Performance Evaluations of the Mine Blast and Water Cycle Algorithms for Arch Dam Shape Optimization

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ABSTRACT

The arch dam is a structure which has complex stresses and many constraints with the topography and geological conditions. An appropriate shape design has a great influence on the economy, safety and stability of an arch dam. This paper presents the applications of two recently developed optimization methods namely the Mine Blast Algorithm (MBA) and the Water Cycle Algorithm (WCA) to the shape optimization of arch dams. The arch dam shape optimization results of these methods are compared to a number of other optimization methods reported in the literature. The results show significant improvements in obtaining the optimum shape/volume of the arch dam as well as cost in developing the arch dam.

Keywords: Mine blast algorithm; Water cycle algorithm; Arch dam; Shape optimization.

1. INTRODUCTION

Dam is one of the oldest human constructions. There are various types of dams based on specific shape. A dam normally is used to control flood, water storage for irrigation, as well as water supply and a means to generate electricity. In this paper, arch dam is the main focus. Arch dam has a curvy vertical shape on the upstream as well as on the downstream. Arch dam normally is built near the canyon and the safety of the arch dam depends on the strength of the abutment as well as the character of the rock. The foundations must be very stable and proportionate to the concrete. The Arch dam is one of the most complex and difficult structures due to its shape and normally involves a high cost due to the use of high volume of materials. Arch dams are designed, both in the single or double-curvature forms.

Recently some progress has been made in optimum design of arch dams considering different constraints. Numerous studies 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 dam has been developed after appearing and development of finite element method in late 1950's. In Rajan [1], Mohr [2] and Sharma [3] developed solutions based on membrane shell theory. Sharpe (1969) was the first to formulate the optimization as a mathematical programming problem. A similar method was also adopted by Rickeetts and Zienkiewicz [4] who used finite element method for stress analysis and Sequential Linear Programming (SLP) for the shape optimization of arch dams under static loading

Shape optimization of arch dam reported in numerous literatures [6-13]. This research employs two recently developed optimization methods to the shape optimization of arch dam. Arch dam shape optimization is carried out using The Mine Blast Algorithm (MBA) [14] and Water Cycle Algorithm (WCA) [15] and the results are compared to other arch dam shape optimization reported in the literature [7, 13]. Most studies concluded that, the dimensions of an arch dam play an important role in minimizing the cost of the dam without changing the pattern as well as the condition.

The rest of this paper is arranged as follows. Section 2 presents a short description of MBA and WCA optimization methods. Section 3 presents an overview of arch dam. The optimization results and discussions are presented in Section 4. Finally, conclusions are given in Section 5.

Shape optimization of arch dam reported in literature include such as optimization design of arch dam shape with modified complex method [6], Optimum shape design of Arch Dams by a combination of simultaneous perturbation stochastic approximation and genetic algorithm methods [7], colliding bodies optimization for design of arch dams with frequency limitations [13].

In this research, the design and shape optimization of an arch dam is carried out using the Mine Blast Algorithm (MBA) and Water Cycle Algorithm (WCA). The objective is to reduce the dimension of an arch dam without neglecting the importance of strength as well as the stability of the arch dam for long term. This is the first time for MBA as well as WCA to be introduced for arch dam shape optimization. The result obtained from MBA and WCA dam optimization are compared with those reported in literature [7, 13]. In this paper, the results achieved from MBA and WCA shape optimization of arch dam is compared with the results from a combination of simultaneous perturbation stochastic approximation and genetic algorithm [7] and the results obtained from colliding bodies optimization (CBO) reported in [13].

1. OPTIMIZATION ALGORITHMS

1.1. The mine blast algorithm

The idea for the Mine Blast Algorithm(MBA) is based on explosion of mines where a fling of a shrapnel piece strike onto another mine near explosion area which triggers the explosion [14]. The MBA is a population based metaheuristic algorithm. Imagine that an area full of mines scattered around, and according to Sadollah et al [14], the aim is to locate the mine with highest probability of explosion which can create the maximum fatality. Such mine is located at point X^* (min or max $f(x)$ per X^*). Each shrapnel piece has definite directions and distances to collide with other mine bombs which may lead to the explosion of other mines due to the collision. The collision of shrapnel pieces with other mines may lead us to discover the most explosive mine. The casualties caused by the explosion of a mine bomb are considered as the fitness of the objective function at the mine bomb's location. The domain (mine field) solution may be divided into infinite grid where there is one mine bomb in each portion of the grid. Further information on MBA can be found in [14].

