OPTIMAL DESIGN OF ARCH DAMS FOR FREQUENCY LIMITATIONS USING CHARGED SYSTEM SEARCH AND PARTICLE SWARM OPTIMIZATION

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ABSTRACT

In recent years, the importance of economical considerations in the field of dam engineering has motivated many researchers to propose new methods for minimizing the cost of dames and in particular arch dams. This paper presents a method for shape optimization of double curvature arch dams corresponding to minimum construction cost while satisfying different constraints such as natural frequencies, stability and geometrical limitations. For optimization, the charged system search (CSS) and particle swarm optimization (PSO) are employed. To validate the finite element model, a real arch dam is considered as a test example. The results of the present method are compared to those of other optimization algorithms for the selected example from literature.

1. INTRODUCTION

In recent decades, the researchers have focused on optimization of concrete arch dams because of the high construction cost and damage caused by these structures. The main objective of this research is to find a shape of arch dams that has minimum volume or cost while satisfying the corresponding constrains. One of the most important constrains is the behavior constraint. On other hand, natural frequencies are fundamental parameters which

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affect dynamic behavior of the arch dams. Therefore, some limitations should be imposed on the natural frequency range to reduce the domain of vibration and also prevent the resonance phenomenon in dynamic response of arch dams. Traditionally, an arch dam is iteratively analyzed and designed to achieve this goal [1].

Recently some progress has been made in optimum design of arch dams considering different constraints. Almost all of these have used conventional methods for analysis approximation and optimization. These methods usually employ derivative calculations and may be trapped in local optima. The shape optimization of arch dams has been developed after appearing and development of finite element method in late 1950's. Early research works dealt mainly with membrane-type solutions [2]. Later, Rajan [3], Mohr [4] and Sharma [5] developed solutions based on membrane shell theory. Sharpe [6] was the first to formulate the optimization as a mathematical programming problem. A similar method was also adopted by Rickeetts and Zienkiewicz [7] who used finite element method for stress analysis and Sequential Linear Programming (SLP) for the shape optimization of arch dams under static loading.

An optimization problem may be solved by a global search optimization method including both probabilistic and deterministic concepts without any dependency on the gradients or derivatives of functions in searching for the optimal global solution. Unfortunately the gradient/derivative-based optimization methods have a tendency to be trapped in local minima for problems with a complex search domain. The charged system search (CSS) is one of the newly developed meta-heuristic algorithms which has been utilized for optimum design of different types of structures, Kaveh and Talatahari [8]. The governing laws from the physics initiate the base of the CSS algorithm. Particle swarm optimization (PSO) is another meta-heuristic algorithm widely utilized for optimization problems due to its simple principle and ease of implementation, Eberhart and Kennedy [9].

In this study, the CSS and PSO algorithms are employed for cost optimization of arch dams. The arch dam cost consisting of the concrete volume and the casting areas is considered as the objective function. The design variables are geometric parameters of the arch dam. To implement a practical design optimization, many constraints such as stress, displacement, stability requirement, and frequency constraints should be considered. In the present study, for simplicity of the optimization operation and comparison with the existing results from literature, only frequency and some geometrical constraints are considered. The Opensees [10] and Matlab [11] are used for modeling, modal analysis and calculation the cost of the arch dam, respectively.

The results of the solved examples demonstrate that CSS leads to better results than PSO. Also the results of these algorithms are better than those of the previously developed algorithms.

2. CHARGED SYSTEM SEARCH ALGORITHM

2.1. The standard Charged Search System

The Charged System Search is a population-based search approach, where each agent (CP) is considered as a charged sphere with radius a, having a uniform volume charge density which can produce an electric force on the other CPs. The force magnitude for a CP located inside the sphere is proportional to the separation distance between the CPs, while for a CP located

outside the sphere it is inversely proportional to the square of the separation distance between the particles. The resultant forces or acceleration and the motion laws determine the new location of the CPs. The pseudo-code for the CSS algorithm can be summarized as follows:

Step 1: *Initialization.* The initial positions of CPs are determined randomly in the search space and the initial velocities of charged particles are assumed to be zero. The values of the fitness function for the CPs are determined and the CPs are sorted in an increasing order. A number of the first CPs and their related values of the fitness function are saved in a memory, so called charged memory (**CM**).

