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Deformation Model of Deep Soil Mixing Using Finite Element Method

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Graphical abstract

Abstract

Soil improvement is required to decrease the construction impact on the adjacent underground structures, when a deep excavation is carried out. Deep soil mixing (DSM) is a common method to control deformation caused by deep excavation. This method is an in situ soil mixing technology that mixes existing soil with cementitious materials. This paper presents a numerical modeling of DSM columns, which was conducted to compare the affected zone achieved by installing two different partially penetrated soil-cement columns using a small scale physical modelling. Test procedure and the finite element analysis that verify ground displacement patterns were described. The finite element method (FEM) was focused on the plane strain numerical modeling in ABAQUS. It was found that higher numbers of piles increase the effect of soil deformation where it will extend the soil in much deeper depth before it fails.

Keywords: Deep soil mixing; deep excavation; finite element method; ABAQUS; displacement

Abstrak

Pembaikan tanah diperlukan untuk mengurangkan kesan pembinaan ke atas struktur bawah tanah bersebelahan, terutamanya penggalian yang dalam dibina. Pencampuran tanah dalam (DSM) ialah satu kaedah biasa untuk mengawal perubahan bentuk disebabkan oleh pengorekan dalam. Kaedah ini ialah teknologi pencampuran dalam tanah yang sedia ada dengan bahan-bahan bersimen. Kertas ini membentangkan model berangka lajur DSM, yang telah dijalankan untuk membandingkan zon dipengaruhi dicapai dengan memasang dua sebahagiannya menembusi ruangan tanah-simen yang berbeza menggunakan pemodelan fizikal kecil. Prosedur ujian dan analisis unsur terhingga yang mengesahkan corak anjakan tanah dinyatakan. Kaedah elemen terhingga (FEM) ini memberi tumpuan kepada pemodelan berangka terikan satah dalam ABAQUS. Adalah didapati bahawa nombor yang lebih tinggi buasir meningkatkan kesan ubah bentuk tanah di mana ia akan memanjangkan tanah di kedalaman lebih mendalam sebelum ia gagal.

Kata kunci: Pencampuran tanah dalam; penggalian dalam; kaedah unsur terhingga; ABAQUS; displacement

■1.0 INTRODUCTION

Ground improvement technologies such as compaction piles, stone columns, Deep soil mixing, and Cement grouting, jet grouting have been studied by researchers.[1-4]. Deep Mixing (DM) is a soil modification technique commonly employed to improve the bearing resistance of soft soil ground.[5] It is typically used for embankments on soft soils, foundation support, protection of excavation pits, stabilization of slopes, and reduction of liquefaction potential. Various failure modes of the improved soil ground installed by a DSM column group, e.g. shear, bending, tensile failures and rupture breaking have been documented according to ground soil properties, external loading and also the locations of each column.[6-8] It is clear that the failure pattern of the improved soil ground may be subjected to many factors. Nevertheless, there are still some factors which have not been identified. Therefore, numerical models are still worthy to explore the potential and unknown influencing factors that contribute to failure patterns of the improved soil ground.

Numerous research studies have been conducted to determine the effectiveness of using soil-cement for improving soil bearing capacity. The methods of approach include two- and three dimensional finite element simulation [9-11] and small to large scale model tests. However, a few attempts have been made to investigate the failure patterns of DSM with different ratio of improvement area, a_p and column strength, c_{uc} value. In this study, a series of 2D analysis using ABAQUS was conducted to validate physical tests performed by Rashid [12] on investigation of failure mechanism and column behaviour.

2.0 EXPERIMENTAL PROGRAM

Several physical tests were conducted to obtain the improvement of bearing capacity achieved by installing DSM columns.[12] In this regard, to prepare the model ground, Kaolin clay was utilized as a soil material and soil-cement columns were prepared using a mixture of ordinary portland cement (OPC). In these tests, a rigid box with 400 mm width, 150 mm length and 430 mm height was used. The height of the model and the diameter of the column were designed to be 200 mm and 23.5 mm respectively. The model was treated with 17.3%, 26.0% and 34.7% of improvement area ratio (a_p) of columns under a rigid footing.

