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Influence of column yielding on degree of consolidation of soft foundations improved by deep mixed columns

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Abstract. Laboratory and field data showed that deep mixed (DM) columns accelerated the rate of consolidation of the soft foundations. Most analyses of consolidation of DM column-improved foundations so far have been based on the elastic theory. In reality, the DM columns may yield due to the stress concentration from the soft soil and its limited strength. The influence of column yielding on the degree of consolidation of the soft foundation improved by DM columns has not been well investigated. A three-dimensional mechanically and hydraulically-coupled numerical method was adopted in this study to investigate the degree of consolidation of the DM column foundation considering column yielding. A unit cell model was used, in which the soil was modeled as a linearly elastic material. For a comparison purpose, the DM column was modeled as an elastic or elastic-plastic material. This study examined the aspects of stress transfer, settlement, and degree of consolidation of the foundations without or with the consideration of the yielding of the DM column. A parametric study was conducted to investigate the influence of the column yielding on the stress concentration ratio, settlement, and average degree of consolidation of the DM column foundation. The stress concentration ratio increased and then decreased to reach a constant value with the increase of the column modulus and time. A simplified method was proposed to calculate the maximum stress concentration ratios under undrained and drained conditions considering the column yielding. The simplified method based on a composite foundation concept could conservatively estimate the consolidation settlement. An increase of the column modulus, area replacement ratio, and/or column permeability increased the rate of consolidation.

Keywords: column; consolidation; deep mixing; numerical analysis; settlement; soft soil; stress

1. Introduction

Deep mixed (DM) columns have been used to increase bearing capacity and stability and reduce total and differential settlements of soft foundations. It was observed in laboratory and field that DM columns accelerated the consolidation of the foundation. Han (2012) provided a state of the practice review of recent advances in column technologies to improve soft foundations. Three

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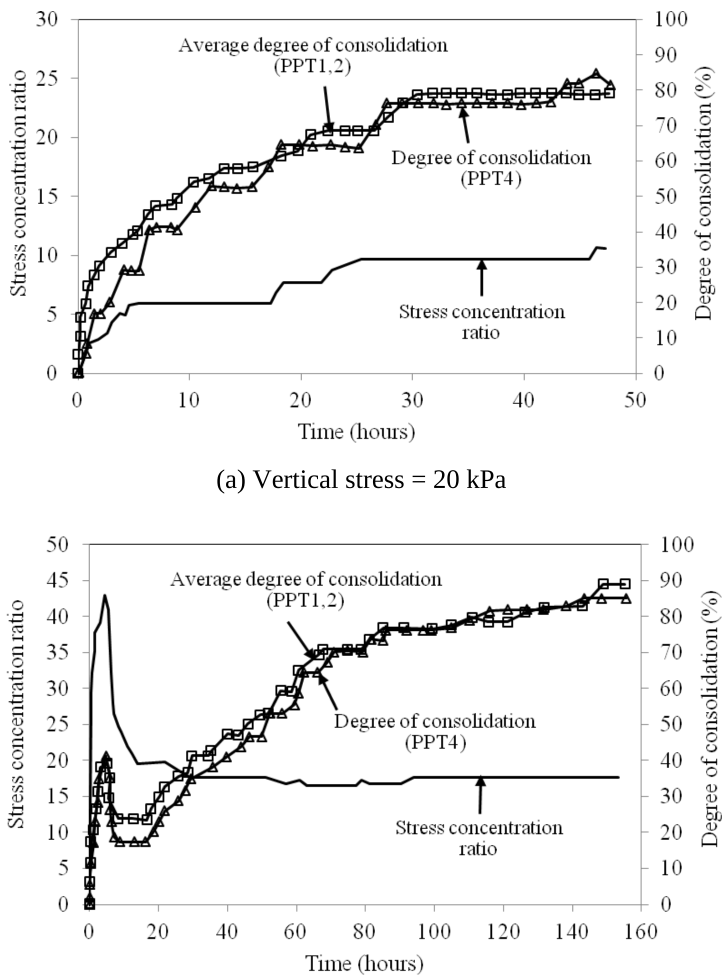
methods have been used to analyze the degree of consolidation of column foundations, i.e., experimental (Sivakumar *et al*. 2004, Yin and Fang 2006, Fang and Yin 2007, Chai and Pongsivasathit 2009), analytical (Han and Ye 2001, 2002, Lorenzo and Bergado 2003, Miao *et al*. 2008, Castro and Sagaseta 2008, Xie *et al*. 2009, Chai and Pongsivasathit 2009), and numerical methods (Tan *et al*. 2008, Huang *et al*. 2009, Huang and Han 2010, Castro and Sagaseta 2011, Jiang *et al*. 2013).

Sivakumar *et al*. (2004) conducted a series of triaxial tests on fully and partially penetrating stone column foundations under uniform and foundation loading to evaluate their bearing capacity and consolidation settlement. Their study showed that the fully penetrating columns could accelerate the rate of consolidation more than the partially penetrating columns. The degree of consolidation with partially penetrating columns was between those with fully penetrating columns and without any column. Yin and Fang (2006) and Fang and Yin (2007) presented physical models of soft foundations improved by DM columns and measured the settlements of the foundations, the loads on the columns and surrounding soil, and the excess pore water pressure in soil. Their results showed that partial radial consolidation existed along the DM column due to the higher permeability of the column than that of the surrounding soil. The relationships between the stress concentration ratio with time in Fig. 1 showed two trends at different stress levels: (1) the stress concentration ratio first increased and then remained constant with time at a low stress level (20 kPa); and (2) the stress concentration ratio first increased to a peak value and then decreased to a constant value at a high stress level (40 kPa).The reduction of the stress concentration ratio was attributed to the yielding of the column. The degree of the consolidation at the beginning was higher under the higher stress than under the lower stress because the former case had a higher stress concentration ratio. However, the degree of consolidation under the higher stress in the later time was lower than that under the lower stress. These comparisons indicated that the column yielded at a high stress and the degree of consolidation decreased with the yielding of the column. Chai and Pongsivasathit (2009) conducted a series of experiments to study the influence of area replacement ratio (i.e., the ratio of column cross sectional area to the unit cell cross sectional area) and depth replacement ratio (i.e., the ratio of column length to the thickness of the soft deposit) on the consolidation of the DM column foundation. Their experiments showed that the consolidation settlement decreased with an increase of area replacement ratio and depth replacement ratio.

Similar to Barron's solution (1947) for sand wells, Han and Ye (2001) proposed a simple analytical solution for calculating the degree of consolidation of stone column foundations. This solution considered the load redistribution between column and soil under the assumption of free-draining columns. Later Han and Ye (2002) proposed a general solution for calculating the degree of consolidation of stone column foundations considering the effects of smear and well resistance. Lorenzo and Bergado (2003) developed a partial differential equation to describe the consolidation of DM columns under two extreme conditions: equal strain and equal stress conditions. Miao *et al*. (2008) used a double layer system to calculate the degree of consolidation of the partially penetrating DM column foundation. In their model, the DM columns were considered impermeable and the DM column foundation was a composite foundation with a higher equivalent modulus than the untreated soil. Castro and Sagaseta (2009) considered the lateral deformation between column and surrounding soil, treated the stone column as a linearly elastic and perfectly plastic material, and then derived a solution for the degree of consolidation of the stone column foundation. Their solution could calculate the degree of consolidation even when the column yielded. However, their solution did not consider the effects of smear and well resistance as Han and Ye (2002) did. Xie *et al*. (2009) presented a solution for the degree of consolidation of



(a) Vertical stress = 20 kPa

(b) Vertical stress = 40 kPa

Fig. 1 Measured stress concentration ratios and degrees of consolidation versus time under two vertical stresses (re-drawn from Yin and Fang 2006)

a stone column foundation with a variation of the permeability of the surrounding soil from the interface between the column and the surrounding soil to the boundary of a unit cell.

