Behavior of ordinary and encased stone columns studied by FEM analysis

Les comportements des pieux granulaires ordinaires et emballés analysés par la méthode des éléments finis

M. Elsawy , K. Lesny & W. Richwien
University of Duisburg-Essen, Germany

ABSTRACT

Construction on soft natural soil is considered a risk due to its low shear strength and high compressibility. Stone columns are an effective improvement method for soft soils under light structures such as rail or road embankments. Stone columns are generally used to increase the bearing capacity which depends on their lateral support. In this research full scale stone columns in Bremerhaven clay, a soft soil layer of 6.0 m thickness, were analyzed using the finite element program Plaxis. The stone columns were loaded under undrained and drained conditions of the surrounding soft soil to investigate the effect of varying parameters like spacing distance between columns, column diameter and stiffness of the geogrid encasement on the behavior of the stone column in short and long term conditions. The results showed that the ordinary stone columns with narrower spacing distances and smaller diameters have a greater bearing capacity and show smaller settlement as well as lateral bulging than wider spacings and greater diameters of stone columns. When using geogrids as encasement for stone columns, a huge increase in the bearing capacity of the stone column as well as a huge reduction in the lateral bulging and the settlement occur. The bearing capacity of the stone columns increases as well as their lateral bulging, settlement and differential settlement decrease with increasing encasement stiffness in both short and long term conditions.

RÉSUMÉ

La construction sur un sol naturel mou est considérée comme un risque dû à sa basse résistance au cisaillement et sa compressibilité élevée. Les pieux en pierre sont une méthode efficace d'amélioration des sols mous sous les légères structures telles que le remblais des chemins de fer ou des routes. Les pieux en pierre sont généralement employés pour augmenter la capacité de portance qui dépend de leurs supports laterals. Dans cette recherche, des pieux en pierres á des completes grandeurs dans une couche d´argile de Bremerhaven, une couche d´argile mou de 6.0 m d´epaisseur, ont été analysés en utilisant le programme des éléments finis Plaxis. Les pieux en pierre ont été chargées dans des conditions non drainantes et drainantes du sol mou environnant pour étudier l'effet de variété des paramètres comme la distance d'espacement entre les pieux, le diamètre des pieux et la raideur de l´encasement de la géogrille sur le comportement du pieux des pierres à court et long terme condition. Les résultats ont prouvé que les pieux en pierre ordinaires avec des distances déspacement plus étroites et des diametres plus petits ont une plus grande capacité de portance et montrent le plus petit tassement ainsi que le bombement latéral par rapport au large espacement et aux plus grands diamètres des pieux en pierre. En employant des geogrilles comme encasement pour les pieux en pierre, une augmentation énorme de la capacité de portance des pieux en pierre ainsi qu´une réduction énorme de bombement de la partie latérale et de tassement se produisent. La capacité de portance des pieux en pierre augmente ainsi que leur bombement latéral, le tassement et le tassement différentiel diminuent avec l'augmentation de la raideur d'encasement dans des conditions à court et à long terme.

Keywords : soft soil, stone column, bearing capacity, finite element analyses, geogrids encasement

1 INTRODUCTION

Soft soil covers a lot of regions all over the world often located in important cities along rivers and seas. Stone columns are considered to be an effective improvement method for soft soil because it gives the advantage of reduced settlement and accelerated consolidation due to the reduction in the drainge path lengths. Another advantage of this method is the simplicity of its construction. The stone columns develop their load carrying capacity through bulging and thereby depending on the shear strength of the surrounding soil.

The stone column technique was adopted in European countries in the early 1960s and thereafter it has been used successfully. Several researches have been published in the past three decades which dealt with the stone column technique (Balaam & booker 1985; Lee & Pande 1998; Wood et al. 2000; Christoulas et al. 2000). Bergado & Long (1994) found from field measurements and numerical studies that the installation of granular piles in soft soil increase the bearing capacity and accelerate the consolidation. They also reported that granular piles imply more reductions in the total settlement of the soft clay when compared with vertical drains. Ambily & Gandhi (2007) stated that the increase of the bearing capacity of the reinforced soft soil with stone columns depends mainly on the spacing distance between the columns.

