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SLOPE STABILITY ANALYSIS OF EMBANKMENT OVER STONE COLUMN IMPROVED GROUND

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Abstract

Two-dimensional (2D) limit equilibrium analyses were conducted in this research to predict the factor of safety (FS) against the circular failure of embankments supported by stone columns improved ground. The analyses were based on equivalent area method. In this method, the treated zone, which comprises of the soft soils and the stone columns are replaced by an equivalent homogeneous soil with equivalent properties. The equivalent properties such as cohesion, friction angle and unit weight for the treated zone were calculated based on the weighted average of the properties of stone columns and soft soils. The influencing factors affecting the stability of embankment over the stone column improved ground were examined. These include the cohesion of soft clay, area replacement ratio, friction angle of stone columns, the height of embankment fill, the slope angle of embankment and stone column length. The limit equilibrium analyses were performed using the excel spreadsheet developed with the capability to identify the critical slip surface and the corresponding factor of safety calculated by Simplified Bishop Method. The accuracy of this limit equilibrium analysis was validated with three-dimensional finite element program (PLAXIS 3D) where good agreement was obtained in terms of location of slip circle and the factor of safety. The results showed that the embankment height was the most influencing factors in the safety analysis of the embankment while the least influencing factor was the friction angle of stone columns.

Keywords: Embankment, Finite element analysis, Limit equilibrium analysis, Slope stability, Stone columns.

1. Introduction

Construction of earth embankment over soft clay faces few geotechnical challenges such as large consolidation settlements, differential settlements, and slope failure. To tackle these problems, ground improvement technique can be adopted, for example, stone columns, soil-cement columns, sand compaction columns, piled raft foundations, vacuum consolidation, and vertical drains. Among many solutions available, stone columns are commonly adopted and applied worldwide due to its ability to reduce settlements, increase the consolidation rate and increase the slope stability. The effectiveness of this ground improvement technique has been proven in many applications, particularly to support embankments [1-4].

Many studies have been carried out to study the behaviour of stone columns five decades ago. For examples, field studies [5-8], experimental studies [9-11], theoretical and analytical studies [12-14], and numerical studies [15-17]. Most of these studies focus on the settlement reduction and the load-carrying capacity of stone columns. There are insufficient studies on the performance of stone column in resisting slope failure especially when the column length is short where the floating system is used.

Conventional slope stability analysis adopts the 2D Limit Equilibrium Method (LEM) to search for the critical slip surface and the associated factor of safety. It is normally done with the help of a spreadsheet or software. The equivalent area method is commonly adopted for the composite soils (matrix of soil and column) with equivalent parameters.

The homogenization of the soil and the columns into a matrix ignores the individual column effect and the soil-column interaction on the slope stability. Several studies have adopted equivalent area method in their analysis [18-20]. Based on a one-dimensional equal strain assumption, the equivalent parameters can be computed as follows:

$$c_{eq} = c_c \cdot \alpha + c_s (1 - \alpha) \tag{1}$$

$$\phi_{eq} = \tan^{-1}(\alpha \tan\phi_c + (1 - \alpha)\tan\phi_s) \tag{2}$$

$$\gamma_{eq} = \gamma_c \cdot \alpha + \gamma_s (1 - \alpha) \tag{3}$$

$$E_{eq} = E_c \cdot \alpha + E_s (1 - \alpha) \tag{4}$$

where E, c, ϕ, γ and α are elastic modulus, cohesion, friction angle, unit weight and area replacement ratio ($\alpha = A_c/A$; A_c = area of the column, A = total influence area) respectively. The subscripts *eq*, *c* and *s* in the equations represent the equivalent area (composite soil), column and soil respectively.

Christoulas et al. [2] examined the stability of stone columns supported embankment utilising Two-Dimensional (2D) limit equilibrium method with a circular slip surface. Two modelling methods were compared namely equivalent strip method (also named as a column-wall method in some literature) and equivalent area method.

Two conditions were adopted in the equivalent strip method: With and without considering stress concentration. The results showed that the computed factor of safety (FS) from the equivalent area method was almost identical to the value from the equivalent strip method for the case of ignoring stress concentration but smaller than the case of considering stress concentration.

A similar comparison was made by Abusharar and Han [21] but adopting a 2D finite difference method. However, their findings showed that the factor of safety obtained by the equivalent area method (ignoring stress concentration) is higher than those by the equivalent strip method. The authors proposed a reduction factor of 0.9 be used to convert the predicted FS by the equivalent area model to that by the equivalent strip model.

