Effect Of Using Stone Columns On The Behavior Of the Raft Foundation.

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Abstract- *A series of axis-symmetry models using finite element analyses (PLAXIS 3D) were performed to investigate the behavior of a raft foundation over clayey soil improved by stone columns (SC). Clayey soil and stone columns were modelled using hardening soil model, which uses an elastic-plastic hyperbolic stress–strain relation, and the raft foundation was modelled as an elastic element. Several parameters, including number of stone columns (n), length of stone columns (L), young's modulus of stone columns (E_{50}^{red}), thickness of raft foundation (t), and diameter of stone columns (D), are selected in this paper to investigate the influence of these parameters on the settlement, bearing capacity of soil, flexural behavior and shear of raft foundation. Finally, the results indicate that by increasing all parametric studies, bearing capacity of soil increased and settlement decreased, while the flexural behavior and shear of the raft foundation decreased in some sections. The most effective parameters for decreasing flexural behavior and settlement are diameter of stone columns (D) and Young's modulus of stone columns E_{50}^{red}; for decreasing shear is (Young's modulus of stone columns) E_{50}^{red}. Some significant observations on the performance of raft-stone column systems with changes in the values of parametric study are presented in this paper.*

Keywords: stone columns, shear, flexural behavior, and bearing capacity

1. INTRODUCTION

The use of stone columns under raft foundation to improve the settlement behavior became an important topic in the last decade. Both theoretical and experimental studies have been performed by several previous researchers to investigate the benefits of stone column system (JAN (2011) [1], Ng. (2018) [2], Nav et al. (2020) [3], Danish et al. (2021) [4], Znamenskii et al. (2021) [5] and Shehata et al. (2021) [6]). This paper discusses the behavior of a raft foundation constructed on clayey soil improved by stone columns under the influence of some factors including number of stone columns (n), length of stone columns (L), young's modulus of stone columns (E_{50}^{red}), thickness of raft foundation (t) and diameter of stone columns (D). Stone columns are ideally suited for sandy soils, according to Law et al. (2015) [7]. Clayey soils necessitate a greater number of stone columns. Due to the necessity for large machinery and a stone storage area, this method may not be ideal for those with limited mobility. Stone column ground improvement is the insertion of vertical stone columns to the ground to a depth of at least 4 meters below the ground surface. The columns can then be covered with compacted gravel in preparation for the construction of new housing foundations. In columns arranged with spacing bigger than three times diameter, Ambily et al. (2007) [8] demonstrated that the diameter of the column does not provide a significant advantage. When a single column is loaded, it fails by bulging with a maximum bulging intensity of approximately 0.5 times the diameter of a stone column. The ratio of limiting axial stress on the column to the equivalent shear of surrounding clay is found to be constant for any given s/d and angle of internal friction of stones, and is independent of the sheer strength of the surrounding clay, Killeen et al (2010) [9]. Due to the enhanced stiffness of the stone backfill, [9] discovered that a footing supported by a high number of stone columns had a substantial effect on the settlement improvement factor. A reduction in the distance between stone columns boosted the effectiveness of footing settlement. Al-Waily et al. (2012) [10] demonstrated that as the number of stone columns increased, the group efficiency decreased; additionally, stone columns were more effective than lime columns in shear (cu= 8 KPA) soil, but lime columns were more effective than stone columns in shear (cu= 14 KPA) soil. Chauhan et al (2017) [11]. According to [11], there is an inverse proportion between the diameter of the stone column and the settlement of the clayey soil, which can be attributed to the confining stresses, which are greater in stone columns with a smaller diameter. Due to confinement stresses, the failure load of the reinforced clay bed is approximately six times that of the unreinforced one, and its ultimate bearing capacity decreases by 40 percent for 100 mm diameter and 6 percent for 70 mm diameter compared to the 50 mm diameter of the stone column. Still, the earth's bearing capability was enhanced in comparison to untreated soil. Reza et al (2019) [12]. These tests demonstrate the variation of ultimate bearing capacity ratio (BCR), settlement reduction factor (SRF), and stiffness improvement factor (SIF) for stone columns with varying lengths, numbers, and diameters. According to the data, increasing the number and length of stone columns will enhance the BCR, but reduce the SRF. The increase in the diameter of stone columns will increase the BCR and reduce (SIF), the increase in lengths, diameter, and a number of stone columns leads to an increase in high ultimate bearing capacity, which reached 2.75 times of untreated soil. Samuel et al. (2019) [13] indicated that using stone columns leads to improvement in ultimate bearing capacity. The most effective material in maximum bearing capacity was hard blue granite aggregate, pebbles, and finally marble waste. Vladimir et al. (2019) [14] indicated that as the length of the stone columns grows longer, the clay layer's settlement normalized to the width of footing dimension (Δ/D) decreases. This decline in the settlement is significant until the length of the stone column is normalized to the diameter of the stone column (L/d) = 10. Nitin et al. (2021) [15] showed that using stone columns to reinforce black cotton soil increases its strength, consolidation, permeability, and swelling qualities simply and cost-effectively. Stone columns increase the load-carrying capacity of black cotton soil significantly. End bearing and floating stone columns are strengthened by increasing the diameter and the length ratio of the stone columns.

The aim of this study is to address the aspects of enhancement of the bearing capacity, settlement reduction, flexural behavior and shear of raft foundation reduction through the use of raft-stone column system. The improvement of bearing capacity, settlement, flexural behavior and shear of a raft improved by a stone column system is studied here to investigate the change of this enhancement when the point displacement is applied.

2. NUMERICAL MODELLING

The numerical models in this investigation were modelled using the PLAXIS 3-D finite element computer software. The program's results have been validated by comparing them to measures gathered from genuine case histories and research. The program can simulate stone columns, soil, footings, and foundation behavior.

