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Optimum design of RC shallow tunnels in earthquake zones using artificial bee colony and genetic algorithms

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Abstract. The main purpose of this study is to perform optimum cost design of cut and cover RC shallow tunnels using Artificial bee colony and genetic algorithms. For this purpose, mathematical expressions of objective function, design variables and constraints for the design of cut and cover RC shallow tunnels were determined. By using these expressions, optimum cost design of the Trabzon Kalekapısı junction underpass tunnel was carried out by using the cited algorithms. The results obtained from the algorithms were compared with the results obtained from traditional design and remarkable saving from the cost of the tunnel was achieved.

Keywords: optimization; shallow tunnels; genetic algorithm; artificial bee colony algorithm

1. Introduction

Tunnels are used for defence, shelter, storage and mainly for transportation purposes. Currently, construction of these structures is of great necessity due to development of cities, improvement in road standards, increase in defence and shelter needs, roughness and value of the land.

Tunnels used for transportation and fluid transmission purposes are generally constructed from reinforced concrete (RC) using cut-cover method. The traditional design of RC structures is a process in which design requirements are tried to be satisfied with mathematical operations. In this process, in case of unsatisfactory design requirements, the sizes of structural elements and/or amount of steel are changed by considering current regulations with engineering judgment. In this way, a new solution is obtained. This new solution is reiterated until a more appropriate result is obtained. Optimum design process which makes the design according to an objective function and definite constraints is known as a superior alternative than the traditional design process.

In technical literature, there are some methods used in optimum design of structures. Haug Jr and Kirmser (1967) applied Generalized Newton Algorithm to isostatic beams in their studies.

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This study is one of the studies in which digital computers were firstly used. On the other hand, in the optimum design of RC beams, geometrical programming by Chakrabarty (1992), non-linear programming by Lin and Frangopol (1996), genetic algorithm by Coello *et al.* (1997) and Govindaraj and Ramasamy (2005), reduced gradient algorithm by Fedghouche and Tiliouine (2012), Artificial Bee Colony Algorithm by Öztürk *et al.* (2012) were used. Also Artificial Bee Colony Algorithm was used in the determination of optimal placement of elastic steel diagonal braces (Aydın *et al.* 2015) and in the optimization of smart FML panels (Ghashochi-Bargh and Sadr 2014). At the same time, using various algorithms, the optimum design of RC columns (ZielinskiI *et al*. 1995, Govindaraj and Ramasamy 2007, Akın and Saka 2010b, Öztürk and Durmuş 2013), retaining walls (Sarıbaş and Erbatur 1996, Ceranic *et al.* 2001, Babu and Basha 2008, Akın and Saka 2010a, Kaveh and Abadi 2011, Pei and Xia 2012), RC cross-sections in corrosive environment (Biondini and Frangopol 2009), precast RC bridges (Marti and Gonzalez-Vidosa 2010), RC culverts with rectangular (Perea *et al*. 2008) and circular arched (Carbonell *et al.* 2011) cross-sections were performed. Many researchers performed optimum design of RC frames. In these designs; Direct Search Algorithm (Choi and Kwak 1990, Kwak and Kim 2008), Simulated Annealing Algorithm (Balling and Yao 1997), Harmony Search Algorithm (Akın 2010) Genetic Algorithm (Rajeev and Krishnamoorthy 1998, Camp *et al*. 2003, Lee ve Ahn 2003, Kwak and Kim 2009) were utilized.

The purpose of this study is to perform minimum cost design of rectangular cross-sectioned tunnels constructed with cut and cover method by using Artificial Bee Colony and Genetic Algorithm.

2. Artificial bee colony and genetic algorithm

2.1 Artificial bee colony algorithm

The Artificial bee colony algorithm was developed by Karaboğa (2005) inspired from nectar-seeking behavior of bees. This algorithm is composed from three main components namely nectar sources, employed bees and unemployed bees. In the optimization problem, possible solutions correspond to nectar sources. In the first phase of Artificial Bee Colony Algorithm, starting nectar sources are produced randomly. This production process is expressed in Eq. (1).

$$x_i^j = x_{\min}^j + rand(0,1)(x_{\max}^j - x_{\min}^j) \tag{1}$$

In Eq. (1), *i=1….SN*, *j=…..D*, x_{min}^{y} and x_{max}^{y} are denoting the lower and upper bound of j^{th} design variable, *D* is denoting the number design variables, *SN* is denoting the number of nectar sources.

The fitness value used in the evaluation of produced results is determined from Eq. (2).

$$f_i^{'}(x) = \begin{cases} f_i \geq 0 \;\Rightarrow\; 1/(1+f_i) \\ f_i \prec 0 \;\Rightarrow\; 1+|f_i| \end{cases} \tag{2}$$

In Eq. (2), f_i is denoting the objective function (cost) value of the i^{th} nectar source.

In the second stage, the employed bees may prefer the new source, selected around the current source, according to the control parameter *MR*. This process can be carried out by Eq. (3).

$$v_i^j = \begin{cases} R_j \prec MR \Rightarrow x_i^j + \Phi_{ij}(x_i^j - x_k^j) \\ R_j \geq MR \Rightarrow x_i^j \end{cases} \tag{3}$$

In Eq. (3), R_j is denoting a uniformly distributed random number in interval [0,1], *MR* is denoting a control parameter in interval [0,1], *i* is the nectar source index, *j* is the random design variable index and *k* is the random nectar source index different from *i*. After completing their research, employed bees return to the hive to transfer the information to the onlooker bees about the sources that is found. Onlooker bees choose a source by considering this information with the help of a probability value. This probability value is determined from one of the correlations given in Eq. (4)

$$p_i = \begin{cases} if \;\; in \;\; appropriate \;\; region \;\; \Rightarrow \;\; 0.5 + \left(f_i^{'}(x) / \sum_{i=1}^{SN} f_i^{'}(x) \right) \cdot 0.5 \\ if \;\; in \;\; inappropriate \;\; region \;\; \Rightarrow \;\; 1 - \left(violation_j / \sum_{j=1}^{SN} violation_j \right) \cdot 0.5 \end{cases} \tag{4}$$

