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Optimum Design of Elastic Continuous Foundations with The Artificial Bee Colony Method

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Abstract

The study presents the investigation of the elastic behavior of the soil in the optimal design of continuous foundations according to the rigid solid case. For the investigation, the optimization algorithm that can find optimal section and reinforcement details of continuous foundations has been developed. The developed algorithm uses one of the well-known meta-heuristic methods named the artificial Bee Colony method to find the optimal design. The Winkler spring hypothesis (analytic solution) is used to calculate internal forces and stresses in elastic continuous foundations. We used the real-size design example previously used in the literature to test the elastic soil effect and algorithm performance. The obtained results show that the current algorithm performs well, and lower cost values are obtained in the elastic design.

Keywords: Continuous foundation design, Elastic line method, Optimization, Artificial Bee Colony

1. Introduction

The continuous foundation is the type of shallow foundation obtained by combining the single foundations in that direction if the size of the foundation in one direction is large in the foundation design. To carry the loads coming from the building and transfer them to the ground in a healthy way, continuous foundations must be designed following the design guidelines. In addition to the suitability of design codes, designing the foundation at an affordable cost is an important parameter. For this reason, an ideal continuous foundation should be both feasible for the design conditions and at minimum cost. However, optimizing such structures is a very complex and difficult task since these structures depend on many parameters such as foundation length, foundation width, foundation thickness, reinforcement length, reinforcement diameter, concrete class, and complex limitation functions.

The optimal design of reinforced concrete (RC) structures is one of the common types of structural optimization problems. In the past, researchers tried to search optimal design parameters for RC retaining walls using different algorithms. Mostly they considered the objective function as the minimum cost.[1-7] Apart from the cost function, researchers used CO2 emission, minimum sizing, and weight objective functions [8-15]. In the optimal design of RC retaining walls following cases were investigated: the performance of various metaheuristic methods [16-18], investigating the effect on the minimum cost for different situations [14, 19, 20].

Apart from retaining walls, studies on the optimum design of different RC structural members are available in the literature such as columns, beams [21-25], frames [26-38], slabs [39-43], pile foundations [44-46], shear walls [47], prestressed RC bridge, RC console bearing wall [27, 37, 48-50].
Meta-heuristic techniques, mostly inspired by nature, have been successfully applied in the optimization of steel and RC structures [12, 51-55]. The Artificial Bee Colony (ABC) method developed by Karaboğa [56] is a well-known metaheuristic algorithm. ABC performed well in structural optimization problems such as steel frames [57], RC columns [58], and retaining walls [59]. Therefore, ABC is a candidate method that performs highly in the presented optimization problem [58, 60-64] and is chosen as the optimization method for the study.
There are studies in the literature on the optimum design of foundations, especially on the optimum design of shallow foundation types. In these studies, the objective functions usually are the minimization of the cost and the CO2 emission [65-74]. Although there are studies for the optimum design of continuous foundations in the literature, the soil is modeled as rigid in these studies [69, 74]. In addition, no study has been found on the effect of elastic soil's behavior on the optimum design. The main motivation for the study is to develop an algorithm that calculates the optimum design of continuous foundations in elastic soil and to present novel results to the literature on the effect of elastic soil behavior on optimum cost. For this purpose, we developed an optimization program in Visual Basic programming language and tested the developed program on the literature example. We optimized the example considering both rigid and elastic behaviors.
The remainder of the manuscript is summarized as follows. Chapter 2 contains information about the mathematical modeling of continuous foundations, theoretical information about the analysis of elastic continuous foundations, the definition of the optimization problem, and the background of the ABC method. Chapter 3 gives details of the example problem and the results. In the last chapter, the discussion and conclusion of the results are available.

2. Methodology

2.1.Analysis of elastic foundations

For continuous foundations to give a realistic result, the soil can be assumed to be elastic. In the study, the Winkler spring hypothesis is used to model elastic soil behavior [75]. In this hypothesis, the continuous foundation is modeled as a beam resting on elastic springs, and the internal effects (shear force and moment) are calculated under the loads from the superstructure (See Figure 1).

