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Assessment the Behavior of Stone Columns under Confined Compression

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Abstract. The emphasis of current work is on assessing the settlement improvement ratio, which is described as the ratio between the settled soils treated with a stone column and the settlement of the non-treated soil ($S_r = S_{\text{treated}}/S_{\text{untreated}}$). The research was conducted using a 300 mm diameter and 300 mm high stone-column container testing model. On 14 modeled stone columns made only from crush stones and using various backfill content, model tests including static axial compression tests were performed. The substance used in the stone backfill column had been changed by sand or lime or cement percentages. The shear strength prepared by the containers varied between 5.5 kPa and 13.5 kPa. Results show that the settlement ratio values, S_r achieved with crush stone, crushed stone +50% sand, crushed stone +5% dry lime, crushed stones +10% dry lime, crushed stone +2.5% cement +5.0% crushed stone +5.0% cement, respectively, was 0.23, 0.12, 0.16, 0.15 and 0.09. In other words, there is a drop in the settlement from 77% to 91%.

Keywords: Stone column; confined; soft clay; settlement.

1. Introduction

There were some issues due to the soft or heavy clay soil's poor potential as foundations ($< 40 \text{ kN/m}^2$). In several parts of the world, soft clay reserves are commonly found. The values for N in standard soil penetration tests differ from 0 to 4, and the untrained shear strength of vane shear tests and the average untrained strength of vane shear tests ranged from 10 to 60kPa [1]. Soft soils need to develop their properties if they need to be used as a base. Several soil improvement methods such as sand drain, dynamic compaction, and stone columns are used as inexpensive alternatives to deep foundations worldwide. The stabilization of soft soil by constructing stone columns, which in many countries have been commonly used in the last 50 years, seems most appealing. This has to do with the viability and appropriateness of the stone column technology.

Stone columns were rediscovered in France in the 1830s, and the function of their loaded behavior is not well known. This approach involves forming vertical holes in the field filled with crushed stone, creating columns or soil-restricted 'piles.' They are suitable for soft clays and silts and for sand loss. The basic foundations, such as small isolated foundations, strip foundations, and very popular for large raft foundations, large loads and rectangles, were used for stone columns. Stone columns are typically used in geotechnical projects for ground improvement. They are mainly aimed (1) increasing shear strength to cohesive and non-cohesive soils (thus increasing carrying capacity); (2) increasing their rigidity (thus reducing settlements); (3) Increasing soil mass permeability, thus accelerating consolidation of cohesive



soils or reducing grain soil liquid susceptibility [2-12]. In the analysis of the stone column, [13] stated that the area replacement ratio (A_r) is a basic parameter, as the A_r is for the triangle pattern of the stone column

$$A_r = 0.907[D/s]^2 \quad (1)$$

where:

D: stone column diameter.

s: spacing between stone columns.

Priebe [14] suggested a semi-empirical approach to evaluate the settlement of foundations on an endless stone column grid. The soil used in this system is supposed to be moved as long as the column is installed to a point where its initial resistance coincides with the liquid status, i.e., the earth pressure coefficient is $K=1$. The assessment results are expressed as a fundamental factor of progress n_o .

$$n_o = 1 + \frac{A_c}{A} \left[\frac{1/2 + f(\mu_s, A_c/A)}{K_{ac} \cdot f(\mu_s, A_c/A)} - 1 \right] \quad (2)$$

$$f(\mu_s, A_c/A) = \frac{(1-\mu_s)(1-A_c/A)}{1-2\mu_s + A_c/A} \quad (3)$$

$$K_{ac} = \tan^2(45 - \phi_c/2) \quad (4)$$

A Poisson's ratio of $\mu=1/3$, in some instances, is sufficient for the state of final settlement, resulting in a clear expression.

$$n_o = 1 + \frac{A_c}{A} \left[\frac{5-(A_c/A)}{4K_{ac} \cdot (1-A_c/A)} - 1 \right] \quad (5)$$

Where

$A_r = A_c/A$, is the area replacement ratio;

A_c = cross-sectional area of one stone column;

A = the area of soil surrounding each column,

ϕ_c is the stone column's internal friction angle.