Using the pneumatic piston, a consolidation stress was performed. In order to obtain a vertical stress (50 kPa), two drainages (in the top and bottom) were prepared to allow dissipation of excess pore water pressure. Subsequently, to provide a 200 mm high bed overconsolidation ratio (OCR) equal to 10 an average undrained shear strength equal to 6 kPa, the stress was decrease to 5 kPa.

A variable speed AC motor as well as worm gear configuration were mounted during loading to make strain-controlled loading capabilities. In the consolidation process, consolidation plate was instrumented with a displacement transducer to provide data, while the loading plate incorporated both a displacement transducer and a 2kN load cell. In front of the test system a Canon E05 350D digital camera was fixed to take photos for the displacement tracking process. Figure 1 shows a photo of the test apparatus.

A rigid footing with dimensions of 100 mm was utilized to investigate the performance of DSM method. These tests were conducted by utilizing a rigid footing in a rectangular pattern with 6, 9 and 12 columns respectively. In addition, a test was also carried out in untreated condition.

Close range photogrammetry and particle image velocimetry (PIV) were employed to observe the failure mechanism of the soil treated with the DSM (e.g. partially penetrated columns). PIV is a velocity-measuring procedure originally developed in the field of experimental fluid mechanics, and is reviewed by Adrian.[13] GeoPIV uses the principles of PIV to gather displacement data from sequences of digital images captured during geotechnical model and element tests. GeoPIV is a MATLAB module, which runs at the MATLAB command line. The development and performance of the software are described in detail by White [14] and Take.[15] Concise details are presented in White *et al*. works.[16, 17]

3.0 NUMERICAL DSM MODELS

This research investigates the effects of DSM on the soil deformation during certain pressure load and also under failure load. The column strength properties were based on the triaxial test conducted by Rashid.[12] Table 1 shows the soil and column properties used in these tests. In this study, only three tests out of all conducted tests by Rashid [12] were investigated.

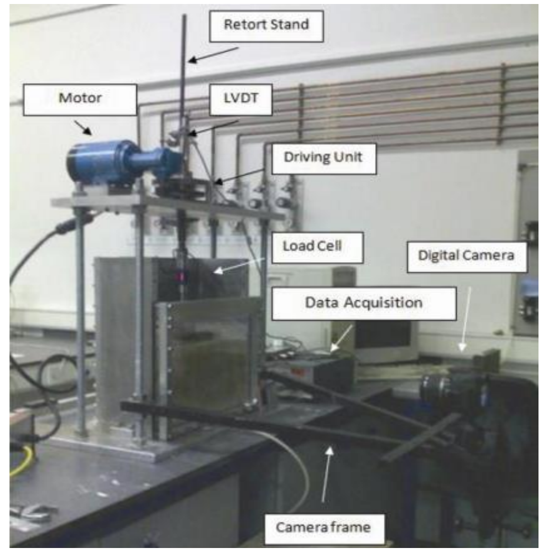

Figure 1 Photograph of the test system

They include one untreated test and two partially penetrated tests where a simple notation was used to represent the condition of the tests. Initially, a plane strain test was carried out in untreated soil with shallow foundation (Model 1). In this model, ground displacement under certain pressure load and failure load were modeled. Also, two other plane strain tests on the soft soil installed soil-cement columns with 17.3% and 26.0% improvement area ratio (Model 2 and 3, respectively) were performed to investigate surrounding soil movement.

The Finite Element Method (FEM) is a method of approximation the behavior of continua. In this numerical technique, the system is discretecized into many meshes or element, then the equability and compatibility of each element, and whole system will be examined.[18]

Several studies on structure/soil interaction involving soil deformations such as Liyanapathirana[19], Charbet[20] have been successfully modeled by ABAQUS. Charbet reported that the results obtained from the finite element analyses display good agreement with the experimental results for the bending failure mode of lime/cement columns. [20]

In this study, a finite element (FE) program (ABAQUS v.6.10.1)[21] was used to model FE analysis of three model tests (Model 1 to 3). By using the FE analysis, displacements of all points in untreated and treated soil models can be identified. The finite element mesh consisted of 1450 rectangular CPE8RP elements was utilized in the modelling as shown in Figure. 2. A uniform vertical pressure 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. A rigid foundation of width 100mm at the ground surface was modeled underlying soil for two dimensional analyses in the width direction. The elements are comprised of rectangular quadrilaterals for displacements coupled to 4-node rectangular quadrilaterals for pressures. The interaction between the footing and soil elements involves the transfer of contact pressure between the interacting surfaces.