In Eq. (4), $violation_j$ is denoting the violation value of the constraint of j^{th} nectar source. In the last phase namely the scout bee phase, new solutions are added to the generation in the place of undeveloped solutions to provide diversity. This solution is evaluated by choosing a random source in which the bee of undeveloped solution (exhausted source) is transformed to scout bee. In this stage, the two control parameters of algorithm namely SPP and LIMIT are used (Akay 2009). During the search, if a source is to be abandoned, a counter which has been updated is used. LIMIT is a predetermined counter value. If the value of the counter is greater than the LIMIT, then the source associated with this counter is assumed to be exhausted. Scout production period (SPP) is another control parameter. At each SPP cycle, it is controlled if there is abandoned food source or not.

It is appropriate to emphasize that Deb's (2000) constraint handling method which is accommodated to Artificial Bee Colony Algorithm by Karaboğa and Akay (2011) is used in the process. Pseudo-code of ABC algorithm is given below

1: Initialize the population by using Eq. (1)
2: Evaluate the population by using Eq. (2)
3: cycle=1
4: **repeat**
5: Produce new solution $v_{i\,j}$ by using Eq. (3) and evaluate them
6: Apply selection process (according to Deb's constraint handling method)
7: Calculate the probability values P_i for the solutions by Eq. (4)
8: Produce the new solutions $v_{i,j}$ for onlooker bees from the solution $x_{i,j}$ selected depending on P_i and evaluate them
9: Apply selection process (according to Deb's constraint handling method)
10:Determine the abandoned solution for the scout, if exists and replace it with a new randomly produced solution by Eq. (1)
11: Memorize the best solution
12: cycle =cycle + 1
13: **until** cycle =MCN

2.2 Genetic algorithm

The Genetic algorithm is known as a frequently used optimization algorithm in technical literature developed by John Holland (Goldberg 1989). In the Genetic Algorithm used in this study, adaptable penalty function method was used (Toğan ve Daloğlu 2006). According to this method, penalty coefficient is determined from Eq. (5).

$$PC = \begin{cases} g(i) \geq g_{avg} \Rightarrow & (g_{\max} + g(i))/(g_{\max} - g_{avg}) \\ g(i) \prec g_{avg} \Rightarrow & (g_{avg} + g(i))/(g_{avg} - g_{\min}) \\ g(i) = 0 \quad \Rightarrow & 0 \end{cases} \tag{5}$$

In this method, $g(i)$ is denoting the violation amount of i^{th} constraint, $g_{\min}$, g_{avg} and $g_{\max}$ are denoting the minimum, average and maximum violation value in the generation, respectively.

By using penalty coefficient, penalized objective function is determined from Eq. (6) in which $f(x)$ is denoting the objective function.

$$\Phi(x) = f(x) \cdot (1 + PC) \tag{6}$$

The fitness degree and the fitness value of an individual in the generation is determined from Eqs. (7) and (8), respectively.

$$f_i^d(x) = \left[\Phi_{\max}(x) + \Phi_{\min}(x)\right] - \Phi_i(x) \tag{7}$$

$$f_i^{'}(x) = \frac{f_i^d(x)}{f_{avg}} \tag{8}$$

In Eqs. (7) and (8), $\Phi_{\max}(x)$, $\Phi_{\min}(x)$ and f_{avg} are denoting the maximum and minimum penalized objective function value in the generation, the average fitness degree of individuals in the generation, respectively.

In addition to these, the cross-over and mutation techniques used in the study are adaptable. According to this method, the cross-over (p_c) and mutation (p_m) probability values are determined from Eqs. (9) and (10), respectively.

$$p_c = \begin{cases} f_m \geq f_{avg} \Rightarrow (f_{\max} - f_m)/(f_{\max} - f_{avg}) \\ f_m < f_{avg} \Rightarrow 1.0 \end{cases} \tag{7}$$

$$p_m = \begin{cases} f' \geq f_{avg} \Rightarrow 0.5 \cdot (f_{\max} - f')/(f_{\max} - f_{avg}) \\ f' < f_{avg} \Rightarrow (f_{avg} - f')/(f_{avg} - f_{\min}) \end{cases} \tag{8}$$

In Eqs. (9) and (10), f', f_{min}, f_{avg}, f_{max} and f_m are denoting, fitness value of any individual, minimum, average and maximum fitness value in a generation, the value of cross-overed individual that has the smallest fitness value, respectively. Pseudo-code of adaptive GA algorithm is given below

1: Initialize the population
2: Evaluate the population
3: cycle=1
4: **While** cycle=MCN **do**

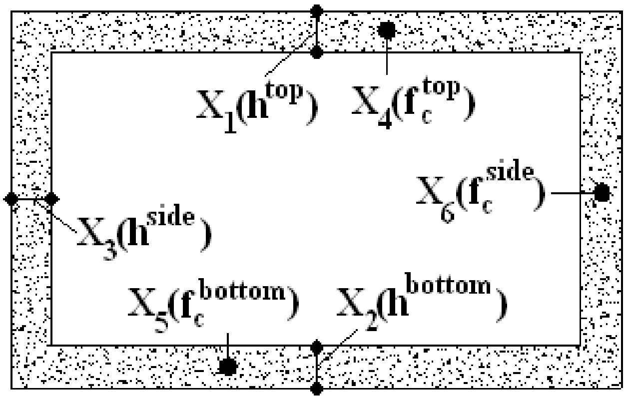


Fig. 1 Design variables associated with dimensions and concrete classes of the tunnel