A numerical method, as compared with an analytical method, does not require some undesirable assumptions for simplification and is therefore more applicable to analysis of a complicated problem, such as the degree of consolidation of stone column or DM column foundations. However, a numerical method requires computational time, which depends on the complexity of a problem. To save time, researchers sometimes simplify a complicated three-dimensional problem to a plane strain or axisymmetrical problem. For example, Tan *et al.* (2008) converted the three-dimensional unit cell model of a stone column foundation into the two-dimensional plane strain model in two simplified ways, i.e., the equivalent permeability method and the equivalent column area method. Huang *et al*. (2009) and Huang and Han (2010) adopted both two-dimensional and three-dimensional models to study the settlement of geosynthetic-reinforced DM column-supported embankments with time. They concluded that the DM columns could accelerate the rate of consolidation of the foundation. Castro and Sagaseta (2011) numerically studied the consolidation of the stone column foundation considering the stone column as a linearly elastic and perfectly plastic material. Their numerical results agreed with those from their previous analytical solution reasonably well.

As discussed above, most of the studies so far, especially analytical solutions, have been based on the elastic theory and limited studies have addressed the consolidation of stone column foundations considering the yielding of the columns. However, DM columns are different from stone columns in two aspects related to the consolidation: (1) DM columns have much higher modulus than stone columns; and (2) DM columns have much lower permeability than stone columns. Therefore, it is necessary to investigate the consolidation of DM column foundations considering the column yielding.

In this paper, a mechanically and hydraulically coupled three-dimensional numerical method was adopted to study the consolidation of DM column foundations. A unit cell model was adopted, in which the soil was modeled as an elastic material but the DM column was modeled as a linearly elastic and perfectly plastic material to consider the yielding of the column. This assumption is based on the fact that the column has a higher modulus, carries more stress, and yields first before the surrounding soil as shown in Fig. 2. In this study, the strain softening or hardening of the column was not considered, instead, the column was assumed to have perfect plasticity after yielding. In addition, this study assumed the soil did not yield because a failure of the foundation was not a focus of this study. The numerical results from the models with the yielding of the column are compared with those modeling the DM column as a linearly elastic material. A parametric study was conducted to analyze the influence of four key factors (length, area replacement ratio, modulus, and permeability of the DM column) on the stress concentration ratio, settlement, and average degree of consolidation of the DM column foundation.

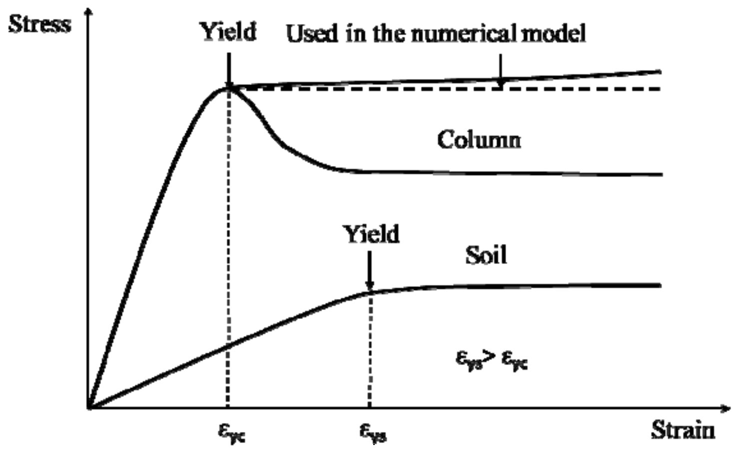


Fig. 2 Stress-strain relations of column and soil

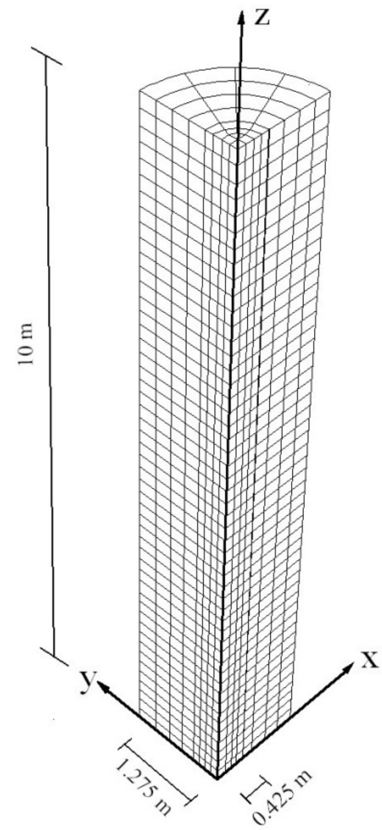


Fig. 3 Mesh of the one-quarter unit cell model (Jiang *et al*. 2013)

2. Numerical model

2.1 Model dimension

A unit cell model was adopted for the analysis of the consolidation of a DM column foundation considering the column yielding. The original model was selected from Tan *et al*. (2008), in which the consolidation of the stone column foundation was investigated. In Tan *et al*.'s (2008) paper, the stone column was modeled as a linearly elastic material and the software, PLAXIS, was used. The same model was created by Jiang *et al*. (2013) using the software, ABAQUS, for the model verification. The details of the model verification can be found in Jiang *et al*. (2013) and will not be included in this paper. In this study, the stone column was replaced by the DM column and the model was also simulated by the software, ABAQUS.

The finite element mesh of the one-quarter unit cell of the DM column foundation model is presented in Fig. 3.This model had a height of 10 m and an outer radius of 1.275 m. The DM column had a radius of 0.425 m (i.e., the area replacement ratio of 0.1) and fully penetrated to the bottom of the model. The column and its surrounding soil were modeled as pore fluid/stress 8-node brick elements.

Table 1 Material parameters of the DM column foundation in the baseline case

Material	E (MPa)	ν	γ (kN/m^3)	c (kPa)	φ (degrees)	k_r (m/d)	k_v (m/d)
Soil	3	0.3	15	-	-	2.998×10^{-4}	1.002×10^{-4}
Deep mixed column	30	0.3	15	150	0	1.002×10^{-4}	1.002×10^{-4}

*Note: E = elastic modulus; ν = Poisson's ratio; γ = unit weight; c = cohesion; φ = friction angle; k_r = radial permeability; and k_v = vertical permeability

2.2 Material parameters

Table 1 lists the parameters of the DM column foundation for the baseline case. Some of these parameters were varied during the parametric study. The DM column was modeled as a linearly elastic and perfectly plastic material following the Mohr-Coulomb failure criterion. For a comparison purpose, the DM column was also modeled as a linearly elastic material for some analyses. The soft soil was modeled as a linearly elastic material. Due to the modulus difference between the column and the soil, the soil is subjected to a low stress; therefore, an elastic model for the soil is suitable under a typical application in field. Castro and Sagaseta (2011) demostrated that the consideration of soil yielding was unnecessary under normal conditions when stone columns were used. The modulus of the DM column was assumed to be ten times that of the surrounding soil based on Huang *et al*. (2009). Strain softening of the DM column was not considered in this study. The Poisson's ratios for soil and deep mixed columns in the table correspond to a drained condition. However, at the moment of loading, all the load was carried by water; therefore, the actual Poisson's ratio of the model was 0.5 due to its incompressibility. The permeability of the DM column in both vertical and radial directions was assumed to be the same as the permeability of the surrounding soil in the vertical direction. The equal permeability of the DM column in the vertical and radial directions was based on the fact the soil is mixed with additives in field. Due to the symmetry of the problem, only one quarter of the unit cell model in three dimensions was used in the numerical analysis.