Further developments of the stone column technique include the reinforcement of the column using either horizontal layers of reinforcement (Sharma et al. 2004) or encasing the individual stone column by geosynthetics (Nabil 1995; Murugesan & Rajagopal 2006). The geosynthetic encasement leads to a greater increase of the load bearing capacity of the stone column and reduces its bulging due to the additional confinement from the encasement (Malarvizh & Ilamparuth, 2007). However, the published literature on the performance of the encased stone columns is limited especially in the long term conditions.

The scope of this study is to understand the behavior of the stone columns in soft soil and to extract the parameters which play a dominant role in bearing capacity increase and in settlement reduction in short and long term conditions. Based on this objective, the influence of the parameters such as the spacing distance between columns, the column diameter, the geogrid encasement and the geogrid stiffness is analyzed.

2 FINITE ELEMENT SIMULATIONS

In order to make realistic predictions of the behavior of the geosynthetic reinforced stone column-soft soil system, full scale stone columns in Bremerhaven clay are analyzed. The Mohr Coulomb model is used for the stone column material and the Soft Soil Creep model is used to describe the behavior of the Bremerhaven clay. The finite element program Plaxis 8 has been used for the FE analyses. The properties of the stone column materials and Bremerhaven clay were adopted from the study of Ambily & Gandhi (2007) and the study of Geduhn

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(2005), respectively. The properties of these soils are tabulated in Table 1. In the current research, the "unit cell" analysis has been conducted for a column and the surrounding soft soil using axisymmetric conditions, as illustrated in Figure 1. Half of the model has been used. The vertical and the horizontal displacements at the bottom boundaries were restrained while only the horizontal displacement at the lateral boundaries was restrained. A medium finite element mesh has been used with 15 nodes triangular elements.

Three types of reinforcement with different stiffness are used as encasement for the stone column, Secugrid 20/20 Q1, Secugrid 30/30 Q1 and Combigrid 40/40 Q1 (Naue GmbH). The last type is a composite of geogrid/nonwoven geotextile. The geotextile is arranged in such a way that it would not contribute either to the vertical or lateral stiffness of the encased stone column. The properties of geogrid materials are tabulated in Table 2.

Table 1. Properties and parameters of stone column and soil

Parameter	Stone column	Bremerhaven clay
Model conditions	Mohr coulomb drained	Soft soil creep undrained and drained
γ_{wet} (kN/m^3)	19	15
E (kN/m^2)	55,000	-
υ (-)	0.3	-
λ^* (-)	-	0.203
κ^* (-)	-	0.025
μ^*(-)	-	0,007
c' (kN/m^2)	0	5
φ' °	43	37,75
ψ°	10	0

Table 2. Properties of the geosynthetic materials

Property	Secugrid 20/20 Q1	Secugrid 30/30 Q1	Combigrid 40/40 Q1
Mass per unit area (g/m^2)	155	200	240
Axial stiffness, J (kN/m)	400	600	800
Aperture size (mm x mm)	33 x 33	32 x 32	31 x 31