Zhang et al. [22] further compared these two methods using three-dimensional (3D) finite difference method. The equivalent strip method and the equivalent area method with consideration of stress concentration produced nearly identical results but slightly overestimated the FS as compared with the 3D numerical method. Therefore, the authors concluded that the stress concentration effect should not be considered in the stability analysis of the stone column-supported embankment.

The equivalent strip method is a better representation of the actual case as compared to the equivalent area method. However, the modelling of the method is more tedious and time-consuming, especially when a large group of columns is installed. On the other hand, the equivalent area method is well accepted by the practitioner due to the simplicity in modelling.

This study aimed to examine the accuracy of 2D LEM by comparing the results with those obtained from the 3D numerical method. Equivalent area method was used for LEM while individual columns are used in the 3D analysis.

Spreadsheet platform was used to perform the limit equilibrium analysis for stone columns supported embankment. The comparative study was made in terms of the location of the critical surface and the corresponding minimum factor of safety.

A parametric study was conducted to investigate the most influential parameters affecting the stability of the embankment. Six parameters were studied, which include area replacement ratio, the cohesion of soft clay, friction angle of stone columns, the height of embankment fill, the slope angle of embankment and stone column length.

2. Two-Dimensional Limit Equilibrium Analysis

2.1. Stone columns supported embankment

This study adopted a 2D problem of stone columns supported embankment from Zhang et al. [22] as the baseline case. Similar dimensions were used by Abusharar and Han [21] in 2D finite-difference study.

Figure 1 shows that the problem consists of an embankment founded on a stone column improved ground. The thickness of the soft clay is 10 m, above a 2 m thick sand layer. The stone column is 0.5 m in diameter with 1 m spacing to each other, thus, making the area replacement ratio, α of 0.2. The column is 10 m long and fully penetrated the soft clay. The height of the embankment is 5 m and the crest width of the embankment is 20 m (half of the width in Fig. 1).

The slope gradient is 2H:1V. No groundwater table was modelled. Table 1 shows the short-term properties of the materials.

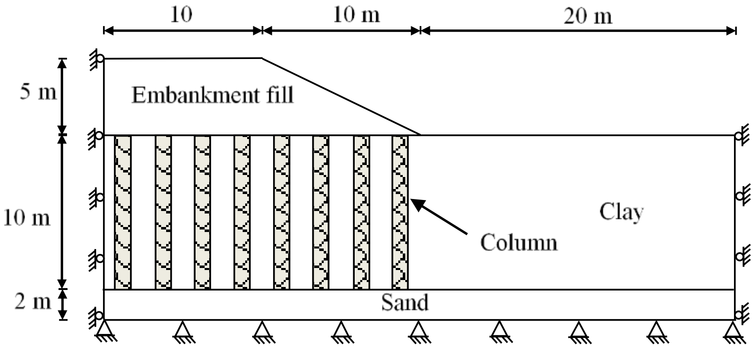


Fig. 1. Geometry of stone columns supported embankment.

Table 1. Materials properties of stone column supported embankment (adapted from Zhang et al. [22]).

Material	Type	γ (kN/m^3)	E' (MPa)	v'	c'/c_u (kN/m^2)	ϕ_c' (^{o})
Embankment	Drained	18	30	0.3’	10	32
Clay	Undrained	16	4	0.3	20	0
Sand	Drained	18	100	0.3	0	30
Stone column	Drained	17	40	0.3	0	38
Equivalent area	-	16.4	-	0.3	16	8.9

2.2. Computation of slip circles and factor of safety

Excel spreadsheet was developed to examine the short-term stability of an embankment supported by stone columns. For the LEM, Simplified Bishop Method, which satisfies both the force and moment equilibrium, was adopted in this study. The slope was divided into 20 slices. The equivalent area method was adopted for the composite soil where the equivalent parameters are obtained from Eqs. (1) to (3) grip search was performed to locate the critical slip circles and the corresponding minimum factor of safety. The tolerance for locating the critical slip surface by the convergence process is 0.0001, which is sufficiently accurate for the current study. The result obtained is shown in Fig. 2. Deep-seated failure is observed, and the factor of safety, FS of the embankment slope is 1.58.

The result of the above equivalent area method was validated by the 3D numerical method. 3D PLAXIS geotechnical software was used to conduct the analysis. Due to symmetry of the problem, a 1.0 m thick 3D slice (out of plane dimension) was modelled instead of a full 3D model to keep the computational effort within acceptable limits while having representative numbers of in situ stone columns. The model setup is presented in Fig. 3. The model boundaries are roller at the side and fixed at the bottom. The model consists of 42,252 10-node tetrahedral elements and 67,808 nodes. In the 3D finite element analyses, the embankment fill, the subsoil, and the stone columns were modelled as Mohr-Coulomb model. Undrained type (B) was chosen for soft soil due to low permeability while drained properties were used for other materials as column and embankment are made of high permeability material. The shear strength reduction technique was adopted to estimate the factor of safety.

