Effect of Stone Density and Stone Cushion on the Behavior of Soft Soils Improved by Stone Columns

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Abstract: For low-rise buildings and structures such as liquid storage tanks, abutments, embankments and factories that can tolerate some settlement when found on soft soils. Stone columns (also known as granular piles or granular columns) provide an economical method to increase the bearing capacity, reduce the settlement and accelerate the consolidation of soft soils. Their behavior depends on several factors such as the density of stone that forms the columns. This paper presents the results obtained from finite difference analysis. Three dimensional finite difference numerical model FLAC^{3D} was used in this study. The effect of stone density on the behavior of stone columns group in soft clay soil was studied. Also, the effect of adding a stone cushion between the footing and the stone columns was studied. The numerical analysis indicated that the settlement of footing, the vertical stresses and the lateral displacement of stone columns are decreased with increasing both the value of internal friction angle (φ) of stone column material and the stone cushion thickness for the same stone column geometry and the soil condition.
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1. Introduction

Recently with the increase of population, the prices of land has increased significantly. This has made the use of areas with soft soils inevitable. Due to the lack of bearing resistance of these soils, different methods of soil improvement techniques, including stone columns as a method of strengthening the weak soil are used. Stone columns have been used in many difficult foundation sites throughout the world to increase the bearing capacity, to reduce the total and differential settlements, to increase the rate of consolidation, to improve slope stability of embankments and also to improve the resistance to liquefaction

Several researches which dealt with the stone column technique [3,5,11] have been published in the past. Alamgir*et al.*[1] presented a theoretical approach for the prediction of deformational behavior of the soft ground improved by columnar inclusions and loaded with uniform load. Ambily and Gandhi[2] stated that the increase of the bearing capacity of therein forced soft soil with stone columns depends mainly on the spacing distance between the columns. The stone columns with narrower spacing distances and smaller diameters have a greater bearing capacity and show smaller settlement as well as low lateral bulging than wider spacing and larger diameters of stone columns. Deb *et al.*[4] found significant improvement in load-carrying capacity of soft soil due to the placement of sand cushion over stone column-improved soft clay.

Ramadan *et al.*[10] found from numerical studies that the axial capacity of stone columns increases and the settlement decreases up to spacing to diameter ratio(S/d) of 2 and there is a negligible effect on the ultimate bearing capacity ratio (UBCR), if the length /diameter ratio is more than 10.

The main aim of this research is to establish a numerical model to represent improving soft clay soil reinforced with stone columns. The study was carried out using a three dimensional finite difference numerical model FLAC^{3D} to investigate the behavior of a footing resting on group of stone columns in soft clay soil. The effect of stone density of stone columns and the cushion on improved soft clay soil was studied.

2. Numerical model

The analysis was carried out using a three dimensional finite difference numerical model FLAC^{3D}. The calculation scheme performed by FLAC^{3D} takes a large number of calculation steps, each progressively redistributing an unbalanced force caused by changes to stress or displacement boundaries through the mesh, [6]. The unbalanced force is the algebraic sum of the net nodal-force vectors for all of the nodes within the mesh. The model is considered to be in equilibrium when the maximum unbalanced force is small compared with the total applied forces within the problem. If the unbalanced force approaches a constant non-zero value, this normally indicates that the failure and the plastic flow occurred within the model. By default the model is assumed to be in equilibrium when the maximum unbalanced force ratio (i.e. the ratio between the magnitude of the maximum unbalanced force and the magnitude of the average applied mechanical force within the mesh) falls below 1×10^{-5},[6].

3. Model details

For the purpose of the parametric study a model was developed containing soil, stone columns, cushions and footing as shown in figure 1. The soil was modeled to behave as a conventional elastic-perfectly plastic model based on Mohr-Coulomb failure criterion in $FLAC^{3D}$ software. Brick elements were used to model the soil. The stone column was modeled as a massive circular element with outside interface with soil. The column was divided in radial direction to four parts. The stone column was modeled to behave as a conventional elastic-perfectly plastic model based on Mohr-Coulomb failure criterion in $FLAC^{3D}$ software. The cushion had the same properties of stone column. The footing was modeled as square brick elements with 0.7 m thickness, width and length are depending on the spacing between columns. Interface element was used to represent the connection between soil and both footing and columns. The values of soil parameters described in literature were used as input for the numerical models. The used numerical model was verified by Kotp, [7].

In $FLAC^{3D}$, the Mohr Coulomb constitutive model requires wet density (γ), angle of internal friction (φ), angle of dilation (ψ), undrained cohesion (c_u), bulk modulus (K) and shear modulus (G). The bulk and shear modulus are both functions of the Young's modulus (E) and Poisson's ratio (ν) of a material that are calculated using the following equations,[6]:-

$$K = \frac{E}{3(1-2\nu)} \quad \text{..........(1)}$$

$$G = \frac{E}{2(1+\nu)} \quad \text{..........(2)}$$

A summary of the physical and elastic material properties are provided in Table 1. The groundwater table was assumed to be located at the surface of the soft clay layer.

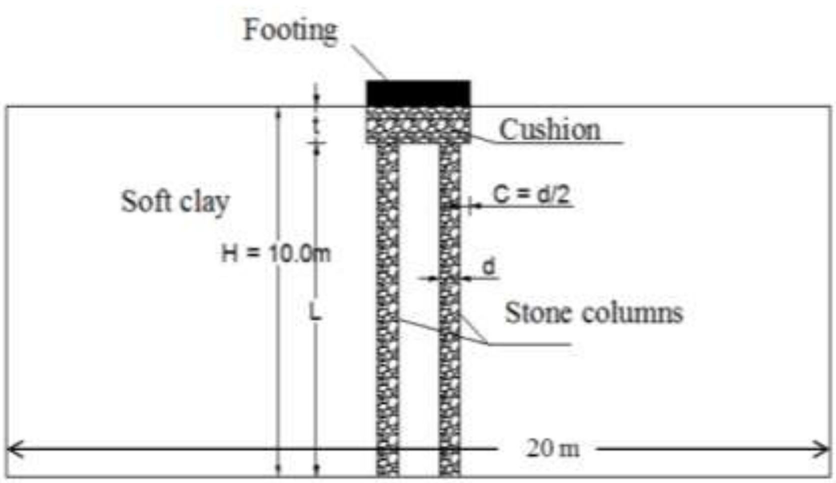


Figure 1. Model geometry

Table 1. Physical properties of used material

parameter	γ (kN/m^3)	E (kPa)	φ (º)	ψ (º)	ν	c_u (kPa)
Soft clay	17	4×10^3	0	0.0	0.45	20
Stone column	18	66×10^3, 55×10^3, 36×10^3	45º, 40º, 32º	15º, 10º, 2º	0.3	0
Footing	0	25×10^6	0		0.2	0

4. Cases of study

The main factors taken into consideration were: depth of soil layer (H), height of stone column (L), stone column diameter (d), internal friction angle of stone column material (φ) and thickness of cushion (t), the general plan of the cases of study is given in Table 2.

