OPTIMAL DESIGN OF GRAVITY DAM USING DIFFERENTIAL EVOLUTION ALGORITHM

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ABSTRACT

The shape optimization of gravity dam is posed as an optimization problem with goals of minimum value of concrete, stresses and maximum safety against overturning and sliding need to be achieved. Optimally designed structure generally saves large investments especially for a large structure. The size of hydraulic structures is usually huge and thus requires a huge investment. If the optimization techniques are employed in the design stage, the project investment can be effectively minimized. There are many optimization techniques were used to optimize the gravity dam. In the present work, optimization of gravity dam is carried out using the differential evolution technique. Differential evolution is an evolutionary algorithm which process iteratively to locate best solution in the large search space. Searching of optimal solution to a problem is carried out by the process of mutation, cross over and reproduction from the initial developed candidate solutions. After undergoing a number of iterations, it is possible to get the minimum cross sectional area of dam which can satisfy various constraints and thus the reduction in volume of concrete can be achieved. From the results obtained, it is found that differential evolution is one of the efficient techniques for solving such a problem over continuous space. The success of differential evolution in solving a specific problem critically depends on appropriately choosing trial vector generation strategies and their associated control parameter value. The optimum solution obtained is compared with analytical method and it is found that there is 20.44 % of reduction in the requirement of concrete is envisaged.

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1. INTRODUCTION

Optimization techniques plays an effective role in structural design in which the structure can be designed in such a way that the area and volume can be optimized and hence the requirement of the materials can be effectively reduced and thus it minimises the cost of construction. It is an important means to save investment at the same time factor of safety and stability of the structure need to be ensured without compromise. They are several optimization techniques available to optimize a structure. In the present work, differential evolution algorithm has been adopted to optimize the gravity dam. Gravity dam is a hydraulic structure that is constructed using rigid materials. Construction of concrete gravity dam is quite common and optimizing its size can result significant reduction in the construction materials. The external forces acting on the gravity dam are entirely resisted by the weight of the dam itself. The main advantages of gravity dam are, it is simple to design, it can be constructed upto any height, failure of gravity dam gives sufficient warning and moreover it requires least maintenance. Although it has several advantages it has a disadvantage that the requirements of material to construct gravity dam is very high which ultimately lead to high cost of construction. The main objective of this paper is to optimize the shape of the gravity dam using differential evolution such that to minimize the cross-sectional area of the dam and reduce the material requirements so that construction cost is economized.

2. LITERATURE REVIEW

Concrete gravity dam is a well known hydraulic structure constructed across the river valley to impound the water to use for various purposes. The economy and safety of the structure are the key elements in shape design. To achieve the economical design without safety violations, several attempts were made to optimize the shape of concrete gravity dam that ultimately can bring the concrete reduction. Khatibinia and Khosravi [1] attempted shape optimization of gravity dam using gravitational search algorithm and orthogonal cross over. Kshirsagar [2] studied the effect of variation of earth quake intensity on stability of Tilari gravity dam located in Maharastra, India. Nannan li et al. [3], used particle swarm algorithm coupled with ANSYS software to carried out optimum design of gravity dam. Ali et al [4] were developed genetic algorithm based model for optimal design of a gravity dam under seismic excitation with reservoir-dam-foundation interactions. Xinmiao Wu et al. [5] illustrate the application of improved particle swarm algorithm to optimize the gravity dam and sluice gate. Salmasi [6], designed the gravity dam by means of genetic algorithm. The optimal geometry of the dam section is obtained changing the various values of top width, the values of bottom width of upstream batter and bottom width of downstream batter are determined such that the dam section is safe for reservoir empty as well as for reservoir full conditions. The top width corresponding to the minimum cross section of profile will be the optimal top width section. GA optimization tool in excel software is used for the design of dam corresponding to the optimal top width through an iterative process involving a

preliminary layout of the structure followed by stability and stress analysis. This process here is repeated until an acceptable cross section is attained. Kaveh and Mahdavi [7] presented an optimization model for minimizing the weight of arch dam subjected to natural frequencies, stability and geometrical constraints using charged system search and particle swarm optimization. Kaveh and Mahdavi [8] used colliding bodies optimization algorithm for the design of arch dams.The objective of formulated problems includes minimizing the total weight of arch dam subjected to natural frequencies, stability and geometrical limitations. This paper proposes differential evolution model for optimal shaping of Tilari gravity dam located in Maharastra, India. The data available in Kshirsagar [2] is used to optimize the gravity dam and the obtained shape is compared with its existing size.

