Shape Optimization of Gravity Dam using Invasive Weed Optimization Algorithm

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Abstract

Optimization algorithms allow designers to find and evaluate a multitude of possible solutions by trial and error. Hence, they have been a necessity in real design problems, in particular infrastructures' design. Dams are important infrastructures, which have different types regarding their materials and their behavior to endure loads. Gravity dams are one the most popular types of dams. Various methods have been attempted for designing optimum shape of them. In the current paper, invasive weed optimization (IWO) algorithm is employed to find the best possible shape of a concrete gravity dam (Tilari Dam in Maharashtra, India). Mathematical model of this problem was builtby considering the major factors and all design parameters. Parameters of the IWO were calculated using sensitivity analysis. Stress and stability (overturning and sliding) were considered as design constraints, based on the following two models: Model I (M1): Upstream dam face is sloped and Model II (M2): Upstream dam face is upright and vertical. Optimization by using IWO for M1 showed 20% reduction in cross section as compared to prototype and no changes in comparison with the algorithms in the literature (i.e. differential evolution, charged system search, colliding bodies optimization, and enhanced colliding bodiesoptimization). Results for M2 revealed 26% reduction in cross sectional area.

Keywords:Concrete Gravity Dams, Shape Optimization, Invasive Weed Optimization (IWO) Algorithm, OptimumDesign.

1. INTRODUCTION

Dams are essential infrastructures, which are built all over the world for meeting various water demands including flood control, water supply (urban, domestic, industrial etc.), hydropower, recreational activities, navigation, groundwater recharge etc.

It is estimated that the gravity dams are the first water barriers in the history of human lives. A gravity dam is a heavy structure made of concrete or masonry built across the river to increase the volume and height of water. In fact, gravity dams are among the most common types of concrete dams that have received special attention because of their simple design and their applications in different valleys. The stability of a concrete gravity damis entirely depended on their masses. Normally, the weight of gravity dams will suffice for stability against all design loads. Although gravity dams have been constructed in different shapes in the cross-section, they are generally made of roughly triangular cross-sections.They were built with masonry materials before the 1800s. Nowadays, they are mostly constructed with concrete [1].Trapezoidal and rectangular profiles were used to build the first samples of gravity dams' cross-sections. Although the recent dams' shapes are emerged by the development of new materials and design techniques, attempts to find more optimal shapes are in progress by researches.

Optimization is an interesting technique in hydraulic structures designthat finds the best solutions by searching the decision variables in the search space [2].The structural optimization problems can be divided into three categories such as (I) size optimization, (II) shape optimization, and (III) topology optimization [3].Salmasi (2011) optimized gravity dam section using genetic algorithm [4]. Khatibinia and Khosravi (2014) solved shape optimization problem of a concrete gravity dam using an improved gravitational search algorithm [5]. Deepika and Suribabu (2015) used Differential Evolution (DE) algorithm in order to find the best optimal shape of a gravity dam. The best solution was compared with an analytical model and the results showed about 20% reduction in concrete usage of dam [6].Kaveh and Zakian (2015) optimized a concrete gravity dam section using Charged System Search (CSS), Colliding Bodies Optimization (CBO), and Enhanced Colliding Bodies Optimization (ECBO) algorithms [3]. The results were compared to DEA results of Deepika and Suribabu (2015) [6]. All three used algorithms had superior results to DEA.Memarian and Shahbazi (2017) used DE algorithm in optimization of some gravity dam prototypes under various constraints [7].

In the present study, invasive weed optimization algorithm is employed in solving shape optimization problem of a concrete gravity dam based on two models. The selected gravity dam modelswere optimized using some evolutionary algorithms in the previous works, which their results are compared to the current findings. Besides, in the present research, decision variables bounds are changed to find better solutions for shape optimization problem of a concrete gravity dam.In general, one of the main objectives of the current research is highlighting the importance of optimization algorithms in designing of infrastructures.