Table 2. The general plan of the parametric study

<table>
<tr><th>Test No.</th><th>Case</th><th>D (m)</th><th>S/d</th><th>L (m)</th><th>H (m)</th><th>L/d</th><th>φº</th><th>T (m)</th></tr>
<tr><td>1</td><td>Footing on soft clay</td><td>0.0</td><td>--</td><td>0.0</td><td>10</td><td>0.0</td><td>0.0</td><td>0.0</td></tr>
<tr><td>2</td><td rowspan="6">Footing on soft clay + stone columns</td><td rowspan="3">0.4</td><td rowspan="10">2.0</td><td rowspan="3">4</td><td rowspan="6">10</td><td rowspan="6">10</td><td>45</td><td rowspan="6">0.0</td></tr>
<tr><td>3</td><td>40</td></tr>
<tr><td>4</td><td>32</td></tr>
<tr><td>5</td><td rowspan="3">0.5</td><td rowspan="3">5</td><td>45</td></tr>
<tr><td>6</td><td>40</td></tr>
<tr><td>7</td><td>32</td></tr>
<tr><td>8</td><td rowspan="4">Footing on soft clay + cushion + stone columns</td><td rowspan="4">0.4</td><td>10</td><td rowspan="4">10</td><td>25</td><td rowspan="4">40</td><td>0.0</td></tr>
<tr><td>9</td><td>9.5</td><td>23.75</td><td>0.5</td></tr>
<tr><td>10</td><td>9</td><td>22.5</td><td>1.0</td></tr>
<tr><td>11</td><td>8.5</td><td>21.25</td><td>1.5</td></tr>
</table>

In all cases, the footing is supported by four circular stone columns. The center to center distance of the stone columns (S) to column diameter (d), spacing ratio (S/d) was 2.0. Internal friction of stone column material (φ) was changed from 32º to 45º.Thickness of stone cushion (t) was changed from 0.0 to 1.5 m.

5. Results and analysis

All obtained results from the numerical analysis for cases of study are represented in this section. The main investigated relationships are:-

1- Stress-settlement relationships
2- Contact stress distribution under footing.
3- Vertical displacement distributions.
4- Lateral deformation of stone columns.

5.1 Effect of stone column density on the behavior of soft clay soil.

The main objective of this section is to investigate the effect of stone density on the behavior of stone column- soft clay soil system. Six cases include the tests number 2 through 7, as shown in table (2), are carried out with different values of angle of internal friction (φ) of stone column material.

Figures (2a&b) show the axial stress applied on the footing versus the settlement for different values of angle (φ) of stone column material for stone column diameters, d=0.4m and 0.5m, respectively, where S/d = 2 , L/d = 10 and the depth of soft clay layer, H=10m. From these figures, it can be noticed that the ultimate axial stress on the footing increases and settlement decreases with increasing the value of angle (φ) of stone column material for both stone column diameters. The ultimate axial stress was determined by drawing double tangent to axial stress- settlement curve.

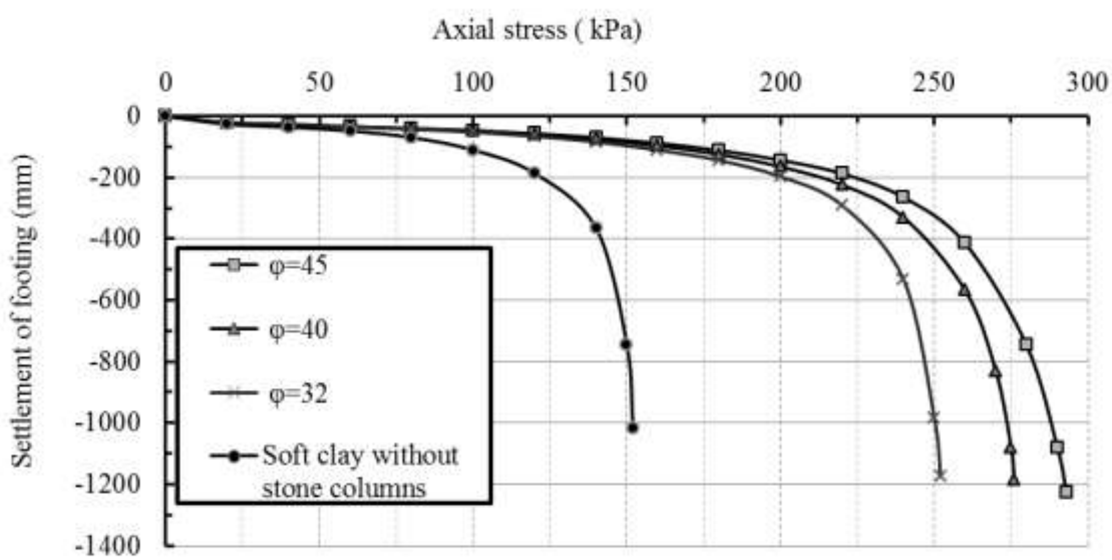


Figure 2a. Axial stress versus settlement for various values of φ (d = 0.40 m, L/d=10, S/d=2.0)

