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Optimum Design of Stepped Spillways Using Genetic Algorithm

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Abstract: -In the past years considerable research was done on stepped spillways. Investigations were conducted to understand the hydraulics on the stepped face of Roller Compacted Concrete (RCC) dams and overlays for embankment dams. Also a number of embankments were designed with concrete overtopping protection shaped in a stepped fashion. During large overflows on stepped chutes, there is no skin friction between mainstream and steps, and flow resistance is basically form drag. Significant energy losses occur along the stepped chute so that the energy dissipation structure, e.g. the stilling basin, becomes smaller and more economic. In addition, in design conditions when discharge, slope of the normal ground and the height of spillway are available, there are so many combinations of width and the number of steps, which leads to different head losses. In each feasible case the remained head should be dissipate by the energy dissipaters in down stream, which are much cost consuming. So the cost of project which is consist of spillway and it's down stream dissipaters should be minimized. In this study, the Genetic Algorithm has been applied to find the best combination of design variables to minimizing the total cost of both structures. The results show the efficiency of GA in this field of application. Furthermore, GA has a very rapid convergence to feasible and sufficient optimum.

Key-Words: Genetic Algorithm, Stepped Spillways, Optimum Design.

1 Introduction

During the last three decades, a number of embankment dam spillways were designed with concrete overtopping protection shaped in a stepped fashion. [5] In recent years, the design floods of a number of dams were re-evaluated and the revised flows were often larger than those used for the original designs. In many cases, occurrence of the revised design floods would result in dam overtopping because of the insufficient storage and spillway capacity of the existing reservoir. This is unacceptable for embankment structures without overtopping protection systems. The interest in stepped spillways is still growing, because of the cost efficient construction method. Compared with smooth spillway chutes the unit flood discharge is smaller and limited so far up to some 20 m^2/s for which no cavitation damage was observed. Some dams do not allow wide chutes because of particular site condition. In principle a stepped dam chute dissipates more energy than a smooth chute. Therefore, the downstream energy dissipation structure often is smaller.

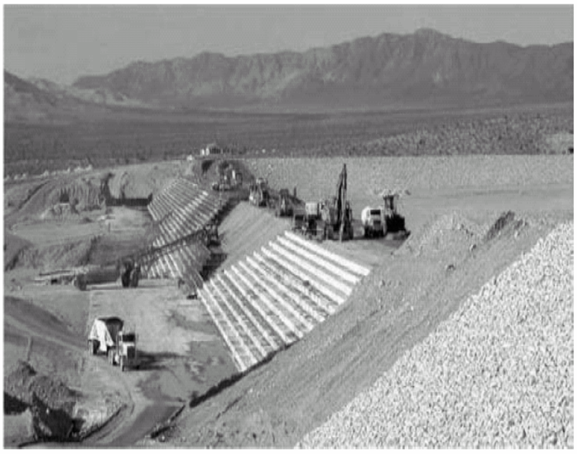

Fig.1 Schematic of stepped spillways

The stepped spillways are very suitable hydraulic structures for the RCC method, only needing at the crest a smooth ogee shape followed by some smaller steps (fitted to the ogee shape) before the spillway changes into the stepped chute that is in fact the downstream face of the RCC dam [8]. Besides these economic and time construction advantages this kind of hydraulic structure permits much higher energy dissipation along the chute than a conventional (smooth) spillway, reducing the dimensions of the downstream stilling basin.

Most modern stepped spillways were designed as prismatic rectangular chutes with flat horizontal steps. In skimming flows on stepped chutes, there is no skin friction between free-stream and stepped invert, but at the step edges which are hydrodynamic singularities. Flow resistance is basically form drag. Alterations of flow recirculation and of fluid exchanges between free-stream and cavity flow may affect drastically the form losses and in turn the rate of energy dissipation [15].