2. OPTIMIZATION ALGORITHM

Invasive Weed Optimization (IWO) algorithm is one of the nature-inspired algorithms, which inspired by colonizing weeds. Mehrabian and Lucas from University of Tehran introduced this algorithm in 2006 [8]. Comparison of the results of the IWO with four types of Evolutionary Algorithms (EAs) such as Genetic Algorithms (GAs), Memetic Algorithms (MAs), Particle Swarm Optimization (PSO) and Shuffled Frog Leaping Algorithms (SFLA) showed superior performance and convergence rate etc. [8].Efficiency of IWO in optimization has proved in different studies in water engineering [9-12].

The process of achieving the optimal solution in the IWO is as follows:

I. Initializing a population

The implementation of this algorithm begins with the distribution of a certain number of seeds (initial population) in the search space.

II. Reproduction

Each seed grows according to its merits and produces new seeds. The number of seeds produced by each plant increases linearly from the lowest possible number of seeds to the highest possible number.

III. Spatial dispersal

In this section, the generated seeds are randomly dispersed in the multidimensional search space by the normal random distribution. Its average value is zero and its standard deviation varies at different stages. This step is similar to the random propagation of the seeds around the parent plant. At each step, the value of the standard deviation σ corresponding to the random function is reduced from the initial value of $\sigma_{initial}$ to the final value of σ_{final}. In the simulations, the nonlinear change expressed in Eq. (1) has shown a performance:

$$\sigma_{iter} = \frac{(iter_{\max} - iter)^n}{(iter_{\max})^n}(\sigma_{initial} - \sigma_{final}) + \sigma_{final} \tag{1}$$

In Eq. (1), $iter_{max}$ represents the maximum number of iterations, σ_{iter} the standard deviation in the current time step, and n the nonlinear modulation index.

IV. Competitive exclusion

If no seed is produced by the plant, it will become extinct and otherwise, it can spread throughout the world. Therefore, some competition is needed to limit the maximum number of plants. After several iteration, the number of plants will reach their maximum. At this stage, it is expected that the more competent plants will proliferate than the other plants. When the maximum number of plants (P_{max}) is reached, the process of removing plants begins with less fitness [8].

3. GRAVITY DAM OPTIMUM DESIGN MODEL

Fig. 1 shows the schematic of a gravity dam (plan and section). The purpose of shape optimizing of a structure is to find the most appropriate dimensions and shape so that it can withstand all loads and pressures. The loads in the gravity dam models are divided into two major categories including vertical and horizontal loads. The vertical loads include self-weight, uplift pressure force, silt pressure force, and seismic force. In addition, the vertical loads include water force, silt pressure force, wave pressure force, and seismic forces. The equations are these loads are represented in Table 1. Sliding and shear failure occur when the horizontal forces on each horizontal plane of a dam exceed its shear strength. Overturning of the dam and additional compressive stresses (and possibly tensile) can be prevented by selecting the appropriate cross-section. Normally, a gravity dam may be failed for one or all of these reasons:

1) sliding on a horizontal plane
2) overturning on toe
3) weakness in material (stress > allowable stress)

