Challenges in modelling DCM column-supported embankments with post yield strain-softening behaviour

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Abstract

The most realistic approach to numerically simulate a Deep Cement Mixed (DCM) column-supported field embankment is the use of a three-dimensional (3D) finite element model. However, two-dimensional (2D) plane-strain numerical models are popular compared to 3D models due to the efficiency in computational time and computer memory. When a column-supported embankment is modelled using a 2D plane-strain model, the individual columns are converted into equivalent column walls and it is assumed that the strains do not change in cross sections along the longitudinal direction of the embankment. During the conversion, material properties or the geometry of the columns are modified based on the conversion method applied. According to the literature, 2D plane-strain idealisation based on equivalent area (EA) method yields the results closest to the 3D model predictions and field measured data. However, all these studies are carried out considering the elastic or elasto-plastic behaviour for columns. As far as the mechanical behaviour of DCM columns is concerned, DCM columns experience strain-softening beyond yielding. The column strength reduces during the strain-softening resulting large deformations in the improved ground. If a constitutive model, which has the ability to simulate strength reduction based on the level of plastic strains, is adopted to simulate the softening behaviour, the accuracy of predicted embankment behaviour is largely depend on the plastic strains developed in DCM columns. Hence, results of a 2D model and a 3D model differ to a large extent. The aim of this study is to investigate this problem in detail and to propose an approach to obtain an equivalent set of parameters for the softening incorporated constitutive model to obtain realistic predictions for a field problem using both 3D and 2D numerical models.

Keywords: Deep cement mixing, Column-supported embankments, Finite element modelling, Plane-strain idealization, strain-softening

1. INTRODUCTION

Numerical modelling is a very popular tool for analysing performance of geotechnical structures such as column-improved embankments. Three-dimensional (3D) numerical models represent embankment problems more realistically whereas two dimensional (2D) plane-strain models are highly efficient in terms of analysis time and computer memory. Therefore, column-improved embankments are usually converted to 2D plane-strain models in numerical modelling. When a 3D embankment is converted to a 2D plane-strain model, the individual columns in the actual problem are converted to equivalent column walls. There are many conversion methods proposed in the literature and those methods require modifications of material properties or the geometry of the columns in the 2D model (Ariyarathne et al. 2013; Chan and Poon 2012; Tan et al. 2008). According to Ariyarathne et al. (2013); Chan and Poon (2012) and Tan et al. (2008), 2D plane-strain models converted based on

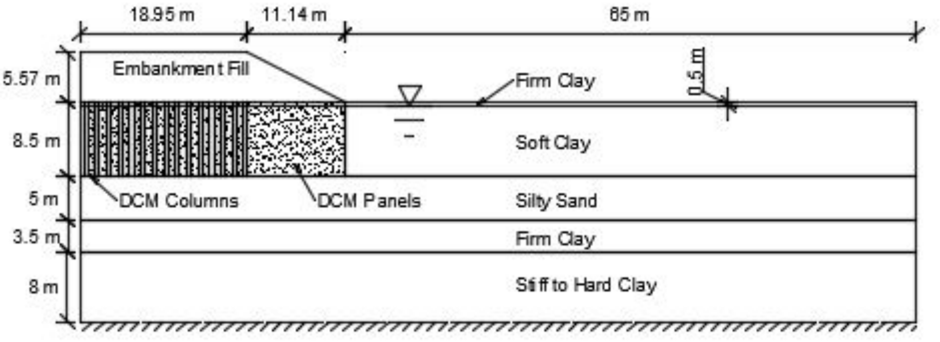
equivalent area method show a good agreement with field data than 2D models converted using other methods.
Many researchers have modelled deep cement mixed (DCM) column-improved embankments using 2D plane-strain models (Han et al. 2005; Huang et al. 2009; Zheng et al. 2009). However, most of the studies have not considered the strain-softening behaviour of the DCM columns. The DCM column strength reduces with increasing plastic strain during strain-softening. Therefore, predicting the stress and strain levels accurately is important to capture the performance of an embankment during softening. A 3D model can easily capture the stresses and strains in the columns accurately since it represents the actual geometry and material properties. However, the accurate prediction of strain-softening behaviour using 2D plane-strain models is challenging because stress levels in the column can differ from the 3D model due to the alterations made in the model during 2D conversion.
Only few 2D numerical models are reported in the literature that incorporates strain-softening behaviour (Yapage et al. 2014; Yapage et al. 2015). However, these studies do not provide an insight into the differences between 3D and 2D models during softening. The objective of this study is to identify the challenges in converting a 3D model into a 2D model when the strain-softening behaviour is incorporated. A case history of an embankment located in the Eastern coast of Australia was selected for this study. First, the embankment was numerically modelled in 2D space and validated. Then a 3D model of the embankment was developed and the performances of the 2D and 3D models were compared using settlements, lateral displacements and pore water pressures.

