ĐÁNH GIÁ HIỆU ỨNG VÒM Ở TRONG NỀN ĐƯỜNG ĐƯỢC HỖ TRỢ HỆ THỐNG CỘT ĐẤT TRỘN SÂU
EVALUATION OF SOIL ARCHING IN EMBANKMENT SUPPORTED DMM COLUMNS SYSTEM

Nguyễn Minh Tâm*, Trần Xuân Thọ**, Hui-Joon Kim*, Du-Hwoe Jung*

* Lab. of Advanced Soil Testing, Civil Engineering, Pukyong National University, Korea
** Faculty of Civil Engineering, Ho Chi Minh City University of Technology, Vietnam

BẢN TÓM TẮT

Xác định sự phân phối tải trọng bên trong và bên dưới nền đất được xử lý bởi các cột đất trộn sâu là công việc rất quan trọng trong việc thiết kế đường trên đất yếu. Sự phân phối này bị ảnh hưởng bởi nhiều hệ số, trong đó module đàn hồi của nền đường, độ cứng và độ cứng tương đối của cột và đất yếu xung quanh cột, cũng như tỉ số diện tích thay thế là những hệ số quan trọng nhất. Trong bài báo này, những ảnh hưởng của những hệ số này đến độ lún lệch giữa cột và đất yếu xung quanh cột, và hệ số giảm ứng xuất khi nền đất được chất tải của nền đường sẽ được giải quyết bằng phương pháp số được thể hiện bằng chương trình Plaxis.

ABSTRACT

Determination of the load distribution within and under the soil foundation improved by deep mixing method (DMM) columns is very important work involved in the design of an embankment in the soft subsoil. This distribution is influenced by many factors, among them, the modulus of the embankment fill, the stiffness and the relative stiffness ratio of the column and the unstabilized soil around the columns, the height of embankment fill, and the replacement area ratio are the most important major factors. A numerical study is conducted using Plaxis program to study these influences on the differential settlement between the DMM columns and soft clay surrounding columns and the stress reduction ratio after the soft soil foundation treated by DMM columns system and subjected to the embankment fill load.

1. INTRODUCTION

The vertical load in the columns and the distribution of the load between the columns and the unstabilized soil are governed by the interaction between the columns, the soil, the embankment. This complex interaction is almost explained by soil arching phenomenon that plays a significant role in the behavior of embankments supported on DMM columns. As an embankment founded DMM column is constructed, the soft foundation material consolidates and differential movement occurs between the relatively columns and the soft foundation material. Shear stresses are generated in the fill material, and through the arching effect, the vertical stresses are transferred from the soft foundation material onto the piles. Based on field measurements, some researchers (e.g. Reid and Buchanan 1984, Ooi et al. 1987, Huat et al. 1994) have reported that the load carried by the columns increases with time, which is attributed to arching developing above the columns. The degree of arching is a function of the diameter and spacing of the columns, the height of the embankment, the properties of the fill material, the relative stiffness of the columns and of the soil, the location of columns, the depth below the ground surface etc.

2. NALYTICAL METHODS CALCULATING DEGREE OF SOIL ARCHING

The degree of soil arching or transfer of vertical load on column was normally investigated by based on four following terms

- Column stress ratio, CSR,
- Stress reduction ratio, SRR,
- Stress concentration ratio, n, and
- Efficacy, E.

These terms are difined by following equations

$$CSR = \frac{\sigma_c}{\sigma} \quad (1)$$

$$SRR = \frac{\sigma_s}{\sigma} \quad (2)$$

$$n = \frac{\sigma_c}{\sigma_s} \quad (3)$$

$$E = \frac{\sigma_c \cdot a_s}{\sigma} \quad (4)$$

where $\sigma = \gamma_{fill} H_{fill} + q$ (5)

γ_{fill} = unit weight of embankment fill

H_{fill} = height of embankment fill

q = surcharge load

a_s, area replacement ratio, is defined

$$a_s = \frac{\text{area of pile}}{\text{total tributary area of pile}} = \frac{A_{col}}{A_{col} + A_{soil}} \quad (6)$$

where A_{col} = area of column

A_{soil} = area of the soil associated with the column

$A_{col} + A_{soil}$ = effective area, or the total tributary area associated with each column.