3. OPTIMIZATION MODEL FOR GRAVITY DAM

The basic dam profile is presented in Fig. 1. It is divided into three portions as upstream triangular section, central rectangular section and downstream side triangular portion. Here, X_1 is the height of grade change point of U/S dam slope, X_2 is the bottom width of u/s slope, X_3 is the bottom width of d/s slope, X_4 is the height of grade change point of d/s dam slope, n is the slope of u/s face, m is the slope of d/s face, B is the top width of the dam, B_1 is the bottom width of the dam and H is the total height of the dam. The objective is to minimize the cross sectional area of the dam which is expressed as sum of the individual area of three portions of the dam.
Objective function

$$\text{Minimize A(x)} = 0.5\ X_1 X_2 + \text{BH} + 0.5 X_3\ X_4 \qquad\qquad (1) \text{ Constraints}$$

Constraint conditions including geometrical constraint, stability constraint and stress constraint.
Geometric constraints

$$0.1\ \leq\ n\ \leq\ 0.2 \qquad\qquad (2)$$
$$0.6\ \leq\ m\ \leq\ 0.9 \qquad\qquad (3)$$
$$0.8H\ \leq\ X_1\ \leq\ 0.95H \qquad\qquad (4)$$
$$0.05\ \leq\ \alpha_v\ \leq\ 0.2 \qquad\qquad (5)$$
$$0.05\ \leq\ \alpha_H\ \leq\ 0.2 \qquad\qquad (6)$$

Here, α_v, α_H are the seismic co-efficient.

Stress constraints
Stress at toe and heel should be less than allowable concrete compressive stress (σ_c) and it is expressed as follows

Principal stress at toe (σ_{pD})

$$F_1(\text{x}) = [\sigma_{pD}] - [\sigma_c] \leq 0 \tag{7}$$

The principal stress is calculated as per equation given below

$$\sigma_{pD} = \sigma_{yD} \sec^2 \phi_D - \left(p'_H - p'_{eH} \right) \tan^2 \phi_D \tag{8}$$
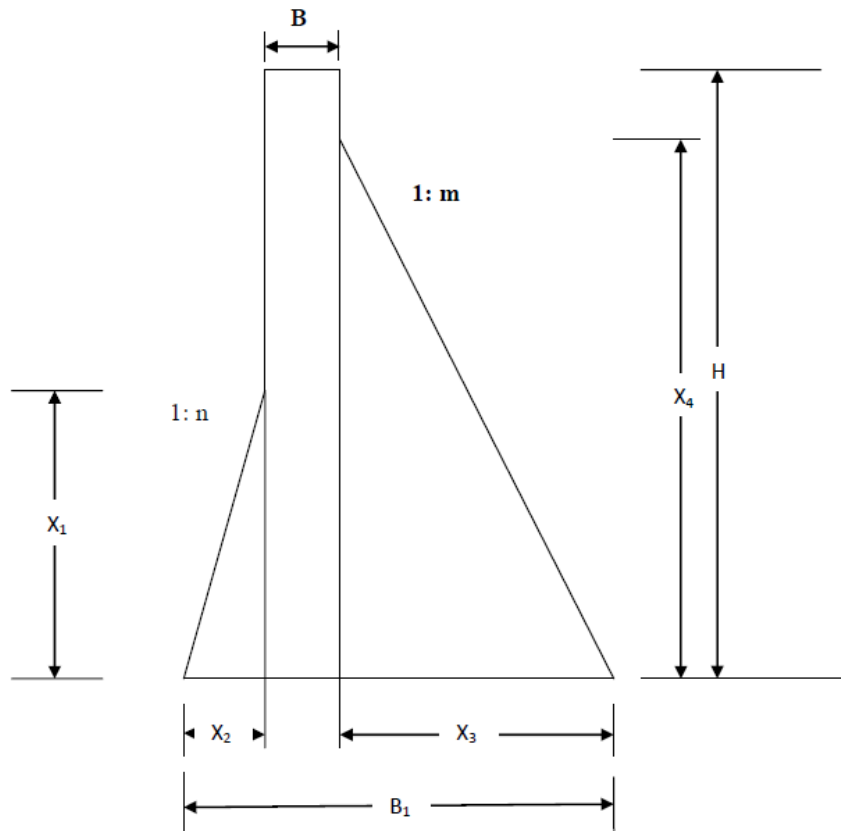