Step 2: *Determination of the forces on CPs.* The force vector is calculated for each CP as

$$F_j = \sum_{i,i \neq j} \left\langle \frac{q_i}{a^3} r_{i,j} . i_1 + \frac{q_i}{r_{i,j}^2} . i_2 \right\rangle ar_{i,j} p_{i,j} (X_i - X_j) \left| \begin{array}{l} j = 1,2,...,N \\ i_1 = 1, i_2 = 0 \Leftrightarrow r_{i,j} < a \\ i_1 = 0, i_2 = 1 \Leftrightarrow r_{i,j} \geq a \end{array} \right. \tag{1}$$

where $\mathbf{F}_j$ is the resultant force acting on the jth CP; N is the number of CPs. The magnitude of charge for each CP (q_i) is defined considering the quality of its solution as

$$q_i = \frac{fit(i) - fitwrost}{fitbest - fitwrost}, \qquad i = 1,2,....N \tag{2}$$

Where *fitbest* and *fitworst* are the best and the worst fitness of all particles, respectively; *fit(i)* represents the fitness of the agent *i*; and N is the total number of CPs. The separation distance $r_{i,j}$ between two charged particles is defined as follows:

$$r_{i,j} = \frac{||X_i - X_j||}{||(X_i + X_j)/2 - X_{best}|| + e} \tag{3}$$

where X_i and X_j are respectively the positions of the ith and jth CPs, X_{best} is the position of the best current CP, and e is a small positive number. Here, $p_{i,j}$ is the probability of moving each CP towards the others and is obtained using the following function:

$$p_{i,j} = \begin{cases} 1 & \frac{fit(i) - fitbest}{fit(j) - fit(i)} > rand \wedge fit(j) > fit(i) \\ 0 & else \end{cases} \tag{4}$$

In Eq. (1), $ar_{i,j}$ indicates the kind of force and is defined as

$$ar_{i,j} = \begin{cases} 1 & rand > 0.8 \\ 0 & else \end{cases} \tag{5}$$

where *rand* represents a random number.

Step 3: *Solution construction.* Each CP moves to the new position and the new velocity is

calculated as

$$X_{j,news} = rand_{j,1}.K_a.F_j + rand_{j,2}.K_v.V_{j,old} + X_{j,old} \qquad (6)$$

$$V_{j,new} = X_{j,new} - X_{j,old} \qquad (7)$$

where K_a is the acceleration coefficient; K_v is the velocity coefficient to control the influence of the previous velocity; and $rand_{j,1}$ and $rand_{j,2}$ are two random numbers uniformly distributed in the range (0,1). In this paper K_a and K_v are taken as:

$$K_a = 1 + \frac{iter}{iter_{max}}, \quad K_v = 1 - \frac{iter}{iter_{max}} \qquad (8)$$

Where *iter* is the iteration number, and *iter$_{max}$* is the maximum number of iterations.

Step 4: *Updating process.* If a new CP exits from the allowable search space, a harmony search-based handling approach [9] is used to correct its position. In addition, if some new CP vectors are better than the worst ones in the **CM**, these are replaced by the worst ones in the **CM**.

Step 5: *Termination criterion control.* Steps 2-4 are repeated until a termination criterion is satisfied [8].

3. PARTICLE SWARM OPTIMIZATION

The PSO is based on a metaphor of social interaction such as bird flocking and fish schooling, and is developed by Eberhart and Kennedy [9]. The PSO simulates a commonly observed social behavior, where members (particles) of a group (swarm) tend to follow the lead of the best of the group. In other words, the particles fly through the search space and their positions are updated based on the best positions of individual particles denoted by p_i^k and the best position among all particles in the search space represented by p_g^k.

