Three-dimensional numerical study on consolidation behavior of reclamation with ground improvement

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ABSTRACT

A series of three-dimensional numerical study was carried out to investigate consolidation behaviour of soft soil treated with deep cement mixing (DCM) columns. Effect of different modelling approaches (modelling sequence, drainage condition of DCM columns and constitutive model of DCM columns and soft soil) on reclamation settlement prediction has been studied. It is found that settlement predicted by commonly used elastic perfectly plastic Mohr-Coulomb model for soft soil in industry practice would underestimate the settlement significantly compared with more advanced models such as Modified Cam Clay. Nonetheless, computed stress in soil and DCM columns are insensitive to soil model. Consolidation would be accelerated with the presence of DCM columns even DCM was modelled as a nonporous material (i.e. permeability is zero). It is believed that it is the stiffness of DCM columns that controls consolidation speed of an improved ground. When DCM was modelled as an elastic perfectly plastic material, large shear strain would develop at column top and that would result yielding of DCM columns if reclamation loading is large enough. Based on these findings, suggestions have been given for engineers carrying out routine reclamation design.

Keywords: reclamation; soft soil; deep cement mixing; consolidation; numerical modelling

1 INTRODUCTION

The emerging of deep cement mixing (DCM) as a ground improvement technique has made it possible for reclamation being carried out without dredging soft soil which is frequently encountered in coastal areas. Much study has been conducted on DCM, focusing on investigating its mechanical properties (i.e. strength and stiffness). A comprehensive review of that can be found in Kitazume and Terashi (2013). Application-oriented research, such as physical tests reported in Kitazume and Maruyama (2006, 2007), field tests reported in Jamsawang et al. (2011) has also been carried out on embankment constructed on soft soil improved by DCM. Design procedures have been provided, for example, in Bruce et al. (2013) and Kitazume and Terashi (2013). Reclamation design adopting DCM technique usually follows the practice in embankment projects, where the stiffness and strength properties of DCM clusters are smeared within the improvement zone using a parameter termed area replacement ratio. Kitazume and Terashi (2013) introduced a stress concentration ratio when analytically calculating the consolidation settlement of a ground improved by column type of DCM clusters, where the stress concentration ratio is simply the inverse of compressibility of unimproved and improved soil. The hidden assumption is that the settlement at top of unimproved soil and improved soil is the same. Recent understanding of settlement and stability behaviour of embankment constructed on DCM improved ground has been advanced through numerical modelling (Chai et al. 2015; Yapage et al. 2014; Jamsawang et al. 2016; Huang and Han 2009), which demonstrated that the above assumption is not correct as differential settlement was observed between top of unimproved and improved soil. The objective of this paper is to extend the numerical study to reclamation setting and investigate effects of different numerical modelling techniques, such as soil and DCM constitutive models, modelling sequence of reclamation process etc. on predicted consolidation behaviour and DCM column performance. This is of practical significance to industry if advanced numerical modelling is to be adopted in routine reclamation design.

2 ANALYTICAL APPROACH FOR ESTIMATING CONSOLIDATION SETTLEMENT OF DCM IMPROVED GROUND

The routinely adopted method for estimating settlement of a fixed type (bottom of DCM columns sit on competent layer) improved ground has been described in Kitazume and Terashi (2013), in which it is assumed that the DCM column and the surrounding ground settle uniformly. The final settlement is calculated by:

$$S = [1/(1+(n-1)a_s)]*H_c*C_c*\log(\sigma_1'/\sigma_0')/(1+e_0) \quad (1)$$

where n is stress concentration ratio defined by m_{vc}/m_{vs}

(coefficient of volume compressibility of soft soil over that of DCM); a_s is area replacement ratio; H_c is thickness of improved soil; C_c is compression index of soft soil; e_0 is initial void ratio of soft soil; σ_0' is initial vertical effective stress; σ_1' is final effective stress when consolidation completed (evaluated as if no ground improvement is carried out). This equation is included in this paper for comparison purpose (in calculation the soft soil layer is divided into sublayers with 0.5 m thick). It is also noticed that there is a more radical design method which assumes all reclamation loading is taken by DCM column and thus the settlement is solely due to shortening of DCM columns. This fundamentally assumes that DCM is elastic material and no yielding would occur regardless of the magnitude of reclamation loading. As far as the authors are aware, this has not been a main steam design method. As such this is not discussed here. The inherent shortage of any analytical equations is that they cannot give a prediction of settlement-time relation. For reclamation this is, however, extremely important as upper structures would often need to be built on it, of which residual settlement would affect foundation design.

