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Non-invasive portable geophysical tool to monitor water content in earthen long linear infrastructures

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Abstract

The use of electrical conductivity measurements from a non-invasive hand held electromagnetic probe is showcased to monitor the water content of earthen embankments at routine inspections. A methodology to convert the electrical conductivity measurements from the electromagnetic device into water content values is illustrated. The methodology is based on measuring the soil electrical conductivity variation with respect to a baseline reference condition and calibrating a water content – electrical conductivity relationship by comparing electrical conductivity readings from the electromagnetic probes with water content readings taken from geotechnical probes installed in a few sections of the embankment.

The values of water content converted from the conductivity measurements according to the proposed procedure were found to be in very good agreement with independent measures of water content taken at times well beyond the calibration period.

Keywords: geophysics; health monitoring; electrical conductivity; water content; deterioration; electromagnetic portable device.

Introduction

Earthen embankments are built for a variety of purposes the main ones being transportation, e.g. road and railway embankments, and to act as flood barriers. Usually flood defence embankments are made of lower quality materials than transportation embankments [1]. With regard to the latter, the increased focus on sustainability in the

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engineering sector brings renewed attention to health monitoring in the long term; while with regard to the former, they are subject to significant deterioration due to aging [2] so increasingly large resources are dedicated to their health monitoring.

Monitoring and condition assessment of embankments worldwide are mainly carried out by visual inspections at set intervals [3-5]. Purely visual inspections present several shortcomings, namely inconsistencies due to different levels of training and experience of the inspectors and providing qualitative measurements of deterioration rather than quantitative ones with failures often occurring without any visible warning signs of deterioration being detected. Therefore, experts agree on the fact that although visual inspection provides extremely valuable information, inspections alone cannot be relied upon to assess the fitness of earthen embankments [3, 6].

Here, the use of non-invasive electromagnetic geophysical probes is advocated for the long term monitoring of the water content in embankments made of cohesive soils. The probe employed in the study is a hand held devise that can be easily operated by untrained personnel and that could be added to the standard inspector kit. Potentially it could also be used to monitor material deterioration occurring over long time spans. In the following it will be shown how periodic measurements of electrical conductivity taken by a portable electromagnetic devise can be converted into water content. A methodology to calibrate the electrical conductivity – water content relationship was first proposed in [7]. In this paper a new simplified methodology is proposed with the aim of extending the application of the method to cases of embankments where less data are available, e.g. absence of weather stations and few geotechnical probes.

Nomenclature

A_{CMD}	portion of embankment cross-section where the induced electric field is non-zero.
m	inclination of slope in Figure 3
q	intercept of slope in Figure 3
x	horizontal coordinate in the embankment cross-section
y	vertical coordinate in the embankment cross-section, positive downwards
s	coordinate along the longitudinal axis of the embankment
$w(x,s,z,t)$	water content
$w_{i;k} = w\left(x, s=s_i, z, t=t_k\right)$	water content at cross section i measured at time t_k
$\bar{w}(s,t)$	cross-sectional average water content
$\bar{\bar{w}}(t)$	water content averaged over the entire embankment
$\bar{w}_0(s,t)$	normalised cross-sectional average water content
$\underline{\bar{w}}_0(s)$	time average of the normalised cross-sectional average water content
$\gamma_i(s)$	weight functions
$\sigma(x,s,z,t)$	electrical conductivity
$\bar{\sigma}(s,t)$	cross-sectional average electrical conductivity
$\bar{\sigma}_k(s) = \bar{\sigma}(s,t=t_k)$	cross-sectional average electrical conductivity measured at time t_k
$\bar{\bar{\sigma}}(t)$	electrical conductivity averaged over the entire embankment
$\bar{\sigma}_0(s,t)$	normalised cross-sectional average electrical conductivity
$\underline{\bar{\sigma}}_0(s)$	time average of the normalised cross-sectional average electrical conductivity
T	temperature
T_{ref}	reference baseline temperature to account for temperature effects on electrical conductivity

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2. Measurements

In 2007, the construction of an earthen flood defence embankment enclosing a floodplain along the river Irvine was completed in Galston (Scotland, UK). The embankment is made of an uppermost layer (5-10 cm) of a sandy topsoil below which lies a core of glacial till containing several boulders (Figure 1). A typical cross-section is sketched in Figure 1b.

