CALIBRATION OF TDR TEST PROBE FOR MEASURING MOISTURE IN THE BODY OF THE RAILWAY SUBSTRUCTURE AND ITS SUBGRADE

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Abstract

In the introduction of the paper there is characterized a way of monitoring the moisture in the railway substructure in the experimental stand, which is a part of the experimental workplace of the Department of Railway Engineering and Track Management. A substantial part of the paper is devoted to the calibration of TDR test probe for selected rock materials as a basic prerequisite for the determination of the actual moisture in the body of the railway substructure and subgrade.

Keywords:

Dielectric Constant;
Time Domain Reflectometry (TDR);
Moisture;
Calibration Curve;
Time Interval.

1. Introduction

Moisture content of materials in the body of railway substructure and its subgrade has decisive effect on their deformation resistance and ultimately the stability and security of the roadway. The amount of water that is contained in the body of railway substructure materials depends primarily on the type of soil, its bulk density / permeability and climatic conditions, and the level of groundwater and subsoil capillarity in the case of railway subgrade body. The moisture of railway substructure is not constant but varies during the year depending on the amount of precipitation (water, snow), temperature and water regime of railway substructure of the body, as well as its shape (embankment, cutting, cut).

Department of Railway Engineering and Track Management (DRETM) has been dealing with the influence of non-traffic load (influence of weather factors – water, frost, snow cover) on the temperature regime of the railway track – subgrade over a long period. For this purpose there were built two experimental sections of railway track in gauge 1:1, namely:

- Experimental stand DRETM I, located in the site of the former Faculty of Civil Engineering – Fig. 1,
- Experimental stand DRETM II, located in the site of University of Žilina – Fig. 2.

Fig. 1: Experimental stand DRETM I.

Fig. 2: Experimental stand DRET II.

Given to the experimental stands that represent the real part of the railroad within their structural composition, in-built materials and dimensions, the influence of climatic factors on temperature regime of subgrade, expressed mainly through the penetration of zero isotherm into the structure of subgrade has been monitored since 2002 (Experimental stand DRET I), or 2013 (Experimental stand DRET II). There were determined thermo-technical parameters of materials in the laboratory of DRET I [1], which are constructed from individual structural parts of the experimental stand (subgrade, protective layers and earthworks). Based on determination of selected characteristics of these materials (bulk density, moisture, thermal conductivity) and climatic factors (mean daily temperature T_s) it is possible to simulate the temperature regime of experimental stand structure using Canadian software SoilVision and programme software SV HEAT and then confront it with real values of temperature measured using thermometers built into the experimental stand [2].

Since the bulk density of in-built materials of experimental stand is almost identical throughout the year and also thermal conductivity, laboratory provided for all materials inbuilt in the structure of subgrade for 0 % moisture is constant, temperature regime of the subgrade structure is affected "only" by the course of the mean daily temperatures during the winter period, the sum is expressed using freezing index I_m and moisture fluctuations.

As already mentioned above, the moisture content of subgrade structure materials varies during the year and is influenced by the amount of precipitation falling in the form of rain or snow, in our case, on the surface of the experimental stand and then seeping into the structural layers. In order to monitor and identify the moisture in the different parts of Experimental stand DRET II test II, there were incorporated, in addition to the temperature probes, moisture probes consisting of TDR sensor, which can continuously monitor the fluctuations in moisture and also at any time identify the moisture in the material in-built in experimental stand profile. Since TDR moisture probes are designed primarily to determine the moisture of fine-grained materials (in bulk density of 1700 kg.m^{-3}) and include calibration curves just for this earth material and subgrade (railway ballast, structural layers of railway

substructure, including earthwork) of Experimental stand DRETM II consists of coarse-grained (inconsistent) materials, it is necessary to establish calibration curves for these moisture probes for all materials, which are inbuilt in the stand in question in order to simulate in parallel and then confront the temperature regime in the Experimental stand. For this purpose, there were used test methods and procedures specified below to implement calibration of moisture probe.