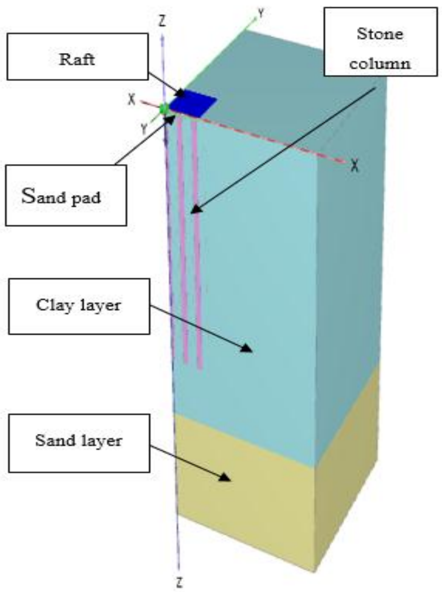
2.1. Problem definition and parametric studies

An axisymmetric model is used to replicate the model shape, with a 9 x 9 m raft foundation and a 0.06 m point displacement load positioned along the axis of symmetry. The depth and width of clayey soil are taken 27 m and 38 m respectively with square dimensions as shown in Fig 1. These model dimensions were set such that the amplitude of the collapse load remains constant even when depth and width are raised beyond the selected values. The model's vertical borders were restraint horizontally and free vertically, whereas the bottom boundary was constrained in both horizontal and vertical directions. In all finite element studies, the parameters given to the clayey soil, stone columns, sand pad, sandy soil, and raft foundation were assumed to remain constant. Various parameters affect the system's behavior. In this analysis, number of stone columns (n) =13 and 25 stone columns as it examines how stone column numbers affect system behavior. To simulate floating and end-bearing stone columns, the column length is normalized to the clay layer thickness. In order to measure the enhancement, (L/H) is varied (0.4, 0.6, and 0.8). The Young's modulus of stone column E_{50}^{red}=30, 70, 90 mPa, stone column's diameter (D=0.4, 0.6, 0.8 m) and the thickness of raft foundation (t) (0.5, 0.8, 1 m) are parametric studies in this current study.

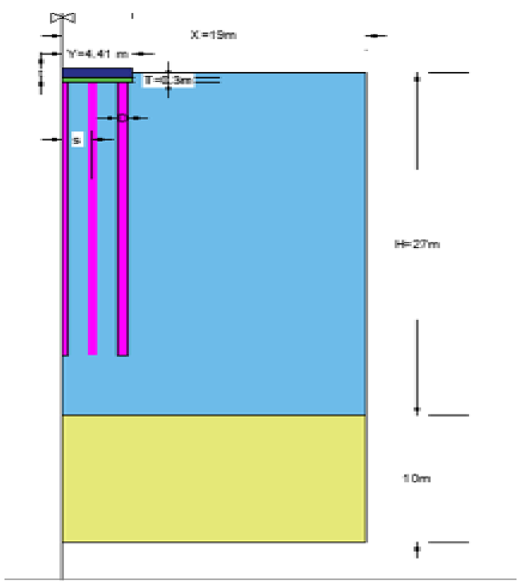
3. MATERIAL MODELLING AND MESH GENERATION

3.1. The clayey soil and stone columns.

In this numerical investigation, a hardening-soil model was employed to represent the non-linear behavior of clay and stone columns. The Hardening-Soil model represents the hyperbolic relationship between vertical strain, (e1), and deviator stress, (q). A hyperbola can adequately reflect the observed relation between axial strain and deviator stress in the current situation of a drained triaxle test. In this study, the limiting state of stress is described by the secant Young's modulus $\boldsymbol{E_{50}^{red}}$, the odometer modulus as $\boldsymbol{E_{oed}^{ref}}$ as being ($\boldsymbol{E_{50}^{red}} \cong \boldsymbol{E_{oed}^{ref}}$) according to (Elshazly et al., 2009)[16], Poisson's ratio($\boldsymbol{U_{ur}^{/}}$), unloading reloading modulus($\boldsymbol{E_{ur}^{ref}} \cong 3\boldsymbol{E_{50}^{ref}}$),effective cohesion ($\boldsymbol{C_{ref}^{/}}$), angle of internal friction ($\boldsymbol{\phi^{/}}$), angle of dilatancy (Ψ) which is ($\boldsymbol{\phi^{/}}$-30) according to McCabe et al. (2009) [17] for stone columns and ($\Psi = -\mathbf{sin}^{-1}(\frac{d}{2-d})$) using 0.0564 as the value for d) for clayey soil according to Salah et al. (2021) [18], and failure ratio (Rf). The parameters of hardening soil model for clay soil and stone columns in this current study are selected according to Salah et al. (2021) [18] and Killeen et al. (2010) [9] respectively and shown in Table -1.



(a)



(b)

Fig -1 : Raft . stone column system and soil layer (a) 3D. View (b) Side view.

Table -1: Clayey soil and stone column dates.

Material name	Clayey soil	Stone column
Material model	Hardening soil model	Hardening soil model
Drainage type	Drained	Drained
γ unsat	20 KN/m^3	19 KN/m^3
γ sat	22 KN/m^3	21 KN/m^3
E_{50}^{ref}	3400 KN/m^2	70000 KN/m^2
E_{oed}^{ref}	3600 KN/m^2	70000 KN/m^2
E_{ur}^{ref}	12000 KN/m^2	210000 KN/m^2
$C_{ref}^{/}$	33.58 KN/m^2	1 KN/m^2
$\phi^{/}$	17.51°	45°
Ψ	1.6°	15°
R_f	0.9	-
Power (m)	0.7	0.3
$U_{ur}^{/}$	0.2	-
K_0^{nc}	0.6991	0.3

3.2. Sand pad soil.

The Mohr-Coulomb failure criteria are commonly used to describe the strength of soils. A failure theory is required to relate the available strength of soil as a function of measured attributes and applied stress conditions. Its primary premise is that combining normal and shears leads to a more critical limiting condition than would be reached if either the major principle stress or maximum shear were considered individually. The major stresses caused failure, while the normal and shears produced the failure plane. Linear elastic that is perfectly elastic The Mohr-Coulomb model takes five input factors into account: young's modulus (E) and Poisson's ratio (v) for soil elasticity; cohesion (c) for soil plasticity; an angle of friction ($\phi^{/}$) and an angle of dilatancy (Ψ) which is ($\phi^{/}$ -30) according to McCabe et al. (2009) [17]. Sand pad is modelled as a Mohr Coulomb failure in this study because it is used to distribute load in all stone columns. All data for the sand pad is taken from Samanta et al. (2017) [19] and shown in Table -2.

3.3. Sandy soil.

In this research, sand represents the element volume (15-node). The sand pad is drained soil. The sand pad is modelled as a Mohr Coulomb. Table -2 shows all date for sandy soil.

Table -2: Sand Pad and sandy soil dates

Material name	Sand pad	Sandy soil
Material model	Mohr_ Coulomb	Mohr_ Coulomb
Drainage type	Drained	Drained
▯ unsat	20 KN/m^3	19 KN/m^3
▯ sat	20 KN/m^3	19 KN/m^3
E'	45000 KN/m^2	25000 KN/m^2
c'	0 KN/m^2	0 KN/m^2
ϕ'	40◦	35◦
Ψ	10◦	5◦
u'	0.3	0.3

3.4. Concrete raft foundation.

A linear elastic model considers a material to be an idealized linear-elastic material that does not deform, which prevents irreversible stresses from forming during loading and unloading. The model requires two factors to simulate the behavior: Young's elastic modulus, E, and Poisson's ratio, v. The model was used to model the concrete raft foundation behavior in this study and all the data is shown in Table -3.

