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Comparison of Coupled Flow-Deformation and Drained Analyses for Road Embankments on CMC Improved Ground

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Abstract

The use of controlled modulus columns (CMC) is gaining increased popularity in the support of rail and road bridge approach embankments on soft soils. The further columns are driven into the competent firm soils, the further the design will rely on the inclusions to take the bulk of the vertical loads, as they become rigid inclusions. The advantage of this design approach is that it produces increased control over the settlement, but as a result the columns will attract greater loads, including bending moment and shear force in situations where non-uniform loading or ground conditions exist. The load on the composite soil-CMC is uniformly distributed by the upper layer of granular load transfer platform (LTP), which also includes a layer of reinforcement. Finite difference program FLAC3D has been used to numerically simulate an embankment on the improved ground with end-bearing CMC. A geosynthetic reinforcement layer has been simulated using the inbuilt FLAC^{3D} geogrid element. In this paper, a comparison has been made between the drained and coupled flow-deformation analyses. The force in the reinforcement layer, in particular, has been compared for the two analysis approaches. It was found that according to the numerical simulation, the drained analysis provides lower estimates of the settlement, lateral displacement; and therefore, predicts less tension in the geosynthetic layer.

Keywords: Ground improvement, Controlled modulus columns, FLAC 3D, Coupled flow-deformation, Drained

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1 Introduction

Bridge approach embankments constructed on soft ground are prone to long term settlements which could potentially lead to unacceptable differential settlements at the interface with the piled foundations of the bridge. Constructing controlled modulus columns (CMC) is one of the most effective methods to minimize such differential settlements when there is a stringent settlement criterion and tight schedule; however, there are less costly methods of ground improvement such as preloading and vertical drains (Azari et al., 2014; Parsa-Pajouh et al., 2015). Unlike piles with a reinforced slab, the load is shared between the soft soil and CMC; however, rigid inclusions may also share the load with the surrounding soil by using shorter length for piles or extending a limited length in the stiff layer (Wong and Muttuvel, 2012). Nevertheless, the load transfer mechanism is very different for the rigid piles where the load is transferred through a rigid reinforced concrete slab. Fioravante (2012) showed through centrifuge physical model tests that the existence of a granular layer beneath a raft changes the pile shaft behavior significantly due to the generation of negative skin friction compared to the case where the pile is in direct contact with the raft. With no pile cap and/or reinforced concrete (RC) slab and using shorter length of inclusions, CMC has proven to be a more cost effective option compared to piled foundations (Yee et al., 2012).

There have been several numerical studies on geosynthetic reinforced column supported (GRCS) embankments. Numerical modeling is a flexible way to improve our understanding of the geotechnical problems due to its cost and time efficiency compared to experimental modeling. Many studies on geosynthetic reinforced embankments have used two dimensional or axisymmetrical models for numerical simulations (Yapage et al., 2015; Jenck et al., 2007; Han and Gabr, 2002).

Ariyarathne et al. (2013) evaluated the different methods to convert a three-dimensional problem into a two-dimensional model, and compared the results from different conversion approaches. They concluded that the equivalent area method yields the closest results to the three-dimensional model. However, even the results from the equivalent area method are different to three-dimensional simulation which is a more realistic approach. Where the embankment side slope effect is not taken into account, unit cell concept is utilized to axisymmetrically approximate the problem. Smith and Filz (2007) investigated this approximation by comparing the results with a three-dimensional model. They concluded that the axisymmetric analyses produce realistic values of average vertical stress acting on geosynthetic reinforcement in column-supported embankments. However, axisymmetric analyses are not expected to produce realistic values of tension in the geosynthetic reinforcement. In the present study, full three-dimensional models have been simulated to model the realistic pattern of the columns, and also take the slope batter effect into account.

Usually, to avoid the complications of the coupled modeling, long term or short term behavior of the model is investigated only by assigning drained or undrained moduli to the material. In this research, coupled hydraulic and mechanical analysis was performed for a long period and was compared with the drained analysis results.