2. EMBANKMENT CASE HISTORY

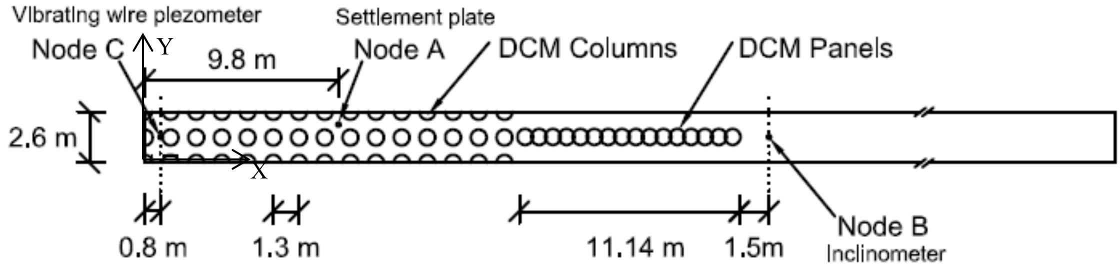
The embankment selected for this study is a part of the Ballina bypass section of the Pacific highway upgrade project in the Eastern coast of Australia. The embankment is 5.57 m high. The width of the embankment is 60.18 m at the base level and 37.9 m at the crest level. Figure 1 shows the subsoil profile and the soil improvement details of the embankment. As shown in Figure 1, the sub soil profile consists of five soil layers; a 0.5 m thick firm clay layer, an 8 m thick soft clay layer, a 5 m thick silty sand layer, a 3.5 m thick firm clay layer and an 8 m thick stiff to hard clay layer. The water table exists 0.5 m below the ground surface. The soft clay layer is improved with single DCM columns beneath the crest and overlapping DCM column walls beneath the side slopes. All DCM columns were of 8.5 m length and 0.8 m diameter. The DCM columns beneath the crest were arranged in a square pattern with a centre to centre distance of 1.3 m. The DCM column walls were spaced at 3 m intervals.
The first 5.27 m height of the embankment was constructed at a rate of 0.125 m/day throughout 42 days. The construction of the final 0.3 m height fill layer was started immediately after the first construction stage and carried out over 50.9 days. Figure 1(b) indicates the placement of monitoring equipment for the case study. Settlement at Node A, lateral displacement at Node B and pore water pressure at 4.5 m depth beneath Node C were recorded using a settlement plate, an inclinometer and a vibrating wire piezometer, respectively, during the construction of the embankment. Further details about this case history was published by Yapage et al. (2014).

