even distribution of soil water through sustained careful mixing, and 3) the determination of the reference gravimetric humidity directly at the TMS sensor measurement site.

Disadvantages

In opposition, the main disadvantage is disturbing the soil when homogenizing and mixing it with water. This means that the soil will never completely match the original soil characteristics when using this method. Even when you achieve the same bulk density through the below-described compacting, the soil may have a different particle arrangement and pore size distribution.

Comments

The largest deviations between naturally deposited and laboratory-treated soils are expected to be in cohesive fine-grained soils with high silt and clay content. These fine-grained soils usually change their volume (swell and shrink) depending on the moisture content and the arrangement of particles or aggregates of particles. In such cases, field calibration would be preferable.

Field calibration

Advantages

The main advantage of field calibration is the ability to measure soil moisture in its natural deposition while maintaining soil layers as well as the arrangement of particles or aggregates of particles.

Disadvantages

Its main disadvantage, on the other hand, is the necessity of multiple field trips for the purpose of soil sampling under varying moisture conditions. Being able to record the driest and dampest conditions during the monitoring period is particularly important. Furthermore, in some cases (e.g. deeper layers sampling, gravel, dry cohesive soil), it can be difficult to extract the sample undisturbed. Another disadvantage is that in the field, the reference gravimetric soil water content cannot be determined directly where the TMS is measuring. The reason being that soil sampling for the gravimetric reference method is destructive as the soil is disrupted, and a part of it is taken to the laboratory to be dried out. It is essential to collect the samples at a sufficient distance to ensure the sampling does not disrupt the contact of the sensor with the soil nor the natural hydrological regime at the point of TMS measurement.

Comments

The field method can be improved through a combination of soil sampling with a more accurate portable indirect moisture measurement method such as TDR. You can thus minimize soil disruption close to the sensors, obtain more moisture reference values, and you are able to sample close to the installed TMS.

Appendix 1: establishing mass moisture, bulk density, and porosity in laboratory calibration

Establishing the mass moisture using the gravimetric method lies in weighing the collected and subsequently dried soil sample. The sample can be disturbed, and its volume can remain unknown. The soil must be weighed right after its collection and subsequently dried up to a constant weight (for 20g of soil, at least 6 hours of drying at a temperature of 60 °C). We recommend using a laboratory dryer intended for this use. From the difference in weights of the collected dried sample, the weight of the water can be determined. The ratio of the water weight to the dry soil is the mass moisture.

In order to establish the bulk density and porosity, undisturbed soil samples of a known volume (see Appendix 2) should be collected in the field. The soil should once again be dried. For a sample of a volume of 100 cm3, it is advised to let it dry for at least 72 hours at 60 °C. After the samples are dry, they can be weighed again. The ratio of the weight of the dried sample to the volume of the collected sample (generally 100 cm3) will equal the bulk density (density of the soil sample).
To determine the porosity, the following equation may be used:

$$P = \frac{\rho_M - \rho_S}{\rho_M} = 1 - \frac{\rho_S}{\rho_M}$$

where ρS is the bulk density and ρM the density of the soil particles, this density depends on the mineralogical composition. The prevailing mineral in the soil is often silica, which has a density of 2.65 g/cm3.

Appendix 2: Collecting undisturbed soil samples for the purpose of determining bulk density

