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Optimization of the design of soil-steel high profile arch using particle swarm optimization

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Abstract

A Soil-steel structure, because of its advantages, is a good substitute for similar concrete and steel bridges. The aim of the present research is to optimally design the high profile arch bridges for reducing the cost of construction. In this study, the high profile arch is designed based on the Canadian Highway Bridge Design Code (CHBDC). The design variables considered for this structure include soil compaction percentage, soil cover height, thickness and type of corrugated steel plate. The constraints taken into account are compressive stress, bending stress during and after construction as well as structural constraints. After the formulation of the problem, the optimization of the soil-steel bridge is performed using the particle swarm optimization (PSO) algorithm. The optimization results indicate that the cost of constructing the high profile arch bridge can be reduced by 20.28 % compared to that of the design by CHBDC method.

Keywords: Soil-steel structure, Optimization, Particle swarm optimization.

1. INTRODUCTION

In recent years, the construction of soil-steel structures has been increased widely in different countries. Using the soil-steel structures as a substitute for different types of the bridge especially the bridges with short span has been increased rapidly [1]. Different types of soil- steel structures include High Profile Arch, Low Profile Arch, round, Arch, and etc. The various shapes and dimensions of such structures allow using them as railway bridges, tunnels, culverts, and etc. Soil-steel bridges are considered as an appropriate alternative for similar steel and concrete bridges due to their speed and ease of construction, diversity of dimensions, and shapes, etc.

Compact granular soil and corrugated steel plates are two main constituents of soil-steel structures. Corrugated steel plates make a structural ring that is covered by several soil layers. The condition of soil stress around the structure plays a determining role in the overall performance of the High Profile Arch bridges and this fundamental concept was reflected in the design philosophy (Pettersson et al. 2015). The arch geometry of the structure leads to the radial distribution of loads. In addition, the interaction between the soil and corrugated steel plates causes structural stability. The steel ring tends to deform in the transverse direction under the loading effect, thus the lateral forces of the soil are activated and lead to the prevention of the steel ring deformation. Therefore, the structure will remain stable under the effects of the vertical loads. The metal part of the structure, inclusive of corrugated steel plate is very flexible without its surrounding soil. Therefore, flexible arches are needed to resist disjointing, settlement and infiltration of the surrounding soil. Thus, the major contribution of bearing in these structures depends on the interaction between the metal part and its surrounding soil. Some of the research on the soil-steel structures is discussed below.

Duncan described a method for designing soil-steel culverts and then compared it to currently used design procedures. One of the main advantages of the presented method is providing a logical procedure for determining the minimum depth of the required soil volume on the arch structures. It should be noted that the minimum depth of cover was determined experimentally before this research [2, 3].

Abdel-Sayed and Salib Sameh used the finite element method (FEM) to investigate the possibility of soil failure due to live loads. This study was conducted on a circular culvert with a 15.24 -m span and an Arch curved structure with a 21.3- m span. In this study, a relationship was proposed for determining the minimum required soil amount for structures [4].

Flener et al. conducted a full-scale test on box culverts and compared their performance during backfilling with the results of the finite element modeling. The comparison of full-scale tests and Canadian and Swedish design methods indicated that these methods underestimate the compressive forces [5-7].

Simpson et al. measured the strain in a series of buried corrugated steel culvert pipes via a large-scale test. They reconstructed a corrugated steel pipe being under static loading. In addition, the soil around the pipe carries less of the surface load applied above the pipe [8, 9].

Walton Harold et al. used laboratory testing and numerical simulations of a buried composite arch bridge for the deep understanding of the interaction of soil and structure. In their experimental results, they reported the influence of different types of loadings [10].

In this study, it is attempted to minimize the cost function using the Particle swarm optimization algorithm. In the following, the formulation of the optimization problem for the High Profile Arch bridge structure based on the Canadian Highway Bridge Design Code (CHBDC 2006) is presented [11].

2. OPTIMIZATION

Solving an optimization problem includes the minimization of a cost function considering some constraints. The constraints can be introduced in the form of equalities or inequalities. The cost function and the constraints are presented in this section.

2.1 DESIGN VARIABLES

As mentioned earlier, the design parameters taken into consideration in this study are: soil cover height (H_{soil}), soil compaction percentage (RP), thickness (t) and types (n) of corrugated steel plate. These constraints are shown in Table 1. The range of these constraints is based on the CHBDC. These upper and lower bound values for the design variables are summarized in Table 1.

