

ENHANCED CHARGED SYSTEM SEARCH FOR OPTIMUM DESIGN OF INDUSTRIAL TUNNEL SECTIONS

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ABSTRACT

Tunnel structures are known as expensive infrastructures and determining optimum designs of these structures can play a great role in minimizing their cost. The formulation of optimum design of industrial tunnel sections as an optimization is considered in this paper and then the enhanced charged system search, as a recently developed meta-heuristic approach, has been applied to solve the problem. The results and comparisons based on numerical examples show the efficiency of the optimization algorithm.

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1. INTRODUCTION

Infrastructures such as tunnels play significant roles in human life, nowadays. In the mountainous regions, the tunnels create short-cuts for railways and roads, so that a higher traffic capacity is achieved and the car and train users can enjoy a shorter and more comfortable travel. Tunnels are also used as alternatives to bridges for connections across waterway: straits, rivers, canals etc. [1]. In urban environment or densely populated areas, underground transport facilities can be the only way to establish the necessary mobility. The utilization of underground space for storage, power and water treatment plants civil defense and other activities is often a must in view of limited space, safe operation, environmental protection and energy saving [2]. This type of structures is known as industrial tunnels.

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Beside the advantages of tunnel structures, the construction of tunnels is risky and expensive and requires a high level of technical skill [2]. There are many methods for modeling of the complex problems and geometrical structures [3-6]. In this paper, we use the Enhanced Charged System Search (ECSS) [7-9], to determine optimum design of industrial tunnel cross sections. The ECSS is inspired by the governing laws of Coulomb and Gauss from electrical physics and the governing laws of motion from the Newtonian mechanics.

In physics, the space surrounding an electric charge has a property known as the electric field which is specified by Coulomb's law [7]. According to Coulomb's law, the electric force between any two small charged spheres is inversely proportional to the square of the separation distance between the particles directed along the line joining them and proportional to the product of the charges of the two particles. Also, the magnitude of the electric field at a point inside a charged sphere can be obtained using Gauss's law that it is proportional to the separation distance between the particles. Utilizing these principles, the CSS optimization algorithm contains a determined number of solution candidates or charged particle (CP). Each CP is treated as a charged sphere and can exert an electrical force to other agents (charged particles). Also, the algorithm utilizes the principal of the Newton's second law to change the CPs positions. According to the Newtonian mechanics, the position of a particle considered as a point-like mass having infinitesimal size is completely known at any time if its position, velocity and acceleration in the space are known at a previous time. Application of these laws provides a good balance between the exploration and the exploitation of the algorithm [7].

2. PROBLEM STATEMENT

In the optimum design of tunnel sections, the shape of cross sections or profile of tunnels is the first point that should be determined. Considering the performance requirements of the tunnel, the profile can be chosen. The optimum profile tries to minimize bending moments in the lining (or displacements) as well as costs for excavation and lining [2]. Therefore the objective function can be defined as [6]:

$$\text{minimize } A + \varphi d \quad (1)$$

where A is the area of the profile and d is the maximum value of displacements. Also, φ is a constant parameter.