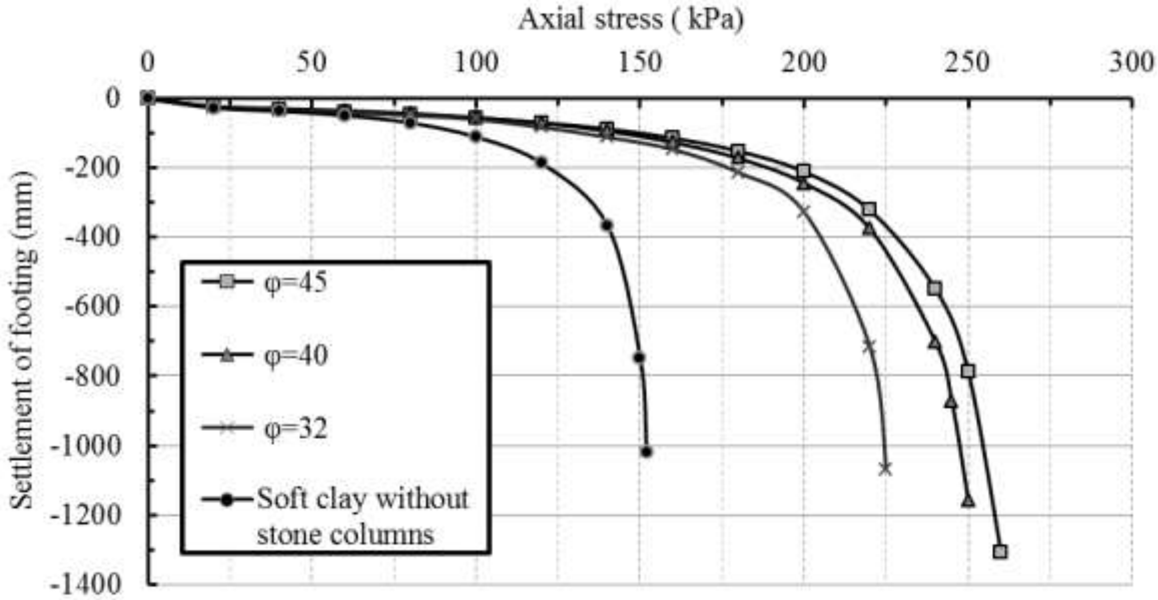


Figure 2b. Axial stress versus settlement for various values of φ (d = 0.50 m, L/d=10, S/d=2)

5.1.1 Effect of stone density on the ultimate bearing capacity ratio

To evaluate the effect of stone column on the bearing capacity of soft clay reinforced with stone column, dimensionless parameter called UBCR (Ultimate bearing capacity ratio) was used. This UBCR was defined as:

$$UBCR = \frac{\text{Ultimate bearing capacity of improved soft clay soil}}{\text{Ultimate bearing capacity of unimproved soft clay soil}} \times 100\% \quad \text{.......(3)}$$

Figure (3) shows the relationship between UBCR and different values of angle (φ) of stone column material for stone column diameter, d = 0.4m and 0.5m. It can be observed that the UBCR increases linearly with the increase of internal friction angle of stone column material(φ). With the increase of angle (φ) from 32º to 45º the UBCR increases from146.62% to 162.16% for stone column diameter 0.5 m and from162.16% to 184.5%for stone column diameter 0.4 m. Also, this figure shows that the degree of improvement of soft clay increases with decreasing stone column diameter with constant S/dratio.

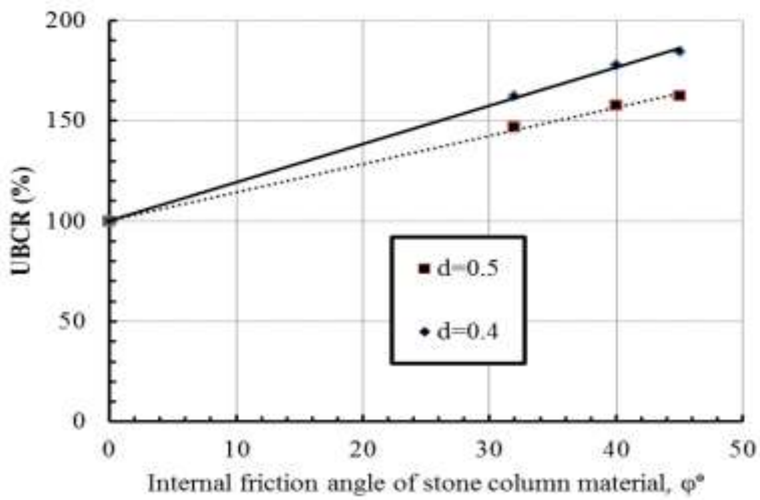


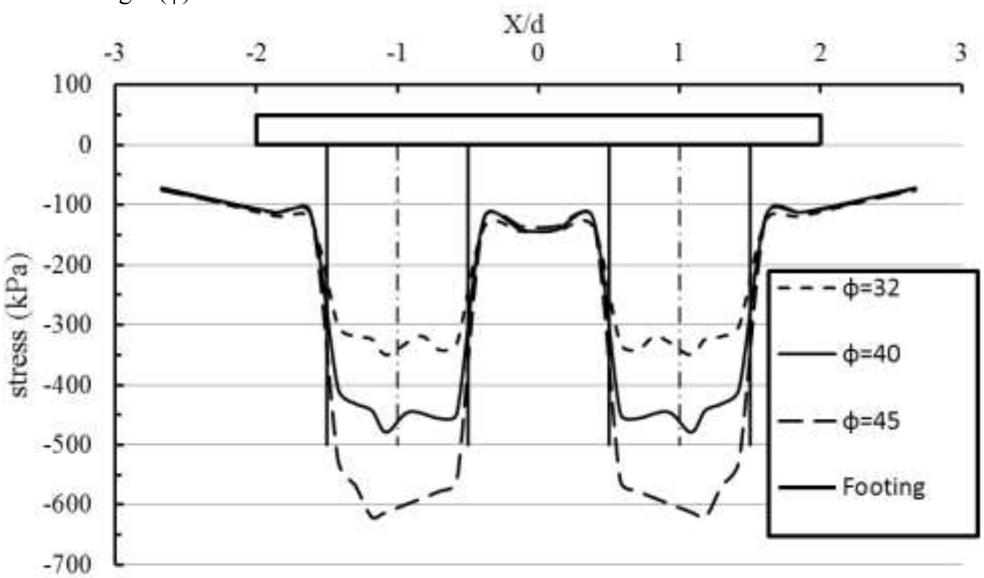
Figure 3. UBCR versus internal friction angle of stone material