This area replacement ratio can also be expressed in terms of the diameter, D and spacing S of columnar inclusion as shown in Figure 3.

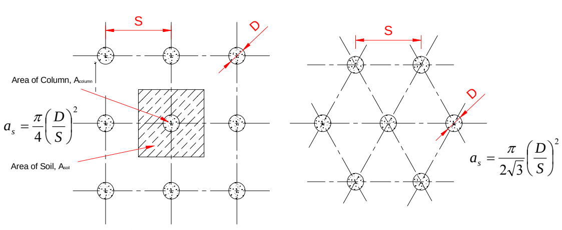

Figure 3. Area replacement ratio

Researchers have developed several methods up to date to consider the degree of soil arching based on column size and spacing, and embankment height. The calculated functions of the SRR from these researches are summarized briefly in Table 1.

3. PARAMETERS STUDY ON SOIL ARCHING WITH FEM

As seen in Table 1, some researchers showed an evaluation the degree of soil arching effect to vertical distribution of embankment fill system founded on piles or columns used to improve the soft soil foundation. However, these evaluated methods only consider on the some main factors influenced to degree of soil arching, including height of embankment fill, area replacement ratio, different stiffness ratio between column and soft soil surrounding the column, and friction internal angle of embankment fill, ϕ, Nevertheless, to knowledge of authors, the degree soil arching is affected by others many factors, besides the factors aforementioned. Therefore, to have a wide view on evaluation of many factors influenced on the degree of soil arching, FEM analysis is used to solve problem in this section.

FEM has been proven to be a credible analytical tool to estimate the field performance of clay treated by deep cement mixing columns under structures. The FEM have also been used to simulate the model tests under different conditions. The results were consistent and were in good agreement with the measurements. Using the numerical simulation provides a better general understanding of the mechanical performance of structure. The FEM has been used by several investigations to analyze the behavior of soft soils stabilized by DMM columns (e.g. Balaam and Poulos 1983, Alamgir et al. 1996, Ravaska and Kujala 1996, Kivelo 1998, Baker 1999, Kaiqiu 2000, and Han and Gabr 2002). The FEM provides a good mathematical model for interaction between the columns, the unstabilized soil and the embankment at working load and even when the failure is approached. As known, there are many factors which affect the soil arching. It is not feasible to examine all of them in the field trial embankment study and in laboratory model tests due to economic efficiency. Thus The FEM has been considered as a convenient and reliable tool to use for this studying purpose.

Due to the complexity of properties of soft soil, DMM columns, embankment fill affected on the behavior of soft soil foundation, thus in this section the parameters related to modulus of embankment fill, the stiffness of the column and unstabilized soil around the columns, relative stiffness ratio between column and untreated soil E_{col}/E_{soil}, the height of embankment fill, and replacement area ratio would be focused to investigate. Results are presented as a discussion related to how each of these factors would influence to SRR.