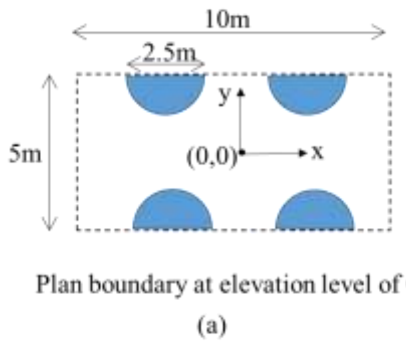
3 THREE-DIMENSIONAL NUMERICAL ANALYSIS

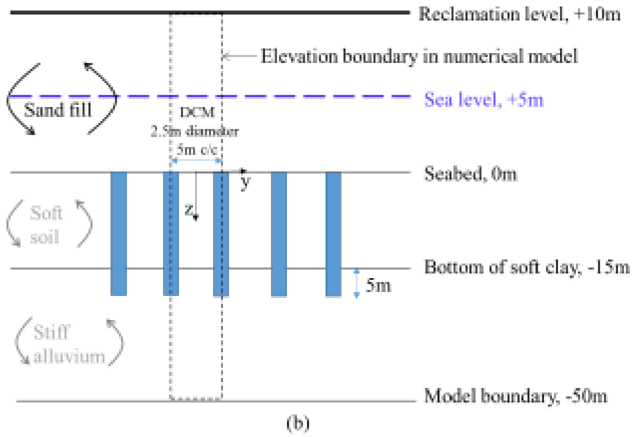
3.1 Model configuration

Fig. 1 shows the configuration of the numerical model. A so-called unit cell of which boundaries are symmetrical on plan was modelled as shown in Fig. 1(a). The dimension is 10m width and 5 m length in x- and y-direction, respectively. The diameter of the DCM column modelled is 2.5 m and the spacing between each individual DCM column is 5 m. The soil strata as shown in Fig. 1(b) is comprised of 15 m thick soft clay underlain by stiff alluvium. The seabed is assumed at the level of 0m. The targeted reclamation level is +10m. The sea water level is assumed at the level of +5m. Fig. 1(c) shows a snapshot of the PLAXIS3D model. The total number of element is 37353 with an average element size of 0.77 m. Mesh refinement was applied to soft soil and DCM column. Standard displacement boundary conditions (roller at four sides while pin at the bottom) were applied. For flow boundary conditions, all four circumferential sides were impermeable while drainage was allowed at top and bottom levels.

3.2 Analysis programme

Table 1 summarises the numerical analysis programme, which was so designed to achieve the purpose of studying effects of modelling sequence, soft soil constitutive models and DCM constitutive models on consolidation behaviour of the improved ground. Cases 1 to 3 were designed to study the effect of modelling sequence on consolidation settlement prediction. Specifically, in Case 1, the reclamation process was modelled phase by phase with 2 m each (thus in total 5 phases) and consolidation was allowed





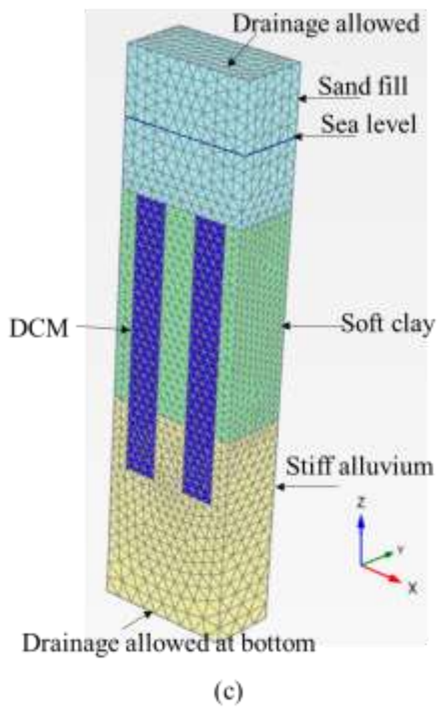


Fig.1. (a) Plan view of the model boundary; (b) elevation view; (c) snapshot of the 3D finite element model. (not to scale)