5: Set the adaptive penalty coefficient by Eq. (5)
6: Calculate penalized objective functions by Eq. (6)
7: Calculate fitness by Eq. (8)
8: Select parents for crossover
9: Set the crossover and mutation probability by Eqs. (9)-(10)
10: Perform crossover and mutation
11: Evaluate population
12: Memorize the best solution
13: cycle =cycle + 1
14: **EndWhile**

3. Mathematical expression of optimum design problem

3.1 Objective function

In this study, the objective function which considers the cost of concrete, steel, formwork, scaffolding, excavation and backfill processes and their corresponding labor is expressed as the total cost minimization of unit length of tunnel. This objective function f_{cost} is expressed mathematically in Eq. (11).

$$f_{\cos t} = C_c + C_s + C_f + C_{pi} + C_{ex} + C_{bf} \tag{11}$$

In Eq. (11), C_c, C_s, C_f, C_{pi}, C_{ex} and C_{bf} are denoting the cost of concrete, steel, formwork, scaffolding, excavation, backfilling and their corresponding labor costs, respectively.

3.2 Design variables

In this study, design variables were classified into three categories namely variables associated with dimensions, concrete class and steel. The total number of design variables corresponding to these three categories is 28 and these were shown by the letter “X” in Figs. 1-3. The first three of the design variables are related with dimensional properties. These design variables are bottom,

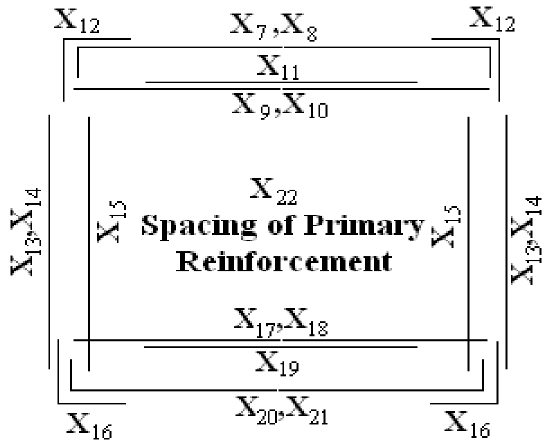


Fig. 2 Design variables of primary and additional reinforcement

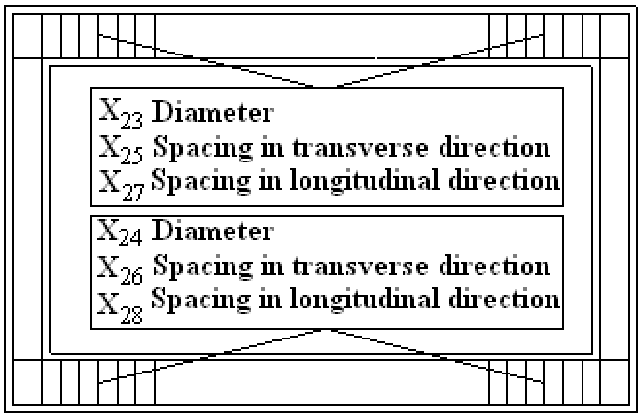


Fig. 3 Design variables of shear reinforcement

top and side walls' thicknesses of the tunnel. The other three design variables are the classes of concrete used in the top, bottom and side walls of the tunnel. All of these were given in Fig. 1.

Design variables associated with dimensions take their values from a domain in the range of 400 mm-1500 mm with 50 mm increments to provide the practical applicability. Design variables associated with concrete were selected from the domain of concrete classes produced in Turkey (from C20 to C50). The other 22 design variables are associated as follows: the diameters of primary and additional reinforcements (15 design variables), the diameters of shear reinforcements (2 design variables) and spacing between these reinforcements (5 design variables). The enumeration of design variables associated with primary and additional reinforcement and shear reinforcement are given in Figs. 2-3, respectively.

The domain of the variables associated with the diameter of primary reinforcements is constituted from reinforcement diameters starting from 12 mm and ending at 32 mm with 2mm increments (12-14-16-18-20-22-24-26-28-30-32). In the same manner, the domain of the variables associated with the diameter of shear reinforcements is constituted from reinforcement diameters starting from 8 mm and ending at 32 mm with 2 mm increments (8-10-12-14-16-18-20-22-24-26-

Table 1 Lower, upper bounds and increments of design variables

Design Variable	Lower Bound	Upper Bound	Increment
X_1, X_2, X_3	400 mm	1500 mm	50 mm
X_4, X_5, X_6	{C20, C25, C30, C35, C40, C45, C50}		
X_7, X_8, X_9, X_{10}, X_{11}, X_{12}, X_{13},X_{14} X_{15}, X_{16}, X_{17}, X_{18} X_{19}, X_{20}, X_{21}	12 mm	32 mm	2 mm
X_{22}	{50, 75, 100, 125, 200 } mm		
X_{23},X_{24}	8 mm	32 mm	2 mm
X_{25}, X_{26}	{50, 100, 150, 200} mm		
X_{27}, X_{28}	{50, 75, 100, 125, 150, 200, 250, 300} mm		

28-30-32). There exist 50, 75, 100, 125 and 200 mm spacing values in the domain of design variables associated with primary reinforcement spacing. In the same way, there exist 50, 75, 100, 125, 150, 200, 250 and 300 mm spacing values in the domain of design variables associated with spacing of shear reinforcement in the longitudinal direction of the tunnel. Lastly, there exist 50, 100, 150 and 200 mm spacing values in the domain of design variables associated with spacing of shear reinforcement in the lateral direction of the tunnel. Also, there should be a harmony between the spacing of primary and shear reinforcements in order to be tied up to each other. The spacing of shear reinforcement cannot be denser than the spacing of primary reinforcement. Moreover, the spacing of shear reinforcement should be equal or equal times to spacing of primary reinforcement. In the algorithm, the suitability of the reinforcement spacing of shear and primary reinforcement were controlled by a constraint in order to provide practical applicability. Lower, upper bounds and increments of design variables are shown in Table 1.