3. NUMERICAL MODELLING

The embankment performance was analysed using a 3D numerical model and a 2D numerical model developed in ABAQUS/standard finite element programme. In the 3D numerical model, a 2.6 m wide section of the embankment with the plan view as shown in Figure 1(b), was developed. The 3D model was converted into a simplified 2D plane-strain model based on the equivalent area approach (Ariyarathne et al. 2013; Chan and Poon 2012). In this method, the individual DCM columns beneath the crest of the embankment were modelled as continuous plane-strain column walls. Equivalent column wall thickness (t_{eq}), was calculated as $\pi D^2/4s$, where D is the diameter of DCM columns and s is the spacing between DCM columns. The geometry of the column walls beneath the side slopes of the embankment was unchanged. Average material properties of the DCM columns and natural soil, calculated based on the area replacement ratio were used, for the column walls.



(a)



(b)

Figure 1. Geometry of the improved embankment and ground conditions (a) Section view (b) Plan view.

All materials below the ground water table in the 3D model are discretised using twenty-node quadratic brick solid elements with reduced integration and pore pressure degrees of freedom at corner nodes (C3D20RP). The materials above the ground water table are discretized using twenty-node quadratic brick solid elements with reduced-integration and without pore pressure degrees of freedom (C3D20R). In the 2D model, eight-node quadrilateral elements with reduced integration and pore pressure degrees of freedom at the corner nodes (CPE8RP) are used for elements below the water table. Above the water table, eight-node quadrilateral elements with reduced integration and without pore pressure degrees of freedom (CPE8R) were used.

In both 2D and 3D models, the vertical boundary at the centerline of the embankment (X=0) was assigned a symmetrical boundary condition and the vertical boundary away from the embankment (X=95.09 m) was assigned zero lateral displacements. In the 2D model, displacements at the bottom boundary were restricted in both vertical and horizontal directions. Displacements at the bottom boundary in the 3D model were restricted in all three directions. Y=0 plane and Y=2.6 m plane (Figure 1(b)) in the 3D model were assigned symmetrical boundary conditions. In both models, a zero pore water pressure boundary was assigned at the top surface of the soft clay layer.

The material properties used for DCM columns, subsoil layers and embankment fill material are given in Table 1 and Table 2. The material properties reported by Yapage et al. (2014) were used in this study. The top firm clay layer and the soft clay layer were modelled using modified cam clay model. The silty sand layer, firm clay layer, Stiff to hard clay layer and embankment fill material were modelled using elasto-plastic Mohr coulomb model. The measured settlement of the embankment at Node A was 392 mm whereas the predicted settlement during the design stage was only 190 mm. This suggests that the DCM columns may have yielded during the construction. Therefore, DCM columns were modelled using an extended version of the Mohr Coulomb model, which incorporates the strain-softening behaviour of cement mixed soils. This model was initially proposed by Yapage et al. (2015) for the simulation of cement mixed soils. The variation of mobilised friction angle and mobilized cohesion in the strain-softening incorporated constitutive material model is shown in Figure 2. In the 2D model, the softening was initiated at the plastic deviatoric strain of 1% and the residual state was reached at plastic deviatoric strain of 12% (Yapage et al. 2015). The ratio of residual strength properties to peak strength properties (c'_{res}/c'_p and $\varphi'_{res}/\varphi'_p$) was taken as 0.5, based on the investigations carried out on triaxial test data for a number of cement mixed soils (Yapage et al. 2014).

Table 1. Material properties of subsoil layers and DCM columns

Parameter	Top firm clay	Soft clay	Silty sand	Firm clay	Stiff-to-hard Clay	DCM columns
Unit weight, γ (kN/m3)	18	14.5	18	16.5	16.5	18
Coefficient of lateral earth pressure, k_0	4.6	0.9 (0.5-4.5) 0.64 (4.5-8.5)	0.55	0.55	0.55	0.55
Void ratio, e_0	2.0	3.0	2.23	2.0	2.0	2.0
Slope of the isotropic normal compression line, λ	0.5	0.5	-	-	-	-
Slope of the isotropic unload line, κ	0.053	0.053	-	-	-	-
Stress ratio, M	0.98	0.98	-	-	-	-
Effective friction angle, ϕ′ (degrees)	-	-	30	25	25	27 (Peak) 13.5 (residual)
Effective cohesion, c′ (kPa)	-	-	0	0	0	57.5 (Peak) 28.5 (residual)
Poisson's ratio, ν	0.3	0.3	0.3	0.3	0.3	0.3
Elastic modulus, E (MPa)	-	-	15	9	17	27.1
Permeability, k (m/s)	9.1×10^{-8}	6.0×10^{-8}	8.3×10^{-7}	6.0×10^{-10}	5.3×10^{-10}	6.0×10^{-8}