The softening behaviour of the DCM column has been incorporated by employing Mohr-Columb constitutive model. The interaction between the shaft and soil elements involves the transfer of contact pressure and shear stresses due to friction between the interacting surfaces. The peak shear strength of the columns is mobilized at the same time as the peak shear strength of the unstabilized soil between the columns. This means that there is a full interaction between soil and columns. Failure is assumed to occur along a slip surface through the columns and the surrounding soil.

Mechanical contact properties consist of normal and tangential behaviors and have to be defined in order to be used with contact pairs.[22] Normal behavior interaction is specified as a contact pressure overclosure relationship. This surface interaction behaviour, which referred to as "hard" contact, is the default pressure-overclosure relationship in ABAQUS. The column-soil interface was modeled using the tangential behavior penalty-type Coulomb's frictional model. The soil was modeled as an isotropic elastic-perfectly plastic continuum with failure described by the Mohr-Coulomb yield criterion. The elastic behavior was defined by Poisson's ratio, ν, and Young's modulus, E. The plastic behavior was defined by the residual angle of internal friction, ϕ, dilation angle, ψ, and the cohesion, c.

■4.0 RESULTS AND DISSCUSSION

The failure pattern of the soil surrounding the soil-cement column was generated using numerical analysis. Figure. 3 shows the cumulative vector displacement of the soil using ABAQUS 2D modeling. In this figure, ABAQUS 2D modeling (model 1) the shallow foundation was under certain pressure load. Failure mechanism is defined where velocity discontinuity line and soil mass above that undergoes unrestricted flow at failure in comparison to the rest of the soil mass.[23] Figure. 3 shows vector displacement which consist of vector direction for strip footing on clay soil (model 2) compared to the laboratory result by PIV analyses. It was found that the punch shear failure happened on clay soil. As it can be seen in Figure. 4, soil movement results by experiment are very similar to FE results and the extent of displacement was predicted quite well by ABAQUS software.

Figures 5 and 6 show the cumulative vector displacement of the treated soil (model 2 and 3) using ABAQUS. Based on these figures, soil movements in two cases are similar to each other and these movements were predicted well by ABAQUS software. For the partially penetrated case, in general, the columns at the centre of the footing (see Figure 7) were penetrated deeper straight into the soil. The software results showed similar column failure with the laboratory test where bending failure were observed on both columns edge.

The geometry of group pile input was done in two-dimensional view, and a homogenisation method was used in the ABAQUS 2D for the reinforced region. [24,25]

The homogenised of undrained shear strength, $c_{u,hom}$ and Young's Modulus, E_{hom} is configured by Equations 1 and 2:

$$c_{u\,hom} = (a_p \times c_{u,\,column}) + ((1 - a_p) \times c_{u,\,soil}) \quad (1)$$

$$E_{hom} = (a_p \times E_{column}) + ((1 - a_p) \times E_{soil}) \quad (2)$$

where $c_{u,\,column}$ and $c_{u,\,soil}$ are the undrained shear strength of column and soil respectively while E_{column} and E_{soil} are the Young's Modulus of the column and soil respectively.

The plateau was taken as the ultimate bearing capacity, q_{ult} of the untreated and treated soil. The average undrained shear strength of the soil, c_{us}, was used to obtain the bearing capacity factor, N_c for each case as shown in Equation 3.

