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11TH INTERNATIONAL SYMPOSIUM FIELD MONITORING IN GEOMECHANICS

Installation of a flood protection embankment's monitoring system

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Abstract

This article summarises the installation procedure and the initial data from a unique monitoring system installed in a primary flood protection embankment. The embankment is the first line of defence against floods along the Tisza river. The monitoring system is composed of combined soil moisture - temperature sensors and tensiometers. The instruments are placed in a carefully selected cross-section located north of Szolnok, Hungary. The aim is to monitor the changes in moisture content inside the dike and to assess the desiccation potential. The uniqueness of the monitoring system is that an existing operating embankment was instrumented. Installing the soil moisture sensors at various depths provided a challenge. The design of the monitoring system, installation, received data from the field and its comparison with laboratory measurements were presented in this article.

Keywords: Monitoring system, flood protection embankment, soil moisture content, crack formation

1. Introduction

Flood protection embankments, also known as dikes, are structures along rivers, lakes and coastal areas. They are usually made of local materials, such as clay, peat, silt and sand, available in the vicinity of the construction site. These earth structures were constructed using historical methods (Dyer et al. 2009). Namely, cross transportation was used, and the material was extracted from ditches at the waterfront. Desiccation cracks form due to the combination of construction errors, material choice and climatic reasons. Compaction is an important construction step. Uncompacted sections of the BIONICS test embankment exhibited more and deeper cracks than the compacted (Yu et al. 2021). To investigate the environmental effects on embankments, test sites such as the previously mentioned (Hughes et al. 2009) were built, scaled-down laboratory models (Sentenac and Zielinski 2009; Zielinski et al. 2011) and newly built dikes were also instrumented (Utili et al. 2015). So far, existing embankments haven't been instrumented with moisture sensors and tensiometers.

The extent of the droughts in the Carpathian Basin will increase due to climate change. It has the most significant effect on the water content and pore water pressure of near-surface soil layers, as the infiltration from precipitation decreases and the evaporation increases due to the higher temperature (Pap 2020). The construction of Hungary's dike system began with river regulation in the 19th century, before the development of modern soil mechanics (Nagy 2006). The different layers created by consecutive raising and strengthening of the dikes resulted in an onion shell structure, visible in Figure 3. Cross-section development of dikes along the river Tisza is documented in multiple studies (Tóth and Nagy 2006; Schweitzer 2009). The desiccation fissures on the flood protection embankments of the Tisza valley had been investigated in the past (Szepessy 1991; Lazányi and Horváth 1997), and the clays' swelling-shrinkage property is well known.

Visual inspection is the primary method to monitor and assess the condition of flood-defence embankments worldwide. In 2018 the General Directorate of Water Management (OVF) ordered the 12 territorial Water Directorates to carry out a nationwide survey of paved flood protection embankments (Illés et al. 2022). This survey was used to identify the possible locations of the monitoring system where clays with volume variable potential are present.

The current study presents the main installation steps of a monitoring system. The received data from the fitted soil moisture sensors and tensiometers are evaluated. Furthermore, the results of the field measurements were compared with the laboratory measurements. One of the most relevant goals of the monitoring system's installation and operation is to benefit the water management bodies from the practical research results. In this regard, one of the key questions is: how many drying cycles does a dike experience during its lifetime? How do these drying and wetting cycles affect the appearance of cracks on the surface and inside the embankment? Eventually, can the deterioration lead to the failure of the earthworks?

2. Site description

The survey described by Illés et al. (2022) helped select the location for the monitoring system where clays susceptible to volume change are likely to be present, as indicated by the pavement cracks. The chosen location is at Doba; the river bent of Tisza at the section of 87+620 km of the right-side embankment, located a few kilometres North of Szolnok, Hungary.

The region is well known for high plasticity clays with considerable swelling and shrinkage potential. As expected, the geotechnical drillings at the site revealed high plasticity soils (w_L: 51,2-60,7 %, Ip: 29,4-37,4 %). Just like the previous investigation made at the protected side toe of the embankment (w_L: 69,5-71,5 %, Ip: 40,0-47,5 %). Earlier detailed soil investigations of the dike material were carried out further upstream at Sajfok (Nagy 2010; Nagy and Huszák 2012; Nagy and Illés 2016), showing high plasticity clays with considerable swelling and shrinkage potential. The two locations of Doba, Sajfok and the major cities are presented in Figure 1.