2 Numerical Modeling

Finite difference program FLAC (Fast Lagrangian Analysis of Continua) is widely used to simulate geotechnical problems (Hokmabadi and Fatahi, 2015; Fatahi and Tabatabaiefar, 2014). Finite difference program FLAC3D (version 5.01) was used in this study for numerical modeling. Two types of analyses were performed to compare the results for both approaches. The geometry and the mesh used for the models are presented in Figures 1and 2. Since the embankment is symmetrical in cross-section, half of the embankment has been modeled. The model is considered to be very long in the traffic direction; therefore, one row of columns has been simulated to save the calculation time. The columns are circular in cross-section, and interface elements have been considered between the columns and soil to allow slip and separation. Soft clay and the embankment soil have been modeled as elastic perfectly plastic material using Mohr-Coulomb failure criterion, and the CMC were modeled as elastic elements. The geosynthetic layer was modeled using the in-built geogrid element in FLAC3D. These elastic geogrid elements are only able to sustain in-plane forces. Table 1 presents the properties considered for the soft clay, embankment, columns, and the geosynthetic layer. The initial in-situ stresses were established for the existing ground condition using the initial stresses and gravity in FLAC 3D. The initial static pore pressures were also generated in the model and the water level was specified. If FLAC 3D is configured for fluid flow, a transient fluid-flow analysis can be performed, and pore pressures, as well as the phreatic surface are able to change. Pore pressures are calculated at gridpoints, and zone values are derived using averaging. Both effective-stress (static pore-pressure distribution) and undrained calculations can be carried out in the fluid mode. In addition, a fully coupled analysis can be performed, in which changes in pore pressure generate deformation, and volumetric strain causes the pore pressure to evolve. The change in the pore water pressure was monitored as the stages of construction were carried out and the road was opened to traffic (application of surcharge on the embankment). The embankment height was considered 2 m, and its construction was assumed to take place in four stages of 0.5m thickness. A distributed load of 12 kPa, simulating the traffic load, was then applied on the embankment crest. For the drained simulation, drained parameters were assigned to the material to study the behavior of the system in long term. The consolidation for the coupled analysis was performed for 1 week for every stage of embankment construction and for 28 months after the road was opened to traffic (12kPa surcharge application). The shear behavior of the geogrid-soil interface is cohesive and frictional in nature and a reduction factor of 0.8 was considered as a reduction coefficient of interaction for the interface strength (cohesive strength, c; and friction angle, ϕ) between the geosynthetic and the embankment soil (Huang and Han, 2009). As shown in Figure 1, soil can move freely in the vertical direction on the four boundaries, but has been fixed in the horizontal direction. The base of the model has been fixed in all the directions. However, in reality CMC are usually founded in stiff clays; hence, providing a certain amount of deflection at the base of inclusions, and reducing stress differential between the soil and inclusions.

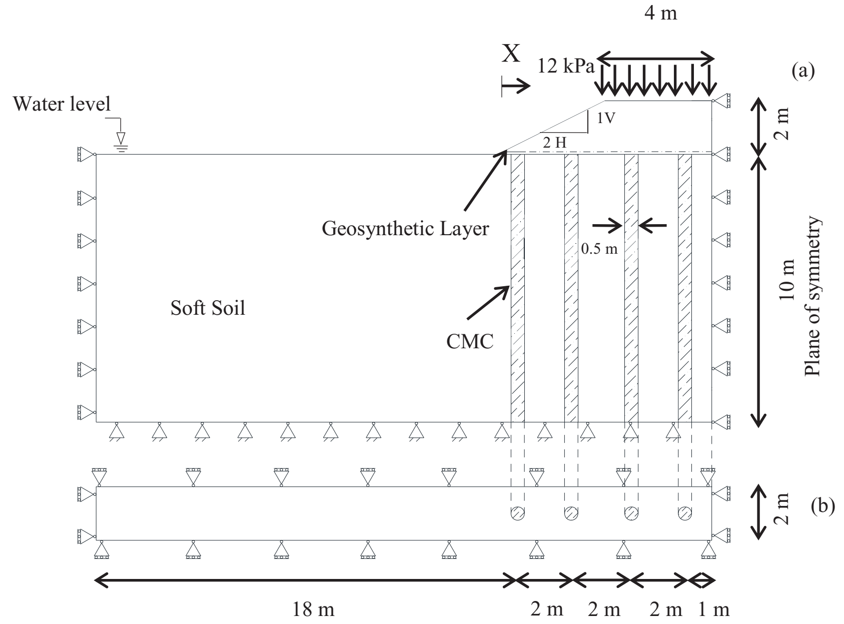

Figure 1: Model geometry for end-bearing CMC (a) cross-section view (b) plan view