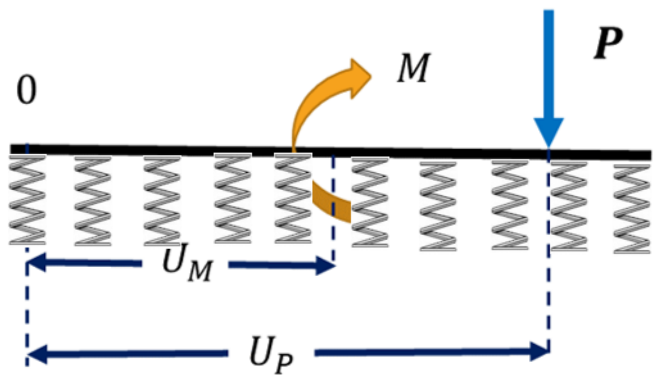


Fig. 1 An example of an elastic foundation

The cross-sectional effects for the continuous foundation positioned on the elastic foundation are analytically calculated using a solution of the differential equation as follows:

$$EI\frac{d^4y(x)}{dx^4} = q - ky(x) \tag{1}$$

where, *E* is the young modulus of concrete used in the foundation, *I* is the moment of inertia of the foundation cross-section, *y(x)* is the deflection function of the foundation, and *q* represents the loads from the superstructure. After solving the differential equation analytically, the soil stress ($\sigma(x)$), moment ($M(x)$), and shear force ($V(x)$) equations are obtained as follows:

$$\begin{aligned}\sigma(x) = k_0 \Big[y_0\, F_1(\lambda x) + \frac{1}{\lambda}V_0 F_2(\lambda x) - \frac{1}{\lambda^2 EI}MF_3(\lambda x) - \frac{1}{\lambda^3 EI}V_0 F_3(\lambda x) \\ - \frac{1}{\lambda^2 EI}MF_3(\lambda(x - U_M) + \frac{k}{\lambda^2 EI}PF_4\big(\lambda(x - U_p)\big)\Big]\end{aligned} \tag{2}$$

$$\begin{aligned}M(x) = M_0 F_1(\lambda x) + \frac{1}{\lambda}V_0 F_2(\lambda x) + \frac{k}{\lambda^2}y_0\, \mathrm{F}_3(\lambda x) + \frac{k}{\lambda^3}\theta_0 \mathrm{F}_4(\lambda x) \\ + M\mathrm{F}_1(\lambda(x - U_M) - \frac{1}{\lambda}PF_2\big(\lambda(x - U_p)\big)\end{aligned} \tag{3}$$

$$\begin{aligned}V(x) = V_0 F_1(\lambda x) + \frac{k}{\lambda}y_0 F_2(\lambda x) + \frac{k}{\lambda^2}V_0\, \mathrm{F}_3(\lambda x) - 4\lambda M_0 F_4(\lambda x) \\ - 4\lambda \mathrm{M} F_4(\lambda(x - U_M) - PF_1\big(\lambda(x - U_p)\big) \\ \lambda = \sqrt[4]{K/4EI}\end{aligned} \tag{4}$$

where, y_0 , θ_0, M_0, and V_0 respectively are vertical displacement, rotation, moment, and shear force of the foundation where x=0. M and P represent external moment and vertical force. U_M and U_p are the locations of the M and P respectively. $F_1(\lambda x)$, $F_2(\lambda x), F_3(\lambda x), F_4(\lambda x)$ are the shape functions given as follows.

$$\begin{aligned}F_1(\lambda x) &= \cosh \lambda x \cos \lambda x \\ F_2(\lambda x) &= \frac{1}{2}(\cosh \lambda x \sin \lambda x + \sinh \lambda x \cos \lambda x) \\ F_3(\lambda x) &= \frac{1}{2}\sinh \lambda x \sin \lambda x \\ F_4(\lambda x) &= \frac{1}{4}(\cosh \lambda x \sin \lambda x - \sinh \lambda x \cos \lambda x)\end{aligned} \tag{5}$$

2.2. Design of continuous foundations

The design of continuous foundations consists of two stages: preliminary design, and final design. In the preliminary design, the foundation width (b) is determined as follows:

$$b \geq \frac{\sum P}{L \, . \, q_t} \tag{6}$$

where, L is the length of the foundation, q_t is bearing soil stress. After the determination of the foundation, soil-bearing control is performed as follows:

$$q_{t,net} = q_t - 1.4 * 18 \cdot \mathrm{b} \rightarrow q_{t,net} \geq \; q_o \tag{7}$$

Here, $q_{t,net}$ is nominal soil stress, h is the height of the foundation, and q_o is the stress that occurred in the soil (see Section 2.1 for the computation). If $q_{t,net} < q_o$, b should be increased.