1.2. The water Cycle Algorithm

The idea for the Water Cycle Algorithm (WCA) is based on observation of water cycle process especially in rivers and streams flow towards the sea [15]. The WCA creates a uniform random population of raindrops (design variables). First, it is assumed that there is rain or precipitation. The best individual (best raindrop) is chosen as a sea. Then, a number of good quality raindrops are chosen as a river and the rest of the raindrops are considered as streams which flow to the rivers and sea. Depending on their magnitude of flow, each river absorbs water from the streams. The amount of water in a stream entering a rivers and/or sea varies from other streams. In addition, rivers flow to the sea which is the most downhill location.

In WCA, rivers (a number of best selected points except the best one (sea)) act as ‘‘guidance points’’ for guiding other individuals in the population towards better positions in addition to minimize or prevent searching in inappropriate regions in near-optimum solutions. Furthermore, rivers are not fixed points and move toward the sea (the best solution). This procedure (moving streams to the rivers and, then moving rivers to the sea) leads to indirect move towards the best solution. The WCA also uses ‘‘evaporation and raining conditions’’ which may resemble the mutation operator in Genetic Algorithm. The evaporation and raining conditions can prevent WCA algorithm from getting trapped in local solutions. Further information on WCA can be found in [15].

2. ARCH DAM SHAPE OPTIMIZATION

In this paper, the main objective is to im1prove the cross sectional dimension of an arch dam without affecting the conditions. Both MBA and WCA were employed using 10 runs on a computer with CPU performance of intel I5-5200U/BGA with a ram of DDR3L 8G using Matlab environment. The objective function $f(x)$ is based on the total cross sectional volume of the arch dam in addition to the considered constraints used to solve the problem.

Two case studies were considered in this study and the optimum volumes of the arch dams were achieved using MBA and WCA. The objective functions as well as the constraints were taken as identical to those reported in [7, 13].

3.1. Case study 1

3.1.1. Arch dam geometry

From Figure 1, the curve of upstream face is considered by Zhu (1987, 1992) as follows:

$$y(z) = b(z) = -s\,z + s\,z^2 /(2\beta\,h) \tag{1}$$

where h and s are the height of the dam and the slope at crest, respectively. The point where the slope of the upstream face equals to zero is $z = \beta h$ in which $0 < \beta \leq 1$ is a constant.

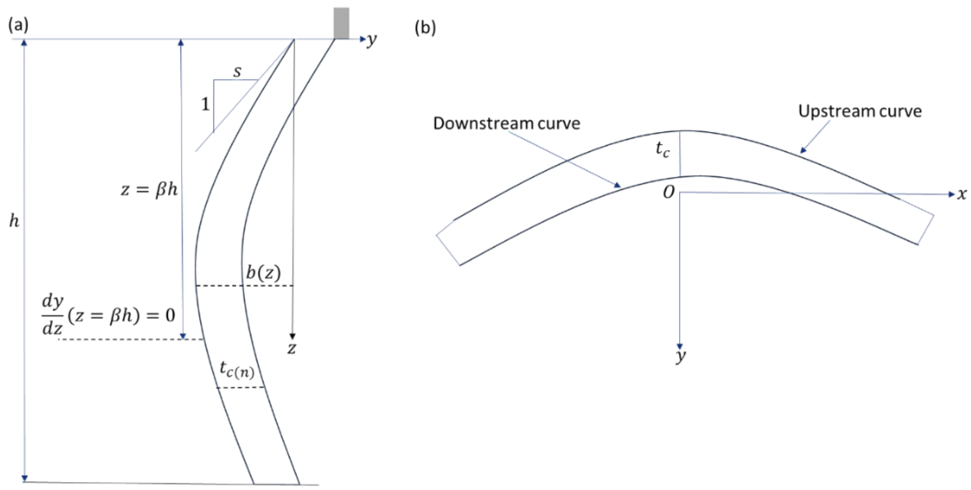

Figure 1: (a) Central vertical section of arch dam (b) A horizontal section of parabolic arch dam [7]

