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Desiccation cracking detection using 2-D and 3-D Electrical Resistivity Tomography: Validation on a flood embankment

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ABSTRACT

Desiccation cracks forming in earthen structures are a known source of engineering concern. In particular such fissures forming in flood embankments can affect their stability leading to failure when overtopped. These and other problems related to safety have raised the importance of using efficient and reliable tools, especially when relatively fast, non-invasive and extensive investigations are required. Geophysical techniques, such as Electrical Resistivity Tomography (ERT), allow for accurate assessment and monitoring of shallow depths within engineering structures.

The presented study examines the use of miniature and field scale ERT on a fissured flood embankment near Hull, UK. Two separate sections were surveyed in summer and winter using both 2-D and 3-D configurations, allowing seasonal evaluation of embankment condition.

The field results were validated through forward modelling, with different fissure configurations and the effect of topography. The results show that the resolution of the cracks increased with smaller electrode spacing. It was found that ERT can be used on a larger scale to detect zones of fissuring with fissured networks being displayed. The ability to detect cracks was diminished when surveying in winter with cracks reducing in size due to seasonal swelling of the soil. The resistivity models obtained showed anomalies with far lower resistivity than those obtained in summer.

The study showed that miniature surveys could be used to examine small sections in detail allowing imaging for horizontal subsurface fissures. The larger scale surveys provided important spatial information allowing the distribution of fissures on the embankment to be made.

The study recommends that geophysical surveying of flood defences should be used as a routine assessment tool to detect desiccation cracks within the embankment, and that these surveys should be completed in the summer, where cracks are most prominent.

1. Introduction

In the UK more than 34,000 km of flood embankments protect homes and vital infrastructure along its coast and estuaries. With potential increase in sea levels estimated to be around 0.5 m or more (Pardaens et al., 2011; Van Vuuren et al., 2011) as a result of global climate change, the strength and integrity of such flood defences are expected to be placed under increased scrutiny. When coupled with the predicted increase in precipitation (Met Office, 2011a) the importance of maintenance and inspection of flood defences is of increasing public importance in the UK. Recent extreme weather in winter 2013 has pushed the British Government to announce £140 M of new funding for repairing and improving flood defences. These events have reinforced the need for effective flood mitigation and have brought the issue to the forefront of public debate, further emphasising the need for regular maintenance and assessment of existing flood embankments.

Currently flood embankments are only assessed through visual surveying, requiring the surveyor to walk the entire length of the structure to observe any possible weaknesses. The presence of defects such as desiccation cracks can be obscured by dense vegetation and as a result surveys are generally taken during the winter months when vegetation is lighter. Despite this, vegetation can still be heavy enough to impede the visual survey particularly on the landward side which is rarely maintained. The severity of the cracks inside the structure can be underestimated due to seasonal swelling of the soil during wetter months. In addition to visual surveys, only destructive techniques, such as sampling and trenching can be used to detect fissuring in depth. Hence, new techniques are needed which would allow non-invasive detection and characterisation of cracking in the near surface. In this study, non-destructive Electrical Resistivity Tomography

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(ERT) is proposed as a tool to detect the extent of desiccation in earthen structures. The use of miniature, 2-D and 3-D ERT arrays previously tested on laboratory models (Jones et al., 2012; Sentenac and Zielinski, 2009), was validated in situ on a desiccated flood embankment and compared with results obtained from forward modelling. The use of field scale ERT was also investigated and validated through forward modelling. The results from different seasonal surveys on a desiccated embankment were compared and discussed.

1.1. Cracking due to desiccation

Desiccation due to moisture loss results in shrinkage of a soil mass. When shrinkage is restrained, as in massive structures such as flood embankments, cracks form due to build-up of internal stresses (Shin and Santamarina, 2011). With extended periods of desiccation, cracks can grow to form interconnected networks, providing a pathway for fluid flow (Sanchez et al., 2013). In flood embankments, such networks of fissures can result in failure during overtopping (Cooling and Marsland, 1954; Marsland and Cooling, 1958). Desiccation cracks separate the soil into polygonal blocks at the surface while continuous shrinkage can result in a shear plane beneath the surface of the soil (Konrad and Ayad, 1997; Style et al., 2010), resulting in the separation of the top layer of soil from the remainder of the structure (Fig. 1). Such cracking is of concern in several engineering and agricultural applications; e.g. compacted clay landfill liners (Albright et al., 2006; Kleppe and Olson, 1985; Omidi et al., 1996; Southen and Rowe, 2005) and irrigation quality (Janssen et al., 2010; Liu et al., 2003). In general terms the problems relate to the creation of direct flow paths through the material, due to the increased permeability as the result of interconnection between adjacent fissures.