After the ground soil bearing control is achieved, the final design phase is started. the final design phase, the first critical shear force (V_{cr}) is performed as follows:

$$V_{cr} = 0.65. f_{ctd} \, .b. d \;\; \rightarrow V_{cr} \; > V_d \; ; d = h - d' \tag{8}$$

where, f_{ctd} represents the characteristic tensile strength of concrete and d' represents the concrete cover. V_d is the design shear force (the value of the maximum shear force at a distance d from the column face) value.

Required stirrup reinforcement area (A_s) and stirrup spacing (s) are calculated according to the following equation.

$$A_s/s = (V_d - 0.8V_{cr} \,) \left(f_{ywd} \; d \right) \geq A_{smin}/s \tag{9}$$

Here, A_{smin}/s is the minimum required stirrup reinforcement calculated as follows.

$$A_{smin}/s = 0{,}3. b_w . f_{ctd}/f_{ywd} \tag{10}$$

In Equation (10), b_w is the foundation's upper width, f_{ywd} is the yield stress of the stirrup reinforcement.

The longitudinal reinforcement area (A_l) is calculated according to the equation as follows:

$$A_l = \frac{0.85 * b * a}{f_{yd}} \geq A_{lmin}; a = d - \sqrt{d^2 - \frac{2|M_d|}{0.85 f_{cd} b}} \tag{11}$$

where, M_d is the design moment force (see Section 2.1 for the calculation), f_{yd} is the yield design stress of the longitudinal reinforcement, a is the neutral axis length. A_{lmin} is the minimum required longitudinal reinforcement area calculated as follows.

$$A_{lmin} = 0.8 \frac{f_{ctd}}{f_{yd}} * b_w * d \tag{12}$$

According to A_l and A_s/s, reinforcement amounts and diameters are computed.

2.3. Optimization problem of the RC foundation

The study aims to find the most suitable foundation cross-section parameters and reinforcement details in a way that minimizes the foundation cost. For this purpose, the optimization problem of the study is presented mathematically as follows.

Find the optimum design variable vector $\vec{\boldsymbol{x}} = [\boldsymbol{b}, \mathbf{h}, \boldsymbol{\phi}_{\mathbf{l}}, \boldsymbol{\phi}_{\mathbf{s}}, \boldsymbol{n}_{\mathbf{l}}, \boldsymbol{n}_{\mathbf{s}}]$ to minimize the foundation cost:

$$\text{Min. cost}(\vec{\boldsymbol{x}}) = U_C\, V_C + U_S\, W_S \tag{13}$$

Subject to;

$$g_1(x) = \frac{q_o}{q_{t,net}} - 1 \leq 0 \tag{14}$$

$$g_2(x) = \frac{V_d}{V_{cr}} - 1 \leq 0 \tag{15}$$

$$g_3(x) = \frac{V_d}{V_{max}} - 1 \leq 0 \tag{16}$$

In Equation (13), U_C and U_S respectively are the unit costs of concrete and steel materials. V_C is the volume of the concrete in the foundation. W_S is the total steel weight of the foundation. ϕ_{l} and ϕ_{s} represent diameters of longitudinal and stirrup reinforcements. n_{l} and n_s are the total number of longitudinal and stirrup reinforcement bars. In Equation (16), V_{max} is the maximum shear force occurred in the foundation.

2.4. Optimization method: ABC

Artificial Bee Colony Optimization, developed by Karaboğa [56], was inspired by the foraging behavior of honey bees. In the method, bees are divided into 3 groups according to their duties: employed, onlooker, and scout. Employed bees are responsible for collecting food and sharing food information with the colony. Onlooker bees collect like employed bees, but they select the food source based on the information received from the worker bees. Scout bees are responsible for finding new food sources to replace depleted food sources.

In this method, bees visit a food source during each flight. The food sources chosen by the worker bees should be different from each other. Therefore, the total number of employed bees and the number of food sources are equal. Although onlooker bees do not have to choose different food sources, the total number of flights is equal to the number of food sources. Therefore, the colony size of ABC is equal to the food source. The quality of the food source is inversely proportional to the objective function value. In the method, the food source, the location of the food source, the quality of the food source, the flight of bees to the food source, and the research of the food source represent the foundation design, design variable vector of the design, performance (better objective function value) of the design, change of the design and creation of the design, respectively. The food source is considered used if its performance does not improve when the food source is changed. If the use of the food source exceeds the limit value, the food source is considered exhausted and is deleted from the algorithm. The steps of the ABC algorithm can be detailed as follows [57].