2. Methods for determining the dielectric constant [3]

Dielectric constant indicates the ability of non-conducting material (in our case a natural material) to transmit electromagnetic waves. The dielectric constant of water is much greater than the value for solid particles and air (see Table 1). This means that even relatively small changes in the amount of water in the soil, thus change of soil moisture, has a great effect on its dielectric constant. The water content in the soil can be determined through the calibration model, depending on the dielectric constant of the soil and the volume of water in the soil.

Table 1: Typical values of the dielectric constant.

Medium	Water	Air	Earth particles
Dielectric constant	79 - 81	1	2 - 6

The value of the dielectric constant is therefore a key parameter for the determination of water content in the materials (their moisture w), in our case, used into the railway structure, so to determine the moisture of individual structural parts of the railway substructure, its structural layers and subgrade.

The first step that needs to be done to determine the water content in the material is the calibration of dielectric constant for each material in general. Approaches using the method of dielectric constant provide a relatively quick measurements and accurate results when properly implemented calibration. To determine dielectric constant of earth mixtures and an estimate of the volumetric water content, there are two experimental reflectometry approaches on the basis of:

- time domain (TDR probes);
- frequency domain (FDR probes).

2.1 Reflectometry based on time domain measurement (TDR)

TDR devices were originally developed to measure time needed for penetration of electromagnetic waves to identify the failures of electrical conductors. However, they found a better use later realizing they are also suitable for the determination of water content in ground soil. The principle of the dielectric constant measurement of the soil using a TDR probe is that the TDR system spreads electromagnetic waves along the metal coaxial cable connected to the parallel guide probes, which act as a wave guide element in the ground soil. The signal broadcast is reflected from the end back to the external unit used for measurement. The system measures the time between the transmitted and received wave and calculates the speed of its spread. This is affected by the dielectric constant of the material that surrounds measuring element guiding electromagnetic waves, taking into account its structural length. The speed of spread of electromagnetic waves thus indirectly relates to the dielectric constant of the soil. The higher the speed of wave spread is, the less the dielectric constant of the soil is, and therefore the lower the water content of the soil, moisture.

A classic type of TDR element spread, or conducting electromagnetic waves, which is inserted into the ground soil consists of a number of rod probes, while the probe consists of two or three rods of stainless steel, separated by about 25 mm. The probes may be built into railway structure horizontally, vertically or at an angle of 45°, where the dielectric constant is then determined as the average value measured along the entire length of the probe. The basic types of TDR probes include the following devices:

- Campbell Scientific probe – Fig. 3,
- Dynamax probe TR-100 – Fig. 4,
- Trime Pico-Profile probe – Fig. 5,

- soil moisture gauge Aquaflex – Fig. 6,
- soil moisture gauge FieldScout TDR 300 – Fig. 7.

Fig. 3: Campbell Scientific.

Fig. 4: Dynamax TR-100.

Fig. 5 – Trime Pico-Profile.

Fig. 6: Aquaflex.

Fig. 7: FieldScout TDR 300.

2.2 Reflectometry based on frequency domain measurement (FDR)

To determine the dielectric constant of soil, reflectometer, the measuring principle is based on frequency domain (FDR), measures capacitive resistance of the soil, while the TDR probe measures the velocity of electromagnetic waves. The principle is based on the high-frequency radio waves (about 150 MHz), which oscillates over a pair of electrodes (sensors) located in the ground soil. The probe senses the natural resonant frequency or frequency shift between the transmitted and received frequencies that are emitted due to the capacitive resistance of the soil. There can be determined dielectric constant from the frequency measurement, since the capacitive resistance of the soil is directly proportionally dependent on the size of the dielectric constant. This means that if the amount of water in the soil increases, thus the soil moisture, the FDR probe detects an increase in the capacitive resistance due to the change of the dielectric constant of soil, which is directly correlated with the change in the content of water present in the soil. There may be used the following three types of probes for FDR electrodes:

- probe in the access (protective) tube – SentekEnviroSCAN, Adek Down Hole, AquaPro, Delta-T PR2,
- hand pressure probe – VertecSMR, Aquaterr M-300,
- sensor probe – WaterScout SM100, Decagon.