Table -3: Concrete raft foundation date.

Material name	Concrete raft
Material model	Elastic
▯	25 KN/m^3
E1	25000000 KN/m^2
U12	0.2

4. MESH SENSITIVITY

In order to remain analysis and collapsing load constant, mesh is getting smaller and smaller.

5. VALIDATION

In order to support this study, the current numerical models are compared with the results obtained by Reza et al. (2019) [12]. Reza et al. (2019) [12] examined a model with a 0.4x0.4x0.02 m steel plate as a footing was loaded by 0.06 m a point displacement, sandy soil and stone columns were modelled as Mohr coulomb model and all date is shown in Table -4. Reza et al. (2019) [12] parametric studies were variation of stone column lengths such as 30, 40 and 50 cm for 5 stone columns and different stone column numbers for the same length such as 4 and 5 stone columns. The results are compared to Reza et al. (2019) [12] envelope improvement in (settlement/width of footing) versus applied load curve. The identical experimental model is modelled using the finite element method in PLAXIS 3D. Fig -2 shows that the ultimate bearing capacity of 30 cm stone columns from FE modeling is 34 KN and from experimental results is 32.5 KN and from FE modeling is 36.5 KN and from experimental results is 36.5 KN for 40cm in length. Fig -3 shows that the ultimate bearing capacity for 4 for the same length from FE modeling is 37 KN, and from experimental results is 33 KN for 4 stone columns and from FE modeling is 37.5 KN and from experimental results is 37.6 KN for 5 stone columns. This study's finite element results and Reza et al. (2019) [12] agree well.

Table -4: Reza et al. (2019) [12] date

parameter	Sand bed	Sand pad	Stone column	steel
Young's Modulus(mPa)	11	25	45	2x10^5
Poisson's ratio	0.3	0.3	0.25	0.2
Density (kN/m3)	14.5	15.8	17.25	78.5
Internal friction angle	31	41	45	-

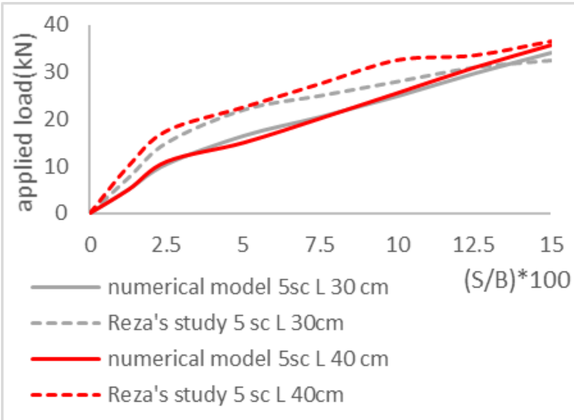


Fig -2: Envelop settlement-load curve for present work and experimental results Reza et al (2019) for different lengths.

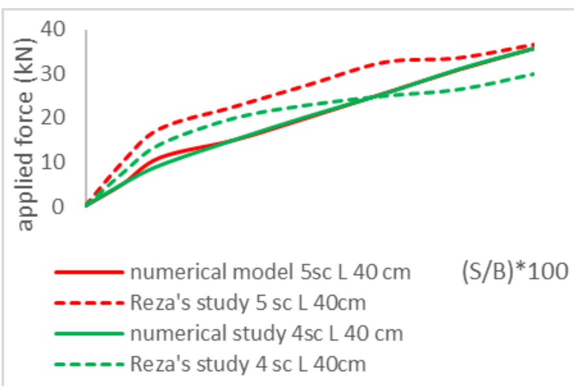


Fig -3: Envelop settlement-load curve for present work and experimental results Reza et al. (2019) for numbers of stone columns.

6. ANALYSIS CASES

Figure 1 illustrates the geometry of the model used in this analysis. The parametric study included young's modulus of stone columns (E_{50}^{red}) , thickness of raft foundation (t) and diameter of stone columns (D). This Parameters is normalized (non-dimensional) to thickness of clay layer L/H to describe the effect of the length of stone columns. Table -5 shows parametric studies in this study.

7. RESULTS AND DISCUSSIONS

A series of axis-symmetric finite element analyses were performed to investigate the improvement in bearing capacity, settlement reduction, flexural behavior, and induced shear on the raft foundation caused by the use of stone columns under a raft foundation exposed to a point displacement as load. The bearing capacity increasing factor (BIF) is used to express the increase in the bearing capacity of the raft stone column system compared to the raft foundation without stone column and is defined in Eq 1 The moment reduction factor (MRF) is used to express the decrease in the flexural behavior of the raft stone column system compared to the raft foundation without stone column and is defined in Eq 2. The shear reduction factor (SRF) is used to express the decrease in the shear of the raft stone column system compared to the raft foundation without stone column and is defined in Eq 3. In this paper, the raft foundation is symmetry, so shear is skew symmetry and moment is symmetry. Shear is drawn for half-sections in the other side moment for full sections. Flexural behavior and shear on the raft foundation analyses are divided into two sections, shown in Fig 4 and 5.

$$BIF = \frac{Bearing\ capcity_{treated} - Bearing\ capcity_{untreated}}{Bearing\ capcity_{untreated}} x100. \quad (1)$$

$$MRF = \frac{Moment_{untreated} - Moment_{treated}}{Moment_{untreated}} x100. \quad (2)$$

$$SRF = \frac{Shear_{untreated} - Shear_{treated}}{Shear_{untreated}} x100. \quad (3)$$

Table -5: Parametric studies

Group	Constant parameters	Variable parameters	Remarks
1	Untreated soil (raft foundation without stone columns)		
2	E_{50}^{red}=70 mPa, t= 0.8m, D=0.6 m, n=13 SC E_{50}^{red}=70 mPa, t= 0.8m, D=0.6 m, n=25 SC	L/H= 0.4 , 0.6, 0.8	Influence of length of stone columns
	L/H= 0.6, t=0.8m, D=0.6m, n=13 SC		Influence young's

3	L/H= 0.6, t=0.8m, D=0.6m, n=25 SC	E_{50}^{red} = 30, 70, 90 mPa	modulus of stone columns
4	L/H= 0.8, E_{50}^{red}=70 mPa, D=0.6 m, n=13 SC	t=0.5, 0.8, 1 m	Influence thickness of raft foundation
	L/H= 0.8, E_{50}^{red}=70 mPa, D=0.6 m, n=25 SC		
5	L/H= 0.8, E_{50}^{red}=70 mPa, t=0.8 m, n=13 SC	D=0.4, 0.6, 0.8 m	Influence of diameter of stone columns
	L/H= 0.8, E_{50}^{red}=70 mPa, t=0.8 m, n=25 SC		