Step 1: The ABC generates initial foundation designs randomly as follows:

$$\mathbf{X}_{i,j} = lb_j + \left(ub_j - lb_j\right) \cdot r \; ; i = 1.2, \dots N_{fs}; j = 1.2, \dots, n \tag{17}$$

Here, **X** is the matrix containing all foundation designs, ub_j and lb_j respectively are the upper and lower boundaries of the j^{th} design variable, r is the pseudo-random number generated in the interval (0,1), N_{fs} is the number of food sources, and n is the dimension of the optimization problem. Initial foundation designs are evaluated according to Section 2.3 and their costs are saved in the algorithm memory.

Step 2: Employed bees modify their foundation designs as follows:

$$\mathbf{X}_{i,j}^{new} = \mathbf{X}_{i,j} + \left(\mathbf{X}_{i,j} - \mathbf{X}_{k,j}\right) \cdot (r - 0.5) \cdot 2 \; ; i = 1.2, \dots N_{fs}; j = 1.2, \dots, n \tag{18}$$

Subscript k represents the neighbor solution (determined randomly) of the i^{th} solution. Then the ABC calculated the modified foundation designs' costs and compares them with their old ones. If new designs have lower costs, new designs replace old ones. Otherwise, old designs remain in the algorithm memory. This procedure is called "Greedy selection"

Step 3: The ABC computes selection rates of the foundation designs in the memory as follows:

$$R_i = 1 - 0.9 \frac{cost_i}{cost_{max}} ; i = 1.2, \dots N_{fs} \tag{19}$$

Subscript max is the index of the foundation design having the highest cost value in the memory. Onlooker bees select designs based on their selection probabilities and modify them using Equation (18). Then ABC uses the Greedy Selection operator.

Step 4: Scout bees check all designs whether they are exhausted or not. If any design is exhausted, the ABC removes it from the memory and the scout bee finds a new solution for the removed ones using Equation (17).

The ABC repeats steps 2-4 until it reaches the maximum design evaluation (iteration) number. ($iter_{max}$). Search parameters of the ABC for this study are available in Table 1.

Table 1. Search parameters of the ABC for this study

Search Parameter	Numeric Value
N_{fs}	20
Food Limit	150
n	5
$iter_{max}$	10000

3. Design Example

In the study, two design examples are used to test performance of the optimization algorithm and effect of elastic soil behaviour.

3.1. Design example 1

A continuous foundation with a length of 12.6 meters used in the literature(not optimized) is chosen for the current study [76]. Foundation dimensions, loading conditions and are given in Figure 2. This continuous foundation is optimized for both rigid and elastic soil behavior cases.