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

$$tc(z) = n_1(z)tc_1 + n_2(z)tc_2 + n_3(z)tc_3 + n_4(z)tc_4 \tag{2}$$

where tc_1, tc_2, tc_3 and tc_4 are the thicknesses of the central vertical section at $z=0$, $z=\lambda_1 h$, $z=\lambda_2 h$ and $z=h$, respectively and $n_1(z)$, $n_2(z)$, $n_3(z)$ and $n_4(z)$ are Lagrange interpolation functions for the four-nodes line element. λ_1 and λ_2 are factors in the range of (0,1) and in this study are considered as $\lambda_1 = 0.40$ and $\lambda_2 = 0.75$.

From Figure 1(b), 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 parabolic surfaces as proposed by Zhu (1987):

At the upstream face of dam:

$$y_u(x,z) = \frac{1}{2r_u(z)}x^2 + b(z) \tag{3}$$

At the downstream face of dam:

$$y_d(x,z) = \frac{1}{2r_d(z)}x^2 + b(z) + t_c(z) \tag{4}$$

where r_u and r_d are radii of curvature correspond to upstream and downstream surfaces, respectively and the functions of n^{th} order with respect to z can be used for those radii. In this study, assuming $n = 3$, r_u and r_d are considered as cubic functions.

3.1.2. Optimization model

The optimization problem is formally stated as follows:

$$\begin{aligned} Minimize{:}\quad & q(X) \\ Subject\ to{:}\quad & g_j(X) \leq 0, \qquad j = 1,\ldots,m. \end{aligned} \tag{5}$$

in which X is the vector of design variables with n_v unknowns and g_j, $j = 1,\ldots, m$ are the inequality constraints including the side constraints. The $q(X)$ represents the objective function that should be minimized.

The cross section of the arch dams can be defined by defining the eleven parameters which is needed in order to solve the problem as shown:

$$X^T = \{S, \beta, t_{c1}, t_{c2}, t_{c3}, r_{u1}, r_{u2}, r_{u3}, r_{d1}, r_{d2}, r_{d3}\} \tag{6}$$

where X^T is the vector is design variable for which $t_{c(n)}$ is the thickness and $r_{d(n)}$ is the radius of curvature of the arch dam.

The objective functions as defined as:

$$f(x) = p_v v(X) + p_t t(X) \tag{7}$$

where *v(X)* is the volume of concrete and *t(X)* is the areas of casting in da m. Equation (7) is subject to the constraints used in the behavior constraints, geometric constraints and sliding stability constraints function shown on the next paragraph. Both p_v and p_t are the costs of concrete and casting per cubic yard which are equal to $33.34 and $6.67. The *v(X)* and *t(X)* are given as:

$$v(x) = \int_{area} \left| \begin{matrix} \left[\frac{1}{2(r_{d1} + r_{d2} + r_{d3} + r_{d4})} x^2 + b(z) + t_{c1} + t_{c2} + t_{c3} + t_{c4}\right] - \\ \left[\frac{1}{2(r_{u1} + r_{u2} + r_{u3} + r_{u4})} x^2 + b(z)\right] dxdz \end{matrix} \right| \tag{8}$$

$$t(x) = \iint_{area} \left| \sqrt{\left[1 + \left(\frac{x}{r_{d1} + r_{d2} + r_{d3} + r_{d4}}\right)^2 + \left(-s + \frac{sz}{\beta h}\right)^2\right]} \right| dxdz \tag{9}$$

Based on Figure 1, the height of the dam *h* is taken as 180m. The design constraints will be the input constraints which are identical to [7] which are divided into 3 section such as; behavior constraints, geometric constraints, and sliding stability constraints.