The basic improvement factor n_o , also known as Priebe's settlement improvement factor, can be summarized as follows:

$$\text{Settlement improvement factor} = \frac{\text{Settlement of untreated soil}}{\text{Settlement of treated soil with stone column}} \quad (6)$$

or

$$\text{Settlement improvement factor} = \frac{S_{\text{untreated}}}{S_{\text{treated}}} \quad (7)$$

Figure 1 illustrates the relationship between the improvement factor n_o , the corresponding A/A_c ratio, and the backfilling angle of the ϕ_c , which is in the derivation. This paper aims to investigate the behavior of stone columns in confined compression to determine the settlement improvement ratio. Sr. The crushed stone was examined separately then mixed with different additives such as sand, lime, and cement with sand or lime or cement in different percentages. The modifications of the backfill material and their effect on settlement improvement ratio S_r were also investigated.

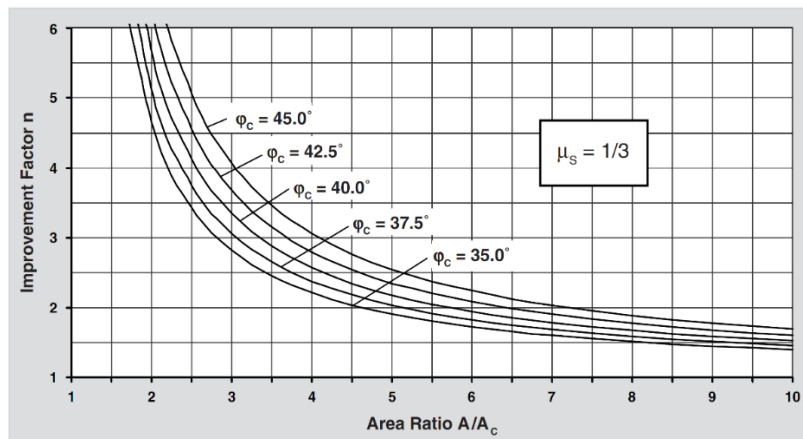


Figure 1. Design chart for vibro replacement [14].

2. Testing equipment and procedure

The entire setup consisting primarily of a steel container, a loading frame, and other accessories. These include three-dial gauges (with an accuracy of 0.01 mm) above of model to measure the settlement of the stone column and surrounding soil, and two proving rings at the top of the model to measure the applied total stress simultaneously and the stress supported by the stone column. The model tests were carried out in a cylindrical steel container, 300 mm in diameter and 350mm in height made of steel plate (6 mm in thickness). The soil used was brought from the vicinity of Al-Musaib technical college in Babylon, Iraq. The soil consists of 32% sand, 41% silt, and 27% sand. Table 1 shows the physical properties of soil used in model tests. The tests were carried on a single stone column of 100 mm in diameter and 300mm in height. The natural calcium carbonate crushed stone was used as a backfill material. These sizes were chosen in accordance with the guidelines suggested by [16], where the particle size 1/6 to 1/7 of the diameter of columns. Uniform fine sand (diameter =2 mm) was mixed with crushed stone to prepare (stone + sand) column. A commercial hydrated lime was used in this investigation as a stabilizer. A Sulphate Resisting Portland cement was used in this investigation as a stabilizer. The experimental work can be divided mainly into six groups of stone column according to the material that composes it, as follows:

- 1) Crushed stone without additives.
- 2) Crushed stone plus 50 percentage of sand.
- 3) Crushed stone plus 5 percentage of dry lime.
- 4) Crushed stone plus 10 percentage of dry lime.
- 5) Crushed stone plus 2.5 percentage of cement.
- 6) Crushed stone plus 5 percentage of cement.

Table 1. Physical properties of the soil sample.

Property	Soil used
Liquid limit (LL)	33%
Plastic limit (PL)	17%
Plasticity index (PI)	16%
Specific gravity (GS)	2.72
% Passing sieve No. 200	68%
Sand content	32%
Silt content	41%
Clay content < 0.002 mm	27%
Maximum dry density kN/m^3	17.8
Description according to unified	CL

3. Model Preparation and Testing

3.1 Preparation of the Bed Soil

A relation between the water content and the undrained shear strength of the soil was formed before the preparation of the bed of soil. Swedish falling cone penetrates measured the untreated shear strength; see Figure 2.

