Arching stress/deformation behaviour in geosynthetic reinforced column supported embankments

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ABSTRACT: Recent research studies investigating the performance and behaviour of full scale geosynthetic reinforced embankments on semi-rigid inclusions located in Melbourne has highlighted the role of sub-soil settlement in the development of the arching mechanism. Following on from this field case study, non-destructive imaging has been undertaken to further investigate these field scale observations. Displacement fields obtained from synchrotron imaging of small-scale embankment models indicates that arching evolves as sub-soil settlement progressively occurs. In the field, this is typically observed to occur as a time-dependent post-construction mechanism and has important implications for the post-construction performance of the embankment. This paper provides an overview of the research undertaken over the past 5 years and presents an analytical method which describes the development of arching as a function of sub-soil settlement in embankments with semi-rigid inclusions. By incorporating sub-soil settlement as a governing parameter, the development of arching is described through the entire design life of the structure and not just in the ultimate condition.

RÉSUMÉ : Des études récentes sur la performance et le comportement des matelas renforcées par géosynthétiques des remblais construis sur des sols améliorés par inclusions semi-rigides situées à Melbourne ont mis en évidence le rôle du tassement sols dans le développement du mécanisme des voutes. À la suite de cette étude de cas sur le terrain, des images non destructives ont été prises pour approfondir ces observations. Les champs de déplacement obtenus à partir de l'imagerie par synchrotron de modèles de remblai à petite échelle indiquent que la voute évolue en fonction du tassement progressif du sol. Sur le terrain, on observe généralement que cela se produit sous la forme d'un mécanisme de post-construction qui dépend du temps et a des implications importantes sur la performance après construction du remblai. Cet article donne un aperçu de la recherche entreprise au cours des 5 dernières années et présente une méthode analytique qui décrit le développement des voutes en fonction du tassement des sols sous des remblais reposant sur des inclusions semi-rigides. En intégrant le tassement des sols comme un paramètre régissant, le développement des voutes est décrit pendant toute la durée de vie de la structure et pas seulement à l'état ultime.

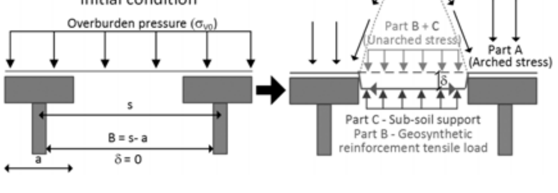
KEYWORDS: column supported embankments, piled embankments, arching, load transfer platforms

1 INTRODUCTION

A great number of studies have investigated the soil arching phenomena since Terzaghi's early work (Terzaghi, 1943). Knowledge from these studies has led to the development of analytical and empirical theories that have been applied to, or developed to understand, a range of problems, such as: tunnelling, buried conduits, plugging in open-ended piles and cave formation in karstic terrain, amongst others. In recent years, the soil arching behaviour that also occurs in geosynthetic reinforced column supported embankments (GRCSE) has been studied extensively. In a GRCSE, a load transfer platform is used to transfer embankment stresses to the columns supporting the embankment through a combination of both soil arching, and though the use of geosynthetic reinforcement in the load transfer platform to transfer the stress from the unarched zone to the columns through membrane action.

Assessment of arching behaviour and membrane action is undertaken as a "two-step" process in several widely adopted design standards, such as the German (EBGEO 2010) and British (BS8006-1 2010) design standards, amongst others. In Step 1, a limit equilibrium arching model is adopted to assess arching stress distribution. Based on this assessment, a constant value of "design" stress that acts in the unarched zone (Load component B + C) is used in Step 2 to calculate the load distribution between the geosynthetic reinforcement and the sub-soil support. This "two-step" approach de-couples the relationship between arching stresses and base settlement (sub-soil settlement and/or geogrid deflection) as the arching stresses in Step 1 are assumed to be constant with respect to time and base settlement.

This interpretation of arching stresses contrasts a significant amount of experimental research (Evans 1983; Iglesia 1991; Ladanyi and Hoyaux 1969; Ono and Yamada 1993; Vardoulakis et al. 1981) which has investigated arching stress development in the trapdoor test and has observed an arching stress-deformation relationship. This arching stress-deformation behaviour has been further investigated in a field case study (King et al. 2017a) where it was shown that the Ground Reaction Curve (GRC) method (Iglesia *et al.* 2013), which described the phases of arching development: initial, maximum, load recovery and terminal, could be used to describe the development of arching stresses. In this paper the development of arching stress as a function of base settlement is examined further and compared with the output of limit equilibrium models. In addition, results of an on-going laboratory study are presented, which has implemented advanced tomography techniques to visualise the 3D progressive development of arching within a small-scale column supported embankment.