Table 1: A summary of functions used to calculate the stress reduction ratio

Method	Stress reduction ratio (SRR)	Reference
BS8006 Method	$\mathrm{SRR} = \frac{2\cdot s\cdot(\gamma H + q)(s-a)}{(s^2-a^2)^2\cdot\gamma H}\cdot\left[s^2 - a^2\left(\frac{p_c'}{\gamma H}\right)\right]$ for $H \le 1.4(s-a)$ $\mathrm{SRR} = \frac{2.8\cdot s}{(s+a)^2\cdot H}\cdot\left[s^2 - a^2\left(\frac{p_c'}{\gamma H}\right)\right]$ for $H > 1.4(s-a)$ $\frac{p_c'}{\gamma H} = \left(\frac{C_c a}{H}\right)^2$	BS8006 (1995)
Adapted Terzaghi's Method	$\mathrm{SRR} = \frac{(s^2-a^2)}{4\cdot H\cdot a\cdot K\cdot\tan\phi}\cdot\left\{1-\exp^{\left[\frac{-4\cdot H\cdot a\cdot K\cdot\tan\phi}{(s^2-a^2)}\right]}\right\}$	Russell and Pierpoint (1997)
Hewlett and Randolph Method	$\mathrm{SRR} = \frac{1}{\left(\frac{2K_p}{K_p+1}\right)\left[\left(1-\frac{a}{s}\right)^{(1-K_p)} - \left(1-\frac{a}{s}\right)\cdot\left(1+\frac{a}{s}\cdot K_p\right)\right] + \left(1-\frac{a^2}{s^2}\right)}$	Hewlett and Randolph (1988)
Low's Method	$\mathrm{SRR} = \frac{(K_p-1)(1-\delta)s}{2H\cdot(K_p-2)} + (1-\delta)^{(K_p-1)}\left[1-\frac{s}{2H}-\frac{s}{2H(K_p-2)}\right]$	Low et al. (1994)
Adapted Guido Method	$\mathrm{SRR} = \frac{s-a}{3\cdot\sqrt{2}\cdot H}$	Guido et al. (1987)
Carlsson Method	$\mathrm{SRR} = \frac{s-a}{4\cdot H\cdot\tan 15°}$	
Swedish practice method	$CSR = \frac{1}{a_s + \frac{E_{soil}}{E_{col}}(1-a_s)}$ $\mathrm{SRR} = \frac{E_{soil}}{[E_{col}a_s + E_{soil}(1-a_s)]}$	Kivelo (1998)

where H = embankment height, γ = unit weight of embankment fill, q = surcharge load

s = center-to-center spacing of the columns, a = width of columns

C_c = arching coefficient, which is dependent upon the height of the fill, the width of the pile caps, and the rigidity of the piles. These conditions are prescribed as follows:

- for non-yielding piles, such as steel or concrete columns founded on an incompressible stratum, C_c= 1.95 (H/a) – 0.18
- for steel or concrete friction piles, or timber piles, C_c= 1.70 (H/a) – 0.12
- for stone columns, lime columns, and sand compaction columns, C_c= 1.5 (H/a) – 0.07

ϕ' = angle of friction of the embankment fill, K = coefficient of later earth pressure = 1

$K_p = \frac{1+\sin\phi'}{1-\sin\phi}$: Rankine coefficient of passive earth pressure, $\delta = \frac{a}{s}$

E_{col} = modulus of elasticity of the column

E_{soil} = modulus of elasticity of the unstabilized soil surrounding the column

4 DESCRIPTION OF MODELING

In fact, the columns were ususally arranged in a rectangular or triangular grid pattern in practice. The rectangular grid pattern as shown in Figure 3a has been selected in analysis herein for demonstrating the mechanisms of the problem. To simplify the analysis, each single column is considered as having an effective equivalent circle (or cylindrical column in the three-dimensional view) with the contributory plane area was used to change into a circle. The equivalent diameter of the circle is

$D_e = 1.13\,S$ (14)

Where D_e is diameter of the equivalent area circle; and S is the column spacing from centre to centre.

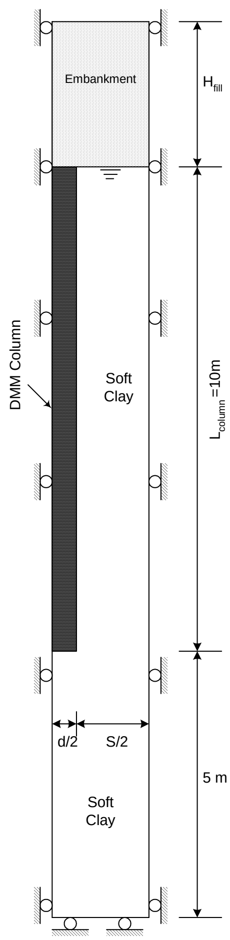

Fig. 4 Analysis model

The geometry of the model and the boundary conditions are shown in Figure 4. The left vertical boundary represents the axis of symmetry of the model. Column spacing is determined basing on the area replacement ratio, a_s, of DMM column. In this study, five of replacement ratio conducted for analysis are 4.5%, 9%, 18%, 36%, and 56% corresponding to the equivalent diameter of the circle in the model are 2.8, 2, 1.4, 1, and 0.8 m, respectively. The column with 10 m length 0.6 m in diameter does not penetrate fully the 15 m thick soft clay layer. The height of embankment fill is varied to study its effect on the degree of soil arching. The ground water table is assumed to be coincident with the elevation of column head. After loading, the consolidated process of subsoils and DMM column were performed until the pore pressure is completely dissipated.