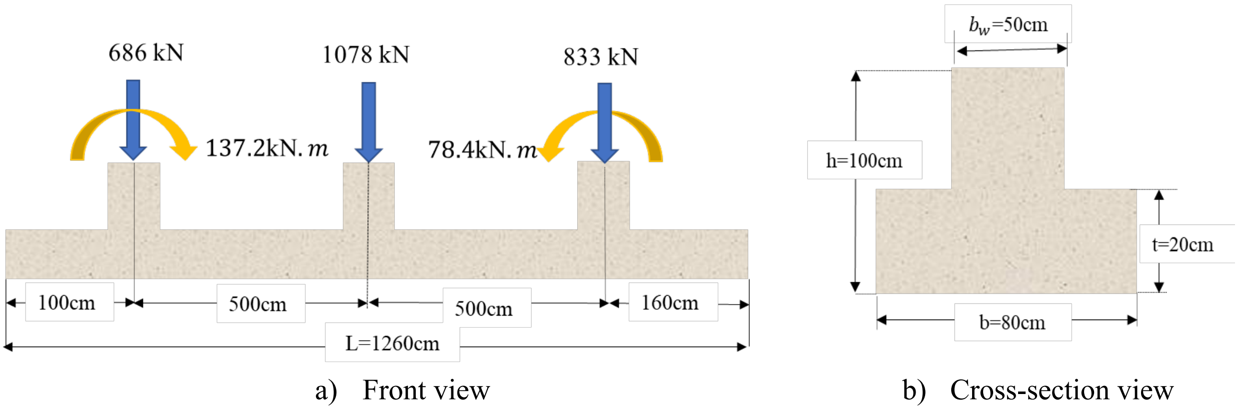


Fig. 2. Design example views

Although the concrete class is taken as C16 in the referenced example, the concrete class is selected as C25 to comply with earthquake standards [77]. S420 is selected as the steel class. Since the soil is semi-hard clay, the bearing coefficient is taken as $K_0 = 14700\ kN/m^3$, the allowable soil stress is 294 kN /m^2, and the columns are 30x40 (40 cm in the direction of the foundation axis). Unit concrete and reinforcement prices respectively are taken as 37.5$/m^3, 2.19$/kg. Upper and lower boundaries of cross-section parameters are defined as follows: width b=0.7-2m, height h=0.5-1.5m, and thickness t=0.2-0.6m.
Internal force-stress diagrams of the optimum foundation design for rigid and elastic cases are given in Figure 3. According to these figures, in the rigid case, the soil stress is constant along the foundation base which is equal to 245.25 kN/m^2. However, in the elastic case, the soil stress distribution is parabolic low stresses occurred at the edges and high stresses occurred in the middle of the foundation. In the moment diagram of the rigid design, higher moment values take place in both span and column connection regions. Shear force distributions of elastic and rigid designs are very close to each other.
The optimum cost and design details are given in Table 2. According to Table 2, the lowest optimum cost value was obtained in the elastic design condition ($1275.12). This cost is 6.9% lower than the optimum cost for the rigid case. When the elastic solution is compared to the reference result, the cost of the elastic solution is 32.27% less than the cost of the reference solution. Stirrups spacing details of all solution areas same which equals minimum requirements. Width is used at the same value in rigid and elastic solutions. However, the height value is less in the elastic design. Since the height value is lower in the elastic design, it contributed to the reduction of the concrete and reinforcement costs.