These findings are related to those of the field case study and concepts from the GRC method.

Figure 1. Stresses acting on a load transfer platform in a GRCSE

2 ARCHING

Many of the earliest studies of the arching phenomena considered plane strain conditions with the interpretation of the failure development aided through the use of photographic records and tracer materials embedded in a sand box (Evans 1983; Ladanyi and Hoyaux 1969). In recent years, advanced imaging techniques have enabled improved visualisation of deformation patterns and localised strain development (shear banding). Stone and Wood (1992) used digitized photographic and radiographic records to relate shear band development to dilatancy angle in active trapdoor tests, and recently, Jacobsz (2016) used Particle Image Velocimetry (PIV) techniques to provide high resolution imagery of shear band development over a large displacement range.

However, it is the arching stress development in 3D (i.e., circular or square trapdoor) that is of interest to GRCSEs, and many other practical geotechnical problems. Compared with plane strain tests, the number of these studies is much smaller. One of the main limitations with 3D simulations is the difficulties in visualizing the development of the failure surfaces. The use of tomographic imaging techniques such as X-ray Computed Tomography (CT) (Chevalier and Otani 2011; Eskişar et al. 2012), has in recent years overcome some of these difficulties and enabled the visualisation of failure surfaces in small scale models.

These studies have developed a relatively consistent interpretation of the arching development; a schematic representation is shown in Figure 2. Arching development is characterised by the simultaneous development of both internal and external shear bands during an active (downward moving) trapdoor test. Stone and Wood (1992) and others (Evans 1983; Santichaianant 2002) have shown that internal shear bands propagate from the corner of the trapdoor at an angle, inclined from the vertical, and equal to the dilatancy angle (a variable of relative density and confining stress) at that point in time. The curvature of the shear bands reflects variation in the dilatancy angle as the overburden stress reduces along the length of the shear band.

The development of the first internal shear band (OA), and the development of the final external shear band (OC), broadly define the failure surfaces which are used to formulate the analytical descriptions of maximum and terminal phases of arching respectively based on limit analysis techniques. These conditions characterise the two extremes of arching deformation; maximum arching at small trapdoor displacement and a terminal state at very large trapdoor displacement. Terzaghi (1943) and Handy (1985), amongst others, have described the terminal state of arching as a mass of soil sliding downwards between vertical shear planes. These theories have applications in the so-called silo problem and pile plugging problems. Ono and Yamada (1993) have described the conditions at maximum arching, as have a number of researchers in the context of GRCSEs.

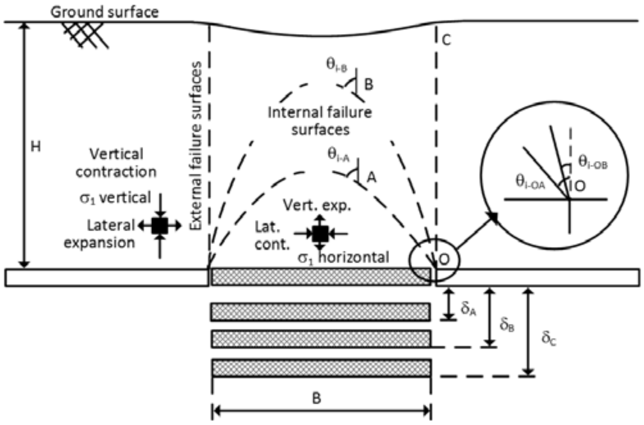


Figure 2. Schematic of arching development in shallow active mode trapdoor tests (modified from Costa *et al.* 2009)

A range of arching models have been proposed for GRCSE design however it is the category of limit equilibrium methods such as the Hewlett and Randolph model (1988), the method of Zaeske (2001) and the Concentric Arches model (van Eekelen et al. 2013) which have found wide spread use. These models describe the vertical stress acting in the un-arched zone based an assumed failure surface. The failure surface which forms the basis of these limit equilibrium methods, may, or may not, have a sound theoretical basis. i.e., depending on the dilatancy angle, the failure surface may, or may not, accurately describe the initial shear band development (line OA in Figure 2).

The appropriateness of an arching model to the problem of LTP behaviour in GRCSEs is highlighted in Figure 3 through the use of an analogy with a material exhibiting strain softening behaviour. When using limit analysis techniques, such as the slip-line method, limit analysis methods, and the limit equilibrium method as adopted here for GRCSE design, it is necessary to ignore the strain softening behaviour of the stress-strain curve when predicting collapse loads (due to the assumption of perfect plasticity). The validity of an assessed collapsed load is dependent on the deformation range, the problem geometry and boundary stress; the relative position of the collapse load will be somewhere between the bounds of peak and residual shear strength (Chen and Liu 1975) (Figure 3a).