Figure 1: Doba, monitoring system and soil investigation, Sajfok detailed soil investigation of the dike material

The region's surface is covered with Holocene silty-clay sediment, transported by the river Tisza and its tributary Zagyva. The area's climate can be considered one of the driest in Hungary. The groundwater level is less than 2.0 m (Dövényi 2010). The availability of studies, the dike's proximity to river Tisza and the dry climate made it a preferential choice for the location of the monitoring system. The dike section's paved crest and the flood side slope are visible in Figure 2.

Figure 2: Paved crest of the embankment and flood side slope at Doba 87+620 tkm

The following criteria were also determined and set against the selected cross-section: i) old embankment, should not have been reconstructed in the past few years, ii) an untreated section, no cement or fly-ash stabilisation, iii) the presence of a meteorological station nearby for precipitation data, iv) data logger installation in a safe area, v) relatively easy access to the location.

3. Monitoring System

Built-in cohesive soils with high water content and droughts can trigger desiccation cracks. Water content is a direct indicator of extensive fissuring in the ground, as suggested by (Dyer et al. 2009). It is important to continuesly monitor this property. As an established method, a water content profile is created when signs of shrinkage cracks are visible on an embankment from disturbed samples (Nagy and Illés 2016). However, it is only at discrete points at a discrete time. Our goal was to continuously monitor a flood protection embankment's water content at as many points as possible.

The monitoring system is composed of 17 sensors: 14 TEROS 11 soil moisture sensors, 3 TEROS 21 tensiometers and 3 ZL6 data loggers, all supplied by METER Group. The instruments are located at Doba, section 87+620 and installed in 4 borings shown in Figure 3., flood side slope, flood side crest, the crest axis and the dike's charging bench.