FEM presented by the Plaxis program was used to numerically analyze the problem. The Mohr-Columb failure criterion has been used to model the behaviour of column, untreated soft clay, and the embankment. It is assumed that the interaction between column and soft soil surrounding the sides of column is completed and thus no interface elements were used along the column in analysis.

The undrained behavior of material is assumed to use in this study because of low permeability of DMM column material and soft soil. The elastic modulus of DMM column and soft clay was chosen based on the ratio of two this modulus ranged from 10 to 200 (Kivelo, 1998). The initial stresses of the soft soil were established using gravity forces and the earth pressure coefficient, $K_o=1-\sin\phi$ (based on Jaky's formula) was adopted. All parameters of materials investigated for the base case and comparison cases in the analysis are summarized in Table 2.

Table 2: Materials parameters used for analyses.

Item	Properties	Base Case	Comparison Cases
Emb. Fill	Model	MC	NA
	γ (kN/m^3)	18	NA
	c (kPa)	10	NA
	ϕ (^{o})	25	NA
	E_{fill} (Mpa)	4	2, 4, 8, 12,15
	ν	0.3	NA
	H_{fill} (m)	3	1, 2, 3, 5, 7
	$k_v=k_h$ (m/sec)	10^{-9}	NA
Soft Soil	Model	MC	NA
	γ (kN/m^3)	16	NA
	c_u (kPa)	10	NA
	ϕ_u (^{o})	0	NA
	E_{soil} (Mpa)	1.5	0.5, 1, 1.5, 2
	ν	0.495	NA
	H_{soil} (m)	15	NA
	$k_v=k_h$ (m/sec)	10^{-9}	NA
Column	Model	MC	NA
	$\gamma_{.col}$ (kN/m^3)	17	NA
	c (kPa)	80	NA
	ϕ (^{o})	35	NA
	E_{col} (Mpa)	50	15, 25, 50, 100, 150, 200
	D (m)	0.6	NA
	a_s (%)	8	4.5,9,18,36,56
	D_e (m)	2	2.8,2,1.4,1, 0.8
	ν	0.495	NA
	$k_v=k_h$ (m/sec)	10^{-10}	NA

In the parametric study, various parameters of model materials were changed around the base case in order to evaluate their effects on behavior of soft soils treated by DMM columns under embankment. For most cases, only one parameter is varied as plotted in the x axis, otherwise, more description is presented on the figures.

5 RESULTS OF ANALYSIS

5.1 Effect of the Modulus of Embankment Fill

A large number of FEM analyses were carried out to study the effect of the modulus of embankment fill on the behavior of embankment stabilized by DMM column. The E_{fill} values of 1, 2, 4, 8, 12, 15 Mpa were adopted in the analyses.

The variation of the differential maximum settlement, ΔS, which is determined after completing consolidation process, at the ground surface, defined as the settlement difference between the center of the column head and the surface of soft soil in mid column spacing, with the modulus of embankment fill is shown in Figure 5. The difference in the settlement between column and soft soil around the column results in the downdrag force added to the column due to the stress transfer from the surrounding soil to the column. It can be seen that ΔS tends to decrease as the fill modulus increases. The ΔS increase rapidly as the elastic modulus of embankment is smaller than 4 MPa. Beyond this value, the rate of increase of the rate of this increase in ΔS reduces slightly with increasing embankment modulus.

