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Serviceability design for geosynthetic reinforced column supported embankments

Daniel J. King [a, b], Abdelmalek Bouazza [a, *], Joel R. Gniel [b], R. Kerry Rowe [c], Ha H. Bui [a]

[a] *Department of Civil Engineering, 23 College Walk, Monash University, Melbourne, Vic. 3800, Australia*
[b] *Golder Associates Pty. Ltd. Building 7, Botanicca Corporate Park, 570 – 588 Swan Street, Richmond, Vic. 3121, Australia*
[c] *GeoEngineering Centre at Queen's-RMC, Queen's University, Ellis Hall, Kingston, ON K7L 3N6, Canada*

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ABSTRACT

In recent years, geosynthetic reinforced column supported embankments (GRCSEs) have become an increasingly popular design solution for road and rail infrastructure constructed over soft soil sites. However, the serviceability behaviour and deformation that often govern the suitability of their design is not well understood. This is due, in part, to the difficulties in describing the arching stress development in the load transfer platform (LTP). This paper highlights the need for coupled arching stress-deformation models to describe accurately serviceability behaviour. This approach contrasts the widely adopted two-step design approach, which uses limit-equilibrium models that de-couple the arching stress-deformation relationship to describe ultimate limit state behaviour. Using an analytical example, an arching stress/deformation model and an empirical relationship (developed by others) relating base LTP settlement to surface settlement, the relationship between serviceability behaviour and soft soil parameters is highlighted and the conditions leading to progressive collapse in GRCSEs are described. The approach presented provides a means to predict serviceability behaviour, and at the same time, raises questions about the long-term performance and the manner in which acceptable performance has been achieved in the short-term in several field case studies. In particular, those constructed at, or near, a minimum embankment height.

1. Introduction

Ground improvement using geosynthetic reinforced column supported embankments (GRCSEs) is an increasingly popular design solution to support embankments for road and rail applications. In recent years, the national standards used for the design of GRCSEs have been updated in Germany (EBGEO, 2010), the United Kingdom (BS8006-1, 2010) and the Netherlands (CUR226, 2016). One of the key components of GRCSE design is the load transfer platform (LTP) design. In these design standards, the LTP design follows a two-step process: Step 1 – assessment of arching and distribution of load acting on rigid or semi rigid elements (Part A load) and load in the area between the column heads (Parts B + C load); Step 2 – assessment of the "membrane behaviour", where the load acting on the geosynthetic reinforcement (Part B) and load provided by the sub-soil support (Part C) are separated. As part of Step 2 the tensile force (T), tensile strain (ε) and maximum sag in the geosynthetic reinforcement, typically a geogrid, is assessed and the specification of this material is provided accordingly.

The limit equilibrium models incorporated into these design standards calculate arching stresses as a constant with respect to deformation. This constant load-deformation relationship has been shown, over the years, to be reasonable for the ultimate limit state design of GRCSE. However, it is shown herein that a coupled load-deformation relationship, which is well described in trapdoors tests over many decades (Terzaghi, 1936; Ladanyi and Hoyaux, 1969; Vardoulakis et al., 1981; Evans, 1983; Stone, 1988; Iglesia, 1991; Ono and Yamada, 1993; Dewoolkar et al., 2007), is necessary to describe the serviceability behaviour of GRCSEs accurately. The aim of this paper is to highlight the role that the time dependent stress development, and the associated deformation, play in the behaviour of GRCSEs under serviceability conditions. These concepts are introduced and illustrated with an analytical example. The relationship between serviceability behaviour and soft soil parameters

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* Corresponding author.
E-mail addresses: daniel.king@monash.edu, dking@golder.com.au (D.J. King), malek.bouazza@monash.edu (A. Bouazza), jgniel@golder.com.au (J.R. Gniel), kerry.rowe@queensu.ca (R.K. Rowe), ha.bui@monash.edu (H.H. Bui).

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is described and used to interpret serviceability behaviour in a number of previously published field case studies. The importance of serviceability behaviour for GRCSEs who's geometries are below the critical height described by McGuire (2011) is highlighted.

2. Background

A large number of models are available for calculating the arching stress in Step 1, however, those in the category of limit equilibrium models have found the most widespread use in recent years. These include the Hewlett and Randolph (1988) method adopted in the French ASIRI guideline (2012) and suggested as an alternative in BS8006-1 (2010), the model of Zaeske (2001) in EBGEO (2010) and CUR226 (2010) and more recently the Concentric Arches model (van Eekelen et al., 2013) included in the revised Dutch standard (CUR226, 2016). These methods calculate arching stresses based on geometric parameters (column spacing s, column head width a, and embankment height h) and LTP material parameters (effective friction angle ϕ'). The result is a value of stress acting between the columns (Parts B + C) which is independent of geosynthetic reinforcement deflection, sub-soil settlement and time. The two-step design approach has the effect of de-coupling the arching stress-displacement relationship as the displacement calculated in Step 2 is based on a constant value of arching stress from Step 1 (independent of displacement).