2.3 Boundary condition

The displacements of the one-quarter unit cell in the x and y directions were set to zero at the $x = 0$ and $y = 0$ planes, respectively. Around the outside of the one-quarter cylindrical vertical surface, the displacements in both x and y directions were set to zero. The displacements at the bottom of the unit cell in the three directions x, y, and z were also set to zero. A uniform vertical pressure of 300 kPa was applied on the top of the foundation instantaneously through a rigid plate, which was bonded with the top surface of the foundation to simulate a rough plate base. As a result, an equal vertical strain condition at the top boundary was ensured. To investigate the effect of column yielding, a higher vertical pressure of 300 kPa instead of 100 kPa used in Jiang *et al*. (2013) was adopted in this study. The phreatic level was set at the top surface, which was the only drainage boundary for the dissipation of excess pore water pressure throughout the model.

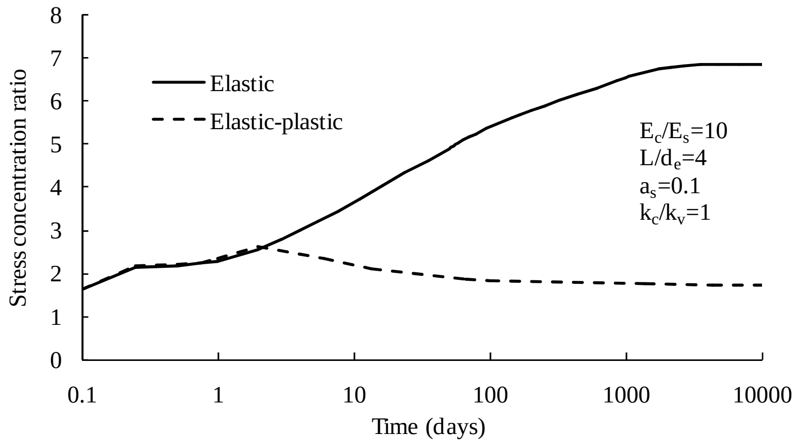


Fig. 4 Comparison of stress concentration ratios based on elastic and elastic-plastic column models

3. Consolidation of DM of foundation considering column yielding

3.1 Stress concentration ratio

Due to the modulus difference between column and soil, stress transfer occurs from the soil to the column during the consolidation of the column foundation (Han and Ye 2001, Huang *et al*. 2009, Zheng *et al*. 2011). This stress transfer is often defined by a stress concentration ratio, which is defined as the ratio of the vertical stress on the column to that on the soil as follows

$$n = \frac{\sigma_c}{\sigma_s} \tag{1}$$

where n is the stress concentration ratio, σ_c is the average vertical stress on the column, and σ_s is the average vertical stress on the soil. Fig. 4 shows the comparison of the stress concentration ratios computed based on the elastic and elastic-plastic column models. In Fig. 4, E_c/E_s is the ratio of the column modulus to the soil modulus, L is the length of the column, d_e is the diameter of the unit cell, and a_s is the area replacement ratio. The computed stress concentration ratios were close initially for both models, but became different after the DM column yielded at approximately three days. The stress concentration ratio decreased with time after the column yielded, while the ratio increased with time when the column was elastic. These phenomena are similar to those observed from the experiment in Yin and Fang (2006). At the end of the consolidation, the stress concentration ratios based on the elastic and elastic-plastic models were 6.94 and 1.72, respectively, which are both less than E_c/E_s (i.e., 10). The column lateral deformation could explain the stress concentration ratio in the elastic model was less than E_c/E_s. The yielding of the column further reduced the stress concentration ratio in the elastic-plastic model.

3.2 Maximum and steady-state stress concentration ratios

The maximum vertical stress the column can carries (ignoring the low effective overburden stress near the ground surface) is

$$\sigma_{c\max} = q_u + K\sigma_s \tag{2}$$

where q_u = unconfined compressive strength and K = coefficient of lateral earth pressure, which is between the coefficient at rest and the coefficient of passive earth pressure. Since the soil in this study was assumed to be elastic, no coefficient of passive earth pressure exists. The coefficient of lateral earth pressure at rest, K_o, can be calculated as follows

$$K_o = \frac{\nu_s}{1-\nu_s} \tag{3}$$

where ν_s = Poisson's ratio of soil.

Based on the force equilibrium of a unit cell under an equal strain condition, the following relationship can be established

$$p = a_s\sigma_c + (1-a_s)\sigma_s \tag{4}$$

where p = average vertical stress on the unit cell. If the column yields, the maximum vertical stress on the column in Eq. (2) can be substituted into Eq. (4) resulting in

$$\sigma_s = \frac{p - a_s q_u}{a_s K + (1-a_s)} \tag{5}$$

Therefore, the maximum stress concentration can be calculated as follows

$$n_{\max} = \frac{\sigma_{c\max}}{\sigma_s} = \frac{q_u\left[a_s K + (1-a_s)\right]}{p - a_s q_u} + K \tag{6}$$

In the baseline case, p = 300 kPa, q_u = 300 kPa, and a_s = 0.1. When K = 1.0 (i.e., K_o under an undrained condition), the calculated $n_{\max}$ = 2.11, which is close to the peak value 2.62 in Fig. 4. When K = 0.43 (i.e., K_o under a completely drained condition), the calculated $n_{\max}$ = 1.48, which is close to the steady-state stress concentration ratio of 1.72 in the numerical analysis. To match the ratio of 1.72, K is required to be 0.64, which is larger than K_o. Borges *et al*. (2009) assumed a similar value of K = 0.7 when they developed the best-fitting formula for stone column foundations to match the numerical results.

3.3 Lateral deformation

Fig. 5 shows the lateral deformation of the DM column increasing with time. Lateral deformation started from the upper portion of the column and extended to the bottom as the consolidation progressed. This phenomenon can be explained that the excess pore water pressure in the upper portion of the column dissipated faster than that in the lower portion of the column; therefore, more effective stress existing in the upper portion of the column led to larger lateral deformation. The lateral deformation extended to the bottom of the column as the dissipation of the excess pore water pressure got deeper. The lateral deformation in the lower portion of the column reached approximately the same value when the consolidation was complete. The lower deformations at two ends resulted from the fixed boundaries.

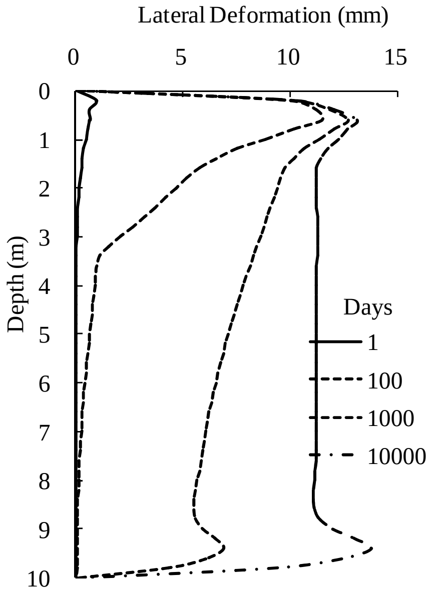


Fig. 5 Lateral deformation of the DM column at different consolidation time

3.4 Settlement

The final settlements computed based on the elastic and elastic-plastic models were 412 and 649 mm, respectively. The larger settlement in the elastic-plastic model resulted from the yielding of the column during the consolidation. A simplified equation can also be used to calculate the settlement based on the composite foundation concept as follows

$$s = \frac{\sigma}{[1 + a_s(n-1)]D_s} H \tag{7}$$

where s is the consolidation settlement, σ is the average vertical stress, a_s is the area replacement ratio, n is the stress concentration ratio, H is the thickness of the foundation, which is equal to the length of the DM column, and D_s is the constrained modulus of the surrounding soil. The constrained modulus of the surrounding soil can be calculated by

$$D_s = \frac{E_s(1-\nu)}{(1+\nu)(1-2\nu)} \tag{8}$$

where E_s is the elastic modulus of the surrounding soil, and ν is Poisson's ratio of the surrounding soil. Even though the column yielded in the elastic-plastic model, the surrounding soil was still elastic and therefore Eq. (7) is still valid if the corresponding stress concentration ratio is used. Based on the soil and column properties in Table 1, the calculated final consolidation settlements for the elastic and elastic-plastic models using Eqs. (7) and (8) were 449 and 688 mm, which are approximately 8.8% and 5.6%, respectively, larger than what were computed by the numerical method.