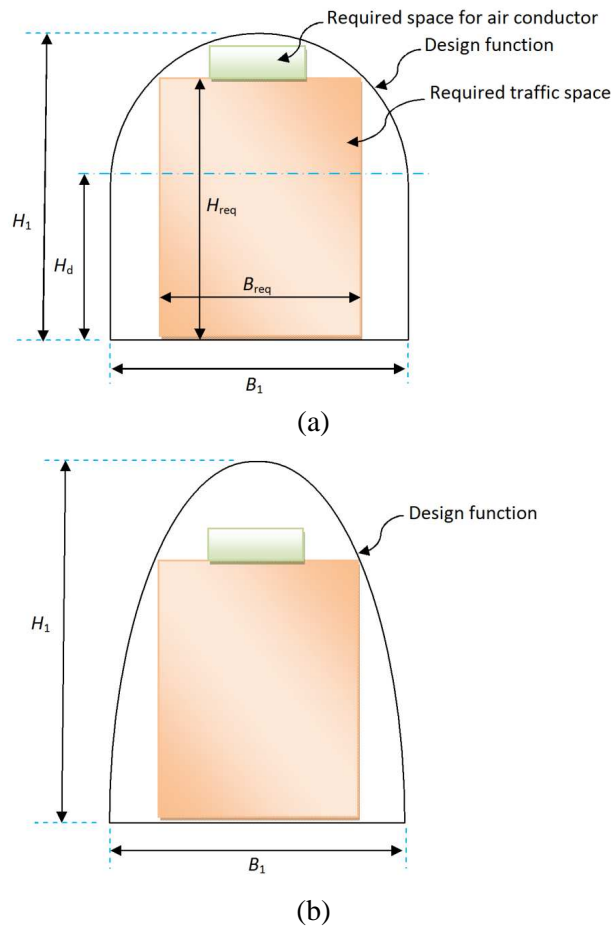


Figure 1. The different profiles of tunnel cross sections

A typical problem of tunnel design is to fit two rectangles (one is required as traffic space and the other is required as air conductor space) into a mouth profile as shown in Fig. 1. The figure shows two types of cross sections; In Fig. 1(a), for a determined height (H_d), a vertical wall is considered while in Fig. 1(b), the vertical wall does not utilized. For both types, the design functions of crown should be determined. Based on the kind of the selected function for crown, different shapes of profiles will be achieved. Here, we utilized the polynomial functions. As a result, the aim of optimization problem is to determine the parameters of the crown polynomial functions. The value of H_d for profile type I is also should be considered as a variable. The geometry constraints of the problem can be summarized as [6]:

- For the profile with vertical wall (type I):

$$\begin{aligned}
 H_{dmin} &\leq H_d \leq H_{dmax} \\
 H_{req} &\leq H_1 \\
 B_{req} &\leq B_1 \\
 A_s + B_{req} \times H_{req} &\leq A
 \end{aligned}
 \tag{2}$$

- For the profile without vertical wall (type II):

$$\begin{aligned} B_{req} &\leq B, \\ A_s + B_{req} \times H_{req} &\leq A \end{aligned} \quad (3)$$

where H_{req} and B_{req} are the required height and width of traffic space, respectively. min and max denote lower and upper bounds, respectively. A_s is the required space for the air conductor.

3. ENHANCED CHARGED SYSTEM SEARCH

3.1 Explanation of charged system search

The standard Charged System Search contains a number of Charged Particles (CPs) where each one is treated as a charged sphere and can insert an electric force to the others. The pseudo-code for the CSS algorithm is summarized as [7]:

- **Step 1: Initialization.** The magnitude of charge for each CP is defined as

$$q_i = \frac{fit(i) - fit_{worst}}{fit_{best} - fit_{worst}} \quad i = 1, 2, \dots, N \quad (4)$$

where fit_{best} and fit_{worst} are the best and the worst fitness of all the CPs; $fit(i)$ represents the fitness of the agent i ; and N is the total number of CPs. The separation distance r_{ij} between two charged particles is defined as follows:

$$r_{ij} = \frac{\|\mathbf{X}_i - \mathbf{X}_j\|}{\|(\mathbf{X}_i + \mathbf{X}_j)/2 - \mathbf{X}_{best}\| + \epsilon} \quad (5)$$

where \mathbf{X}_i and \mathbf{X}_j are the positions of the i th and j th CPs, respectively, \mathbf{X}_{best} is the position of the best current CP, and ϵ is a small positive number. The initial positions of CPs are determined randomly. Also, a number of the best CPs and the values of their corresponding fitness functions are saved in the Charged Memory (CM).