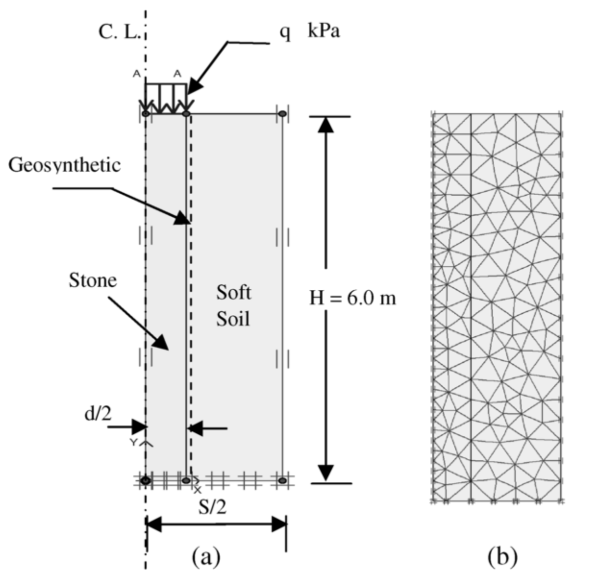

Figure 1. Model of the unit cell (a) Model parts, (b) FEM mesh

3 RESULTS AND DISCUSSION

In the unit cell analyses technique, the soft soil layer with 6.0 m depth is reinforced with stone columns. The ordinary and the encased stone columns have been loaded in undrained and drained condition of the surrounding soft soil.

3.1 *Effect of relative spacing between columns S/d*

In this analysis, ordinary stone columns with a diameter of 1.0 m have been loaded with varying surrounding soft soil volumes which are represented by spacing to diameter ratios of S/d = 2, 3, and 4.

The vertical displacement at the surface and the lateral bulging at the stone column-soft soil interface were computed at a load of 180 kPa which acts the minimum failure column load of the studied cases in undrained conditions. Firstly, in undrained condition the settlement of the stone column is approximately constant across its diameter. The settlement gradually decreases beside the stone column and converts to heave. The maximum value of heave is near the column generating a high differential vertical displacement between the stone column and the surrounding soft soil. The settlement increases and the heave decreases with increasing spacing distance, as illustrated in Figure 2. Then the heave decreases gradually with distance away from the column while the smaller spacing between columns has the greater heave values over its distance. This phenomenon is due to a stress overlap occurring between the closed columns as well as the constant volume in undrained loading condition. When two narrow standing columns are loaded, they displace downwards and laterally causing lateral displacements in the surrounding soft soil on both sides. So, the soft soil between the two columns must be displaced upwards with a significant distance to keep the overall soft soil volume constant.

Secondly, in drained conditions the stone columns have an approximately constant settlement across the diameter. The settlement decreases gradually in the surrounding soft soil causing a high differential settlement, as shown in Figure 2. The settlement of the stone column increases with increasing spacing distance between the columns while the settlement in the soft soil decreases. Therefore, the differential settlements increase with increasing spacing distance between the columns. The soft soil between narrow columns shows the maximum settlement because the soft soil volume between the stone columns is more confined than that in the case of larger spacings. This causes greater settlements during the consolidation process.

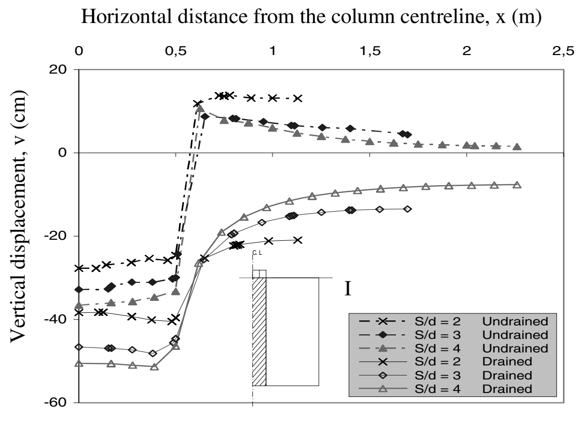

Figure 2. Vertical displacement distributions for columns with diameter of 1m and various spacings under a load of 180 kPa

The lateral bulging of the stone column increases with increasing spacing distance in undrained conditions. The values of the lateral bulging approach zero below a depth that equals two times the column diameter (2d) for all column spacing ratios, as shown in Figure 3.