5.1.2 Effect of stone density on the vertical stress distribution

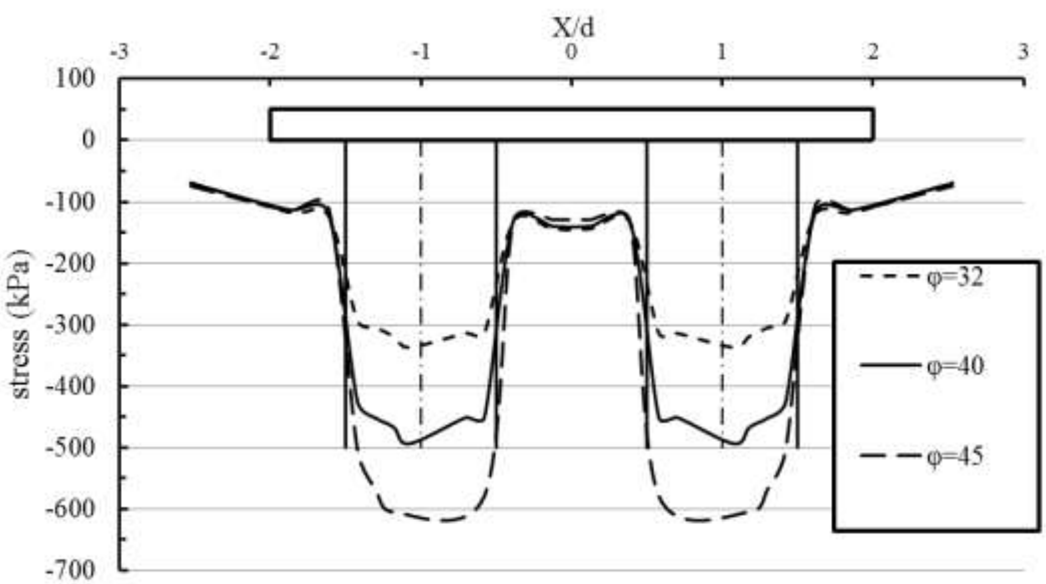
Figures (4a & b) show the contact stress distribution calculated near the surface of soft clay layer, at a distance (x) from the footing centerline at the ultimate bearing stage for the various values of angle(φ) of stone column material and stone columns diameter (d). From these figures, it can be seen that as the angle (φ) increases the stress at the stone column increases due to the increase of the bearing capacity of stone columns. Also, it can be seen that the stresses on the inner soft clay layer have no significant effect with changing the value of angle (φ).

5.1.3 Effect of stone density on the vertical displacement

Figures (5a & b) show the vertical displacement distribution calculated near the surface of soft clay layer under the footing for various values of angle (φ) of stone and stone columns diameter (d). From this figure, it can be noticed that the vertical displacement decreases with increasing the values of internal friction angle (φ). The heave of outer soil decreases with increasing the values of internal friction angle (φ).