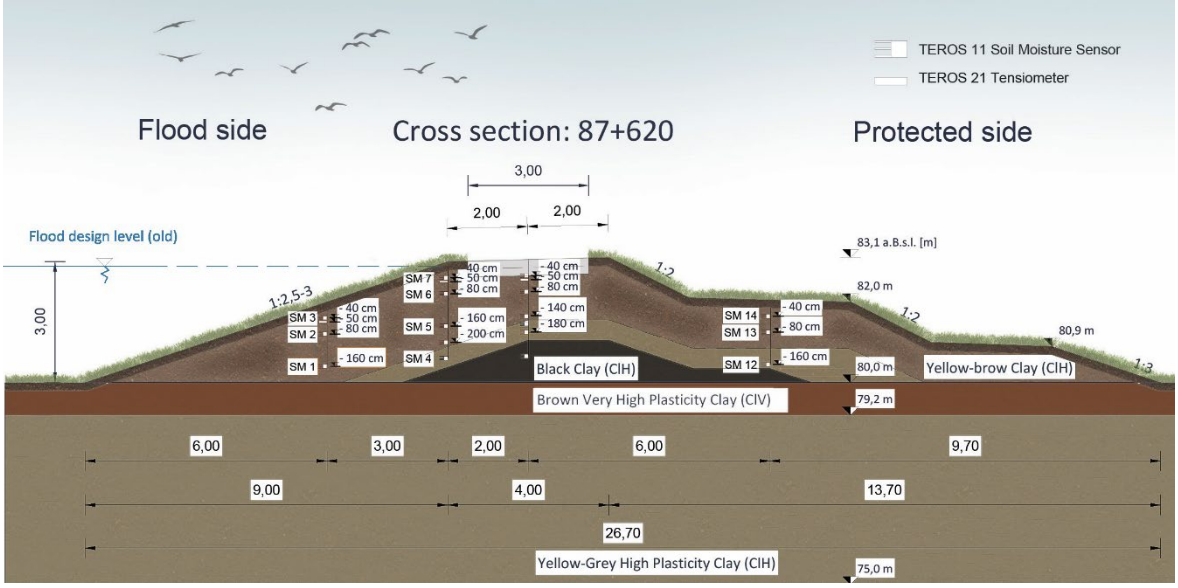

Figure 3: Installation layout of the instruments at Doba section 87+620 tkm

The soil moisture sensors (TEROS 11) were the same type of instruments used in Hungary's drought and water scarcity monitoring system, which has more than 150 operational monitoring stations. The water content of the soil at different depths and meteorological parameters, such as precipitation and relative humidity, are measured (Fiala et al. 2018; Drought monitoring). The same type of tensiometers (TEROS 21) were used by Schulz-Poblete et al. (2022). The main technical details of the sensors are summarised in Table 1. photos of them are presented in Figure 4. The soil moisture sensors (TEROS 11) were placed into the drillings with a unique installation tool rented from METER Group.

Figure 4: Soil moisture sensor (TEROS 11) and tensiometer (TEROS 21)

On the other hand, tensiometers are installed manually. Moist soil from the boring is placed tightly around the ceramic disc to ensure that the soil is in contact with the disc. The sensor inside the bulb of soil was placed into the pockets scraped to the side of the borings.

Device	Soil moisture sensor	Tensiometer
Product name	TEROS 11	TEROS 21
Manufacturer	METER Group	
Catalogue	https://www.metergroup.com/	
Operation range (temperature)	−40 to +60 °C	
Resolution, accuracy	0.1 °C, ± 1 °C	
Volumetric water content	0.00 – 0.70 m^3/m^3	
Negative pore water pressure		−5 to −100,000 kPa
Resolution	0.001 m^3/m^3	0.1 kPa
Accuracy	Depends on the calibration	±(10% of reading + 2 kPa) from −100 to −5 kPa

Table 1: Main Technical Features of the instrumentation used

4. Measurements

The measurements of the sensors installed on the flood side are analysed, as this part experienced the most severe drying. At the time of the article submission, only two months of data were available.

4.1 Initial water content

As mentioned earlier, for the fitting of the sensors, 4 approximately 2 m deep borings with a diameter of 10 cm were made; from these, disturbed and undisturbed samples were retrieved. The gravimetric water content distribution of the cross-section was determined, presented in Figure 5. The core of the flood protection embankment is relatively wet, while the southward facing flood side slope is already dry (spring of 2022). The winter and spring of 2022 were arid, and Hungary experienced severe drought. The embankment was not rewetted by floods either, as there were no major ones along the river Tisza in the past decade.

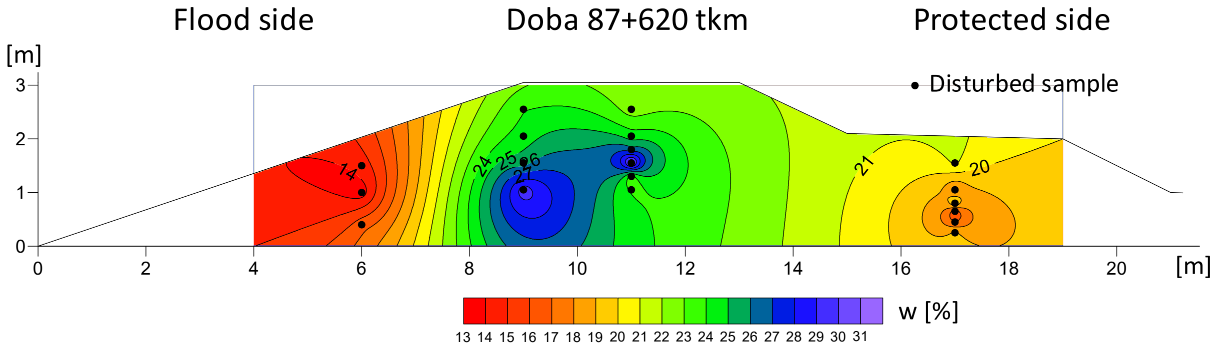

Figure 5: Gravimetric water content distribution of the cross-section (May of 2022)

The initial water content is compared with the ones measured by the sensors. This comparison is presented for the flood side in Figure 6.