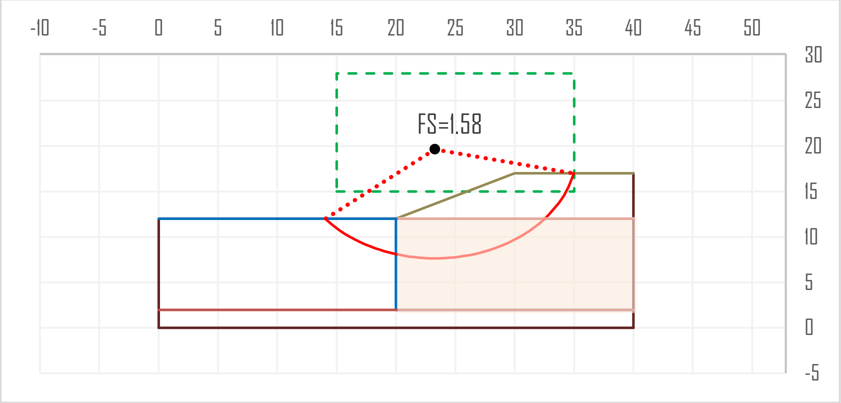


Fig. 2. Spreadsheet results for equivalent area method in LEM.

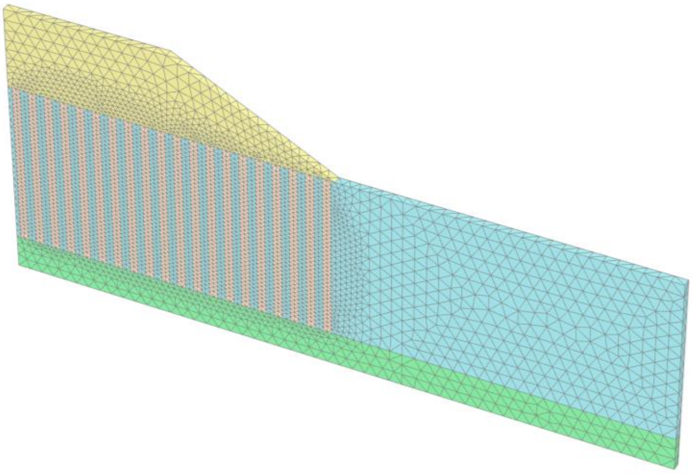


Fig. 3. Finite element model for baseline case.

The computed FS by 3D numerical analysis is 1.74, a ten percent difference compared with 2D LEM. A further comparison was made to Abusharar and Han [21] where 2D finite-difference analysis with equivalent area method was used. The factor of safety obtained was 1.70, about 7.6 percent higher compared to that of 2D LEM. Figure 4 shows the location of the slip surface (shear band) for 3D FEM. There are two slips surfaces observed for the embankment. First slip surface (more reddish colour indicates larger displacement) agreed well with the slip circles produced by 2D LEM while the second slip surface (dark blue colour indicates no movement) occurred deeper into the soil layer and appear to be more controlling.

A study was also conducted to predict the factor of safety for the embankment on the untreated ground. The FS of 1.24 was obtained for both 2D LEM and 3D FEM, with 27% and 36% increment respectively compared with an embankment on stone column improved ground. The failure mechanism of the test embankment is shown in Fig. 5. The location of the slip surface in 2D LEM falls between the two distinct shear bands in 3D FEM.

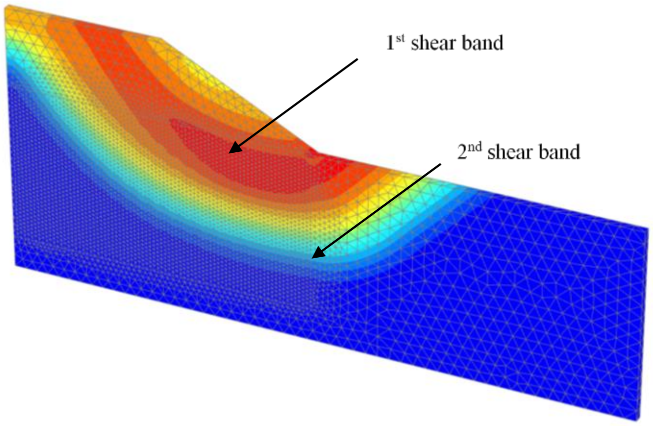


Fig. 4. Shading of total displacement increment in 3D finite element analysis.