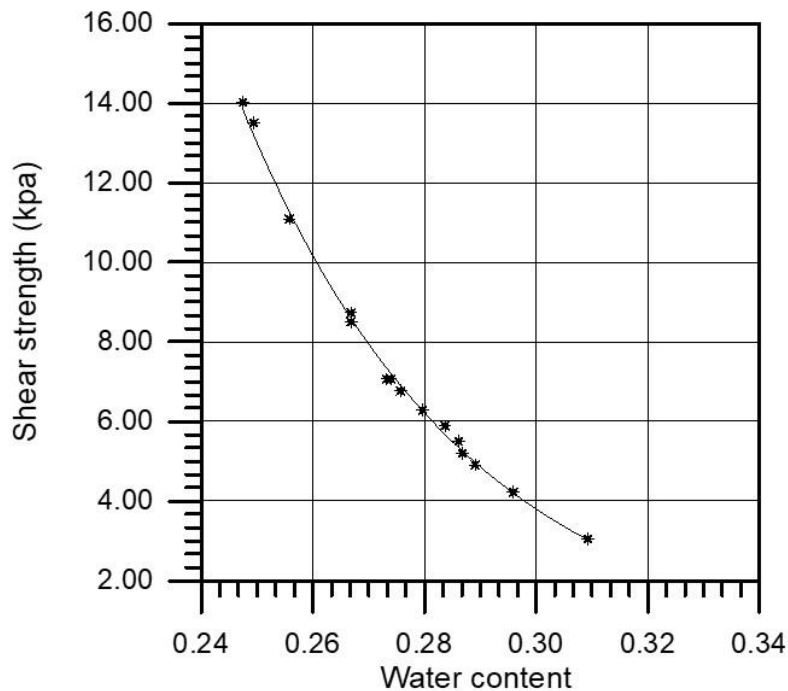


Figure 2. Shear strength-water content relationship.

The soil was mixed with sufficient water quality to obtain the desired shear strength. In each layer, a special tamping hammer (50 mm × 50 mm) was used to compact the soil inside the mold. The thickness of each layer was around 50 mm. The operation proceeded to the end of the soil bed at 300 mm thick. After the preparation of the soil bed was completed, nylon sheets were firmly covered, and the cure time remained for four days.

3.2 Construction of stone column

The following points can describe the process of constructing stone columns:

- 1) The top of the bed of the clay sample was lifted at the end of the curing time. A hollow PVC tube (32 mm) and (2 mm) of external diameter was pushed vertically to the necessary depth in the center of the clay sample layer.
- 2) During the lifting process, the tube was slowly drawn and twisted. The soil was removed from the tube, and samples of the soil were taken at various depths to determine the water content.
- 3) The crushed stone was compacted with a roll in diameter of 30 mm and in layers into the hole with and without sand or lime or cement. As compacted the crushed stone weighed 16.3 kN/m³.
- 4) The entire bed of clay sample was covered with a nylon board, isolated from any humidity losses, and left 10 days. The temperature was measured regularly during the time span.

3.3 Model testing procedure

After ten days, the footing assembly was positioned such that the center of the footing coincided with the center of the hydraulic jack. Loads were then applied through a loading disk in the form of load increments. Each rise in load lasted 2.5 minutes constantly. The dial gauge readings were registered at the end of each load cycle. Dial gauge measurements of two proving rings were taken during each load

increment. The load rises continued to exceed 300 kPa in total pressure. Untreated soil samples for comparative purposes have been loading performed.