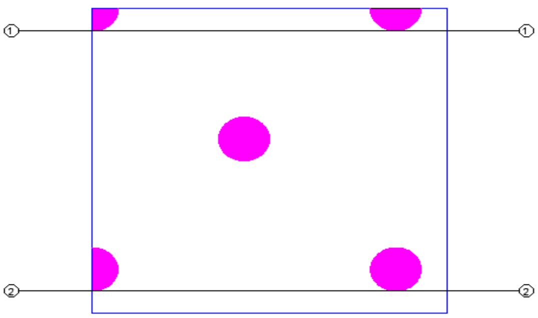


Fig -4: sections for 13 stone columns

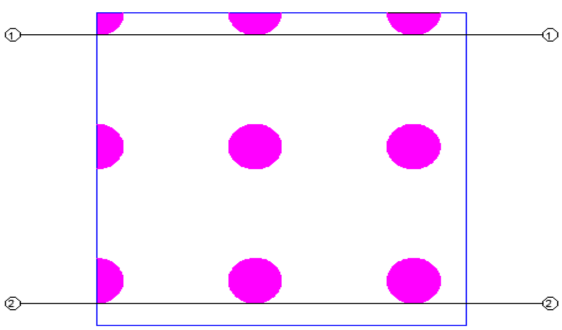


Fig -5: sections for 25 stone columns

7.1 Influence of length of stone columns

Six analytical cases are included using the axis-symmetric finite element method to explore the behavior of the raft-stone column system under point displacement. Group 2 is examined in Table -5 to determine the effect of variation of stone column lengths on the performance of the raft-stone column system for 13 and 25 stone columns while keeping the young's modulus of stone columns (E_{50}^{red}), raft foundation thickness (t), and stone column diameter (D) constant.

7.1.1 Load – settlement behavior of clayey soil

Fig -6 depicts an example of load settlement curves for both raft-stone column systems and untreated soil without stone columns. It can be noted from Fig 6 that there is a light effect of variation in stone column lengths/thickness of clayey soil (L/H). When stone column lengths/thickness of clayey soil (L/H) increased by 0.4, 0.6, and 0.8, bearing capacity increasing factor (BIF) increases for 13 stone columns by 33.24%, 36.7%, and 37.3% respectively and for 25 stone columns by 53.02%, 58.7%, and 60.08% respectively. Bearing capacity increasing factor (BIF) increases with an increasing number of stone columns.

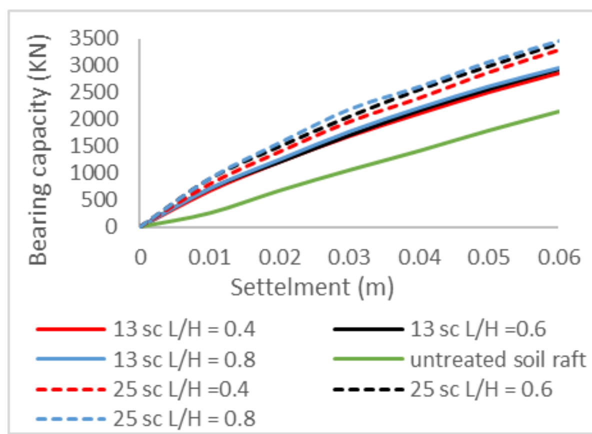


Fig -6 : Comparison between load and settlement for 13 and 25 stone columns for variation length with respect to thickness of clayey soil.

7.1.2 Flexural behavior of the raft foundation (M1-1) and shear (Q2-3).

Figs 7 and 8 show the flexural behavior of the raft-stone column system and raft foundation without stone columns for sections 1 and 2 respectively with different values of stone column lengths/thickness of clayey soil (L/H) such as 0.4, 0.6, and 0.8 and with different numbers of stone columns.

By increasing the length (L/H), moment reduction factor (MRF) increases. For 13 stone columns, the moment reduction factor (MRF) increases for section 1 by 1.98%, 2.15%, and 2.25% respectively, and for section 2 by 6.69%, 6.27%, and 7.58% respectively. For a 25-stone column group, moment reduction factor (MRF) reduces by increasing (L/H) for section 1, 2.5%, 2.42% and 2.29% respectively and for section 2, up to 10.25%, 9.46% and 9.43% respectively

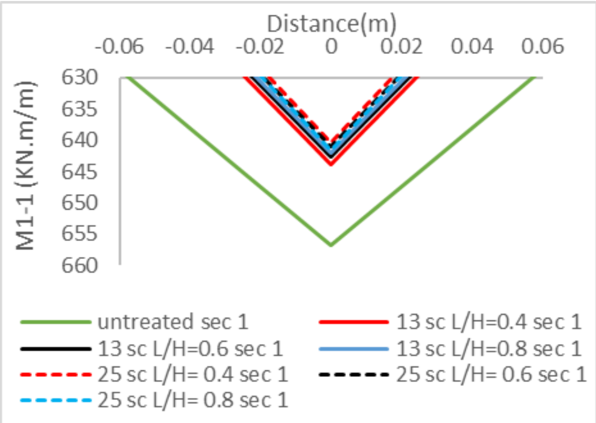


Fig -7: Flexural behavior of the raft foundation (M1-1) of section 1 for 13 and 25 stone columns (variation of stone column lengths with respect to the thickness of clayey soil (L/H))

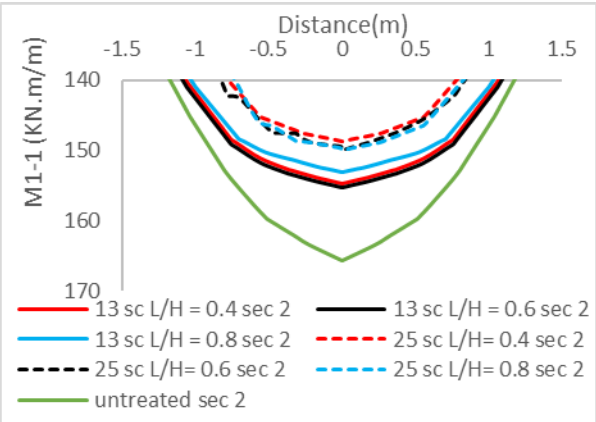


Fig -8: Flexural behavior of the raft foundation (M1-1) of section 2 for 13 and 25 stone columns (variation of stone column lengths with respect to the thickness of clayey soil (L/H))

Figures 9 and 10 illustrate the shear of the raft-stone column system and the raft foundation without stone columns for sections 1 and 2 with different values of stone column lengths/thickness of clayey soil (L/H) such as 0.4, 0.6, and 0.8 and with varied numbers of stone columns. By increasing the length (L/H), shear reduction factor (SRF) increases. For 13 stone columns, the shear reduction factor (SRF) increases for section 1 by 3.88%, 4.32% and 3.91% respectively, and for section 2 by 16.84%, 19.67% and 17.53% respectively. For 25 stone columns, shear reduction factor (SRF) reduces for section 1 up to 2.82%, 2.76% and 2.74% respectively, and for section 2 up to 28.4%, 25.8% and 27.02% respectively. While stone column numbers increase, (MRF) and (SRF) increase.