For high flow rates (q=15–20 m^2/s), design engineers prefer a more costly conventional spillway than a stepped chute where there is a lack of elements that assure prevention against possible damages on the structure caused by the dynamic loads induced by the flow.

2 Stepped spillways

At stepped spillways two different flow types may occur, namely nappe flow and skimming flow. Nappe flow involves a sequence of free falling water jets over steps. The energy dissipation process is mainly affected by turbulent interaction of these plunging jets. Skimming flow occurs at higher discharges. It appears as a coherent stream flowing over the steps [11]. Most of the hydraulic energy is dissipated by maintaining the circulation of the vortices. "Figure 2" shows all relevant parameters of a stepped spillway.

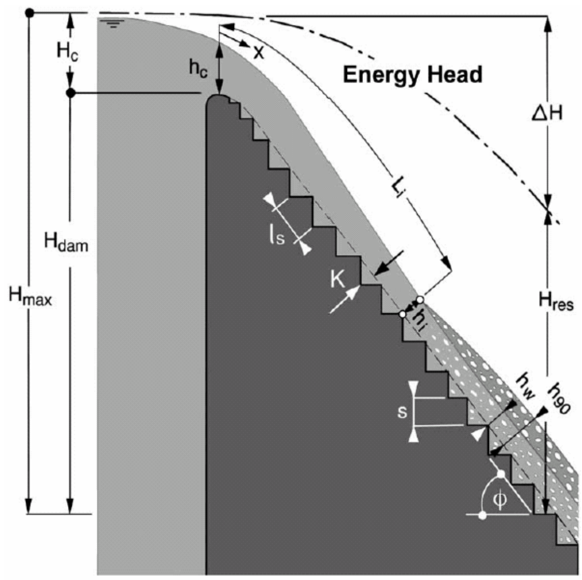

Fig.2 All relevant parameters of a stepped spillway

2.1 Skimming Flow in Stepped Spillway over RCC Dams

Skimming flow regime is usually present in stepped spillways over RCC dams, being the nappe flow limited for small specific discharges. This flow regime is characterized by a coherent stream that skims over the steps. Distinct regions in skimming flow regime can be identified along the stepped chute. "Fig. 3"

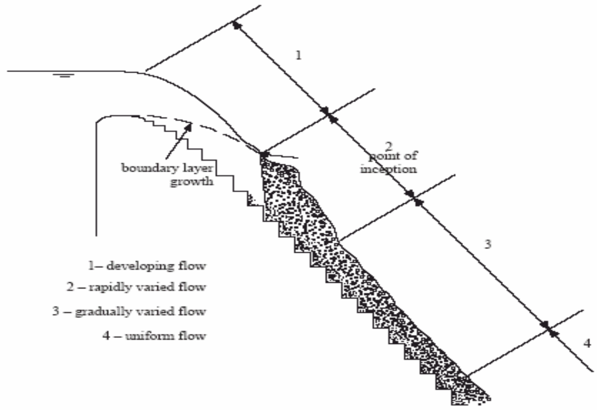

Fig.3 Distinct regions in skimming flow regime

2.2 Energy Dissipation Enhancement

During the 19th century, overflow stepped spillways were selected frequently with nearly one third of the dams built in USA being equipped with a stepped cascade. [4] Most structures had flat horizontal steps (e.g. Gold Creek dam, Titicus dam), but some were equipped with devices to enhance energy dissipation. Some spillways had pooled steps with vertical walls (Sorpe dam, 1932) or rounded edges. [3] (Fig. 2). suggested an alternative of pooled steps and flat steps for maximum energy dissipation [10]. demonstrated greater energy dissipation with inclined upward steps. All these techniques add considerable structural loads to the stepped structure and might not be economical. Enhancement of energy dissipation may be provided by superposition of small and large steps [6].