- **Step 2: Forces determination.** The resultant force vector for each CP is calculated as

$$\mathbf{F}_j = q_j \sum_{i, i \neq j} \left(\frac{q_i}{a^3} r_{ij} \cdot i_1 + \frac{q_i}{r_{ij}^2} \cdot i_2 \right) p_{ij} (\mathbf{X}_i - \mathbf{X}_j) \begin{cases} j = 1, 2, \dots, N \\ i_1 = 1, i_2 = 0 \Leftrightarrow r_{ij} < a \\ i_1 = 0, i_2 = 1 \Leftrightarrow r_{ij} \geq a \end{cases} \quad (6)$$

In which, the probability of moving each CP toward the others is determined using the following function:

$$p_{ij} = \begin{cases} 1 & \frac{fit(i) - fit_{best}}{fit(j) - fit(i)} > rand \vee fit(j) > fit(i) \\ 0 & \text{otherwise} \end{cases} \quad (7)$$

• **Step 3: Solution construction.** Each CP moves to the new position as

$$\mathbf{X}_{j,new} = rand_{j1} \cdot k_a \cdot \frac{\mathbf{F}_j}{m_j} \cdot \Delta t^2 + rand_{j2} \cdot k_v \cdot \mathbf{V}_{j,old} \cdot \Delta t + \mathbf{X}_{j,old} \quad (8)$$

$$\mathbf{V}_{j,new} = \frac{\mathbf{X}_{j,new} - \mathbf{X}_{j,old}}{\Delta t} \quad (9)$$

where k_a and k_v are the acceleration and the velocity coefficients, respectively; and $rand_{j1}$ and $rand_{j2}$ are two random numbers uniformly distributed in the range (0,1).

• **Step 4: Updating process.** If a new CP exits from the allowable search space, a harmony search-based handling approach can be used to correct its position [10]. According to this mechanism, any component of the solution vector violating the variable boundaries can be regenerated from the CM or from randomly choosing one value from the possible range of values. In addition, if some new CP vectors are better than the worst ones in the CM, then they are replaced by the worst ones in the CM, and the worst ones are ignored.

• **Step 5: Terminating criterion control.** Steps 3-7 are repeated until a terminating criterion is satisfied.

3.2 Enhanced charged system search

In the enhanced CSS [8], the “continuous space– time” concept improves the efficiency of the algorithm. In the standard CSS algorithm, when the calculations of the amount of forces are completed for all the CPs, the new locations of agents are determined. Also Charged Memory updating is fulfilled after moving all the CPs to their new locations. All these conform to discrete time concept. In the optimization problems, this is known as iteration. On the contrary, in the enhanced CSS the time changes continuously and after creating just one solution, all updating processes are performed. Using this enhanced CSS, the new position of each agent can affect the moving process of the subsequent CPs while in the standard CSS unless an iteration is completed, the new positions are not utilized.

4. CONSTRAINT HANDLING APPROACH

One of well known approaches to handle constraints is to employ a penalty function. Although this method is simple, however deterring suitable values for the parameters is not an easy work. The feasible-based approach [11] deals with constrained search spaces by using the separation of constraints and objectives. Nouhi et al. [12] have presented a

modified feasible-based method which employs the following four rules as

- **Rule 1:** Any feasible solution is preferred to any infeasible solution.
- **Rule 2:** Infeasible solutions with slight violations of the constraints are treated as feasible ones.
- **Rule 3:** Between two feasible solutions, the one with better objective function value is preferred.
- **Rule 4:** Between two infeasible solutions, the one having smaller sum of constraint violations is preferred.

5. NUMERICAL OPTIMUM DESIGNS

5.1 Optimization process

In this study, the optimization process begins by inputting the initial data. The required height and width are 4 and 15 meters, respectively. As , the required space for air condition, is set to 1.8×1.8 meters. The process using the ECSS algorithm consists of three levels as follows:

Level 1: Initialization.

Step 1. Select the random values for particles. In this paper, the number of CPs is set to 20. Variables are selected randomly between the lower and upper limits in each problem. In this way, the initial positions of CPs are defined.

Step 2. In this step, for each CP, the constraints are checked and, if all conditions are satisfied, the value of the cost function is calculated, and CPs are sorted increasingly. Otherwise, that cost function is penalized.

Step 3. Store the CMS number of the first CPs and their related cost function values in the CM. The size of CM is chosen as 5 in this article.

Level 2: Search.

Step 1. In this step, the distance between the CPs, and the charge of the CPs, are calculated. Then, the probability of moving the CPs toward others, and attracting forces for the CPs, is determined.

Step 2. After determination of attracting forces, the new position and velocity of each CP are determined. k_a and k_v are set to 0.5.

Step 3. When some of the new CPs violate the boundaries, then, the CSS corrects their position using the harmony search based handling approach.