The behavior constraints (*bc(x))* is used to prevent the arch dam from the failure of each element (*i)* of an arch dam using specific safety factor (*sf*) which is defined as:

$$bc(x) = \left(\frac{f}{f_c} - \frac{sur}{2}\right) \leq 0, \tag{10}$$

where *f* is function of the principal stress ($\sigma_1 \leq \sigma_2 \leq \sigma_3$) and *sur* is failure surface which is normally expressed in terms of principle stress and uniaxial compressive strength of concrete (f_c). The details criterion can be found in [5] and theory reference of ANSYS (2006). The function of the principle (*f)* and failure surface (*sur)* are defined as:

$$f = \frac{1}{\sqrt{15}}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]^{\frac{1}{2}} \tag{11}$$

$$sur = \frac{2r_2(r_2^2 - r_1^2)cos\eta + r_2(2r_1 - r_2)[4(r_2^2 - r_1^2)\cos^2\eta + 5r_1^2 - 4r_1r_2]\text{^}(1/2)}{4(r_2^2 - r_1^2)\cos^2\eta + (r_2 - 2r_1)^2} \tag{12}$$

whereas the angle of similarity (η) explain the relationship between magnitude and the principle of stresses where $\eta = 0° \; and \; \eta = 60°$ as:

$$cos\eta = \frac{2\sigma_1 - \sigma_2 - \sigma_3}{\sqrt{2}[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2]^{(\frac{1}{2})}} \tag{13}$$

Other than that, the geometric constraints also play a major role in optimizing the shape of an arch dam. There are three different types of constraints under geometric constrain criteria. One of the constraints which is known asg_1 is used for the prevention from intersection between upstream and downstream defined as:

$$g_1 = \frac{r_{dn}}{r_{un}} - 1 \leq 0, n = 1, \ldots, 4 \tag{14}$$

The other geometric constraints which is needed to applied for facile construction as follow:

$$g_2 = \frac{S}{S_{allow}} - 1 \leq 0 \tag{15}$$

where *S* is the slope overhang for both upstream and downstream faces of the dam and S_{allow} it the allowable value, usually equal to 0.3.

In additional to this, the sliding stability constraints also play a major role in ensuring the stability of the arch dam, and it is expressed as follow:

$$g_{slid}^{u} = \frac{\theta_n}{\theta^u} - 1 \leq 0\,, n = 1, \dots.,4 \tag{16}$$

$$g_{Slid}^{l} = 1 - \frac{\theta_n}{\theta^l} \leq 0\,, n = 1, \dots..,4 \tag{17}$$

where $\theta^l \leq \theta_n \leq \theta^u$ usually in the range of $90 \leq \theta_n \leq 130$ and this θ_n is the *nth* central angle of an arch dam.

All the constraints were used as conditions which were used to create a better optimization in term of efficiency and getting a minimal value without jeopardizing the stability and the strength of an arch dam.

3.2. Case study 2

In this study, both MBA and WCA will be compared with the result achieved from the colliding bodies optimization (CBO) with frequency limitations [13].

The cross section of the arch dam is modeled by 11 shape design variables as:

$$X = \{S\ \beta\ t_{c1}\ t_{c2}\ t_{c3}\ r_{u1}\ r_{u2}\ r_{u3}\ r_{d1}\ r_{d2}\ r_{d3}\} \tag{18}$$

where *S* is the slope of overhang at the downstream and upstream faces of the dam and β is a constant which is related to the center and the height of the arch dam as shown in [13].

The variables t_{cn} and r_{cn} are the thickness of the central vertical section and the radii of curvature corresponding to the upstream and downstream curves of the arch dam respectively as shown in Figure 1.

The dimensions of an arch dam for case 2 are the same as the dimensions used in case 1 with a height of 180m, a valley width of 40m and 220m respectively as shown in Figure 2. In this research, the construction costs and the dimensions of arch dams utilize the objective function as shown in equation (14). $P{:}CA = \$33.34$ and $P{:}CO = \$6.67$ is the unit price for concrete and casting per cubic yard.

The objective function for this case is given as:

$$f(x) = P{:}CA \times V(x) + P{:}CO \times A(x) \tag{19}$$

where *V(x)* is the concrete volume and *A(x)* is the casting area of an arch dam body.