3. Genetic algorithm

Optimization plays a central role in operations research/management science and engineering design problems. Optimization deals with problems of minimizing or maximizing a function with several variables usually subject to equality and/or inequality constraints. Optimization techniques have had an increasingly great impact on our society. Both the number and variety of their applications continue to grow rapidly, and no slowdown is in sight [1]. However, many engineering design problems are very complex in nature and difficult to solve with conventional optimization techniques.

Many optimization problems from the industrial engineering world, in particular the manufacturing systems, are very complex in nature and quite hard to solve by conventional optimization techniques Since the 1960s there has been an increasing interest in imitating living beings to solve such kinds of hard optimization problems. Simulating the natural evolutionary process of human beings results in stochastic optimization techniques called conventional optimization methods [13]. when applied to difficult real-world problems [1], [2]. There are currently three main avenues of this research: genetic algorithms (GAs), evolutionary programming (EP), and evolution strategies (ESs). Among them, genetic algorithms are perhaps the most widely known type of evolutionary algorithms today.

Recently, genetic algorithms have received considerable attention regarding their potential as a novel optimization technique for complex problems and have been successfully applied in the area of industrial engineering. The well-known applications include scheduling and sequencing, reliability design, vehicle routing and scheduling, group technology, facility layout and location, transportation, and many others.

3.1 General structure of genetic algorithms

The usual form of genetic algorithm was described by Goldberg (1989) [9]. Genetic algorithms are stochastic search techniques based on the mechanism of natural selection and natural genetics. Genetic algorithms, differing from conventional search techniques, start with an initial set of random solution called population. Each individual in the population is called a chromosome, representing a solution to the problem at hand. [2] A chromosome is a string of symbols; it is usually, but not necessarily, a binary bit string. Mutation is a background operator which produces spontaneous random changes in various chromosomes. A simple way to achieve mutation would be to alter one or more genes. In genetic algorithms, mutation serves the crucial role of either replacing genes lost from the population during the selection process so that they can tried in a new context or providing the genes that were not present in the initial population [7].

The mutation rate (denoted by Pm) is defined as the percentage of the total number of genes in the population. The mutation rate controls the rate at which new genes are introduced into the population for trial. If it is too low, many genes that would have been useful are never tried out; but if it is too high, there will be much random perturbation, the offspring will start losing their resemblance to the parents, and the algorithm will lose the ability to learn from the history of the search.

Genetic algorithms differ from conventional optimization and search procedures in several fundamental ways. Goldberg has summarized this as follows:

1. Genetic algorithms work with a coding of solution set, not the solutions themselves.
2. Genetic algorithms search from a population of solution, not a single solution.
3. Genetic algorithms use payoff information (fitness function), not derivatives or other auxiliary knowledge.
4. Genetic algorithms use probabilistic transition rules, not deterministic rules.

3.1.1 Selection

The principle behind genetic algorithms is essentially Darwinian natural selection. Selection provides the driving force in a genetic algorithm, and the selection pressure is critical in it. At one extreme progress will be slower than necessary. Typically, low selection pressure is indicated at the start of the genetic algorithm search in favor of a wide exploration of the search space, while high selection pressure is recommended at the end in order to exploit the most promising regions of the search space. The selection directs a genetic algorithm search toward promising regions in the search space.

3.1.2 Crossover

This kind of crossover operators is analogous to that of the binary implementation [14]. The basic one is one-cut-point crossover. Let two parents be X=[X1,X2,…,Xn] and Y=[Y1,Y2,…,Yn]. If they are crossed after the Kth position, the resulting offspring are:

$$X' = [X1, X2,\ldots, Xk, Yk+1, Yk+2,\ldots, Yn] \quad (1)$$
$$Y' = [Y1, Y2,\ldots, Yk, Xk+1, Xk+2,\ldots, Xn] \quad (2)$$

The further generations of one-point crossover are two-cut-point, multi-cut-point, and uniform crossover.