The average degree of consolidation of a foundation is commonly defined as follows

$$U_t = 1 - \frac{\int_0^H u_t dy}{\int_0^H u_0 dy} \tag{9}$$

where u_0 is the initial excess pore water pressure, u_t is the excess pore water pressure at time t, and y is the depth in the foundation from the ground surface.

However, it is not convenient to calculate the average degree of consolidation at every moment during the entire consolidation process using Eq. (9) from the numerical results because it requires the calculation of the average excess pore water pressure based on the actual excess pore water pressure distribution at every moment. The following equation may be used to approximately estimate the average degree of consolidation based on the settlement at time, t

$$U_t = \frac{s_t}{s_f} \tag{10}$$

where s_t is the top surface settlement at time t and s_f is the final consolidation settlement when the consolidation is complete. Fig. 6 shows the average degrees of consolidation based on the dissipation of excess pore water pressure and the settlement are reasonably close to each other. Thus the approach based on the settlement was used to calculate the average degree of consolidation in the following parametric study because it is more convenient to use.

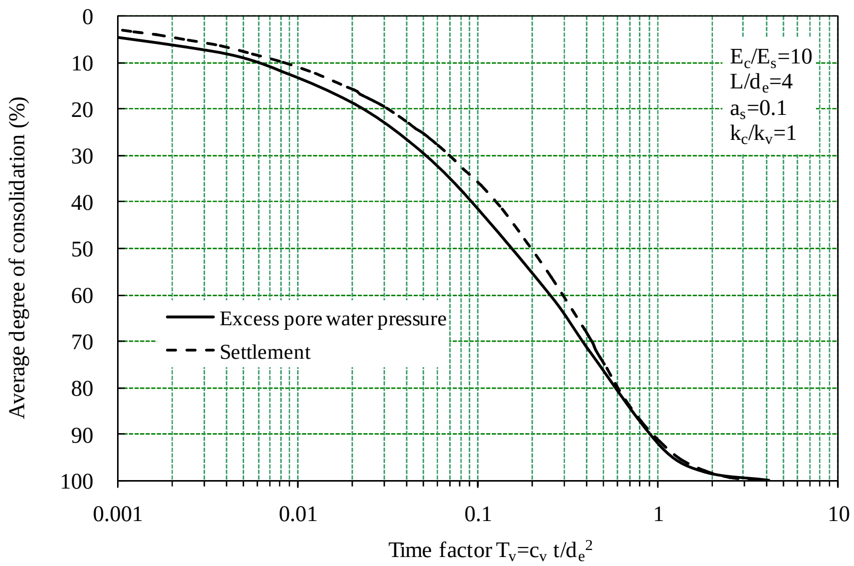


Fig. 6 Degrees of consolidation calculated based on excess water pressure and settlement

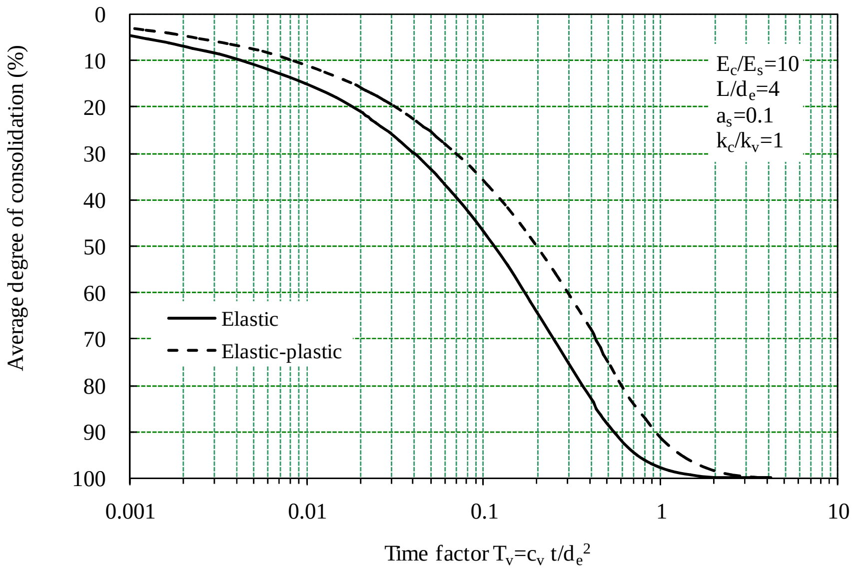


Fig. 7 Degrees of consolidation of DM column foundations based on elastic and elastic-plastic models

Fig. 7 shows that the average degree of consolidation of the DM column foundation based on the elastic-plastic model was lower than that based on the elastic model due to the yielding of the DM column during the consolidation. The yielding of the DM column during the consolidation resulted in the load redistribution between column and soil. In the elastic model, the stress transferred from soil to column until the end of the consolidation. In the elastic-plastic model, however, the stress first transferred from soil to column until the yielding of the column and then the stress transferred from column back to soil. The stress transfer from column to soil slowed down the dissipation of the excess pore water pressure in the soil and therefore reduced the average degree of consolidation of the DM column foundation.

4. Parametric study

A parametric study was conducted to investigate the influence of four key factors on stress concentration ratio, settlement, and degree of consolidation of the DM column foundation by varying the parameters from the baseline case. The key factors include the ratio of column length to influence diameter, the area replacement ratio, the modulus ratio of DM column to soil, and the permeability ratio of DM column to soil. One parameter was deviated from the baseline case to investigate the influence of that specific factor. The details of the investigated factors are listed in Table 2. Due to the variation of the DM elastic modulus, the cohesion c of the column based on the typical relationship of $c = E_c / 200$ (Porbaha *et al*. 2000, Bruce 2001) was varied as well.

4.1 Stress concentration ratio

4.1.1 Ratio of column length to influence diameter

Fig. 8 shows the variation of the stress concentration ratio with time at different ratio of column length to influence diameter. It is shown that the stress concentration ratio increased with time, reached a maximum value, and then decreased with time to a constant value, which was refereed as the steady-state stress concentration ratio by Han and Ye (2002). Fig. 8 shows that the ratio of column length to influence diameter had an insignificant effect on the stress concentration ratios including the steady-state stress concentration ratio. This result is based on the fact that an end-bearing column was investigated. The effect of the column length may become more significant if it is a floating column.

4.1.2 Area replacement ratio

The change of the area replacement ratio can be achieved by varying the diameter of the column or the influence diameter. Fig. 9 shows the variation of the stress concentration ratio with time at different area replacement ratio obtained by changing the diameter of the column. Similar results, even though not presented, were obtained at different area replacement ratios by changing the influence diameter. It is shown that an increase of the area replacement ratio slightly increased the maximum and steady-state stress concentration ratios. At a higher area replacement ratio, the yielding of the column was delayed due to slower stress transfer from soil to column and less lateral deformation of the column towards the soil.