3.3 Structural constraints

Structural constraints are provisions by currently used regulations that should be satisfied in the design of the tunnel. The first two structural constraints are providing the control of the maximum and minimum reinforcement ratios. By considering the minimum and maximum reinforcement ratios given in Turkish Standards (TS500 2000), these provisions were controlled with the constraints given in Eq. (12) whether they are satisfied or not.

$$\left.\begin{aligned} g_1(x) &= \frac{\rho_{\min}}{\rho} - 1 \leq 0 \\ g_2(x) &= \frac{\rho}{\rho_{\max}} - 1 \leq 0 \end{aligned}\right\} \tag{12}$$

where $\rho_{\max}$, $\rho_{\min}$ and ρ is the maximum reinforcement ratio, minimum reinforcement ratio and the reinforcement ratio in reinforced concrete section, respectively. The resisting moments were checked by using the constraint given in Eq. (13) whether they are satisfying design moments obtained from structural analyses or not.

$$g_3(x) = \frac{M_d}{M_r} - 1 \leq 0 \tag{13}$$

In Eq. (13), M_d and M_r are denoting design and resisting moments, respectively.
The deflection of ceiling slab is checked by using the constraint given in Eq. (14) whether it is satisfying the permitted deflection (l/250) with regard to usability boundary condition or not (Eurocode-2 2005).

$$g_4(x) = \frac{\delta_d}{\delta_{\max}} - 1 \leq 0 \tag{14}$$

In Eq. (14), δ_d and $\delta_{\max}$ are denoting the calculated design deflection at the center of ceiling slab and the value of maximum permitted deflection, respectively.

In the same way, the resisting shear strength is checked by using the constraint given in Eq. (15) whether it is larger than the design shear strength obtained from structural analyses or not.

$$g_5(x) = \frac{V_d}{V_r} - 1 \leq 0 \tag{15}$$

In Eq. (15), V_d and V_r are denoting design shear strength and resisting shear strength of the cross-section, respectively. According to the opinion of the authors, the suitability of the spacing of the shear reinforcement in the longitudinal direction of tunnel with the spacing of primary reinforcements should be checked (Öztürk 2013). In this case, the constraint violations are determined from the expressions given in Eq. (16).

$$g_6(x) = \begin{cases} s_1 \prec s_a \Rightarrow \dfrac{s_a}{s_1} - 1 \\ s_1 \geq s_a \ \textit{and} \ s_1 \ \textit{is divisible to} \ s_a \quad \Rightarrow \quad 0 \\ s_1 \geq s_a \ \textit{and} \ s_1 \ \textit{is not divisible to} \ s_a \Rightarrow \dfrac{\mathrm{mod}(s_1, s_a)}{s_a} \end{cases} \tag{16}$$

In Eq. (16), s_a and s_l are denoting the spacing of primary reinforcement and spacing of the shear reinforcement in the longitudinal direction of tunnel.

4. Numerical application

In this study, the optimized tunnel is a RC underground structure that connects Trabzon State Coastal Road with Yavuz Selim Boulevard to Şenol Güneş Street in Turkey constructed with cut-cover method under the supervision of Turkish Republic Ministry of Transport 10^{th} Regional Directorate of Highways. In order to analyze the structural model of the tunnel, finite element method was used. The 2D finite element model has 44 nodes, the response of the ground is represented by elastic springs and the material properties are isotropic linear elastic (Fig. 4).

4.1 Loads

4.1.1 Dead loads

In this study, the total dead load is calculated from Eq. (17).

$$G = G_z + G_t \tag{17}$$

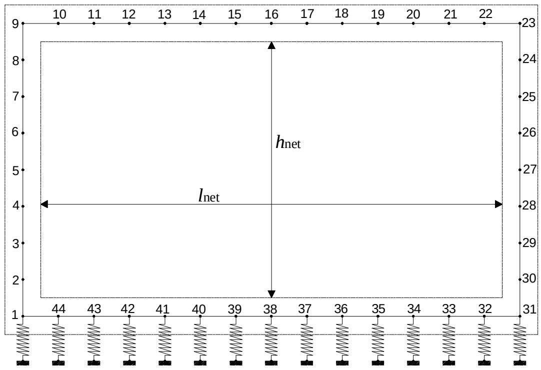


Fig. 4 Finite element model of the tunnel

In Eq. (17), G_z and G_t are denoting the permanent load due to the weight of soil on the tunnel and self-weight of the tunnel, respectively.

4.1.2 Live loads

Live loads are constituted from standard truck loads defined in regulations or lane loads equivalent to the standard truck loads. In this study, the vehicle load defined with H_{30}-S_{24} symbol in Turkish Technical Specifications for Highway Bridges is used (TSHB 1973).

In order to consider the dynamic effects of vehicles passing through the tunnel, the standard vehicle loads were multiplied with dynamic load factor (φ_d). This factor can be calculated from Eq. (18), where L is denoting the span.

$$\varphi_d = 1 + \frac{15}{L+37} \leq 1.30 \tag{18}$$

In this study only surface live loads were taken into consideration. The loading conditions (Q_1 and Q_2) that give the largest absolute values of span and support moments were taken into account. Q_1 loading condition gives the maximum value of bending moment at the span of tunnel top wall according to H_{30}-S_{24} design tandem and design lane load, and Q_2 loading condition gives the minimum value of bending moment near the support of tunnel top wall according to H_{30}-S_{24} design tandem and design lane load.