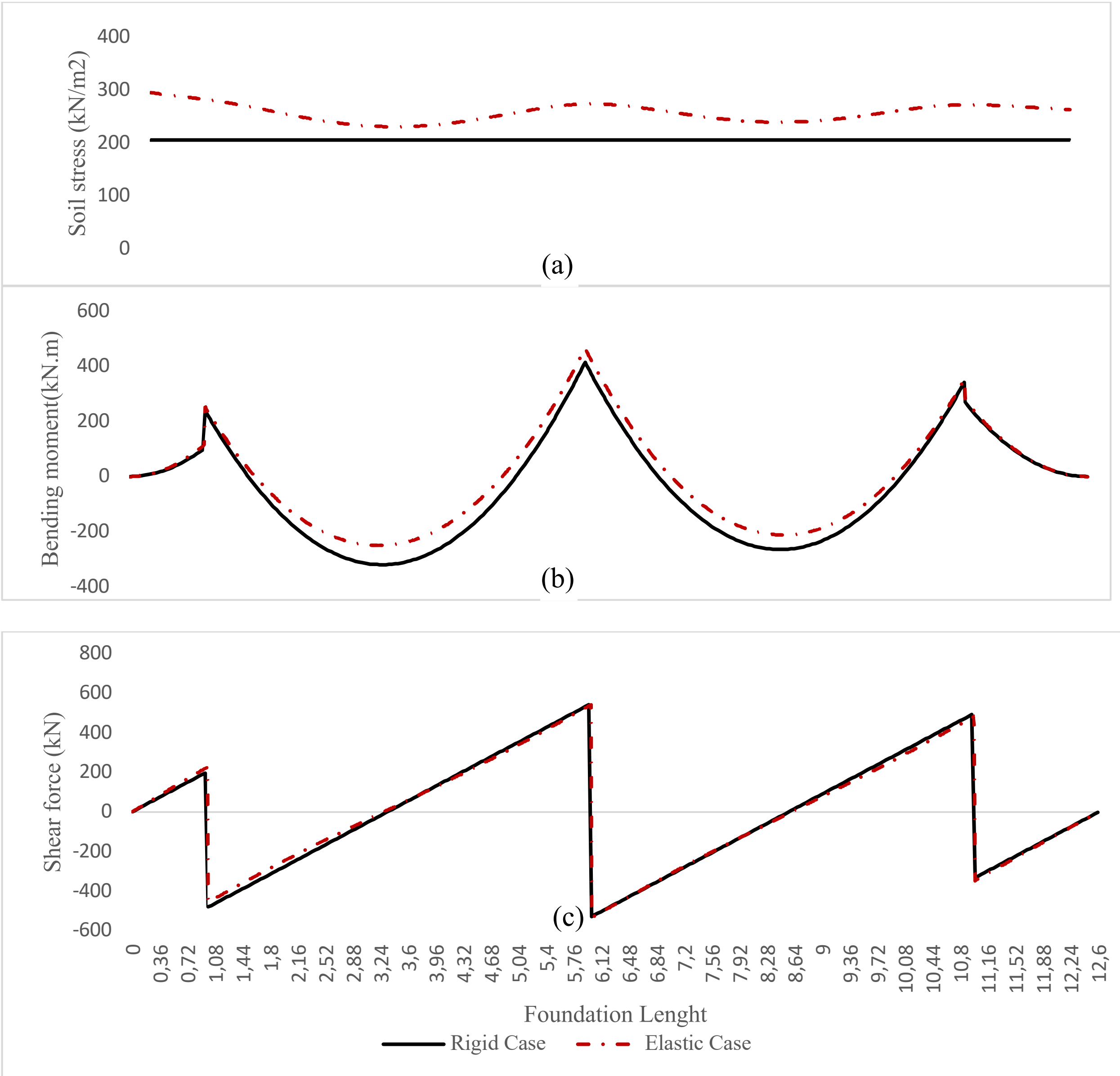


Fig. 3. Internal action diagrams of the optimum foundation design for rigid and elastic case (a): Soil stress, (b): Moment diagram, (c): Shear force diagram. Units

Table 2. Cost and design details of the designs

	Rigid solution	**Elastic solution**	**Ref. solution**
With	75cm	75cm	80 cm
Height	65cm	55cm	100 cm
Thickness	30 cm	30cm	20 cm
Stirrups spacing (mid-zone)	20cm	20cm	20 cm
Stirrups spacing (sup- zone)	15cm	15cm	15 cm
Stirrup reinforcement	ϕ10	ϕ10	ϕ10
Tension long. reinf.	4ϕ20+4ϕ22	4ϕ18	4ϕ20
Comp. long. reinf.	4ϕ14+2ϕ14i+4ϕ20+4ϕ16i	3ϕ18+ 3ϕ16i+7ϕ22i	4ϕ16+12ϕ14i
Web reinforcement	2ϕ14	-	4ϕ14
Dist.-bar reinforcement	ϕ12	ϕ12	ϕ12
	ϕ10	ϕ10	ϕ10
Total cost ($)	1363.94 USD	1275.12 USD	1686.66 USD

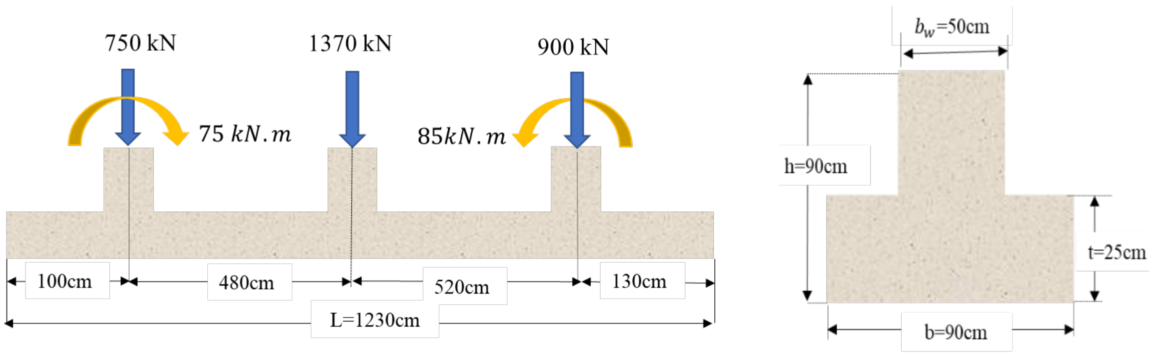
Limit constraint ratios (Soil bearing, shear, bending, and stirrup) of the foundation design are given in Table 3. In table 3, for all solutions, the soil-bearing load capacity ratios exceed 95%. For optimum designs (both for elastic and rigid cases), stirrup load capacity ratios are the highest ratios among other constraints. However, in the reference solution, soil-bearing control is the dominant constraint. According to shear Control, the capacities of all solutions are under 40%. If the value is above 1 in stirrup control, the required reinforcement is preferred instead of the minimum reinforcement. The reason why it gives 1.680* and 1.846* values in rigid and elastic solution is due to this situation.