Step 4. This step is similar to step 2 of level 1, with the new position of the CPs.

Step 5. If some CPs are better than the particles saved in the CM, the new ones are replaced with them.

Level 3: Termination Criterion.

Repeat level 2 until the termination criterion is satisfied.

5.2 Numerical investigation

Fig. 2 shows the obtained optimum profiles of tunnel cross sections (type I) when the order of polynomial functions is changed from 2 to 20. For type II, Fig. 3. Presents the obtained

results of tunnel cross sections. Due to symmetry of the section only one half of the tunnel are shown in these figures.

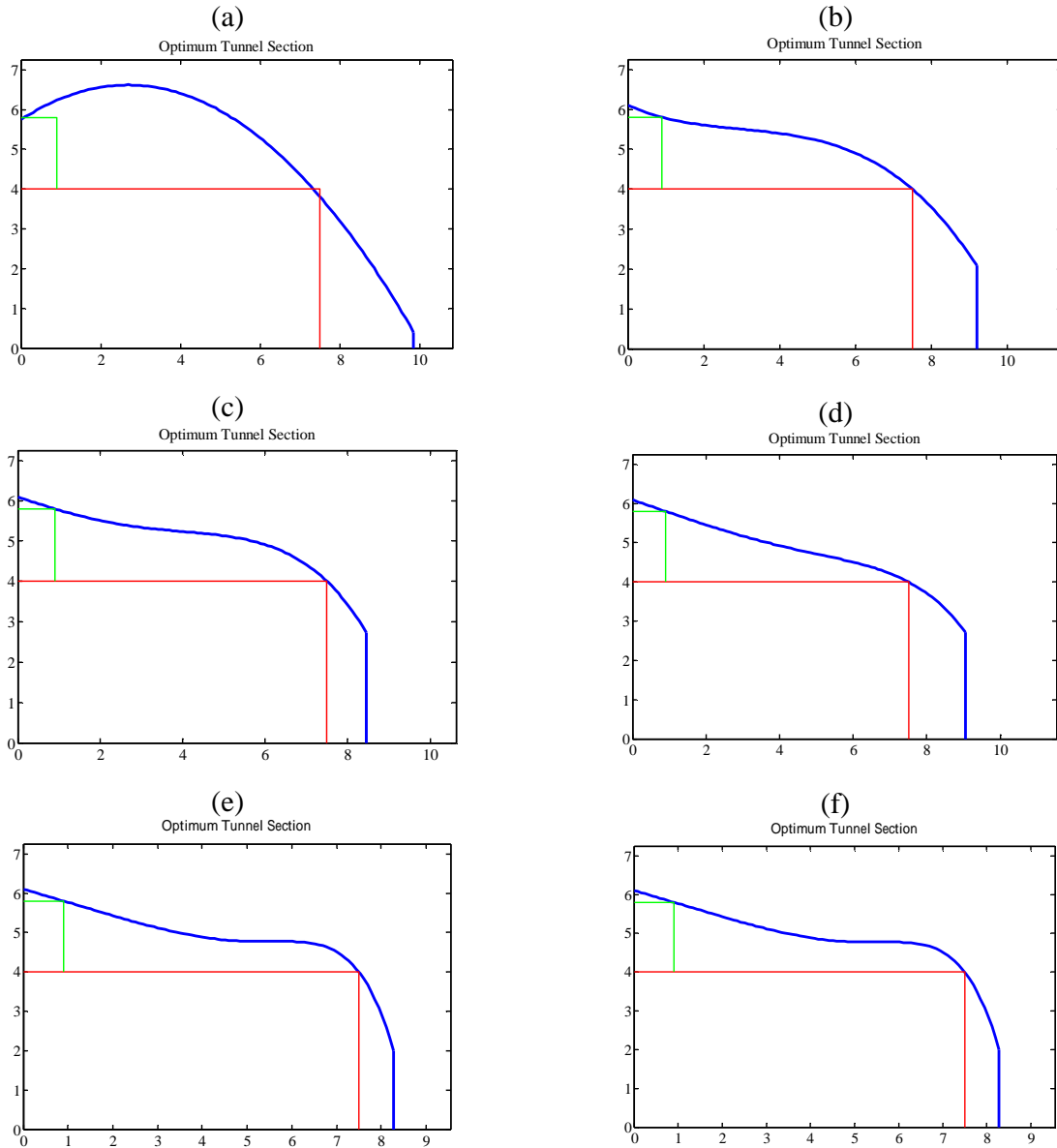


Figure 2. The optimum profiles of tunnel cross sections (Type I); Order of function = (a) 2; (b) 3; (c) 4; (d) 5; (e) 6; (f) 7; (g) 8; (h) 9; (i) 10; (j) 20

