The Impact of Using Different Types of Soft Soils Treated by Stone Columns on Creep Behavior

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Abstract. The stone column technique is an effective method to increase the strength of soft cohesive soil, which results in a reduction in foundation settlement and an increase in bearing capacity. The topic of restraining creep settlement through the use of stone columns techniques has gained increasing attention and consideration; because stone columns are widely used to treat soft soil deposits, caution should be applied in estimating creep settlement. We discovered a reversible relation between shear parameters and the creep settlement in floating stone columns; while, in case of end-bearing stone columns shows a direct positive relation between shear parameters and the creep settlement, and the creep settlement began at the primary settlement. The shear parameters affected the improvement factor (n) of creep settlement in both floating and end-bearing stone columns. The standard creep coefficient’s n values in floating and end-bearing conditions were more significant than the low creep coefficient’s n values in forwarded geometric conditions. The stress in both floating and end-bearing stone columns was increasing and uniformly distributed along the length of the floating stone column and in the case of end-bearing stone column was limited to the stiffness layer; the maximum vertical stress was in the central point of the embankment. The embankment’s maximum horizontal displacement occurred on the edge.

KEYWORDS: Stone Column, settlement creep, Improvement factor, vertical stress, horizontal displacement, spacing, finite element method, plaxis 3D.

1. Introduction

Highly compressible soft soil layers are distributed in many countries globally, especially in the south part of Iraq. Geotechnical engineers have to deal with this type of soil. The stone column technique is one of the best methods used to increase the strength of cohesive soil; result in a decrease of the settlements under foundations, and an increase of the bearing capacity. The majority of research on stone columns in soft soil to date has concentrated on how to increase the bearing capacity and reduce the primary settlement [1].

The Effectiveness of stone columns (n= untreated/treated) is referred to as the ratio between the untreated ground settlement over the treated ground settlement by stone columns, both were subjected to the same loading. The n values were obtained from measurements for large area loadings, embankments, and small area loadings, tanks, and footing in cohesive soil. There are global n values.
that do not distinguish between primary, initial compression and creep settlements. Although checking the time necessary to arrest creep settlements is a clear obstacle in the practical work, but determining the creep settlement improving factor is a critical factor for the stone column settlement design. The majority of laboratory tests conducted to characterize the behaviour of stone columns were concentrated on the bearing capacity or short-term settlement response [2, 3]. Moorhead (2013) carried out a series of laboratory tests to examine settlement in soils with low and high creep potential; they concluded that stone columns did not affect initial settlement, consolidation settlement, or creep reduction [4]. The creep effect on the settlement performance of stone column in a soft one layer, soil profile was investigated numerically using an isotache-based soil model in combination with the Plaxis 2D FE program. They concluded that stone columns significantly reduced the creep settlement in the long term, but not to the limit of the primary settlement; similarly, conclusions were reached by Sexton and McCabe for a multi-layer soil profile [5, 6].

Fattah and Majeed (2012) study the performance of usual and encased floating stone columns under a variety of conditions and discovered that the increase of bearing improvement ratio linked to the increase of length/diameter (L/D) ratio; to the extent when the L/D ratio exceeding the 8 for all the area replacement ratio, also in the case with encasing stone column, there is no practical limit to the L/D ratio. The stone column strength increase, when encased with geogrid as opposite to the not encased stone column, also the increasing of bearing capacity (qtreated/quntreated) is improved as the L/D ratio increase. For all the L/d ratios, using a cap above the stone column increases the bearing improvement ratio and reduces the settlement [7]. Fattah et al. (2016) studied the performance of a model of embankment supported by soft soil treated by usual stone columns and stone columns encased in geogrid. Soil with an undrained shear strength of 10 kPa, the study of the model was conducted with various spacing and two different L/D ratios of the stone columns, additionally to the different heights of the embankment. The results indicated that a critical parameter is the ratio of the embankment’s heights to the spaces between columns (h/s–d). While there is no apparent effect of arching at (h/s–d) 1.2 and 1.4 for OSC and ESC respectively (h=embankment’s height, s=column spacing, d=diameter of stone columns), the settlement at the embankment’s surface is significant [8].