Table 2 Material properties for the parametric study

Influence factor	Range of value
L/d_e	2, 4*, 8, 16 (L varies)
$a_s = A_c/A = (d_c/d_e)^2$	0.1*, 0.2, 0.3, 0.4 (d_c varies)
E_c/E_s	5, 10*, 50, 100 (E_c varies)
k_c/k_v	0.1, 1*, 5, 10 (k_c varies)

Note: L = length of DM column; d_e = diameter of unit cell; d_c = diameter of column; a_s = area replacement ratio; A_c = cross-sectional area of DM column; A = cross-sectional area of unit cell; E_c = elastic modulus of DM column; E_s = elastic modulus of surrounding soil; k_c = permeability of DM column; k_v = vertical permeability of surrounding soil; and indicates the parameters used in the baseline case

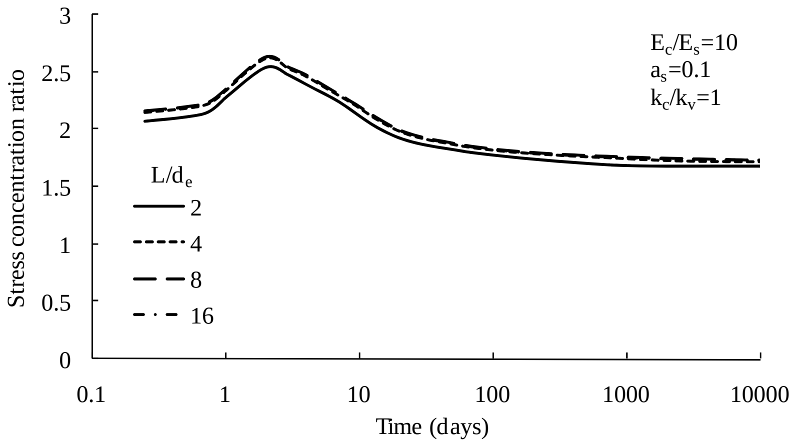


Fig. 8 Influence of ratio of column length to influence diameter on stress concentration ratio

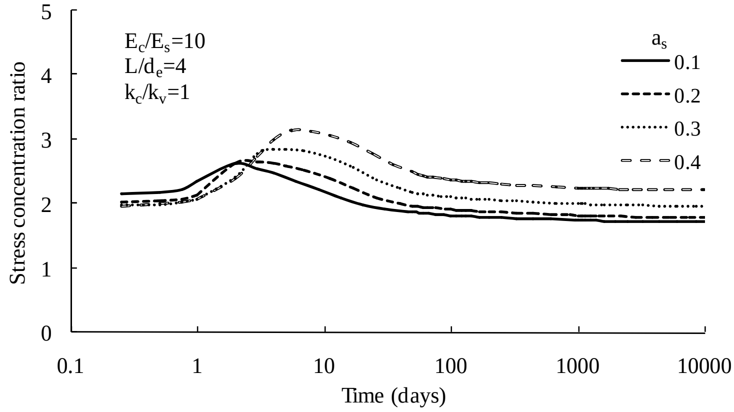


Fig. 9 Influence of area replacement ratio on stress concentration ratio

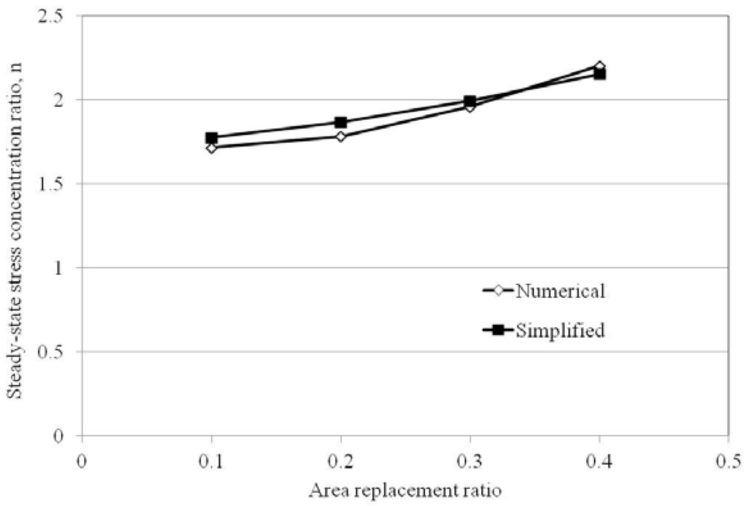


Fig. 10 Calculated steady-state stress concentration ratios

Fig. 10 presents the calculated steady-state stress concentration ratios by the numerical and simplified methods discussed earlier, which show good agreement. The coefficient of lateral earth pressure, K = 0.7, was used in the calculations using the simplified method.

4.1.3 Modulus ratio

Fig. 11 shows the stress concentration ratio increased with the increase in modulus ratio of column to soil. When the modulus ratio of column to soil increased to 100, the variation of the stress concentration ratio increased with time and reached a constant value, which was the same as that in the elastic model (Jiang *et al*. 2013). This result indicates that the strength of the DM column was high enough to support the load applied on it. In this study, the strength of the DM column was proportional to its modulus. As a result, the increase of the column modulus increased the column strength. However, when the modulus ratio was equal or less than 50, the column

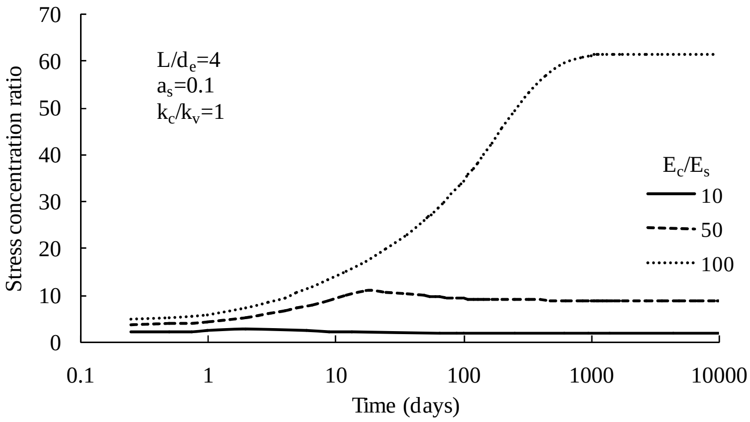


Fig. 11 Influence of modulus ratio on stress concentration ratio with time

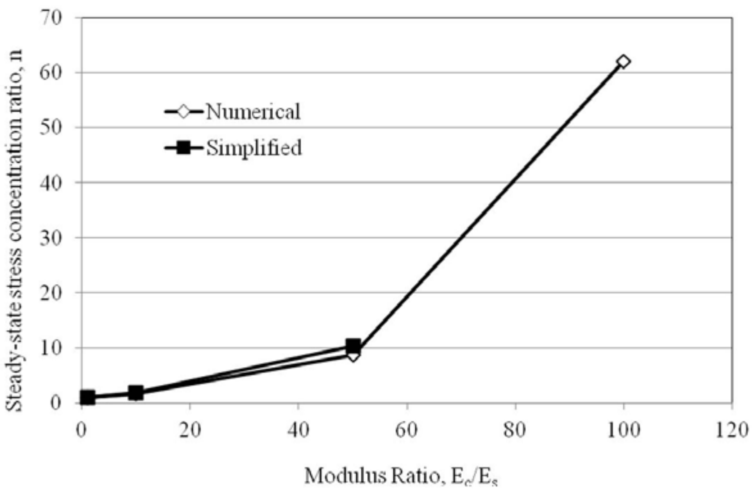


Fig. 12 Influence of modulus ratio on steady-state stress concentration ratio

yielded at a certain time. The time for the yielding of the column increased with the column modulus (i.e., column strength).

The steady-state stress concentration ratios at different modulus ratios are presented in Fig. 12, which shows a slow increase of the stress concentration ratio with the modulus ratio less than 50 but increased rapidly with the ratio greater than 50. It is also shown that the simplified method calculated close steady-state stress concentration ratios as compared with the numerical method up to the modulus ratio of 50. After the modulus ratio is greater than 50, the column will not yield; therefore, the simplified method is not applicable.

4.1.4 Permeability ratio

As discussed in the introduction, the permeability of DM columns can be lower or higher than its surrounding soil. In this study, the influence of the permeability ratio ranging from 0.1 to 10 (by changing the column permeability) was investigated. Fig. 13 shows that an increase of the column permeability increased the stress concentration ratio before reaching the maximum ratio, at which the column yielded. However, the permeability ratio did not affect the magnitude of the steady-state stress concentration ratio.

4.2 Settlement

The consolidation settlement for each case was determined based on the final settlement at which the consolidation was complete.