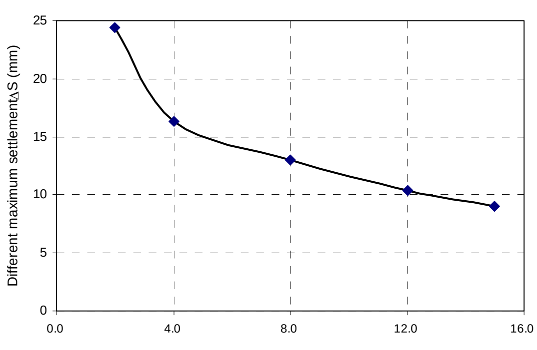

Figure 5. Influence of elastic modulus of embankment on ΔS

SRR decreases with the increasing E_{fill}, as illutrated through Fig. 6. This is explained by the reason that higher fill modulus, the higher shear resistance of embankment would be achieved, and thus a stronger arching effect is established. SRR also decreases with increasing consolidation time, and obtains the smallest value at the end of consolidation time for all of E_{fill} cases. This can be seen in Fig. 7.

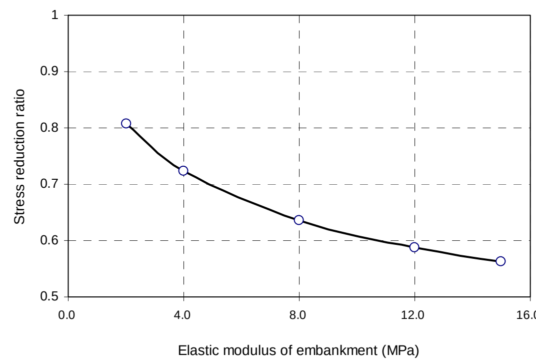

Figure 6. Influence of elastic modulus of embankment fill on stress reduction ratio

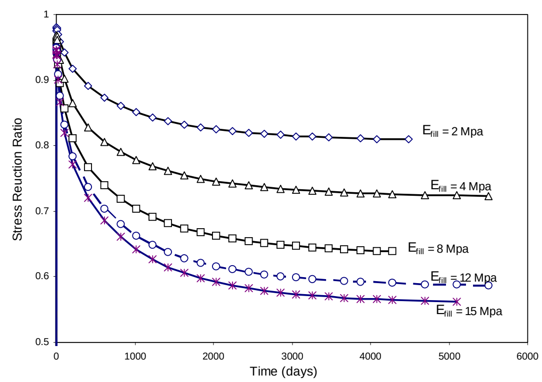

Figure 7. Time soil stress reduction for various elastic moduli of embankment fill

5.2 Effect of the young modulus of DMM columns and soft soil

The undrained secent modulus of elasticity of the column, E_{50}, is usually related with its unconfined compressive strength by using the ratio of E_{50}/q_u. Generally, this ratio varied in wide range depending on many factors. The modulus of DMM column is ranged from 15 MPa to 200 Mpa corresponding to the variation of typical design unconfined compressive strength is from 100 kPa to 150 Kpa. The modulus of DMM column E_{col} of 15, 25, 50, 100, 150, 200 Mpa is chosen more detail in this investigation.

As shown in Fig. 8, the differential maximum settlements, ΔS, at the elevation of column head increase with an increase of the elastic modulus of DMM column and with a decrease of elastic modulus of soft soil. This increase trend can be explained by the modulus different between the DMM column and the soil materials. The larger modulus difference promotes more different settlement. After the elastic modulus of column exceeds 100 Mpa, variation of ΔS with the column modulus becomes insignificant.

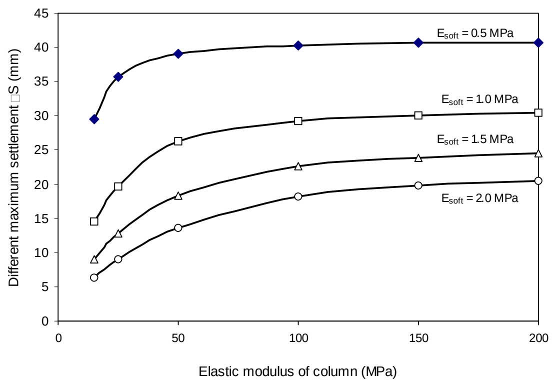

Figure 8. Influence of elastic modulus of column and soft soil on ΔS

The influence of elastic modulus of columns on SRR is evaluated and represented in Fig. 9. It can be seen that SRR decrease with decreasing elastic modulus of soft soil. When E_{col} exceed 100 Mpa, the decrease in SRR and becomes insignificant

