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COMPOSED COEFFICIENT TECHNIQUE FOR MODELLING BARRETTE GROUPS

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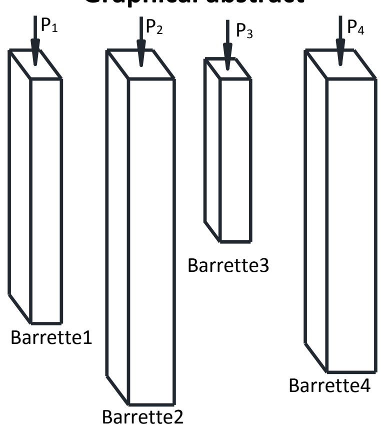
Graphical abstract



Abstract

Most of soil structure interaction methods for analyzing large-section supports such as barrette foundation modeling and the surrounding soil are using 3D finite element (FE) models. In which, the model leads to a large finite element mesh, and consequently a large system of linear equations to be solved. In this paper, Composed Coefficient Technique (CCT) is adapted for analyzing barrette group. The technique considers the 3D full interactions between barrettes and the surrounding soil. Due to the high rigidity of the barrettes relative to the surrounding soil, a uniform settlement for the barrettes can be considered. This is done to compose the stiffness coefficients of the soil matrix into composed coefficients, which consequently leads to a significant reduction in the soil stiffness matrix. An application for analyzing barrette group by CCT technique is carried out on a real subsoil. The application presents guidelines and diagrams for barrette group that may be used in real practice.

Keywords: Soil structure interaction, Deep foundation, Barrette, Barrette group, Settlement

1.0 INTRODUCTION

Early researches on barrette foundations focused on hand calculation techniques with the help of empirical formula and charts for single pile and pile group to design barrettes. With the advent of computers and numerical procedures, Finite Element techniques were developed to analyze barrette group. Which, taking into account full interactions between barrettes and the surrounding soil leads to a huge stiffness matrix. Consequently, a large system of linear equations must be solved, and thus these analyses are time consuming even for the fast computers of today.

Composed Coefficient Technique (CCT) was first proposed by El Gendy (2007). He applied the technique on single pile, pile group and piled raft to reduce the size of the entire soil stiffness matrix. In this technique, the pile is treated as a rigid member having a uniform settlement for all nodes along its shaft and base. CCT enables to assemble pile coefficients in composed coefficients. This technique was examined and applied efficiently for many studies (Hattab, 2007; Reda, 2009; Rabiei, 2009, 2010, 2016; Kamash, 2009, 2012; Kamash *et al*., 2014; Ibrahim *et al*., 2009; Mobarak, 2010; El-Labban, 2011; Moubarak, 2013; Chieruzzi *et al*., 2013; El Gendy *et al*., 2013, 2014). The Advantage of the CCT is that the interaction of soil elements, raft elements with the barrette elements are taken into consideration. The proposed analysis reduces considerably the number of equations that needs to be solved. The CCT enables the application of nonlinear response of the barrette by a hyperbolic relation between the load and settlement of the barrette.

Recently, this technique is also further developed by El Gendy *et al*. (2017) to be used for analyzing the barrette considering two cases of analyses. In the first one, the stiffness matrix of the soil is generated from flexibility coefficients neglecting the elasticity of the barrette body. This relate to the assumption of the analysis which considers the barrette moves as full rigid body. In the second case of analysis, the entire stiffness matrix is determined from full three-dimensional

Finite Element (3D FE). However, in this case, using CCT has considerably reduced the matrix, but it was still large and needs more time to be solved. Therefore, this technique is enhanced by El Gendy *et al*. (2018). In the technique, the CCT was used for analyzing barrette considering the elasticity of the barrette body by the finite element method, while that of the soil by flexibility coefficient method. The compatibility between the vertical displacements of the barrette and the soil settlements at the soil-barrette interface was taken in the vertical direction only. This assumption comes from the fact that the external load on the barrette head, which is expected to be heavy load, was applied in the vertical direction. For comparative examinations, the barrette elasticity is determined using either 1D or 3D finite elements. A series of examinations was carried out to verify the application for analyzing barrette by CCT. In this paper, the enhanced CCT was used for analyzing barrette group.

2.0 MATHEMATICAL MODELING

2.1 Modelling Barrette Groups Using Flexibility Coefficients

The composed coefficient technique is used to perform the analysis of barrette groups taking into account the interaction effect among barrettes. To generate a soil stiffness matrix of composed coefficients for barrette groups, consider the simple barrette groups shown in Figure 1 as an example, which has n_b = 4 barrettes and total nodes of n = 292.

