A Parametric Study of Geosynthetic Reinforced Column Supported Embankments

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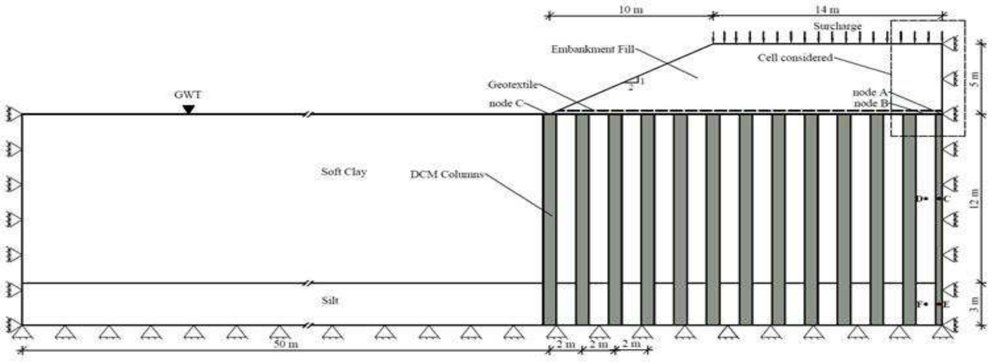
ABSTRACT: This paper presents a parametric study for Geosynthetic Reinforced Column Supported (GRCS) embankments considering the full three-dimensional geometry. Influencing factors considered in the parametric study are: (i) elastic modulus, spacing and diameter of Deep Cement Mixed (DCM) columns, (ii) elastic modulus and permeability of soft foundation soil, (iii) tensile stiffness of geosynthetic, (iv) thickness of the platform layer, (v) embankment height and (vi) friction angle of the embankment fill material. Only the most important parameters governing the embankment behaviour are presented in this paper, which include (i) total and differential settlements, (ii) tension developed in the geosynthetic, (iii) lateral deformation of columns, (iv) efficiency coefficient of columns and (v) arching ratio. Based on the results of the parametric study, it was found that the most important design parameters to be considered in GRCS embankment design procedures are column spacing, elastic modulus of soft soil and embankment height followed by column diameter.

1 INTRODUCTION

In the literature, a limited number of three-dimensional parametric studies have been found investigating the performance of Geosynthetic Reinforced Column Supported (GRCS) embankments.Due to large computer memory requirements and complexity involved in modelling, these studies were carried out considering simplified three-dimensional models with four columns (unit cell) or one row of columns across the cross section of the embankment. However, the load transfer mechanism due to soil arching between columns and the lateral embankment deformations are not appropriately simulated in those models. Hence in this paper, a three-dimensional finite element model with two rows of columns across the embankment cross section is considered allowing soil arching between columns in both longitudinal and transverse directions of the embankment. Also this model has the ability to simulate the lateral deformations. Influencing parameters considered in the parametric study are the elastic modulus of DCM columns, the area replacement ratio based on spacing and diameter of DCM columns, and the elastic modulus and permeability of soft foundation soil. In addition, embankment behaviour is investigated by varying the tensile stiffness of geosynthetic, the distance to the geosynthetic layer from the top of the DCM columns and the friction angle of fill material. Embankment performance during the parametric study is investigated by comparing maximum settlements, maximum tension in the geosynthetic, maximum column lateral deformation, efficiency coefficient and arching ratio. Finally the parametric study results are summarised identifying the degree of influence of each influencing parameter on the performance of GRCS embankments.

2 PROBLEM DIMENSIONS

The geometry and boundary conditions of the three-dimensional finite element model used for this case study are shown in Fig. 1. Due to symmetry of the problem, only half of the geometry is considered for the numerical model. By considering planes of symmetry in the longitudinal direction, only a three-dimensional slice with a width of 2 m and two rows of half columns on either side are selected as shown in Fig. 1(b). This model allows development of full 3D arches within the embankment fill and hence load transferred to DCM columns is well represented. Circular shaped columns are converted to square shape because then the mesh generation becomes less cumbersome.



