3[rd] International Conference on New Developments in Soil Mechanics and Geotechnical Engineering,
28-30 June 2012, Near East University, Nicosia, North Cyprus

Finite element modeling of stone columns in alluvial soils under an embankment

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KEYWORDS: Stone columns, alluvial soils, Plaxis, settlement, excess pore pressures.

ABSTRACT: This paper examines the performance of stone columns in alluvial deposits. The vertical settlement, excess pore water pressure dissipation and consolidation time were studied by finite element analysis using Plaxis software. An undrained analysis was carried out for alluvial soils, and a drained analysis for stones and the compacted embankment soil using Mohr-Coulomb's criterion over a period of 500 days. The results have shown that the stone column model designated by MS1 (placed at 1.5 m spacing) and MH4 (with 15 m length) have significantly reduced settlement and consolidation time.

1 INTRODUCTION

In recent years, due to increasing population and expanding cities, engineers had to build structures on weak soil deposits. Construction on these soils leads to numerous problems such as excessive settlement, low shear strength and loss of stability. Therefore, it is necessary to reinforce soils beneath structures. The use of encased stone column can be effective as a new method for improving clay or silt foundation under different structures such as building, road embankment, dikes, etc. Stone columns can improve the soil strength by the following mechanisms: accelerating the consolidation time, reducing the amount of total settlement, preventing the additional development of excess pore water pressure due to higher hydraulic conductivity, and increasing the load carrying capacity of the soil. In addition, it is easier to install stone columns than the other ground modification methods, such as vacuum preloading, lime column, etc. Various researchers have carried out numerical and experimental studies of the stone column as a new reinforcement technique. Samieh (2002) researched numerically on the effect of stone columns in 11 m deep soft soil under an embankment, and detected the maximum settlement to be at the toe.

Alexiew et al. (2005) utilized pile under a compacted embankment for improvement of the soft soil foundation. Oh et al. (2007) evaluated the amount of settlement of 4 m embankment construction on estuarine clay supported by stone columns in 457 days. The detected settlement of treated part was less than the untreated part. Saroglou et al. (2008) studied the stone column as a ground improvement method and observed that the column at 14 m depth decreased the settlement from 14 cm to 7 cm and reduced the consolidation time from 16 months to 7 months. Malarvizhi and Ilamparuthi (2008) investigated the settlement of stone column at different load conditions. Andreou et al. (2008) studied the several parameters of stone columns, such as grain size of stone column material, drainage situation and the rate of deformation as key controlling parameters in design of stone columns. However, when used in sensitive clays, settlements may increase due to absence of lateral restraint. In addition, the clay particles may clog the stones, reducing radial drainage. To overcome these problems, and thus to improve the efficiency of the stone columns in strength and compressibility, they are encased using geogrids/geocomposites. Recently, the idea of encasing stone columns with geosynthetics to increase their capacity has been studied by many researchers (Kempfert et al. 2003; Murugesan and Rajagopal 2006, 2008, 2009; Gniel and Bouazza 2008).

The main goal of this paper is to present the numerical study of stone columns under a 4 m embankment by using Plaxis software. The study includes settlement versus time relationship at different spacing and height of columns, the excess pore water pressure distribution with depth and the effect of stone columns on consolidation time.

2 NUMERICAL MODELING

2.1 Study Area

This study is based on a bore log data obtained from Tuzla area, located in the northwest of Famagusta, within 1 km distance to the coast. The soils in the region are alluvial deposits of the delta of River Pedios (Kanlidere), comprised of heterogenous layers of saturated clays and silts of low to high plasticity, and sands intermittently distributed within the studied depths.

2.2 Materials and Model Parameters

The properties of the embankment soil were adopted from the study of Abusharar et al. (2009) and the properties of stone column materials were adopted from the study of Ambily and Gahndhi (2007). The stone column and embankment soil are modeled as drained whereas the subsoil layer is modeled in undrained condition. Mohr-Coulomb model has been used for all materials. Because of the symmetry of the embankment, the right part of the embankment has been considered in this research. The plane strain finite element analysis has been used for group of stone columns. A closed consolidation boundary is applied to both sides of the model preventing horizontal drainage. The embankment fill has been constructed in two equal layers. Each layer has 2 m height and built in 5 days. The water table is assumed at the ground surface and the consolidation analyses are accomplished for every stage, Figure 1 shows the cross section of stone column under embankment soil. The material properties of every section are shown in Tables 1 and 2. Point A (0, 27), B (10, 27), C (0, 23), D (0, 19), E (0, 15), F (0, 11), G (0, 7), and H (0, 3) have been selected for different analyses.