The objective of the present study is to find the effect of different shear parameters of soft soils treated by stone columns on different soil profiles of soft soil creep behaviour.

2. EXPERIMENTAL WORK

2.1. Soil index characteristics

Brown clayey soil from a location near Al-Rashid Camp, south of Baghdad. To estimate the parameters used in the case study (Table 1 and 2), laboratory tests (physical properties, consolidation test, compaction test, vane shear test, and triaxial test) were conducted using the Plaxis- 3D 2020 software.

| Test                  | Value | Specification               |
|-----------------------|-------|----------------------------|
| Liquid limit (LL%)    | 43    | ASTM D4318-(2010) [9]      |
| Plastic limit (PL%)   | 22    | ASTM D4318-(2010) [9]      |
| Plasticity index (%)  | 21    | ASTM D4318-(2010) [9]      |
| Specific gravity (Gs) | 2.75  | ASTM D854-(2010) [10]      |
| Gravel %, >4.75mm     | 0     | ASTM D422-(2010) [11]      |
| Sand %, 0.075 - 4.75mm| 3     | ASTM D422-(2010) [11]      |
| Silt, 0.005 - 0.075mm (%) | 24 | ASTM D422-(2010) [11]   |
| Clay, <0.005mm (%)    | 73    | ASTM D422-(2010) [11]      |
### TABLE 2: consolidation test results according to ASTM D2435. [12]

| Parameters          | Soil A  | Soil B  | Soil C  |
|---------------------|---------|---------|---------|
| Compression index (Cc) | 0.232   | 0.313   | 0.220   |
| Expansion index (Cr)  | 0.035   | 0.049   | 0.014   |
| Creep coefficient    | 0.0049  | 0.006   | 0.0087  |
| c' (kPa)             | 15      | 30      | 50      |
| Angle of friction ' (°) | 0.5     | 1.5     | 3       |

### 3. METHODOLOGY AND DEVELOPMENT OF MODEL

#### 3.1. Geometry

The analysis is conducted using a three-dimensional finite element commercial program (PLAXIS). The stone columns that supported the embankment analysis illustrate the geometry of the FE analyses and mesh (Figure 1& 2).

![Figure 1(A)](image1A.png)

![Figure 1(B)](image1B.png)

**FIGURE 1:** The finite element analyses geometry, (A) floating stone column, (B) end bearing stone column.
Half of the geometry is analyzed in three dimensions boundaries of all sides are constrained in the "out of plane" directions, the bottom boundaries are fixed. Thus, each boundary is impenetrable to flow. The soft soil layer is 16 meters thickness in the floating stone column, and 6 meters thickness in case of end bearing stone column, lies on dense to a very dense silty or clayey sand layer of 10 meters thickness. The level of groundwater is 2.5 meters under the ground surface. The embankment's side slope is 2H:1V. The stone columns measure 8 meters in length. Four space (S = 2.5D) of stone columns in the rectangular pattern were chosen in this study to shows the effects on creep settlement, the diameter of the stone column is 0.6 m, the L/D = 13, and Soils A, B, and C were used for treatment in the analysis.

3.2. Material Parameters
The effect of creep on the settlement performance of stone columns is investigated using two groups of analyses: the first group with standard soil criteria from Table 3 and the second group with very low creep coefficients, $\mu^* \leq 1\%$ of the standard value, effectively reduce the majority of the creep effects. Using of $\mu^* = 0$ cannot be used because it results in division by zero [5].

| Properties          | Dense sand   | Stone column | Soil A         | Soil B         | Soil C         | Embankment fill |
|---------------------|--------------|--------------|----------------|----------------|----------------|-----------------|
| Model               | Mohr-Coulomb | Mohr-Coulomb | Soft soil creep | Soft soil creep | Soft soil creep | Mohr-Coulomb    |
| Type of behavior    | Drained      | Drained      | Drained        | Drained        | Drained        | Drained         |
TABLE 3: The parameters of soil Embankment and Stone column used in the analysis.