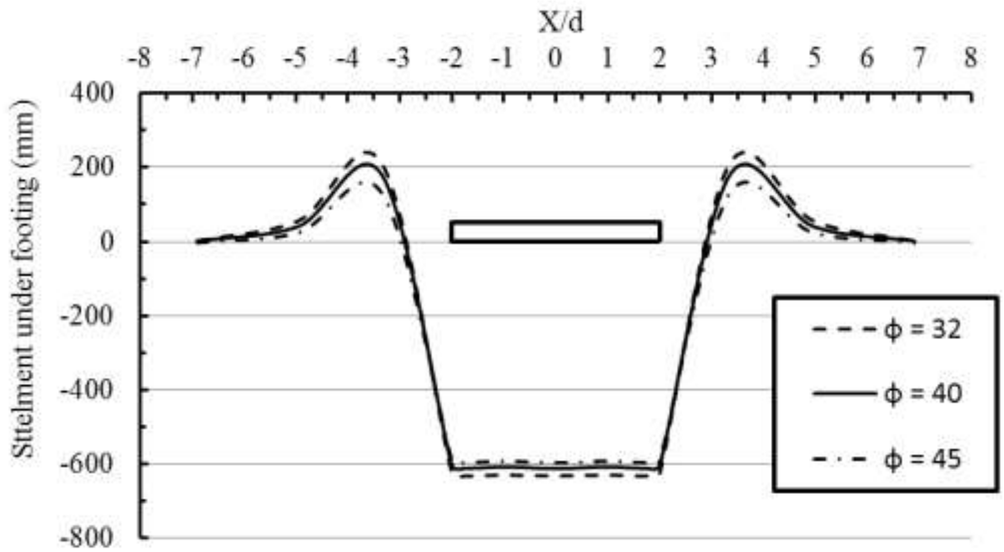


(a) d=0.4 m

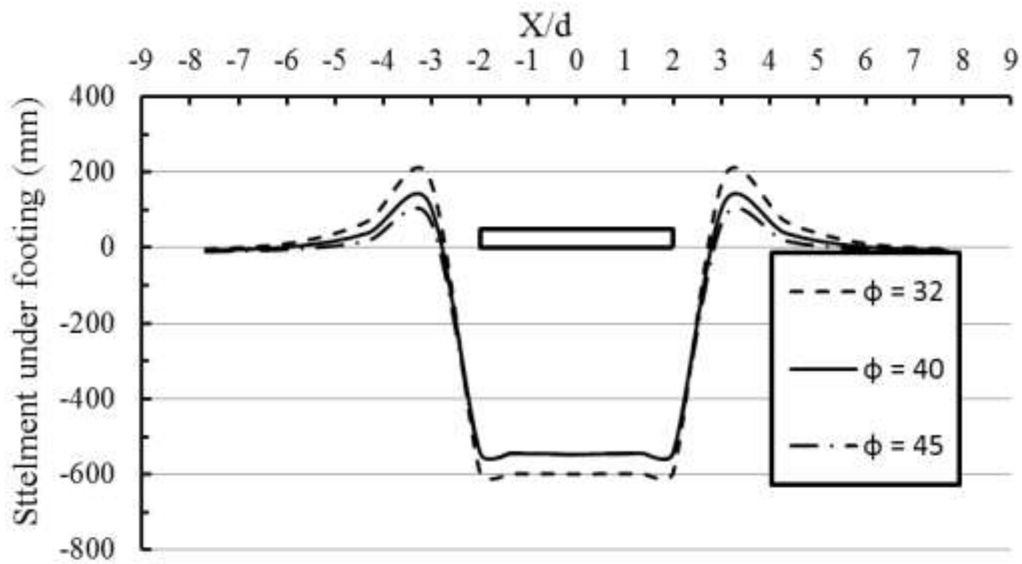


(b) d=0.5 m

Figure 4 Contact stress distribution for various values of angle of internal friction of stone (φ) (L/d=10, S/d=2.0]



(a) d=0.4 m

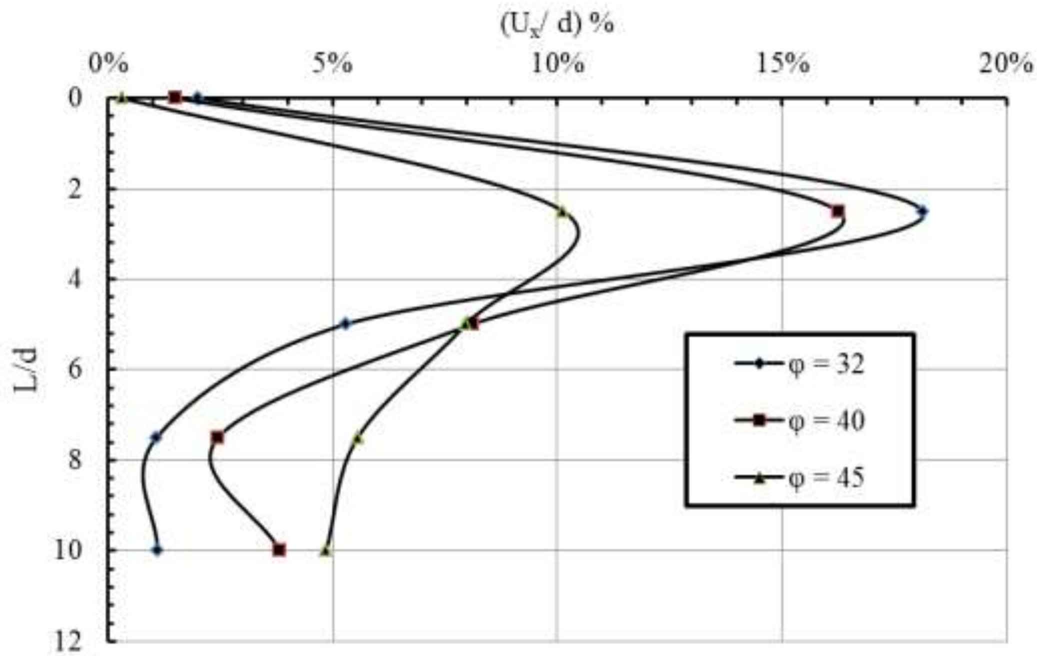


(b) d=0.5 m

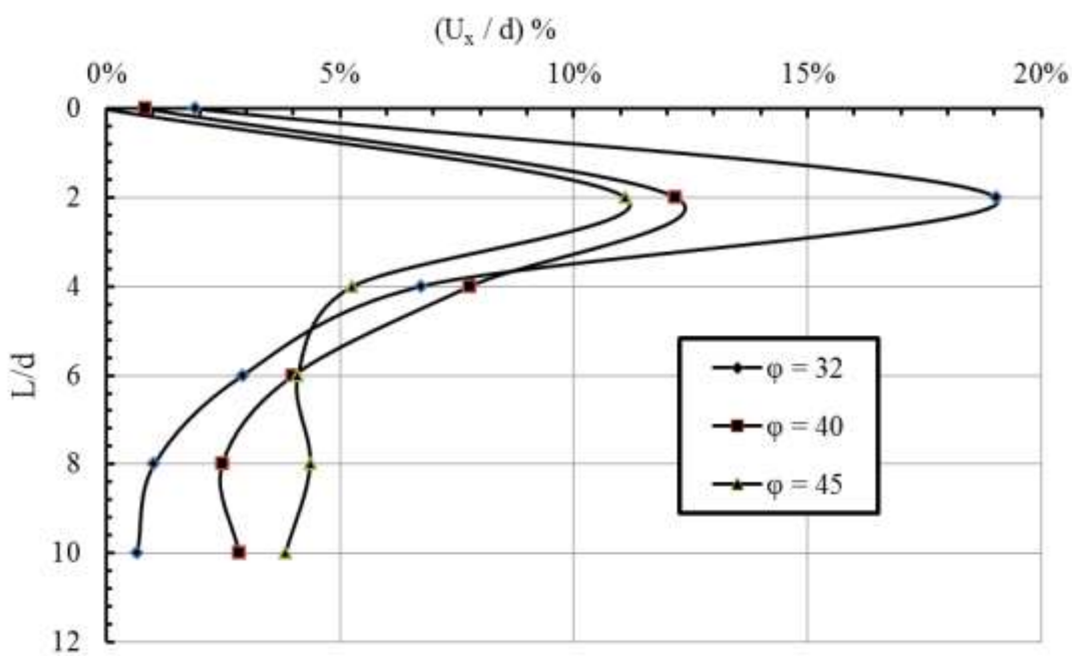
Figure 5 Vertical displacement distribution for various values of internal friction of stone (φ) (L/d=10, S/d=2.0]

5.1.4 Effect of stone density onthe lateral displacement

Figures (6a&b) show the lateral displacement of exterior stone column side to stone column diameter ratio, U_x/d, at the ultimate bearing stage for various values of angle (φ) and stone column diameter, d=0.4m and d = 0.5. From these figures, it can be noticed that the maximum lateral deformation decreases with the increase of angle (φ). Also, the depth of maximum lateral displacement increases as the stone column diameter decreases, where it equals to 2.5L for stone column diameter equals to 0.4 m and equals to 2.0 L for stone column diameter equals to o.5 m.