4.1.3 Lateral earth pressures

The lateral pressures occurred due to soil on the right and left wall of the tunnel divided into two parts as P_{G1} and P_{G2}. P_{G1} is denoting the lateral earth pressures in rectangular shape and P_{G2} is denoting the lateral earth pressures in triangular shape. The lateral pressures in rectangular shape occurred due to soil on the right and left wall of the tunnel P_{G1}^{right} and P_{G1}^{left}, can be calculated from Eq. (19).

$$P_{G1}^{left} = P_{G1}^{right} = h_{avg} \cdot K_0 \cdot \gamma_s \tag{19}$$

In Eq. (19), K_0 (0.50), h_{avg} and γ_s are denoting the lateral pressure factor in static case, average thickness of soil on tunnel and unit weight of soil, respectively.

In the same manner, the lateral earth pressures in triangular shape, P_{G2}^{right} and P_{G2}^{left}, can be

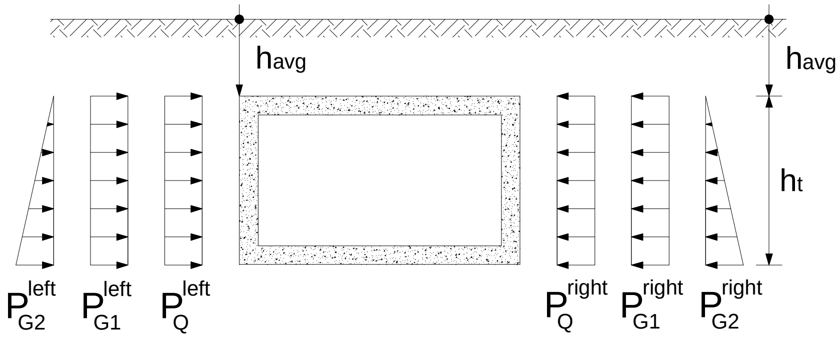


Fig. 5 The lateral earth pressures affecting the tunnel

calculated from Eq. (20).

$$P_{G2}^{left} = P_{G2}^{right} = (h_{avg} + h_t) \cdot K_0 \cdot \gamma_z \tag{20}$$

The symbols in Eq. (20) are denoting the same parameters as in Eq. (19). The only difference, h_t, is denoting the height of the tunnel. Also, the lateral pressures due to live loads, P_Q^{left} P_Q^{right} and can be calculated from Eq. (21).

$$P_Q^{left} = P_Q^{right} = q \cdot K_0 \tag{21}$$

q is denoting the distributed equivalent live load. All of these pressures were given in Fig. 5.

4.1.4 Earthquake loads

The earthquake loads were calculated according to Turkish Seismic Code (TSC 2007) based on Mononobe-Okabe method. By using the data of soil in which the tunnel constructed, the active lateral pressure factor in static case was calculated as K_{as}=0.2963. In Turkish Seismic Code, lateral equivalent earthquake parameter can be calculated from Eq. (22).

$$C_h = 0,2\left(I+1\right)A_o \tag{22}$$

Where A_0 is the active soil acceleration parameter and I is structure importance coefficient (I=1,00 for this structure). The vertical equivalent earthquake parameter can be calculated as from Eq. (23).

$$C_v = \frac{2C_h}{3} \tag{23}$$

Then total active pressure factor in dynamic case is determined in Eq. (24) as

$$K_{at} = \frac{(1 \pm C_v)\cos^2\left(\varphi - \lambda - \alpha\right)}{\cos\lambda\,\cos^2\alpha\,\cos\left(\delta + \alpha + \lambda\right)}\left[1 + \sqrt{\frac{\sin\left(\varphi+\delta\right)\sin\left(\varphi - \lambda - \beta\right)}{\cos\left(\delta+\alpha+\lambda\right)\cos\left(\beta - \alpha\right)}}\right]^{-2} = 0,3515 \tag{24}$$

Where φ is the angle of internal friction, α is the angle of back of the wall with the vertical, δ is

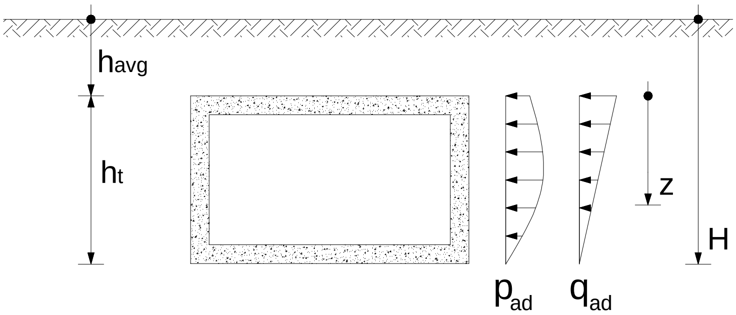


Fig. 6 The lateral pressures on the tunnel due to earthquake

the angle of friction of soil-wall, β is the angle of the slope. Also, the angle λ can be calculated in Eq. (25) as

$$\lambda = arctan\left[\frac{C_h}{(1 \pm C_v)}\right] \tag{25}$$

Therefore, the active pressure factor due to earthquake can be calculated from Eq. (26).

$$K_{ad} = K_{at} - K_{as} = 0.0552 \tag{26}$$

The variation of lateral pressure with height (z) due to earthquake, p_{ad}, can be calculated from Eq. (27).

$$P_{ad}(z) = 3 * \left(1 - \frac{z}{H}\right) * \gamma_s * z * K_{ad} \tag{27}$$

Also, the lateral pressure due to live load at the time of earthquake, q_{ad}, can be calculated from Eq. (28) (see Fig. 6).

$$q_{ad}(z) = 2 * q_0 * K_{ad} * \left(1 - \frac{z}{H}\right) * \frac{cos\,\alpha}{cos(\alpha - \beta)} \tag{28}$$

In Eq. (27) and (28), γ_z, H, α, q_0 and β are denoting the unit weight of the soil, total depth of the tunnel, the angle of tunnel wall, the amplitude of uniformly distributed outer load and the angle of the slope, respectively.