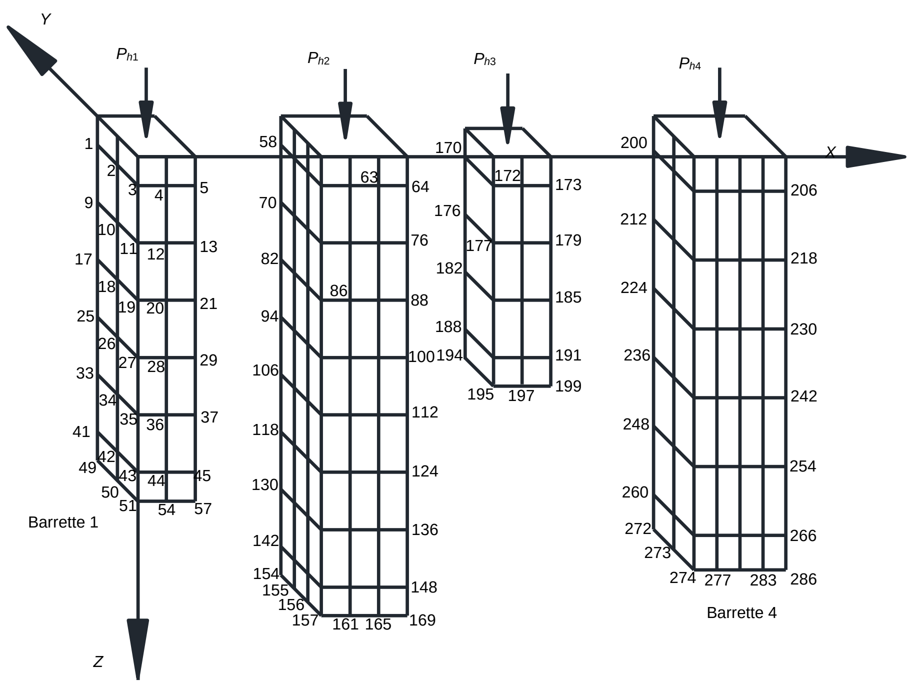


Figure 1 Barrette groups

The total soil stiffness matrix of the system of the barrette groups can be expressed in expanded matrix, Eq. (1)

Where: Q_i is contact force on node i, kN; w_i is soil settlement on any node i either on the shaft or on the base, m; and $k_{i,j}$ is stiffness coefficient of the soil stiffness matrix, kN/ m.

Due to the rigidity of the barrette in the length direction, the settlement in every barrette itself is considered as a uniform. This assumption can establish the relationship between the uniform barrette settlement and the applied load on the barrette head in the barrette groups. It can be done by equating all settlements in each barrette by a uniform settlement.

$$
\begin{Bmatrix} \begin{Bmatrix} Q_1 \\ \dots \\ Q_{57} \end{Bmatrix}_1 \\ \begin{Bmatrix} Q_{58} \\ \dots \\ Q_{169} \end{Bmatrix}_2 \\ \begin{Bmatrix} Q_{170} \\ \dots \\ Q_{199} \end{Bmatrix}_3 \\ \begin{Bmatrix} Q_{200} \\ \dots \\ Q_{286} \end{Bmatrix}_4 \end{Bmatrix} = \begin{bmatrix}
k_{1,1} & \dots & k_{1,57} & k_{1,58} & \dots & k_{1,169} & k_{1,170} & \dots & k_{1,199} & k_{1,200} & \dots & k_{1,286} \\
\dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\
k_{57,1} & \dots & k_{57,57} & k_{57,58} & \dots & k_{57,169} & k_{57,170} & \dots & k_{57,199} & k_{57,200} & \dots & k_{57,286} \\
k_{58,1} & \dots & k_{58,57} & k_{58,58} & \dots & k_{58,169} & k_{58,170} & \dots & I_{58,199} & k_{58,200} & \dots & k_{58,286} \\
\dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\
k_{169,1} & \dots & k_{169,57} & k_{169,58} & \dots & k_{169,169} & k_{169,170} & \dots & k_{169,199} & k_{169,200} & \dots & k_{169,286} \\
k_{170,1} & \dots & k_{170,57} & k_{170,58} & \dots & k_{170,169} & k_{170,170} & \dots & k_{170,199} & k_{170,200} & \dots & k_{170,286} \\
\dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\
k_{199,1} & \dots & k_{199,57} & k_{199,58} & \dots & k_{199,169} & k_{199,170} & \dots & k_{199,199} & k_{199,200} & \dots & k_{199,286} \\
k_{200,1} & \dots & k_{200,57} & k_{200,58} & \dots & k_{200,169} & k_{200,170} & \dots & k_{200,199} & k_{200,200} & \dots & k_{200,286} \\
\dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots & \dots \\
k_{286,1} & \dots & k_{286,57} & k_{286,58} & \dots & k_{286,169} & k_{286,170} & \dots & k_{286,199} & k_{286,200} & \dots & k_{286,286}
\end{bmatrix} \begin{Bmatrix} \begin{Bmatrix} w_1 \\ \dots \\ w_{57} \end{Bmatrix}_1 \\ \begin{Bmatrix} w_{58} \\ \dots \\ w_{169} \end{Bmatrix}_2 \\ \begin{Bmatrix} w_{170} \\ \dots \\ w_{199} \end{Bmatrix}_3 \\ \begin{Bmatrix} w_{200} \\ \dots \\ w_{286} \end{Bmatrix}_4 \end{Bmatrix} \quad (1)
$$