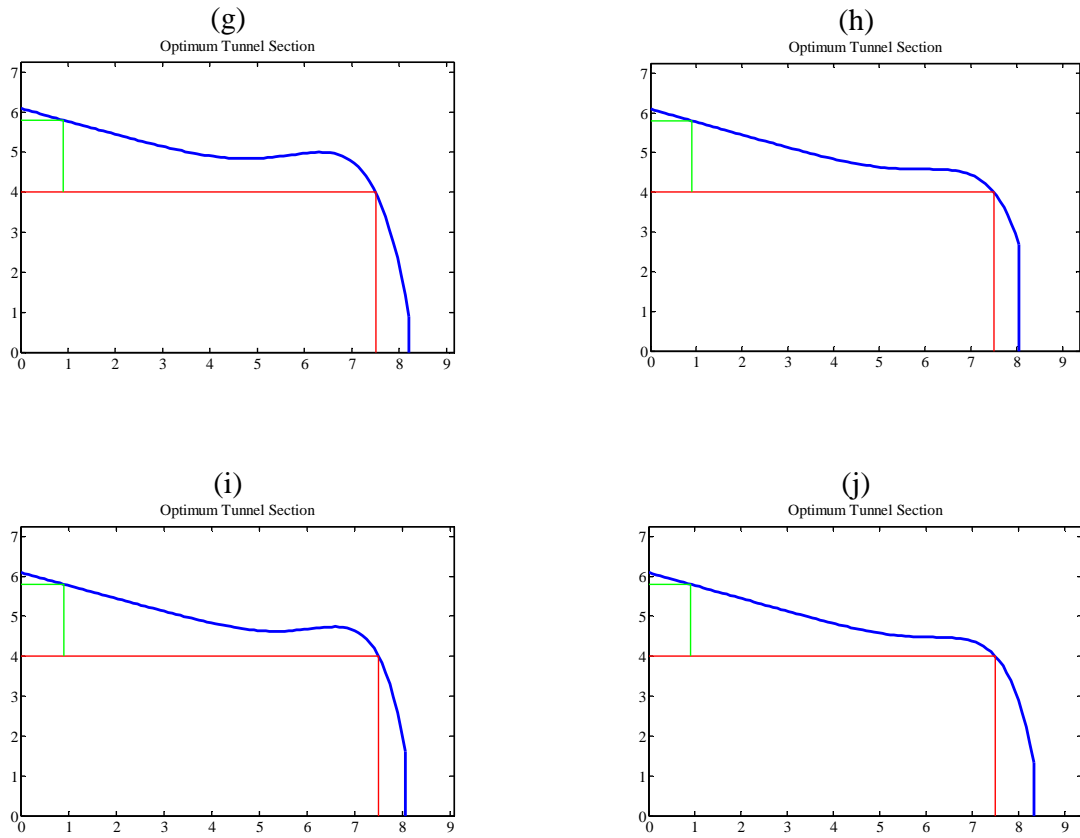


Figure 2. continued

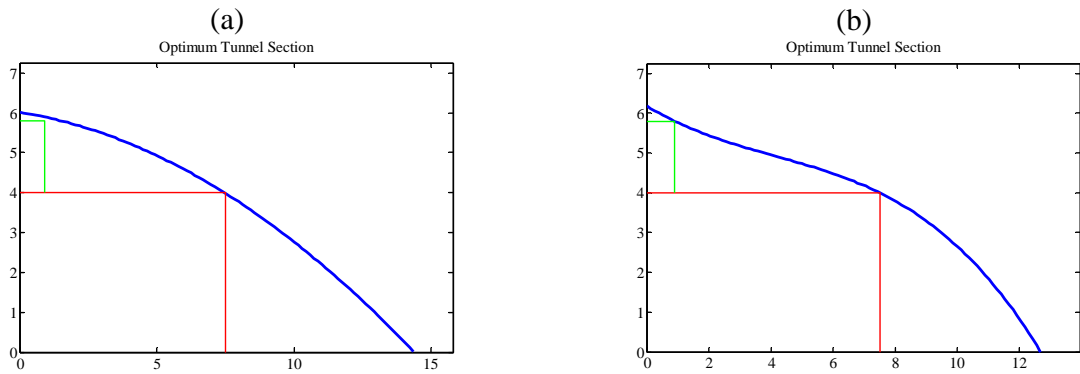


Fig. 3. The optimum profiles of tunnel cross sections (Type II); Order of function = (a) 2; (b) 3; (c) 4; (d) 5; (e) 6; (f) 7; (g) 8; (h) 9; (i) 10; (j) 20