Based on positive references and affordability from the above mentioned dielectric devices, there was used TDR probe called Trim Pico-Profile to measure moisture referred to Fig. 5.

3. Calibration of TDR probe for inhomogeneous materials [4]

Protection of TDR probe Trim Pico-Profile against mechanical damage is made providing its own insertion into a protective PVC tube access. Protective tube must be built into the material being measured at least 2 weeks before the actual measurement of moisture, where the material especially around protective tube must be sufficiently compacted in order not to appear air gaps around tube that would affect the measurement result (lower values of measured moisture content of about 1-10 %, depending on the moisture of the medium measured). The sensitivity of measurement is the highest around the tube and decreases exponentially with distance into the medium as shown in Fig. 8.

Fig. 8: Distribution of electromagnetic field around the probe.

As already pointed out, TDR probes were developed especially for fine-grained materials and therefore contain basic calibration curves appropriate for these materials, which are valid when observing the following parameters of material measured:

- clay content of less than 50%,
- organic content of less than 10%,
- bulk density of 1100 kg.m^{-3} to 1700 kg.m^{-3} .

Since all building materials applied in the body of Experimental stand DRETM II did not meet the conditions, it was necessary to carry out test measurements of materials inbuilt and create the appropriate calibration curves.

3.1 Procedure of how to create a linear calibration curve for the TDR probes

It is possible to create up to 15 different calibration curves for different building materials for TDR probe Trim Pico-Profile. The probe has 4 calibration curves in-built in the basic setup, which allow to measure moisture of basic fine-grained materials. For other materials, it is possible to calibrate and then create a linear or non-linear dependence (to polygon of fifth order) of tested building materials.

In order to create a linear calibration curve, there is used a probe connected to module SM-Bus (Fig. 9) and then the entire calibration is performed using a software product PICO-CONFIG. After creating a calibration curve, it is possible to make measurement using data logger GlobelogIMKO.

Fig. 9: Calibration of clay moisture measurement with admixture of gravel.

The calibration curve is established based on two measurement points. The first measurement point is obtained from the measurement of the dry sample (or a small sample of moisture), and the second measurement point is obtained from the sample to be as far as the highest moisture w (maximum moisture). Measuring points should be sufficiently apart to achieve the greatest accuracy. There is in-built a protective tube into the sample with low moisture for inserting the measuring probe and there is measured time interval t_p for known, laboratory determined moisture according to standard [5]. The same procedure is repeated on a sample with high moisture. Then, based on these two points, there are calculated coefficients m_0 and m_1 using the relation:

$$m_1 = \frac{w_{m2} - w_{m1}}{t_{p2} - t_{p1}}, \quad (1)$$

$$m_0 = w_{m2} - m_1 \cdot t_{p2}, \quad (2)$$

where: w_{m1} – moisture of dry or slightly damp material, (%),
 w_{m2} – moisture of saturated material, (%),
 t_{p1} – time interval obtained on dry or slightly damp sample, (ps),
 t_{p2} – time interval obtained on saturated sample, (ps).

On the basis of the coefficients calculated, programme *PICO-CONFIG* creates a calibration curve for the determination of moisture in the material.

3.2 Establishment of the calibration curve for crushed aggregate fraction 0/32 mm

In order to achieve the highest possible accuracy of the values of moisture of the rock material there was used a combination of linear and non-linear method of coefficient determination to create a calibration curve. There were determined 6 calibration points in total within the measurement (for 6 time intervals depending on 6 different moistures). Time intervals t_p measured relating to the moisture of crushed aggregate fraction 0/32 mm determined by laboratory are shown in Table 2.

Table 2: Time intervals measured for crushed aggregate fraction 0/32 mm corresponding to certain moisture content w .

w_m (%)	t_p (ps)
0.00	152.851
2.70	275.032
3.74	282.910
5.35	373.212
6.37	418.305
9.69	515.959

Time intervals were determined as the arithmetic average of 10 measurements performed using TDR probe. There are 4 linear calibration curves of different numbers of calibration points created from the calibration points using Excel programme. Subsequently, on the basis of further independent measurements there has been chosen optimum curve for measurement, for which it was received the highest accuracy in comparison with moisture, determined under the procedure referred to in [5]. The coefficients m_0 and m_1 were calculated from the end points of trend lines established between the calibration points. Trend lines have been created as a dependency between the 2, 4, 5 and 6 calibration points. Fig. 10 shows an obvious trend created as a connector of 6 points the coefficient of determination was the highest.