Figure 1. Cross- section of gravity dam

Normal vertical stress at toe,

$$\sigma_{yD} = \frac{\Sigma V}{B_1}[1 + \frac{6e}{B_1}] \tag{9}$$

$$p'_H = \gamma H' \tag{10}$$

Hydrodynamic pressure intensity at the base of the dam for tail water side,

$$p_{eH\prime} = C_m{}' \times \alpha_H \times \gamma \times H' \tag{11}$$

$tan\varphi_D = $ Slope of downstream face of dam
Where, ΣV - Total vertical force acting on dam under seismic condition

$$e = \frac{B_1}{2} - \bar{x} \tag{12}$$

γ - Specific weight of water
H' - Height of tail water

$$C'_m = 0.735 \left[1 - \frac{\varphi_U'}{90} \right] \tag{13}$$

$tan\varphi_U'$ = Slope of downstream face of dam
Principal stress at heel (σ_{pu})

$$F_2(\text{x}) = [\sigma_{PU}] - [\sigma_c] \leq 0 \tag{14}$$
$$\text{Here, } \sigma_{pU} = \sigma_{yU} \, sec^2 \, \varphi_U - (p_H + p_{eH}) tan^2 \, \varphi_U \tag{15}$$
$$\text{Normal vertical stress at heel, } \sigma_{yU} = \frac{\Sigma V}{B_1}\left[1 - \frac{6e}{B_1}\right] \tag{16}$$
$$p_H = \gamma H \tag{17}$$

Hydrodynamic pressure intensity at the base of the dam,

$$p_{eH} = C_m \times \alpha_H \times \gamma \times H \tag{18}$$
$$\tan \varphi_U = X_2/B_1 \tag{19}$$

Where, H- Full reservoir level height

$$C_m = 0.735\left(1 - \frac{\varphi_U}{90} \right) \tag{20}$$

Shear stress at toe (τ_{yxD})

$$F_3(\text{x}) = [\tau_{yxD}] - [\sigma_c] \leq 0 \tag{21}$$

Here,

$$\tau_{yxD} = \left[\sigma_{yD} - \left(p'_H - p'_{eH}\right)\right] \tan \varphi_D \tag{22}$$

Shear stress at heel (τ_{yxu})

$$F_4(\text{x}) = [\tau_{yxU}] - [\sigma_c] \leq 0 \tag{23}$$
$$\text{Here, } \tau_{yxU} = \left[\sigma_{yU} - (p_H + p_{eH})\right] \tan \varphi_U \tag{24}$$

Stability constraints
The safety factor of sliding stability of dam foundation should be less than that required as per IS 6512-1984.

F.O.S against overturning,

$$F_5(X) = \sum M_R / \sum M_0 > 1.5 \qquad (25)$$

Here,

$\sum M_R$ - Net positive moment acting about toe
$\sum M_0$ - Net negative moment acting about toe
Shear friction factor,

$$F_6(X) = (\mu \sum V + q.B_1)/(\mu \sum H) > 3 \qquad (26)$$

Here,

μ   - Co-efficient of friction
q   - Permissible shear stress at foundation
$\sum H$ - Total horizontal force acting on dam under seismic condition