Table 1. Design variables of the High Profile Arch bridge

Variable type	Symbol	Unit	Variable type	Change interval	Symbol of optimization
Soil cover	H_{soil}	m	Continuous	$1.5 \leq H \leq 3$	X_1
Soil compaction	RP	%	Continuous	$85 \leq RP \leq 100$	X_2
Plate Thickness	t	mm	Continuous	$3 \leq t \leq 7$	X_3
Plate type	n	-	Discrete	n=1, 2, 3, 4, 5	X_4

Figure 1 shows the characteristics of different parts of the corrugated steel plate. This specification includes pitch (c), depth (hcorr), thickness (t), radius (R), tangent angle (α), and tangent length (mt). Different plates are named by pitch × depth. The five types of plates used in this study are 125×26 mm, 150×50 mm, 200×55 mm, 381×140 mm, and 400×150 mm.

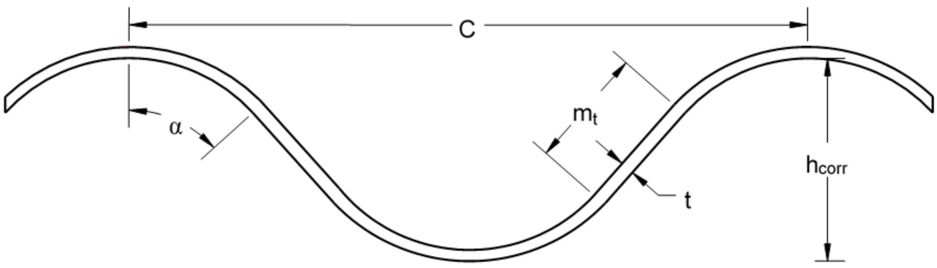

Figure 1. Properties of corrugated steel plate

2.2 OBJECTIVE FUNCTION

The objective of optimization in this paper is to minimize the cost of construction. According to Eq. 1, the cost function depends on the cost of corrugated steel plates, soil and soil compaction.

$$F(x) = C_{steel} \times A_{steel} \times P + (C_{soil} + C_{RP}) \times V_{soil} \quad (1)$$

Where C_{steel} is the unit cost of corrugated steel plate, A is cross-section of corrugated steel plate, P is the perimeter of the arc, C_{soil} is the unit cost of soil preparation, C_{RP} is the unit cost of compaction, and V is the volume of the embankment. The cost coefficients of the High Profile Arch bridges are shown in Table 2.

Table 2. The cost coefficient of producing and installing corrugated sheet and soil

Name of cost coefficient	$(\frac{\$}{m^3})$
Corrugated profile 125×25	12.00
Corrugated profile 150×50	13.20
Corrugated profile 200×55	14.10
Corrugated profile 381×140	15.60
Corrugated profile 400×150	18.00
Soil preparation	1.37
Embankment and compaction of soil	Eq. (2)
The total cost of soil operations	$C_{soil\ type} + C_{RP}$

$$C_{RP} = (0.6\ RP^3 - 162.40\ RP^2 + 14667\ RP - 440380)/10000 C_{RP} \quad (2)$$

2.3 CONSTRAINTS

According to CHBDC, the main constraints of the High Profile Arch include compressive constraint, bending constraints during building the structure, and post-building bending constraint. These constraints are shown in equations 3 to 5.

$$g_{1(x)} = \sigma - f_b \leq 0 \quad (3)$$

Where σ is stress due to thrust in a conduit wall due to factored loads; f_b is factored failure stress in compression in a metal conduit wall.

$$g_{2(x)} = \left(\frac{P}{P_{Pf}}\right)^2 + \left|\frac{M}{M_{Pf}}\right| - 1 \le 0 \tag{4}$$

Where P is unfactored thrust; P_{Pf} is factored compressive strength; M is unfactored moment in a soil-metal structure; M_{Pf} is factored plastic moment capacity of a corrugated metal section.

$$g_{3(x)} = \left(\frac{T_f}{P_{Pf}}\right)^2 + \left|\frac{M_f}{M_{Pf}}\right| - 1 \le 0 \tag{5}$$

Where T_f is maximum thrust in a conduit wall due to factored loads per unit length; M_f is modification factor for multi-lane loading.