Carrying out the summation of rows and columns corresponding to the barrette *i* in Eq. (1) leads to:

$$
\begin{Bmatrix} \left\{ \sum_{i=1}^{57} Q_i \right\}_1 \\ \left\{ \sum_{i=58}^{169} Q_i \right\}_2 \\ \left\{ \sum_{i=170}^{199} Q_i \right\}_3 \\ \left\{ \sum_{i=200}^{286} Q_i \right\}_4 \end{Bmatrix} = \begin{bmatrix}
\sum_{i=1}^{57}\sum_{j=1}^{57} k_{i,j} & \sum_{i=1}^{57}\sum_{j=58}^{169} k_{i,j} & \sum_{i=1}^{57}\sum_{j=170}^{199} k_{i,j} & \sum_{i=1}^{57}\sum_{j=200}^{286} k_{i,j} \\
\sum_{i=58}^{169}\sum_{j=1}^{57} k_{i,j} & \sum_{i=58}^{169}\sum_{j=58}^{169} k_{i,j} & \sum_{i=58}^{169}\sum_{j=170}^{199} k_{i,j} & \sum_{i=58}^{169}\sum_{j=200}^{286} k_{i,j} \\
\sum_{i=170}^{199}\sum_{j=1}^{57} k_{i,j} & \sum_{i=170}^{199}\sum_{j=58}^{169} k_{i,j} & \sum_{i=170}^{199}\sum_{j=170}^{199} k_{i,j} & \sum_{i=170}^{199}\sum_{j=200}^{286} k_{i,j} \\
\sum_{i=200}^{286}\sum_{j=1}^{57} k_{i,j} & \sum_{i=200}^{286}\sum_{j=58}^{169} k_{i,j} & \sum_{i=200}^{286}\sum_{j=170}^{199} k_{i,j} & \sum_{i=200}^{286}\sum_{j=200}^{286} k_{i,j}
\end{bmatrix} \begin{Bmatrix} \{ wo_1 \}_1 \\ \{ wo_2 \}_2 \\ \{ wo_3 \}_3 \\ \{ wo_4 \}_4 \end{Bmatrix} \quad (2)
$$

Eq. (2) can be rewritten for the simple barrette groups in composed coefficients as:

$$
\begin{Bmatrix} Ph_1 \\ Ph_2 \\ Ph_3 \\ Ph_4 \end{Bmatrix} = \begin{bmatrix} K_{1,1} & K_{1,2} & K_{1,3} & K_{1,4} \\ K_{2,1} & K_{2,2} & K_{2,3} & K_{2,4} \\ K_{3,1} & K_{3,2} & K_{3,3} & K_{2,4} \\ K_{4,1} & K_{4,2} & K_{4,3} & K_{2,4} \end{bmatrix} \begin{Bmatrix} wo_1 \\ wo_2 \\ wo_3 \\ wo_4 \end{Bmatrix} \quad (3)
$$

Where: wo_i is ssettlement in barrette *i*, m; $K_{i,j}$ is composed coefficient, kN/m; and Ph_i Force on the head of barrette *i*.

Solving the above system of linear equations will gives the uniform settlement on each barrette. Substituting barrette settlement from Eq. (3) into Eq. (1), gives contact forces on the barrette nodes.

3.0 NUMERICAL RESULTS

The proposed method for analyzing barrette group using CCT as outlined in this paper was implemented in the program *ELPLA* (El Gendy, M./El Gendy, A. 2017). With the help of this program, an analysis of parametric study is carried out as follows.

3.1 Case Studies of Barrette Group

An application for analyzing barrette group by CCT technique is carried out on a real subsoil. The soil of the new area of East Port-Said is considered, in which the typical soil is very weak and structures in this area need to be supported by deep foundations. This section presents the main features of the numerical models used to analyze the behavior of barrette groups in East Port-Said. Different case studies investigated the effect of barrette spacing S, barrette length L and barrette height H on the settlement. Furthermore, the analysis was carried out considering various calculation methods as well as different subsoil models. The main features of the most effective numerical model suitable for the barrette group analysis in east Port Said area were also discussed. The main variables of the parametric study were described in the next paragraphs. The effect of barrette groups is illustrated through the study of settlement and differential settlement between barrettes. Four groups of barrettes are considered as shown in Table 1.