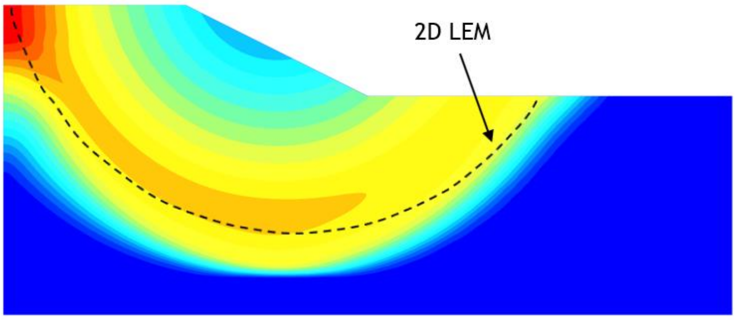


Fig. 5. Failure mechanism of embankment without stone columns.

3. Parametric Study

A parametric study was carried out to investigate the effect of parameters on the safety of the slope. The six parameters are the area replacement ratio, the undrained shear strength of soft soils, friction angle of stone columns, the embankment height (H), slope gradient (β), and column length (L). The ranges of each parameter are shown in Table 2. One parameter was altered from the baseline case each time to investigate the influence or the sensitivity of each parameter on the slope stability. The results are compared in terms of factor of safety.

Table 2. Parametric study.

Parameter	Values
α	0.1, 0.2*, 0.3, 0.4, 0.5
c_u (kPa)	10, 20*, 30, 40, 50, 75,100
ϕ_c' (°)	35, 38*, 41, 44, 47, 50
H (m)	1, 2, 3, 4, 5*
β	3:1, 2:1*, 1:1, 1:2, 1:3
L	4, 6, 8, 10*

*Baseline value

3.1. Effect of area replacement ratio

The typical value of area replacement ratio used in design practice is ranging from 0.1 to 0.4 for the large loaded area as in this case, while in the small loaded area, the ratio can be even higher, e.g., 0.6 to 0.7 [16, 20]. The results of the effect of area replacement ratio on the slope stability can be seen in Fig. 6. The factor of safety for the embankment increases as the area replacement ratio increases, in the linear form for 2D limit equilibrium method, while slightly non-linear for 3D finite element method. The increase is due to the increase in the overall stiffness of the treated ground. A similar finding was also reported by Zhang et al. [22]. In 2D LEM, when the area replacement ratio increases by 30% ($\alpha = 0.2 - 0.5$), the gain in FS is 43%. However, in 3D FEM, the gain in FS is slightly less, i.e., 24% for the same range. 2D LEM under predicted the FS for lower range ($\alpha = 0.1 - 0.3$) but over predicted when the area ratio is high, i.e., $\alpha = 0.5$ when compared with 3D FEM.

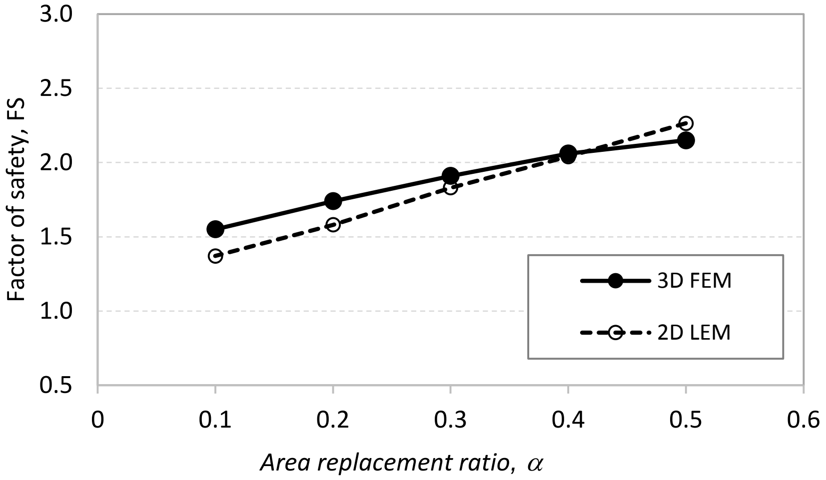


Fig. 6. Effect of area replacement ratio.

3.2. Effect of undrained shear strength

The effect of the undrained shear strength of the soft soil on the factors of safety is shown in Fig. 7. The FS increases when the undrained shear strength increases from 10 kN/m^2 to 40 kN/m^2 as a higher strength of soil gives better resistance to shearing. No increment is observed when the undrained shear strength is higher than 40 kN/m^2. Similar results obtained for both 2D LEM and 3D FEM albeit slightly conservative results were obtained for 2D LEM when the undrained shear strength is very low, i.e., $c_u \leq 20$ kPa, which is good when 2D LEM is used in the design practice for slope stability in soft soil.