3. Particle Swarm Optimization (PSO)

Particle swarm optimization (PSO) is an evolutionary algorithm inspired by the researches of the predation behavior of birds group (Eberhart and Kennedy 1995). The PSO algorithm consists of a certain number of particles that randomly get the initial value. For each particle, two values of velocity and state are defined and modeled with a space vector and a velocity vector, respectively. These particles, move in the n-dimensional space (number of variables in the cost function) of the problem to search for possible new answers by evaluating the optimal value. The flowchart of the PSO algorithm is shown in Fig. 2.

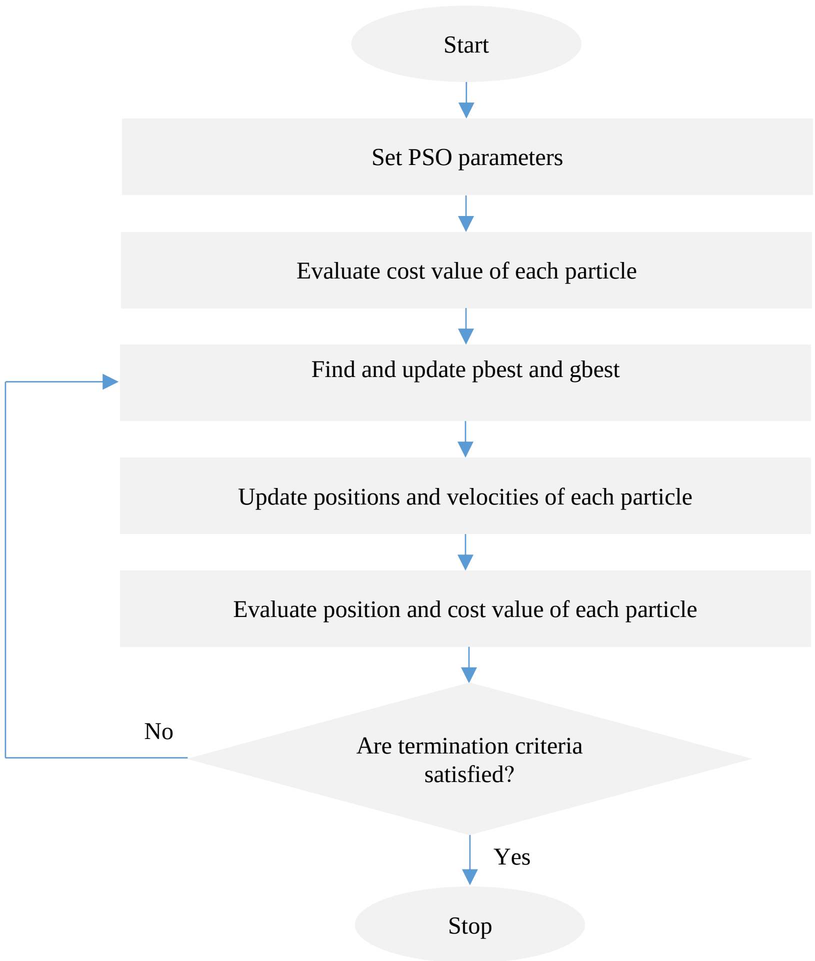

Figure 2. Particle swarm optimization flowchart [13]

4. NUMERICAL SIMULATION

In this study, an example of a High Profile Arch bridge design based on the CHBDC method is selected from the Handbook of Corrugated Steel Pipes Institute [12]. The design example is coded in MATLAB and to validate the written program, it is compared with the results of the Handbook example.

In Fig. 2, the geometric characteristics of the High Profile Arch bridges are displayed including bottom span, horizontal dimension (Dh), vertical dimension (Dv), radius (Rc, Rt, and Rs), total Rise, and angles. The input parameters for the design of High Profile Arch bridges are shown in Table 3. Table 3 includes the length of spans, horizontal dimension (D_h), vertical dimension (D_v), crown radius (Rc), upper side radius (Rt), lower side radius (Rs), soil unit weight (γ_{soil}), yield strength of corrugated plate (Fy), and elasticity modulus (E_{steel}).