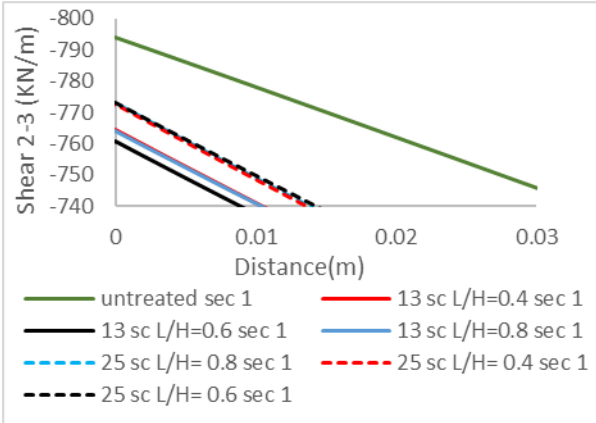


Fig -9: Shear of the raft foundation (Q2-3) of section 1for 13 and 25 stone columns (variation of stone column lengths with respect to the thickness of clayey soil (L/H))

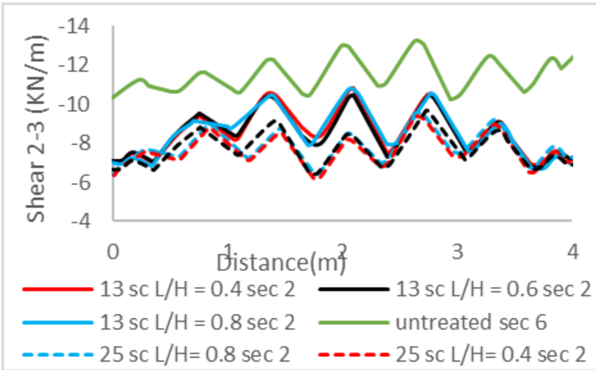


Fig -10: Shear of the raft foundation (Q2-3) of section 2 for 13 and 25 stone columns (variation of stone column lengths with respect to the thickness of clayey soil (L/H))

7.2 Young's modulus of stone columns (E_{50}^{red}).

To investigate the behavior of the raft-stone column system under point displacement, six analytical examples are conducted using the axis-symmetric finite element method. In Table -5, for group 3, the effect of varying the young's modulus of stone columns (E_{50}^{red})) on the performance of the raft-stone column system for 13 and 25 stone columns is investigated, while keeping stone column length/thickness of clayey soil (L/H), raft foundation thickness (t), and stone column diameter (D) constant.

7.2.1 Load – settlement behavior of clayey soil

Figure 11 depicts an example of load settlement curves for both raft-stone column systems and untreated soil without stone columns. Figure 11 shows that variation in the young's modulus of stone columns (E_{50}^{red}) and the number of stone columns has a significant influence. When the young's modulus of stone columns increases by 30, 70, and 90 mPa, bearing capacity increasing factor (BIF) for 13 stone columns exceeds by 26.19%, 37.3%, and 39.42% respectively, and 41.82%, 60.08%, and 63.54% respectively for 25 stone columns. Bearing capacity increasing factor (BIF) rises significantly as the number of stone columns increases.

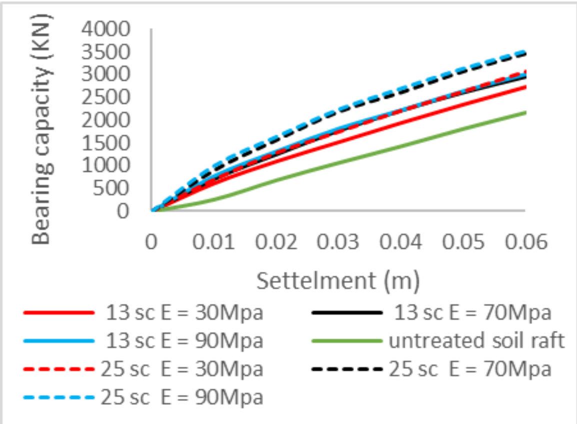


Fig -11: Comparison between load and settlement for 13 and 25 stone columns for variation of young's modulus of stone columns.

7.2.2 Flexural behavior of the raft foundation (M1-1) and shear (Q2-3).

Figures 12 and 13 depict the flexural behavior of a raft-stone column system and a raft foundation without stone columns for sections 1 and 2 respectively with different values of the young's modulus of stone columns (E_{50}^{red}) such as 30, 70, and 90 mPa and varying numbers of stone columns. For 13 stone columns, the moment reduction factor (MRF) rises by 0.7%, 1.7%, and 0.75% respectively for section 1 and up to 4.69%, 7.58%, and 5.8% respectively for section 2. For a 25-stone column group, moment reduction factor (MRF) increases by increasing (E_{50}^{red}) for section 1 by 1.95%, 2.41%, and 2.37% respectively and for section 2 by up to 8.17%, 9.43%, and 9.54% respectively.

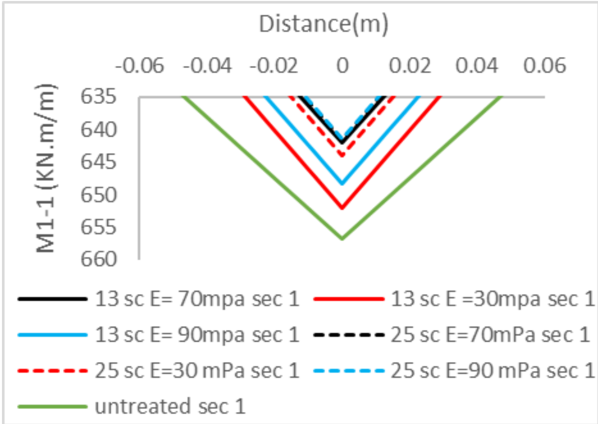


Fig -12: Flexural behavior of the raft foundation (M1-1) of section 1for 13 and 25 stone columns (variation of Young's modulus of stone columns E_{50}^{red})