4.1.5 Load combinations

In the design of the cut and cover tunnel that is considered in this study, the load combinations determined according to AASHTO-HB-17 (2002) were used. Design loads are determined with these combinations. These combinations were given as follows

$$1.30\left[G + 1.67Q_1 + 1.15(p_{G1}^{right} + p_{G2}^{right} + p_{Q}^{right}) + 1.15(p_{G1}^{left} + p_{G2}^{left} + p_{Q}^{left})\right] \tag{29}$$

$$1.30\left[G + 1.67Q_2 + 1.15(p_{G1}^{right} + p_{G2}^{right} + p_{Q}^{right}) + 1.15(p_{G1}^{left} + p_{G2}^{left} + p_{Q}^{left})\right] \tag{30}$$

$$1.30\left[G+1.67Q_1+1.15(p_{G1}^{right}+p_{G2}^{right}+p_{Q}^{right})+0.575(p_{G1}^{left}+p_{G2}^{left}+p_{Q}^{left})\right] \quad (31)$$

$$1.30\left[G+1.67Q_2+1.15(p_{G1}^{right}+p_{G2}^{right}+p_{Q}^{right})+0.575(p_{G1}^{left}+p_{G2}^{left}+p_{Q}^{left})\right] \quad (32)$$

$$1.30\left[G+1.67Q_1+0.575(p_{G1}^{right}+p_{G2}^{right}+p_{Q}^{right})+0.575(p_{G1}^{left}+p_{G2}^{left}+p_{Q}^{left})\right] \quad (33)$$

$$1.30\left[G+1.67Q_2+0.575(p_{G1}^{right}+p_{G2}^{right}+p_{Q}^{right})+0.575(p_{G1}^{left}+p_{G2}^{left}+p_{Q}^{left})\right] \quad (34)$$

$$1.00\left[G+1.30(p_{G1}^{right}+p_{G2}^{right}+p_{Q}^{right})+1.30(p_{G1}^{left}+p_{G2}^{left}+p_{Q}^{left})+p_{ad}+q_{ad}\right] \quad (35)$$

In the design of the tunnel, the internal forces obtained from the most unfavorable load combinations given above were taken into account. In monitoring the deflections occurred under normal usage conditions, the combination given below was used.

$$G+Q_1+Q_2+p_{G1}^{right}+p_{G2}^{right}+p_{Q}^{right}+p_{G1}^{left}+p_{G2}^{left}+p_{Q}^{left} \quad (36)$$

Table 2 The parameters of the tunnel considered in this study

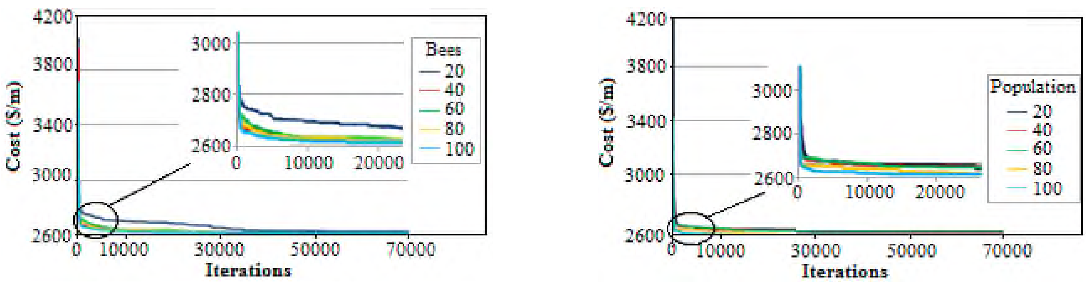
Parameter	***Value***
Parameters Associated with Dimensions	
Horizontal free span	9.00 m
Vertical free span	5.35 m
The thickness of the soil on tunnel	0.50 m
Concrete cover	0.05 m
Parameters Associated with Soil Type	
Unit weight of soil	19 kN/m^3
Angle of internal friction (φ)	30^o
Angle of the slope (β)	0^o
The angle of back of the wall with the vertical (α)	0^o
The angle of friction of soil-wall (δ)	22.50^o
Soil bed parameter	20000 kN/m^3
Parameters Associated with Reinforcements	
The characteristic yield strength of reinforcement	420 MPa
The design yield strength of reinforcement	365 MPa
The unit weight of reinforcement	78.50 kN/m^3
Parameters Associated with Earthquake	
Active soil acceleration parameter (A_0)	0.15
Lateral equivalent earthquake parameter (C_v)	0.060
Vertical equivalent earthquake parameter (C_h)	0.040
Dynamic active pressure parameter (K_{ad})	0.0552

Table 3 The mechanical parameters of concrete classes used in optimization

Description	Unit Weight (kN/m^3)	Compressive Strenght (MPa)	Tensile Strenght (MPa)	Modulus of Elasticity (MPa)
C20 type concrete	25	20	1.60	28000
C25 type concrete	25	25	1.80	30000
C30 type concrete	25	30	1.90	32000
C35 type concrete	25	35	2.10	33000
C40 type concrete	25	40	2.20	34000
C45 type concrete	25	45	2.30	36000
C50 type concrete	25	50	2.50	37000