Table 2. Properties of embankment fill material.

Parameter	Unit weight, γ	Effective friction angle, ϕ′	Effective cohesion, c′	Poisson's ratio, ν	Elastic modulus, E
Value	19 (kN/m3)	300	2 (kPa)	0.3	15 (MPa)

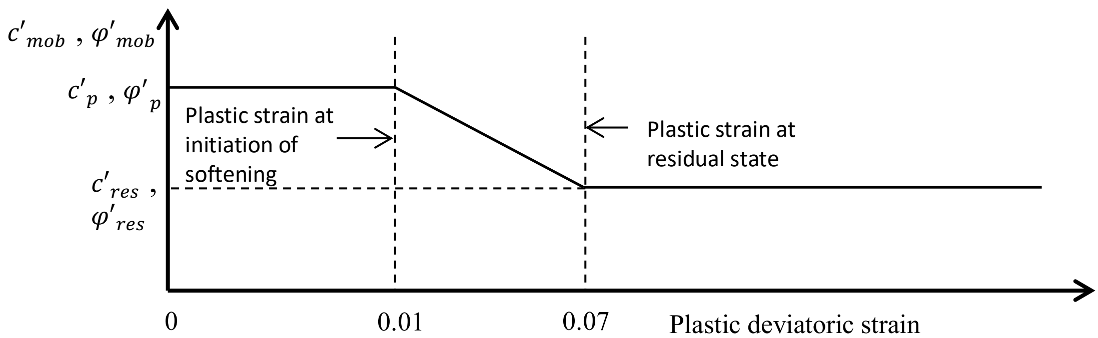


Figure 2. Variation of mobilized cohesion and friction angle with plastic deviatoric strain.

The 2D finite element modelling results shown in Figure 3 agrees well with the field measurements. However, with the same material properties, the deformations predicted by the 3D model are significantly low compared to the 2D model and field measurements. This was due to the slower rate of strain-softening of DCM columns occurred in the 3D model. Therefore, the plastic deviatoric strain at the residual stage in the strain-softening incorporated constitutive material model for the 3D model was decreased to achieve a faster rate of strength reduction during softening. The residual plastic strain was reduced from 0.12 until an accurate prediction for the deformations were obtained. Eventually, a good agreement for deformations (in both vertical and lateral directions) from the 3D model was obtained at a residual plastic deviatoric strain of 0.07. In what follows, the 3D model with the modified parameters in the strain-softening incorporated material model is referred to as the modified 3D model.

4. COMPARISON OF 2D AND 3D MODEL RESULTS

Figure 3(a) and 3(b) show the results for settlements at Node A and lateral displacements at Node B, predicted using 2D model, 3D model and modified 3D model along with the field measured data. The settlements predicted by the 2D model agree well with the field measurements (Figure 3a). When the performance of the 3D model is compared with the 2D model results, 3D model predictions show a slower rate of increase in settlements and lateral displacements after the first construction stage (after 42 days). This indicates that the rate of strain-softening occurred in DCM columns in the 3D model is slower than that occurred in the 2D model. The final settlement and lateral displacement predicted by the 3D model are also lower than those given by the 2D model. The modified 3D model shows a good agreement with the field measured data and the 2D model predictions. The field measured lateral displacements show a sharp drop during the consolidation period. This is assumed to be due to an instrument malfunction in the field.