(a) d=0.4 m



(b) d=0.5 m

Figure 6. Lateral displacement to diameter ratio versus L/d for various values of φ

Generally, it can be concluded that the increase of stone column density, i.e. increase angle (φ) affects the improvement of soft clay soil by increasing the bearing capacity of group, decreasing the settlement of footing and increasing the stiffens of stone column to resist the vertical and lateral displacement.

5.2 Effect of stone cushion resting on stone columns on the behavior of soft clay

The aim of this part is to study the effect of stone cushion resting on the stone columns on the behavior of soft clay under the footing. Three stone cushion thickness, t=0.5, 1.0 and 1.5 m with stone columns diameter, d = 0.40 m, S/d = 2, L/d=10 and depth of soft clay layer, H=10m were studied.

Figure 7 shows the relationship between the axial stress and settlement for different values of stone cushion thickness. These curves are compared with the curve of footing resting on stone columns without cushion and the curve of footing resting on soft clay without stone columns. Settlement calculated at the center of footing under applied axial stress. From this figure, it can be noticed that the presence of stone cushion has a significant effect on increasing the axial stress and reducing the settlement of footing compared with the case without cushion. This result agrees well with that obtained by Deb *et al*.[4].

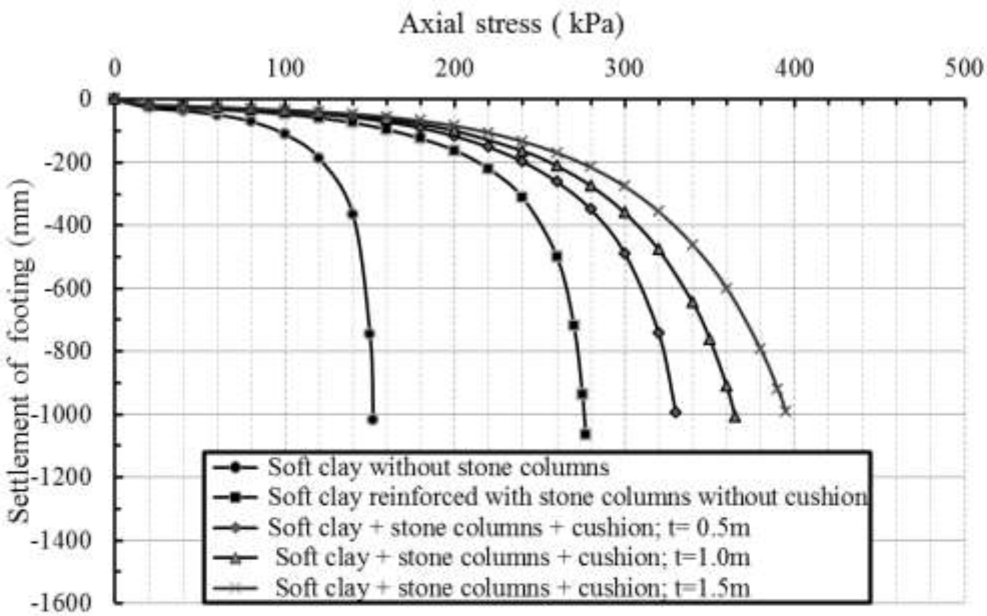


Figure 7. Axial stress versus settlement for different values of stone cushion thickness (d=0.40 m, S/d=2)

5.2.1 Effect of stone cushion thickness on the UBCR

Figure (8) shows the relationship between UBCR and stone cushion thickness for stone column diameter, d = 0.4m. It can be noted that the UBCR increases with increasing stone cushion thickness. Comparing with unimproved soft clay, the UBCR reaches to 175.67%, 212.84%, 223% and 230.4% for cases soft clay improved with stone column without and with stone cushion has thicknesses of 0.5m, 1.0m and 1.50m resting on stone column, respectively.

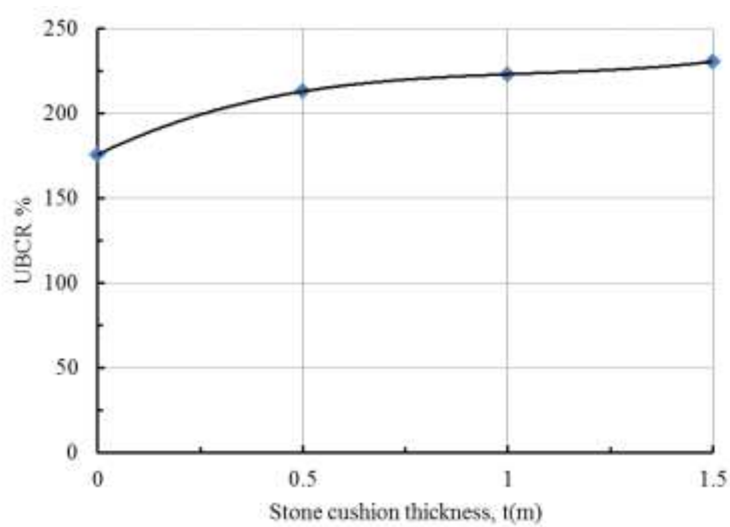


Figure 8. UBCR versus different values of stone cushion thickness (d=0.40 m, S/d=2)

5.2.2 Effect of stone cushion thickness on the bearing capacity improvement factor (BCIF).

To demonstrate the degree of improvement due to using stone cushion resting on the stone column, a non-dimensional parameter called bearing capacity improvement factor (BCIF) is introduced as:-

$BCIF = q_{imp} / q_o$……………………………….(3)

Where:-

q_{imp}:- The average bearing capacity of improved soft clay at a settlement corresponding to the settlement at the ultimate bearing capacity of unreinforced soft clay, q_{uo}.

Table 3 shows the results obtained from the numerical analysis for different study cases. These results were plotted graphically as shown in figure 9. From this figure, it can be observed that as the thickness of stone cushion increases the BCIF increases and the relation can be considered linear.