during each phase. For simplicity, each phase was ideally assumed to be completed within one day. In Case 2, the reclamation was assumed to be completed in a single phase within five days and consolidation was allowed during this phase. In Case 3, the reclamation process was modelled in one single phase however consolidation was not allowed, thus making the time not relevant. Cases 3 to 5 were to investigate the effect of DCM constitutive model on consolidation settlement. Linearly elastic and non-porous model was adopted in Case 3 for DCM. Linearly elastic with Mohr-Coulomb failure criteria was adopted for Cases 4 and 5. In the former case DCM is non-porous while in the latter case DCM is porous, having the same permeability to the surrounding soft soil. Cases 4, 6 and 7 were to study effect of soft soil constitutive model on settlement and stress redistribution between soil and DCM columns. For comparison, Modified Cam Clay (Case 4) and depth-dependent linearly elastic with Mohr-Coulomb failure criteria (Cases 6 and 7) were adopted for the soft soil. Further distinction was made for the depth-dependent Mohr-coulomb model, with undrained A (effective stress stiffness and strength parameters) for Case 6 and undrained B (effective stress stiffness but undrained strength parameters) for Case 7. In all cases the sand fill and stiff alluvium were both modelled using drained linearly elastic with Mohr-Coulomb failure criteria.

Table 2 presents the soil and DCM parameters adopted. For the normally consolidated soft clay, the parameter λ in Modified Cam Clay model is calculated from Cc using the standard correlation $\lambda = C_c/2.3$. The unloading stiffness κ is simply assumed to be $\lambda/10$. In current problem setting, this parameter is of minimal significance as no unloading stress path would be involved. To achieving a comparable comparison, the Young's modulus adopted in the Mohr-coulomb model is also correlated to Cc using standard equations as listed in the notes under Table 2. The undrained shear strength of soft soil adopted in undrained B model in Case 7 is correlated using the well-established equation provided in reference such as Wood (1990). The effective friction angle ϕ' is used to calculate the stress ration M in Modified Cam Clay model using $M=6\sin\phi'/(3-\sin\phi')$. For DCM, its unconfined compressive strength q_u is assumed to be 800 kPa. The Young's modulus is assumed to be $150q_u$. For the DCM modelled using Mohr-Coulomb model, a factor of safety 1.5 is further adopted to transfer the q_u to c', implicitly incorporating the strain-softening behaviour of DCM.

Table 1 Numerical analysis program using PLAXIS3D

Case*	Soft soil#	DCM#	Modelling sequence
1	MCC	Linearly elastic, non-porous	Multiple filling stages during which consolidation allowed
2			One single filling stage during which consolidation allowed
3			One single filling stage during which consolidation NOT allowed
4		Linearly elastic with M-C failure criteria, non-porous	
5		Linearly elastic with M-C failure criteria, porous	
6	Depth dependent linearly elastic with M-C failure criteria (undrained A)	Linearly elastic with M-C failure criteria, non-porous	
7	Depth dependent linearly elastic with M-C failure criteria (undrained B)		

*In all cases, sand fill and stiff alluvium were modelled as linearly elastic with Mohr-Coulomb failure criteria.
#MCC: Modified Cam Clay; M-C: Mohr-Coulomb.

Table 2 Soil and DCM parameters

	Normally consolidated soft soil*			DCM#			Sand Fill	Alluvium
	MCC	Depth dependent M-C, undrained A	Depth dependent M-C, undrained B	Elastic, non-porous	M-C, non-porous	M-C, porous	M-C	M-C
E' (kPa)	-	$367+92d$	$367+92d$	120×10^3			15×10^3	50×10^3
c' (kPa)	-	0	-	-	267		0	0
ϕ' (°)	20	20	-	-	0		30	35
s_u (kPa)	-	-	$1.5d$	-	-		-	-
ν'	0.3	0.3	0.3	0.2			0.3	0.2
λ	0.22	-						
κ	0.022	-						
k (m/s)	1×10^{-8}			-		1×10^{-8}	1×10^{-4}	1×10^{-6}
γ_s (kN/m^3)	16			20			18	19