The procedure of the PSO is reviewed below:

Step 1: Initialization. An array of particles and their associated velocities are initialized with random positions.

Step 2: Local and global best creation. The initial particles are considered as the first local best and the best of them corresponding to the minimum objective function will be the first global best.

Step 3: Solution construction. The velocity and location of each particle are changed to the new position using the following equations:

$$X_i^{k+1} = X_i^k + V_i^{k+1} \qquad (9)$$

$$V_i^{k+1} = wV_i^k + C_1 r_1 \mathbf{o}(P_i^k - X_i^k) + C_2 r_2 \mathbf{o}(P_g^k - X_i^k) \qquad (10)$$

Where X_i^k and V_i^k are the position and velocity for the ith particle at iteration k; w is an inertia weight to control the influence of the previous velocity; r_1, and r_2 are two random numbers uniformly distributed in the range of (0, 1); c_1 and c_2 are two acceleration constants; p_i^k is the best position of the ith particle up to iteration k; p_g^k is the best position among all particles in the swarm up to iteration k and the sign "$\mathbf{o}$" denotes element-by-element multiplication.

Step 4: Local best updating. The objective function of the particles is evaluated and p_i^k is updated according to the best current value of the fitness function.

Step 5: Global best updating. The current global minimum objective function value among the current positions is determined and thus p_g^k is updated if the new position is better than the previous one.

Step 6: Terminating criterion control. Step 3 to Step 5 are repeated until a terminating criterion is satisfied [9].

4. GEOMETRICAL MODEL OF ARCH DAM

4.1. Shape of the central vertical section

The shape of an arch dam has two basic characteristics, namely the curvature and thickness. Both the curvature and the thickness change both in horizontal and vertical directions. For the central vertical section of double-curvature arch dam, as shown in Figure 1, one polynomial of nth order is used to determine the curve of upstream boundary and another polynomial is employed to determine the thickness. In this study, a parabolic function is considered for the curve of upstream face as [12]:

$$y(\,z\,) = b(\,z\,) = -sz + \frac{sz^2}{2\,bh} \tag{11}$$

where h and s are the height of the dam and the slope at crest respectively, and the point where the slope of the upstream face equals to zero is $z=\beta\,h$ in which β is constant.
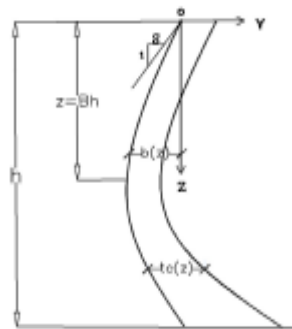

Figure 1. Central vertical section of an arch dam

A quadratic function for the thickness of central vertical section is also chosen as:

$$t_c(z) = n_1(z)t_{c1} + n_2(z)t_{c2} + n_3(z)t_{c3} \tag{12}$$

Where

$$n_1(z) = \frac{(\frac{z}{h} - 1)(\frac{z}{h} - 1)}{1}, \quad n_2(z) = \frac{(\frac{z}{h})(\frac{z}{h} - 1)}{1(1 - 1)}, \quad n_3(z) = \frac{(\frac{z}{h} - 1)(\frac{z}{h})}{(1 - 1)} \tag{13}$$

in which t_{c1}, t_{c2} and t_{c3} are the thicknesses of the central vertical section at $z=0$, $z=\lambda h$ and $z=h$, respectively and λ is a factor in the range of (0,1) and in this study is considered as $\lambda=0.55$.