4.2.1 Ratio of column length to influence diameter

Fig. 14 shows that the consolidation settlement of the DM column foundation increased linearly with the ratio of column length to influence diameter. In this case, the settlement of the DM

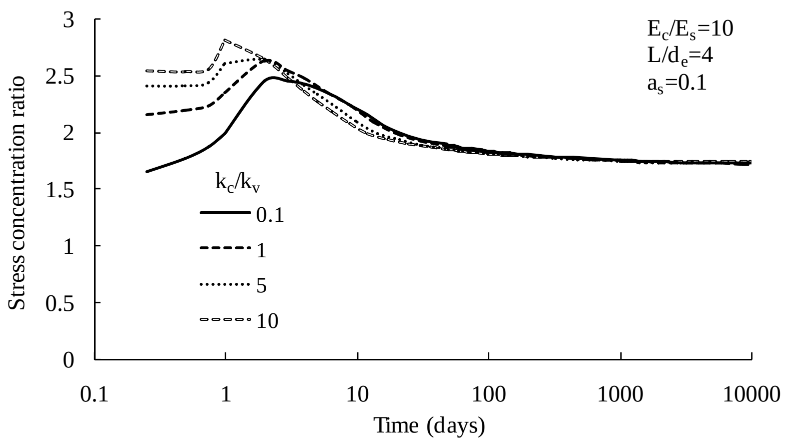


Fig. 13 Influence of permeability ratio on stress concentration ratio with time

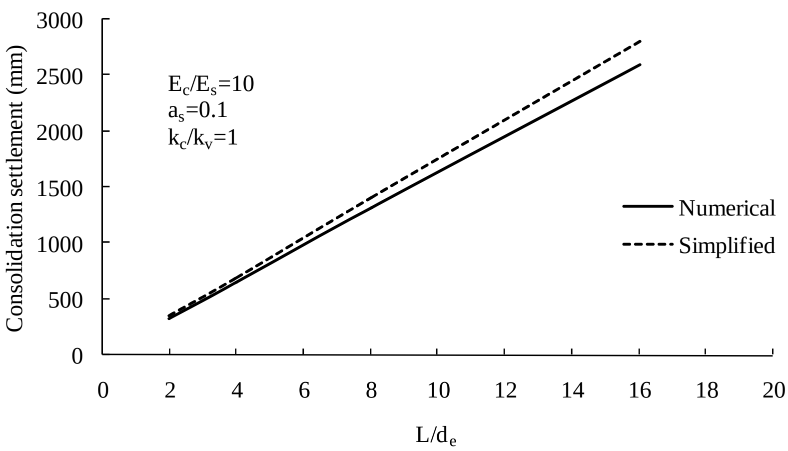


Fig. 14 Influence of ratio of column length to influence diameter on consolidation settlement

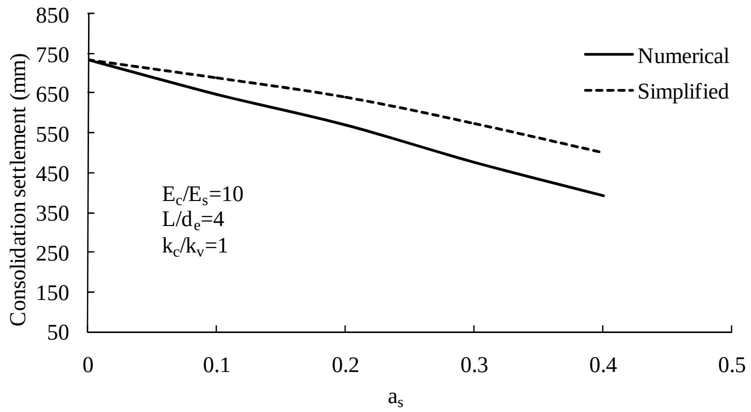


Fig. 15 Influence of area replacement ratio on consolidation settlement

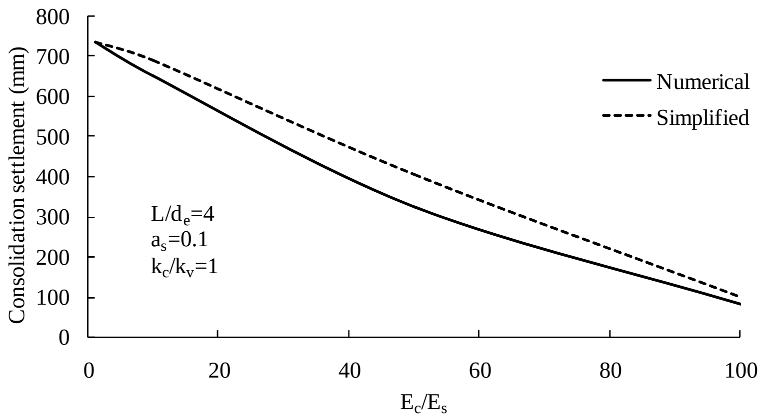


Fig. 16 Influence of modulus ratio on consolidation settlement

foundation depended on the thickness of the soft soil layer. In other words, the DM foundation with a thicker layer of soft soil could have more settlement. The simplified method based on Eqs. (7) and (8) using the steady-state stress concentration ratio slightly (approximately 10% or less) overestimated the consolidation settlement due to the fact of lateral expansion towards the surrounding soil as explained earlier. The 10% or less overestimation of the consolidation settlement is conservative and acceptable for most practical applications.

4.2.2 Area replacement ratio

Fig. 15 shows that the calculated consolidation settlements by both the numerical and simplified methods decreased with an increase of the area replacement ratio. The area replacement ratio at 0 represents an untreated foundation. It is shown that the calculated settlements for the untreated foundation by the numerical and simplified methods were identical because the soil was under a one-dimensional compression. However, the simplified method increasingly overestimated the consolidation settlement at the area replacement ratio greater than 0 as compared with the numerical method. At the higher area replacement ratio, the lateral displacement of the column towards the surrounding soil had more effect on the reduced settlement in the soil, which is not fully considered the simplified method.

4.2.3 Modulus ratio

Fig. 16 shows that the consolidation settlements calculated by both the numerical and simplified methods decreased with an increase of the modulus ratio. The modulus ratio equal to 1.0 represents an untreated foundation. Again, the numerical and simplified methods calculated the same settlement for the untreated foundation. The simplified method slightly overestimated the consolidation settlement at the modulus ratio greater than 1.0 as compared with the numerical method. However, at the higher modulus ratio (for example, 100), the lateral deformation of the column was small and had a limited effect on the settlement of the soil; therefore, the difference in the calculated settlements by these two methods was small.

4.2.4 Permeability ratio

The numerical results showed that the permeability ratio did not have any effect on the consolidation settlement of the DM column foundation. This finding is intuitively correct; therefore, the plot of numerical results is not provided here to save the paper space.

4.3 Degree of consolidation

The average degree of consolidation for each case was computed based on the settlement at a certain time using Eq. (10).