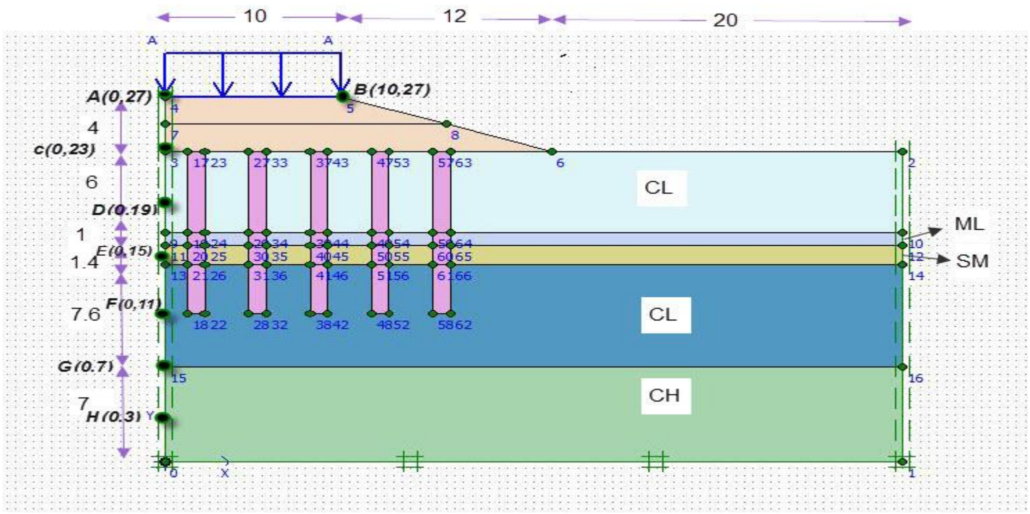

Figure 1.Cross section of stone columns under embankment (All dimensions in metres).

Table1. Properties of soil strata beneath the embankment.

Depth		e	γ_{dry}	γ_{sat}	E_s (MPa)	Φ (◦)	s_u (kPa)	k (cm/s)
0-6	CL	0.855	14.69	19.3026	10.4	---	18	10^{-7}
6-7	ML	0.979	13.29	18.2332	8.6	---	12	10^{-5}
7-8.4	SM	0.641	15.85	19.7556	9.8	26.4	---	10^{-5}
8.4-16	CL	0.923	14.07	18.8686	13.13	---	27	10^{-7}
16-23	CH	0.908	14.28	19.0399	17.95	---	43	10^{-7}

Table 2. Material properties of stone and embankment soil.

Parameter	Symbol	Stone Soil, (Ambily and Gandhi, 2007)	Fill embankment
Material model	Type	Mohr-Coulomb	Mohr-Coulomb
Loading	Condition	Drained	Drained
Wet soil unit weight	γ_{wet} (kN/m^3)	19	20
Horizontal permeability	k_h (m/day)	12	0.009
Vertical permeability	k_v (m/day)	6	0.009
Young's modulus	E (kN/m^2)	55000	8000
Poisson's ratio	υ	0.3	0.3
Cohesion	c ′ (kN/m^2)	0	1
Friction angle	φ′ °	43	30
Dilatancy angle	ψ°	10	0

3 RESULTS AND DISCUSSIONS

Two different model categories of stone columns have been considered to analyze the effect under compacted embankment with 10 kPa traffic load: H-group in which the spacing is kept constant while height is varied, and the S-group, in which the height is kept constant while the spacing is varied. Table 3 summarizes these categories.

Table 3. Different models of stone column for finite element analysis.

