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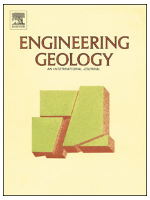

Failures in transport infrastructure embankments

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ABSTRACT

To ensure that road and rail transport networks remain operational, both highway and railway embankments require continual maintenance and renewal to mitigate against ongoing deterioration and repair any sections damaged by realised failures. This paper provides a review of recent developments in the understanding of highway and railway embankment degradation and failure. Failures due to pore water pressure increase, seasonal shrink-swell deformation and progressive failure are considered. The material composition and construction of highway and railway embankments differ, which influences the dominant type and timing of embankment failure. There is evidence for highway embankment failures induced by pore water pressure increase, but not seasonal deformation and progressive failure. Some railway embankments are susceptible to pore water pressure increase, seasonal shrink-swell deformation and progressive failure due to the age and nature of the dumped clay fill used in their construction. The approaches used to measure and explore embankment failure mechanisms are compared and discussed. Field observations have been used to understand pore water pressure increase and seasonal shrink-swell deformation in embankments, while the investigation of progressive embankment failure has mainly utilised physical and numerical modelling approaches. Further field and laboratory investigation is required before the rigorous analysis of embankment failure can be routinely undertaken. However, progress is being made to empirically identify and evaluate the various risk factors affecting transport infrastructure embankment failure.

1. Introduction

Transport infrastructure embankments consist of fill material placed to maintain the vertical alignment of road, rail and canal routes by raising their level above that of the surrounding natural ground. They are distinct from cuttings, which reduce the ground level by excavating in situ soil and rock. There are approximately 9660 km of embankments in the UK owned by the four main infrastructure owners Network Rail (5000 km), Highways England (Formerly Highways Agency; 3500 km), British Waterways (1100 km) and London Underground Ltd. (60 km) (Perry et al., 2003).

Embankment failures occurred both during and shortly after embankment construction during the expansion of the railway in the 1800s (Skempton, 1996). Highway embankment slope failures were reported to affect about 7% of the highway network in the 1960s (Symons, 1970), following their first construction in 1958 (Perry et al., 2003). The failure of both highway and railway embankments requires continual maintenance and repair to be undertaken by infrastructure owners. For example, the maintenance of railway earthworks (embankments and cuttings) including refurbishment, renewal and vegetation clearance cost £90 million per annum in the UK between 2006 and 2012 (Arup, 2013). The repair of highway embankment and cutting slopes cost approximately £20 million per annum in the UK in 2010 (Arup, 2010). Embankments form half of all earthworks (cuttings and embankments) by asset length (Perry et al., 2003) and represent a significant proportion of the maintenance cost incurred by infrastructure owners. However, embankments have not received the same attention in the literature as cut slopes (e.g. Chandler and Skempton, 1974; Potts et al., 1997; Cooper et al., 1998; Leroueil, 2001; Vaughan et al., 2004).

This paper provides a review of recent developments in the understanding of highway and railway embankment degradation and failure. The differing construction methods and performance requirements of these embankments are described. The approaches used to measure and explore embankment failure mechanisms are compared and discussed, including field observations, centrifuge modelling, finite element modelling.

1.1. Scope of the review

This review describes slope failures in highway and railway infrastructure embankments, with an emphasis on failure of the embankment fill. The review does not include the failure of cut slopes

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(Leroueil, 2001), embankments on extensive soft ground (Chai et al., 2002; Lehtonen et al., 2015) or water retaining embankments such as canal embankments (Perry et al., 2003) and embankment dams (Vaughan et al., 2004; Charles and Bromhead, 2008; Lees et al., 2013), which have received attention elsewhere in the literature. The review considers embankment failures due to the influence of weather and long term deterioration but does not consider failures where transport embankments intentionally or accidently act as coastal or fluvial flood defences (e.g. Sharp et al., 2013).

2. The design and construction of highway and railway embankments

A timeline of embankment construction in the UK is shown in Table 1 (adapted from Perry et al., 2003). The differing construction methods and material composition of highway and railway embankments (Fig. 1) reflect the contemporary availability of construction materials, material specification and construction plant, as well as the experience and geotechnical understanding of the designers.

Early railway embankments were built empirically and were not designed in the context of modern soil mechanics (e.g. Harrison, 1881). The large scale construction of railway embankments began in 1827 with the construction of the Liverpool and Manchester Railway. Between 1834 and 1841 nine main lines of railway were built in England covering over 660 miles (Skempton, 1996). This required the excavation of 54 million m^3 of material, most of which was used to construct embankments. Skempton (1996) described how clay was excavated and transported from nearby cuttings and then tipped onto the natural ground surface (Fig. 2) to form an embankment of heterogeneous, poorly compacted, 'dumped' clay fill (Vaughan et al., 2004). The foundation was not prepared prior to embankment construction, with topsoil and any soft superficial deposits usually being left in place. The extensive excavation and investigation of fills carried out as part of remediation works have revealed that dumped clay fills have a clod-matrix structure which differs from compacted, engineered fill or natural clay (Fig. 3; O'Brien, 2007). Intact clods of clay influence the compressibility and shear modulus of the dumped clay fill while a matrix of remoulded clay and foreign matter (silt, sand, gravel) influences the shear strength and the permeability (O'Brien et al., 2004; O'Brien, 2007).