3.3. History of Loading
The stone columns were constructed in a total of 124 days during the period from 26th Jan. to 30th May 1998, according to Mohamedzein and Al-Shibi (2011) [13].

TABLE 4: Phase Description of study case.

| Phase description                  | Duration (day) |
|-----------------------------------|----------------|
| Initial conditions (K₀ procedure)  | ----           |
| Construction of stone columns     | 13             |
| Consolidation                     | 111            |
| First stage 1meter lift           | 16             |
| Second stage 1meter lift          | 16             |
| Third stage 1meter lift           | 16             |
| Forth stage 1meter lift           | 13             |
| Consolidation                     | 14415          |

4. RESULTS AND DISCUSSION
The obtained results from the present study show the effect of different soft soils treated with the stone column on the creep settlement under the embankment. Three types of soft soil A (very soft soil), Soil B (medium soft soil), and Soil C (hard-soft soil) were used in the analysis.

4.1. TIME-SETTLEMENT BEHAVIOR (VERTICAL DISPLACEMENT)
The time-settlement behavior plots on a semi-logarithmic scale for floating and end bearing standard creep, and low creep coefficient for the three different soils, Soil A, Soil B, and Soil C; as shown in Figure 3 and Table 5.
Figure 3: Time-settlement behavior, (A) standard creep coefficient (floating), (B) low creep coefficient (floating), (C) standard creep coefficient (end bearing), (D) low creep coefficient (end bearing).

Table 5: the vertical creep settlement in the middle of the embankment.

| Geometry           | Creep coefficient | Soil A   | Soil B   | Soil C   |
|--------------------|-------------------|----------|----------|----------|
|                    |                   | Untreated| Treated  | Untreated| Treated  | Untreated| Treated  |
| Floating stone column | Standard         | 0.340    | 0.274    | 0.320    | 0.267    | 0.319    | 0.262    |
|                    | Low creep         | 0.088    | 0.081    | 0.096    | 0.088    | 0.096    | 0.089    |
| End-bearing stone column | Standard      | 0.127    | 0.115    | 0.129    | 0.115    | 0.130    | 0.113    |
|                    | Low creep         | 0.051    | 0.049    | 0.057    | 0.053    | 0.059    | 0.054    |

In the case of floating stone column, with standard creep coefficient, before and after treatment the settlement of soils (A, B, and C) shows reversible relation between shear parameters and the creep settlement; while in the case of floating stone column, with low creep coefficient, before and after treatment the soil (A, B, and C) shows a direct positive relation between shear parameters and the creep settlement, with notice that soil (B) and (C) shows same results.

In the case of end-bearing stone column, with standard and low creep coefficient, before and after treatment the settlement of soils (A, B, and C) shows a direct positive relation between shear parameters and the creep settlement.

4.2. EVALUATION OF SETTLEMENT IMPROVEMENT WITH TIME
The evolution of n with time for the ‘creep’ and ‘low creep’ cases was plotted in Figure 4; it was found that the best improvement factor n of low creep and standard creep coefficient in floating stone column was in soil C, followed by soil A and then soil B, Figure 4 A and C; while in case of end-bearing the best improvement factor n of low creep and standard creep coefficient was in soil C, followed by soil B and then soil A, Figure 4 B, and D.
Figure 4: Improvement factor \( n \) with time, (A) Standard creep coefficients (floating), (B) Standard creep coefficients (end bearing), (C) Low creep coefficients (floating), (D) Low creep coefficients (end bearing).

4.3. Comparison of settlement Improvement Factor

The expected \( n \) values were less than the primary values because the treated soil settles more rapidly than untreated soil (Sexton 2014 and 2016); however, in Figure 5, the present study discovered that the \( n \) values for standard creep coefficients in floating and end bearing stone column are in contrast with what Sexton studies found, table 6.