2.1. Electromagnetic probe

Several electromagnetic probes measure the electrical conductivity of the ground. The CMD-2 probe from Gf Instruments was chosen since it is cheap and simple to use. In [8] the working principles of the device are illustrated. Measurements were taken by an operator walking on the horizontal upper surface (crest) of the embankment along the longitudinal direction at a constant pace of 5km/h, holding the CMD-2 approximately 1m above ground with the device oriented perpendicular to the longitudinal direction.

2.2. Geotechnical suite

To calibrate the electrical conductivity – water content relationship, measurements of water content were taken by a geotechnical suite over a period of two years into two cross-sections (A and B in Figure 1) with the property of being perpendicular to each other to better account for the influence of topographical orientation on water content.

Two different instruments were employed: a portable profile probe (PR2, Delta–T Devices) to measure water content along several vertical lines up to a depth of 1 m, and a portable diviner (Diviner 2000, Sentek, Stepney Australia) to measure water content along various vertical lines every 10 cm from ground level down to 1.6 m of depth. In section A, 10 access tubes were employed: 5 for the profile probe and 5 for the diviner. In section B there were 12 measuring points: 6 for the profile probe and 6 for the diviner. Both tools were carefully calibrated in situ (for details see [7]).
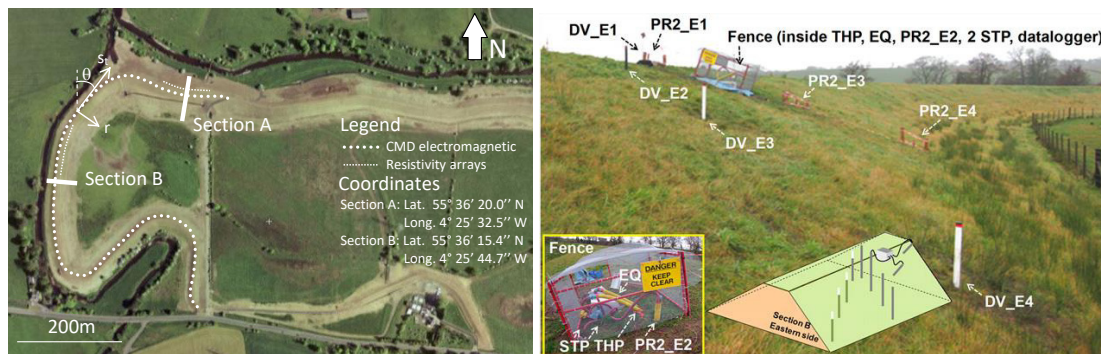

Fig. 1. (a) Plan view of the monitored embankment; (b) view of cross-section B with probes to measure water content (after [11]).

3. Establishment of the water content function

Herein the variable σ is employed to represent the ground electrical conductivity which is a function of both space and time, hence $\sigma = \sigma(x, s, z, t)$. Electromagnetic probes only provide a measure of σ which is averaged over a prismatic volume of ground where the induced electrical field is non-zero. Considering a generic cross-section of the embankment, we define:

$$\bar{\sigma}(s,t) = \frac{\int_{A_{CMD}} w(x,s,z,t)\,dx\,dz}{A_{CMD}} \tag{1}$$

with $A_{CMD}=b*d$, b = the distance between the two ends of the electromagnetic probe (hence corresponding to the width of the portion of the embankment cross-section where the induced electrical field is non-zero) and d = so-called effective depth, i.e. the depth of the induced electromagnetic field. Note that A_{CMD} is independent of the cross-section considered. The effective depth is a function of the type of ground and of the vertical distance from the portable device to ground level. d is an unknown to be determined by selecting the value providing the best correlation between measurements of electrical conductivity and water content (see Figure 4).

In Figure 2a, the measurements taken by the CMD-2 device at six different times (called t_k) along the entire embankment, $\bar{\sigma}_k(s) = \bar{\sigma}(s, t = t_k)$, are shown. It emerges that the shape of the curves is approximately the same for all the times considered. Now the spatial average of $\bar{\sigma}(s,t)$ over the entire embankment length can be calculated as:

$$\bar{\bar{\sigma}}(t) = \frac{\int_{s=0}^{s=L} \bar{\sigma}(s,t)ds}{L} \tag{2}$$

with the second above score bar denoting spatial average over the longitudinal coordinate s. Then, we can introduce the normalised cross-sectional average electrical conductivity as:

$$\bar{\sigma}_0(s,t) = \frac{\bar{\sigma}(s,t)}{\bar{\bar{\sigma}}(t)} \tag{3}$$