- Group 1: Three barrettes in one direction.
- Group 2: Four barrettes in one direction.
- Group 3: Five barrettes in one direction.
- Group 4: Five barrettes in two perpendicular directions.

The group of three barrettes is considered to study the effect of barrette group on each other settlements. The groups of four and five barrettes in one direction are considered to study the effect of number of barrettes. Finally, the group of five barrettes in two perpendicular directions is considered to study the effect of arrangement of barrettes. Most of relations in this study are plotted between the dimensionless length factor *f* and the other studied factors. The dimensionless length factor *f* is expressed by:

$$
f = \frac{S}{L} \quad (4)
$$

Where: *S* is span between center line of barrettes, m; and *L* is length of the internal barrette, m. for chosen values of *f* = 2, 3 and 4, the corresponding values of *S* are listed in Table 2. The span between center lines of barrettes S and the length of internal barrette L are shown in Figure 2.

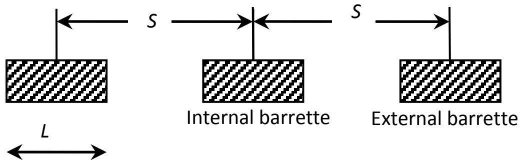


Figure 2 Geometry of barrettes and spacing S

Twelve case studies of each group were considered as given in Table 3. This brings a total of 144 case studies. The subsoil of each case assumed to be the soil properties of east Port-Said area as given in Table 4. The barrette is analyzed nonlinearly using a hyperbolic function to represent the real load settlement relation. The limit barrette load *Ql* is taken as listed earlier in Table 5. In the analysis, the barrette is assumed to be full rigid having a uniform settlement. Loads on the barrette head are 1800 kN for the internal barrette and 1350 kN for the external barrette.

Table 1 Studied groups of barrettes

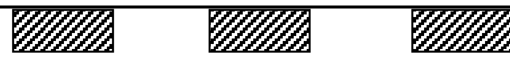
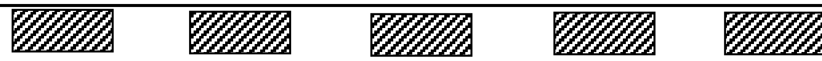
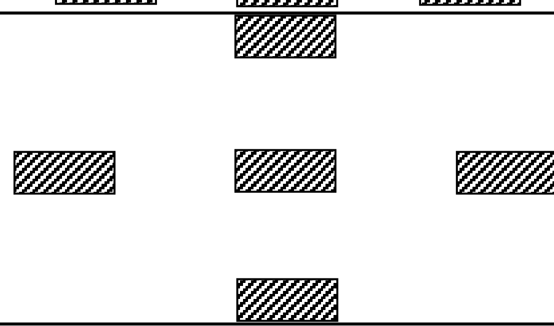
Group No.	Group arrangement
1	
2	
3	
4	

Table 2 Span between center lines of barrettes *S* for different barrettes

Length factor *f*	Barrette length *L* m			
	1.5 m	2.0 m	2.5 m	3.0 m
f = 2	3	4	5	6
f = 3	4.5	6	7.5	9
f = 4	6	8	10	12

Table 3 Studied cases of groups

Barrette Length & Height	*L*=1.5 m	*L*=2.0 m	*L*=2.5 m	*L*=3.0 m
H = 24 m	Case 1	Case 2	Case 3	Case 4
H = 30 m	Case 5	Case 6	Case 7	Case 8
H = 36 m	Case 9	Case 10	Case 11	Case 12

Table 4 Subsoil properties, (Hamza *et al.* 2000)

Layer No.	Soil type	z m	E_s kN/m^2	ν_s
1	Clay	5	2400	0.2
2	Sand	13.5	30000	0.25
3	Clay	28.5	8120	0.2
4	Clay	38.5	9940	0.2
5	Clay	48.5	11340	0.2
6	Clay	58.5	12810	0.2
7	Clay	92.5	60000	0.2
8	Sand	120	144000	0.2

Table 5 Limit barrette load Ql kN for different barrette geometries

Barrette height *H* m	Q_l kN
H = 24 m	30240
H = 30 m	37800
H = 36 m	45360

3.2 Effect of Barrette Group on Each Other Settlements

The effect of barrette group on settlement of barrettes was studied by comparing the settlement and the soil stiffness for the internal and external barrettes to that of a single barrette. The settlement effect is expressed by settlement ratio r_s, which is given by:

$$r_s = \frac{S_v}{S_o} \tag{5}$$

Where: S_v is settlement of the studied barrette group, m; and S_o is settlement of the single barrette, m. The soil stiffness effect is expressed by soil stiffness ratio r_k, which is given by:

