Construction and Building Materials xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Moisture monitoring in clay embankments using electrical resistivity tomography

D.A. Gunn [a,*], J.E. Chambers [a], S. Uhlemann [a,c], P.B. Wilkinson [a], P.I. Meldrum [a], T.A. Dijkstra [a], E. Haslam [a], M. Kirkham [a], J. Wragg [a], S. Holyoake [a], P.N. Hughes [d], R. Hen-Jones [b], S. Glendinning [b]

[a] *British Geological Survey, Nottingham NG12 5GG, UK*
[b] *School of Civil Engineering and Geosciences, Newcastle University, Newcastle upon Tyne NE1 7RU, UK*
[c] *ETH Zurich, Institute of Geophysics, Sonneggstrasse 5, 8092 Zurich, Switzerland*
[d] *School of Engineering and Computer Sciences, Durham University, DH1 3LE, UK*

HIGHLIGHTS

- New remote monitoring technologies/approaches.
- Proactive maintenance using subsurface images.
- Increased time for early interventions.

ARTICLE INFO

Article history:
Received 2 February 2014
Accepted 5 June 2014
Available online xxxx

Keywords:
Resistivity
Embankments
Moisture
Railway

ABSTRACT

Systems and methods are described for monitoring temporal and spatial moisture content changes in clay embankments using electrical resistivity tomography (ERT) imaging. The methodology is based upon development of a robust relationship between fill resistivity and moisture content and its use in the transformation of resistivity image differences in terms of relative moisture content changes. Moisture level and moisture content movement applications are exemplified using two case histories from the UK. The first is the BIONICS embankment, near Newcastle (NE England), which was constructed in 2005 using varying degrees of compaction of a medium plasticity sandy, silty clay derived from the Durham Till. The second is a Victorian embankment south of Nottingham (Central England), constructed in 1897 using end tipping of Late Triassic siltstone and mudstone taken from local cuttings. Climate change forecasts for the UK suggest that transportation earthworks will be subjected to more sustained, higher temperatures and increased intensity of rainfall. Within the context of preventative geotechnical asset maintenance, ERT imaging can provide a monitoring framework to manage moisture movement and identify failure trigger conditions within embankments, thus supporting on demand inspection scheduling and low cost early interventions.

1. Introduction

Engineered slopes, embankments, canals, earth dams, sea walls and flood defences are increasingly susceptible to catastrophic failure due to changes in global climatic conditions and land use. The 4th Assessment Report of the Intergovernmental Panel on Climate Change [23,24] predicted that mid- to high-latitude regions can expect more extreme events with up to 20% more precipitation, more flash floods, and a rise in sea levels up to 59 cm by the end of the century. The predicted environmental changes will have inevitable consequences for the serviceability and maintenance of our engineered infrastructure, but while the impact is still largely unknown, we require intelligent platforms and science to monitor current condition and assess risk over the whole life cycle of UK assets. Aged assets include: Canal & River Trust/Scottish Canals with 3450 km of aged canal earthworks, Network Rail with over 20,000 km of earthwork embankments and cuttings, and London Underground with 236 km of embankments and cuttings in Greater London, all contributing significantly to the UK economy.

A significant number of UK earthworks between 100 and 200 years old were constructed using tipping methods, which was standard in the 19th century. This has left a legacy of ageing, highly fissured, weak and heterogeneous earth structures, which are still intensively used but prone to failure under aggressive climatic stresses [28]. Common problems in certain subgrade soil

---

[*] Corresponding author.
E-mail address: dgu@bgs.ac.uk (D.A. Gunn).

http://dx.doi.org/10.1016/j.conbuildmat.2014.06.007
0950-0618/Crown Copyright © 2014 Published by Elsevier Ltd.

Please cite this article in press as: Gunn DA et al. Moisture monitoring in clay embankments using electrical resistivity tomography. Constr Build Mater (2014), http://dx.doi.org/10.1016/j.conbuildmat.2014.06.007

types include shear failure and mud pumping caused by loss of strength and cohesion [33,25], heave, deformation and the formation of ballast pockets [31,5], which also occur in zones of low density and stiffness. In most cases, subgrade problems are associated with high moisture levels, a key factor in reducing consistency and strength, and ultimately leading to failure [32,18].

Modelling undertaken during the recently completed FUTURENET project [3,4] showed how climate or weather event sequences affect the traffic capacity of transportation networks. Weather events have direct effects on the permanent way such as increased temperature on risk of track buckling (or pavement rutting) and related effects on potential failure of the subgrade and surrounding ground including landslide, shrink–swell and scour. Climate resilience planning for transportation networks requires access to near real-time, volumetric, and hence holistic, assessment of infrastructure condition, including ground water movement and the moisture levels within the earthworks asset. Maintenance practice, based primarily on surface observations, is a barrier to proactive approaches because these represent the latter stages of failure and reinforce responsive solutions. Risk-based prevention and early interventions require identification of the incremental development of internal conditions that ultimately trigger failure. Key to this process will be adaptive technologies delivering real-time images of the true 3D spatial variation of groundwater and geotechnical properties affecting stability. While providing useful ground truth, a full understanding of vital ground processes with sufficient temporal and spatial resolution is often not possible from invasive investigation alone. We assert that this role can be filled by non-invasive geophysical methods that not only provide real-time images of moisture movement but are also calibrated so as to indicate full 3D, quantitative geotechnical property changes. This can be achieved if the geophysical relationships between electrical resistivity and geotechnical properties (such as moisture content, pore pressure and strength) are well understood.