Table 3. The values of BCIF for different study cases

Cases of study	q_o (kPa) at s_{uo}=100 mm	q_{imp}(kPa) at $s=s_{uo}$=100m	BCIF
Soft Clay without stone column	148	--	1
Soft clay reinforced with stone column and without stone cushion	--	180	1.22
Soft clay + stone column + stone cushion, t=0.5 m	--	188	1.27
Soft clay + stone column + stone cushion, t=1.0 m	--	200	1.35
Soft clay + stone column + stone cushion, t=1.5 m	--	215	1.45

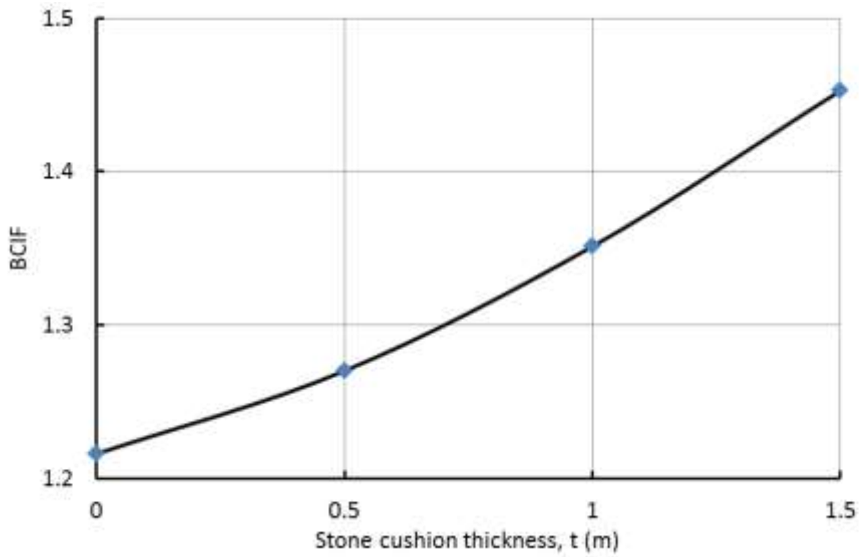


Figure 9. BCIF versus stone cushion thickness (d=0.40 m, S/d=2)

5.2.3 Effect of stone cushion thickness on the percentage reduction of settlement (PRS)

For convenience in expressing the degree of settlement reduction when stone cushion is used, nondimensional parameter referred to as the percentage reduction of settlement (PRS) introduced as:

$PRS =((S_o-S_{imp}) /S_o)\times100\%$…………………..(4)

Where: -

S_o:- The settlement of footing resting on soft clay soil without improvement corresponding to ultimate axial stress, q_o.

S_{imp}:-The settlement of footing resting on improved soft clay corresponding to axial stress equal to q_o.

The obtained results are tabulated in table 4 and plotted in figure 10. From this table and figure, it can be concluded that there is a significant effect when using stone cushion resting on stone column to improve soft clay soil. At bearing capacity equals to the ultimate bearing capacity of soft clay soil without improvement, the percent of reductions of settlement reaches values of 22%, 41%, 47% and 50% when using stone columns with stone cushions of thicknesses 0.5m, 1.0m and 1.5m, respectively. Also, from figure 10, it can be seen that the rate of increase in percent reduction of settlement is more when using stone cushion with thickness 0.5 m resting on stone column and after that the rate is decreasing with increasing stone cushion thickness.

Table 4. The values of PRS for different study cases

Cases of study	Settlement (mm) at $q=q_o$=148 kPa	PRS(%)
Soft Clay without stone column	100	0
Soft clay reinforced with stone column and without stone cushion	78	22
Soft clay +stone column + stone cushion, t=0.5 m	59	41
Soft clay +stone column + stone cushion, t=1.0 m	53	47
Soft clay +stone column + stone cushion, t=1.5 m	50	50

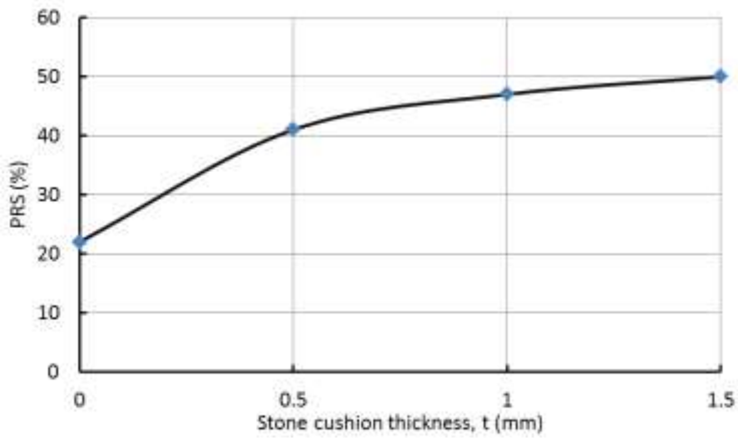


Fig. 10. Percentage reduction of settlement versus stone cushion thickness (d=0.40 m, S/d=2)

5.2.4 Effect of stone cushion thickness on the vertical stress distribution

Figure (11) shows the contact stress distribution calculated near the surface of soft clay layer under the stone cushion, at a distance (x) from the footing centerline. Theses stresses are calculated at the ultimate bearing stage for the various values of cushion thicknesses (t). From this figure, it can be observed that as the thickness of cushion increases the stresses at stone columns zone decrease. This means that the arching effect is more effective when the thickness of cushion increases. The stresses at outer soil also increase as the cushion thickness increases. The stresses at inner soil increase with the presence of stone cushion compared with that case without stone cushion. However, the stresses at inner soil decreases with increasing stone cushion thickness.

