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Optimal placement of reinforcement in piggyback landfill liners

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A B S T R A C T

The optimal placement of geogrid reinforcement in clay liners subject to differential settlement was investigated both numerically and with centrifuge modelling. Two unreinforced liners, a liner reinforced at the top-quarter depth, a liner reinforced at the bottom-quarter depth and a double reinforced liner were modelled in the centrifuge. Differential settlement was induced on the model liners by lowering a trapdoor overlain with sand. By considering: 1) the magnitude of differential settlement required to induce micro-cracks in the liners, 2) the strain fields across the liners during differential settlement and 3) the distribution of these strain fields, it was found that dividing the available reinforcement equally between the top-quarter and bottom-quarter of the liner, i.e. double reinforcement, represents the optimal reinforcement strategy.

1. Background

Several landfills and dump sites in South Africa were constructed before legislation mandating the lining of landfills was published. The current South African legislation requires a composite barrier system consisting of a compacted clay liner (or equivalent) and an HDPE geomembrane for all waste types except construction rubble and spoils (DEA, 2013). Consequently, before old landfill sites can be reused, a lining system has to be built on top of the existing waste to prevent further contamination of the environment. This concept is known as a piggyback landfill.

Municipal solid waste is a highly heterogeneous combination of materials with potential for differential and local settlement throughout the waste body (El-Fadel and Khoury, 2000; Zekkos et al., 2017). Despite its ductility, a clay liner founded on waste, as in the case of a piggy-back landfill, will eventually fissure and crack as the underlying waste settles. As these cracks grow, the permeability of the liner will increase until its ability to protect the groundwater from leachate is compromised.

One approach to preserve the integrity of the clay liner during settlement of the underlying waste is the use of geogrid reinforcement. A geogrid can both increase the stiffness of the system, thus decreasing its deflection, and it can inhibit excessive crack growth. Geogrid reinforcing of clay liners has previously been investigated in a geotechnical centrifuge by Viswanadham and Jessberger (2005), Viswanadham and Muthukumaran (2007) and Rajesh and Viswanadham (2009, 2011, 2012). However, limited research has been done to determine the optimal placement of reinforcement in clay liners.

2. Mechanisms of geogrid reinforcement

A geogrid can be used to reinforce a clay liner through one of two distinct mechanisms. Firstly, the geogrid can increase the stiffness of the clay liner. In Fig. 1a, a section of an unreinforced clay liner and a transformed section of a geogrid-reinforced liner are shown. The increased stiffness of the reinforced liner results in a cross sectional moment of inertia higher than that of the unreinforced clay. Consequently, the reinforced liner will settle, and crack, less than the unreinforced liner under the same load or deflection.

The first reinforcement mechanism is independent of the bond between the geogrid and the clay liner. Without any bond, load can still be transferred from the clay to the geogrid below. Consequently, the clay above the geogrid will settle less than when unreinforced. However, the clay below the geogrid might delaminate from the liner and crack.

This use of a geogrid to increase the stiffness of the system is the basis for most geogrid-reinforced liner designs. In these designs the geogrid is placed below the clay liner and is assumed to span over a void as a tensioned membrane (Giroud, 1981; Giroud et al., 1990). The geogrid is selected to be both strong enough to prevent collapse of the liner and stiff enough to limit the strain in the clay below its fracture limit.

The second mechanism of geogrid reinforcement depends on the bond between the geogrid and the clay. In Fig. 1b the stress distribution at the tip of a crack in a bending, unreinforced liner is shown. Due to the crack the neutral axis of the liner moved to centre of the intact section. Consequently, the stress at the tip of the crack remains tensile. As there is a tensile load and a pre-existing crack, both components required for crack growth are present (Griffith, 1920). However, when

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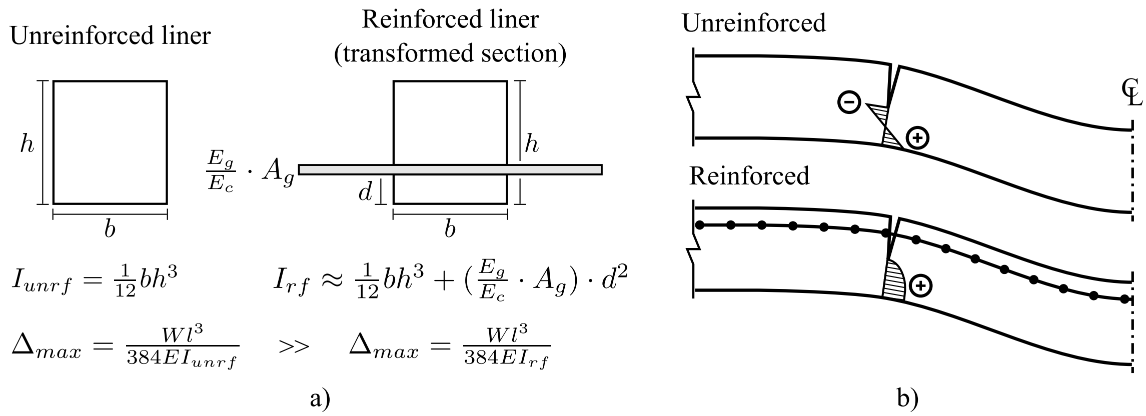

Fig. 1. Mechanisms of geogrid reinforcement: a) increase in stiffness of the system and b) change in stress distribution at crack tip.

embedding reinforcement in the liner (see Fig. 1b) the neutral axis (position of zero strain) moves above the intact section as the tensile stress is now supported by the geogrid. Consequently, the intact section of the liner is in compression and the crack will not propagate. Thus, the second reinforcement mechanism serves to change the stress distribution at the crack tip.