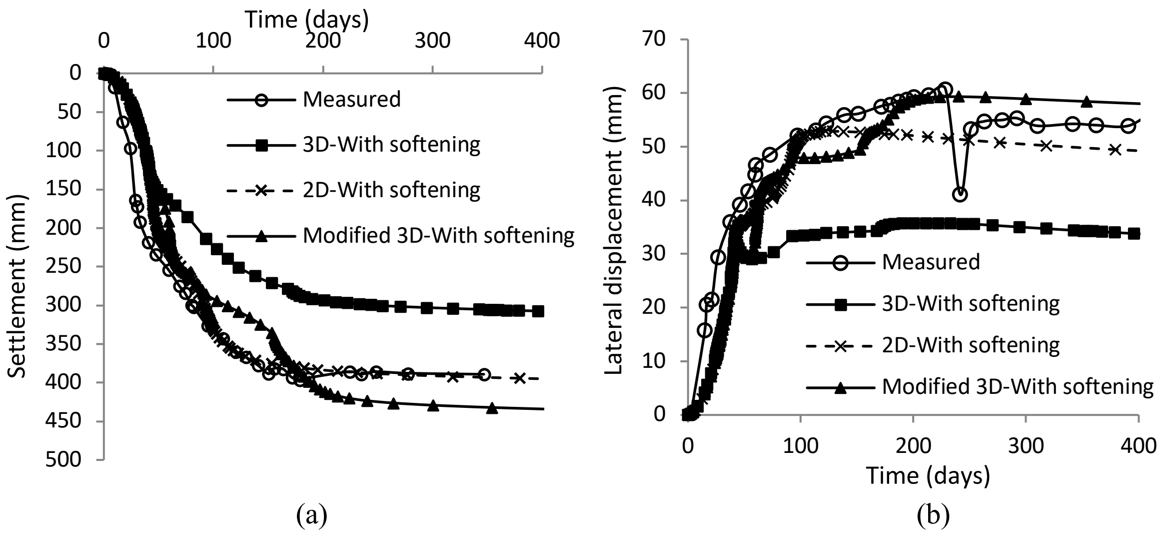


Figure 3. Comparison of performance of the embankment calculated using the 3D model and equivalent 2D model (a) Settlements (b) Lateral displacements.

Figure 4 shows the variation of excess pore water pressures at the mid-depth of the soft clay layer beneath Node C. The pore water pressure generation and dissipation trends in the three numerical models show good agreement with the trends in the measured data. However, the magnitudes of the pore water pressures show a significant difference between the measured data and the numerical model predictions. The maximum pore water pressure recorded at the site is 28.9 kPa whereas the maximum pore water pressure predicted by the 2D model, 3D model and modified 3D model are about 18-19 kPa. The numerical models indicate faster pore water pressure dissipation compared to the actual ground. The numerical models show over 98% consolidation during 250 days and the field data show only 73% consolidation over 250 days. When the settlements at the site are considered, the final settlements have become stable after around 250 days. These data suggest that, the higher percentage of consolidation predicted by the numerical models compared to field data over 250 days is reasonable.

The peak pore water pressure was observed at the end of the first construction stage in field measurements as well as in the numerical predictions. Field measurements show a second peak immediately after the first peak, with a similar magnitude. The 2D model and modified 3D model also show a second peak in pore water pressures during the second construction period, few days after the first peak. The second peak is due to the softening occurred in DCM columns beyond yield. The 3D model does not show the second peak of pore water pressure during the second construction stage. Another increment in pore water pressures is recorded in the field data at the end of the second construction period. Numerical models also show an increase in pore water pressures at the end of the second construction period. However, the increase in pore water pressure in the 2D model at the end of the second construction period is larger than that predicted by the 3D models. Both field measured data and the modified 3D model show another increment in pore water pressures at about 160 days, after completion of the construction. This indicates that the softening of DCM columns is still taking place in the modified 3D model and in the field. However, the pore water pressures in the 2D model and the 3D model with same material properties gradually decreases after the second construction stage and does not show an increment at 160 days. These observations confirm that the strain-softening occurred in the 2D model and the 3D model with same material properties as in the 2D model has completed earlier than that occurred in the modified 3D model.