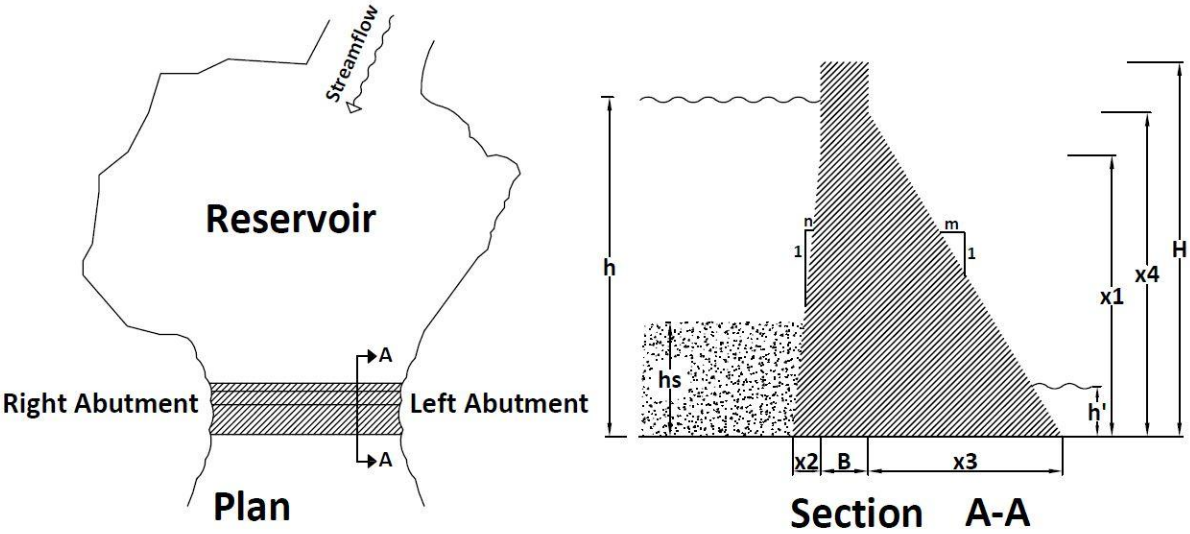

Figure 1. A gravity dam schematic including geometric parameters

Design constraints are generally related to safety consideration according to the physics of the engineering problems and more often according to the design codes. The architectural and usability issues can be also considered as design constraints, but these issues are generally considered as the solution ranges of design variables so as to constrain the generation of possible optimum solutions.

An optimization problem requires objective function(s) or cost function(s), which is widely related to the cost of the design, but safety, usability and architecture problems can be added into the formulation [13].The decision variables directly affect the objective function, which their values at the beginning of solving problems are unknown.Evolutionary algorithms based on the optimization process obtain their values. The calculated values of decision variables must be within a desired range.The optimal solution is acceptable in case it contains all constraints and limitations in design problem. To apply constraints, penalty function is usually employed to consider them into objective function [2,9,14].

Objective Function

The objective function in optimization of the gravity dam's shape is formulated as follows:

$$Minimize \quad A_{dam} = 0.5x_1x_2 + BH + 0.5x_3x_4 \tag{2}$$

where A_{dam} is the area of gravity dam cross-section (m^2) and other parameters are shown in Fig. 1.