Arching stress development in a GRCSE is however displacement controlled (by the geosynthetic reinforcement and sub-soil support), and so while the limiting stress is not a collapse load, the limit equilibrium model must still ensure a compatible deformation range if ultimate limit state stress conditions are to be described successfully. Iglesia (1991) has shown for a trapdoor test that maximum arching occurs within the range of 2 % to 4 % relative displacement. It follows then, that for models which describe maximum arching, deformation compatibility may only be achieved up to a relative displacement of 4 %. The appropriateness of an ultimate limit state arching model which is formulated to describe maximum arching is questionable on the following basis: 1) this is the least conservative state with respect to the stress acting in the un-arched zone and is analogous to a collapse load formulated at peak strength (Figure 3a), 2) deformation (base settlement) must be limited to a very small relative displacement range (up to about 4 %). This is difficult to achieve even where very high strength geogrids are adopted. Unless, there is a considerable reliance on sub-soil support, which in itself is questionable at ultimate limit state.

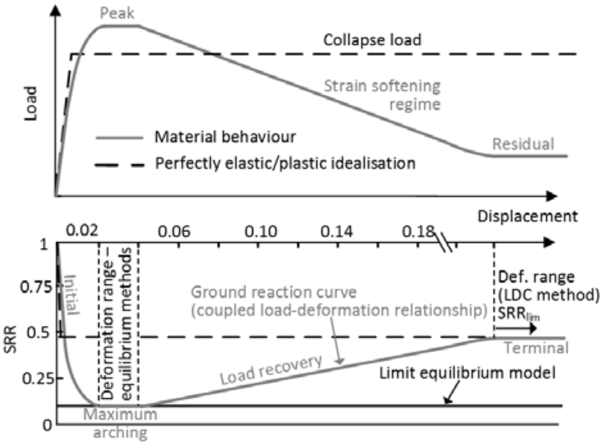


Figure 3. (a) Arching analogy with strain softening material and (b) arching behaviour

Arching stress development in a GRCSE is therefore a problem of deformation compatibility (Figure 4). In Figure 4, arching stress-deformation relationships which are not constant are also shown. These include the bi-linear relationship adopted in the Load-Displacement compatibility (LDC) method (Filz et al. 2012) and the Ground Reaction Curve (GRC) method developed by Iglesia (1991) and Iglesia et al. (2014). The LDC method uses a modified version of the Adapted Terzaghi Method (Russell and Pierpoint 1997) to describe what is a terminal state of arching. Values of up to about 10 % relative displacement can be expected for GRCSE. The difference in arching stress values depends significantly on the stiffness of the geosynthetic reinforcement (and sub-soil support). These differences in arching stress development are very important when serviceability behaviour is considered, as has been shown in (King et al. 2016d)

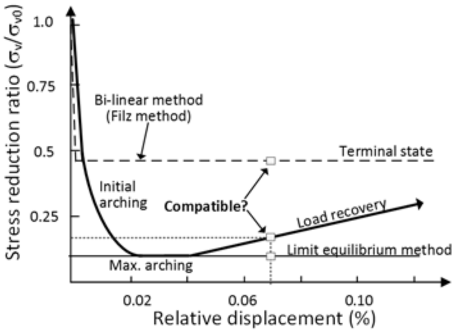


Figure 4. (a) Initial condition with no sub-soil settlement and (b) long-term ultimate limit state design condition in GRCSE

3 ADVANCED COMPUTER TOMOGRAPHY

The 3D progressive development of soil arching has been investigated using advanced CT techniques, including neutron and synchrotron x-ray sources. This work builds on the limited studies that have examined the three-dimensional soil arching behaviour with conventional x-rays (Chevalier and Otani 2011; Eskişar et al. 2012), by implementing techniques that are able to achieve relatively higher energies, greater radiation flux and less imaging artefacts compared to previous studies. Model tests of small scale column supported embankments (CSEs, without geosynthetic reinforcement) were undertaken at the neutron imaging station called DINGO (Garbe et al. 2015) located at the OPAL reactor (ANSTO, New South Wales, Australia) and the Imaging and Medical Beamline at the Australian Synchrotron (ANSTO, Victoria, Australia).

The small scale model tests included a group of 4 columns (15 mm in diameter) in a square 2 by 2 grid (45 mm centre to centre spacing), which penetrated through a displacement controlled plate (settlement plate). Surrounding the columns was an outer shell (125 mm in diameter), which provided confinement to fine grained silica sand. Sand was placed and compacted within the model, achieving a uniform density, before an overburden pressure was applied to the sand surface. Once the model was prepared and placed on the imaging rotation stage, the settlement plate was slowly lowered. Imaging was undertaken at increments up to a maximum displacement of 6 mm from the initial state.