$$N_c = \frac{q_{ult}}{c_{us}} \quad (3)$$

Table 1 Material properties for numerical analysis

Rashid [12]			
Test	**Model 1**	**Model 2**	**Model 3**
Soil		**Kaolin clay**	
Unit weight of soil below phreatic level, $\gamma_{saturated}$ (kN/m^3)	18.0	18.0	18.0
Young's modulus, E (kN/m^2)	4171	4171	4171
Poisson's ratio, ν	0.49	0.49	0.49
Cohesion at the top, c_{ref} (kN/m^2)	6.27	7.13	7.13
Cohesion at the bottom, c_{inc} (kN/m^2)	5.15	5.47	5.78
Soil-cement column		**Massive circular pile**	
Unit weight of soil below phreatic level, $\gamma_{saturated}$ (kN/m^3)	-	18.0	18.0
Young's modulus, E (kN/m^2)	-	13208	19089
Poisson's ratio, ν	-	0.4	0.4
Strength, c_{uc} (kN/m^2)	-	87.66	121.84

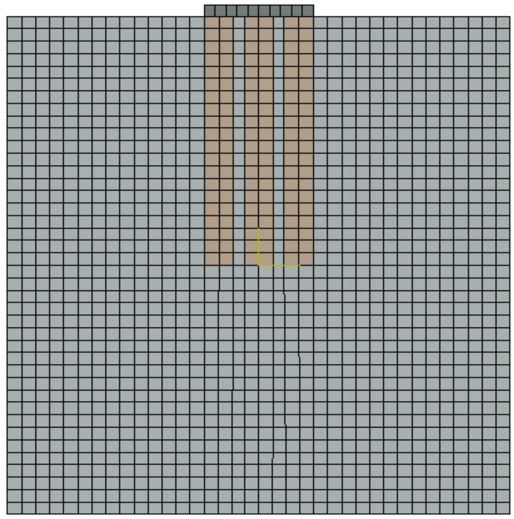

Figure 2 Finite element mesh for plane strain analysis, ABAQUS

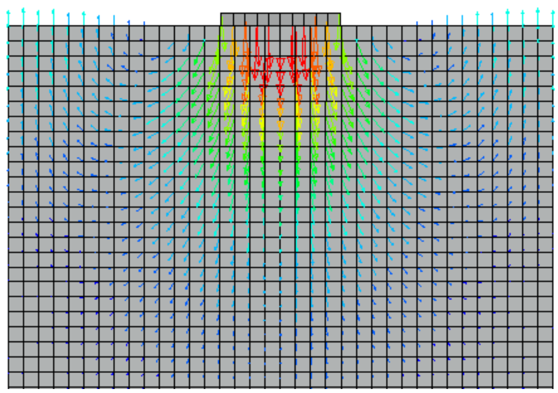

Figure 3 Ground displacement for Model 1, obtained by ABAQUS

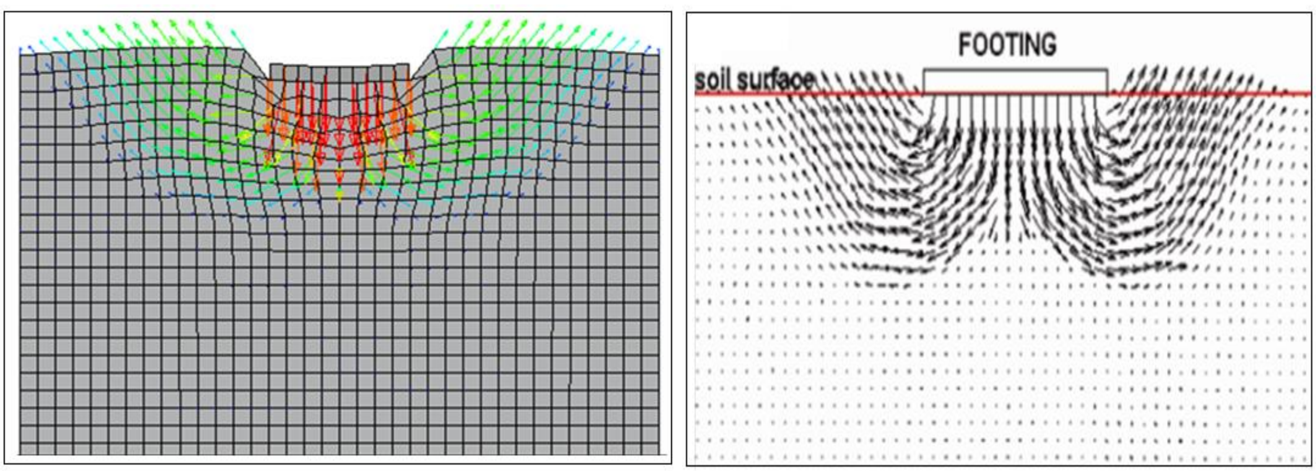

Figure 4 Failure zone for Model 1, obtained by (a) ABAQUS (b) GeoPIV analyses

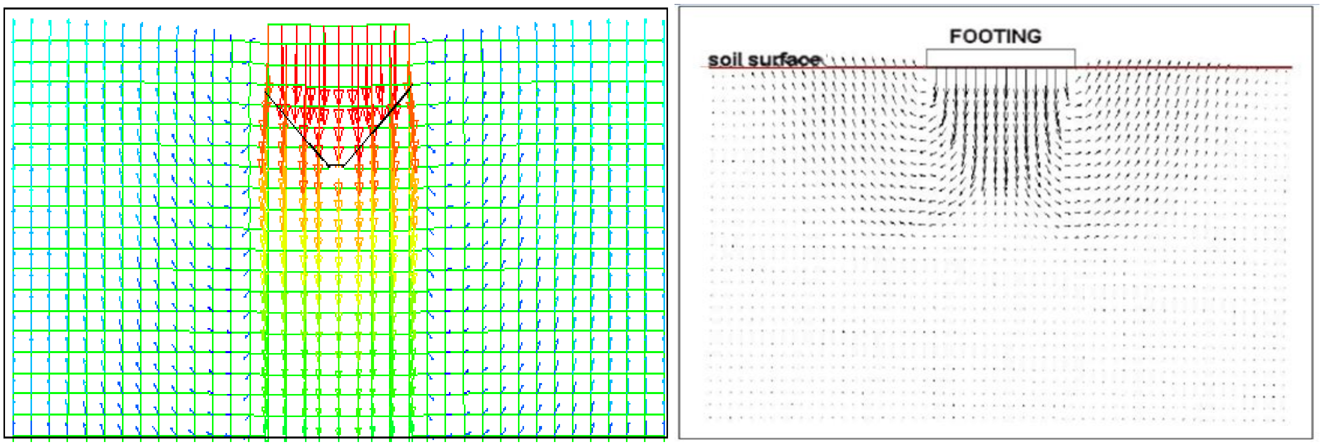

Figure 5 Ground displacement for Model 2, obtained by (a) ABAQUS (b) GeoPIV analyses