$$r_k = \frac{k_{sv}}{k_{so}} \tag{6}$$

Where: k_{sv} is soil stiffness of the studied barrette group, kN/m; and k_{so} is soil stiffness of the single barrette, kN/m. The decreasing percentage in settlement P_s % for the studied barrettes with the increasing barrette length *L* from *L*1 to *L*2 m, which is given by:

$$P_s = \frac{S_{L12}}{S_{L1}} \times 100 \quad (7)$$

Where: S_{L12} is difference in settlement when using barrette length *L*1 and *L*2, m; and S_{L1} is settlement when using barrette length *L*1, m. As samples for settlement and soil stiffness ratios, Figure 3 to Figure 6 show the relation between the settlement ratio r_s and soil stiffness ratio r_k for the internal and external barrettes with the barrette of length *L* m. These results for the groups of three barrettes in one direction and the length factor is taken to be *f* = 2, while the barrette width *W* is constant and equal to 1.0 [m]. 0Tables 6 to 8 show the decreasing percentage in settlement Ps % for studied barrettes with the increasing barrette length L from 1.5 to 2.0 m, from 1.5 to 2.0 m and from 1.5 to 2.0 m, respectively, with constant barrette width *W* = 1.0 m.

Table 6 Decreasing percentage in settlement *Ps* % with increasing barrette length *L* (from 1.5 to 2.0 m) with constant width *W* = 1.0 m

Barrette length *H* [m]	**Internal barrette length factor *f***			**External barrette length factor *f***		
	2	3	4	2	3	4
24	11.7	12.2	12.6	12.5	13.3	13.7
30	11.1	11.6	11.9	12.1	12.8	13.2
36	10.8	11.3	11.6	11.8	12.6	12.9

Table 7 Decreasing percentage in settlement *Ps* % with increasing barrette length *L* (from 2.0 to 2.5 m) with constant width *W* = 1.0 m

Barrette length *H* [m]	**Internal barrette length factor *f***			**External barrette length factor *f***		
	2	3	4	2	3	4
24	9.6	10.0	10.3	10.5	11.1	11.4
30	9.2	9.6	9.9	10.1	10.6	10.9
36	9.0	9.4	9.6	10.0	10.5	10.6

Table 8 Decreasing percentage in settlement *Ps* % with increasing barrette length *L* (from 2.5 to 3.0 m) with constant width *W* = 1.0 m

Barrette length *H* [m]	**Internal barrette length factor *f***			**External barrette length factor *f***		
	2	3	4	2	3	4
24	8.2	8.6	8.8	9.1	9.5	9.7
30	7.9	8.3	8.4	8.7	9.2	9.4
36	7.8	8.1	8.2	8.7	9.0	9.2