Table 1- Forces in gravity dam design

Direction	Category	Equation	Liver arm about toe
Vertical	Self-weight	$W_1 = \frac{1}{2}\gamma_c x_1 x_2$	$x_3 + B + \frac{1}{3}x_2$
		$W_2 = \gamma_c BH$	$x_3 + \frac{B}{2}$
		$W_3 = \frac{1}{2}\gamma_c x_3 x_4$	$\frac{2}{3}x_3$
		$P_{V_1} = \frac{1}{2}\gamma_w x_1 x_2$	$x_3 + B + \frac{2}{3}x_2$
		$P_{V2} = \gamma_w x_2 (h - x_1)$	$x_3 + B + \frac{1}{2}x_2$
		$P_{V'} = \frac{1}{2}\gamma_w (mh')h'$	$\frac{mh'}{3}$
	Uplift pressure force	$U_1 = \frac{1}{3}\gamma_w (x_2 + d_g)(h - h')$	$x_3 + B + \frac{1}{3}(2x_2 - d_g)$
		$U_2 = \frac{1}{3}\gamma_w (x_2 + d_g)(h + 2h')$	$x_3 + B + \frac{1}{2}(x_2 - d_g)$
		$U_3 = \frac{1}{2}\gamma_w (x_3 + B - d_g)(\frac{h - h'}{3})$	$\frac{2}{3}(x_3 + B - d_g)$
		$U_4 = \gamma_w (x_3 + B - d_g)h'$	$\frac{1}{2}(x_3 + B - d_g)$
	Silt pressure force	$P_{Vs} = \frac{1}{2} \times 0.925\gamma_w n h_s^2$	$x_3 + B + x_2 - \frac{nh_s}{3}$
	Seismic force	$EV_1 = \alpha_v W_1$	$x_3 + B + \frac{1}{3}x_2$
		$EV_2 = \alpha_v W_2$	$x_3 + \frac{B}{2}$
		$EV_3 = \alpha_v W_3$	$\frac{2}{3}x_3$
		$EV_4 = \alpha_v P_{V_1}$	$x_3 + B + \frac{2}{3}x_2$
		$EV_5 = \alpha_v P_{V_2}$	$x_3 + B + \frac{1}{2}x_2$
		$EV_6 = \alpha_v P_{V'}$	$\frac{mh'}{3}$
Horizontal	Water force	$P_H = \frac{1}{2}\gamma_w h^2$	$\frac{h}{3}$
		$P_{H^1} = \frac{1}{2}\gamma_w h'^2$	$\frac{h'}{3}$
	Silt pressure force	$P_{H_s} = \frac{1}{2} \times 0.36\gamma_w h_s^{\;2}$	$\frac{h_s}{3}$
	Wave pressure force	$P_W = 2\gamma_w h_w^{\;2}$	$h + \frac{3}{8}h_w$
	Seismic forces	$EH_1 = \alpha_H W_1$	$\frac{x_1}{3}$

		$EH_2 = \alpha_H W_2$	$\frac{H}{2}$
		$EH_3 = \alpha_H W_3$	$\frac{x_4}{3}$
		$P_{eH} = 0.726 p_{eH} h$ $p_{eH} = C_m \alpha_H \gamma_w h$ $M_{eH} = 0.299 C_m \alpha_H \gamma_w h^3$	-
		$P_{eH'} = 0.726 p_{eH'} h'$ $p_{eH'} = C'_m \alpha_H \gamma_w h'$ $M_{eH'} = 0.299 C'_m \alpha_H \gamma_w h'^3$	-

Fixed Parameters

1. Dam height (H)= 38.55 (m)
2. Maximum (upstream) water level (h)= 36.2 (m)
3. Maximum (downstream) water level (h')= 3 (m)
4. Silt deposit level (h_s)= 13 (m)
5. Specific weight density of water (γ_w)= 9.81 (kN/m^3)
6. Specific weight density of concrete (γ_c)= 2.4γ_w
7. Friction coefficient of (μ)= 0.75
8. Permissible shear stress at foundation (q)= 1200 (kPa)
9. Permissible compressive strength of concrete (σ_c)= 3000 (kPa)
10. Crest width (B)= 4.9 (m)
11. Downstream face height (X_4)= 33.35 (m)
12. Fetch (f)= 10 (km)
13. Wind velocity (V_w)= 80 (km/h)
14. Centre of drainage gallery from axis (d_g)= 1 (m)

Decision variables

Five variables are selected as decision variables. Theses variables and their upper and lower bounds are represented in Eq. (3). Two models are considered in present paper. Normally, the upstream and downstream slopes (n and m) are considered between 0–0.2, and 0.6–0.8, respectively [1].These parameters in model I (M1) were chosen as 0.1-0.2 and 0.6-0.9 according to studies of [3] and [6].In model II (M2) the upper face of gravity dam is considered perpendicular (n=0).

$$Decision\ \text{variables}\begin{cases} 0.1 \le n \le 0.2 \\ 0.6 \le m \le 0.9 \\ 0.8h \le x_1 \le 0.95h \\ 0.05 \le a_v \le 0.2 \\ 0.05 \le a_h \le 0.2 \end{cases} \tag{3}$$

Constraints

Stability (overturning and sliding), stress, and geometry constraints are applied in shape optimization in the current study. The stability and stress constraints are shown in Eqs. (4) and (5).The geometry constraints are applied to design problem using upper and lower bounds on decision variables.