*d: depth measured from seabed; $s_u=0.25\sigma_{vc}'$, where σ_{vc}' is pre-consolidation pressure (Wood, 1990); $E'=[(1+\nu')*(1-2\nu')/(1-\nu')]*[(\sigma_1'-\sigma_0')*(1+e_0)/(C_c*\log(\sigma_1'/\sigma_0'))]$, where assuming $e_0=2.5$, σ_0' is initial stress before consolidation, σ_1' is stress after consolidation completed.
#: $c'=(q_u/2)/\mathrm{FoS}$, q_u=800 kPa, FoS=1.5, $E'=150q_u$

3.3 Modelling sequence

The initial condition was established by applying k_0 condition. The reclamation fill was then activated, of which the manner differs for different cases. Detailed modelling sequencing of the reclamation fill in Cases 1 to 3 is described above. For Cases 4 to 7, single reclamation process during which consolidation was not allowed was modelled. After the reclamation process, further consolidation was allowed until excess pore-water pressure was fully dissipated.

4 RESULTS AND DISCUSSION

4.1 Reclamation settlement

Fig. 2 depicts total settlement (immediate settlement plus consolidation settlement) at reclamation surface for Cases 1 to 3. It is worth pointing out that in all cases, no differential settlement was observed at the reclamation surface. This would be discussed more in later section. It can be seen that Case 3 (reclamation is completed in a single phase and consolidation is not allowed) gives the largest total settlement. The implication is that if there is any uncertainty about construction program this modelling sequence would predict the upper bound in terms of total settlement.

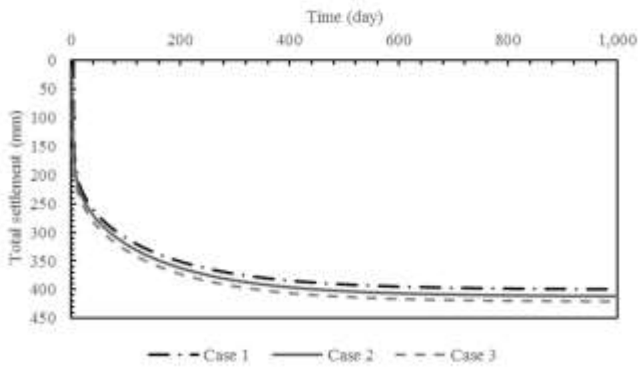
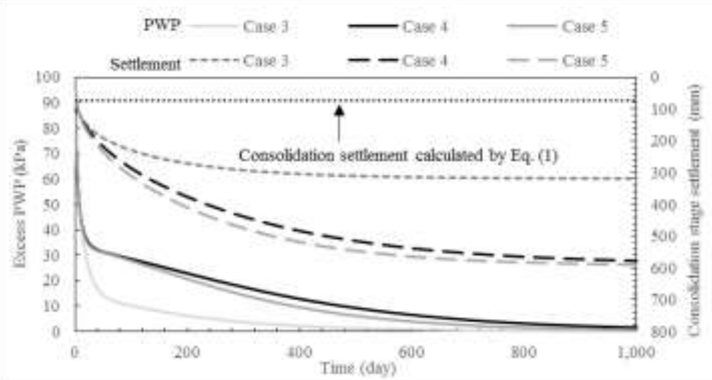


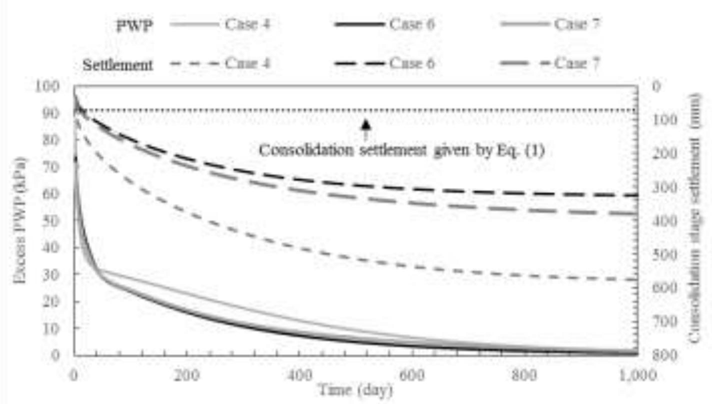
Fig.2. Effect of modelling sequence on total settlement