4.2. Shape of the horizontal section

As shown in Figure 2, for the purpose of symmetrical canyon and arch thickening from crown to abutment, the shape of the horizontal section of a parabolic arch dam is determined by the following two parabolas:
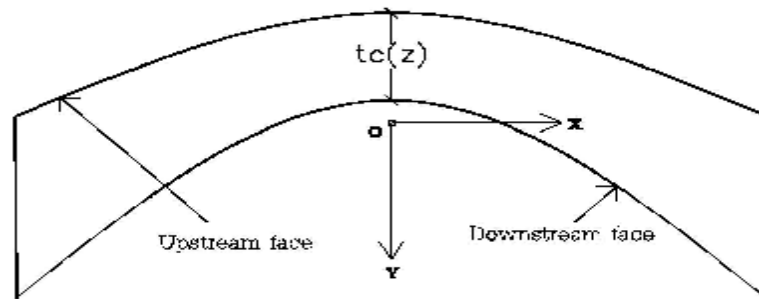

Figure 2. The shape of the horizontal section of a parabolic dam

At the upstream face of the dam:

$$y_u(x, z) = \frac{1}{2r_u(z)} x^2 + b(z) \tag{14}$$

At the downstream face of the dam:

$$y_d(x,z) = \frac{1}{2r_d(z)} x^2 + b(z) + t_c(z) \tag{15}$$

where r_u and r_d are radii of curvatures correspond to upstream and downstream curves respectively, and functions of nth order with respect to z can be used for those radii. In this study, $n=2$ is assumed, and r_u and r_d are considered as quadratic functions:

$$
\begin{aligned}
r_u &= n_1 r_{u1} + n_2 r_{u2} + n_3 r_{u3} \\
r_d &= n_1 r_{d1} + n_2 r_{d2} + n_3 r_{d3}
\end{aligned}
\tag{16}
$$

where r_{u1}, r_{u2}, r_{u3} and r_{d1}, r_{d2}, r_{d3} are values of r_u and r_d at $z=0$, $z=\lambda h$ and $z=h$, respectively.

5. VERIFICATION OF THE FINITE ELEMENT MODEL

In order to validate the finite element model with the employed assumptions, an idealized model of Morrow Point arch dam which is located 263 km southwest of Denver, Colorado, is investigated, Figure 3. The properties of the dam in details can be found in Ref. [13]. The physical and mechanical properties involved here are the concrete density ($2483 N.s^2/m^4$), the concrete poison's ratio (0.2) and the concrete elasticity (27580×10^4 MPa). It is assumed that the reservoir is empty and dam foundation is rigid.
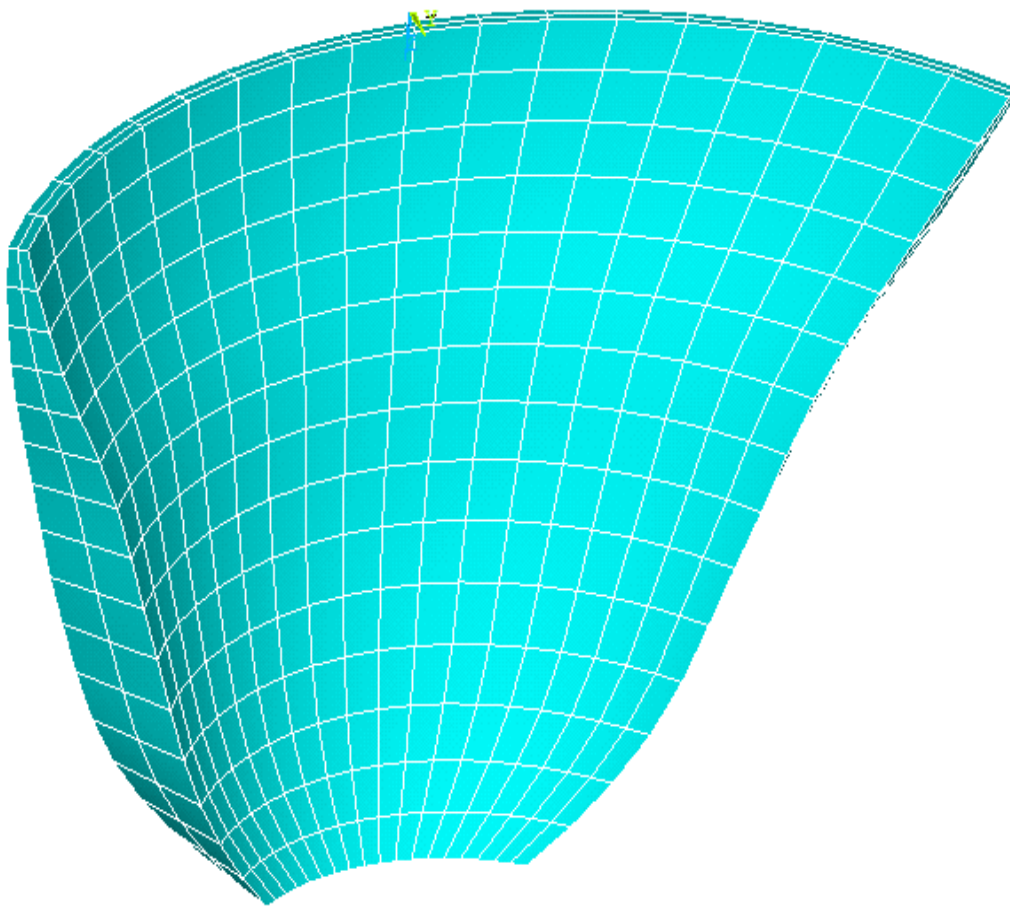