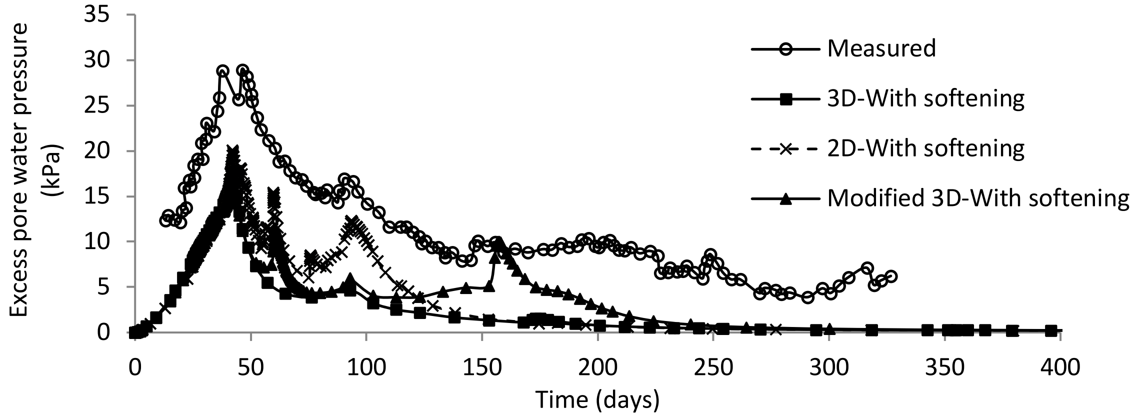


Figure 4. Variation of pore water pressures in the two numerical models and field measured data.

The results discussed above show that, the 3D model and 2D model predictions does not match well when the same parameters are used in the strain-softening incorporated constitutive material model for the DCM columns. According to the numerical model results, vertical stresses in DCM columns were similar in the 2D model, 3D model and modified 3D model, before yielding. This confirms that the difference in settlements and lateral displacements in the 2D model and 3D model are not due to differences in load transfer mechanisms in the two models. The reason for this disagreement is the different rates of strain-softening in DCM columns in 2D and 3D models, when the strain-softening behaviour is incorporated. This difference can be reduced by reducing the residual plastic deviatoric strain in the 3D model, which will lead to a faster rate of strain-softening of the DCM columns. For the embankment discussed in this study, the 3D model with a residual plastic strain of 0.07 was comparable with a 2D plane-strain model with a residual plastic strain of 0.12. These results suggest that the parameters for the strain-softening incorporated material model should be modified, when converting a 3D model into a 2D plane-strain model.

5. CONCLUSIONS

The challenges in converting a 3D model of a DCM column-improved embankment into a simplified 2D plane-strain model when the columns experience post yield softening, was investigated in this study. A 2D plane-strain model of the embankment was first developed using ABAQUS (2014) finite element programme and validated using field measured data. Then a 3D model of the embankment was simulated with the same material properties and constitutive models. The 3D model results were compared with 2D model results to understand the differences in the performance between the two models.

The final settlements and lateral displacements in the 3D model were lower than those predicted by the

2D model. 2D model showed a rapid rate of increase in deformations during the strain-softening compared to the 3D model. In order to obtain a good agreement between the 2D and 3D models, the variation of DCM column strength against plastic deviatoric strain in the strain-softening incorporated constitutive material model should be modified when 2D model is converted to a 3D model. This can be done by reducing the plastic deviatoric strain corresponding to residual strength of DCM column, in the 3D model.

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