The volume of concrete can be written as:

$$V(x) = \iint_{Area} \left| y_d(x,z) - y_u(x,z) \right| dxdz \tag{20}$$

The casting area of an arch dam can be written as:

$$a(x) = a_u(x) + a_d(x)$$
$$= \iint_{Area} \sqrt{1 + \left(\frac{dy_u}{dx}\right)^2 + \left(\frac{dy_u}{dz}\right)^2}\, dxdz + \iint_{area} \sqrt{1 + \left(\frac{dy_d}{dx}\right)^2 + \left(\frac{dy_d}{dz}\right)^2}\, dxdz \tag{21}$$

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

As shown in Figure 2, the shape of the horizontal section of a parabolic arch dam is determined by two parabolas at upstream and downstream faces.

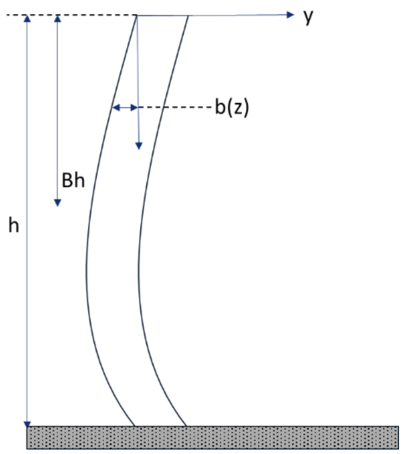

Figure 2:. Central vertical section of an arch dam

At the upstream face of the dam the parabolic shape is given by:

$$y_u(x,z) = \frac{1}{2r_u(z)}x^2 + b(z) \quad (22)$$

and at the downstream face of the dam the parabolic shape is given by:

$$y_d(x,z) = \frac{1}{2r_d(z)}x^2 + b(z) + t_c(z) \quad (23)$$

where both r_u and r_d are radii of the curvature of the upstream and downstream curves of the arch dam. The radii of the curvature of the upstream curve, r_u, is given by:

$$r_u = \sum_{i=1}^{n} L_i r_{ui} \quad (24)$$

and the radii of the curvature of the downstream curve, r_d, can be written as:

$$r_d = \sum_{i=1}^{n} L_i r_{di} \quad (25)$$

where both r_{ui} and r_{di} are the values of r_u and r_d at the *ith* level, respectively. *h* is the height of the arch dam which is equal to 180m and *s* is the slope at the crest and where the slope of the upstream face of the arch dam is equal to $z = \beta h$ is which β is constant.

The thickness of the central vertical section can be expressed as:

$$t_c(z) = \sum_{i=1}^{n} L_i(z) t_{ci} \quad (26)$$

In which the $t_{ci}$is the thickness of the central vertical section at the ith level. The relation $L_i(z)$ is a Lagrange interpolation function which can be defined as:

$$L_i(z) = \frac{\prod_{k-1}^{n+1}(z - z_k)}{\prod_{k-1}^{n+1}(z_i - z_k)} \quad i \neq k \quad (27)$$

where z_i denotes the *z* coordinate of the *ith* level in the central vertical section.

In addition to the objective function, constraints play a major role in optimizing the dimension of the arch dam with aim to meet the objective.

The constraints known as design constraints, which is consists of the design variable of the arch dam. These design constraints are divided into a specific group such as behavioral constraints, geometrical constraints and stability constraints.

As for the behavioral constraints, it is the restricted natural frequency which can be written as:

$$frl_n \leq fr_n \leq fru_n \rightarrow \begin{cases} 1 - \frac{fr_n}{frl_n} \leq 0 \\ \frac{fr_n}{frl_n} - 1 \leq 0 \end{cases}, \quad n = 1,2,\ldots\ldots, n_{fr} \quad (28)$$

where fr_n, frl_n and fru_n are the *n*th natural frequency, lower bound and upper bound the *n*th frequency. Where else, the n_{fr} is the number of natural frequency.