$$Constra\,\mathrm{int}\,s\begin{cases}\text{Stability}\begin{cases}Overturning \rightarrow FOS = \dfrac{\sum M_R}{\sum M_O} \geq 1.5\\ Sliding \rightarrow FSS = \dfrac{\mu \sum F_V}{\sum F_H} \geq 1\\ Shear\ Friction\ Factor \rightarrow SFF = \dfrac{\mu \sum F_V + qB_1}{\sum F_H} \geq 3\end{cases}\\ Stress\begin{cases}\mathrm{Pr}\,incipal\begin{cases}Toe \rightarrow \sigma_{pD} \leq \sigma_c\\ Heel \rightarrow \sigma_{pU} \leq \sigma_c\end{cases}\\ Shear\begin{cases}Toe \rightarrow \tau_{xyD} \leq \sigma_c\\ Heel \rightarrow \tau_{xyU} \leq \sigma_c\end{cases}\end{cases}\end{cases} \tag{4}$$

in which

$$\begin{aligned}\sigma_{pD} &= \sigma_{yD}\sec^2\phi_D - (p'_H - p_{eH'})\tan^2\phi_D\\ \sigma_{pU} &= \sigma_{yU}\sec^2\phi_U - (p_H - p_{eH})\tan^2\phi_U\\ \tau_{xyD} &= [\sigma_{yD} - (p'_H - p_{eH'})]\tan\phi_D\\ \tau_{pU} &= [\sigma_{yU} - (p_H + p_{eH})]\tan\phi_U\end{aligned} \tag{5}$$

where $\sigma_{yD} = \dfrac{\sum F_V}{B_1}(1+\dfrac{6e}{B_1})$, $p'_H = \gamma_w h'$, $\sigma_{yU} = \dfrac{\sum F_V}{B_1}(1+\dfrac{6e}{B_1})$, and $p_H = \gamma_w h$.

4. RESULTS AND DISCUSSIONS

Optimization algorithms have different parameters which should be determined at first step of optimization. Some algorithms have more parameters than others such as IWO. A sensitivity analysis for choosing the IWO parameters was conducted and its results are shown in Table 2. In fact, sensitivity analysis is necessary to gain the best value of the objective function.

Table 2- Parameters of IWO

Parameter	Symbol	Value
Number of initial population	N_0	10
Maximum number of plant population	p_{max}	100
Minimum number of seeds	S_{min}	2
Maximum number of seeds	S_{max}	5
Nonlinear modulation index	n	3
Initial value of standard deviation	$\sigma_{initial}$	1
Final value of standard deviation	σ_{final}	0.001
Maximum number of iterations	it_{max}	50

In Fig. 2, the convergence of the objective function for M1 using the IWO isshown. As it obvious, the objective function of shape optimization problem converged in 50 iterations.