Model categories	Diameter (m)	Height (m)	Spacing (m)	Number of stone columns
H	1	7.0 10.0 12.0 15.0	2.0	5
S	1	12	1.5 2.0 2.5 3.0	5

9 different models are studied including the embankment on unreinforced soil, as listed below:

1. M : No support
2. MS1: 5 stone columns at 1.5 m spacing
3. MS2: 5 stone columns at 2.0 m spacing

4. MS3: 5 stone columns at 2.5 m spacing
5. MS4: 5 stone columns at 3.0 m spacing
6. MH1: 5 stone columns of 7 m height
7. MH2: 5 stone columns of 10 m height
8. MH3: 5 stone columns of 12 m height
9. MH4: 5 stone columns of 15 m height

3.1 Settlement Analysis with respect to Time

Figure 2 depicts the settlement versus time relationships at point A for the H and S group models in comparison with the unreinforced soil over a period of 500 days. As can be observed the soil without reinforcement (Model M) has the largest amount of settlement, which is 229 mm. By using stone columns the amount of settlement decreases by 37 %. In addition, among the stone columns with different spacing, MS1 has the best performance, decreasing the settlement to 93 mm. Among the stone columns of varying heights, the MH4 model reduces the settlement to 89 mm. Thus, it can be concluded that by decreasing the spacing of the columns and increasing the depth of the columns amount of settlement will be decreased.

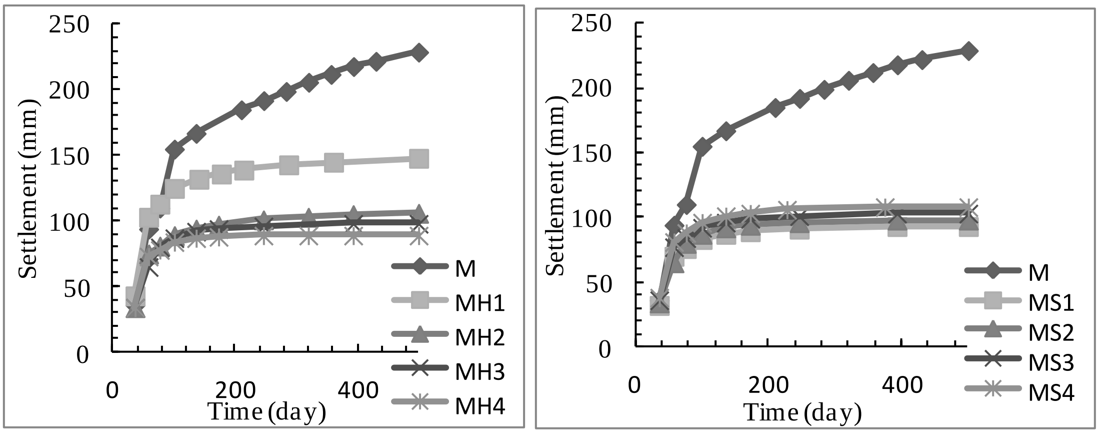

Figure 2. Settlement versus time.

Settlement Analysis with respect to Depth

Settlement-depth relationship is studied at points A-C-D-E-F-G-H on the centerline of the embankment (Figure 1). Figure 3 presents the results, the maximum settlement occurring at point A.

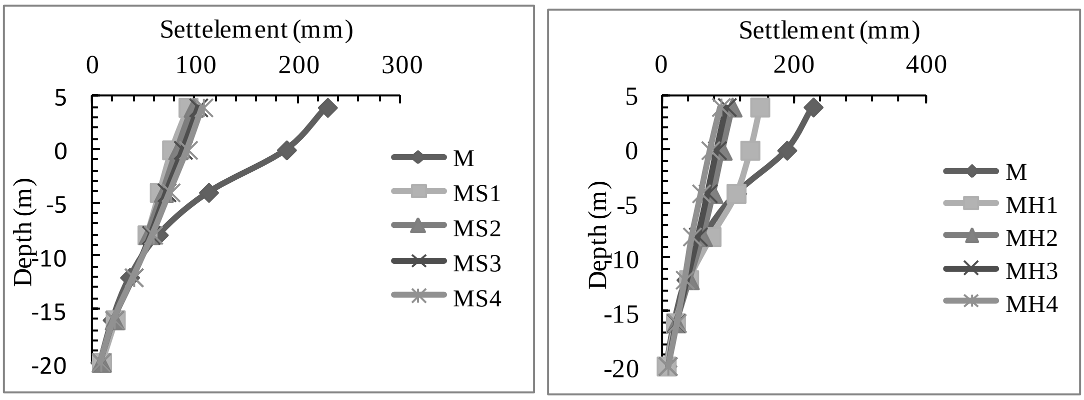

Figure 3. Settlement versus depth.

3.2 Differential Settlement

The differential settlement is also evaluated between points A and B. Figure 4 shows the maximum differential settlement between points A and B occurring in model M, which is the unreinforced case. Utilizing stone columns, however there is a marked reduction in this amount.

