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Numerical simulation of compaction-induced stress for the analysis of RS walls under working conditions

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ABSTRACT

This paper aimed to verify numerical modelling of compaction-induced stress (CIS) for the analysis of geosynthetic-reinforced soil (GRS) walls under working stress conditions. Data from a full-scale well-instrumented GRS wall was used for a numerical analysis. The results from the wall used in this study have already been used for validation in several other numerical modelling studies. Nevertheless, in none of these studies was the real value of CIS specified for the vibrating plate compactor used in the wall employed. In the present study, the real value of CIS is employed. The CIS is modelled using a new procedure presented in this paper in addition to two other procedures found in the literature. The results indicate that when the real value of CIS was simulated using a strip load applied to the top of each backfill layer, the numerical model accurately represented the measurements. The accuracy of the results, however, depends on the width of the strip load used to model the CIS. Nevertheless, as this type of compaction modelling procedure is time consuming, modelling of CIS by applying a distribution load at the top and bottom of each soil layer is suggested as an alternative procedure.

1. Introduction

Compaction may significantly affect the internal stresses of reinforced soil walls. To correctly model the behaviour of these structures, the effect of backfill compaction must be considered. Depending on the magnitude of the induced stress due to backfill compaction and the wall height, the horizontal residual stresses in the reinforced soil mass may be much greater than those from a geostatic origin, which may lead to a significant increase in the reinforcement loads. Note that the soil type may also affect this behaviour; high interlocking may lead to higher induced stress due to backfill compaction. Due to these induced stresses, the structure becomes less sensitive to post-construction movements. Surcharge loads may lead to a smaller stress increase in the reinforced soil mass than the induced stresses during construction by backfill compaction. The final effect of this process can be understood as a kind of over-consolidation or pre-loading of the reinforced soil mass that may significantly reduce post-construction movements (Ehrlich and Mitchell, 1995; Ehrlich et al., 2012).

In most of the current design methods for reinforced soil walls, the effect of the compaction-induced stress is not explicitly taken into consideration—e.g. AASHTO (2014) in the USA and BS 8006 (BSI, 2010) in the UK. Note that in RS walls, two different failure conditions may occur: (a) a pullout occurs or the soil may reach its limit condition but the reinforcements do not fail; (b) the reinforcements fail by tension first, followed by the soil. Compaction may lead to a significant increase in reinforcement tension, and this may promote failure by tension or pullout if the reinforcements are not appropriately designed to support those loads. This may specially occur when stiff reinforcements are used (failure type b). This type of failure cannot be explicitly considered by the AASHTO and BS design methods that are not for working stress conditions. These procedures assume that enough lateral deformation may occur resulting in relaxation of compaction residual stress without failure of the reinforcements (failure type a).

Mirmoradi and Ehrlich (2016) investigated the prediction capability of the AASHTO simplified method, considering different controlling factors on reinforced soil (RS) walls, including the compaction-induced stress. It was shown that this method may underestimate the maximum reinforcement loads for walls upon which a high compaction-induced stress is applied. There are some methods, however, which explicitly consider the effect of this factor on their calculations (e.g. Ehrlich and Mirmoradi, 2016; Ehrlich et al., 2017). Comparison of the predicted results using these methods showed good agreement with measured reinforcement load data for several full-scale walls containing a range of reinforcement types.

Numerical modelling may be a powerful tool to properly represent field conditions, if boundary conditions, geometry, constitutive models, parameters, and representative modelling procedure are correctly employed. One of the advantages of this method is that it guarantees good

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parametric analyses in which only one factor may be varied in isolation. Over the last few decades, several numerical studies have been carried out to investigate the influence of different controlling factors on the behaviour of reinforced soil structures. Examples include: Hermann and Al-Yassin (1978), Rowe and Ho (1993), Ho and Rowe (1997), Ling and Leshchinsky (2003), Liu and Won (2009), Gu et al. (2017), among others. Nevertheless, the effect of compaction-induced stress has rarely been considered in these analyses. Among the studies in which the compaction-induced stress was numerically modelled, two procedures have been used for the simulation (hereafter referred to as procedures type I and type II):

- Type I) A uniform vertical stress applied only to the top of each backfill layer, as the wall was modelled from the bottom up (e.g. Hatami and Bathurst, 2005; Guler et al., 2007; Ambauen et al., 2015; Yu et al., 2016, 2017).
- Type II) An equally distributed load at the top and bottom of each soil layer (e.g. Mirmoradi and Ehrlich, 2015a; Scotland et al., 2016).

Mirmoradi and Ehrlich (2014, 2015a,c) stated that a model of compaction procedure type II could properly simulate the effects of compaction observed in the physical model studies. On the other hand, a model of compaction procedure type I overestimated the measurements, and the discrepancy increased with depth and magnitude of the compaction effort. Yu et al. (2016) stated that “there is no obvious advantage of one method over the other on theoretical grounds”. Thus, additional study is required to clarify this discrepancy.