4.3.1 Ratio of column length to influence diameter

Fig. 17 shows the average degree of consolidation of the DM column foundation versus the

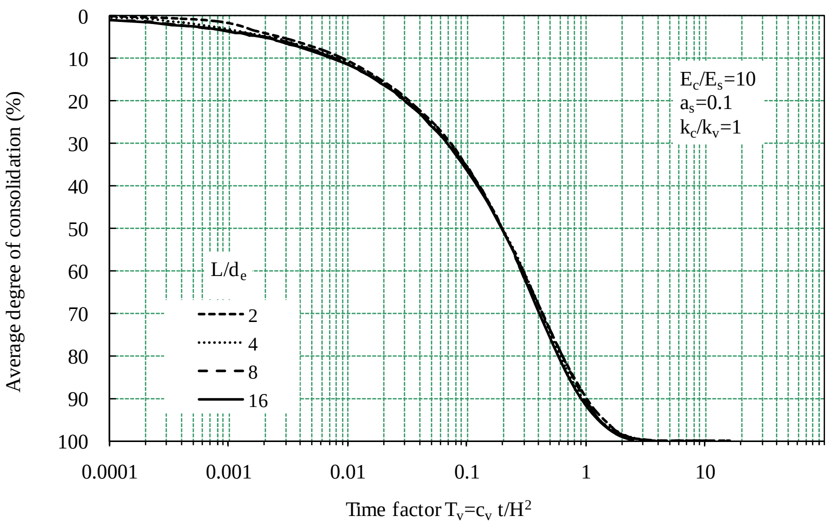


Fig. 17 Influence of ratio of column length to influence diameter on degree of consolidation versus time factor T_v

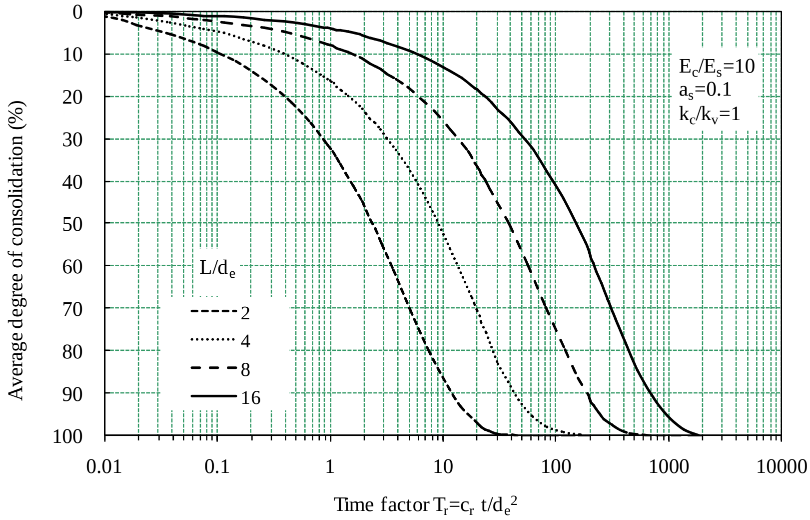


Fig. 18 Influence of ratio of column length to influence diameter on degree of consolidation versus time factor T_r

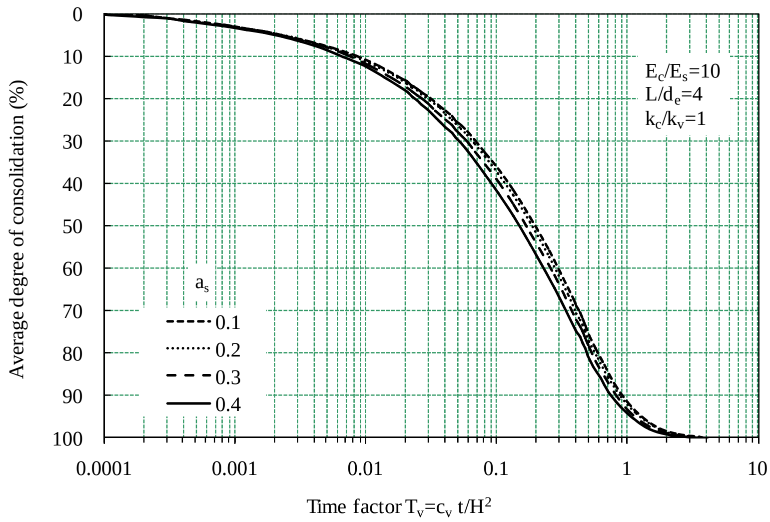


Fig. 19 Influence of area replacement ratio on average degree of consolidation

time factor in the vertical direction T_v (i.e., $T_v = c_v$ t/H^2, c_v is the coefficient of consolidation of the surrounding soil, H is the thickness of the surrounding soil, which is equal to the column length L, and t is time) at different L/d_e ratio. It is shown that the average degrees of consolidation of the DM foundations were almost same at different L/d_e ratios. It needs to be pointed out that the time factor T_v decreased with an increase of column length. However, when the average degree of consolidation is plotted against the radial time factor T_r (i.e., $T_r = c_r$ t/d$_e^2$, c_r is the coefficient of consolidation of the surrounding soil in the radial direction) at different L/d_e ratio as shown in Fig. 18, the average degree of consolidation decreased with an increase of the L/d_e ratio due to a longer vertical drainage path with an increase of the soft soil thickness. In other words, radial drainage is not a dominant mechanism for consolidation of a DM column foundation, which is different from a stone column foundation. Since Fig. 17 provides a unique presentation of the consolidation curve, the time factor, T_v, in the vertical direction is used for later presentations.

4.3.2 Area replacement ratio

Fig. 19 shows that the average degree of consolidation of the DM column foundation increased with an increase of the area replacement ratio. This result implies that the DM column accelerated the consolidation even though the permeability of the column was the same as that of the surrounding soil. This finding is in agreement with that of Huang *et al*. (2009). The increase of area replacement ratio can be achieved by reducing column spacing or increasing column diameter. These two approaches resulted in the similar results of the average degree of consolidation.

4.3.3 Modulus ratio

Fig. 20 shows that the average degree of consolidation increased significantly with an increase of the modulus ratio. As discussed earlier, an increase of the modulus ratio increased the stress concentration ratio of the DM column foundation. Han and Ye (2001, 2002) found that the consolidation of a stone column foundation was contributed by drainage and stress concentration. Even though DM columns had equivalent permeability as the surrounding soil in this analysis, the higher modulus of the column had a higher stress concentration ratio and accelerated the consolidation. As the modulus ratio increased from 10 to 100, the difference in the average degree of consolidation could be as much as 50%. The significant increase of the average degree of consolidation, when the modulus ratio was increased from 10 to 100, is due to the fact that the stress concentration ratio was significantly increased as a result of the change from the plastic column to the elastic column. Fig. 20 also shows that when the column yielded, the modulus ratio increased from 10 to 50 had a minor effect on the average degree of consolidation.

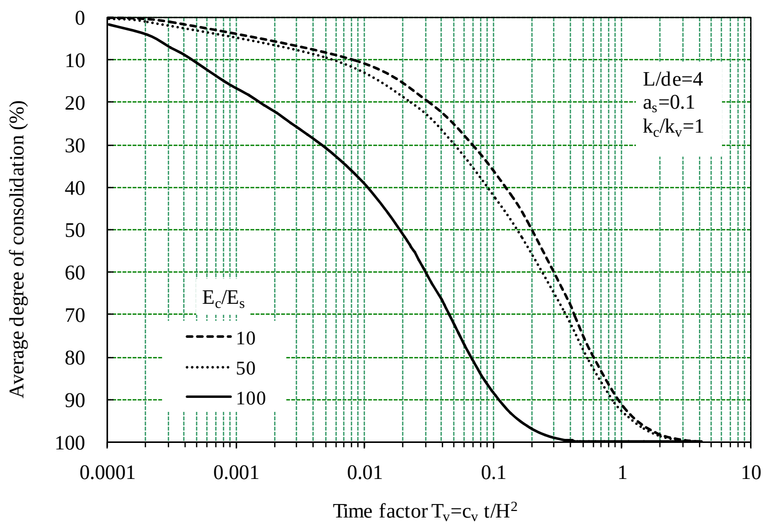


Fig. 20 Influence of modulus ratio on average degree of consolidation

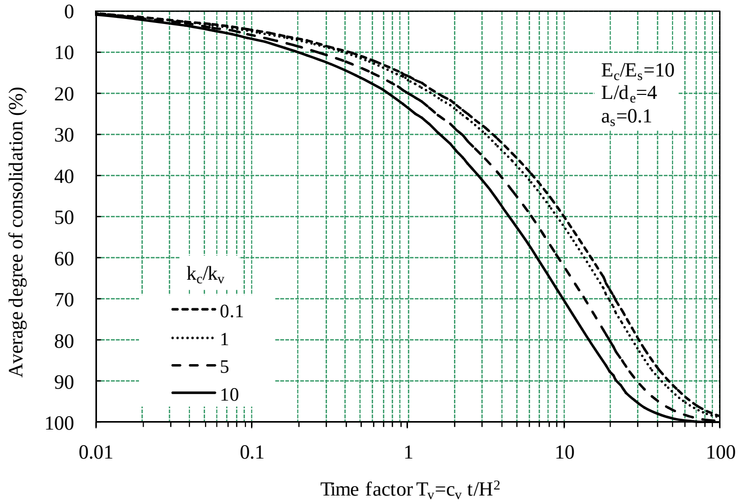


Fig. 21 Influence of permeability ratio on average degree of consolidation

4.3.4 Permeability ratio

Fig. 21 shows that the average degree of consolidation increased with an increase of the column permeability. However, when the permeability ratio decreased from 1.0 to 0.1, the reduction of the average degree of consolidation was minimal because vertical drainage in the surrounding soil dominated the consolidation of the DM column foundation when the permeability ratio was less than 1.0. When the permeability ratio was increased from 1.0 to 10, radial drainage in the surrounding soil became more important. Therefore, there was an apparent increase in the average degree of consolidation when the permeability ratio was increased from 1.0 to 10.