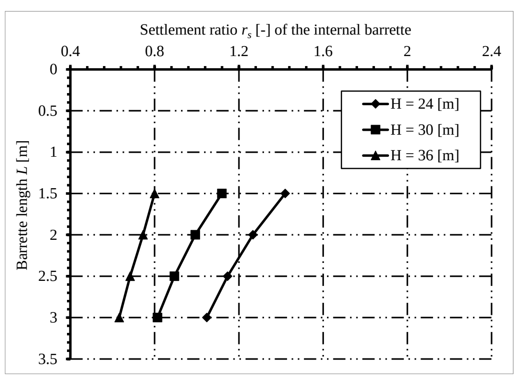


Figure 3 Settlement ratio r_s of the internal barrette for *f* = 2

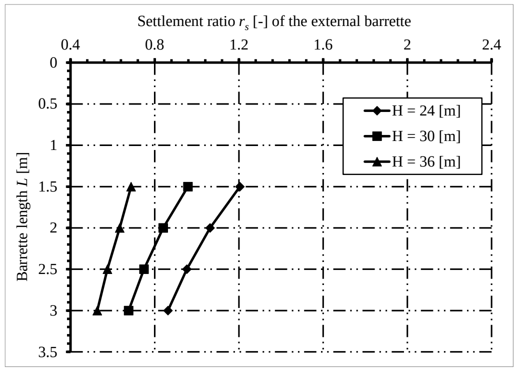


Figure 4 Settlement ratio r_s of the external barrette for f = 2

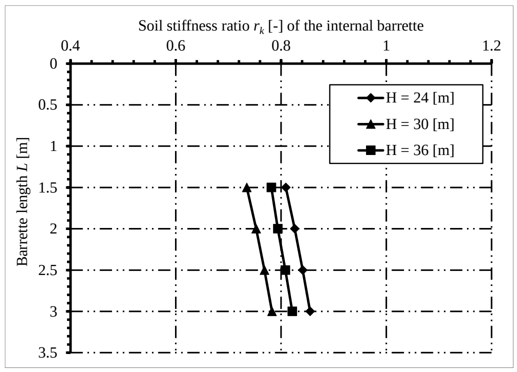


Figure 5 Soil stiffness ratio r_k of the internal barrette for f = 2

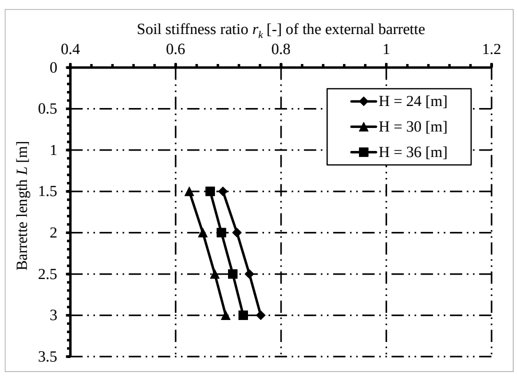


Figure 6 Soil stiffness ratio r_k of the external barrette for f = 2

From figures and tables, the following conclusions can be obtained:

- Settlement ratio r_s of the internal barrette exceeds that of the external barrettes by about 20%.
- It is clear that the settlement decreases with increasing the distance between barrettes, where the barrette-barrette interaction decreases.
- It is clear that the settlement in barrettes decreases with increasing the barrette length.
- From the analysis, the suitable length factor f is 3 or more, which have settlement ratio r_s less than 1.2.

3.3 Effect of Number of Barrettes in One Direction

To study the effect of number of barrettes and the spacing between them on the settlement, three groups of barrettes in one direction were presented as shown in Figure 7, where the numbers of barrettes vary between three and five. The study for barrette settlement was taken on the internal and external barrettes.

Figure 8 to Figure 13 present the settlement at the internal and external barrettes, with the length factor f. The barrettes have a length of L = 1.5 m, width of W = 1.0 m and variable height H = 24, 30 and 36 m. Length factor f is taken 2, 3 and 4. From these figures the following conclusions can be obtained:

- When the number of barrettes in one direction increases from one group to other, the settlement of the internal and external barrettes increases.
- The effect of increasing the number of barrettes on settlement decreases according to increasing the distance between barrettes.

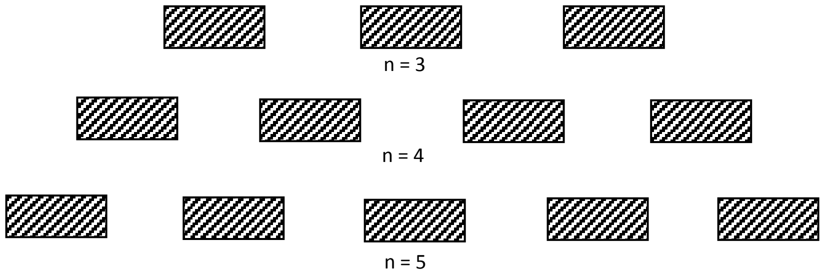


Figure 7 Groups of barrettes in one direction.

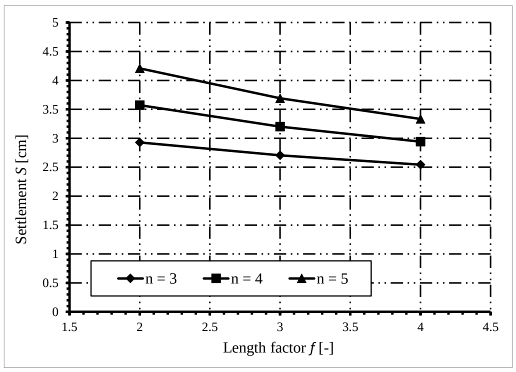


Figure 8 Settlement at the internal barrette against length factor f for L = 1.5 m and H = 24 m

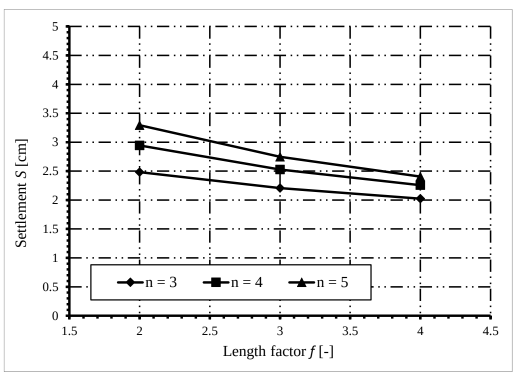


Figure 9 Settlement at the external barrette against length factor f for L = 1.5 m and H = 24 m

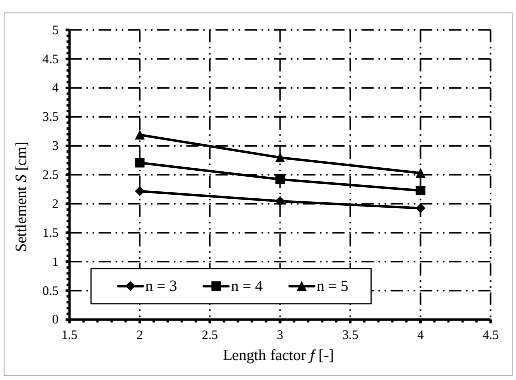


Figure 10 Settlement at the internal barrette against length factor f for L = 1.5 m and H = 30 m