4. DAM OPTIMIZATION PROBLEM

Kshirsagar [2] conducted theoretical study on the effect of variation of earthquake intensity on stability of gravity dam of Tilari project located at village Dhamane, taluka Chandgad, District Kolhapur of Maharashtra State. The same data is utilized to optimize its cross-section. This dam was constructed in 1986 on Tilari river and the location of this dam falls under seismic zone III as per I.S. 1893-1984. Length of the gravity dam structure is 485m and maximum discharge is designed as 1028 m³/s. Total height of the dam and maximum reservoir level are 38.55m and 36.2 m respectively. Top width of dam is 4.9m, Upstream face slope of 0.10:1, Downstream face slope of 0.85:1, 13 m height is reserved for silt deposition. Kshirsagar [2] assumed unknown data and same is retained in the present study. The tail water level is 3 m from foundation level and centre of drainage gallery from axis of the dam is taken as 1m. The following data are used (Krhrisagar, 2014).

   Specific gravity of dam material -2.40
   Coefficient of friction (μ) 0.75
   Design wind velocity - 80km/h
   Permissible compressive strength of concrete - 3000 kPa,
   Permissible shear stress at foundation - 1200 kPa.

5. DIFFERENTIAL EVOLUTION ALGORITHM

Differential Evolution (DE) algorithm is a population based stochastic optimization algorithm proposed by Storn and Price [9]for solving complex continuous design variable optimization problems as a major development over genetic algorithm. The DE algorithm searches best solution through population exploration with the help of mutation, crossover and selection operators. DE discovers the best candidate solutions for a formulated optimization problem iteratively until the stopping criterion is reached. The initial

population can be generated randomly with in design variables bounds. The fitness value of each candidate solution obtained from the initial population is calculated according to the chosen objective function. The weighted differential vector is obtained after selecting two candidate solutions from the population and multiplying its vectororial difference between them by multiplying factor called mutation (0 to 1) and resulting weighted vector is added with the third randomly selected candidate solution which needs to be selected from the population other than earlier selected two candidate solutions. Thus, the new candidate solution so obtained is designated as noisy vector and it is now subjected to crossover process with a target vector selected randomly from the population. The candidate solution obtained at the end of crossover process is called trial vector. The vector having better fitness among trial and target vectors is considered as a potential candidate solution to move the next generation. The number of candidate solutions for next generation is filled up for chosen population size by repeating the above mentioned procedure number of times equal to the population size. The entire process is repeated either predefined number of generations or until specified termination criteria is achieved.
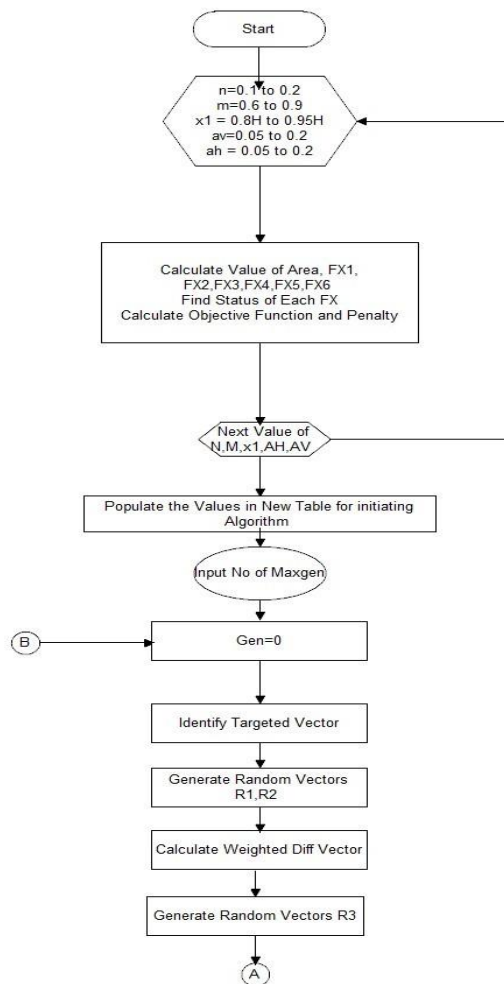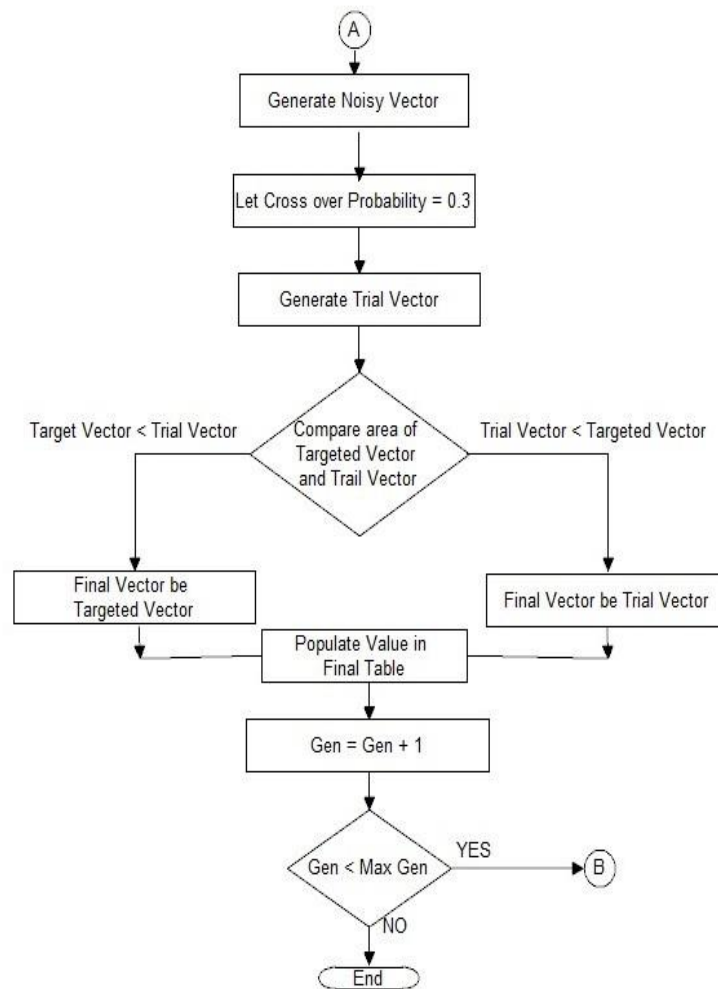
Figure 2. Flow chart on the process of differential evolution