5. Conclusions

In this study, hydraulically and mechanically coupled three-dimensional models were used to analyze the influence of yielding on consolidation rate of DM column foundations. Four key factors were selected to investigate their influences on the stress concentration ratio, settlement, and degree of consolidation of the DM column foundations. A simplified method was developed to estimate the steady-state stress concentration ratio considering the yielding of the column. The simplified method for settlement calculation based on the composite foundation concept was examined. The following conclusions can be drawn:

- The numerical results showed that both the stress concentration ratio and the degree of consolidation of the DM column foundation in an elastic model were higher than those of the DM column foundation in an elastic-plastic model. The yielding of the column limited the stress concentration onto the column and the stress was transferred back to the surrounding soil after the yielding of the column.
- The stress concentration ratio increased with the column modulus and time, but the degree of increase was limited by the yielding of the column. The effect of the column length, area

replacement ratio, and column permeability on the stress concentration ratio was not significant.

- The simplified method for the steady-state stress concentration ratio resulted in close values to those obtained by the numerical method if there was yielding of the column.
- The settlement of the DM column foundation decreased with an increase of the column modulus and area replacement ratio, but increased with an increase of the foundation thickness. The effects of column modulus and area replacement ratio on the settlement reduction were limited by the yielding of the column.
- The simplified method for settlement calculation based on the composite foundation concept could be used to estimate the settlement of the DM column foundation even with the yielding of the column if the actual stress concentration ratio considering the yielding of the column was used. The simplified method over-estimated the consolidation settlement by 10% or less as compared with the numerical result.
- The column and its surrounding soil in the unit cell did not deform one-dimensionally because lateral deformation occurred at their interface. The lateral deformation started from the upper portion of the column and extended to the bottom of the column as the consolidation progressed. Approximately uniform lateral deformation developed at the end of consolidation.
- An increase of the column modulus, area replacement ratio, and column permeability increased the average degree of consolidation of the DM column foundation.
- The radial drainage became more important to the consolidation when the permeability of the column was higher than that of the surrounding soil.

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References

Barron, R.A. (1947), “Consolidation of fine-grained soils by drain wells”, *J. Soil Mech. Found. Div., ASCE*, **73**(6), 811-835.

Borges, J.L., Domingues, T.S. and Cardoso, A.S. (2009), “Embankments on soft soil reinforced with stone columns: Numerical analysis and proposal of a new design method”, *Geotech. Geol. Eng.*, **27**(6), 667-679.

Bruce, D.A. (2001), *An Introduction to the Deep Mixing Methods as Used in Geotechnical Applications – Volume III: The Verification and Properties of Treated Ground*, FHWA-RD-99-167, p. 455.

Castro, J. and Sagaseta, C. (2009), “Consolidation around stone columns. Influence of column deformation.” *Int. J. Numer. Anal. Methods Geomech.*, **33**(7), 851-877.

Castro, J. and Sagaseta, C. (2011), “Consolidation and deformation around stone columns: Numerical evaluation of analytical solutions.” *Comput. Geotech.*, **38**(3), 354-362.

Chai, J.C. and Pongsivasathit, S. (2009), “Prediction of consolidation settlements of floating column improved soft clayed subsoil”, *Proceedings of International Symposium on Geotechnical Engineering, Ground Improvement and Geosynthetic for Sustainable Mitigation and Adaptation to Climate Change including Global Warming*, Bangkok, Thailand, pp. 107-115.

Fang, Z. and Yin, J.-H. (2007), “Responses of excess pore water pressure in soft marine clay around a

soil-cement column", *Int. J. Geomech.*, *ASCE*, **7**(3), 167-175.
Han, J. (2012), "Recent advances in column technologies to improve soft soils", (Invited Keynote Lecture) *Proceedings of International Conference on Ground Improvement and Ground Control*, (Indraratna, B., Rujikiatkamjorn, C. and Vinod, J. Eds.), Wollongong, Australia, October-November, Research Publishing, Vol. 1, pp. 99-113.
Han, J. and Ye, S.L. (2001), "Simplified method for computing consolidation rate of stone column reinforced foundations", *Int. J. Geotech. Eng.*, *ASCE*, **127**(7), 597-603.
Han, J. and Ye, S.L. (2002), "A theoretical solution for consolidation rates of stone column-reinforced foundations accounting for smear and well resistance effects", *Int. J. Geomech.*, **2**(2), 135-151.
Huang, J. and Han, J. (2010), "Two-dimensional coupled hydraulic and mechanical modeling of geosynthetic-reinforced column-supported embankments", *Comput. Geotech.*, **37**(5), 638-648.
Huang, J., Han. J. and Oztoprak, S. (2009), "Coupled mechanical and hydraulic modeling of geosynthetic-reinforced column-supported embankments", *Int. J. Geotech. Eng.*, *ASCE*, **135**(8), 1011-1021.
Jiang, Y., Han, J. and Zheng, G. (2013), "Numerical analysis of consolidation of soft soils fully-penetrated by deep-mixed columns", *KSCE J. Civil Eng.*, **17**(1), 96-105.
Lorenzo, G.A. and Bergado, D.T. (2003), "New consolidation equation for soil-cement piles improved ground", *Can. Geotech. J.*, **40**(2), 265-275.
Miao, L., Wang, X. and Kavazanjian, E. (2008), "Consolidation of a double layered compressible foundation partially penetrated by deep mixed column", *Int. J. Geotech. Eng.*, *ASCE*, **134**(8), 1210-1204.
Porbaha, A., Shibuya, S. and Kishida, T. (2000), "State of the art in deep mixing technology: part III. Geomaterial characterization", *Ground Improv.*, **4**(3), 91-110.
Sivakumar, V., McKelvey, D., Graham, J. and Hughes, D. (2004), "Triaxial tests on model sand columns in clay", *Can. Geotech. J.*, **41**(2), 299-312.
Tan, S.A., Tjahyono, S. and Oo, K.K. (2008), "Simplified plane-strain modeling of stone-column reinforced ground", *Int. J. Geotech. Eng.*, *ASCE*, **134**(2), 185-194.
Xie, K.H., Lu, M.M., Hu, A.F. and Chen, G.-H. (2009), "A general theoretical solution for the consolidation of a composite foundation", *Comput. Geotech.*, **36**(1-2), 24-30.
Yin, J.H. and Fang, Z. (2006), "Physical modelling of consolidation behaviour of a composite foundation consisting of a cement-mixed soil column and untreated soft marine clay", *Geotechnique*, **56**(1), 63-68.
Zheng, G., Jiang, Y., Han, J. and Liu, Y.F. (2011), "Performance of cement-fly ash-gravel pile-supported high-speed railway embankments over soft marine clay", *Mar. Georesour. Geotec.*, **29**(1), 145-161.

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