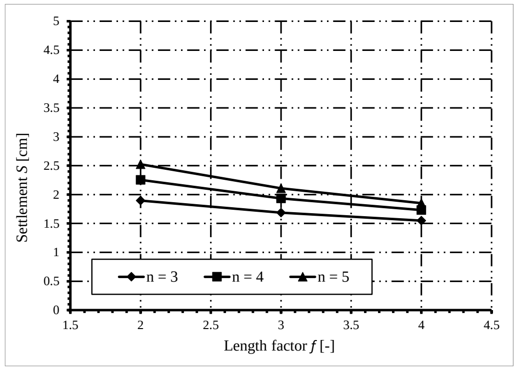


Figure 11 Settlement at the external barrette against length factor *f* for *L* = 1.5 m and *H* = 30 m

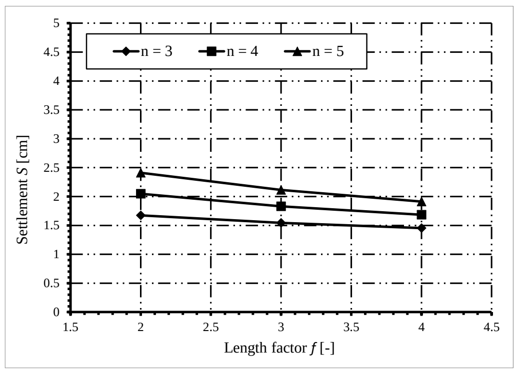


Figure 12 Settlement at the internal barrette against length factor *f* for *L* = 1.5 m and *H* = 36 m

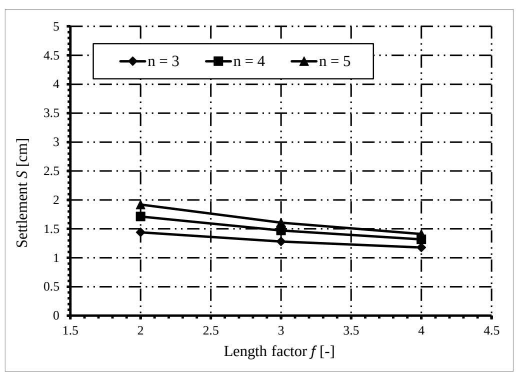


Figure 13 Settlement at the external barrette against length factor *f* for *L* = 1.5 m and *H* = 36 m

3.4 Effect of Arrangement of Barrettes

Two cases of arrangement of barrette groups were considered, as shown in Figure 14, case (A) is three barrettes in one direction, case (B) is five barrettes in two perpendicular directions. The two cases were carried out to study barrettes in two perpendicular directions. The study of settlement was taken for the internal and external barrettes to see the effect of arrangement of barrettes on settlement.

Figure 15 to Figure 20 show the settlement *s* with the length factor *f* to study the effect of arrangement of barrettes on settlement. From these figures the following conclusions can be obtained:

- The effect of arrangement of barrettes in two perpendicular directions on the settlement of barrettes decreases when increasing the distance between barrettes.
- Changing from case (A) to case (B), increases the settlement for the internal and external barrettes.

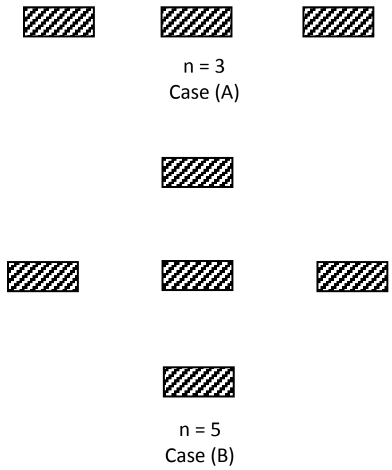


Figure 14 Two groups of different arrangement of barrettes

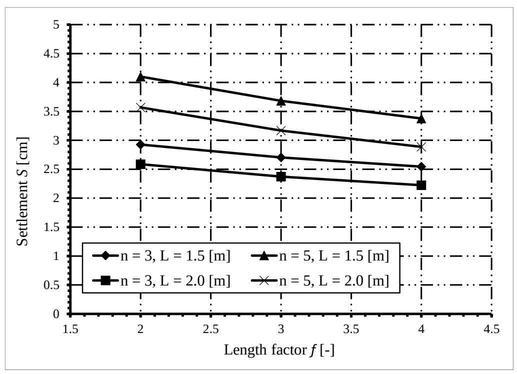


Figure 15 Settlement at the internal barrette against length factor *f* for *L* = 1.5 & 2.0 m and *H* = 24 m