Figure 3. Finite element model of the Morrow Point arch dam

In literature, the natural frequencies of some mode are eliminated due to considering only half of the dam. Thus, in order to perform an exact analysis, it is necessary to consider the complete dam. In the present work complete model is considered and the first three natural frequencies of the mode of Morrow Point dam are determined from the frequency response function for the crest displacement and the results are compared to those reported in the literature [13-14]. The natural frequencies from the other literatures and present work are given in Table 1. It can be observed that a good conformity is achieved between the results of

present work with those of the previously reported results.

Table 1. Natural frequencies (Hz) of the Morrow Point arch dam

mode	Tan and Chopra [13]	Salajegheh et al. [14]	Present work
1	4.27	4.29	4.28
2	-	-	4.59
3	-	6.71	6.78

6. ARCH DAM OPTIMIZATION

6.1. Mathematical model and optimization variables

The optimization problem can formally be stated as follows:

$$
\begin{aligned}
&\text{Find} \qquad X = [x_1, x_2, x_3, .., x_n] \\
&\text{to minimizes } Mer(X) = f(X) \times f_{penalty}(X) \\
&\text{subjected to} \quad g_i(X) \leq 0,\ i=1,2,\ldots,m \\
&\qquad\qquad\quad x_{imin} \leq x_i \leq x_{imax}
\end{aligned}
\tag{17}
$$

where X is the vector of design variables with n unknowns, g_i is ith constraint from m inequality constraints and $Mer(X)$ is the merit function; $f(X)$ is the cost ; $f_{penalty}(X)$ is the penalty function which results from the violations of the constraints corresponding to the response of the arch dam. Also, x_{imin} and x_{imax} are the lower and upper bounds of design variable vector.

Exterior penalty function method is employed to transform the constrained dam optimization problem into an unconstrained one as follows:

$$
f_{penalty}(X) = 1 + g_p \sum_{i=1}^{m} max(0, g_j(x))^2
\tag{18}
$$

where γ_p is penalty multiplier.

6.2. Design variables

The most effective parameters for creating the arch dam geometry were mentioned in Section 2. The parameters can be adopted as design variables:

$$
X^T = \{s \quad b \quad t_{c1} \quad t_{c2} \quad t_{c3} \quad r_{u1} \quad r_{u2} \quad r_{u3} \quad r_{d1} \quad r_{d2} \quad r_{d3}\}
\tag{19}
$$

where the vector of design variables contains 11 shape parameters of arch dam.