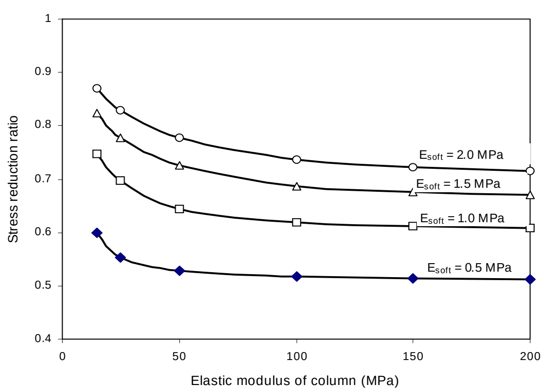

Figure 9. Influence of elastic modulus of column and soft soil on stress reduction ratio

Figure 10 shows the relationship of SCR and E_{col} / E_{soil} ratio, for area replacement ratio of 9%, obtained from this numerical analysis and from calculated function suggested in Sweden.

It can be seen from this comparison that the numerical analysis results has the same tendency to results suggested in Swedish. The SCR increase with increasing E_{col} / E_{soil} ratio, and when the modular ratio exceeds about 100, the effect of this ratio to SCR becomes minor. However, there is a large difference in SCR between results obtained from numerical analysis and calculated results. This difference can be explained due to SCR depending not only on E_{col} / E_{soil} ratio and a_s as proposed equation in Sweden, but also on many different factors such as properties of embankment fill, height of embankment fill, properties of soft soil and geotextile etc.

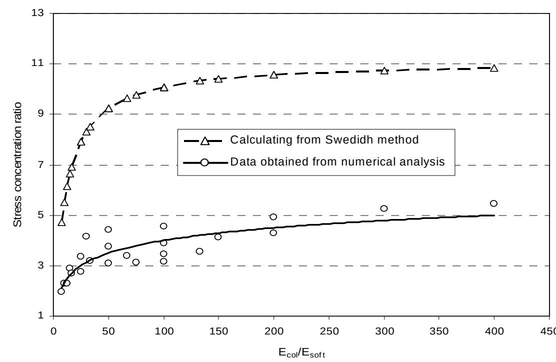

Figure 10. Numerical analysis results compared with results from Swedish

5.3 Effect of the height of embankment fill

The influence of height of embankment on differential maximum settlements at the ground surface is shown in Figure 11. Five different embankment heights H_{fill} of 1, 2, 3, 5, and 7 m have been considered. It can be seen from this figure that the differential maximum settlement at the elevation of the pile head increases with the height of the embankment fill.

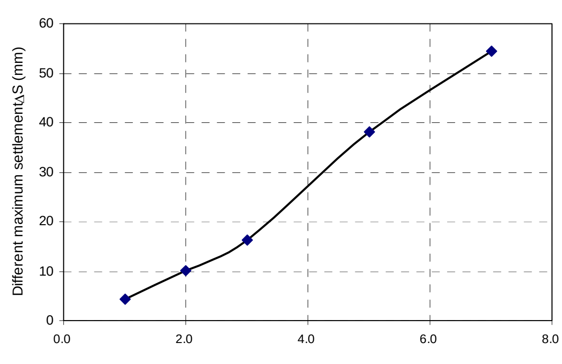

Figure 11. Influence of height of embankment fill on ΔS

Observations on the relation curves between SRR and height of embankment calculated from different methods as well as from numerical analysis, as presented in Fig. 12, it can be seen that SRR reduces with increasing height of embankment. Compared to calculated methods as indicated in Table 1, the reduction of stress reduction ratio with height of embankment gotten from numerical analyzed data is very small. This seems to be the same as calculations indicated from Hewlett and Randolph's method. The largest variation of SRR with height of embankment is observed in Low's method which also give the highest value of SRR, while lowest SRR is found in the Carlsson's method which is similar to Guido' method.