Table 4 The unit costs of the materials used in the construction

Description	Unit Cost ($/unit)
C20 type concrete ($\$/m^3$)	40.869
C25 type concrete ($\$/m^3$)	42.608
C30 type concrete ($\$/m^3$)	45.217
C35 type concrete ($\$/m^3$)	47.391
C40 type concrete ($\$/m^3$)	50.434
C45 type concrete ($\$/m^3$)	62.174
C50 type concrete ($\$/m^3$)	65.652
The processing and placement of reinforcements with diameter Ø8 - Ø12 mm ($/tonnes)	701.41
The processing and placement of reinforcements with diameter Ø14 – Ø50 mm ($/tonnes)	632.26
Forming of concrete ($\$/m^2$) (multiplied by the forming area for unit length of tunnel)	9.65
Scaffolding ($\$/m^3$) (multiplied by the interior volume for unit length of tunnel)	5.98
Excavation ($\$/m^3$) (multiplied by the volume of tunnel + volume of the soil on tunnel for unit length of tunnel)	3.39
Backfill ($\$/m^3$) (multiplied by the volume of the soil on tunnel for unit length of tunnel)	1.86



(a) Artificial bee colony algorithm (b) Genetic algorithm

Fig. 7 The variation of the cost of the tunnel with iterations

4.2 Design prameters

The data that is constant through the optimization process and independent from the algorithm operation is called optimization parameters. In this study, the design parameters were divided into four groups: parameters associated with dimensions, reinforcement, ground type and arthquake. The parameters associated with these cited groups were given in Table 2.

Mechanical parameters of concrete according to classes were given in Table 3. In determining the cost parameters of the tunnel, the unit costs of Turkish Ministry of Environment and Urban Planning and The State of Highways published in 2010 were considered. The above cited unit costs of concrete types, reinforcement types, forming, scaffolding, excavation and backfilling were given in Table 4.

4.3 Results

In this study, in order to determine the effect of number of bees in Artificial Bee Colony Algorithm and the number of individuals in generation in Genetic Algorithm on optimum solution, the generations that include 20, 40, 60, 80, 100 bees (individuals) were used and for each

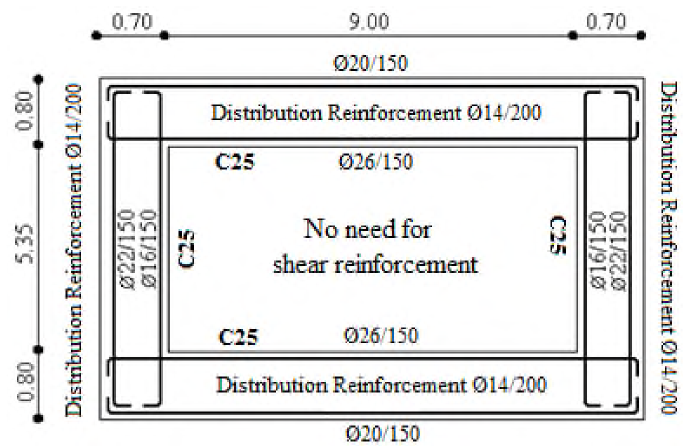
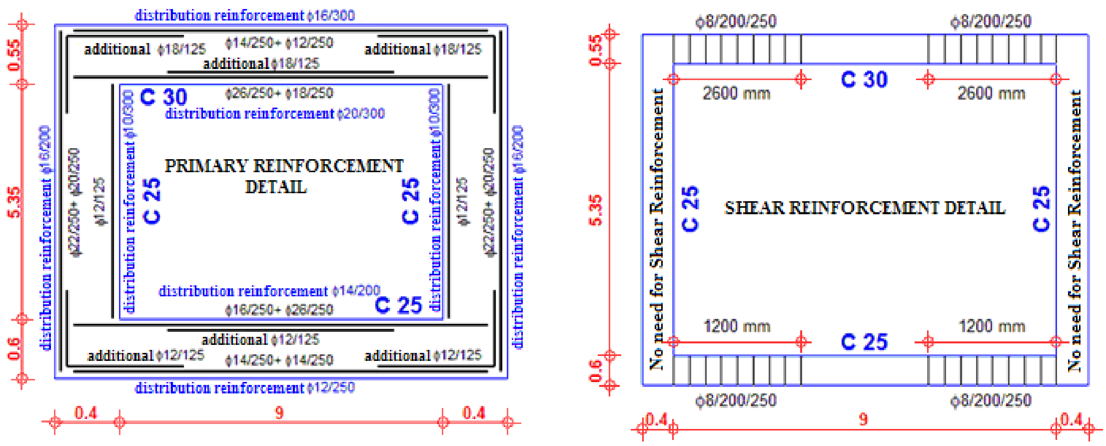
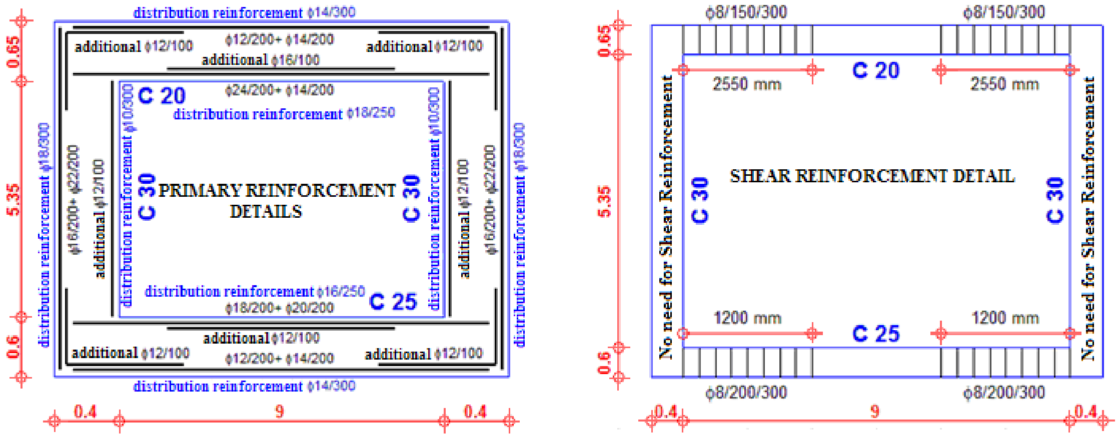