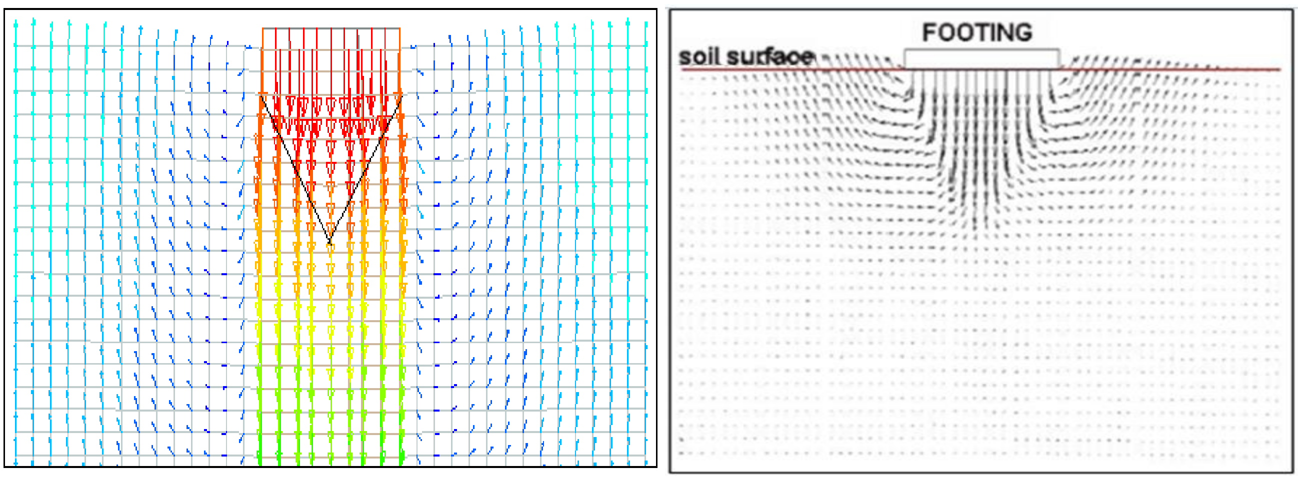

Figure 6 Ground displacement for Model 3, obtained by (a) ABAQUS (b) GeoPIV analyses

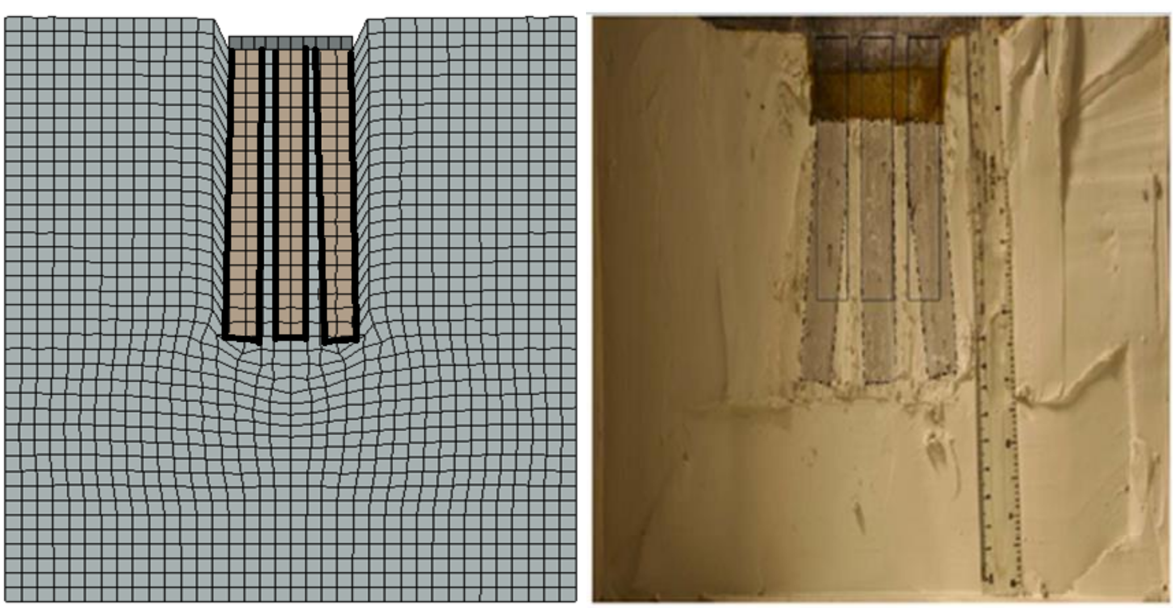

Figure 7 Failure of DSM columns for Model 2, obtained by (a) ABAQUS (b) Experimental result

■5.0 CONCULOSION

A series of physical laboratory tests were carried out to investigate the improvement of bearing capacity achieved by installing DSM columns with different ratios of improvement area. Only results of two treated models with 17.3% and 26.0% of improvement area ratio as well as untreated model were considered to compare with FE (ABAQUS 2D) analyses.

According to the numerical analyses, the following conclusions were drawn:

- The soil models with higher improvement area ratio extended in much greater depth. The higher numbers of piles increase the effect of soil deformation where it will extend the soil in much deeper depth before it fails.
- The patterns of soil-cement column were similar to the patterns obtained by experimental tests. In general, the column at the centre of the footing was penetrated straight deeper into the soil whereas bending occurred at the edge of columns in outward direction.

Three modelled failure patterns produced by FEM:ABAQUS exhibited a slight difference compared to those derived from PIV analysis. These discrepancies were produced as a result of the influence of column failure inside the ground model which could not be fully represented in plane strain. Results of this study can be very useful for identification of the most influential parameters on failure patterns of the improved soil ground.

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