The sudden change of trend is attributed to the change of slip surface in the failed embankment as shown in Fig. 8. When the undrained shear strength is larger than 50 kN/m^2, shallow slip surface with toe failure occurred at the embankment fill and it does not extend down to the soft soil, unlike when the undrained shear strength is small, the deep-seated failure was observed.

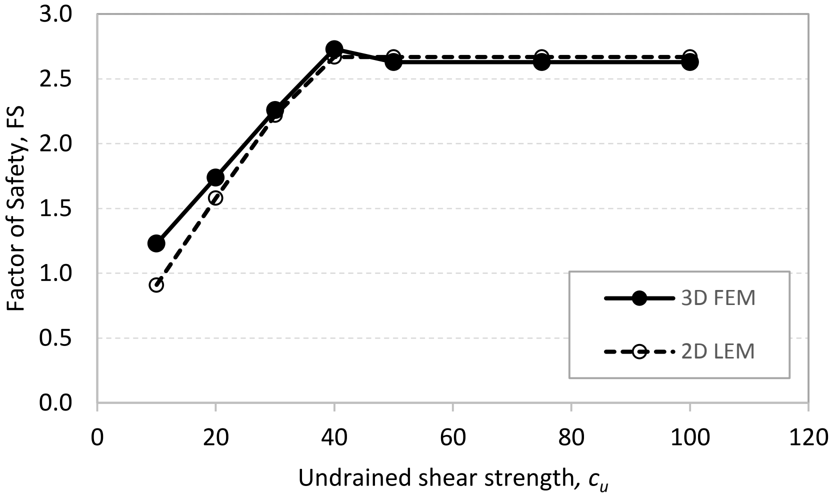
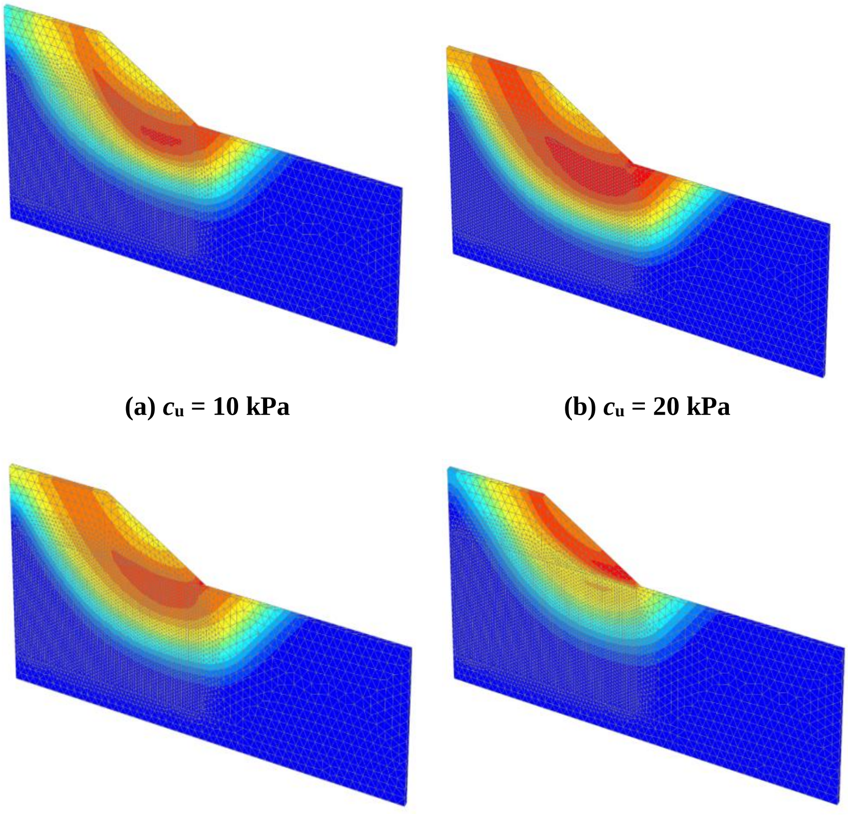


Fig. 7. Effect of undrained shear strength.