The lateral bulging of the stone column in drained conditions increases with increasing spacing distance in the upper part of the column while the lower parts of the column experience small lateral displacements, as shown in Figure 3. The horizontal displacement of the stone column in the lower parts increases with decreasing spacing distance between the columns. This is due to the stress in the stone column transferring downwards during the consolidation process. So, if the spacing distance between the columns is reduced, more stresses are transferred to greater depths due to the greater confinement from the neighbor columns. At the same spacing ratio, the lateral displacements of the stone columns in undrained conditions are greater than those in drained conditions at the upper part as shown in Figure 3. This is due to an increase of the shear strength and stiffness of the soft soil after consolidation which leads to an increase of the lateral support of the column.

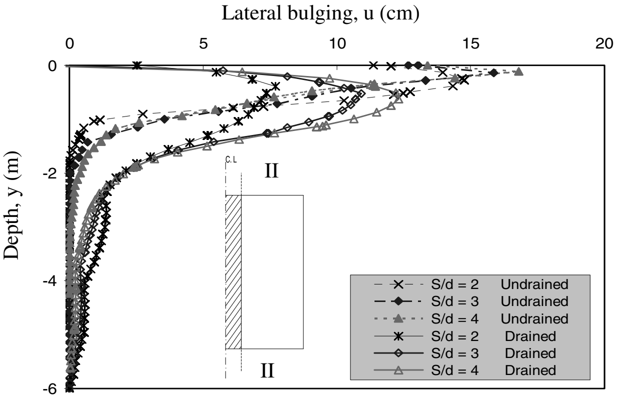

Figure 3. Lateral bulging distributions for columns with diameter of 1m and various spacings under a load of 180 kPa

From the results of the above analysis, it can be concluded that a small spacing ratio of S/d = 2 is better than greater spacing ratios due to the increasing stone column bearing capacity and the decreasing stone column bulging.

3.2 *Effect of Stone Column Diameter (d)*

Stone columns with the same spacing distance ratio S/d of 2 and different diameters of d = 0.6, 1.0, and 1.4 m were loaded in undrained and drained conditions. The vertical displacements at the surface and the lateral bulging values at the stone column-soft soil interface were computed at a load of 180 kPa.

As shown in Figure 4, the stone column settles when loaded in undrained conditions. This settlement is converted to heave in the soft soil. The settlement of the stone column and the heave of the soft soil increase with increasing stone column diameter which is accompanied with an increase of the differential vertical displacements, as illustrated in Figure 4. Beside the confinement effect the constant volume has also an influence on the vertical displacements behavior. At the same spacing, the settlement of the stone column and its lateral displacement increase with increasing column diameter as illustrated in Figure 4 and Figure 5. Hence, the stone column with a greater diameter experiences a greater lateral displacement which leads to increasing heave in the surrounding soft soil to keep its undrained volume constant.

Figure 4 also includes the settlement of the stone column and the surrounding soft soil in drained loading conditions. The stone column settles under the applied load. This settlement decreases sharply in the surrounding soft soil. The settlement in the stone column increases with increasing column diameter while the settlement in the surrounding soft soil shows a slight reduction with increasing column diameter. So, the differential settlement increases with increasing stone column diameter. This phenomenon occurs because the stresses overlap between the columns. When the stone columns have smaller diameters at the same spacing ratio of S/d, the smaller the soft soil volume is between the columns which is more stressed than a larger one. Hence, the soil experiences greater consolidation settlements than in case of larger diameters.

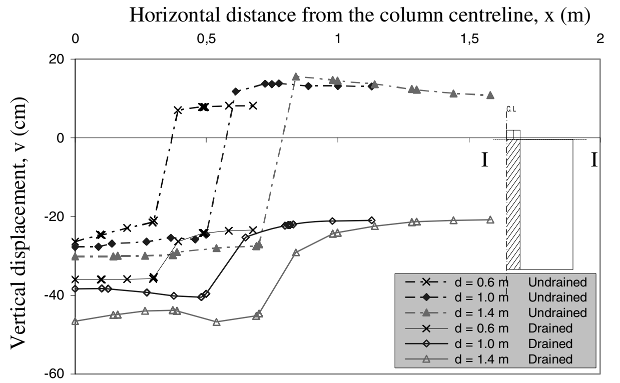

Figure 4. Vertical displacement distributions for columns with spacing ratio of 2 and various diameters under a load of 180 kPa