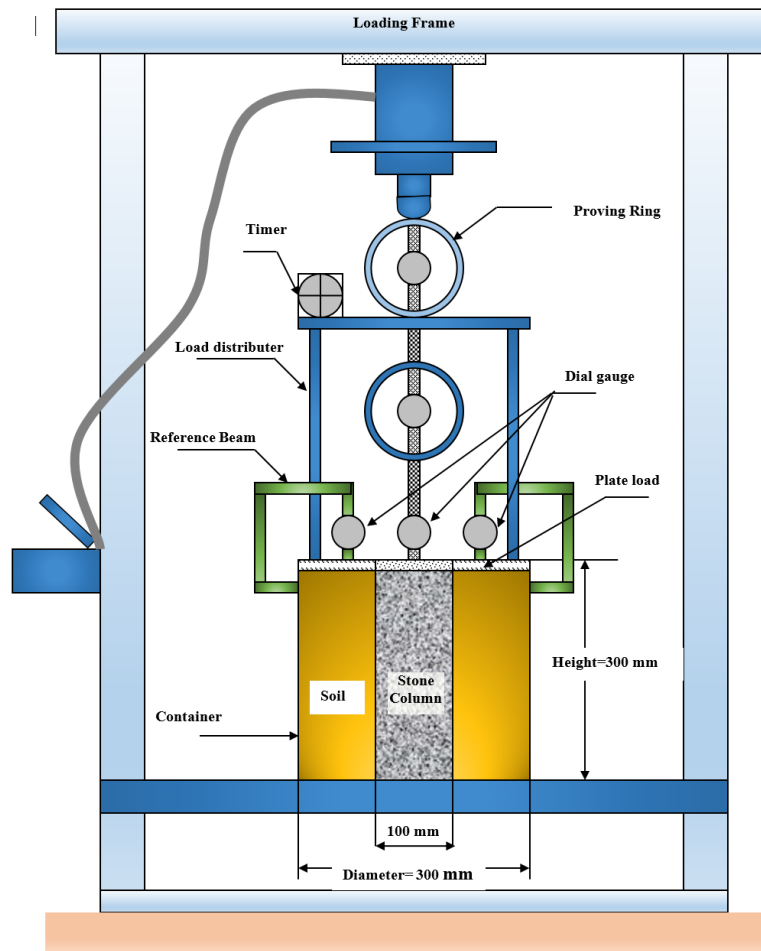


Figure 3. Details of the complete set up.

4. Results and discussion

A parameter or ratio called settlement improvement ratio is used to analyze the results of the current study. The settlement improvement ratio can be described as the ratio of the settlement of stone-column-treated soil to untreated soil settlement ($S_r = S_{\text{treated}}/S_{\text{untreated}}$). The asymmetrical stress around the stone column confined by the soil tank wall was determined by applying the axial loading on composite material (soft clay soil- column) within the circular mold to reflect the confined compression state. The other-dimensional parameter used in the representation and analysis of the research results, called stress ratio or (q/c_u), is the applied load ratio to the undrained shear strength of the soil. Figure 4 shows the variation of S_r with q/c_u ratio for soil treated with stone column only which is tested immediately and after 10 days of curing. It can be seen from Figure 4 that the S_r was 0.17, 0.25, and 0.66 when the soil-column system tested immediately, but when this system tested after 10 days as a curing period, the previous S_r values are decreased to 0.15, 0.23, and 0.34 for soil sample with undrained shear strength, $c_u = 5.5, 8.5, 13.5$ kPa, respectively.

It can be concluded from Figure 4 that the effect of soil treatment with the stone column is evident when the shear strength is low, and that is to increase the stiffness of soft soil due to the use of crushed stone material with high elastic modulus. In addition, the settlement of soil treated with the stone column is reduced after 10 days as a treatment period due to increased water drainage from the soil model surrounding the stone column, which in turn increases the shear resistance of the soil.

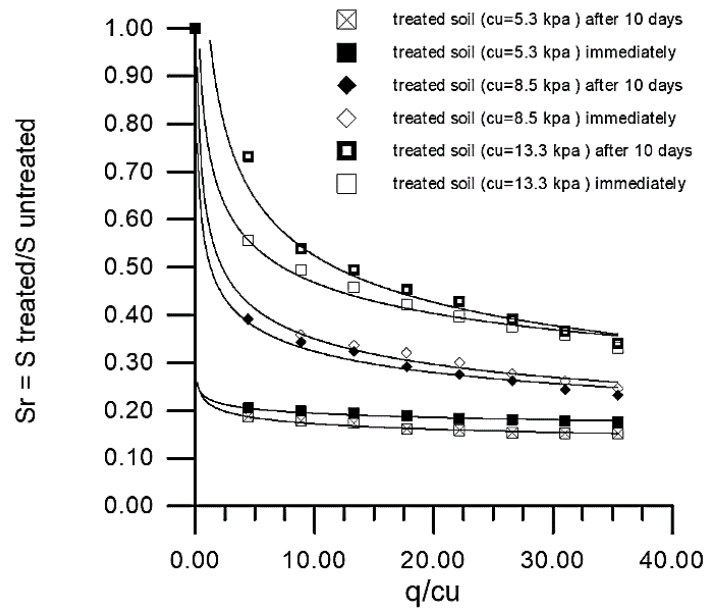


Figure 4. Variation S_r with stress ratio for clay treated with stone column (Tested immediately and after 10 days of curing).