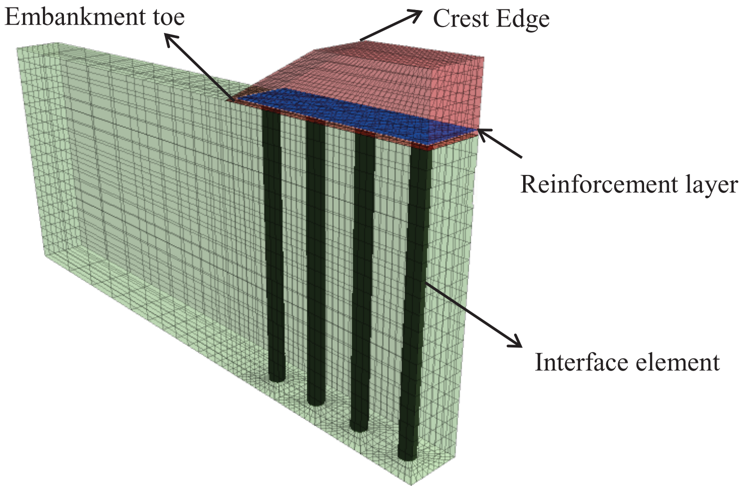

Figure 2: Model mesh with CMC-soil interfaces

Materials	c′ (kPa)	ϕ'	E′ (MPa)	ν	γ (kN/m^3)	k (m/s)
Embankment soil	5	32	30	0.3	20	-
Soft Clay	0	26	2	0.3	17	$1\text{x}10^{-9}$
CMC Columns	-	-	10,000	0.15	24	-
Geosynthetic layer	J= 1100 kN/m ks= 85000 kN/m/m					

Table 1: Material Properties

Note: c′ = effective cohesion, ϕ' = effective friction angle, E= elastic modulus, ν = Poisson's ratio, γ = saturated unit weight, J= geosynthetic stiffness (J=E.t, t= geosynthetic thickness), ks= interface stiffness between the geosynthetic reinforcement and the soil, k= soft soil permeability

3 Results and Discussion

3.1 Settlement

Figure 3 shows the profile of the settlement at the base of the embankment for the end-bearing CMC. The maximum settlement occurs in the middle of the embankment crest for both cases of coupled and drained analyses; however, it is 57mm for the coupled analysis while the drained analysis shows a maximum of 43mm settlement; showing 32% more settlement for the coupled analysis. The settlement on the crest level is also consistently higher for the coupled analysis. Figure 4 demonstrates the differential settlement happening at the base of the embankment. Differential settlement here is defined as the slope of the settlement profile. It is also evident that the coupled analysis yields a higher differential settlement compared to the drained model. Excess pore water pressure generated in the coupled analysis causes the effective stress and shear strength to reduce; and therefore, more deformation is observed in the coupled analysis. Due to the soil plasticity, deformation of the soil is stress path dependent. Thus, the difference in the stress path for the two approaches results in a difference in predictions.