The objective of the present study is to verify a numerical modelling of CIS using data from a full-scale GRS wall under working stress conditions. Note that the results from the wall used in this study (wall 1 built at the Royal Military College of Canada RMC) have already been utilised for validation in several other numerical model studies (e.g. Guler et al., 2007; Hatami and Bathurst, 2005; Mirmoradi and Ehrlich, 2015b; Ambauen et al., 2015). None of those studies, however, has employed the real value of the compaction vertical stress specified for the vibrating plate compactor used on wall 1. In all the aforementioned studies, a compaction stress value of 8 kPa was used in the numerical analyses. However, the specifications of the equipment used for backfill compaction in wall 1 indicate a dynamic contact pressure of 55 kPa. This real specified value of CIS of the equipment used for backfill compaction is employed for the analyses using a new procedure presented in this study for compaction modelling in addition to two other procedures found in the literature.

2. Compaction-induced stress

Duncan and Seed (1986) indicated that the compaction operation may be modelled by load and unload cycles that would induce high horizontal residual stresses in the soil. In the field, the soil backfill goes through a complex stress path because of the various load and unload cycles caused by the passing of compaction equipment. The roller sinks into the soil to a depth sufficient to produce a limit equilibrium condition. Note that the roller-soil contact area varies with the shear resistance and stiffness of the backfill soil that varies with the number of passes. This was simplified by Ehrlich and Mitchell (1994) by assuming only one cycle of load-unload for each layer of backfill. Note that in the modelling of compaction-induced stress-strain, soil parameters representative of the backfill soil at the end of compaction should be used, so that they represent the condition found at the last compaction cycle.

Fig. 1 shows the assumed stress path due to the compaction of the backfill layer by applying a single load-unload stress cycle. In this figure, different stress states were considered, corresponding with four conditions as follows: (1) soil placement; (2) compaction equipment operation; (3) end of compaction; and (4) placement of the next soil layer. Due to the operation of the compaction equipment, the vertical stress increases to the maximum effective vertical stress induced during compaction, $\sigma'_{zc,i}$, and simultaneously the horizontal stresses would increase to their maximum values (point 2). Although after unloading (at the end of the compaction operation) the vertical stress returns to its initial value, σ'_z, (point 3), the same cannot be said to occur for the horizontal stresses, as the soil is not an elastic material. Thus, a residual horizontal stress remains in the soil due to the compaction operation ($\Delta\sigma'_{sx,c}$). The placing of the next layer leads to an increase in vertical stress, and a small variation in horizontal stress (point 4). The residual horizontal stress completely disappears only when the geostatic stress at the top of the soil layer overcomes the value of the vertical stress induced during the compaction operations, $\sigma'_{zc,i}$.

Fig. 2 shows a schematic view of the increase in vertical stress during a roller operation in soil backfill. The vertical stress at the top of each layer during the compaction roller operation may be represented by a strip load, and an elastic solution could be used to represent its evolution with depth. For each soil layer the maximum stress increase during the roller operation occurs at the point of soil-roller contact, and decreases with depth. This depth depends on the width of the load applied for the compaction operation, B. For roller (strip load) and tamper (rectangular load) compactors, the depths of soil in which about 10% of the maximum stress increase would occur during the compaction operation are about six and two times the load width, B, respectively (Lambe and Whitman, 1969).

Ehrlich and Mitchell (1994) stated that “in multilayer construction, the compacted layers are relatively thin, typically 0.15–0.3 m thick, and all points in each soil layer may be assumed to have been driven to the same maximum soil stress state during compaction”. Therefore, it may be assumed that all points are driven to the same vertical induced stress, $\sigma'_{zc,i}$, due to compaction.

It is well known that the lateral strain of the reinforced soil layer, in the direction perpendicular to the face of the wall, reduces the maximum horizontal stress induced by compaction when compared to the maximum stress that would exist in cases where there are no lateral strains. Therefore, the actual maximum horizontal stress induced by compaction is also a function of the reinforcements and facing stiffness (point 3 in Fig. 1). However, the vertical stress induced by compaction may be assumed to be independent from the horizontal strains.

Tables 1 and 2 show the characteristics of various vibrating rollers and vibrating tampers, respectively, which were provided by the producing companies. For plates, the vertical compaction-induced stress, $\sigma'_{zc,i}$, can be assumed to be the average contact pressure at the base of the equipment. The centrifugal forces listed are the maximum vibration amplitude of the rollers. Fig. 3 shows the $\sigma'_{zc,i}$ values of compactor rollers for soil with a specific 18 kN/m^3 weight and various angles of friction, determined using equations developed by Ehrlich and Mitchell (1994). For a cohesionless soil, $\sigma'_{zc,i}$ is given by:

$$\sigma'_{zc,i} = (1 - \upsilon_o)(1 + K_a)(QN_\gamma/\gamma L)^{1/2} \tag{1}$$

where υ_o is the Poisson ratio at rest, K_a is the Rankine active earth pressure, Q is the compactor equipment equivalent static load, L is the roller length, N_γ is the soil bearing capacity factor, and γ is the soil unit weight. Poisson's ratio for at-rest conditions υ_o, is:

$$\upsilon_o = \frac{K_o}{1 + K_o} \tag{2}$$

The soil bearing capacity factor, N_γ, according to the Rankine wedge theory, is:

$$N_\gamma = \tan(45 + \phi'/2)[\tan^4(45 + \phi'/2) - 1] \tag{3}$$

where ϕ' is the effective stress friction angle. As shown in Fig. 3, the value of the induced stress due to compaction operation significantly varies with the soil backfill friction angle. The reader is directed to the paper by Ehrlich and Mitchell (1994) for details about the derivation of the equations.