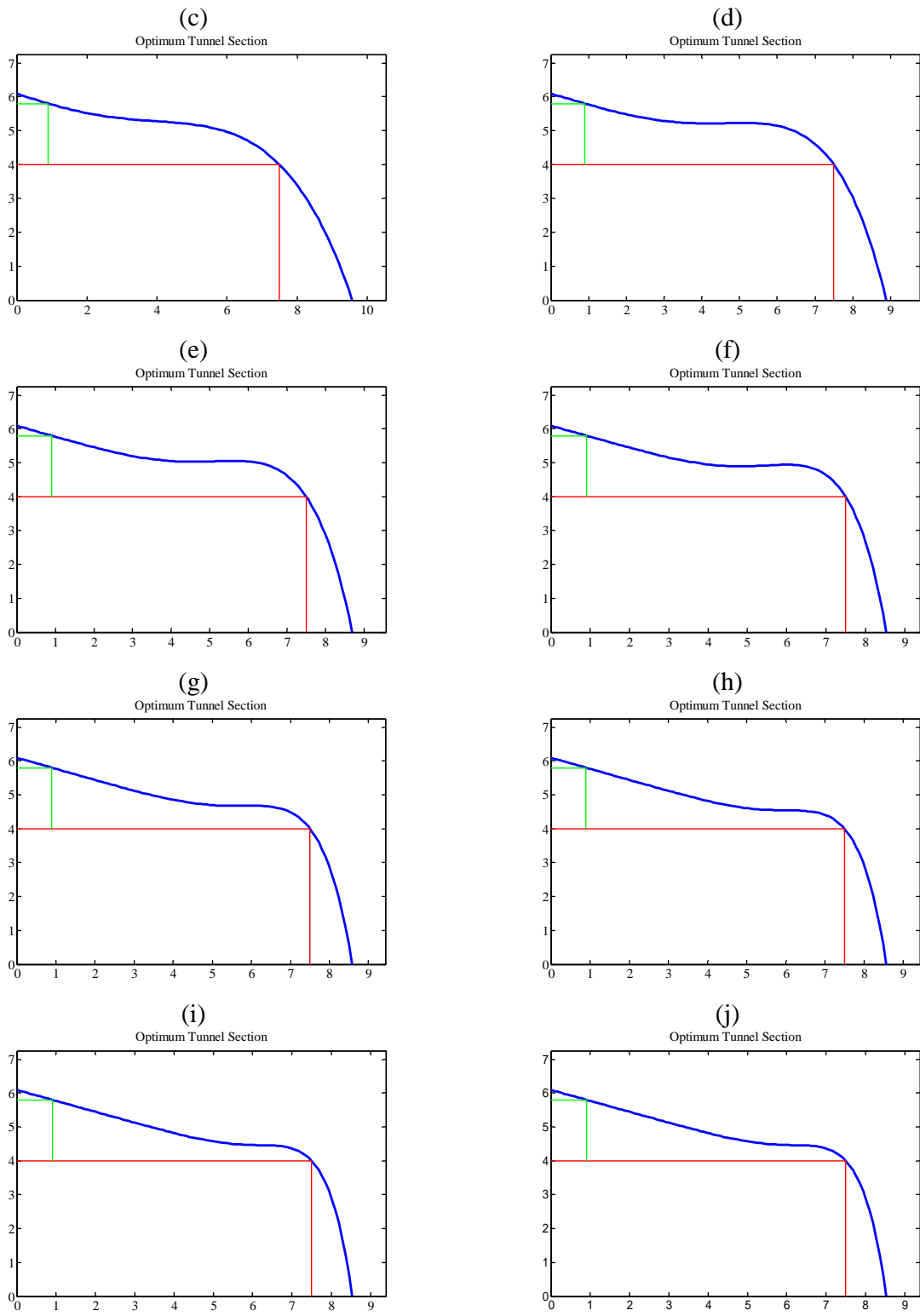


Figure 3. continued

A comparison of final optimum results is performed as shown in Fig. 4. For both types, when the degree of the function increases the final results becomes better. Almost for degrees of 9, 10 and 20, the results are the same for sections with (type 1) and without (type 2) vertical walls.

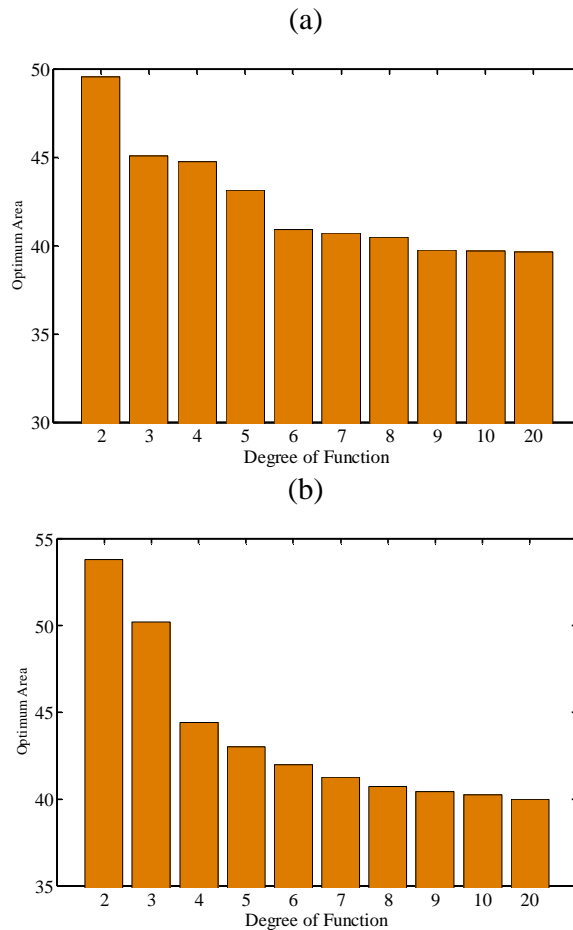


Fig. 4. Final optimum results obtained by the CSS; a) type I; b) type II

6. CONCLUDING REMARKS

This paper utilizes the Enhanced Charged System Search (ECSS) algorithm for design of tunnel sections. This algorithm determines the optimum profiles of tunnel cross sections in a way that the area of the profile and the maximum value of displacements become minimum. The ECSS is inspired by the laws from electrostatics and Newtonian mechanics. ECSS contains a number of charged particles. Each CP is considered a charged sphere of radius a , which can impose an electric force on other CPs. This force and the laws for the motion determine the new location of the CPs. From optimization point of view, this process

provides a good balance between the exploration and the exploitation paradigms of the algorithm which can considerably improve the efficiency of the algorithm.

A complete investigation on the effect of the order of utilized function of the profiles on the final optimum design is performed. It is shown that for small values for the order of function, the final optimum designs are bigger compared to those of larger ones. However, differences between final results of high order functions become small, and as a result we may prefer to use small values to reduce computation costs. In addition, the results indicate that for high degree of function, the optimum values for sections without vertical and without walls are more and less similar. A section without vertical wall is found as the best design when the degree of the function is set to 20. The investigation shows that using a function with order 10 can reduce the computational costs while the final results do not change considerable.

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