The flow chart presented in Fig. 2 illustrate the various steps in differential optimization process in addition to the various calculation involved in the convention design steps of Gravity Dam.

6. RESULT AND DISCUSSION

The actual size of the dam is presented in Fig. 3. The dam is having total bottom width 36.43 m and the height of upstream side sloping portion (X_1) and downstream side inclined (X_2) are 30.95 and 33.35 m respectively with the value of n and m are 0.1 and 0.85 respectively. This geometry of dam cross section makes area of 709.493 m^2. The developed optimization model for minimizing the cross-section of the gravity dam as single objected subjected to

various constraints listed in this study provides an optimal area of 564.496 m^2 at the expense of 500 generation while size of population is being kept as 20. The geometrical values of the dam that obtained in the optimization model (Fig. 4) n=0.1, m=0.6, and X_1=28.96. It can be seen from the study that there is a reduction in cross section size from 709.493 m^2 to 564.496 m^2. Thus, 20.44 % reduction in volume of concrete can be achieved. Hence, the optimized size obtained using differential evolution could be economical geometry at the same time the obtained size does not violate any constraints. Fig 5 shows the how the optimization progress in each generation. The result presented in graph denotes the minimum objective value obtained in each generation. There is a gradual decrease of function value and reaches minimum at 482th generation Same solution is obtained even after selecting different combination of mutation and cross over. Fig. 6 illustrates the variation of slope parameters n and m over the generation. There is a clear indication that both n and m values are decreased which resulted the reduction in the cross sectional area of the dam. The seismic co-efficient values corresponding to optimal design is obtained as α_H = 0.064 and α_V = 0.053. Both these values are closer to the lower limit of the seismic co-efficients. The factor safety against overturning and sliding and shear friction factor will be higher if the seismic co-efficients are closer to lower limit. Hence, the obtained geometry of the gravity dam satisfies the both economic aspect as well as safety constraints.
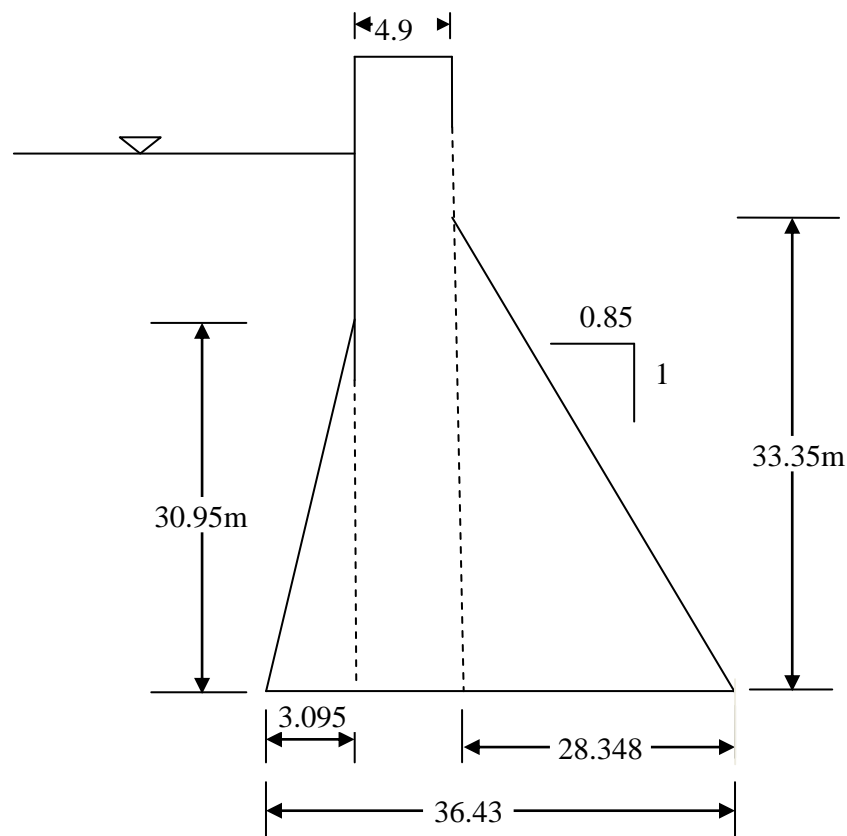

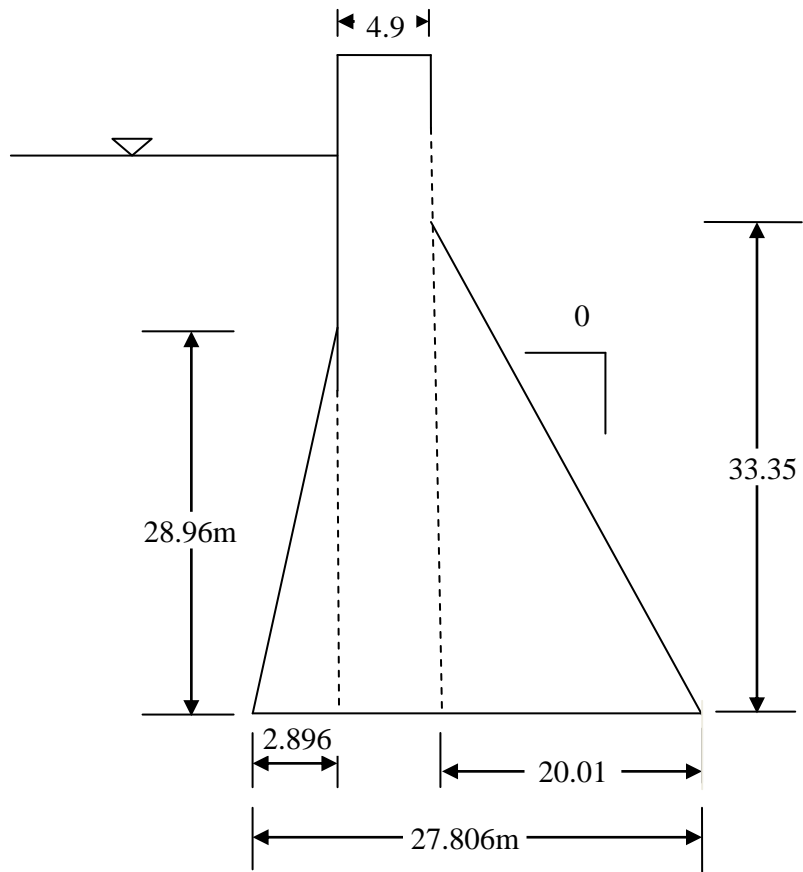Figure 3. Cross Section of dam before optimization