The undisturbed soil sample is usually extracted into stainless steel cylinders, which usually have a volume of 100cm3 and a length of 4,06 cm. It is possible to use cylinders of different sizes. However, it is always vital to know their exact volume. The sampling kit includes a set of steel cylinders, a sampling head, and a mallet for hammering in the sampling head (see laboratory method, Fig. C). You might further make use of a knife or spatula, a smaller shovel (e.g. military), and a trowel. After a determination of the collection spot, make sure to clean and prepare a small area from which you will extract the soil using the cylinder. Place the cylinder into the sampling head and using the sharp edge gently, without wobbling, press or push it into the soil to a depth where the column of the extracted soil exceeds the upper edge of the cylinder by approximately 0.5 - 1 cm (the upper edge of the cylinder is shown by a line on the sampling head). Afterward, using a knife or shovel, carefully separate the cylinder on its sides from the surrounding soil and scoop it up a few centimetres under its bottom edge, e.g. by using a trowel. Then trim off the protruding soil all the way to the edge of the cylinder, making sure to cut it from the centre to the edge of the cylinder into a cone, gradually decreasing its height until fully aligned. Next, close the cylinder from this side with a cap and weigh the sample. If some soil is lost from the cylinder during the trimming or at any point during the manipulation, or if any larger rocks or roots are visible in the cylinder, the sample should be extracted again. The procedure is illustrated below (see Figure A1).