The normalised measurements taken at t_k, i.e. $\bar{\sigma}_{0_k} = \bar{\sigma}_0(s, t = t_k)$, are plotted in Figure 2b. From the figure, it emerges that the curves coincide almost perfectly. This leads to consider the average of $\bar{\sigma}_{0_k}$ over time:

$$\underline{\bar{\sigma}}_0(s) = \underset{k}{average}\, \bar{\sigma}_0(s, t = t_k) = \underset{k}{average}\left(\frac{\bar{\sigma}(s, t = t_k)}{\bar{\bar{\sigma}}(t = t_k)}\right) \tag{4}$$

as the representative curve of the conductivity of the embankment with the underscore bar denoting time average.
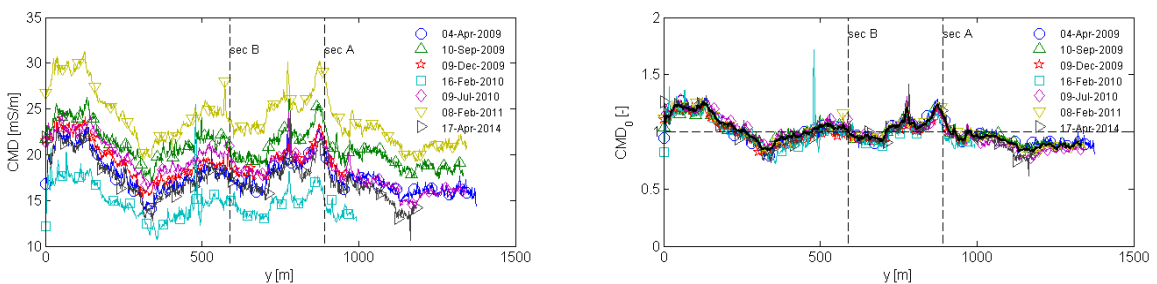

Fig. 2. (a) electrical conductivity measurements along the embankments at seven different times; (b) normalised values of conductivity measurements (after [11]).

The time-independent function $\underline{\bar{\sigma}}_0(s)$ can be thought of as a unique identifier of the embankment expressing the variation of conductivity along the s coordinate due to the variation of geometrical, hydraulic and lithological

properties and to the effects of exposure to weather conditions. On the other hand, the function $\bar{\bar{\sigma}}(t)$ reflects the temporal effect of climatic variations (e.g. rainfall, wind, temperature variations, etc.) and aging on the ground electrical conductivity.

Analogously to $\bar{\sigma}(s,t)$, we define $\bar{w}(s,t)$ as:

$$\bar{w}(s,t) = \frac{\int\limits_{A_{CMD}} w(x,s,z,t)dxdz}{A_{CMD}} \tag{5}$$

and decompose it into two functions:

$$\bar{w}(s,t) = \bar{\underline{w}}_0(s) \cdot \bar{\bar{w}}(t) \tag{6}$$

with $\bar{\underline{w}}_0(s)$ being a time independent dimensionless function expressing the variation of water content along the longitudinal coordinate due to the variation of geometrical, hydraulic and lithological properties and to the effects of exposure to weather conditions, and $\bar{\bar{w}}(t)$ a space independent dimensional function, which accounts for the effect of climatic variations and aging on the ground water content.

Considering measurements of water content at t_k, $w_k = w(x,s,z,t=t_k)$ can be expressed as the weighted average of the values of water content, $w_{i;k} = w(x,s=s_i,z,t=t_k)$, recorded at $t=t_k$ in the instrumented cross-sections (here the generic number N is used):

$$w_k(x,s,z) = w(x,s,z,t=t_k) = \sum_{i=1}^{N} w_{i;k}(x,z) \cdot \gamma_i(s) \tag{7}$$

with $\gamma_i(s)$ being weight functions. The simplest choice for $\gamma_i(s)$ is to consider a linear variation between the values of water content measured at the N instrumented sections:

$$\gamma_i(s) = \begin{cases} 1 & \text{for} & s = s_i & \forall i \in [1,..N] \\ 0 & \text{for} & s = s_{j \neq i} & \forall i, j \in [1,..N] \\ 1 - \dfrac{(s - s_i)}{(s_{i+1} - s_i)} & \text{for} & s_i \leq s \leq s_{i+1} & \forall i \in [1,..N] \\ 1 + \dfrac{(s - s_i)}{(s_{i-1} - s_i)} & \text{for} & s_{i-1} \leq s \leq s_i & \forall i \in [1,..N] \end{cases} \tag{8}$$