(a) Side Elevation

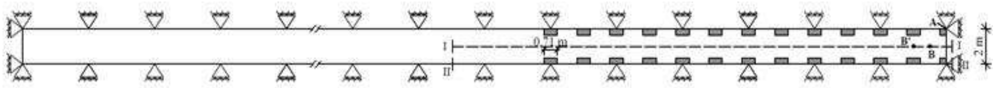


Fig 1. Numerical model of the embankment

(b) Plan view

Table 1. Material properties used in the baseline case

Material	Parameters
Soft clay	E = 2 MPa, c' = 0 kPa, c_t = 0 kPa, k = 10^{-9} m/sϕ' = 25^0, e = 2.0, v = 0.3, γ = 18 kN/m^3
Silty sand	E = 50 MPa, c' = 0 kPa, c_t = 0 kPa, k = 10^{-6} m/sϕ' = 33^0, e = 2.5, v = 0.3, γ = 20kN/m^3
Embankment fill	E = 30 MPa, c' = 3 kPa, ϕ' = 35^0, v = 0.3, γ = 20 kN/m^3
Platform layer	E = 20 MPa, c' = 5 kPa, ϕ' = 32^0, v = 0.33, γ = 20 kN/m^3
DCM columns	E = 150 MPa, c' = 217kPa, c_t = 112.5kPa, k = 10^{-9} m/sϕ' = 30^0, e = 2.0, v = 0.35, γ = 20 kN/m^3
Geosynthetic	E = 500 MPa, J =Et , T = 300 kN/m, c_i = 0.8, J = 2000 kN/m, v = 0.3, t = 4 mm

J - stiffness of the geosynthetic, *t* - thickness of the geosynthetic, *ci* - interaction coefficient between geosynthetic and platform fill, γ - unit weight of soil, *ct* - tensile strength of soil, *k* - permeability, *E* - elastic modulus, *c'* - effective cohesion of soil, ϕ' - effective friction angle, *e* - void ratio, *v* - Poisson's ratio. *T* - yield strength of geosynthetic

As shown in Fig. 1, at the bottom of the finite element mesh, displacements are restrained in all three directions. Displacements in the x-direction at the centre line of the embankment and the boundary at the far field are set to zero. With regard to hydraulic boundary conditions, a zero pore pressure boundary condition is applied at the top of the soft clay layer which coincides with the assumed water table. Due to symmetrical boundary conditions at x = 0, y = 0, and y = 2 m planes, the hydraulic boundary condition should be impervious as drainage cannot take place through those boundaries.

Soft clay, silt and embankment fill are modelled using the elasto-plastic Mohr-Coulomb model and the DCM columns are also modelled using the Mohr-Coulomb model without considering the strain softening behaviour of cement stabilised soils beyond yield. In this case Mohr-Coulomb model is adequate for the soft clay because the loads transferred to the soft clay are not high enough to heavily yield the soft clay. DCM columns, soft clay and silt layers are discretised using quadratic brick solid elements with reduced-integration and pore pressure degrees of freedom at the corner nodes (C3D20RP). Embankment and platform fills are modelled using the same element without pore pressure degrees of freedom (C3D20R). The geosynthetic reinforcement is modelled as a linear elastic perfectly plastic material using three-dimensional eight-node, membrane elements with reduced integration (M3D8R).

3 PARAMETRIC STUDY

In the parametric study, some of the design considerations and potential problems which can be expected during and after construction of the embankment are discussed. During the parametric study, as given in Table 2, one parameter is varied at a time within the range of typical values from the baseline case (bold font in Table 2) to assess the influence of each parameter on the embankment behaviour.

Results for the assessing parameters are extracted from the numerical study at the end of construction (short term behaviour) and after 30 years of service (long term behaviour).