1.1.1. Embankment failure due to desiccation cracks

Desiccation in flood embankments is a global process and is likely to affect the embankment body including the crest and both slopes. Failure can be induced during overtopping where water can infiltrate via large surface cracks and flow through the fissured network (Marsland, 1957). This flow can result in internal erosion of the fissured pathways, leading to instability of the embankment slopes and leading ultimately to breach (Cooling and Marsland, 1954). The failure method resulting in breach in engineering terms can be considered as a rigid block rotating away from the embankment (Utili, 2012), and the landward side of an embankment may be considered to have the highest risk of failure.

In some cases seepage through the fissures can be observed without water reaching the crest of the embankment (Zielinski, 2009). In such case, the effective height of protection is reduced to the height of the intact part of the soil.

Fig. 1. Exposed fissures through trenching on the disused Thorngumbald embankment (after Dyer et al., 2009).

Research conducted by Cooling and Marsland (1954) and Marsland (1968) after the 1953 North Sea floods revealed a large number of wide cracks (≈10 cm) penetrating flood defences to a depth of about 1.5 m. A later study carried out by Dyer et al. (2009) on the disused Thorngumbald embankment, near Hull (UK), discovered a specific character of cracking, forming a relatively shallow (about 60 cm) interconnected network with both, vertical and horizontal fissures present. Another example from the same study shows an individual crack extending to a depth of 1 m.

From these studies it can be seen that the nature of soil fissuring can vary from case to case, and that gathering such information about its extent within the structure is impossible without destructive trenching into the embankment body. This or even less invasive tube sampling, if necessary, has to be limited to a small area since the structure cannot be affected; hence the investigation is very limited. Thus, some advanced and non-invasive techniques are needed for high quality sub-surface assessments, particularly in cases where the fissured structure is at risk.

1.2. Electrical Resistivity Tomography

Electrical Resistivity Tomography (ERT) is a frequently used geophysical technique that allows the electrical properties of a section of ground to be determined by measuring the drop in potential occurring due to an applied electrical current (Reynolds, 1997). Such a method has been used successfully in the laboratory for the detection and monitoring of fissures in clayey soil (Jones et al., 2012; Samouëlian et al., 2003, 2004; Sentenac and Zielinski, 2009). An additional advantage for the use of ERT is its potential use in remote monitoring (Kuras et al., 2009; La Breque et al., 2004; Rucker et al., 2009; Sjödahl et al., 2008; Wilkinson et al., 2010, 2011). Such monitoring is advantageous as it allows the site to be monitored without the presence of a surveying team, with data being sent automatically for processing. When doing long-term monitoring with ERT, temperature variations should be accounted for (Abu-Hassanein et al., 1996; Johansson and Dahlin, 1996; Keller and Frischknecht, 1966; Zha et al., 2010). Previous studies have shown that there is a 2% rise in resistivity with each 1 °C drop, relative to a reference temperature (Ling et al., 2013; Pellicer et al., 2012; Sjödahl et al., 2008).

Since the temperature changes within an estuarine flood embankment are usually complex, and available atmospheric data was restricted to air temperature and precipitation only; it was not possible to apply these methods to predict the temperature within the structure. In this study it was assumed that changes in measured apparent resistivity between different periods would be due to seasonal changes in moisture which are not greatly influenced by seasonal temperature changes.

1.2.1. ERT and cracking

When implementing ERT in fissured soil, it can be considered that single cracks act as barriers impeding the flow of charged particles (positive cations and negative anions), resulting in an apparent drop in potential relative to that observed for the surrounding intact soil (Rhoades et al., 1989). These cracks can be considered to be an anomaly of virtually infinite resistivity given that it can be seen to be an air gap, though the true resistivity of cracks is lower as the measurement includes some part of the surrounding intact soil. In Jones et al. (2012) some consideration was given to the possible range of resistivity values that could be attributed to a fissure forming in clay. Based on observations in literature (Loke, 2014; Reynolds, 1997) it was assumed that a resolved anomaly with values of 100 Ω-m or more could be considered to be a fissure given that this was the upper limit observed for intact clay. This range was verified in the laboratory (Jones et al., 2012) using a small electrode spacing of 4.5 cm.

In the same study, both Schlumberger and Dipole–Dipole arrays were used individually and in a combined inversion to examine the effectiveness of each array for the visualisation of fissures in the subsurface. It was found that the combined inversion provided the most accurate