By the mid 1830s, embankments were rapidly constructed by end-tipping fill from the advancing head of an embankment to its full height, rather than constructed in shallow layers to allow consolidation of the embankment and foundation (Skempton, 1996). Early main line railway embankments were often constructed at a slope gradient of 1:2 (vertical: horizontal) to between 2 m and 8 m high (O'Brien, 2013), with slope gradients up to 1:1.5 and embankment heights up to 16 m described by Skempton (1996). The shape of these embankments was quite variable. Some embankments had a steep, uniform slope while others had a 'coat-hanger' appearance with an over-steepened upper slope and a shallower lower slope (Fig. 1; O'Brien, 2013).

Table 1
A timeline of embankment construction in the UK (adapted from Perry et al., 2003).

Date	Embankment type
Circa 1800s	Canal construction peak
1835	Canal construction largely complete
1827	Construction of the Liverpool & Manchester Railway
Mid-1830s	Railway embankments rapidly constructed by 'end tipping' fill
1841	Great Western Railway construction complete
1850s	Railway construction peak
Circa 1860	London Underground Ltd. embankment construction began
1933	Proctor (1933) publishes a paper on compaction
Circa 1948	London Underground Ltd. embankments complete
1952	Research into the properties of fills at the Road Research Laboratory
1958	M6 Preston by-pass opened
1959	M1 Motorway Watford to Crick opened
1986	M25 Motorway fully opened
2003	Section 1 of the Channel Tunnel Rail Link (CTRL) opened

In contrast to railway embankments, the design of highway embankments benefitted from experience gained during railway construction, from the development of modern soil mechanics and from an improved understanding of the soils used in construction. An understanding of the properties of fill soils and their placement was developed early in motorway construction, based on research at the Road Research Laboratory (1952). Highway embankments were constructed to modern standards (e.g. British Standard 6031 (British Standards Institute, 2009)) on a prepared foundation with installed drainage and regular slope profiles (Fig. 1). The selection, placement and compaction of the fill material was specified to produce a largely homogeneous engineered fill with a consistent density, strength, stiffness and permeability (Highways Agency, 2009).

Highway embankment construction to motorway standard began with the Preston By-Pass, which opened in December 1958 (Perry et al., 2003). This marked the beginning of a rapid growth in highway embankment construction between the 1960s and 1990s (Loveridge et al., 2010). By 1994, 92% of the current motorway network had been built (Wootton, 2010). Highway embankments built to motorway standard were required to maintain a low gradient (4% or 1 in 25) over long distances for high-speed traffic. They differed from earlier roads which followed the natural contours of the ground and differed from road embankment construction on sidelong ground early in the industrial revolution (Vaughan et al., 2004). A survey of 570 km of the motorway network in England and Wales between 1980 and 1988 (21% coverage of the network in 1987) showed that most (>50%) highway embankment slopes were constructed at a slope gradient of 1:2 (vertical: horizontal) and that 86% of embankments were <5 m high (Perry, 1989). Only 6% of the surveyed embankment length was >7.5 m high.

Highway embankments were designed using limit equilibrium methods assuming classical saturated soil mechanics and simple constitutive models. However, this has not eliminated the risk of embankment failure as many processes relevant to actual failure mechanisms relate to the unsaturated behaviour of soils and rely on the use of complex constitutive models.

3. Performance requirements and the observed failure of highway and railway embankments

Embankments must meet performance requirements when supporting overlying transport (road and rail) infrastructure. For example, highway embankments must satisfy ride quality requirements which are based on the variance of a profile level relative to a datum derived from a moving average (Perry, 2003). Railway embankments must satisfy ride safety and track quality requirements for a specified line speed and loading (Perry, 2003). The failure to meet performance requirements can range from an ultimate limit state failure, which may halt or severely restrict traffic flow, to a serviceability limit state failure which does not disrupt traffic flow but prevents the embankment from operating as intended (Perry, 2003). In terms of limit state design, failure by any mode is termed reaching or exceeding an 'ultimate limit state' when soil rupture is caused by shear stresses in the embankment exceeding the shear strength of the soil (Burland et al., 2012). In terms of limit state design, excessive deflection involves breaching a 'serviceability limit state', where excessive soil movement or deformation occurs. In some cases, but not in all cases, a serviceability failure may be linked to an ultimate limit failure in embankments (e.g. excessive deflection may precede a shear failure).

Typical failure modes and mechanisms differ between highway and railway embankments due to their different construction methods and construction materials. Ultimate limit state failures during motorway embankment construction were infrequent. When they did occur they were usually deep seated rotational failures which were typically caused by the presence of weak foundation soils (Greenwood et al.,

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