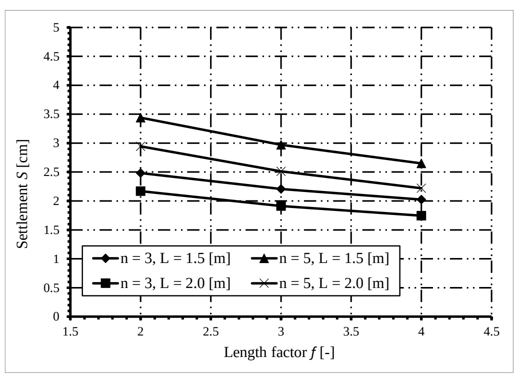


Figure 16 Settlement at the external barrette against length factor *f* for *L* = 1.5 & 2.0 m and *H* = 24 m

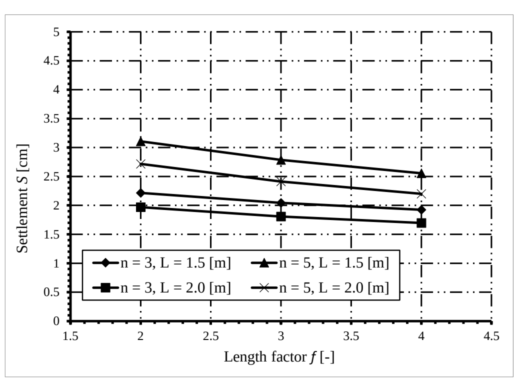


Figure 17 Settlement at the internal barrette against length factor *f* for *L* = 1.5 & 2.0 m and *H* = 30 m

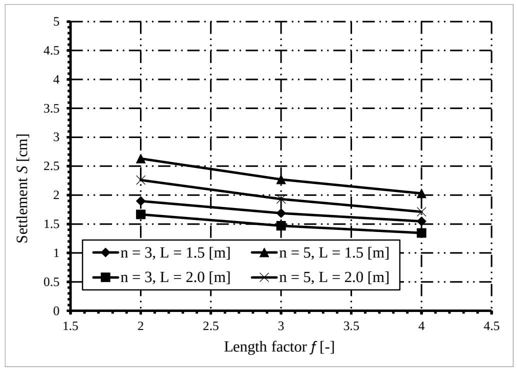


Figure 18 Settlement at the external barrette against length factor *f* for *L* = 1.5 & 2.0 m and *H* = 30 m

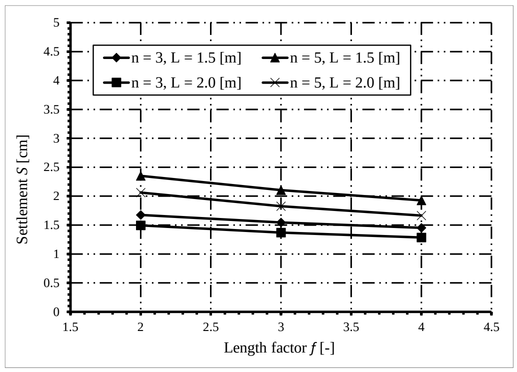


Figure 19 Settlement at the internal barrette against length factor *f* for *L* = 1.5 & 2.0 m and *H* = 36 m

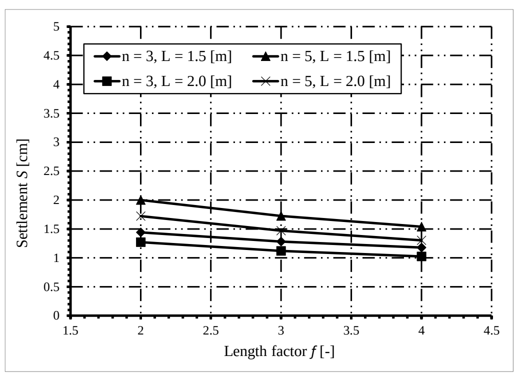


Figure 20 Settlement at the external barrette against length factor *f* for *L* = 1.5 & 2.0 m and *H* = 36 m

4.0 CONCLUSIONS

An application of *CCT* on barrettes group is presented. The proposed technique considers the 3D full interactions between barrette and soil. From application of *CCT* technique on real soil, it can be concluded that:

- From the analysis, the suitable length factor *f* is 3 or more, which have settlement ratio r_s less than 1.2.
- When the number of barrettes in one direction increases from one group to another, the settlement of the internal and external barrettes increases.
- The effect of increasing the number of barrettes on settlement decreases according to increasing the distance between barrettes.
- The effect of arrangement of barrettes in two perpendicular directions on the settlement of barrettes decreases according to increasing the distance between barrettes.
- Due to the smaller number of nodes in CCT model rather than 3D finite element model, the first model consumes less computation time in the analysis.

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