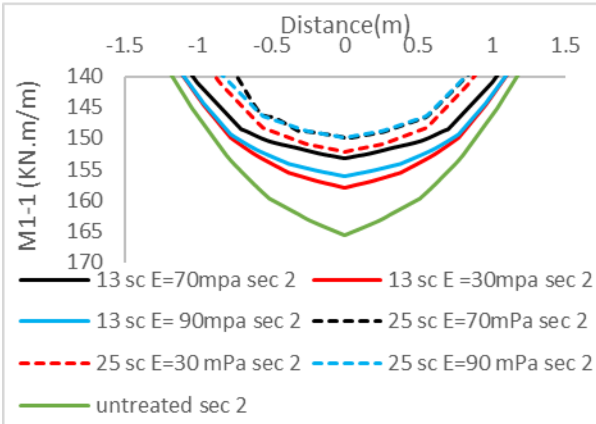


Fig -13: Flexural behavior of the raft foundation (M1-1) of section 2 for 13 and 25 stone columns (variation of Young's modulus of stone columns E_{50}^{red})

Figs 14 and 15 show the shear of the raft-stone column system and raft foundation without stone columns for sections 1 and 2 respectively with different values of Young's modulus of stone columns and with a different number of stone columns. For 13 stone columns, the shear reduction factor (SRF) increases for section 1 by 2.78%, 3.91%, and 3.39% respectively, and for section 2 up to 15.08%, 17.53%, and 18.14% respectively. For 25 stone columns, shear reduction factor (SRF) increases for section 1 up to 2.66%, 2.74% and 2.75% respectively, and for section 2 up to 24.42%, 27.02% and 27.03% respectively. While the number of stone columns raises, the moment reduction factor (MRF) and the shear reduction factor (SRF) increase.

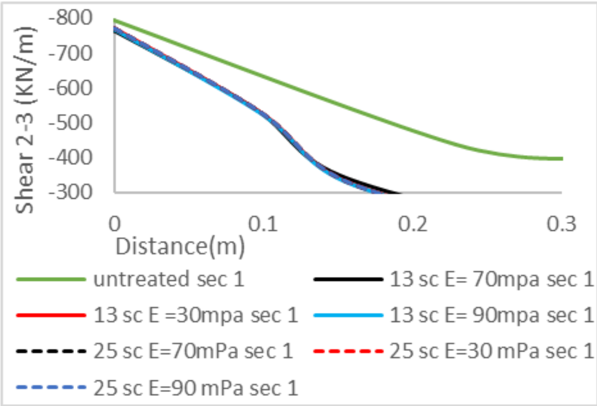


Fig -14: Shear of the raft foundation (Q2-3) of section 1 for 13 and 25 stone columns (Young's modulus of stone columns E_{50}^{red})

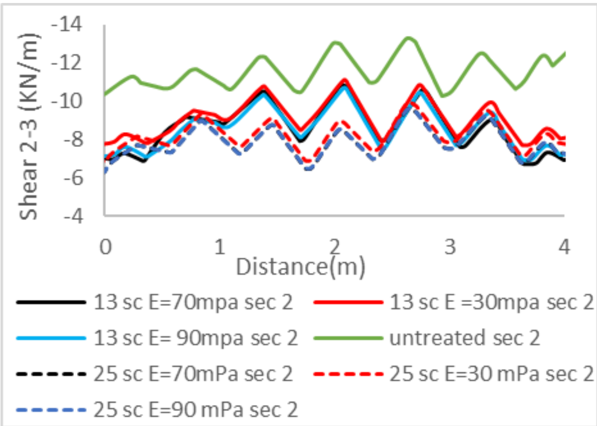


Fig -15: Shear of the raft foundation (Q2-3) of section 2 for 13 and 25 stone columns (Young's modulus of stone columns E_{50}^{red}.

7.3 Thickness of raft footing (t).

Six analytical cases are performed using the axis-symmetric finite element method to explore the behavior of the raft-stone column system under point displacement. The impact of modification in raft footing thickness (t) on the performance of the raft-stone column system is explored in Table -5 for group 4 as various thickness of raft foundation values for 13 and 25 stone columns while keeping stone column length/thickness of clayey soil (L/H), young's modulus of stone columns (E_{50}^{red}), and stone column diameter (D) constant.

7.3.1 Load – settlement behavior of clayey soil.

The effect of the thickness of the raft foundation on the performance of the raft-stone column system is presented in Fig -16. It shows the general trend of load settlement relations for different values of (t) and the number of stone columns. Fig -16 presents the results of the analyses for Group 4. The results show that there is a significant effect of the variation of the thickness of the raft foundation on the load-settlement behavior of the raft-stone column system, and by increasing the number of stone columns, bearing capacity increases.

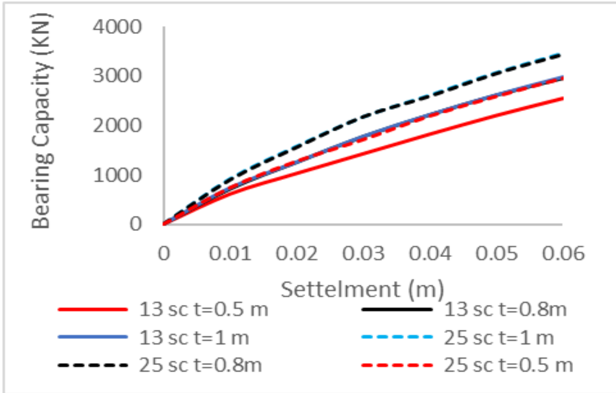


Fig -16: Comparison between load and settlement for 13 and 25 stone columns for variation of raft foundation thickness

7.3.2 Flexural behavior of the raft foundation (M1-1) and shear (Q2-3).

Figures 17 and 18 show the flexural behavior of a raft-stone column system and a raft foundation without stone columns for sections 1 and 2 respectively with various values of thickness of raft foundation (t) such as 0.5, 0.8, and 1 m and varying numbers of stone columns. Figs. 19 and 20 show the shear of the raft-stone column system and raft foundation without stone columns for sections 1 and 2 respectively with different values of the thickness of the raft foundation (t) and with different numbers of stone columns. It can be seen that flexural behavior and shear on the raft-stone column system increase by increasing (t). By increasing stone columns numbers, flexural behavior and shear on the raft-stone column system reduce.