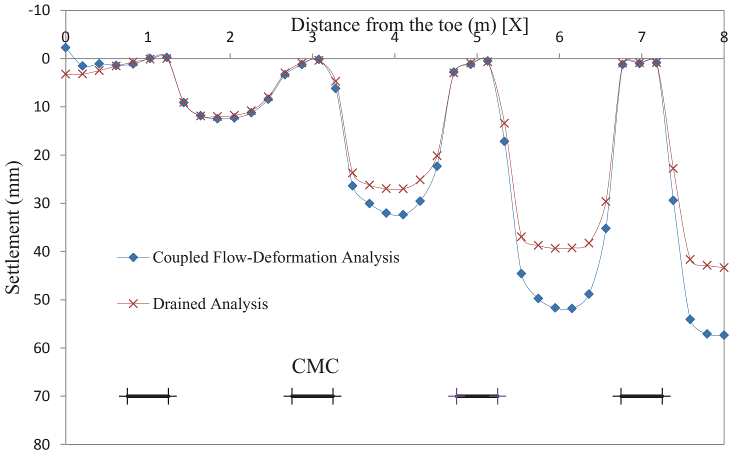

Figure 3: Settlement at the base of the embankment

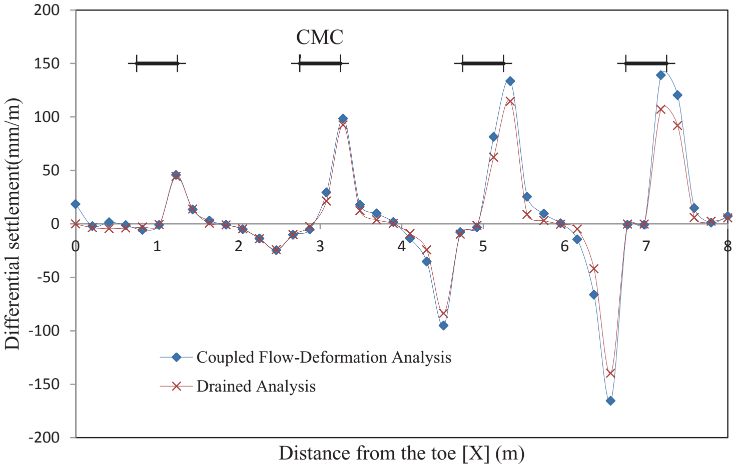

Figure 4: Differential settlement at the base of the embankment

3.2 Force in the Geosynthetic Layer

Figure 5 shows the tension in the geosynthetic layer in the direction perpendicular to the traffic and through the columns center. It can be noted that the maximum tension in the geosynthetic is underestimated in the drained analysis. The maximum tensile force in the drained analysis is 16 kN/m, while for the coupled analysis it is 26 kN/m, which shows an increase of 62%. This could be attributed to the underestimation of differential settlement and also the lateral displacement in the drained analysis. Differential settlement causes the membrane action in the geosynthetic, and the lateral spreading of the embankment generates a tensile force in the reinforcement layer. The graph also demonstrates that the maximum tension happens at the edge of the columns in either case, where the maximum differential settlement occurs as is evident in Figure 5. The minimum force in geosynthetic is generated in the mid-span of the columns for the same reason. More investigation is needed to see the differences in the results for different embankment heights.

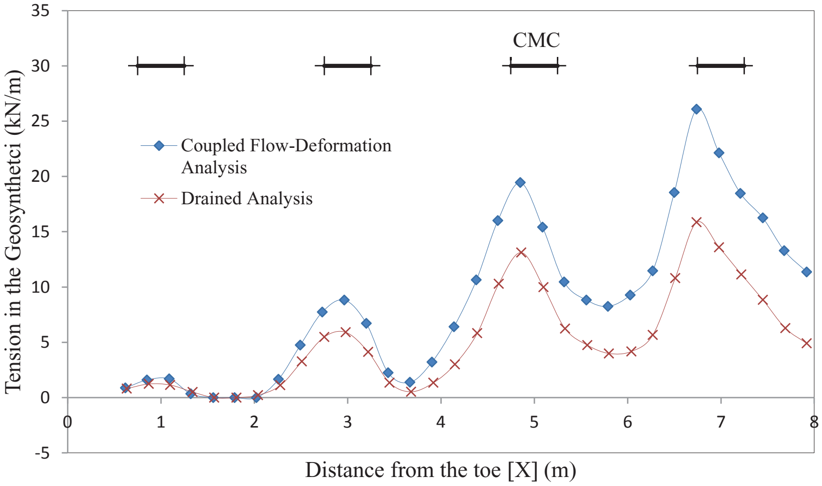

Figure 5: Tension in the geosynthetic layer

3.3 Lateral Displacement

Figure 6 compares the lateral displacement for drained and coupled analyses. It can be observed that the lateral displacement is significantly higher for the coupled analysis. The maximum lateral displacement for the drained analysis is 23mm while for the coupled analysis it increases to 38mm, a difference of 65%. This difference in the two modeling approaches is attributed to the different stress paths in modeling. The effect of reduced shear strength due to the increased pore water pressure is more pronounced in the lateral displacement as the generated shear is more due to the batter effect. The contours of lateral displacement have been presented in Figures 7 and 8 to provide the pattern of lateral displacement. The graphs show a similar pattern for both cases with the maximum displacement occurring close to the embankment toe; however, the values for the coupled case are significantly higher.