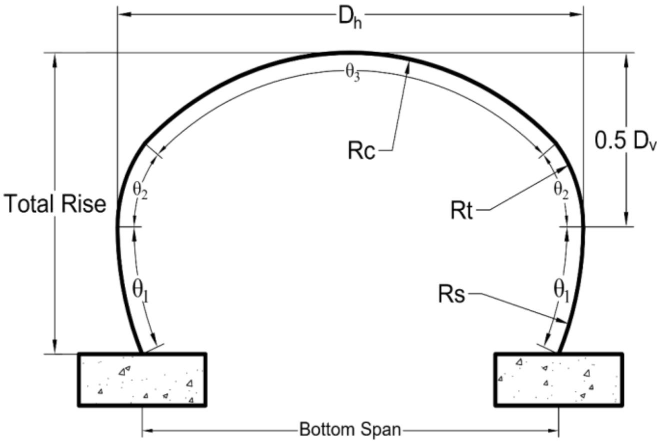

Fig 2. High Profile Arch bridge

Table 3. Input parameters of High Profile Arch bridges

Input parameters	Symbol	Unit	Value
Bottom span	-	m	10.15
Horizontal dimension	D_h	m	13.15
Vertical dimension	D_v	m	6.575
Crown radius	R_c	m	7.17
Upper side radius	R_t	m	2.99
Lower side radius	R_s	m	7.17
Soil unit weight	γ	KN/m^3	22
Yield strength of corrugated plate	F_y	MPa	300
Elasticity modulus	E_{steel}	MPa	200000

The results of the optimal design method and the traditional method are presented in Table 4. The results show that the optimal design method has been able to reduce the cost of constructing the High Profile Arch bridge by 20.28 % compared to the CHBDC method. According to the design results, it can be understood that, the cost of corrugated steel plate is much higher than the cost of embankment and compression. Therefore, the algorithm for finding the optimal design has mainly focused to reduce the thickness of the corrugated steel plates while the design and construction constraints are not violated.

Table 4. Results of the optimal design method and the traditional design

Type of design	RP (%)	t (mm)	n	H (m)	Cost of construction ($/m)
Optimal design	99.46	3.13	2	2.28	1150.59
Traditional design	90	4	3	1.5	1443.20

Figure 3 exhibits the performance of PSO algorithm in terms of cost variations against the iterations of the optimization process. Figure 6 shows that changes in the cost function converge after the tenth cycle.

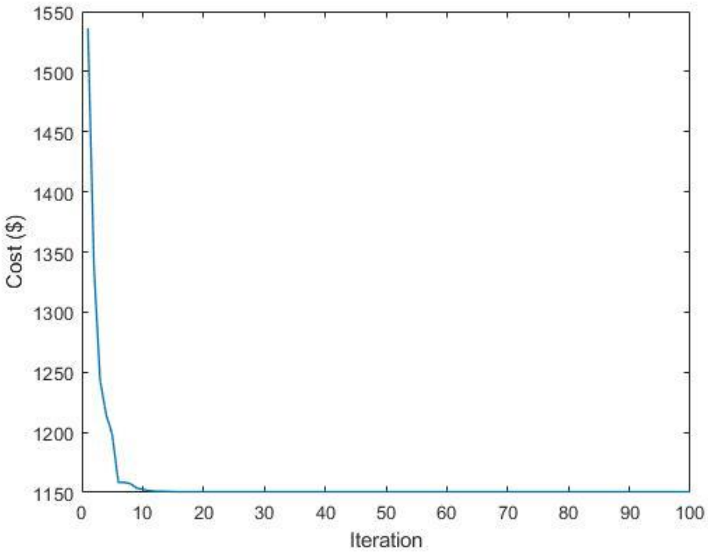

Fig 3. Convergence rate of low-cost optimization design

5. CONCLUSION

In this study, first the High Profile Arch structure designed based on the Canadian Highway Bridge Design Code (CHBDC). The design variables considered for this structure include soil compaction percentage, soil cover height, thickness and type of corrugated steel plate. After the formulation of the problem, the optimization of the soil-steel bridge is performed using particle swarm optimization method.

The results show that the optimal design method has been able to reduce the cost of constructing the High Profile Arch bridge by 20.28 % compared to the CHBDC method. The algorithm for finding the optimal design has tried to reduce the thickness of the corrugated steel plates so that the design and construction constraints are not violated.

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