Although geogrid reinforcement of clay liners subject to differential settlement have previously been investigated extensively, limited research has been done into the optimal reinforcement position for a geogrid in such a clay liner. The design approach for a reinforced soil layer by Giroud et al. (1990) assumes that the geogrid is placed at the bottom of the liner. However, Viswanadham (1996) recommended placing reinforcement at the top quarter of the liner following the results of centrifuge experiments.

Some recommendations on the placement of reinforcement in granular soils is also available. For a sand layer in a ramp test Palmeira and Viana (2003) found that the maximum increase in shear strength was obtained by placing a geogrid one third from the base. Similarly Kuo and Hsu (2003) found the optimal geogrid position in an asphalt overlay to be one third from the base of the road. In repeated load triaxial tests on reinforced granular base material, Abu-Farsakh et al. (2012) found that the lowest permanent deformation occurred when two geogrids were used, one at the top third and one at the bottom third of the sample. For triaxial tests of railway ballast Mishra et al. (2014) found that the maximum increase in shear strength was achieved when two geogrids were used, one placed at 2/5$^{\text{ths}}$ from the top and one 2/5$^{\text{ths}}$ from the bottom. Finally, Mousavi et al. (2017) found that the efficiency of a single layer of geogrid reinforcement in unpaved roads measured in terms of surface deformation decreased from 70% to only 5% when not placed at the optimal positions in the aggregate base course.

3. Methodology

The literature discussion above demonstrates that uncertainty still exists about the optimal placement of geogrid reinforcement in clay liners. As such, the optimal placement of geogrids liner when acting in the first mechanism of reinforcement in a clay liner– increasing the stiffness of the system – was investigated numerically (Marx and Jacobsz, 2016a, 2016b). A linear elasto-plastic, undrained, Mohr Coulomb finite element model was used. Four levels of geogrid reinforcement (bottom, bottom-quarter, middle and top-quarter depths) were modelled with linear elastic beam elements.

It was assumed that the cost of the reinforcement was represented by the sum of the stiffnesses of the geogrids used at the four positions, e.g. doubling the stiffness was equivalent to doubling the cost. By varying the distribution of the available reinforcement stiffness between the four positions, and calculating the corresponding minimum tensile strain in the liner for a given displacement profile, a Pareto Front was generated (Arora, 2004). The Pareto front defined the minimum magnitude of tensile strain across the full liner as a function of the total reinforcement cost.

An example of a Pareto front from Marx and Jacobsz (2016b) is shown in Fig. 2. In Fig. 2a the maximum tensile strain possible in the liner, if the reinforcement is distributed optimally, is shown for a number of total reinforcement costs (sum of geogrid stiffnesses used in the liner), for a given displacement profile. In Fig. 2b the optimal distribution of reinforcement for each of these total reinforcement costs is shown. These designs, i.e. the distribution of the available stiffnesses between the four positions, for optimal reinforcement, were defined as the optimal reinforcement strategy (ORS).

It was found, that despite the magnitude of maximum tensile strain varying with a change in liner thickness or overburden pressure, the ORS remained constant for a given displacement profile (Marx and Jacobsz, 2016b). It can therefore be assumed that when the geogrid acts in the first mechanism, i.e. increasing the stiffness of the system, the behaviour of the reinforced clay liners are independent of liner thickness and overburden pressure. However, the settlement trough geometry and magnitude of central settlement were found to have a significant influence on the optimal reinforcement strategy (ORS). The optimal reinforcement positions were found to be either at the base of the liner, or reinforcement divided equally between the top-quarter and base of the liner, depending on the problem geometry.

By using the results of the numerical analyses as guidance, five centrifuge tests were designed to investigate the optimal placement of reinforcement when the geogrid acts in the second mechanism, i.e. modifying the stress at the crack tip. The two most significant reinforcement positions from the results of the numerical analyses were modelled, i.e. top quarter and bottom quarter depths. As there would not have been sufficient bond between a geogrid at the base of the liner and the clay to suppress crack growth, reinforcement was rather placed at the bottom quarter. No overburden stress was applied to the models as: a) overburden stress did not prove to influence the optimal reinforcement strategy in the numerical analysis (Marx and Jacobsz, 2016b), b) it allowed for in-test observation of surface crack propagation in plan and, c) it would represent the most critical stage in a liner's life as the addition of overburden stress suppresses tensile crack formation and arguably induces less critical shear ruptures in the liner (Jessberger and Stone, 1991).

The five centrifuge tests, modelling four different reinforcement strategies, were: 1) two tests of unreinforced model liners used as baselines to compare the reinforced tests against, 2) one model liner reinforced at the top quarter position, the reinforcement strategy deemed optimal by Viswanadham (1996) and Rajesh and Viswanadham (2009), 3) one model liner reinforced at the bottom quarter position, representing the optimum for the numerical analysis of a liner subject

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