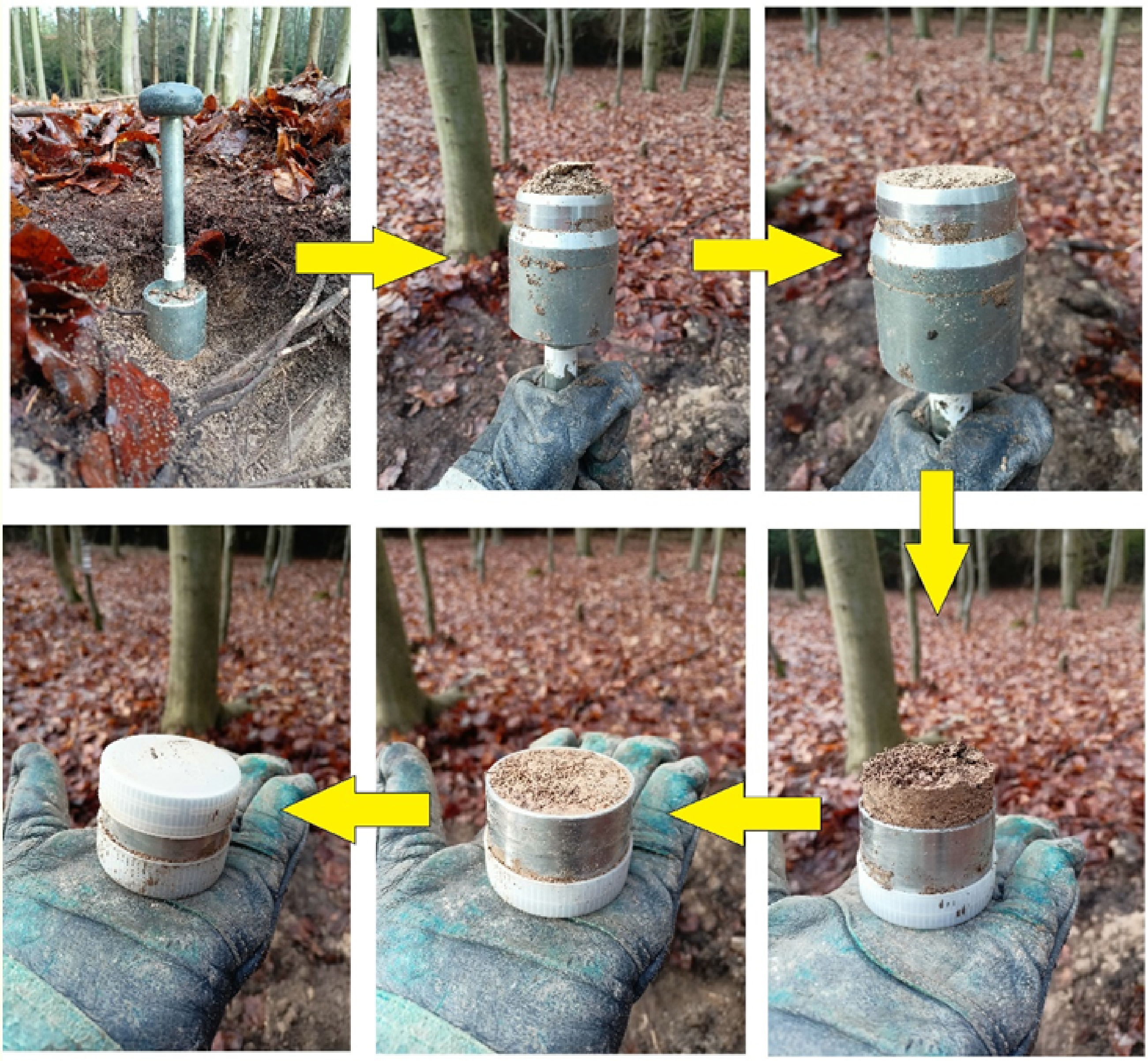

Figure A1: Extracting an undisturbed soil sample

Appendix 3: Determining the volumetric water content from the extracted undisturbed soil in field calibration

The volumetric water content is determined from the undisturbed soil sample, which was weighed immediately after extraction (see Appendix 2); alternatively, it is likewise possible to weight the sample, still enclosed in the steel cylinders, on a precise scale in the laboratory (on the day of extraction). In order to ascertain the weight of the undisturbed soil sample, make sure to carefully take off and weigh both caps and subsequently move the cylinder containing the soil sample onto a pre-weighed slide (see Figure A2).

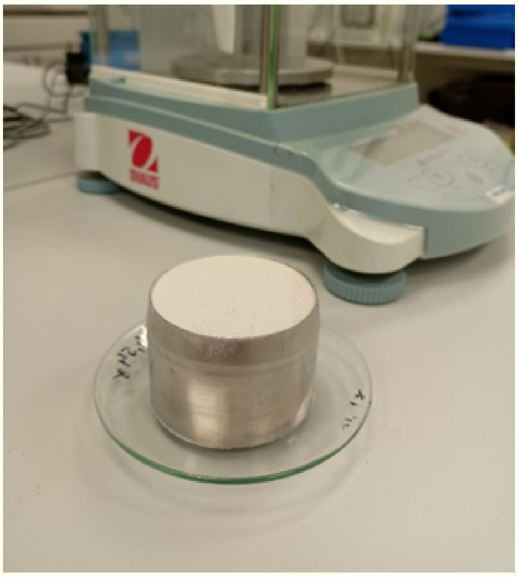

Figure A2: Undisturbed soil sample prior to drying

The volumetric water content is determined from the undisturbed soil sample, which was weighed immediately after extraction (see Appendix 2); alternatively, it is likewise possible to weight the sample, still enclosed in the steel cylinders, on a precise scale in the laboratory (on the day of extraction). In order to ascertain the weight of the undisturbed soil sample, make sure to carefully take off and weigh both caps and subsequently move the cylinder containing the soil sample onto a pre-weighed slide (see Figure A2).

In order to determine the volumetric water content, the weight of water in the sample, which is equal to the volume of water (assuming a water density of 1 g / cm3), must be known. The weight (or rather the volume) of water is determined as the difference between the weight of the collected soil and the dried soil. The weight of the collected soil is worked out from the weight of the undisturbed sample minus the weight of both caps and the cylinder. The weight of the dried sample is worked out from the weight of the dried sample on the slide minus the weight of the cylinder and the slide.

Once the weight of the water from the soil is determined, this value is divided by the volume of the undisturbed soil sample (see formula below), e.g. when using the cylinders indicated, the volume equals 100 cm3. The resulting value is a dimensionless number corresponding to the volumetric water content.
The formula for the volumetric water content calculation:

$$\theta = \frac{V_W}{V_S}$$

where Vw is the weight (or volume) of water and Vs the volume of the undisturbed soil sample.

TOMST S.R.O.
MICHELSKA 964/78
PRAGUE 4, 141 00
CZECH REPUBLIC

WEBSITE: WWW.TOMST.COM
EMAIL: TOMST@TOMST.COM

Prepared by
Lukáš Jačka
Martin Kovář
Marta Kuželková

Translation by
Lucie Haase