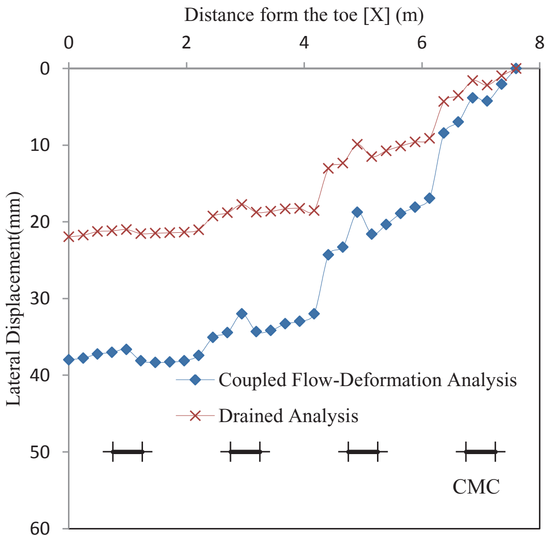

Figure 6: Lateral displacement at the geosynthetic level

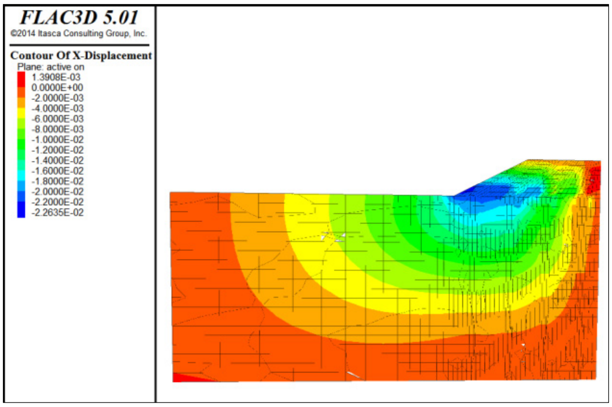

Figure 7: Lateral displacement contours for drained analysis (S_{max}: 23mm)

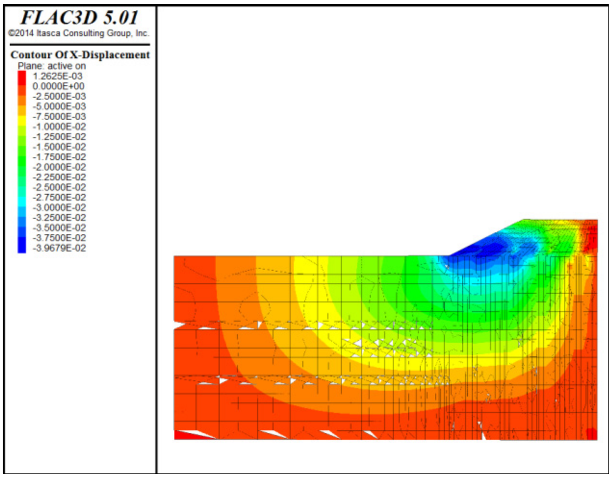

Figure 8: Lateral displacement contours for coupled flow-deformation analysis (S_{max}: 38mm)

4 Conclusions

Controlled modulus columns (CMC) have gained popularity as a ground improvement method. Drained analysis is usually preferred to coupled flow-deformation simulation in the design process due to its convenience and short computation time. However, the simulations in this paper showed that drained analysis yields considerably lower estimates compared to the coupled analysis, especially lateral displacement; and therefore, the forces generated in the reinforcement layer. This requires more investigation and a comparison of the numerical results with the real field monitoring values.

Soil plasticity leads to the stress path dependent behavior of the soil. Although the final stress state is the same for the both approaches, the resulting deformation is not necessarily the same as they follow different stress paths to reach the final stress state. The generated excess pore water pressure causes a reduction in the soil strength and leads to a larger deformation in the coupled flow-deformation analysis. More investigation is also required to evaluate the slope stability safety factors.

Therefore, it is recommended to the practicing engineers to adopt the coupled analysis as the drained simulation may lead to an unsafe design.

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