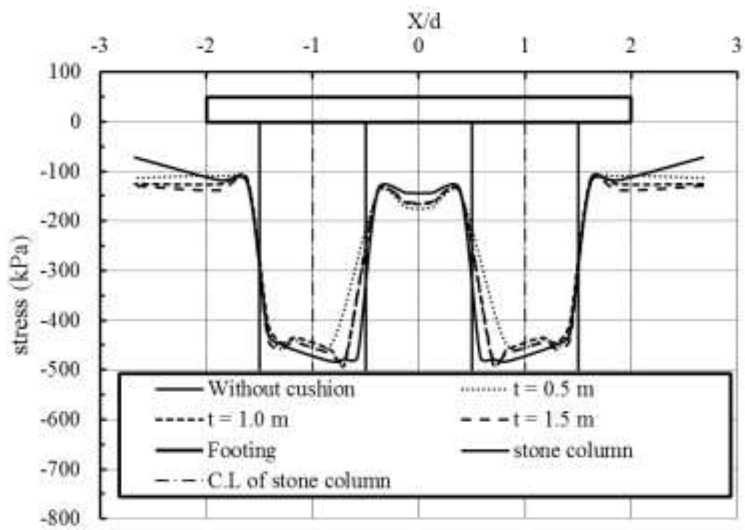


Figure 11. Contact stress distribution for various values of stone cushion thickness (t) (d=0.4m, S/d=2.0)

5.2.5 Effect of stone cushion thickness on the vertical displacement

Figure (12) shows the vertical displacement distribution calculated near the surface of soft clay under the footing. The vertical displacement was measured at a distance (x) from the footing centerline and at the ultimate bearing stage for the various values of stone cushion thickness (t). Fromthis figure, it can be observed that the vertical displacement decreases with increasing the stone cushion thickness. The heave of outer soil decreases with the increase of cushion thickness till it vanishes at t = 1.5m.

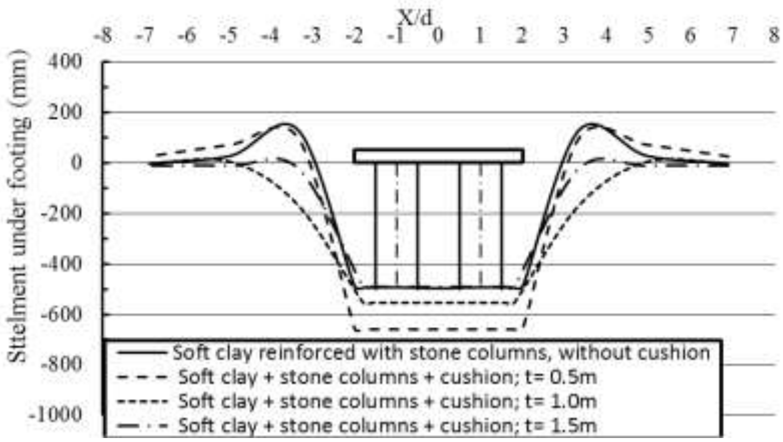


Figure 12. Vertical settlement dist ribution beneath the footing for various values of stone cushion thickness (t) (d=0.4 m , S/d=2)

5.2.6 Effect of stone cushion thickness on the lateral displacement

Figure (13) shows the lateral displacement at exterior side of stone column, U_x to the initial diameter of stone column,(U_x/d) (bulging), at the ultimate bearing stage for the various values of stone cushion thickness (t), at plane passing through the centerline of stone column. From this figure, it can be concluded that for all study cases the failure mode of stone column is bulging failure. This result is in a good agreement with the result which was obtained by previous studies [8, 9], where they stated that if the length of stone column exceeds 4-6times the diameter of column, then the main criteria which controls the failure is bulging failure and occurs at a depth equals to 2 to 3 diameter of stone-column. This means that there is no effect of stone cushion on the failure mode of stone column. Also, it can be seen that, the value of exterior bulging for stone columns without existing stone cushion was gradually started to increase and reached the maximum value at a depth equals to two and half times of the stone column diameter, after that it is started to decrease. This obtained result is in agreement with previous studies, [8,9].

Also, this behavior was occurred for cases with stone cushion resting on stone columns, but the depth of maximum exterior bulging from ground surface depends on the stone cushion thickness, where it is reached the maximum value for stone cushion thickness equals to 1.0m.

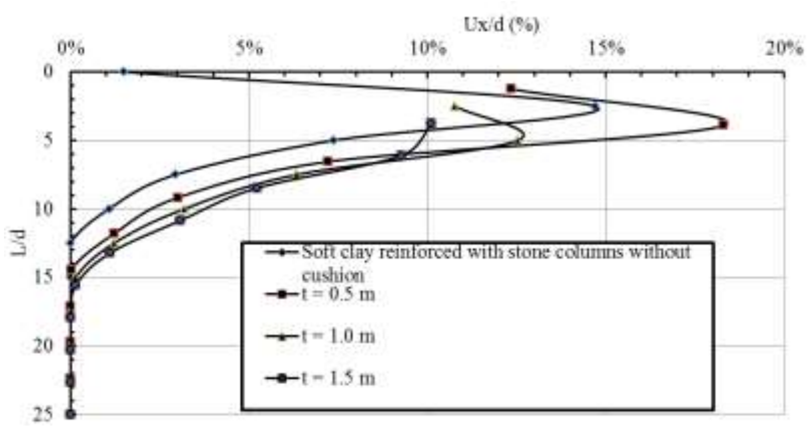


Figure 13. Lateral displacement to diameter ratio (U_x/d) versus L/d for various values of stone cushion thickness (t) (d=0.4 m, S/d=2)

Conclusions

From the numerical study for different cases of reinforced soft clay soil by stone columns with and without stone cushion, several conclusions have been drawn and can be summarized as follows:

a) Inclusion of stone columns in soft clay soil considerably improves the axial stress- settlement characteristics.

b) The ultimate bearing capacity of soft clay soil increases and settlement decreases with increasing the density of stone column, i.e. increasing the angle of internal friction (φ).

c) The vertical stresses and the lateral displacement of stone column (bulging) decreases with increasing the value of internal friction angle (φ) of stone column material for the same stone column geometry and soil condition.

d) The settlement of footing, the vertical stresses and the lateral displacement of stone column decreases with the increase of stone cushion thickness.

e) The UBCR and PRS increase with the increase of stone cushion thickness, t. The suitable and economic stone cushion thickness is recommended to be 1.0m, where there is no significant increase in both the UBCR and PRS for t>1.0 m.

f) The BCIF increases with the increase of stone cushion thickness.

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