Fig. 10: The dependence of moisture w_m created from the time interval $t_{(p)}$ between 6 values measured for crushed aggregate fraction 0/32 mm.

There were calculated coefficients m_0 and m_1 for trend line characterized, which are shown in Table 3.

Table 3: Coefficients m_0 and m_1 calculated for crushed aggregate fraction 0/32 mm.

w_m (%)	m_0	m_1
0; 9.69	- 5.273	0.029
0; 2.7; 5.35; 9.69	- 4.414	0.027
0; 2.7; 3.74; 5.35; 9.69	- 4.273	0.027
0; 2.7; 3.74; 5.35; 6.37; 9.69	- 4.201	0.026

After entering coefficients into the programme PICO-CONFIG there were created 4 calibration curves using which there was measured specific moisture of crushed aggregate sample fraction 0/32 mm taken from protection (underlying) layer of Experimental stand DRETM II, which was then confronted with the moisture of sample determined according to the procedure referred to in standard [5]. Moisture values measured and their comparison with the moisture of the sample determined according to the procedure referred to in standard [5] is shown in Table 4.

Table 4 shows that the calibration curve created from 4 – 6 points provides a high accuracy of measurement.

Table 4: Comparison of the moisture measured with the moisture of the sample determined according to the procedure referred to in standard [5].

Type of curve	Moisture measured in (%)		Moisture in (%) according to [5]
	SM	Globelog	
from 2 calibration points	4.55 – 4.62	4.87 – 4.90	4.81
from 4 calibration points	4.73 – 4.81	4.94	
from 5 calibration points	4.77 – 4.82	4.92	
from 6 calibration points	4.75 – 4.81	4.98 – 5.01	

3.2 Establishment of the calibration curve for crushed aggregate fraction 0/63 mm

Calibration curves for crushed aggregate fraction 0/63 mm were created by the identical way as it was in the case of crushed aggregate fraction 0/32 mm. The values of the calibration points for crushed aggregate fraction 0/63 mm measured are shown in Table 5.

Table 5: Time intervals measure for crushed aggregate fraction 0/63 mm corresponding to certain moisture content (w).

w_m (%)	t_p (ps)
0.00	159.060
2.37	254.848
4.54	315.536
5.34	333.263
6.14	355.492
6.72 ^{*)}	449.317

^{*)} the sample consisted of a few fine fraction and was not able to maintain the required moisture evenly (water occurred on the bottom side of the sample that affected measurement).

Time intervals were also determined as the arithmetic average of 10 measurements performed using TDR probe. There were created 3 trend lines (4th of 6 calibration points was excluded, since it was not possible to create a moisture for the sample as was achieved for crushed aggregate fraction 0/32 mm). There is shown a trend line in Fig. 11 created among 5 calibration points, where the highest value of the coefficient of determination was obtained.

Fig. 11: Dependence of moisture w_m created from time interval t_p among 5 measured values for crushed aggregate fraction 0/63 mm.

There were calculated coefficients m_0 and m_1 for characterized trend lines as shown in Table 6.

After entering coefficients into the programme PICO-CONFIG there were created 3 calibration curves using which there was measured a particular moisture of the sample of crushed aggregate fraction 0/32 mm taken from earthwork of Experimental stand DRETM II, which was then confronted with the moisture of the sample determined according to the procedure referred to in standard [5]. The values of moisture measured and their comparison with the moisture of the sample determined in accordance with the procedure referred to in standard [5] are shown in Table 7.

Table 6: Coefficients m_0 and m_1 calculated for crushed aggregate fraction 0/63 mm.

w_m (%)	m_0	m_1
0; 6.14,	- 4.972	0.031
0; 2.37; 5.34; 6.14	- 5.254	0.031
0; 2.37; 4.54; 5.34; 6.14	- 5.314	0.032

Table 7: Comparison of the moisture measured with the moisture of the sample determined according to the procedure referred to in standard [5].