3.1.3 Mutation

Mutation operators are quite different from the traditional one. A gene, being a real number, is mutated in a specific range. The basic one is uniform mutation. This one simply replaces a gene (real number) with a randomly selected real number within a specified range. Let a chromosome to be muted be X = [X1,X 2,…, Xn]. We first select a random number $k \in [1,n]$ and then produce an offspring X' = [X1,…, X'k,…, Xn], where X'k is a random value (uniform probability distribution) from the rang $[X_k^L, X_k^U]$.

The values of X_k^L and X_k^U are typically the lower and upper bounds on the variable Xk, which can be determined by domain constraint. This range also can be calculated dynamically from the set of constraints (inequalities) 'Syswerda, G'.

The gene X'k can be replaced by either X_k^L or X_k^U, each with equal probability. This kind variation is called boundary mutation [13]. Instead of the lower and upper bounds, this range also can be

formed as [Xk-1, Xk+1]. This kind variation is called plain mutation.' Michalewicz, Z et al'

4 Application of GA

In this study, a stepped spillway with design discharge of 80 m^3/s is considered. The height of this spillway is 5.5m with 22.5° of mean slope. Finding a combination of width and number of steps is considered as the main aim of this study, so that the total construction cost of spillway and downstream energy dissipaters will be minimized.

The construction cost of spillway is assumed equal to excavation cost. Obviously, in a fixed width, excavation cost will decrease as the number of steps increase. The cost of excavation for each $1m^3$ is considered 1 unit. In each combination of number of steps and width of spillway, specified amount of energy will dissipate and down stream structures should dissipate residual amount of energy. The cost of structures for energy dissipation is considered 2 units for 1m of head.

On the other hand in various combinations of number of steps and width of spillway, one of the following conditions may occur:

1- Nappe flow regime
2- Skim flow regime
3- Transition flow regime
4- Infeasible condition

Obviously, in this case nappe flow regime will never occur because of steep slope of topography. In each combination of width and number of steps, corresponding energy dissipation is calculated and summery of constructing of spillway and down stream energy dissipaters are calculated as an objective function.

Variation domain of number of steps is considered between 1 and 500. On the other hand, according to the limitation of q ($2m^2/s \prec q \prec 10m^2/s$), spillways` width will vary between 8m and 40m. In some of these combination, which will be in infeasible region some penalties have been considered. Variation of total cost against the number of steps in a constant width (28.3m) is shown in "Figure 4".

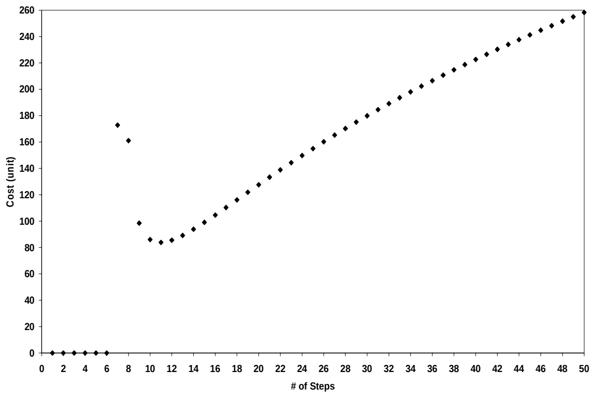

Fig.4 Variation of total cost against the number of steps

In this study, a GA algorithm in 1000 generation with 5 chromosome and 2 genes in each chromosome has been used. Employing the GA in the considered case, variation of spillways`, number of steps, width and percentage of energy dissipation in each iteration are shown in "Figures 5 to 7". Also normalized value of objective function in each iteration is illustrated in "Figure 8".

As it can be seen, in this case, GA converges to the optimum solution very fast. In the case of optimum, the numbers of steps, width of spillway and energy dissipation are 9, 28.3 and 81.15 respectively. The construction cost of project which was objective function is equal to 74.55.