Fig. 3(a) presents consolidation and PWP dissipation behaviour of the improved ground when DCM was modelled as purely elastic material (Case 3) or elastic-plastic material (Case 4 and Case 5, non-porous for the former case while porous for the latter). The location selected for settlement data plotting is at reclamation surface while for excess pore-water pressure (PWP) the mid-depth of soft soil is chosen. When DCM is purely elastic the settlement (~300 mm) is less compared with the result (~600 mm) given by an elastic-plastic model. Since the elastic modulus of these two models were assumed to be same, this indicated yielding of DCM columns occurred in Cases 4 and 5 under the reclamation loading. It is also obvious from this figure that whether the DCM was modelled as porous or non-porous does not affect the consolidation settlement prediction. For comparison purpose, the settlement calculated using Eq. (1) is also included in Fig. 3(a). It can be seen that this simplified approach would significantly underestimate the consolidation settlement even when DCM behaves as an elastic material. Thus it should be used with caution.

It seems that even the DCM was modelled as porous material it would not accelerate the consolidation process as shown by the excess PWP dissipation history plotted in the same figure. Jiang et al. (2014) carried out parametric study and found that when DCM is equally or less permeable than soil, it has minimal effect on consolidation speed. When it is higher than soil, radial drainage increases and thus would accelerate the consolidation. Yin and Fang (2006) also made the same observation in a small-scale physical test (450mm high, 300mm diameter unit cell). Nonetheless, Jiang et al. (2014) commented that permeability of DCM is not a governing factor, instead the stiffness of the DCM dominates the consolidation behaviour of an improved ground. This observation is supported by the quicker dissipation speed of excess PWP in Case 3 than that in other two cases. In Case 3 the DCM behaves elastically while in Case 4 and 5 DCM columns have yielded. Chai et al. (2006) discussed that the consolidation is accelerated as the improved ground has a higher stiffness and thus resulted in a higher coefficient of consolidation. This may not be accurate as in current numerical study the zero permeability (non-porous DCM in Case 5) would make the coefficient of consolidation zero, no matter how high the stiffness of DCM is. In balance, it is fair to say that the stiffness of DCM controls the consolidation behaviour of an improved reclamation and not to overreach to coefficient of consolidation.



(a)



(b)

Fig. 3. Effect of (a) DCM constitutive model and (b) soft soil constitutive model on consolidation settlement and dissipation of PWP.

Effect of constitutive model adopted for modelling soft clay on consolidation behavior is presented in Fig. 3(b). Modified Cam Clay model gives largest consolidation settlement, twice that given by

Mohr-Coulomb model. Undrained A (effective stiffness parameters but effective shear strength parameters) Mohr-Coulomb model gives smallest settlement. Undrained B (effective stiffness parameters but effective shear strength parameters) predicts an intermediate one. Use of Mohr-Coulomb model would likely give a non-conservative prediction. Reasons for this are discussed in later section when stress data are interpreted. It is also noted that dissipation of excess PWP is slower when Modified Cam Clay model is adopted, which means that residual settlement would be larger compared with that predicted by Mohr-Coulomb model. Given the credibility of Modified Cam Clay in modelling normally consolidated soft soil, it is recommended to be adopted in analysis and design. However, it is worth pointing out that it may be more expensive in terms of computation time. For the current problem, computation time of a 3D model adopting Modified Cam Clay took 8 hours compared that of 15 minutes using Mohr-Coulomb model.