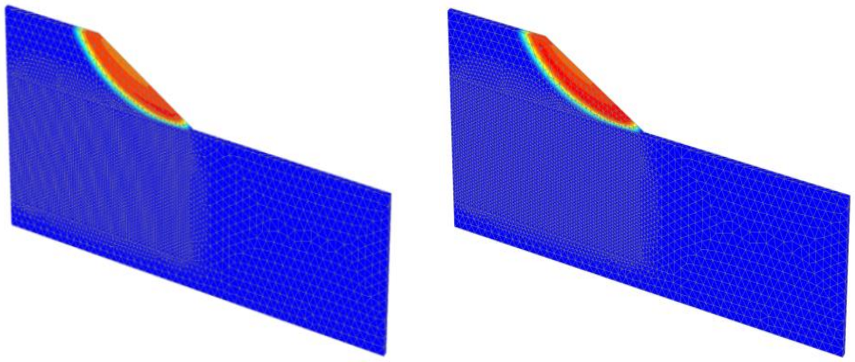


(a) c_u = 10 kPa

(b) c_u = 20 kPa

(c) c_u = 30 kPa

(d) c_u = 40 kPa



(e) c_u = 50 kPa **(f) c_u = 75 kPa**

Fig. 8. Slope failure mechanisms for different undrained shear strengths in 3D FEM.

3.3. Effect of stone column's friction angle

Figure 9 indicates the stability performance of the stone column supported embankment when the value of the column's friction angle increases. As the friction angle of the stone column increases, the factor of safety also increases slightly. Higher friction angle provides better resistance to shearing and thus, give better stability value. Even though the difference is small, the results in 3D FEM are generally higher than 2D LEM. The friction angle of stone column material is normally between 35° to 50° with a typical design value of 40°. Discretion should be exercised if the high friction angle is to be used as a design value because the achieved friction angle depends on the degree of stone compaction and the confining strength of the soil [23].

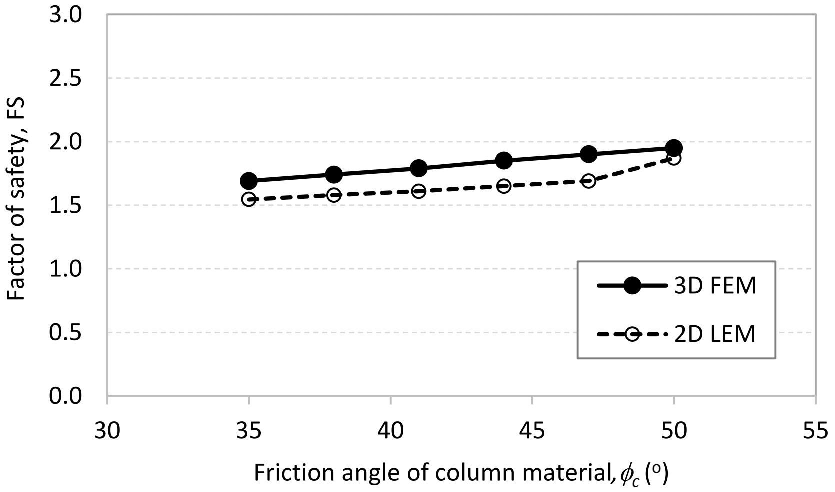


Fig. 9. Effect of stone column friction angle.

3.4. Effect of embankment height

Figure 10 shows the effect of the embankment height on the safety factor of the embankment supported by stone columns. Factor safety reduces rapidly as the height increases. The increase of the embankment height increases the loading to the foundation soils and thus, results in instability of the embankment.

The results of 3D FEM agree quite well with 2D LEM. A full-scaled test embankment on Bangkok soft clay was built rapidly to failure. The full height was only 3.4 m [24]. In another test site on Muar marine clay, the failure height was 5.4 m [25]. These two case studies show the critical height can be quite low for very soft soils.

In this study, the critical height of the embankment on the unimproved ground is 6.1 m while for improved ground, the embankment failed at the height of 9 m. These results are obtained from 2D LEM.

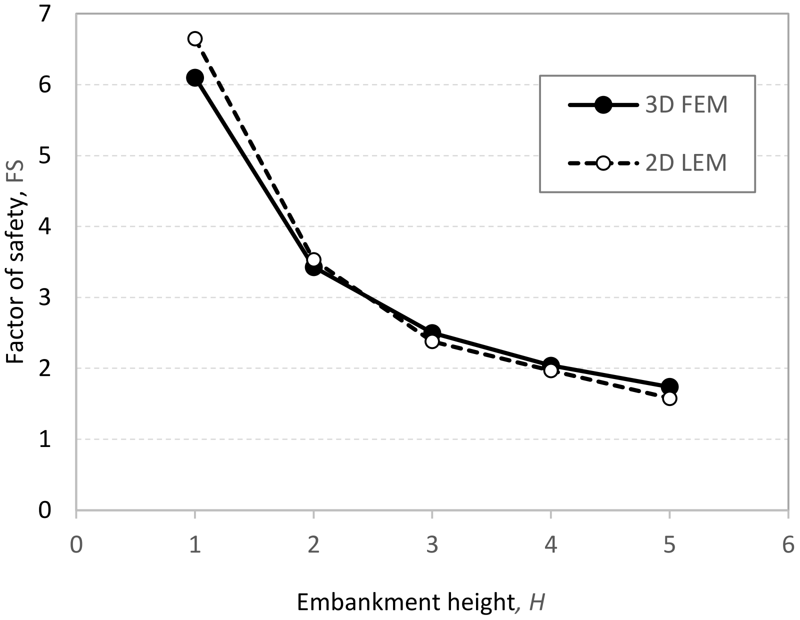


Fig. 10. Effect of embankment height.