The water content in the whole embankment is obtained by interpolating the values of water content measured by the geotechnical probes in the N sections where they are located:

$$w_k(x,s,z) = w(x,s,z,t=t_k) = \sum_{i=1}^{N} w_{i;k}(x,z) \cdot \gamma_i(s) \tag{9}$$

Now the water content averaged over the whole embankment, $\bar{\bar{w}}(t)$, can be calculated from the water content measurements performed by the geotechnical probes in the monitored sections as:

$$\bar{\bar{w}}(t) = \frac{\displaystyle\int_0^L \frac{\displaystyle\int_{A_{CMD}} \sum_{i=1}^{N} w(x, s = s_i, z, t) \cdot \gamma_i(s)\,dxdz}{A_{CMD}}\,ds}{L} \tag{10}$$

$\bar{\bar{\sigma}}(t)$ and $\bar{\bar{w}}(t)$ are the functions be examined to seek a correlation between electrical conductivity and water content. In doing so, the significant dependency exhibited by ground electrical conductivity on temperature [9] needs to be accounted for. According to the work of [10] on glacial tills, the relationship is linear, i.e. $\sigma = \sigma_{25}\left[C(T-25)+1\right]$ with σ being the electrical conductivity measured at temperature T and C=0.02. The measured electrical conductivities need to be expressed in relation to a same reference temperature before being correlated to the water content measurements, so the following expression was employed:

$$\sigma_{ref} = \sigma \frac{1 + C\left(T_{ref} - 25\right)}{1 + C\left(T - 25\right)} \tag{11}$$

with σ_{ref} being the value of electrical conductivity expressed in terms of the chosen reference temperature, T_{ref}. Here, T_{ref}=15 Celsius was chosen to minimise the amount of temperature compensation. Eq. (10) was used to calculate σ_{ref} from the measured values of σ and T.

In Figure 3, the water content measured at t_k, $\bar{\bar{w}}(t = t_k)$, is plotted against the electrical conductivity measured at the same time points, $\bar{\bar{\sigma}}_{ref}(t = t_k)$. It emerges that the relationship between $\bar{\bar{w}}(t)$ and $\bar{\bar{\sigma}}_{ref}(t)$ is well captured by a linear function so that:

$$\bar{\bar{w}}(t) = m\bar{\bar{\sigma}}_{ref}(t) + q \tag{12}$$

with m and q determined by best fit. Substituting Eq. (11) into Eq. (12), we get:

$$\bar{\bar{w}}(t) = m\bar{\bar{\sigma}}(t)\frac{1 + C\left(T_{ref} - 25\right)}{1 + C\left(T - 25\right)} + q \tag{13}$$

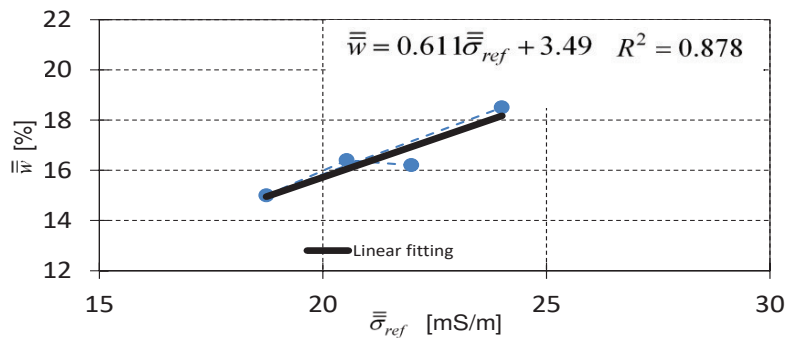Eq. (13) relates the space average of the measured electrical conductivity to the space average water content.

Fig. 3. (a) Correlation between average electrical conductivity, $\bar{\bar{\sigma}}_{ref}(t)$, and average water content $\bar{\bar{w}}(t)$ obtained for d=0.2m and T_{ref}=15°C.

