Comparison of the effectiveness of Deep Soil Mix columns using 2-D and 3-D Plaxis

Hester Leung, Cristien Gani, Wataru Okada SKM Auckland
Sergei Terzaghi, SKM Sydney

Introduction

The purpose of this paper is to compare the behaviour of deep soil mixing columns predicted by Plaxis 2D and 3D programmes in terms of stresses acting in columns and calculated factor of safety (FoS). Deep soil mixing column has been used as one of the remedial solutions on slip repair works of state highways in the Northland region of New Zealand. Slope failure is common in Northland region due to the unique characteristic of the geology in this area and also the heavy rainfall experienced particularly in winter months. Prior to installing the deep soil mixing columns, the road had to be repaired regularly by smoothing of the pavement. A heavy rain event eventually caused sufficient significant damage to the road such that slope stabilisation work was considered necessary.

One such study was selected to both illustrate the repair method, integration with Plaxis, and also to illustrate the issues with the use of FE technology in routine design. Experience to date suggests that conventional limit equilibrium design was not capturing the field behaviour of the columns, and greater understanding of the real behaviour was needed. In this particular study, 2-D and 3-D Plaxis was used, as concerns were raised about the suitability of only two rows of columns in the design by the project reviewers. Field experience also indicates that the effectiveness of the columns is bounded. If columns are too close there is no further gain in overall strength, and too far apart, and the columns begin behaving individually with no net benefits. This paper illustrates some of these issues.

Slip Descriptions

Topography and Ground Condition

The slip discussed in this paper occurred in State Highway 11, Northland. It was a road slip which occurred in a section where the road has been constructed on a natural valley feature. The upper slope of the valley above the road is hummocky and shows a number of headscarp, creep and slump features. The area below the failure is highly vegetated with trees and bush, with the lower flanks of the valley also containing houses. Borehole logs indicate that the sub surface condition consist of soft to firm silty clay sandwiched between fine to coarse grained gravel and firm to stiff silty clay. Mudstone/sandstone forms the bedrock.

Failure Mechanism

Site observations suggest that the failure is likely to have resulted from a circular slip, which has probably been induced by saturation of the slope during a heavy rainfall event. Creep movement was noted below the toe of the slip, which would have contributed to the failure to some extent. A secondary deeper block failure was suspected to be responsible for the crack adjacent to the road centreline. The slip is approximately 50 m long in the longitudinal direction. Photographs of the slip are shown in Figures 1 and 2.

Deep Soil Mixing Column Assessment

Typically, geotechnical parameters used in the design are derived from laboratory test results of selected core samples collected during the site investigation. In some cases, geotechnical parameters are assessed from other site information based on the geology and site observation. An initial analysis is carried out to verify the geotechnical parameters used by simulating the actual slip failure in the model.

Figure 1. Slip on the shoulder of the road

Figure 2. Close up of the slip

Once the actual slope failure is successfully simulated, deep soil mixing columns are introduced into the model. The columns are modelled as soil using volume elements. Typically the design unconfined compressive strength of a deep soil mixing column is about 1.5 MPa. In reality, the achieved strength is much higher in most cases.

In 2D models, the column has been modelled using a replacement ratio method in the out of plane direction. The columns are modelled together with the surrounding soil as a block of composite material. This takes the column spacing into account by assigning appropriate average composite properties. The 3D model uses the design properties of the deep soil mixing column as input.

The columns are positioned in such a way that a block of improved soil bounded by the columns is created in the pavement and the slope below the road.

For the purpose of this paper, the slope is assumed to be dry. Adjustments have been made to the subsurface parameters such that the dry slope models have a pre-existing failure mechanism similar to the interpreted mechanism when taking groundwater into consideration. Two rows of 0.3 m by 0.3 m columns are installed and the lengths of the columns are 5.0 m and 6.0 m. Our research focus on the behaviour of columns for the

following scenarios:

- Variation on column spacing i.e. 0.6 m (2 diameter spacing), 2.5 m (8 diameter spacing) and 4.0 m (13 diameter spacing) in the longitudinal direction (parallel to road). The 2.5 m spacing is the practical maximum spacing we have adopted based on field observations of completed projects.
- The effect of soil model used in the assessment i.e. Mohr Coulomb Soil Model and Hardening Soil Model.