Table 2. Range of properties used for parametric study

Parameter	Influencing factor	Range of value
DCM columns	Elastic modulus (MPa)	50, 100, **150**, 200, 250
	Spacing (m)	1, 1.5, **2**, 2.5, 3, 3.5
	Diameter (m)	0.6, **0.8**, 1.0, 1.2
Soft clay	Elastic modulus (MPa)	1, **2**, 3, 4, 6, 8, 10, 12
	Permeability (m/s)	10^{-6}, 10^{-7}, **10^{-9}**, 10^{-10}, 10^{-12}
Geosynthetic	Tensile stiffness (kN/m)	1000, 1500, **2000**, 3000, 5000, 10000
	Distance from the top of the DCM columns (m)	0.05, 0.15, **0.25**, 0.35, 0.45
Embankment	Friction angle of fill material (^{o})	25, 30, 33, **35**, 37, 40

The differential settlement at the crest is nearly zero. Hence, only the maximum settlement at the crest is presented. Settlement is measured at nodes A and B at the base, at the node directly above node B at the crest and lateral displacement is measured at node C shown in Fig. 1. The maximum tension in the geosynthetic is recorded at the edge of the centre column. Borges and Marques (2011) used column efficiency coefficient to assess the proportion of embankment load transferred to columns, which takes into account the soil arching within the embankment fill layers, load transfer from geosynthetic to columns by membrane action and load transfer from soft soil to columns due to the shear stress developed at the column-soft soil interface. This coefficient is defined as the ratio between the total load supported by a column and the total load of the embankment fill and traffic load applied over a unit cell relevant for a column. The soil arching ratio, ρ, is widely used to estimate the effect of soil arching in embankment fill (Borges and Marques 2011) and it is defined as follows:

$$\rho = \frac{t}{\left(\gamma_{fill} H + q\right)} \tag{1}$$

where t is the average vertical stress applied on the top surface of the geosynthetic in the unit cell.

4 EVALUATION OF INFLUENCING FACTORS ON ASSESSING PARAMETERS

The degree of influence of any influencing factor on any assessing parameter is defined as the ratio between the variation and the mean of the assessing parameter. Calculated degree of influence for each assessing parameter are summarised in Table 3. If an increase in any influencing factor decreases maximum tension, maximum settlement over column head and clay surface, lateral deformation, arching ratio, stress on clay surface, differential settlement at the base and maximum post construction settlement, that influencing factor is considered to havea positive effect on the embankment performance. If an increase in any influencing factor increases the stress concentration ratio, stress on column headand efficiency coefficient, those factors are considered to have a positive influence.

Huang and Han (2010) divided the degree of influence into three levels: high, medium and low when the degree of influence is higher than 60%, in between 30% and 60% and lower than 30%, respectively.Table 4 shows that tensile stiffness of geosynthetic and friction angle of fill material have a low influence on all assessing parameters except for geosynthetic tension and lateral deformation of the embankment. They have a medium influence on lateral deformation and a high influence on tension. For the tension in the geosynthetic, all influencing factors have high degree of influence except column modulus. Therefore, in the design process of geosynthetic reinforcement layer, it is advisable to consider the influence of these parameters.

Maximum settlement is governed by the elastic modulus, spacing and diameter of columns, elastic modulus of soft soils and embankment height. Only elastic modulus of columns has a low influence on lateral deformation of columns. For the stress concentration ratio, elastic modulus of soft soil has the highest influence while elastic modulus of columns, column spacing and permeability have medium influence. Only tensile stiffness and elastic modulus of columns have low influence on the maximum differential settlement while all other influencing parameters have medium or high influence. Overall, column spacing, elastic modulus of soft soils and embankment height have medium to high influences for all considered assessing parameters. Accordingly, they can be considered as the most important design parameters. Column diameter can be considered as the second most important design parameter among the parameters considered. Furthermore, column spacing and diameter are the most influential compared to column modulus. Hence, the use of higher area replacement ratio would be more efficient than the use of stronger columns to improve the performance of GRCS embankments under serviceability conditions.