4.2 Stress redistribution between DCM and soft soil

Fig.4 plots the vertical stress distribution within soil and DCM columns at end of consolidation stage. Cases 4, 6 and 7 were chosen for the purpose of discussing effect of soft soil constitutive model on stress redistribution. It can be seen that the stress in DCM is almost the same regardless of what type of soil model is adopted. This can be explained by the fact that stress is mainly controlled by force equilibrium and thus it is insensitive to the constitutive model. In a preliminary engineering design, it is often ideally assumed that all reclamation loading is to be taken by DCM columns. The stress acting on DCM columns as such has been included in Fig. 4. It can be seen that the computed vertical stress in the column is less than the ideally assumed, implying some load is transferred to surrounding soil. This is proved by the higher effective stress in the soft soil compared with geostatic condition assuming DCM taking all reclamation loading. Arching effect due to the presence of DCM columns is also evident when comparing stress in soil with geostatic stress assuming no DCM is carried out. Arching effect is evident starting from 5 m above the column top, which is equal to the column spacing. This is in broad consistence with design chart for pile-supported embankment provided by Hewlett and Randolph (1988). Moreover, centrifuge tests of embankment constructed on piles carried by Ellis and Aslam (2009a; 2009b) confirmed that when fill thickness is twice more than that of pile spacing, 'full' arching is achieved and no differential settlement at the surface would be developed. This is shown by current numerical analysis where the ratio of fill thickness and column spacing is 2. Oliveira et al. (2011) found that due to the arching effect, the load applied by the embankment is almost concentrated on the DCM and the increment in effective stresses of the soil is negligible. The current numerical analysis shown that this would be true only if the DCM is strong enough and no yielding occurs.

Yin and Fang (2006) through their small scale physical tests found that the stress concentration ratio (calculated using total stress) was not constant during the consolidation process, which increased first and then dropped. They suggested that modulus between DCM and soil may be a good indicator. This is also the approach taken by Eq. (1). The so calculated ratio for current study is 86. In numerical analysis, however, the stress concentration ratio is computed to be around 14, much less than the value given by the modulus ratio. This indicates that once DCM column yields, the modulus ratio may not be a valid indicator anymore. Yapage et al. (2014) reported a stress concentration ratio of 6 between a yielded DCM column (UCS=230 kN/m^3, E'=118UCS) and a soil with the same stiffness as in current study. Given that the DCM stiffness in current study is 4.4 times the value adopted in Yapage et al. (2014), the higher stress concentration ratio obtained in present study is reasonable.

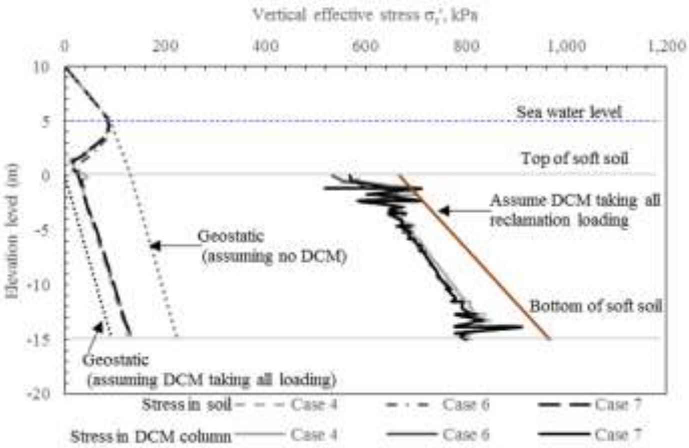


Fig. 4. Effect of soft soil constitutive model on stress distribution between DCM and soft soil

Even though the stress in soil and DCM is insensitive to soil model, deformation, however, is not. Larger shear strain (10% compared with 5%) at top DCM columns is observed when Modified Cam Clay (Case 4) is adopted. It is also noted that this is accompanied by larger shear strain in surrounding soil. The larger shear induced volume change computed by Modified Cam Clay may provide an explanation for the larger ground surface settlement. Undrained A Mohr-Coulomb model gives smaller settlement compared with that of Undrained B Mohr-Coulomb model. This is probably because mobilized shear strength of soft soil in Undrained A model increases as consolidation goes.

5 CONCLUSIONS

Three-dimensional numerical study has been carried out to study the performance of DCM improved reclamation. It is found that the routinely adopted analytical method in assessing reclamation settlement may be too aggressive. Numerical modelling is suggested to be adopted in engineering design. Widely used Mohr-Coulomb model shows its limitation in estimating consolidation settlement. Advanced soil model for soft soil should be used whenever possible. If in any case there is difficulty in approaching those advanced soil models, Mohr-Coulomb model can be chosen to assess the stress in DCM column and then it should be so designed with reference to the reclamation loading to keep DCM columns behave within elastic range. To address settlement problem, top several meters of DCM columns should be strengthened during construction.

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