With the behavioral constraints, the optimization can become more accurate with the presence of geometrical constraints. It is because the geometrical constraints take account of the actual dimension of the arch dam from all angles. This geometrical constraint is used to prevent from intersection between the upstream and downstream face which can be seen from figure 1. (b) and figure 2. A geometric constraint is a limitation placed on an object, which can have two dimensions or more, because there are zero degrees of freedom. It can be written as:

$$r_{dn} \leq r_{un} \rightarrow \frac{r_{dn}}{r_{un}} - 1 \leq 0, \quad n = 1,2,3 \tag{29}$$

where the r_{dn} and r_{un} are the radius of curvature at the downstream and upstream faces of the dam in *n*th position in z-axis direction. In addition to that, another geometrical constraint will be used to assist the construction, and can be written as:

$$s \leq s_{all} \rightarrow \frac{s}{s_{all}} - 1 \leq 0 \tag{30}$$

where s is the slope of the overhang at the downstream and upstream faces of the arch dam and s_{all} is the allowable amount.

4. RESULT AND DISCUSSIONS

This section examines the ability of MBA and WCA in optimizing an arch dam and comparing the results to the same optimization made in literature using stochastic approximation and genetic algorithm and the CBO. From the results, it is evident that MBA and WCA outperforms both the stochastic approximation and genetic algorithm and CBO in optimizing the arch dam optimization problem.

Case study 1

From the first case study, both MBA and WCA shows better improvement compared to stochastic approximation and genetic algorithm. About 23% improvement for MBA and about 39% for WCA on total cost of concrete used in building the dam ($\$8.65 \times 10^6$ for MBA and $\$6.89 \times 10^6$ for WCA) when compared to genetic algorithm ($\$11.36 \times 10^6$). And about 3% to 10% improvement for MBA and 17% to 28% when compare the MBA and WCA with stochastic approximation achieved from this paper [7]).Table 1 show the results achieved from MBA and WCA. Table 2 shows the dimensions of the dam after optimizing using stochastic approximation and genetic algorithm as proposed in [7]. Table 3 shows the best, worst and the average costs given by MBA and WCA after 10 runs.

Table 1: The dimension of the dam after optimization using MBA and WCA

Dam parameters	Type of optimization (Dimension of the arch dam)	
	MBA	**WCA**
$S\ (m/m)$	0.16	0.175
$\beta\ (m/m)$	0.80	0.87
$t_{c1}\ (m)$	3.89	4.68
$t_{c2}\ (m)$	8.95	6.9
$t_{c3}\ (m)$	22.45	35.68
$t_{c4}\ (m)$	19.75	34.54
$r_{u1}\ (m)$	150.45	157.36
$r_{u2}\ (m)$	98.67	98.23
$r_{u3}\ (m)$	38.65	40.39
$r_{u4}\ (m)$	24.20	22.10
$r_{d1}\ (m)$	130.48	134.23
$r_{d2}\ (m)$	70.02	76.2
$r_{d3}\ (m)$	50.32	43.45
$r_{d4}\ (m)$	15.12	15.48
Cost in developing of the concrete arch dam	$\$8.65 \times 10^6$	$\$6.89 \times 10^6$
Number of function evaluations	1890	1670

Table 2: The dimension of the dam achieved by the previous researchers using stochastic approximation and genetic algorithm [7]

Dam parameters	Type of optimization (Dimension of the arch dam)		
	GA	**SPSA**	**SPGA**
$S\ (m/m)$	0.18	0.29	0.29
$\beta\ (m/m)$	0.82	0.83	0.83
$t_{c1}\ (m)$	4.41	5.19	4.10
$t_{c2}\ (m)$	8.70	8.36	8.36
$t_{c3}\ (m)$	27.35	21.99	21.99
$t_{c4}\ (m)$	29.69	22.02	22.02
$r_{u1}\ (m)$	147.92	142.87	138.98
$r_{u2}\ (m)$	108.27	98.94	87.32
$r_{u3}\ (m)$	45.08	49.99	45.92
$r_{u4}\ (m)$	23.10	27.04	27.04
$r_{d1}\ (m)$	137.67	111.57	140.29
$r_{d2}\ (m)$	74.52	79.93	79.93
$r_{d3}\ (m)$	45.52	48.52	48.52
$r_{d4}\ (m)$	17.74	26.72	26.72
Cost in developing of the concrete arch dam	$\$11.36\ \times 10^6$	$\$9.65 \times 10^6$	$\$8.39 \times 10^6$
Number of function evaluations	7000	7000	1700