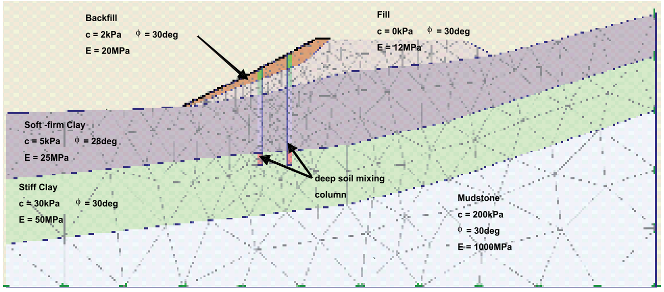

Figure 3. Cross section and parameters used in the model

Results

The output of Plaxis analysis for different scenarios with regard to factor of safety and shear stress acting in column are given in Tables 1 and 2 respectively. The factor of safety prior to columns installation is 1.1 and 1.2 as determined from 2D and 3D modelling respectively. Both models give a similar failure mechanism as shown in Figure 4.

The shear stress mobilised by the columns are determined from the deviatoric stress given in the Plaxis output. In 2D models, this needs to be converted to an equivalent shear stress as the columns have been modelled as a block of composite material instead of an individual column as in the case for 3D. The conversion is based on the assumptions that the shear stress taken by each column is proportional to the stiffness of surrounding soil and takes into consideration of column spacing. This aspect needs to be refined to maximise the effectiveness of the columns.

Table 1. Comparison of factor of safety using Plaxis 2D version 8.2 and Plaxis 3D Tunnel Programme

Column Spacing (m)	**Factor of Safety (FoS)**			
	Mohr Coulomb		**Hardening Soil Model**	
	2D	**3D**	**2D**	**3D**
Pre-existing Case	1.10	1.21	1.10	1.19
0.6	1.54	1.55	1.53	1.54
2.5	1.53	1.45	1.52	1.45
4.0	1.54	1.43	1.51	1.44

Table 2. Comparison of maximum shear acting in columns

Column Spacing (m)	**Maximum Shear Stress (kPa)**			
	Mohr Coulomb		**Hardening Soil Model**	
	2D	**3D**	**2D**	**3D**
0.6	142	70	111	64
2.5	326	73	252	54
4.0	388	70	287	50

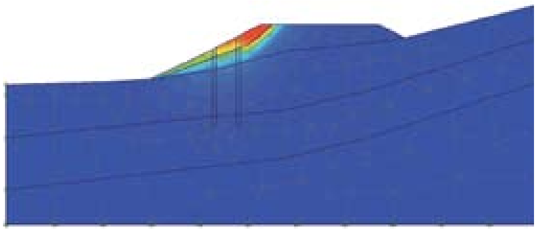

Figure 4. Failure Mechanism

Discussion

Factor of Safety

Table 1 indicates that the computed factor of safety in 3D models are lower than 2D models by 5% to 7%, however this is not reflected for model with the column spaced at 0.6 m. This is because on 3D model, the actual position of column is modelled whilst on 2D model the variation of column spacing is modelled by adjusting the composite column parameters, thus in 2D model the effect of stress distribution for different column spacing's have not been taken into account. Already we see the impact of the bounds noted above. For this problem a spacing of 2.5 m is the maximum, and probably a closer spacing would be more beneficial in reality.

No significant difference is noted in terms of soil model used in the analysis. Both the Mohr Coulomb Model and Hardening Soil Model give in similar results for this particular slip. This is possibly because the problem is modelled as dry thus the strength reduction (and consequent change in stiffness due to strain) due to groundwater has not been seen in the model which otherwise will be better represented by Hardening Soil Model.

Shear Stresses in Column

2D models show significantly higher shear stress compared to 3D model as shown in Table 2 above because the shear stress in 2D model is the equivalent shear stresses acting in columns which calculated using the equivalent stiffness assumption whereas the shear stress in 3D model is the actual stress determined from the finite element analysis.

Mohr Coulomb models show higher shear stresses in the column in comparison to Hardening Soil Model, if E of the Mohr Coulomb model is equal to E50ref of the Hardening Soil Model. However, the impact of the columns being stiffer than the surrounding soil modifies the stress regime and hence the actual stiffness, making the direct comparison more difficult.