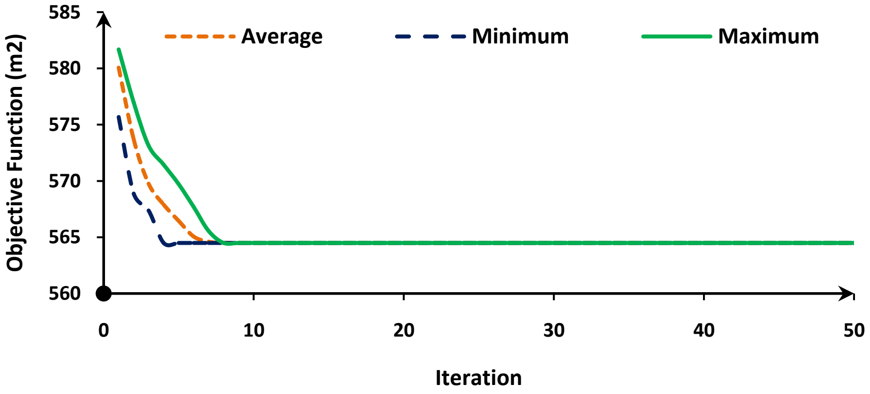

Figure 2. Convergence for IWO

Optimization results of two studied models and algorithms in previous works i.e., Differential Evolution (DE), Charged System Search (CSS), Colliding Bodies Optimization (CBO), and Enhanced Colliding Bodies Optimization (ECBO)are shown in Table 3.In addition, Tilari Dam parameters are shown in aforementioned table. The cross-section area of this dam, which was constructed in India, is 709.493 (m^2). As dams are normally constructed in wide valleys, small changes in their cross-sectional area lead to high-cost saving. M1 has the same upper and lower bounds as studies of [3] and[6]. According to the results, IWO with same conditions of DE, CSS, CBO, and ECBO could find the same objective function of them. In other words, IWO (M1), DE, CSS, CBO, and ECBO were succeeded in reducing total cross sectional area on Tilari Dam more than 20% i.e., decrease from 709.493 (m2) to 564.496. The upstream and downstream slope faces and parameter 'x1' in these optimal models were 0.1, 0.6, and 28.96, respectively.

In M2, gravity dam model had vertical upstream face. This situation can reduce dam's mass and water weight in upstream (resisting moments), and cross-section area. The results showed gravity dam withperpendicular upstream face could lead to design which is more economical. Total cross-sectional area inM2 was calculated 522.56 (m2), which had about 26% reduction in comparison with prototype model (Tilari Dam).In M2 the calculated values of the parameters a_v and a_h were more than other optimal models.It is worth mentioning that these two parameters are chosen based on seismicity of dam's zone. This issue was mentioned in Ref. [3], too. In fact, value of a_h increases in case the more seismicity in the dam's site. In some studies is proposed to choose parameter $a_v$value of 1/2 or 2/3 of a_h. Generally, the magnitude of an earthquake depends on various parameters such as dam's weight and type, dam's material behavior, and earthquake magnitude. Stability, stress,and geometry constraints (Eq. (4)) were applied in the current problem to ensure real-dam-design conditions. These constraints were between desired limits, which are shown in Eqs. (3) and (4).

Table 3- Parameters of prototype and optimal models

Design variable	Tilari Dam	Algorithm					
		IWO (M1)	IWO (M2)	DE [6]	CSS [3]	CBO [3]	ECBO [3]
n	0.1	0.1	0	0.1	0.1	0.1	0.1
m	0.85	0.6	0.6	0.6	0.6	0.6	0.6
x1 (m)	30.95	28.96	-	28.96	28.96	28.96	28.96
a_v	-	0.05	0.2	0.053	0.0589	0.0502	0.05
a_h	-	0.05	0.1491	0.064	0.0558	0.0514	0.05
Cross sectional area (m2)	709.493	564.49583	522.56175	564.496	564.49583	564.49583	564.49583

5. CONCLUSIONS

Optimum shape of infrastructures lead to save cost and effort vastly. Shape optimization of a constructed concrete gravity dam (Tilari Dam, India) is performed using a nature-inspired algorithm, namely Invasive Weed Optimization (IWO). Various loads have effect on dams so the programming model should contains all of them and shows the results in objective function, which is cross sectional area in the current study. Two models are presented and their results are compared with four algorithms in literature. M1 follows the same conditions as previous works and has the same result. This model and those four ones were able to reduce cross sectional area of Tilari Dam about 20 percent. In gravity dams design, like any real problem design of structures, there are different methods and codes,which each proposes certain coefficient and considerations. For instance in evaluating of earthquake impact. These differences don not allow comparing results. In general, in M2, which shows a concrete gravity dam with perpendicular upstream face, results show a more economically design. It is worth mentioning this model only shows one condition (i.e., upstream and downstream have fixed water height of 36.2 and 3 (m), respectively).

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