Table 3. Limit constraint values of the designs

	Rigid solution	Elastic solution	Ref. solution
Soil bearing control	0.989	0.980	0.958
Shear Control	0.357	0.393	0.155
Stirrup Control	1.680*	1.846*	0.872

3.2. Design example 2

A continuous foundation with a length of 12.3 meters used in the literature (not optimized) is chosen for the current study [78]. Foundation dimensions, loading conditions and are given in Figure 4. This continuous foundation is optimized for both rigid and elastic soil behavior cases. Unit concrete price as taken as is 39.5$/m^3.



a) Front view b) Cross-section view

Fig. 4. Design example views

In the reference example, the concrete and steel grades was chosen as C30 and S240 respectively [78]. Soil type is considered as the ground semi-hard clay and the bearing coefficient value of the soil is $K_0 = 14700$ kN/m^3. The bearing soil stress is taken as 300 kN/m^2 and the columns are 30x50 (50 cm in the direction of the foundation axis). Unit reinforcement price, cross section parameters are shown in the previous example.

Internal force-stress diagrams of the optimum foundation design for rigid and elastic cases are given in Figure 5. According to the figure, in the rigid case, the soil stress is constant along the foundation base which is equal to 273 kN/m^2. However, in the elastic case, the soil stress distribution is parabolic low stresses occurred at the edges and high stresses occurred in the middle of the foundation. In the moment diagram of the rigid design, higher moment values take place in both span and column connection regions. Shear force distributions of elastic and rigid designs are very close to each other.