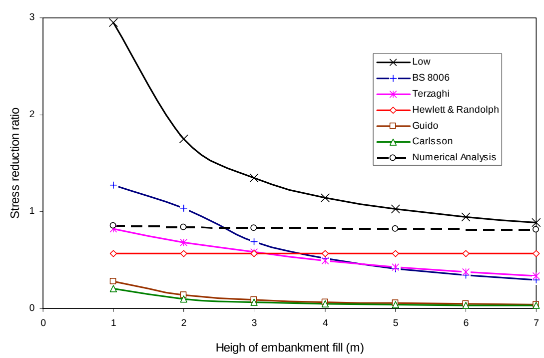

Figure 12. The variation of SRR with height of embankment for different methods

5.4 Effect of Area Replacement Ratio

Column spacing generally increased with increasing column diameter is determined basing on the area replacement ratio, a_s, which is usually larger than for rigid column but smaller than for sand or stone column. In this study, the series of replacement ratio conducted for analysis are 4.5 %, 9%, 18%, 36%, and 56% corresponding to the equivalent diameter of the circle in the model are 2.8, 2, 1.4, 1, and 0.8 m, respectively.

As indicated in Fig. 13, a lower area replacement results in a larger differential maximum settlement between soil and columns. The rate of increase of ΔS reduces as a_s increases. For a_s value between 4.5 % and 56 %, ΔS varies between 29.06 to 1.62 mm.

The relationship between SRR and a_s obtained from numerical analysis is plotted in dashed line as shown in Fig. 14. A comparison between numerical analysis with calculated results is also included in Fig. 14. Generally, trend of relationship between SRR and a_s obtained from the FEM analysis is consistent with that from theory equations. However, there a large variation of SRR calculated from different methods. The Hewlett and Randolph and the Terzaghi's methods indicated similar values of stress reduction ratio. Similarly, The Guido's and Carlsson's methods also provide very similar results that are lower than those from the other methods. The variation of SRR in Low's method is largest, while BS 8006 method most provides higher SRR compared to other methods. Results of SRR obtained from numerical analysis indicated a relatively higher value of SRR than other methods. Nevertheless, as seen in aforementioned analyses, SRR is not only dependent on a_s but also on many different factors which were not considered and included sufficiently in indicated in Table 1 about the effect of soil arching to vertical stress distribution. Therefore, the relationship curve between SRR and a_s may change when the different influenced factors are also varied.

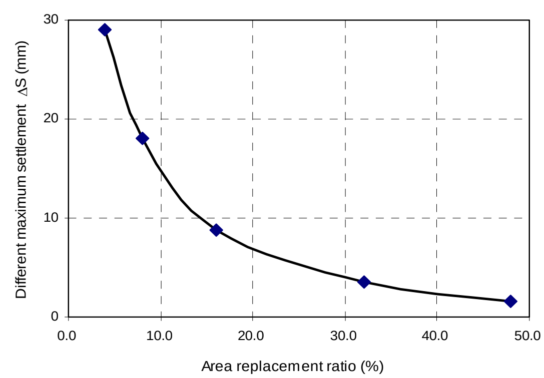

Figure 13. Influence a_s on ΔS

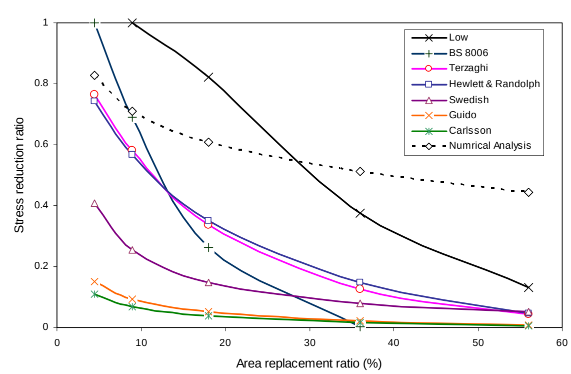

Figure 14. Influence of a_s on SRR

6. CONCLUSIONS

With supporting of powerful FEM tool in this study, it can be realized that the vertical stress distribution as well as the different settlement between column and soft soil surrounding the column is dependent on many parameters which had not yet considered and included sufficiently in researches. The influence of vertical stress distribution and different settlement of embankment stabilized by DMM column in soft soil foundation are most generally explained based on the mechanism of soil arching that takes place when there are a difference in stiffness between column and soft soil around the column.