The results from synchrotron x-ray CT achieved a voxel size of 31.25 µm, which was sufficient to visualise the silica sand grains (d_{50} = 0.28 mm). Image correlation techniques were then applied to the data, allowing displacement vectors to be obtained from the reconstructed volume. Digital Image Correlation (DIC) (Stanier et al. 2015) was used on vertical slices through the reconstructed volume along planes of symmetry, where it was assumed grains would undergo minimal movement perpendicular to the selected plane. Figure 5 shows vertical cross-sections of displacement fields, taken diagonally through the column grid. The fields shown are the incremental displacements between two CT images, where the settlement plate was displaced downwards 0.6 mm and DIC was used to obtain displacement vectors between the two images. The settlement plate displacements (δ_s) have been normalised with respect to the clear spacing between diagonal columns ($s - d = 48.6$ mm).

It can be seen from the results in Figure 5 that the incremental displacement fields evolve with increasing normalised settlement plate displacements. Relatively small displacements (Figure 5a) resulted in a curved arch, whereas with increasing displacements the arch transforms into a more triangular shape (Figure 5b and 5c). With increasing settlement, displacements were also found to propagate higher into the sand layer, indicating that maximum arching may have been exceeded. Such observation are in agreement with the arching deformation pattern proposed by Iglesia et al. (2014).

These small scale model tests were undertaken at 1 g, which results in the stress-strain behaviour of the soil not being appropriately modelled. However, by comparing studies of trapdoor tests, it has been shown that small scale 1 g tests and DEM analysis (Chevalier and Otani 2011) obtain similar GRC behaviour to centrifuge model trapdoor tests (Iglesia et al. 2014).

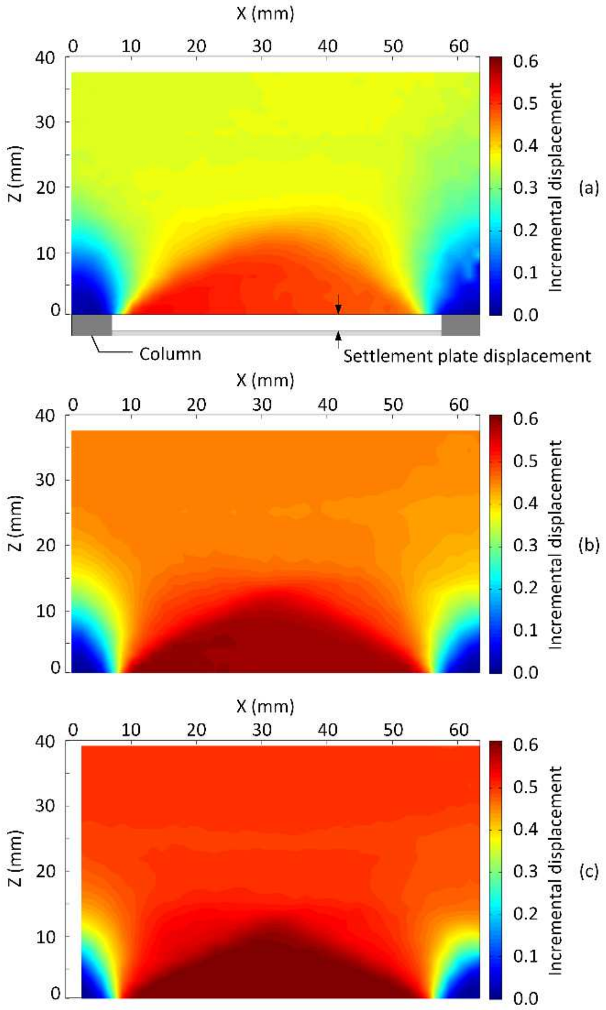


Figure 5. Incremental displacement fields for relative displacements (a) 1.2 to 2.5 %, (b) 3.7 to 4.9 % and (c) 4.9 to 6.2 %

It is therefore expected that the evolution of arching as settlements increase in small scale model column supported embankments is representative of large scale behaviour. Ongoing centrifuge modelling and numerical analysis is being undertaken collaboratively by Monash University and the University of Western Australia to validate this.

4 CONCLUSION

Recent research by King (2017a) has shown that the development of arching stresses can be described as a function of base settlement (geogrid deflection or sub-soil settlement) using the GRC (Iglesia, *et al.* 2014) method. This approach introduced concepts of initial, maximum, load recovery and terminal phases of arching and contrasts the limit equilibrium approaches which are deformation (and time) independent. Ongoing laboratory research, highlighted in this paper, using advanced 3D CT imaging techniques has further highlighted this behaviour and the relationship between arching stress development and base settlement. These results show good agreement with similar work by Chevalier and Otani (2011) and Iglesia et al. 2014.

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