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Deterioration model and condition monitoring of aged railway embankment using non-invasive geophysics

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HIGHLIGHTS

- Structures consistent with the end-tipped construction identified using MASW.
- Infiltration via wetting fronts into the embankment core identified using ERT.
- Ageing includes dissolution, mobilisation and re-precipitation of soluble minerals.
- Heave, rupture, mudstone delamination and de-structuring to clay disrupted fill.
- ERT-shear wave velocity embankment condition monitoring scheme devised.

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ABSTRACT

Effective management of railway infrastructure is becoming increasingly reliant upon remote condition monitoring of geotechnical asset condition. Current monitoring approaches focus on confirmation of the morphological effects caused by subsurface processes driving deterioration. However, geophysical imaging offers new opportunities for 'predict and prevent' practices, providing access to monitoring internal property change patterns preceding these morphological responses. Geophysical methods utilize disturbances that propagate through and holistically sample earthworks and are especially suited to imaging the unique heterogeneity of aged embankments. In this case study, surface wave seismic surveys are interpreted to construct a stiffness ground model consistent with a heterogeneous embankment comprising local borrow materials. Time-lapse electrical resistivity imaging was also used to investigate and visualise ground water ingress and movement within this ground model. Ground water movement was shown to be highly dynamic, responding very quickly to local storm events with infiltration into the embankment within hours. Subsequent wetting and drying cycles throughout the embankment's lifespan have caused the dissolution, mobilisation and re-precipitation of soluble minerals within the fill materials. This process has driven the deterioration of the fill fabric, which is evidenced in thin sections by voids and localised rupture about *in situ* mineral growths. Finally, we provide a framework showing how geophysical methods could support more risk-based asset management practices of the future.

1. Introduction monitoring heterogeneous engineered earthworks

1.1. Construction and heterogeneity of aged railway embankments

Much construction of the UK railway network commenced in the 19th century, during the formative years of the Industrial Revolution, [33]. Excavation of aged railway cuttings commonly employed large teams of navvies using driven wedges, horse-pulled ploughs, hand tools, and on the later railways such as the Great Central, steam-powered excavators [3,34,33]. While the construction materials were influenced by the underlying geological formations, the engineering characteristics of fine-grained, stiff clay or weak mudstone formations favoured relatively easy excavation using these tools, hence, many aged railway earthworks comprise London Clay, Oxford Clay, Gault Clay, Mercia Mudstone and Lias Clay [29]. The absence of established practice resulted in

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embankment construction methods varying considerably between networks, often based upon the experiences of the chief engineer. Aged railway embankments were often end-tipped, using materials from local cuttings [33]. While modern embankments tend to be structured into well compacted layers, aged embankments often have poor levels of compaction, a greater variability of fill material grades, and usually exhibit highly unique heterogeneity [31,33]. As argued by Dijkstra et al. [7], Hughes et al. [19] and Glendinning et al. [11] it is increasingly important to assess the temporal and spatial distribution of engineered earthworks asset conditions, particularly as deterioration processes of these assets are affected by changes in climate and environmental stress. Enhanced effectiveness of the communication of changes in asset condition (in 4D space; see Gunn et al. [14]) is a further important consideration. It is argued that in both cases geophysical monitoring can play a pivotal role.

1.2. Monitoring challenges posed by aged infrastructure

Earthworks assessment requires the determination of soil properties important for the evaluation of performance. Soil type, moisture, stress levels and strength control problems such as plastic deformation, heave, shear failure and mud pumping which lead to a loss of level and support [27]. Repeated visual inspections are mostly used to identify embankment problems, essentially looking for morphological features that confirm movement or anomalous groundwater conditions [27]. This approach is limited, for example because vegetation can often obscure signs of ground movement or the subsurface ground and water conditions are not accessible, and consequently, slopes are perceived to fail ‘rapidly’ without displaying visible signs of distress. But, most common geotechnical monitoring approaches still involve displacement measurements of embankments, often following observations of morphological features associated with instability [9]. Surface and downhole tilt meters or extensometers are often deployed to assess the displacement profile with depth. Such approaches require boreholes and can be accompanied by groundwater level measurements using piezometers. These data inform stability analyses, aid risk assessments and may contribute to remedial design. However, these approaches include the expense of intrusive works, and implicitly accept the potential for failure, which does not honour the strict terms of ‘early warning’.