The lateral bulging of the column significantly increases with increasing diameter of the stone column in undrained and drained conditions as shown in Figure 5. Therefore, the stone column with a diameter of 0.6 m has the smaller lateral displacement. This behavior occurs due to the fact that the stone columns with smaller diameters are more confined by the surrounding soil and the neighbor stone columns.

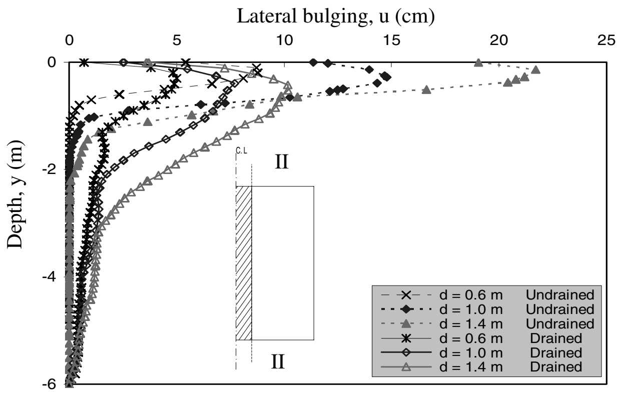

Figure 5. Lateral bulging distributions for columns with spacing ratio of 2 and various diameters under a load of 180 kPa

3.3 *Effect of Geosynthetic Encasement Stiffness (J)*

It can be concluded that from the above discussion the ordinary stone column with a diameter of d = 0.6 m and a spacing ratio of S/d = 2.0 provides the greatest bearing capacity. It has also the smallest stone column settlement as well as the lowest lateral bulging in undrained and drained conditions in comparison with the other studied cases. In a further step the ordinary stone column is encased with three types of geogrid with different stiffness values to study the effect of the encasement stiffness on the behavior of the stone column. The ordinary (OSC) and the encased (ESC) stone columns were loaded until failure in undrained and drained conditions.

When the stone column is encased with geosynthetic materials, a huge increase in the bearing capacity occurs in both short and long term conditions. The bearing capacity of the stone column increases with increasing geogrid stiffness as shown in Figure 6. The higher the applicable loads are, the greater the increase in the bearing capacity for various encased stone column is. The geogrid encasements increase the column confinement and provide a stronger lateral support by generating radial tension forces. The confinement of the stone column increases with increasing geosynthetic stiffness which leads to an increase the overall stiffness of the encased stone column.

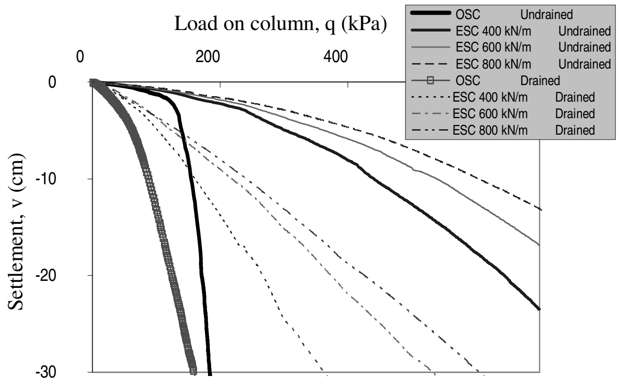

Figure 6. Effect of geogrid stiffness on the load-settlement relationship of the stone column for d = 0.6 m and S/d = 2.0

The vertical displacements at the surface and the lateral displacement along the interface were calculated at column loads of 180 kPa and 300 kPa which represent the minimum failure loads of the studied columns in undrained and drained conditions, respectively. A huge reduction in the settlement and the differential vertical displacement and in the lateral bulging of stone column occurs when encasing stone column with geogrid materials in undrained and drained conditions, as shown in Figures 7 and 8. The heave of the soft soil also disappears in encased stone column in undrained conditions. The settlement of the encased stone column and the soft soil, the differential settlement between them and the bulging of the column decrease with increasing geosynthetic stiffness values.