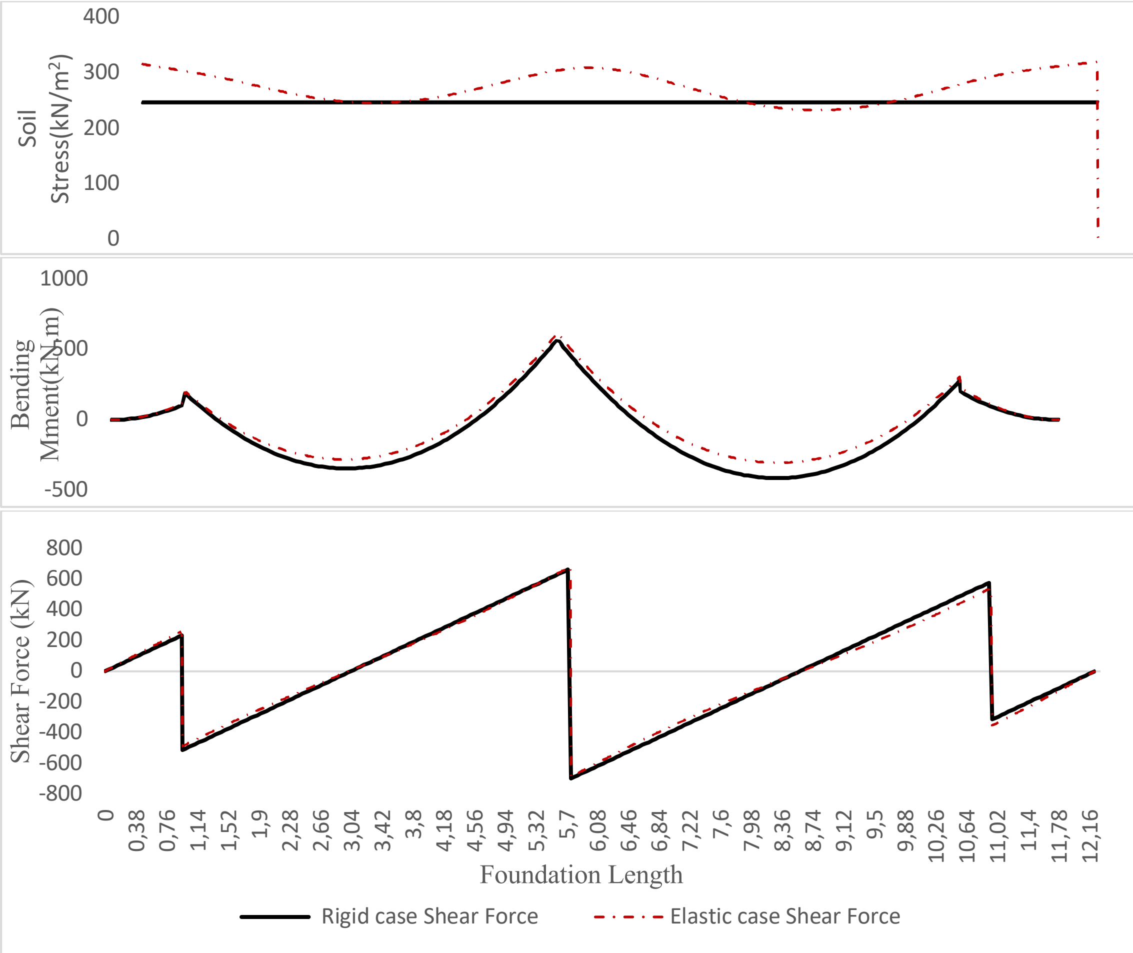


Fig. 5. Internal action diagrams of the optimum foundation design for rigid and elastic case (a): Soil stress, (b): Moment diagram, (c) shear force diagram. Units

The optimum cost and design details are given in Table 4. According to Table 4, the lowest optimum cost value was obtained in the elastic design condition ($1530.75). This cost is 5.2% and 11.48% lower than the optimum cost for the rigid case and reference solution respectively. Stirrups spacing details of all solution areas same which equals minimum requirements. Width is used at the same value in rigid and elastic solutions. Similar to the first example, foundation heights are different and elastic solution has the minimum foundation height. Therefore, in elastic solution the costs of concrete and reinforcement are lower than other solutions.

Table 4. Cost and design details of the designs

	Rigid solution	**Elastic solution**	**Ref. solution**
With	90cm	90cm	90 cm
Height	75cm	70cm	90 cm
Thickness	30 cm	30cm	25 cm
Stirrups spacing (mid-zone)	20cm	20cm	20 cm
Stirrups spacing (sup- zone)	15cm	15cm	15 cm
Stirrup reinforcement	2ϕ10	2ϕ10	2ϕ10
Tension long. reinf.	4ϕ22+4ϕ24	4ϕ18+4ϕ20	4ϕ20+4ϕ22
Comp. long. reinf.	3ϕ18+4ϕ12i+4ϕ22i	4ϕ16+ 1ϕ12i+4ϕ24i+3ϕ14i	4ϕ14+8ϕ14i+4ϕ20i
Web reinforcement	2ϕ16	2ϕ16	4ϕ14
Dist.-bar reinforcement	ϕ12	ϕ12	ϕ12
	ϕ10	ϕ10	ϕ10
Total cost ($)	1611.41 USD	1530.75 USD	1706.55 USD

Limit constraint ratios (Soil bearing, shear and stirrup) of the foundation design are given in Table 5. In table 5, for all solutions, the soil-bearing, stirrup load capacity ratios exceed 98%. For optimum designs (both for elastic and rigid cases), stirrup load capacity ratios are the highest ratios among other constraints. In stirrup control, if the value is above 1, the required reinforcement is preferred instead of the minimum reinforcement. The reason why it gives a value of 1.288* in the reference solution is due to this situation. However, in the reference solution, soil-bearing control is the dominant constraint.

Table 5. Limit constraint values of the designs

	Rigid solution	**Elastic solution**	**Ref. solution**
Soil bearing control	0.976	0.972	0.989
Shear Control	0.317	0.310	0.392
Stirrup Control	1.692	1.657	*1.288

4. Conclusions

In the study, an optimization algorithm has been developed for elastic and rigid continuous foundations. An example used in the literature is optimized for both rigid and elastic analysis with the developed program. In line with the results obtained, the following inferences were made regarding the performance of the current algorithm and the effect of the elastic soil behavior on the optimum foundation design.

In terms of optimum cost, the elastic design outperforms the rigid design. This is because the minimum foundation dimensions and minimum reinforcement quantities relative to the reference solution are sufficient for the foundation to bear the superstructure loads. However, it has been observed that the load capacity ratios of the elastic design are close to the limit value. Especially in the elastic design, 97% of the soil capacity has been reached. In this case, it is estimated that lower costs will be obtained with the elastic design under more difficult loads.

When the optimum results are compared with the literature sample, the optimum results gave lower results than the literature sample results. Therefore, it can be said that the developed algorithm performs well for the existing examples.

Examination of the performance of novel metaheuristic techniques by adding new metaheuristic techniques and optimization with different objective functions such as carbon dioxide emission are considered future studies.

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