Resistivity imaging, or electrical resistivity tomography (ERT), is sensitive to lithological and mineralogical heterogeneity [34] and changes in ground temperature and soil moisture content [10,11,19,12]. In locations where lithology and mineralogy are unchanged, provided ground temperature effects can be corrected, changes in successive ERT surveys over an electrode array of constant geometry and location will be due to ground water movement and subsequent moisture content variations. Thus, by applying appropriate temperature correction and petrophysical relationships linking resistivity and saturation [7,6,12], time-lapse, volumetric (4D) images of water movement and moisture content changes can be constructed from repeated ERT surveys. Alongside the increased use of ERT in site investigation, purpose built ERT monitoring instrumentation has rapidly developed and now incorporates telemetric control and automatic data transfer, scheduling, and processing [30]. This type of instrumentation is now being applied to monitor of natural slopes [27,37,35] and transportation earthworks [19,12].

In this study we describe repeat survey-based approaches using standard field equipment/return visits and fully automated monitoring and data capture on permanent field installations to investigate the structure and processes in sections of two embankments. We provide two case histories: firstly, from the BIONICS research embankment, Nafferton Farm, Northumberland, UK [14,21] constructed using varying amounts of compaction in 2005 from sandy, silty clay derived from partially sorted Durham Till; which includes identification of individual lifts from 2D resistivity sections across the embankment transect; and secondly, from an embankment along the former Great Central Railway near East Leake, Nottingham, UK [2,17,19] constructed via end-tipping of materials derived from the East Leake Tunnel cutting to the south; which includes identification of fill regime changes in a 2D resistivity section along the axis of the embankment, dynamic, seasonal wetting and drying fronts moving through a 2D transect of the embankment and a demonstration of the potential application of 3D volumetric images of moisture movement and geotechnical property visualisation for planning maintenance. Finally, these case histories provide the context for a broad discussion relating to the foundation for new risk-based asset management practices incorporating automated, electrical imaging technologies into early intervention decision processes, such as proactive drainage planning.

2. Soil and rock resistivity

2.1. Resistivity measurements and field systems

Fig. 1a shows that the resistivity, ρ_s of a unit volume of material is given as,

$$\rho_s = \frac{V}{I} \cdot \frac{A}{L} \tag{1}$$

where $\frac{V}{I}$ is the ratio of the difference, V in the electrical potential at the two opposing faces of a unit cube that are orthogonal to the current flow, I and is equivalent to the material resistance, R and $\frac{A}{L}$ is the Geometric Factor (in Fig. 1a) that accounts for how the current flow within the material and the measurement are affected by the electrode geometry, and converts resistance R to resistivity, ρ_s.

Resistivity is measured in the field using a four-electrode array consisting of two current injection electrodes and two potential measurement electrodes. In general, the depth of investigation increases with increasing electrode separation, where the different electrode array configurations determine the specific relationship. For example, Fig. 1b shows how the depth of investigation for a dipole–dipole array is related to the common spacing (denoted ‘a’) between the current and potential electrode pairs. It also shows how a 2D ‘apparent resistivity’ section along a transect can be constructed from a series of resistivity measurements at different inter-dipole spacings (denoted ‘n’). Further processing can also be undertaken to refine these images to produce the best estimate of the true ground resistivity distribution; a process termed ‘inversion’. The ABEM SAS 1000 is typical of the field equipment used to make resistivity-depth soundings or 2D cross-sectional surveys. A series of field measurements are made, usually by varying the electrode spacing in standard four-electrode array configurations, such as the dipole–dipole (or Wenner or Schlumberger) arrays, from which apparent resistivity sections are constructed. The voltage measurement between two potential electrodes can be considered as a single channel. As surveys require multiple measurements, the duration of the survey can be reduced by an equivalent factor to the number of channels used.

Datasets for 3D imaging typically require many thousands of four-electrode measurements over a range of geometries to be carried out across the area of interest. Thus, equipment with lower numbers of input channels are disadvantaged by longer survey times. The AGI SuperSting R8 is typical of field equipment used for 3D surveys, boasting eight channels with the potential to connect up to 65,000 electrodes, (although most surveys don’t utilise anywhere near this potential but the eight channel system reduces surveying times). 3D apparent resistivity images, or models of the true resistivity distribution in the subsurface are constructed from the measured resistivity dataset, in a similar manner to the multi-point construction in 2D surveys (Fig. 1c). The new generation of remote monitoring platforms such as the Automated time-Lapse Electrical Resistivity Tomography (ALERT) and the very recent Proactive Infrastructure Monitoring and Evaluation (PRIME) systems combine emerging electrical resistivity imaging technology with wireless telecommunications, server-based processing, site databases and web portal access [29,38].

Please cite this article in press as: Gunn DA et al. Moisture monitoring in clay embankments using electrical resistivity tomography. Constr Build Mater (2014), http://dx.doi.org/10.1016/j.conbuildmat.2014.06.007