6.3. Design constraints

Design constraints are divided into some groups including the behavioral, geometrical and stability constraints. The behavioral constraints are the restricted natural frequencies that are defined as follows:

$$frl_n \le fr_n \le fru_n \Rightarrow \begin{cases} 1 - \dfrac{fr_n}{frl_n} \le 0 \\ \dfrac{fr_n}{fru_n} - 1 \le 0 \end{cases}, \quad n = 1,2,...,n_{fr} \tag{20}$$

where fr_n, frl_n and fru_n are the nth natural frequency, lower bound and upper bound of the nth natural frequency, respectively. Also, nfr is the number of natural frequencies. The most important geometrical constrains are those that prevent from intersection of upstream face and downstream face as:

$$r_{dn} \le r_{un} \Rightarrow \frac{r_{dn}}{r_{un}} - 1 \le 0, \quad n = 1,2,3 \tag{21}$$

where r_{dn} and r_{un} are the radii of curvatures at the down and upstream faces of the dam in nth position in z direction. The geometrical constrain that is applied to facilities the construction, is defined as:

$$s \le s_{all} \Rightarrow \frac{s}{s_{all}} - 1 \le 0 \tag{22}$$

where s is the slope of overhang at the downstream and upstream faces of dam and s_{all} is its allowable value. Usually s_{all} is taken as 0.3. The constraints ensuring the sliding stability of the dam may be expressed as:

$$f_l \le f \le f_u \tag{23}$$

where φ is the central angle of arch dam and usually $90 \le f \le 110$, Ref. [15]

6.4. Cost function

The cost function is the construction cost of the dam, which may be expressed as:

$$f(X) = p_v v(X) + p_a a(X) \tag{24}$$

where $v(X)$ and $a(X)$ are the concrete volume and the casting area of dam body. The unit price of concrete and casting are chosen as $pv=\$33.34$ and $pa=\$6.67$, respectively.

The volume of concrete can be determined by integrating from dam surfaces as:

$$n(X) = \iint_{Area} |y_d(x,z) - y_u(x,z)| dxdz \tag{25}$$

in which *Area* is an area produced by projecting of dam on *xz* plane. The areas of casting can be approximately calculated by summing of the areas of upstream and downstream faces as follows:

$$a(X) = a_u(X) + a_d(X) = \iint_{Area}\sqrt{1+(\frac{dy_u}{dx})^2+(\frac{dy_u}{dz})^2}\,dxdz + \iint_{Area}\sqrt{1+(\frac{dy_d}{dx})^2+(\frac{dy_d}{dz})^2}\,dxdz \quad (26)$$

where a_u and a_d are the casting areas of upstream and downstream faces, respectively [16].

To evaluate $v(X)$ and $a(X)$ a computer program is coded using MATLAB [10].

7. NUMERICAL EXAMPLES

In order to assess the effectiveness of proposed procedure and compare with other literature results, a well-known benchmark problem in the field of shape optimization of the arch dam with frequency constraints with a height of 180 m is considered. The width of the valley in its bottom and top are 40 m and 220 m, respectively. A finite element model based on modal analysis for the double-curvature arch dam is presented. The arch dam is treated as a three dimensional linear structure. To mesh of the arch dam body twenty-node isoperimetric solid element is used. It is assumed that the reservoir is empty and dam foundation is rigid to avoid the extra complexities that would otherwise arise. To evaluate the eigenvalues of arch dam a computer program is coded using Opensees [9].

The lower and upper bounds of design variables using empirical design methods are considered as:

$$\begin{aligned} 0 \le s \le 0.3 \quad & 4 \le t_{c1} \le 12 \quad & 50 \le r_{u1} \le 180 \quad & 50 \le r_{d1} \le 180 \\ 0 \le b \le 1 \quad & 8 \le t_{c1} \le 30 \quad & 40 \le r_{u1} \le 120 \quad & 40 \le r_{d1} \le 120 \\ & 12 \le t_{c1} \le 40 \quad & 10 \le r_{u1} \le 50 \quad & 10 \le r_{d1} \le 50 \end{aligned} \quad (27)$$

In current study, natural frequency constraints are imposed as:

$$fr_1 \le 3\,Hz \quad fr_3 \le 6\,Hz \quad fr_4 \le 7\,Hz \quad fr_5 \le 8\,Hz \quad (28)$$

Table 2 shows the material properties for this example. Specifications of the CSS and PSO methods are given in Tables 3 to 4. This problem has been investigated by Gholizadeh and Seyedpoor [12] using the GA and VSP algorithm.