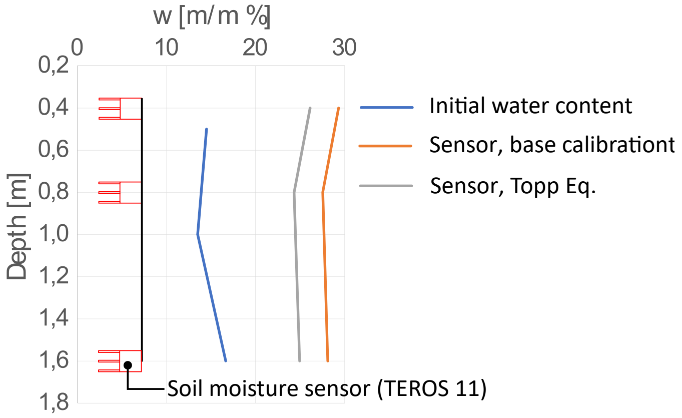

Figure 6: Comparison of the gravimetric water content of the soil on the flood side

The water content measured by the sensors is evaluated in two ways i) "Base calibration", the METER Group proposes for mineral soils. Volumetric water content ($\theta[m^3/m^3]$) is calculated according to the following equation:

$$\theta(m^3/m^3) = 3{,}879 \cdot 10^{-4} \cdot RAW - 0{,}6956 \tag{1}$$

where, RAW is the raw measurements by the TEROS 11 sensor.

The second method involves the calculation of dielectric permittivity (ε_a) according to Eq.(2) provided by METER Group:

$$\varepsilon_a = (2{,}887 \cdot 10^{-9} \cdot RAW^3 - 2{,}080 \cdot 10^{-5} \cdot RAW^2 + 5{,}276 \cdot 10^{-2} \cdot RAW - 43{,}39)^2 \tag{2}$$

The volumetric water content is calculated from the dielectric permittivity according to Eq. (3) (Topp et al. 1980):

$$\theta(m^3/m^3) = 0{,}0000043 \cdot \varepsilon_a^3 - 0{,}00055 \cdot \varepsilon_a^2 + 0{,}0292 \cdot \varepsilon_a - 0{,}053 \tag{3}$$

Gravimetric water content is derived from the volumetric water content with the estimated particle density and the measured dry density.

There is an 8-10 % difference between the lab results and the sensor measurements, as presented in Figure 6. After the sensor installation, the drillings were filled with a slurry made from the embankment material to ensure no voids around the instruments. The filling slurry is likely to be responsible for the difference.

4.2 Moisture content and temperature data

The data of temperature and soil moisture measurements from the flood side of the monitored embankment section is presented in Figure 7.

The daily temperature fluctuation is visible in the temperature data series of the upper 0.5 m of the embankment, while the inside is only affected by seasonal trends. The moisture content of the upper 0.5 m gained from earlier precipitation is gradually lost as the evaporation is not compensated by precipitation. The deeper layers' water content decreased only slightly. It is essential to record the crack development as well as to correlate them with the measured soil moisture content, temperature and suction

The crack pattern of the embankment, both on the paved crest and unpaved slopes, is regularly inspected. We are in a state to finalise our manual survey method, similar to Yu et al. (2021), and involve drone image surveys.