Fig. 8 Section details of constructor's traditional design



(a) Primary reinforcements (b) shear reinforcements

Fig. 9 Optimum section details of reinforcements obtained from Artificial Bee Colony Algorithm



(a) Primary reinforcements (b) shear reinforcements

Fig. 10 Optimum section details of reinforcements obtained from Genetic Algorithm

Table 5 The quantities used in the construction of the tunnel obtained from traditional and optimum design

	Quantities for unit length		
	Traditional Design	Artificial Bee Colony Algorithm	Genetic Algorithm
Concrete	24.13 m^3	15.55 m^3	16.53 m^3
Reinforcement	1809.64 daN	1685.35 daN	1666.41 daN
Forming	33.60 m^2	32.70 m^2	32.90 m^2
Scaffolding	48.15 m^3	48.15 m^3	48.15 m^3
Excavation	77.48 m^3	68.60 m^3	69.58 m^3
Backfill	5.2 m^3	4.90 m^3	4.90 m^3

Table 6 The cost of the tunnel obtained from traditional and optimum design

	Cost for unit length ($/m)		
	Traditional Design	Artificial Bee Colony Algorithm	Genetic Algorithm
Concrete	1028.15	676.63	704.41
Reinforcement	1144.16	1085.44	1081.85
Forming	324.31	315.63	317.56
Scaffolding	287.85	287.85	287.85
Excavation	262.42	232.34	235.67
Backfill	9.68	9.12	9.12
Total	3056.57	2605.70	2636.45

generation, 10 independent runs of the program were carried out. The number of iterations was taken as 70000. For every generation considered in Artificial Bee Colony Algorithm and Genetic Algorithm, the convergences of the algorithms to the optimum solution were given in Figs. 7(a)-7(b), respectively.

As can be seen from Fig. 7(a) that except the generation that includes 20 bees, the other generations nearly and rapidly converge to the optimum solution. In other words, the speed of convergence of the generation that includes 20 bees is slower than the other generations. In the analysis performed by using Genetic Algorithm (Fig. 7(b)), the speed of convergence of generations to the optimum solution is nearly same with each other. Also, the average cost obtained from the generations that include 80 and 100 individuals are lower than the costs obtained from other generations.

The design of the tunnel with minimum cost was obtained in one of the 10 program runs with the generation that includes 60 bees in Artificial Bee Colony Algorithm and with the generation that includes 100 individuals in Genetic Algorithm.

A stopping criterion for the algorithms was developed by combining an exhaustion based criterion, which decided the algorithm to be stopped according to maximum number of iterations, with an improvement based criterion which evaluated the variation of the objective function for 14000 iterations and stopped the algorithm if there was no significance change. By applying this combined stopping criterion to Artificial Bee Colony Algorithm and Genetic Algorithm, the convergence to the optimum solution was obtained in 39199 and 15654 iterations, respectively. It was determined from the analysis that 2351970 objective functions in Artificial Bee Colony Algorithm and 1565500 objective functions in Genetic Algorithm were evaluated up to the convergence to the optimum solution.

Section details of constructor's traditional design were shown in Fig. 8. The optimum values of the design variables obtained from Artificial Bee Colony Algorithm and Genetic Algorithm were given in Figs. 9-10.

The design quantities and costs of the materials for unit length of the tunnel (considered in this study) found from contractor by traditional method were given and compared in Table 5 and 6 with the ones found from Artificial Bee Colony Algorithm and Genetic Algorithm.

5. Conclusions

The main conclusions and suggestions derived from this study were summarized as follows

- For the optimum design of tunnel considered in this study, by interpreting the results of Artificial Bee Colony Algorithm, the speed of convergence of all generations (that include 40, 60, 80 and 100 bees) except the generation that includes 20 bees to the optimum solution are practically same with each other.
- For the optimum design of tunnel considered in this study, by interpreting the results of Genetic Algorithm, the speed of convergence of generations to the optimum solution is nearly same with each other. Also, the average cost obtained from the generations that include 80 and 100 individuals are lower than the costs obtained from other generations.
- The cost of the tunnel constructed with the traditional design method is 3056.57 \$/m whereas the cost of the optimized tunnel with Artificial Bee Colony Algorithm and Genetic Algorithm 2605.70 \$/m and 2636.45 \$/m, respectively. These findings showed that the optimized cost of tunnel with Artificial Bee Colony Algorithm and Genetic Algorithm are 14.75 % and 13.74 % economical with respect to traditional design, respectively.
- By considering the number of objective functions evaluated in optimization processes, it can be clearly seen that the convergence speed of Genetic Algorithm is greater than the speed of Artificial Bee Colony Algorithm to the optimum solution.
- Because internal dimensions of the tunnel are fixed in this study, cost of scaffolding remains

constant while costs of forming, excavation and backfill change little whether the traditional or optimization method is used. Thus, using of objective function including concrete and steel costs doesn't cause a major error for this problem.

In summary, this study showed that the optimum design of cut and cover RC shallow rectangular sectioned tunnels can be carried out by using Artificial Bee Colony and Genetic Algorithms. By this way, a remarkable saving from the cost of the tunnel with traditional design method was achieved. Although, the results and findings of the study belong to one specific case study, they are applicable to many situations. In order to generalize the results obtained from this study, it is considered as beneficial that similar studies should be made on different tunnels.

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