Remotely sensed approaches are better suited for more rapid, cost effective network coverage of the morphological features currently used to define marginal condition. Satellite or ground based radar (LiDAR), robotic total stations and photogrammetry provide high resolution ground displacement information [23], but still essentially confirm the morphological response to underlying subsurface property (condition) changes that form earlier phases of asset deterioration. With no standard practice and no, or very poor, ‘as built’ documentation, capturing the representative heterogeneity in a ground model that will reliably predict progressive failure of aged infrastructure is especially challenging. However, geophysical imaging offers the opportunity to monitor longer term, internal property (condition) change patterns, potentially the precursors to the surface morphological responses currently defining ‘failure’. These property change signatures offer a potential baseline against which internal condition thresholds can be identified and, used as early warning of future instability, would enable more progressive effects of climate and ageing stresses to be assessed [14,17].

This paper presents combined rapid cone penetration and non-invasive geophysical methods for studying the spatial and temporal variations within an end-tipped Victorian embankment. Geophysical imaging methods include use of surface wave surveys [15,17,18] and electrical resistivity tomography (ERT), [6,14]. These provide volumetric infill between boreholes to create a pseudo-3D embankment stiffness model, within which we attribute heterogeneous structures to end tipping construction methods. A hydrogeological model is also presented for the embankment system, where using time lapse ERT images, dynamic ground water movement is visualised. *In situ* fracturing, heave, secondary mineralisation and de-structuring within the fabric of samples taken from the embankment provide further evidence of the long term deterioration driven by this groundwater movement. Hence, this paper raises the potential for new definitions of condition and deterioration based upon monitoring of internal properties and their changes using non-invasive geophysics. To this end, we present a condition monitoring framework based on geotechnical property metrics provided via imaged geophysical proxy.

2. Study site investigation

2.1. Embankment layout and invasive probings

Our study site comprised a 140 m long section of the whole embankment located at East Leake on the former Great Central Railway (GCR) that extends 800 m. The embankment was built up over the Branscombe Formation of the Mercia Mudstone Group in 1897 using local materials excavated from the tunnel cutting to the SW and the bridge cutting to the NE [2]. The fill was end tipped and then compacted by subsequent movement of shunting locomotives and tipping wagons across the tipped material. The embankment has been subjected to several phases of site investigation from 2005 to 2011, which has included drilling beneath the ballast, collection of core samples, invasive probing and non-invasive geophysical surveying; the locations of boreholes, probings, point and line geophysical surveys are shown Fig. 1. The study focused particularly on the section from 0 m to 140 m in Fig. 1, which included 8 MOSTAP samples taken beneath the ballast, through the embankment fill and into the underlying formation (approximately 7.0 m long). Rapid invasive probing also included static cone penetration tests [24], in which a cylindrical cone was pushed vertically into the ground at a constant penetration rate of 20 mm per second. During penetration, measurements were made of the cone resistance, the side friction against the cylindrical shaft and, in piezocone tests, the pore water pressure generated at penetration by the cone.

2.2. Non-invasive geophysical surveys

Non-invasive geophysical surveying at the site included electrical resistivity tomographic (ERT) imaging and surface wave surveys using continuous surface wave (CSW) and multi-channel analysis of surface wave (MASW) methods. ERT is an established method for high resolution mapping of lithological variations [32] and changes in soil moisture [5,4], and has contributed to previous railway stability assessments [8,14]. Chambers et al. [6] detail the ERT layouts and methods used to map the fill materials and image groundwater movement in relation to their distribution throughout the embankment, which is summarised here to provide a site methodology guide. Similarly, surface wave surveys are an established method for characterising the shear wave velocity and stiffness of the shallow subsurface [10,30], which are also suitable for railway earthwork assessment [15,1]. Gunn et al. [12,18] detail the CSW and MASW layouts and methods used to map the stiffness distribution throughout the embankment fill, again summarised here.

Permanent installation of ERT electrode arrays buried approximately 150 mm beneath the surface included a line parallel to the embankment (blue line in Fig. 1 comprising 96 electrodes