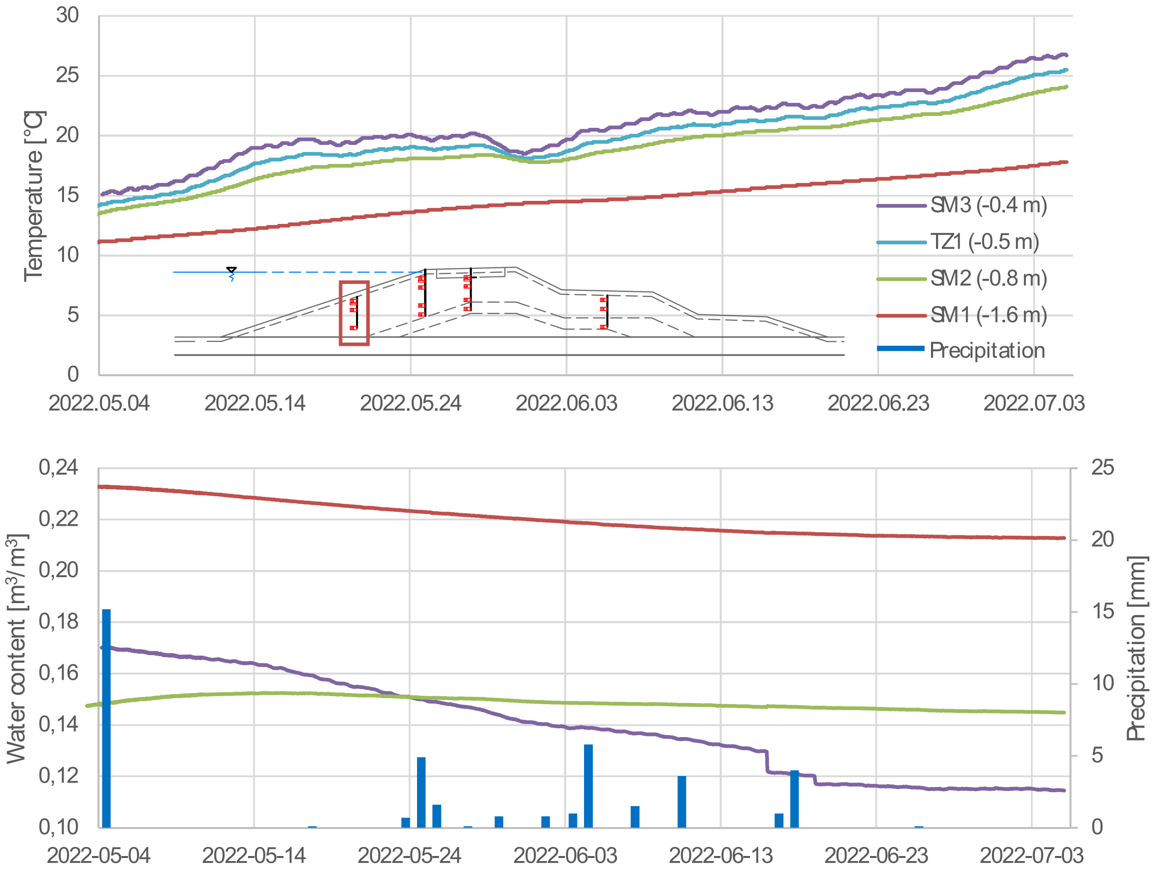

Figure 7: Temperature data series (above), soil moisture and precipitation data series (below)

4.3 Water retention capability

Apart from the soil moisture sensors, tensiometers are also installed at the monitored cross-section. With the help of these instruments, the negatív pore water pressure, causing capillary rise, can be measured. A field (in situ) water retention curve (WRC), can be obtained with the data from the tensiometer and the soil moisture sensor. This curve provides a relationship between the water content and the matric potential. On the retrieved undisturbed samples, with pressure plate apparatus, soil water contents were measured at different negative pressure heights (pF 0, 1.5, 2.0, 2.5, 4.2 and 6.2), and the main drying branch of the water retention curve can be drawn. The laboratory and the field measurements are compared in Figure 8.

Two different water retention models from the literature (van Genuchten 1980; Romero and Vaunat 2000) were fitted to the laboratory measurements. The field measurements indicate a somewhat looser soil structure (higher void ratio), which is most probably the result of soil disturbance during installation.

After rearrangement, the expression proposed by van Genuchten (1980) is the following on the gravimetric water content (w) versus suction (ψ) plane:

$$w = w_{sat}\left[1+\left(\frac{\psi}{P}\right)^{\frac{1}{1-\lambda}}\right]^{-\lambda} \tag{4}$$

where, w_{sat} is the saturated water content, while P and λ are fitting parameters.

The model by Romero and Vaunat (2000) was suggested for compacted deformable clays, such as the analysed flood protection embankments, to settle the relationship between the suction domain and the pore size affected by water exchange in the hydraulic path. In the low suction range (high water content), water is exchanged between the large inter-aggregate pores, while in the high suction range (low water content) between the micro intra-aggregate pores. Cyclic drying and wetting of deformable clays affect the inter-aggregate pore structure where water exchange is much easier. Romero and Vaunat (2000) assumed that the intra-aggregate pore space is constant depending only on the clay activity. The expression proposed is the following:

$$w = w_{max} C(\psi - \psi_0) \cdot \left[\frac{1}{1 + \left(\alpha(\psi - \psi_0)\right)^n}\right]^m \tag{5}$$

where, w_{max} is the saturated water content, ψ_0, n is related to the slope of the curve at the inflexion point, m is related to the residual water content, and α is mainly the inverse of the air-entry value of the soil, C is a correction factor incorporated in the modal to increase its flexibility;

$$C(\psi - \psi_0) = 1 - \frac{\ln\left[1 + \frac{(\psi - \psi_0)}{a}\right]}{\ln(2)} \tag{6}$$