From analysis data which obtained from this numerical study, two following conclusions also given as follows:

1. The differential maximum settlement, ΔS, decreases with increasing elastic modulus of embankment fill, with decreasing elastic modulus of column, with increasing tension modulus of geotextile, with decreasing height of embankment fill, and with increasing area replacement ratio.
2. The stress reduction ratio, SRR, decrease with an increase of the elastic modulus of embankment fill, of the elastic modulus of column, of the height of embankment fill, and it decrease with decreasing area replacement ratio.

REFERENCES

1. Alamgir, M., Miura, N., Poorrooshasb, H. B., and Madhaw, M. R. (1996). "Deformation Analysis of Soft ground Reinforced by Columnar Inclusions" *Computer and Geotechnics*, Vol. 18, 267-290.
2. Baker, S. (1999). "Numerical Analysis of Load Distribution Between Lime/Cement Columns and Surrounding Soil Using Finite Element Method." *Int. Conf. on Dry Mix Methods for Deep Soil Stabilization,* Brendenberg, Holm & Broms. Balkema, Rotterdam, 215-220
3. Balaam, N. P., and Poulos, H. G. (1983). "The behaviour of Foundations Supported by Clay Stabilized by Stone Columns." *Proc. 8th, Euro. Conf. On Soil Mech. And Found. Engng.,* Helsinki, Vol. 3, 199-204.
4. British Standard BS8006. (1995). *British Standard, Code of practice for: Strengthened/reinforced soils and other fills*.
5. Guido, V. A., Knueppel, J. D. and Sweeny, M. A. (1987). Plate Loading Tests on Geogrid-Reinforced Earth Slabs. *Geosynthetic '87 Conference* New Orleans, 216-25.
6. Han, J., Gabr, M. A. (2002). "Numerical Analysis of Geosynthetic-Reinforced and Pile-Supported Earth Platforms over Soft Soil" *Journal of Geotechnical and Geoenviromental Engineering*, ASCE, Vol. 128, No. 1, 44-53
7. Hewlett, W. J. and Randolph, M. F. (1988). Analysis of piled embankments. *Ground Engineering* 21, no. 3, 12-18.
8. Huat, B. B. K., Craig, W. H. and Ali, P. (1994) The Mechanics of Piled Embankment. *Proc., Int. Conf. on Design and Construction of Deep Foundations,* 1069-82.
9. Kaiqiu, L. (2000) Behaviour of DCM Columns under Highway Embankment at Bridge Approaches. *Thesis for the Degree of Doctor of Philosophy, Nanyang Technical University*.
10. Kivelo, M. (1998). "Stabilization of embankments on soft soil with lime/cement columns." Doctoral Thesis, Royal Institute of Technology
11. Low, B. K., Tang, S. K. and Choa, V. (1994). Arching in piled embankments. *Journal of Geotechnical Engineering* 120, 1917-38.
12. Ooi, T. A., Chan, S. F. and Wong, S. N. (1987). Design, Construction, and Performance of Pile Supported Embankments. *9th Southeast Asian Geotechnical Conference,* 2-1 to 2-12.
13. Ravaska, O., Kujala, K. (1996). "Settlement Calculation of Deep Stabilized Peat and Clay." G*routing and Deep Mixing*, Balkema, Rotterdam, 551-555.
14. Reid, W. M. and Buchanan, N. W. (1984). Bridge approach support piling. *Piling and Ground Treatment,* Thomas Telford, London, 267-74.
15. Russell, D. and Pierpoint, N. (1997). An assessment of design methods for piled embankments. *Ground Engineering* 30, 39-44.
16. Terzaghi, K., Peck, R.B., and Mesri, G. (1996). *Soil Mechanics in Engineering Practice*. John Wiley & Sons, Inc.