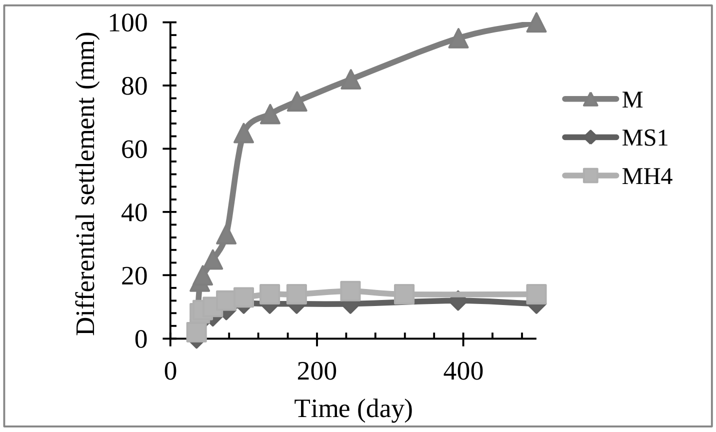

Figure 4. Differential settlement versus time.

3.3 Analysis of Excess Pore Water Pressures

Stone columns with different heights have been selected to assess the excess pore water pressure at points A-C-D-E-F-G-H. Figure 5 shows that initially the excess pore pressure reaches to a peak value, followed by a reduction as dissipation takes place with time. The MH4 has the best performance to dissipate excess pore pressure and accelerate the consolidation time because of long height of the column, therefore longer drainage path. It is obvious that by increasing the height of the columns the amount of excess pore water pressure increases.

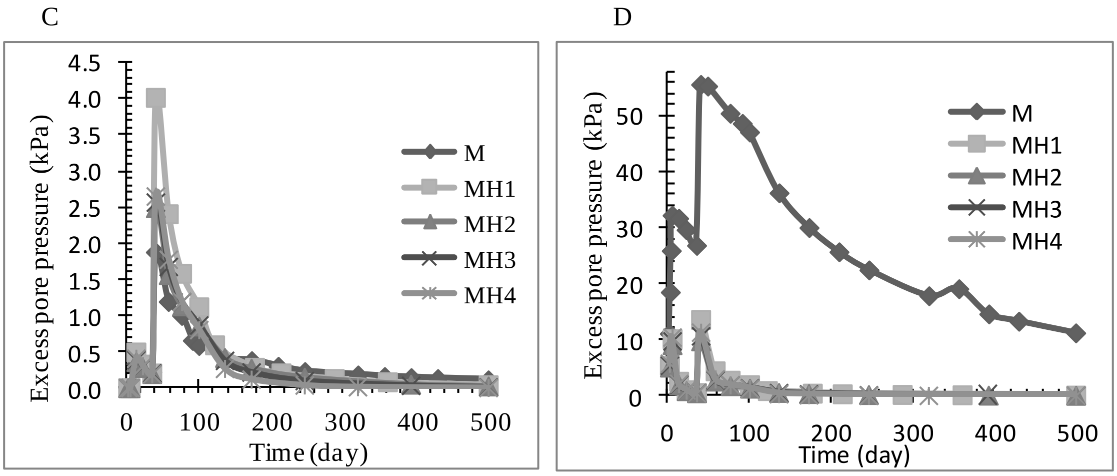

Figure 5. Excess pore water pressure versus time.