Table 3. The degree of influence as a percentage

Factors	T_{max}	S_{max}		D_{max}	SCR	f	ρ	S_{dif}	$S_{max,post}$
		column head	clay surface						
DCM columns									
Elastic modulus	45.74	113.77	84.36	24.15	44.9	18.44	33.99	15.73	147
Spacing	133.68	113.26	115.65	88.31	36.04	115.9	52.73	122.06	176.5
Diameter	80.77	65.86	70.97	83.29	13.63	17	28	83.29	122.34
Soft soil									
Elastic modulus	172	51.93	89.81	170.91	122.88	57.81	109.87	165.98	70.53
Permeability	99.66	7.12	19.18	84.28	38.59	2.7	16.35	35.15	193.18
Geosynthetic									
Tensile stiffness	142.26	0.8	2	51.57	5.29	1.07	12.27	6.48	0.8
Embankment									
Height	138.11	107.53	108.09	119.26	N/P	N/P	N/P	112.51	117.75
Friction angle of fills	71.69	2.79	15.11	57.2	27.31	9.12	3.66	44.46	6.67

Note : T_{max} – maximum tension in geosynthetic, S_{max} – maximum settlement, D_{max} – maximum lateral deformation, SCR – stress concentration ratio, which is the ratio between vertical stress applied on columns and vertical stress applied on soil, f – efficiency coefficient of columns, ρ – arching ratio, S_{dif} – differential settlement, $S_{max,post}$– maximum post construction settlement, N/P – Not Possible

Table 4. The nature of degree of influence

Factors	T_{max}	S_{max}		D_{max}	SCR	f	ρ	S_{dif}	$S_{max,post}$
		column head	clay surface						
DCM columns									
Elastic modulus	Medium (+)	High (+)	High (+)	Low (+)	Medium (+)	Low (+)	Medium (+)	Low (-)	High (+)
Spacing	High (-)	High (-)	High (-)	High (-)	Medium (-)	High (-)	Medium (-)	High (-)	High (-)
Diameter	High (+)	High (+)	High (+)	High (+)	Low (+)	Low (-)	Low (+)	High (+)	High (+)
Soft soil									
Elastic modulus	High (+)	Medium (+)	High (+)	High (+)	High (-)	Medium (-)	High (-)	High (+)	High (+)
Permeability	High (+)	Low (+)	Low (+)	High (+)	Medium (-)	Low (-)	Low (-)	Medium (+)	High (+)
Geosynthetic									
Tensile stiffness	High (-)	Low (-)	Low (+)	Medium (+)	Low (+)	Low (+)	Low (+)	Low (+)	Low (+)
Embankment									
Height	High (-)	High (-)	High (-)	High (-)	N/P	N/P	N/P	High (-)	High (-)
Friction angle of fills	High (+)	Low (-)	Low (+)	Medium (+)	Low (+)	Low	Low (+)	Medium (+)	Low (+)

4 CONCLUSIONS

Calculated degree of influence of each parameter concluded that the stiffness of the geosynthetic and friction angle of fill material considerably influence the maximum tension in geosynthetic and lateral deformation of the embankment and not the total or differential settlements. Design of geosynthetic reinforcement layer should consider the influence of column spacing, diameter, elastic modulus and permeability of soft soil, tensile stiffness of geosynthetic, embankment height and friction angle of fill material.

Maximum settlement is highly influenced by elastic modulus, spacing and diameter of columns, elastic modulus of soft soils and embankment height. Column modulus does not have considerable influence on maximum tension in geosynthetic, maximum differential settlement or maximum lateral deformations. Most important design parameters to be considered in GRCS embankment design procedure are column spacing, elastic modulus of soft soil and embankment height followed by column diameter. Consequently, use of higher area replacement ratio is highly recommended instead of using stronger columns to increase the embankment stability. If a 2D parametric study is carried out, it will over predict the lateral deformations, settlements, tension developed in the geosynthetic and other stress based parameters such as SCR, f and ρ. The main reason is the modelling of the geosynthetic layer cannot be carried out as in a 3D model considering spanning in two orthogonal directions using a membrane element.

REFERENCES

Borges, J. L., and Marques, D. O. (2011). "Geosynthetic-reinforced and jet grout column-supported embankments on soft soils: Numerical analysis and parametric study." Computers and Geotechnics, 38(7), 883-896.

Huang, J., and Han, J. (2010). "Two-dimensional parametric study of geosynthetic-reinforced columns-supported embankments by coupled hydraulic and mechanical modelling." Computers and Geotechnics, 37(5), 638–648.