Table 3: The best, worst and average results achieved by MBA and WCA after 10 runs

Type of result	Total cost in developing of the concrete arch dam	
	MBA	**WCA**
Best	$\$8.65 \times 10^6$	$\$6.89 \times 10^6$
Average	$\$9.14 \times 10^6$	$\$7.988 \times 10^6$
Worst	$\$11.23 \times 10^6$	$\$10.256 \times 10^6$

Case Study 2

For the second case study, once again both MBA and WCA shows improvement in producing optimum results compared to CBO reported in [13]. Both the MBA and WCA able to produce from 25% to 27% reduction of the original cost of concrete arch dam used in PSO. Furthermore, both MBA and WCA also able to reduce the cost up to 23% when compare to CSS. In addition to that, both MBA and WCA also offered about 15% to 50% reduction of the cost in developing the arch dam concrete when compared to CBO both for case 1 and case 2 in the second case study. The dimensions of the arch dam after optimization using the MBA and WCA are shown in Table 4.

Again, both MBA and WCA was run 10 times and the best, worst and average values are given in Table 5.

Table 4: The optimum dimensions of arch dam using MBA and WCA compared to the optimization used in literature [13]

Dam parameters	Type of optimization (Dimension of the gravity dam)					
	MBA	**WCA**	**PSO**	**CSS**	**CBO (Case1)**	**CBO (Case2)**
$S\ (m/m)$	0.28	0.28	0.2577	0.0216	0.2673	0.2717
$\beta\ (m/m)$	0.6	0.7	0.8195	0.6141	0.655	0.6876
$t_{c1}\ (m)$	7.86	6.00902	8.7656	8.0144	6.6061	4.0974
$t_{c2}\ (m)$	8.21	8.1123	8.9711	8.0010	8.0205	26.0802
$t_{c3}\ (m)$	12.75	14.921	17.6736	17.2981	14.5962	12.1907
$r_{u1}\ (m)$	109.8874	119.831	117.6666	159.6764	171.9731	114.9598
$r_{u2}\ (m)$	69.668	59.980	79.1041	91.8348	70.1358	98.9373
$r_{u3}\ (m)$	39.765	30.0243	42.8860	46.7626	30.4945	48.4383
$r_{d1}\ (m)$	69.941	70.0014	63.7034	85.2251	83.1802	114.904
$r_{d2}\ (m)$	47.941	49.771	54.0178	52.3796	49.9592	47.3008
$r_{d3}\ (m)$	19.862	17.966	26.3438	29.8441	27.0186	22.9041
Cost in developing of the concrete arch dam	$\$4.643 \times 10^6$	$\$4.776 \times 10^6$	$\$6.403 \times 10^6$	$\$6.030 \times 10^6$	$\$5.680 \times 10^6$	$\$9.370 \times 10^6$
Number of function evaluations	1143	2100	5000	5000	4000	4000

Table 5: The result achieved by the MBA and WCA

Type of result	Cost in developing of the concrete arch dam	
	MBA	**WCA**
Best result	$\$4.643 \times 10^6$	$\$4.776 \times 10^6$
Average result	$\$6.034 \times 10^6$	$\$5.269 \times 10^6$
Worst result	$\$7.739 \times 10^6$	$\$7.428 \times 10^6$

5. CONCLUSIONS

In this research, both the mine blast algorithm (MBA) and the water cycle algorithm (WCA) which is a newly developed metaheuristic method used in optimizing the arch dam. The results achieved were compared to what being reported in literature. Both the MBA and WCA were able to offer 3% to 39% reductions in cost of the concreted arch dam compare to those being reported in the literature for case 1. In addition to that, there is also huge improvement in term of the cost in developing of the concrete arch dam about 15% to 50% for both MBA and WCA when compared to those reported in literature for case 2. In conclusion, since there is a reduction in cost developing the arch dam, it means there is also an improvement in material used. This also related to an improvement in shape as well as the volume of the arch dam.

After optimizing using both MBA and WCA, the dimension of the arch dam met the safety factor required for stability and the safety requirement for an arch dam.

Hence, it can be concluded that both MBA and WCA are an efficient method for optimizing the hydraulic structures.

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