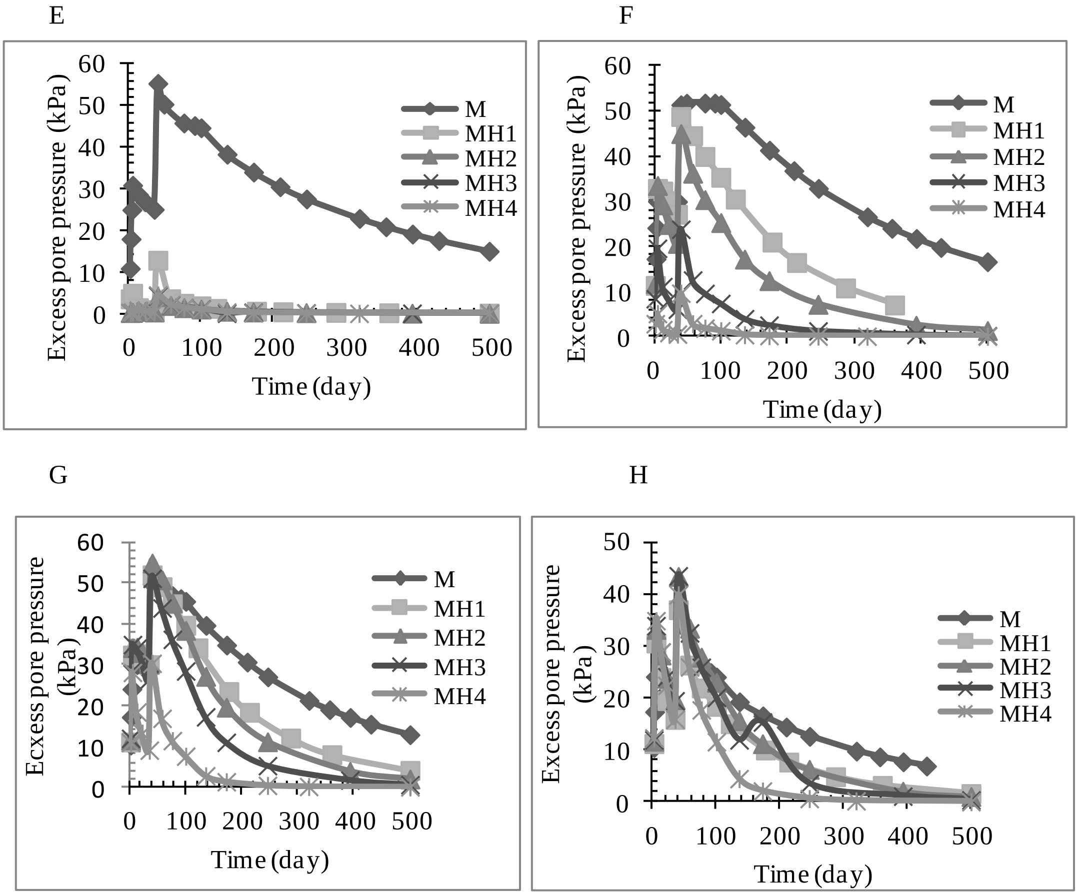

Figure 5. Excess pore water pressure versus time (Cont.'d)

3.4 Consolidation End Time Analysis

The results in Figure 6 show that the use of stone columns has significant effect on decreasing the consolidation time. It can also be observed that the MS4 model accelerates the consolidation time from 2295 days to 521 days.

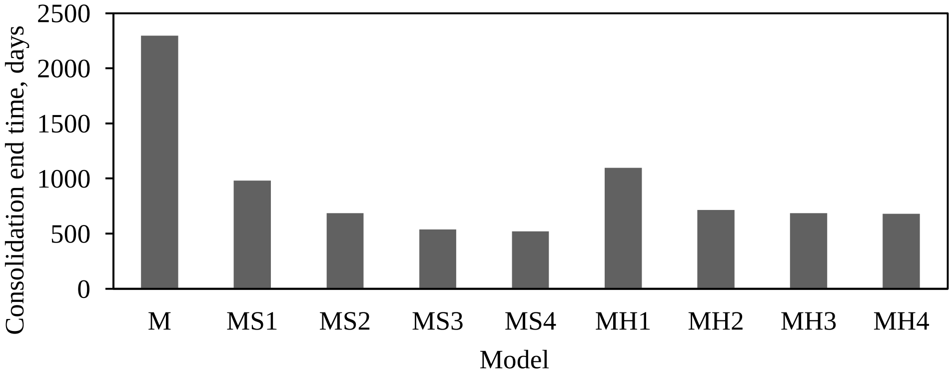

Figure 6. Consolidation end time for all the models studied.

4 CONCLUSIONS

A numerical analysis was undertaken to consider stone columns for improving alluvial soils in Tuzla under a compacted road embankment, where the soft alluvial deposits cause settlement of roads in the region. This is the first study undertaken regarding this local problem, and the following conclusions derived are in good agreement with the ones given in the literature:

1. Utilization of stone columns is an efficient ground improvement method, which considerably reduces the settlement and increases the bearing capacity of the soil.
2. Settlements are mainly influenced by column spacing and height. Decrease of spacing and increase of height decrease settlements.
3. The stone columns have an important role in the dissipation of excess pore water pressures as well. They act as drainage paths, hence reducing the consolidation time.

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