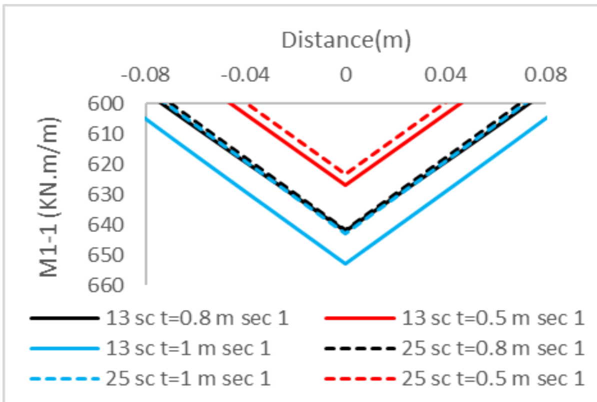


Fig -17: Flexural behavior of the raft foundation (M1-1) of section 1for 13 and 25 stone columns (thickness of raft footing (t))

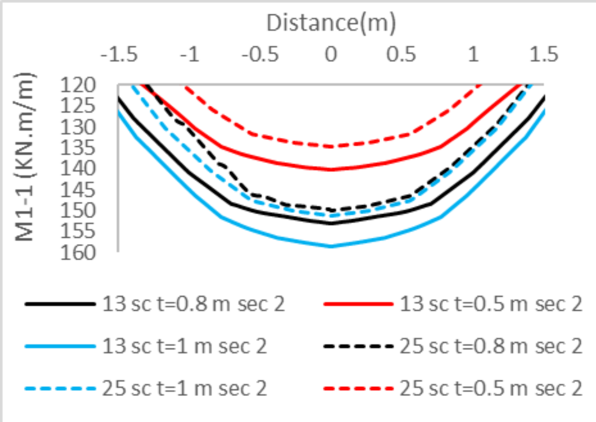


Fig -18: Flexural behavior of the raft foundation (M1-1) of section 2 for 13 and 25 stone columns (thickness of raft footing (t))

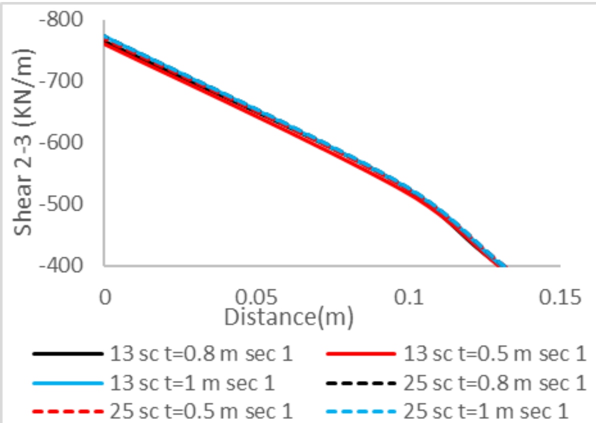


Fig -19: Shear of the raft foundation (Q2-3) of section 1for 13 and 25 stone columns (variation of thickness of raft footing (t))

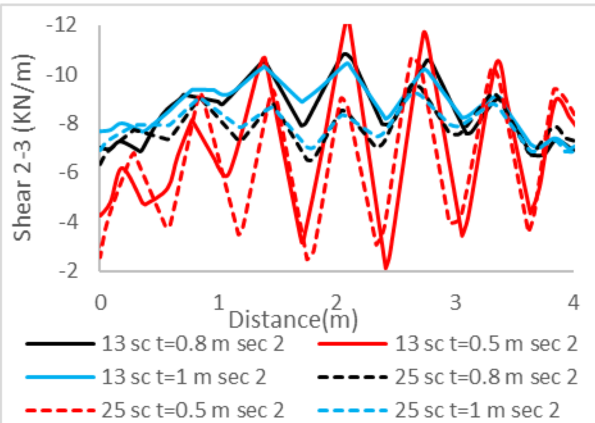


Fig -20: Shear of the raft foundation (Q2-3) of section 2 for 13 and 25 stone columns (variation of thickness of raft footing (t))

7.4 Diameter of stone columns (D).

Six analytical scenarios are conducted using the axis-symmetric finite element method to explore the behavior of the raft-stone column system under point displacement. The effect of changing the diameter of stone columns on the performance of the raft-stone column system is investigated in Table -5 for group 5 as different diameter of stone columns values for 13 and 25 stone columns while keeping the stone column length/thickness of clayey soil (L/H), young's modulus of stone columns (E_{50}^{ref}), and raft foundation thickness (t) constant.

7.4.1 Load – settlement behavior of clayey soil

Figure 21 shows the relationship between the load-settlement for different cases of stone column diameters and the number of stone columns. It has been discovered that raising the area replacement ratio or the diameter of the stone column by 0.4, 0.6, and 0.8 m results in an enhanced bearing capacity increasing factor (BIF). Bearing capacity increasing factor (BIF) exceeds by 19.21%, 37.3%, and 56.16%, respectively, for 13 stone columns and by 27.55%, 60.08%, and 94.35%, respectively, for 25 stone columns. It is observed that an increasing number of stone columns has a significant effect on (BIF).

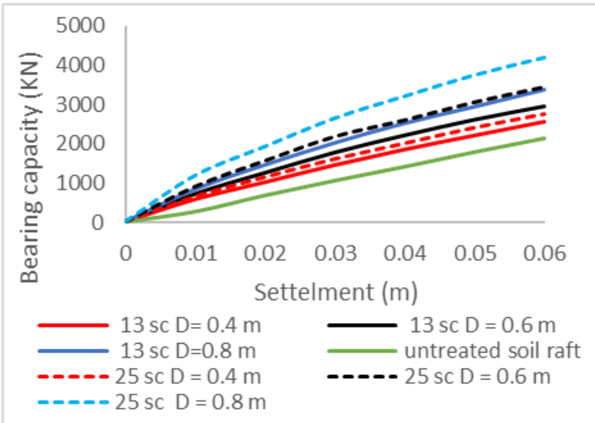


Fig -21: comparison between load and settlement for 13 and 25 stone columns for variation of diameter of stone columns

7.4.2 Flexural behavior of the raft foundation (M1-1) and shear (Q2-3).

Figures 22 and 23 present the flexural behavior of a raft-stone column system and a raft foundation without stone columns for sections 1 and 2 when stone column diameters are 0.4, 0.6, and 0.8 m and the number of stone columns is varied. By increasing (D), the moment reduction factor (MRF) increases. Although there is some scatter, there is an improvement for flexural behavior and shear of raft foundation. The moment reduction factor (MRF) for 13 stone columns increases by 0.55%, 1.7%, and 2% respectively for section 1 and up to 6.42%, 7.58%, and 9.63% respectively for section 2. For the 25 stone column group, moment reduction factor (MRF) reduces by increasing (D) only for section 1 by 6.15%, 2.41%, and 3.3% respectively, but for section 2 The moment reduction factor (MRF) increases by 6.8%, 9.43%, and 13.05% respectively.