Table 2. Material properties of arch dam

Property/unit	Value
E (Modulus of elasticity)/ MPa	21000
poison's ratio	0.2
ρ (Material density)/ kg/m^3	2400

Table 3. Specifications of the CSS method

Parameter	Specification
Number of CPs	50.00
Max acceleration coefficient	1.00
Max velocity coefficient	0.50
Min acceleration coefficient	0.50
Min velocity coefficient	0.00
Magnitude of a	1.00
Maximum iterations	100.00

Table 4. Specifications of the PSO method

Parameter	Specification
Swarm size	50.00
Cognitive parameter	2.00
Social parameter	2.00
Inertia weight	0.50
Maximum iterations	50.00

7.1. Results of optimization

Table 5 represents the design vectors and the cost of the corresponding half the arch dam obtained by different researchers and methods. It can be seen that both CSS and PSO have outperformed their rivals. Also, demonstrate that CSS gives better results than PSO.
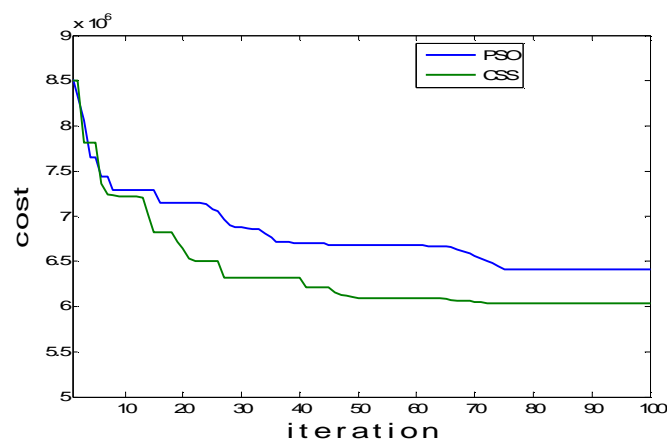

Figure 4. The convergence curves for the CSS and PSO

Figure 4 shows the convergence curves for both CSS and PSO for the optimum design of arch dam.

Table 5. Optimum designs of the arch dam obtained by the various methods

Variable No.	Gholizadeh & Seyedpoor [12]		Present work	
	GA	VSP	PSO	CSS
1	0.2254	0.2508	0.2577	0.0216
2	0.9752	0.7376	0.8195	0.6141
3	4.4306	4.0027	8.7656	8.0144
4	23.2672	18.0125	8.9711	8.0010
5	13.6326	12.0258	17.6736	17.2981
6	129.3949	149.9189	117.6666	159.6764
7	92.0741	94.6904	79.1041	91.8348
8	39.4704	49.2262	42.8860	46.7626
9	129.0289	148.2564	63.7034	85.2251
10	40.8120	53.0239	54.0178	52.3796
11	31.0890	48.2745	26.3438	29.8441
cost of the corresponding half the arch dam (10^6)	8.740	6.576	6.403	6.030

8. CONCLUDING REMARKS

In this paper the shape optimization of an arch dam is performed. The cost of the arch dam includes the concrete volume and the casting areas considered as the objective function, with frequency, geometrical and stability constraints. To optimize the arch dam two meta-heuristic algorithms namely the CSS and PSO are utilized. To validate the finite element model, the Morrow Point arch dam is analyzed. It is observed that natural frequencies of some mode are eliminated due to considering only half of the dam in the results reported in the literature.

Form the results of this study it can be seen that both CSS and PSO have performed better than the other methods available in the literature for the examples considered. The solved example demonstrates that the CSS leads to better results than the PSO.

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