3.5. Effect of slope gradient

Besides the embankment height, slope gradient also affects the stability of an embankment. It is intuitively correct that the FS reduces as the slope gradient increases, as shown in Fig. 11. However, as the slope gradient increases, the failure mechanism changes from deep-seated failure to shallow failure as seen in Fig. 12. The similar failure pattern was observed in 2D LEM as well.

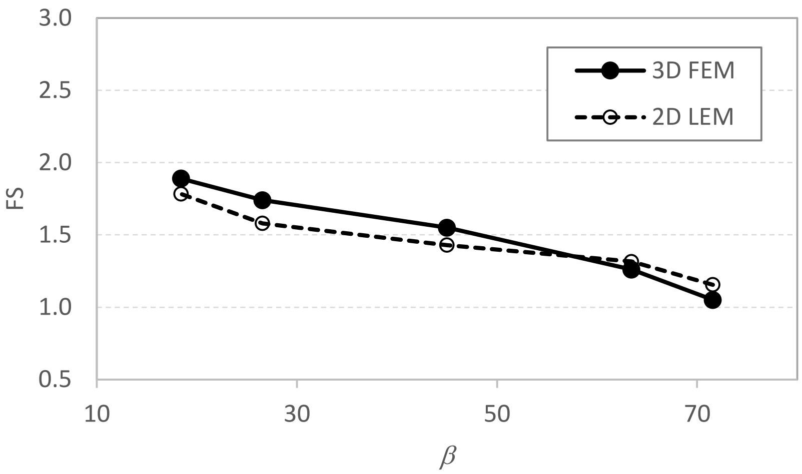
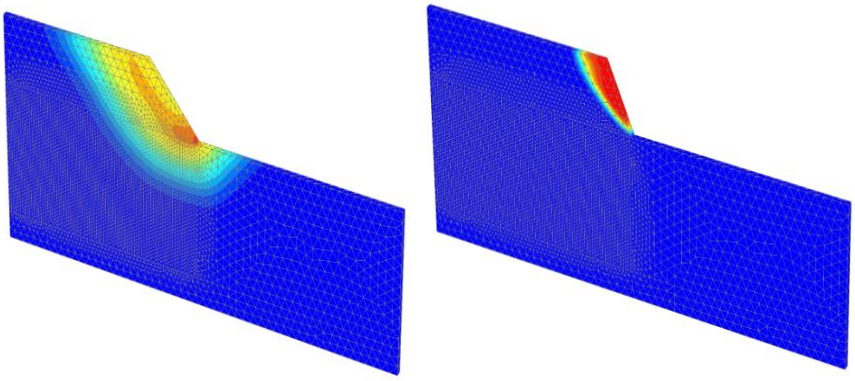


Fig. 11. Effect of slope gradient.



(a) β **= 1:1 m.** **(b)** β **= 2:1 m.**

Fig. 12. Slip surfaces for slope with different gradients in 3D FEM.

3.6. Effect of stone column length

Under widespread loading, fully penetrating columns have proven to result in a better settlement reduction compared to floating stone columns [26]. However, there is a knowledge gap in understanding the effect of column length on the slope stability of an embankment.

The results of this study show the reduction of FS as the column length reduces albeit small in the magnitude, as shown in Fig. 13. With every increment in 2 m, the improvement of stability is increased by a maximum of 12%.

This small improvement is attributed to the larger area of shearing in the improved ground as shown in Fig. 2 for 10 m length columns, compared to Fig. 14 for 6 m length columns. Figure 14 also shows the slip circles developed deeper into the soft layer as the column length reduces.