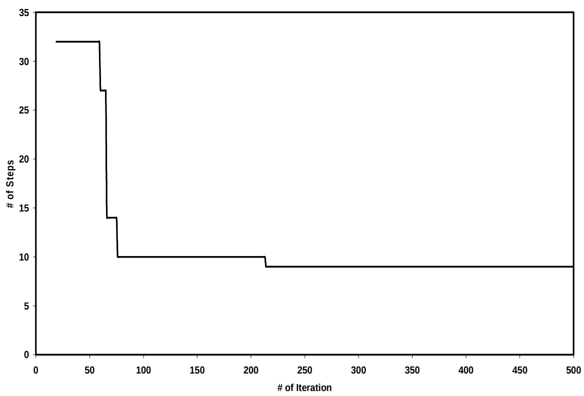

Fig.5 No. of steps meets in each generation

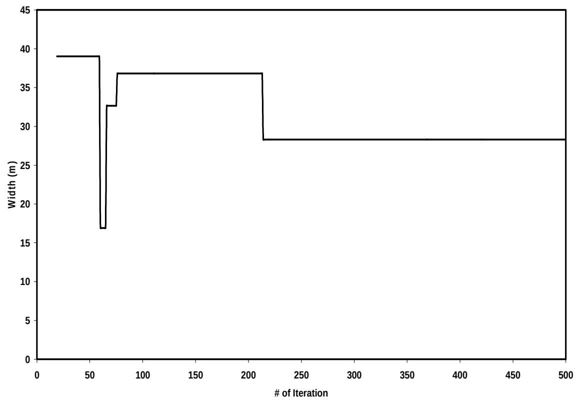

Fig.6 Width of spillway meets in each generation

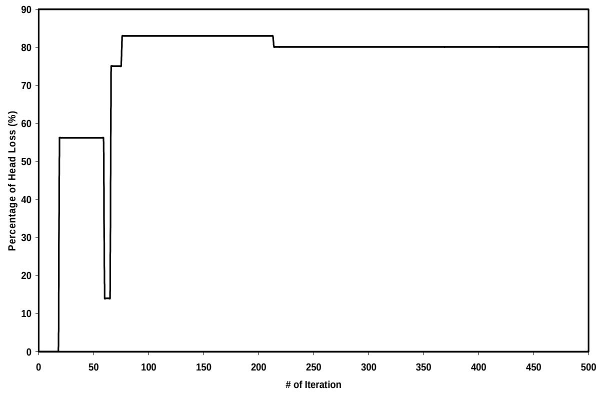

Fig.7 Percentage of head loss meets in each generation

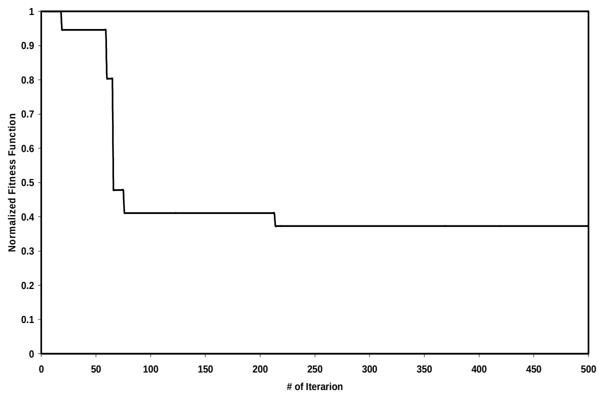

Fig.8 Normalized fitness function meets in each generation

5 Conclusions

In this study, the capability of GA in optimum design of stepped spillways and its down stream energy dissipaters was used as a tool for optimum design and applicability of model has been tested for a real design case.

Obtained results show that GA can solve this kind of problems with high accuracy very fast. Where, the other methods have some difficulties with discrete variables which exist in these types of design problems. Also the complexity of simulation (such as hydraulic and head loss process of considered case) as a part of optimization is the other difficulty in solving problems with ordinary methods which the proposed algorithm can overcome it properly.

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