Figure 5 shows the relationship between S_r and q/c_u , of the soil model treated with stone column modified with dry lime, with two different percentages, 5%, and 10%. It can be noticed from Figure 5; the settlement improvement ratio has been halved. This can be attributed to the fact that the presence of dry lime leads to increased water leakage from the soil sample, leading to its strengthening it. Figure 6 depicts the relation between S_r and q/c_u for a soft clay soil treated with a stone column rehabilitated with two different percentages of cement at 2.5 and 5%. Figure 6 clearly indicates that the settlement improvement factor has been substantially decreased. This is because dry cement's presence stiffens the soil-column structure, causing the soft soil to harden. Figure 7 relates the settlement improvement ratio, S_r plotted versus q/c_u for six groups of model tests of soil of $c_u = 8.5$ kPa, treated with the stone column. All the groups exhibited the same behavior of rapid decrease in S_r occupied by the initial stress increments. When q/c_u exceed 10, the S_r values reached constant values and continued until the end of the test. Among all the improvement techniques, the use of 5% cement with crushed stone provided the most efficient reduction i.e., the lowest settlement improvement ratio shown in Figure 7. Following that is the model with 2.5% cement.

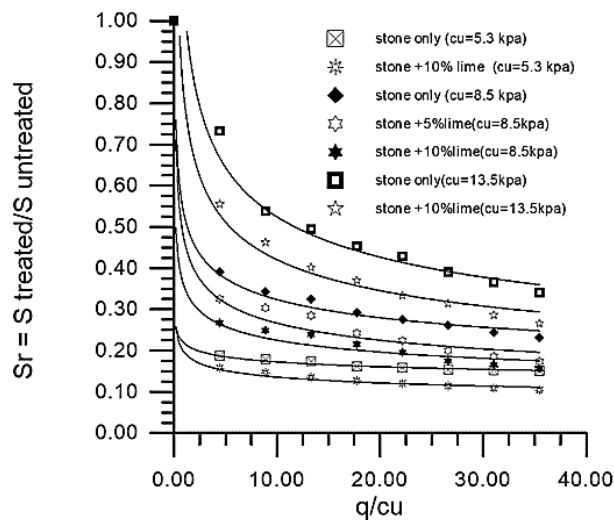


Figure 5. Variation S_r with stress ratio for clay treated with stone only and (stone + lime).

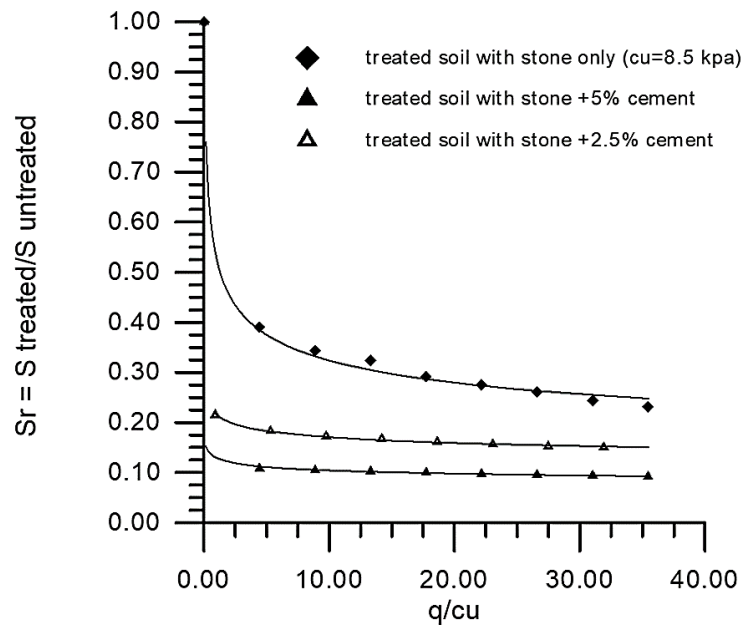


Figure 6. Variation Sr with stress ratio for clay treated with stone only and (stone + cement).