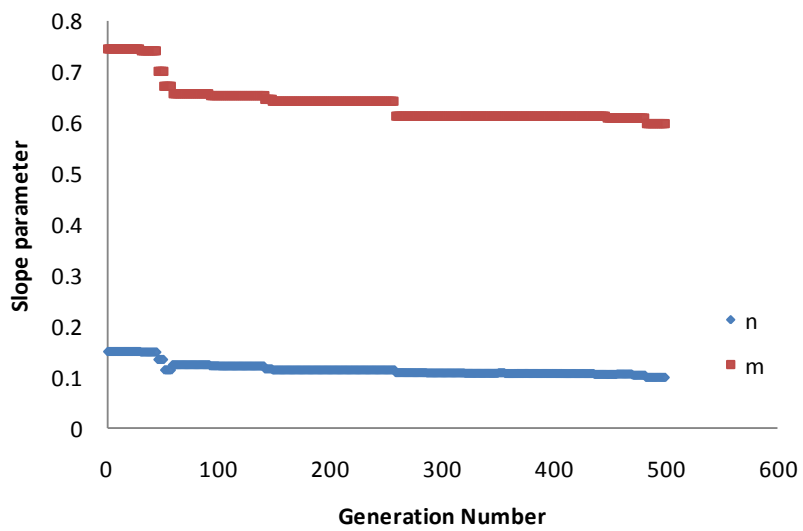Figure 4. Cross Section of dam after optimization

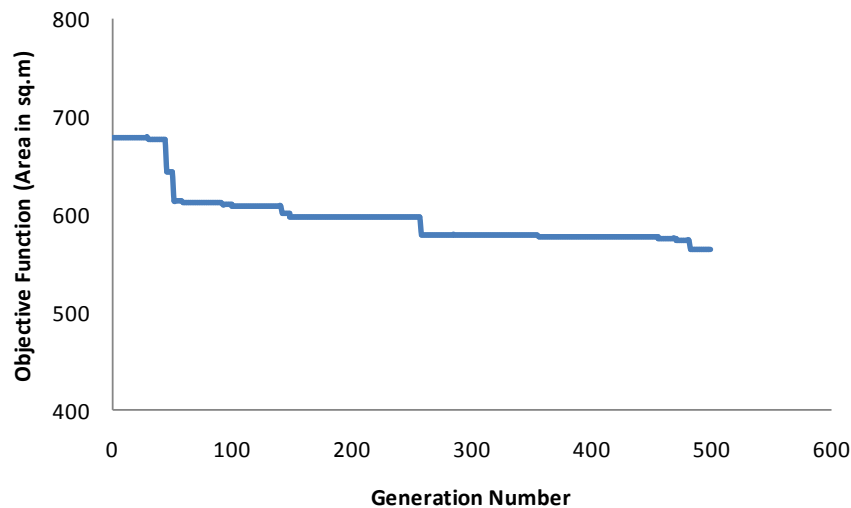Figure 5. Plot showing best solution obtained in each generation

Figure 6. Variation of slope parameters (n and m) over the generation

7. CONCLUSION

This paper presents the optimization model for economical design of gravity dam section. The optimization model is solved by differential evolution. Minimization of cross-sectional area is kept as objective function and constraints used in the model are height of grade change point of U/S dam slope, the slope of U/S face, the slope of D/S face and seismic co-efficient. On comparing with manual calculation based design area, there is significant reduction of size is achieved through optimization. For this dam, volume of reduction in concrete of 20.44% has been achieved while comparing with the existing dimensions. As the material requirements certainly get reduced due to reduction in the cross-sectional geometry of the dam, which ultimately leads to reduction in the construction cost of the dam.

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