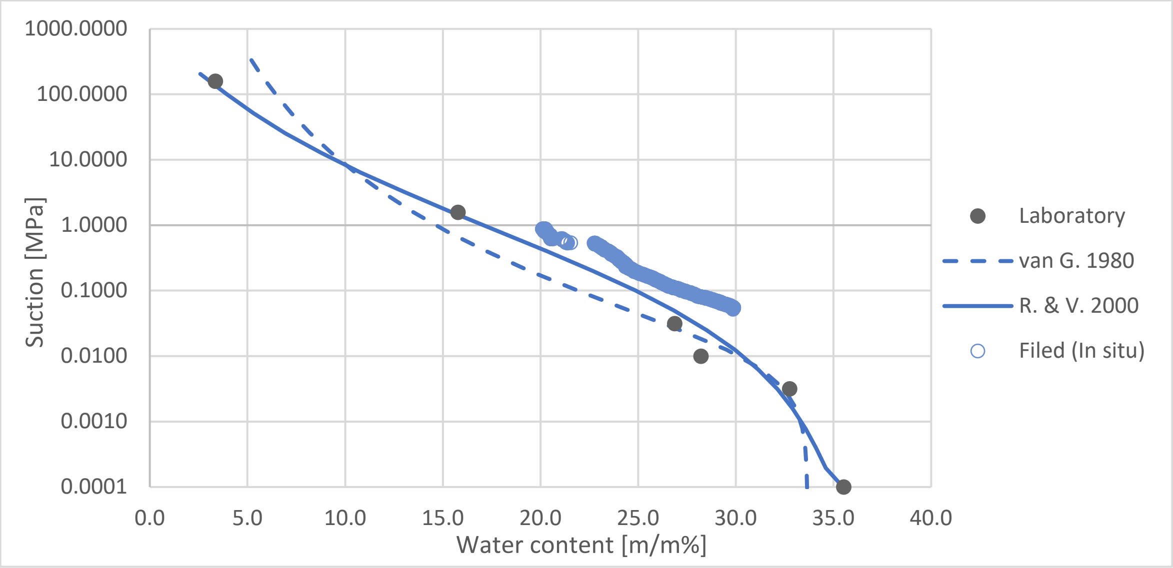

Figure 8: Water retention curves, laboratory and field measurements

The fitting parameters for the two water retention curves are presented in Table 2. The fitting parameters in comparison with the results of Cardoso et al.(2015) indicate that the embankment experienced more than 3 cycles of drying and wetting. Our research aims to see how often an embankment is dried and revetted by different means (rain and flooding).

Van Genuchten (1980)		**Romero & Vaunat (2000)**			
P	λ	a (MPa)	α (Mpa^{-1})	m	n
0,0095	0,15	1000	1,2	1,0	0,4

Table 2: Fitting parameters for the water retention models

5. Discussion and Conclusions

The measurements are in their initial stage. It is anticipated that seasonal trends in the desiccation and rewetting of the embankment will occur. Moreover, the flooding of the Tisza would be an exceptional opportunity to study the embankment's complete wetting and drying cycle.

For the flood side (at 0.5 m depth), the main drying branch of the water retention curve is obtained and correlated with the field measurements (Figure 8). So far, only drying is experienced by the in situ tensiometers. Hopefully, the hysteretic behaviour of the water retention curves will be measured, and the drying and wetting branches of the water retention curves can be distinguished.

Based on the measurement results, we expect to understand better the formation of desiccation cracks and deterioration of the embankments. Another practical benefit is that the role of pavement on the moisture distribution of the embankment can be better understood. These can directly contribute to elaborating practical guidelines and directives regarding the proper pavement selection; layer order, materials and construction methods.

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