Type of curve	Moisture measured in (%)		Moisture in (%) according to [5]
	SM	Globelog	
from 2 calibration points	4.64 – 4.70	5.13 – 5.14	4.82
from 4 calibration points	4.62 – 4.65	4.92 – 4.93	
from 5 calibration points	4.71 – 4.72	4.89 – 4.91	

3.3 Establishment of the calibration curve for clay blended with river gravel corresponding to certain moisture content (w)

The programme PICO-CONFIG contains 4 calibration curves in basic settings determined for measuring fine-grained soils. However, the clay measured contained the river gravel causing significant deviations in the measurement of moisture content. For this reason, it was agreed to create a calibration curve for a given material. Calibration curves for measuring moisture content of clay blended with river gravel were created by identical way as mentioned in section 3.1 and 3.2. The value of points measured for the clay blended with river gravel is shown in Table 8.

Table 8: Time intervals measured for clay blended with fluvial gravel corresponding to certain moisture content (w).

w_m (%)	t_p (ps)
0.000	320.408
9.61	538.230
14.00	661.596
20.51	770.183
25.07	850.429
28.03 ^{*)}	749.142

^{*)} the sample was too moisturised, water penetrated into the protective tube.

Time intervals were also determined as the arithmetic average of 10 measurements performed using TDR probes and there were created 3 trend lines (from 2, 3 or 5 calibration points). There is shown a trend line in Fig. 12 created among 5 calibration points the best coefficient of determination was received.

There were calculated coefficients m_0 and m_1 , for trend lines characterized, which are shown in Table 9.

Fig. 12: Dependence of moisture w_m created from time interval t_p among 5 measured values for clay blended with river gravel.

Table 9: Coefficients m_0 and m_1 calculated for clay blended with river gravel.

w_m (%)	m_0	m_1
0; 28.03	- 20.949	0.0654
0; 14.00; 28.03	- 23.723	0.0654
0; 9.61; 14.00; 20.51; 25.07	- 15.675	0.0470

After entering coefficients into the programme PICO-CONFIG there were created 3 calibration curves using which there was measured a real moisture of the sample of the clay blended with river gravel taken from the subgrade of Experimental stand DRETM II, which was then confronted with the moisture of the sample determined according to the procedure referred to in standard [5]. The values of moisture measured and their comparison with the moisture of the sample determined in accordance with the procedure referred to in standard [5] are shown in Table 10.

Table 10: Comparison of the measured moisture with the moisture of the samples determined according to the procedure referred to in standard [5].

Type of curve	Moisture measured in (%)		Moisture in (%) according to [5]
	SM	Globelog	
from 2 measuring points	20.92 – 21.19	20.95 – 21.05	18.31
from 4 measuring points	21.22 – 21.36	21.18 – 21.24	
from 5 measuring points	18.00 – 18.12	18.07 – 18.12	

7. Conclusions

Using TDR probe and method of measurement of dielectric constants used, which was the input parameter for the determination of moisture, we can achieve high accuracy of the measured values of the moisture with the compliance of the conditions (sufficient consolidation to prevent air gaps, non-seeping of maximum moisture, sufficient insertion of the probe in the soil) and the performance of quality calibration.

As it is demonstrated at Table 4, 7 and 10, calibration curve obtained from 4 to 6 calibration points, this method of measurement guarantees high enough accuracy of the measured values of moisture in the confrontation with the moisture determined under the procedure referred to in standard [5]. *SM-Bus* module creating calibration dependencies provides relatively accurate measurement results of moisture than data logger Globelog, however, the difference in the values of moisture obtained is only about 0.2%, which is negligible. Even thicker grading of the test material does not

affect the accuracy of the measurement, in spite of the fact that moisture probe is designed for fine-grained materials. It is thus clear that the values of moisture measured are objective and can be used for the detection of fluctuations in moisture in the body of the railway substructure in the course of the year, and thus the simulation of the temperature regime using the software SoilVision and programme product SV HEAT.

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