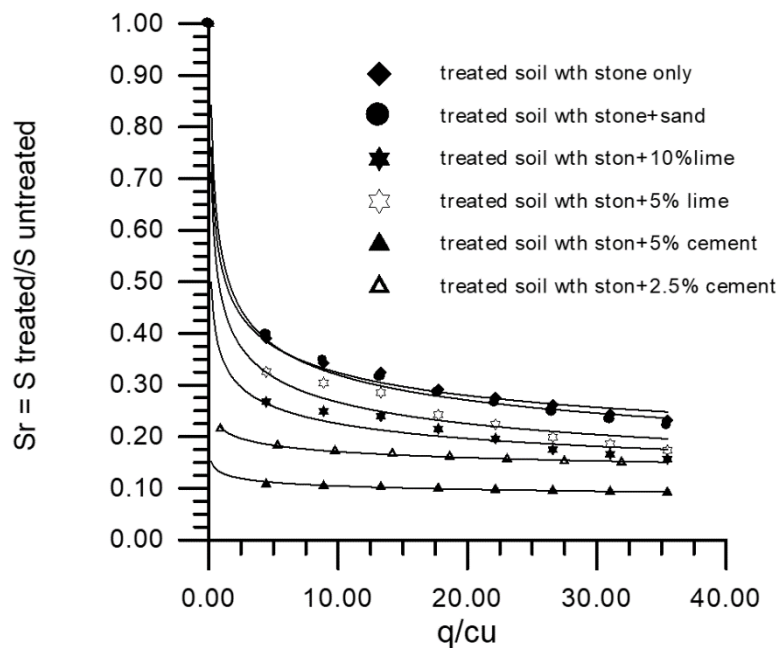


Figure 7. Variation Sr with stress ratio for clay treated with stone only, (stone + lime) and (stone + cement), $c_u = 8.5$ kPa.

The models of stone column and stone mixed with sand provided very close results indicating no effect for the presence of sand. The discrepancy between the stone column and other improvement techniques decreases with increasing the (q/c_u) , and this discrepancy reaches its minimum value when (q/c_u) ranges from 25 to 35. Very close results appear when comparing between (stone+10% lime) column and (stone+5% lime) column within the range of (q/c) between 29 to 35. Figures 4 to 7 show that decreasing the treated soil's shear strength reduces the settlement improvement ratio. The value of settlement improvements was also found to be lower than the value extracted from the treated soil after 10 days of curing if the stress was applied immediately after preparation. The effect of drainage may

be due to this action. The settlement improvement ratio S_r obtained from different model tests is shown in Table 2.

Table 2. Summary of settlement improvement ratio S_r from various model tests.

Model tests	Model tests	c_u (kPa)	S_r
		5.5	0.15
	After 10 days	8.5	0.23
Stone only		13.5	0.34
		5.5	0.17
	Immediately	8.5	0.25
		13.5	0.66
Stone +50% sand	After 10 days	5.5	0.14
		8.5	0.22
Stone +5% dry lime	After 10 days	8.5	0.16
		5.5	0.10
Stone +10% dry lime	After 10 days	8.5	0.16
		13.5	0.27
Stone+2.5% cement	After 10 days	8.5	0.15
Stone+5% cement	After 10 days	8.5	0.09

5. Conclusions

- Results show that the values of S_r obtained by crush stone, crush stone by 50%, crushed stone by 5% by dry lime, crush stone by 10% by dry lime, crush stone by +2.5% cement by crushed stone, crushed stone by 5% by cement by crushes, have been 0.23, 0.22, 0.16, 0.16, 0.15 and 0.9 respectively.
- When the shear strength is low, the effect of soil treatment with the stone column is visible, which is to increase the stiffness of soft soil due to the use of crushed stone material with a high elastic modulus, i.e., the value of settlement ratio, S_r increases as the shear strength of the underlying soil decreases.
- The S_r of soil treated with a crushed stone is clearly reduced after 10 days of curing due to an increase of water drainage from the soil sample surrounding the stone column, which increases the soil's shear strength.
- When the stone column was modified with dry lime, the settlement improvement ratio was cut in half. This is due to the fact that the presence of dry lime increases water leakage from the soil sample, thus reinforcing it.
- As the crushed stone was strengthened by cement, the settlement improvement factor was significantly reduced. This is because dry cement's presence stiffens the soil-column structure, allowing the soft soil to harden.

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