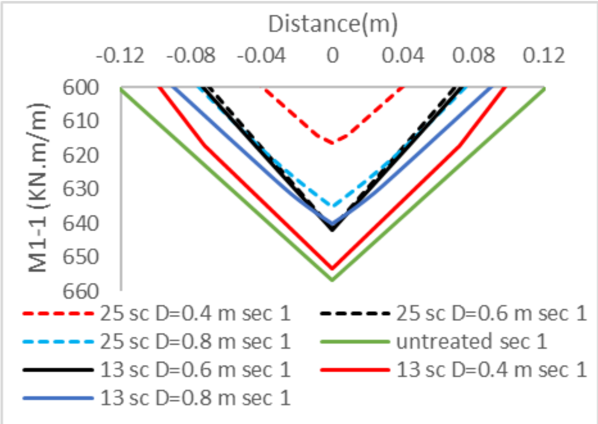


Fig -22: Flexural behavior of the raft foundation (M1-1) of section 1 for 13 and 25 stone columns (stone column diameters (D))

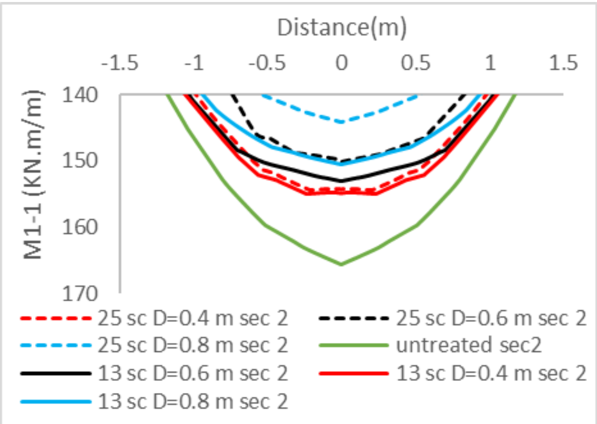


Fig -23: Flexural behavior of the raft foundation (M1-1) of section 2 for 13 and 25 stone columns (stone column diameters (D))

Figures 24 and 25 summarize the shear of a raft-stone column system and a raft foundation without stone columns for sections 1 and 2 when stone column diameters (D) and the number of stone columns are varied. Shear reduction factor (SRF) increases as (D) grows, whereas shear reduction factor (SRF) increases for section 2 for 13 and 25 stone columns by 14.11%, 17.53%, and 23.65% respectively and by 18.91%, 27.02%, and 30.32% respectively, but for section 1 for 13 and 25 stone columns, the shear reduction factor (SRF) reduces by 34.37%, 3.91%, and 0.5% respectively and by 50.79%, 2.74% respectively. While the number of stone columns raises, the moment reduction factor (MRF) and the shear reduction factor (SRF) increase.

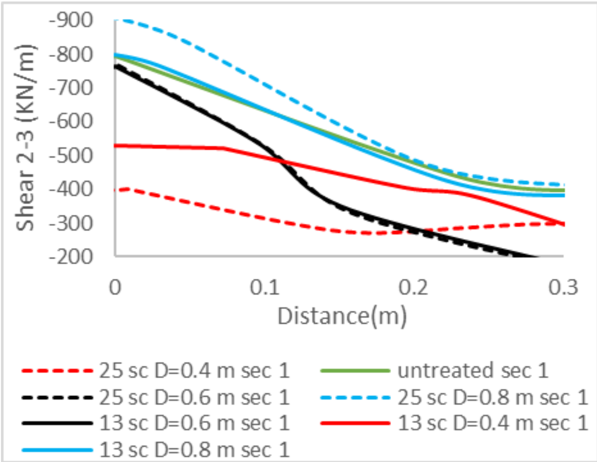


Fig -24: Shear of the raft foundation (Q2-3) of section 1 for 13 and 25 stone columns (variation of stone column diameters (D))

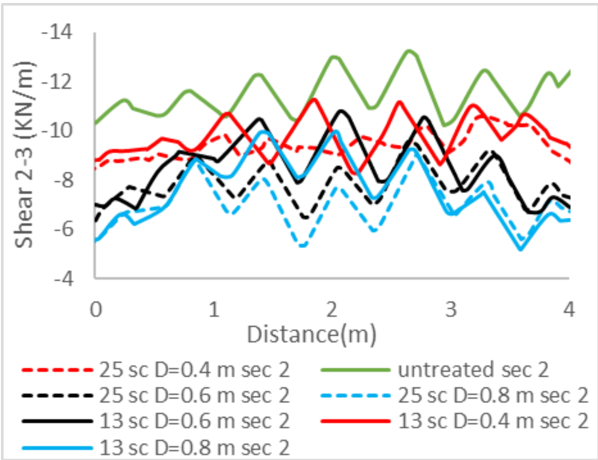


Fig -25: Shear of the raft foundation (Q2-3) of section 2 for 13 and 25 stone columns (variation of stone column diameters (D))

8. CONCLUSIONS

1. 13 and 25 stone columns have better load-settlement behavior compared with untreated soil. The settlement decreases and bearing capacity increases as (length of stone columns/thickness of clay layer) (L/H) increases from 0.4 to 0.8, (young's modulus of stone columns) E_{50}^{red} from 30 to 90 mPa, (thickness of raft foundation) (t) from 0.5 to 1 m, and (diameter of stone columns) (D) from 0.4 to 0.8 m.

2. Increasing number of stone columns results in increasing bearing capacity and settlement decreasing. Most effective are (D), E_{50}^{red}, (t), and (L/H).

3. For all parametric studies for 13 and 25 stone column groups, maximum moment (M1-1) is for section 1and the minimum moment is for section 2. The maximum improvement is for section 2 and The minimum improvement is for section 1, for all parametric studies.

4. For all parametric studies for 13 and 25 stone column groups, maximum shear (Q2-3) is for section 1and the minimum shear (Q2-3) is for section 2. The maximum improvement is for section 2 and The minimum improvement is for section 1, for all parametric studies.

5. The increasing in (length of stone columns/thickness of clay layer) (L/H) from 0.4 to 0.8, there is a decrease in moment and shear.

6. The increasing in (young's modulus of stone columns E_{50}^{red} from 30 to 90 mPa, there is a decrease in moment and shear.

7. The increasing in (diameter of stone columns) (D) from 0.4 to 0.8 m, there is a decrease in moment and shear.

8. The increasing in (thickness of raft foundation) (t) from 0.5 to 1 m, there is an increasing in moment and shear.

9. With The increase in the number of stone columns, shear (Q2-3) on the raft was reduced. The most influential parameter, in this case, is (D), then (L/H), (t) and finally E_{50}^{red}.

10. The increase in numbers of stone columns, M1-1 reduces. The most effective parameter in this case is (D), then E_{50}^{red}, (t) and finally (L/H).

11. Variation of (L/H) for 25 stone column groups has an insignificant improvement for moment and shear on the raft.

12. Variation of E_{50}^{red} and (t) for 25 stone column group has a slight improvement for shear on the raft only for section 1.

13. Variation of (D) for 25 stone column group has an insignificant improvement for moment on the raft only for section 1.

14. Increasing of (D) for 13 and 25 stone column groups, increase shears on the raft only for section 1.

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