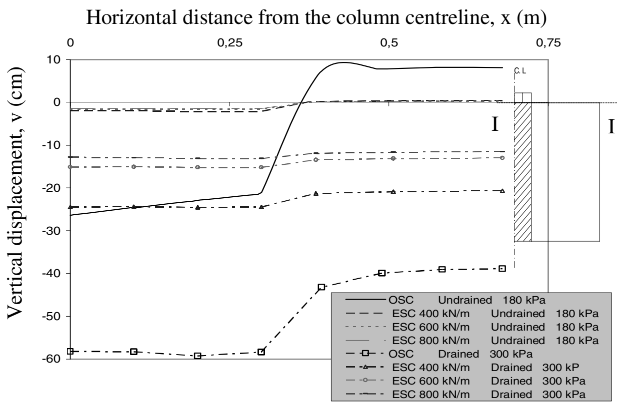

Figure 7. Effect of geogrid stiffness on the vertical displacement for d = 0.6 m and S/d = 2.0

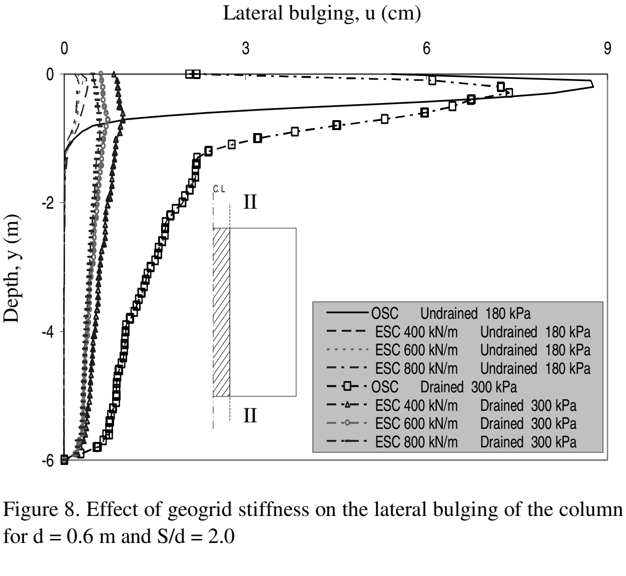

Figure 8. Effect of geogrid stiffness on the lateral bulging of the column for d = 0.6 m and S/d = 2.0

4 CONCLUSIONS

In this research, the performance of ordinary and encased stone columns was studied by varying parameters of spacing distance between columns, column diameter and encasement stiffness, respectively. The numerical analyses were performed by loading the stone column in both undrained and drained conditions. The results obtained from this study showed that the narrow the spacing distance between the stone columns is, the smaller the settlement, differential settlement and the lateral bulging of the column are. The bulging of the stone column disappears in depths below approximately 2.0 m in undrained conditions while the bulging implies values along the column in drained conditions. On the other side, the heave in undrained loading conditions as well as the settlement in drained loading conditions of the surrounding soft soil increase with decreasing spacing distance between columns. The settlement and the bulging of the column as well as the differential settlement between the column and the soft soil and the heave decrease with decreasing stone column diameter.

The load capacity and stiffness of the stone column increase by geogrid encasement. When the stone columns are encased, they are confined and the lateral bulging is minimized. The geogrid stiffness plays an important role in enhancing the capacity and the stiffness of encased column. The stiffer the geogrid is, the higher is the load capacity of the column and the smaller are the settlement, the diffrential settlement, the heave and the lateral bulging.

Therefore, the smaller the spacing distance and the diameter of the column are and the higher the encasement stiffness is, the better the performance of the stone columns is.

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