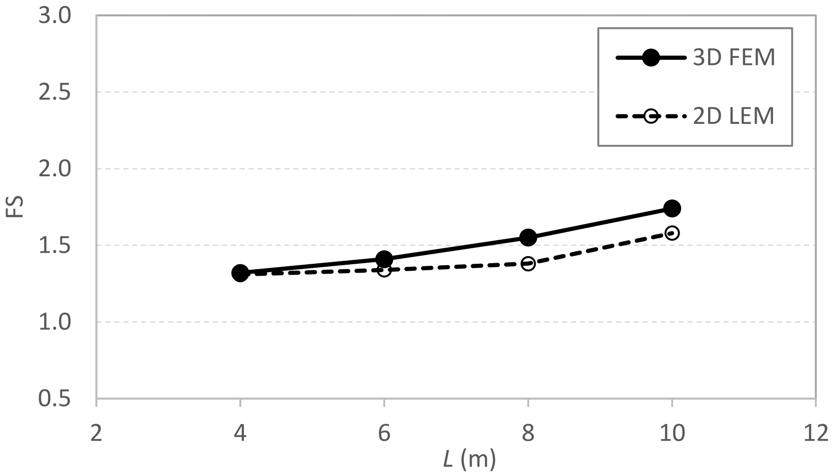


Fig. 13. Effect of column length.

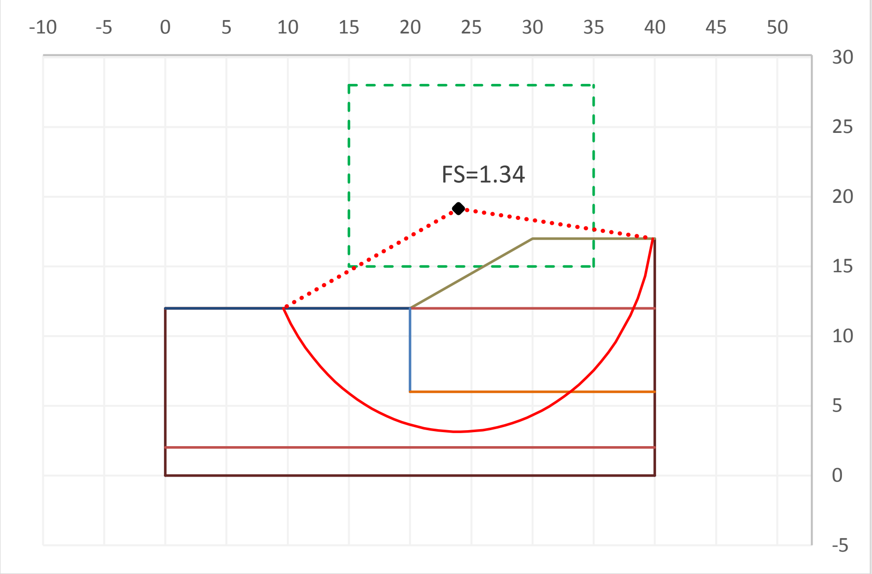


Fig. 14. Embankment supported by 6 m columns.

4. Conclusions

This paper studied the validity of 2D limit equilibrium method in predicting the slope stability performance of an embankment supported by stone columns by comparing it to 3D finite element method. A parametric study was carried out to investigate the effect of parameters on the stability. In general, 2D LEM is able to produce similar results as in 3D FEM in terms of factor of safety and failure modes despite the minor difference in details. Few conclusions can be made:

- In the baseline case comparison, 3D FEM produced slightly higher FS than 2D LEM for stone column supported embankment. On the other hand, the same

FS were obtained for the case with the unimproved ground for both 2D LEM and 3D FEM.

- 2D LEM can capture the change in failure type, i.e., base failure to toe failure when the geometry data changes.
- Unlike 3D FEM, 2D LEM could not produce multiple shear failure surfaces since the limit equilibrium method can only search for most critical failure surface.
- From the parametric study, the three most significant influencing parameters in determining the stability of embankment are the embankment height followed by the area replacement ratio and the undrained shear strength.
- The most insignificant parameters in stone column design for embankment is the friction angles of columns material as the improvement gained is the smallest among other influencing parameters.

The effect of the water table has not been studied in this paper and therefore, future works regarding the validity of 2D LEM can look into the effect of the water table. Besides, the effect of soil suction can also be incorporated in future studies.

Acknowledgement

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Nomenclatures

A	Total influence area, m^2
A_c	Area of column, m^2
c	Cohesion, kN/m^2
c_u	Undrained cohesion, kN/m^2
E	Elastic modulus, kN/m^2
E_c	Elastic modulus for column, kN/m^2
E_{eq}	Equivalent modulus for composite soil, kN/m^2
E_s	Elastic modulus for soil, kN/m^2
H	Embankment height, m
L	Column length, m
v'	Passion's ratio

Greek Symbols

α	Area replacement ratio
β	Slope gradient
γ	Unit weight, kN/m^3
ϕ	Friction angle, ^{o}
ϕ_c	Friction angle of column, ^{o}

Abbreviations

2D	Two-Dimensional
3D	Three-Dimensional
FS	Factor of Safety
LEM	Limit Equilibrium Method

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