To determine the water content in any generic point of the embankment, $w(x,s,z,t)$, the space independent dimensional function $\bar{\bar{w}}(t)$, must be multiplied by the normalised time independent function, $\underline{w}_0(x,s,z)$, so that:

$$w(x,s,z,t) = \underline{w}_0(x,s,z) \cdot \bar{\bar{w}}(t) \tag{14}$$

$\underline{w}_0(x,s,z)$ is the time average of the linear combination of the functions expressing the normalised water content measured at t_k in the instrumented sections, $w_{0\,i;k}(x,z)$:

$$\underline{w}_0(x,s,z) = \underset{k}{average}\left[\sum_{i=1}^{N} w_{0_{i;k}}(x,z) \cdot \gamma_i(s)\right] \tag{15}$$

with $\quad w_{0_{i;k}}(x,z) = w_0(x,s=s_i,z,t=t_k) = \dfrac{w(x,s=s_i,z,t=t_k)}{\dfrac{\int\limits_{A_i} w(x,s=s_i,z,t=t_k)dxdz}{A_i}}$

The function $\underline{w}_0(x,s,z)$, is assumed to be:

$$\underline{w}_0(x,s,z) = \bar{w}(s,t) \cdot \bar{\underline{\sigma}}_0(s) = \underset{k}{average}\left[\sum_{i=1}^{N} w_{0_{i;k}}(x,z) \cdot \gamma_i(s)\right]\bar{\underline{\sigma}}_0(s) \tag{16}$$

The advantage of employing geophysics is now apparent since unlike geotechnical measurements that can be taken only in a few discrete sections, it provides measurements which are continuous along the spatial coordinate *s*.

Substituting Eq. (13), and (16) into Eq. (14), the equation to convert electrical conductivity measurements (taken at the time t_{CMD}) into values of water content is obtained:

$$w(x,s,z,t=t_{CMD}) = \left\{\underset{k}{average}\left[\sum_{i=1}^{N} w_0(x,s=s_i,z,t=t_k)\cdot\gamma_i(s)\right]\cdot\bar{\underline{\sigma}}_0(s)\right\}\cdot\left[m\frac{\bar{\sigma}(s,t=t_{CMD})}{\bar{\underline{\sigma}}_0(s)}\frac{1+C\left(T_{ref}-25\right)}{1+C\left(T-25\right)}+q\right] \tag{17}$$

Note that electrical conductivity measurements can take place when the geotechnical suite is no longer active (i.e. $t_{CMD} > t_k$).

4. Validation

To validate the proposed method, a comparison between the water content values determined from electrical conductivity measures according to the described procedure and water content measured in the laboratory from soil samples retrieved in situ is here illustrated. Contour lines of water contents in two randomly chosen cross-sections (s = 2, 182) calculated using Eq. (17) from electrical conductivity measurements carried out on 17th April 2014 (so for $t_{CMD} > t_k$) during a walk-over are plotted in Figure 4. The values of the water content measured in the laboratory from in-situ retrieved samples are reported in the plots as triangles.

The values of water content converted from the conductivity measurements according to the proposed procedure show to be in very good agreement with the laboratory measures. Note that the conductivity measurements were

taken at a time (17th April 2014) well beyond the 2 year period during which the calibration of the model was performed.
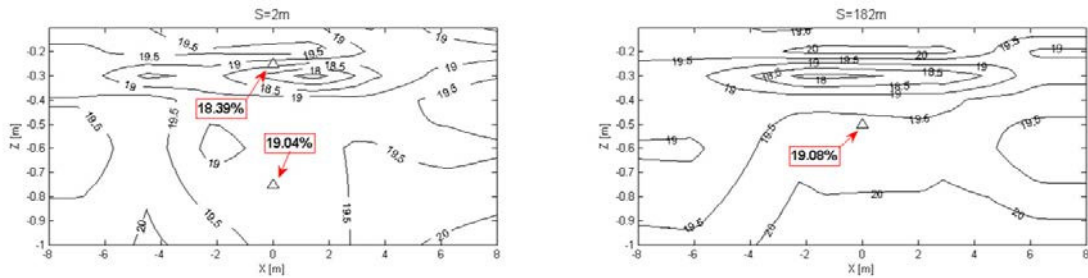

Fig. 4. Values of water content estimated from electrical conductivity measurements (carried out on 17th April 2014) employing the proposed methodology. a) water content calculated at s=2m; b) water content calculated at s=182. The triangles indicate values of water content measured in the laboratory from in-situ retrieved samples.

5. Conclusions

A methodology for the periodic monitoring of water content in embankments to be carried out by a non-invasive hand held geophysical device measuring electrical conductivity is proposed here. The methodology requires the use of geotechnical probes installed in at least two cross-sections of the embankment to calibrate the electrical conductivity – water content relationship.

The values of water content converted from the conductivity measurements according to the proposed procedure were found to be in very good agreement with the laboratory measures even at times well beyond the 2 year period during which the calibration of the model was performed.

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