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Continuation

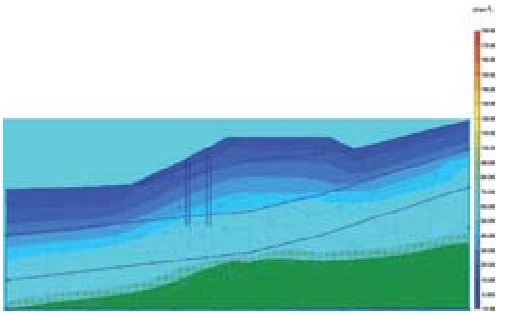

Figure 5. 2D output - Deviatoric stresses for column spacing at 2.5m – Hardening Soil Model

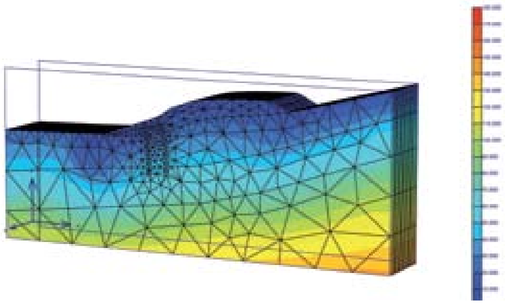

Figure 6. 3D output – Deviatoric Stresses for columns spacing at 2.5m – Hardening Soil Model

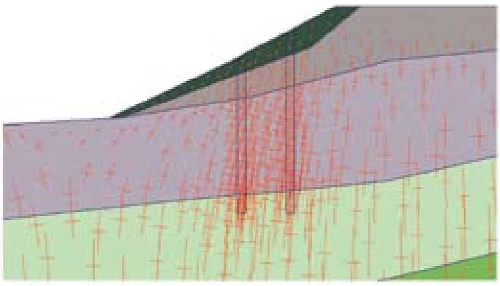

Figure 7. 3D Output - Principal stress direction prior to column installation – Mohr Coulomb Model

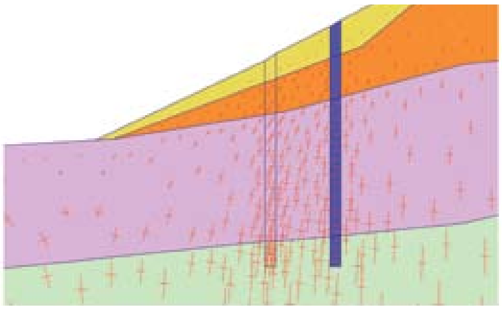

Figure 8. 3D Output - Principal stress direction for column spacing at 2.5m – Mohr Coulomb Model

Figures 5 and 6 show the deviatoric stresses distribution for 2.5 m column spacing with Hardening Soil Model. Figures 7 to 8 show principal stress direction prior and after installation of deep soil mixing.

Dry Slope versus Wet Slope

For the purpose of this paper, the slope is assumed dry. However, the parameters have been adjusted to simulate the condition where the ground water is approximately 2.0 m below road embankment.

Comparison between the modified dry model and the original saturated model confirms a similar failure mechanism on the embankment slope for both models. On the saturated model, a deeper secondary failure mechanism is noted. The reported factor of safety for both models however are the same since the main failure is on the slope.

It is noted that installing deep soil mixing columns have increased factor of safety by 20% to 40%.

Modelling versus Reality

The column spacing of 2.5 m was adopted in the final design. Whilst the factor of safety for the 2.5m spacing design appears the same as that of 4 m column spacing's in the 2D models, the calculated shear stress significantly increases between the 0.6 and 2.5 m spacing and then appears to level out suggesting that the 2.5 m spacing design appears to be close to the threshold spacing for group effect. However, the same impact was not noted in the 3D models on the shear stress, but rather on the factor of safety.

The deep soil mixing columns were constructed in November 2003. The remedial work has performed satisfactorily to date, and has undergone several events of heavy rainfall without developing any signs of further instability in support of the design adopted

Conclusions

This study clearly demonstrates the 3D effects of soil column interaction. For closer column spacings of 0.6 m (two column diameters), interaction becomes more dominant, and 2D and 3D results coincide. For more typical column spacing of 2 to 2.5 m, there are significant differences between the 2D and 3D models which need to be understood. At wider spacings, the 3-D effects dominate, and the 2-D results may not be reliable.

The key conclusion of this study is the need to understand the interaction of deep soil mixing columns with surrounding soil mass. Columns need to be designed so that they create an arching effect, and change stress distribution. Such change in stress distribution should be readily visible in model output, whether in 2D or 3D analyses, and should in most cases be reflected in computed factors of safety.

Field observations suggest 3D effects of column interaction play a key role in the field performance of deep soil mixing columns in road remedial work.