Despite the acceptance of limit-equilibrium models for LTP design in GRCSEs, there is a large quantity of experimental data describing the development of arching as a deformation dependent process. Arching behaviour in granular soils has traditionally been assessed in the well-known trapdoor test. These trapdoor tests are characterised by a width of trapdoor (B), height of the soil mass (H), and soil unit weight (γ). Vertical stress is normalised with respect to the initial overburden as a stress reduction ratio (σ_v/σ_{v0}) or (SRR) which is initially one and reduces to < 1 for an active trapdoor test (downward moving trapdoor) and >1 for passive trapdoor test. The trapdoor displacement is normalised with respect to B and expressed as a percentage relative displacement (the absolute value of trapdoor displacement is denoted δ). One of the earliest systematic studies of arching, undertaken by Terzaghi (1936), observed arching stresses that varied due to trapdoor settlement (Fig. 1a). Studies by Evans (1983) and Ladanyi and Hoyaux (1969) (Fig. 1b and c respectively) obtained similar results as have many other studies which followed Terzaghi's work (Vardoulakis et al., 1981; Stone, 1988; Iglesia, 1991; Ono and Yamada, 1993; Dewoolkar et al., 2007). Iglesia (1991) characterised the arching development observed in these experiments into phases that were termed; initial arching, maximum arching, load recovery and terminal state and developed a so-called Ground Reaction Curve (GRC) to describe these phases of arching.

While the deformation dependent development of arching stresses is at odds with these limit equilibrium models, the limit equilibrium models may be suitable for LTP design, provided that the value of arching stress is representative, and on the safe side, of the ultimate stress acting on the geogrid layers through its design life. This arching stress/deformation compatibility issue is highlighted in Fig. 2 where the transition from initial conditions, to the so-called "ultimate" long-term condition in an LTP is shown. A bi-linear arching stress – deformation relationship (as used in the load-displacement compatibility (LDC) method, see Filz et al., 2012), is also shown for comparison and described later in the paper.

Herein, the authors use the term "serviceability condition" to describe the LTP behaviour between the initial and "working condition". The long-term working condition describes the equilibrium condition where the base settlement of the LTP is no longer influenced by the consolidation and/or creep settlement of the sub-soil (i.e., negligible creep settlement/permanent sub-soil support) or the loss of sub-soil support. The ultimate condition, as defined here, is the end of design life condition, which includes consideration of the creep strain in the reinforcement. The constant value of arching stress predicted by limit equilibrium models is only achieved when the required deformation is reached and this may or may not coincide with the long-term working condition.

For road and rail applications, often, it is stringent surface settlement tolerances that necessitate the use of a GRCSE design approach in the first instance. To describe the deformation of a GRCSE, and confirm the suitability of an adopted design, knowledge of the time-dependent development of arching stress development is required. The limit equilibrium models in EBGEO (2010), BS8006-1 (2010) or CUR226 (2016) do not explicitly state, or provide a means to assess, how much deformation is required to achieve this state of "arching" which they simulate? Or what period of time is required? Or what happens to arching stresses if the base settlement differs from the amount of settlement inherently assumed in these models. While post-construction base settlement of the LTP, and/or geogrid deflection, in the LTP is not in itself a serviceability concern, this post-construction behaviour can translate to surface settlements and failure under serviceability tolerances; particularly in shallow embankments.

EBGEO (2010) provides the following advice in relation to the

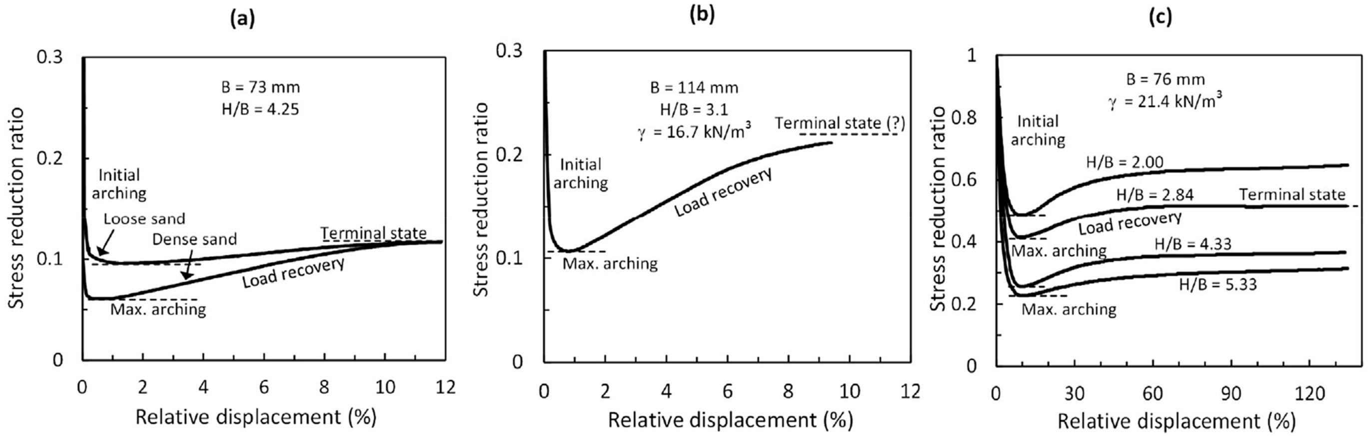

Fig. 1. Load-deformation arching response observed in trapdoor tests by **(a)** Terzaghi (1936) (modified from Evans, 1983) **(b)** modified from Evans (1983) and **(c)** modified from Ladanyi and Hoyaux (1969).

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