Table 6: the improvement factor \( n \) values of creep settlement.

| geometry                      | Creep coefficient | Soil A | Soil B | Soil C |
|-------------------------------|-------------------|--------|--------|--------|
| Floating stone column         | Standard          | 1.240  | 1.198  | 1.220  |
|                               | Low creep         | 1.091  | 1.000  | 1.081  |
| End-bearring stone column     | Standard          | 1.098  | 1.132  | 1.145  |
|                               | Low creep         | 1.033  | 1.067  | 1.082  |
Figure 5: Comparison of improvement factor $n$ values, (A) Soil A (floating), (B) Soil A (end bearing), (C) Soil B (floating), (D) Soil B (end bearing), (E) Soil C (floating), (F) Soil C (end bearing).

4.4 Horizontal displacement

The horizontal displacement effect with the depth at the edge of the embankment for different soil types and geometry (floating and end-bearing stone columns), the analysis was plotted as in figure 6. The horizontal displacement was corresponding reversely to the effective cohesion and internal friction angle of the soil, in both the floating and end-bearing stone column. The effect was shown clearly in Figure 6 A and B.
Figure 6: Comparison of horizontal displacement, (A) floating, (B) end bearing.

The relation between horizontal displacement and log time was plotted in figure 7 and table 8; the relations shows that the horizontal displacement correlated reversibly with the shear parameters for floating and end-bearing stone columns.
Figure 7: Comparison of horizontal displacement with log time, (A) Standard creep coefficients (floating), (B) Low creep coefficients (floating), (C) Standard creep coefficients (end bearing), (D) Low creep coefficients (end bearing).

Table 7: the horizontal displacement values in studied soil types A, B, and C.

| Geometry                  | Creep coefficient | Soil A Untreated | Soil A Treated | Soil B Untreated | Soil B Treated | Soil C Untreated | Soil C Treated |
|---------------------------|-------------------|------------------|----------------|------------------|----------------|------------------|----------------|
| Floating stone column     | Standard          | 0.448            | 0.200          | 0.122            | 0.084          | 0.122            | 0.056          |
|                           | Low creep         | 0.081            | 0.044          | 0.013            | 0.009          | 0.013            | 0.001          |
| End-bearing stone column  | Standard          | 0.142            | 0.066          | 0.049            | 0.036          | 0.027            | 0.023          |
|                           | Low creep         | 0.027            | 0.017          | 0.010            | 0.008          | 0.003            | 0.002          |

4.5. THE VERTICAL STRESS
The stress effects were measured in the central point of the soil under the embankment. The stress in both the floating and the end-bearing stone column was similar in transferring the load in soils A, B, and C, as shown in Figure 8. The obtained results may be because the amount of area replacement and the applied load were the same in all types of studied soils.
5. Conclusions

In the case of the floating stone column, the shear parameters of the three types of soils, a, b, and c show a trivial difference in their effect on the creep settlement under the embankment, the reduction factors were 19.4%, 16.5%, and 17.8% for the soils a, b, and c respectively. In the case of the end-bearing stone column, the shear parameters of the three types of soils, a, b, and c show a negative correlation with the creep settlement under the embankment, the reduction factors were 9.4%, 10.8%, and 13.0% for the soils a, b, and c respectively. In the case of three soils a, b, and c, the improvement factor of floating stone columns was greater in creep settlement than in primary settlement; the difference between improvement of creep settlement and primary settlement was 0.149, 0.198, and 0.139 for the soils a, b, and c respectively. In the case of three soils a, b, and c, the improvement factor in the end-bearing stone columns was greater in creep settlement than in primary settlement; the difference between improvement of creep settlement and primary settlement was 0.065, 0.065, and 0.063 for the soils a, b, and c respectively. The floating stone column horizontal displacement in soils a, b, and c shows a negative correlation with the shear parameters,

![Figure 8: Comparison of vertical stress, (A) floating, (B) end-bearing.](image-url)
the reduction of horizontal displacement was 55.3%, 31.1%, and 54.0% for the soils a, b, and c respectively. The end-bearing stone column horizontal displacement in soils a, b, and c shows a negative correlation with the shear parameters, the reduction of horizontal displacement was 53.5%, 26.5%, and 14.8% for soils a, b, and c respectively. The vertical stress in both floating and end-bearing stone columns, in soils a, b, and c shows the same pattern of stress distribution on the soil under embankment for soils a, b, and c respectively.

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