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A hybrid approach based on an improved gravitational search algorithm and orthogonal crossover for optimal shape design of concrete gravity dams

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ABSTRACT

A hybrid approach based on an improved gravitational search algorithm (IGSA) and orthogonal crossover (OC) is proposed to efficiently find the optimal shape of concrete gravity dams. The proposed hybrid approach is called IGSA-OC. The hybrid of IGSA and the OC operator can improve the global exploration ability of the IGSA method, and increase its convergence rate. To find the optimal shape of concrete gravity dams, the interaction effects of dam–water–foundation rock subjected to earthquake loading are considered in this study. The computational cost of the optimal shape of concrete gravity dams subjected earthquake loads is usually high. Due to this problem, the weighted least squares support vector machine (WLS-SVM) regression as an efficient metamodel is utilized to considerably predict dynamic responses of gravity dams by spending low computational cost. To testify the robustness and efficiency of the proposed IGSA-OC, first, four well-known benchmark functions in literatures are optimized using the proposed IGSA-OC, and provides comparisons with the standard gravitational search algorithm (GSA) and the other modified GSA methods. Then, the optimal shape of concrete gravity dams is found using IGSA-OC. The solutions obtained by the IGSA-OC are compared with those of the standard GSA, IGSA and particle swarm optimization (PSO). The numerical results demonstrate that the proposed IGSA-OC significantly outperforms the standard GSA, IGSA and PSO.

1. Introduction

Concrete gravity dams have been well-known as an important engineering structure that the economy and safety of these structures depend on an appropriate shape design. Hence, finding a proper shape design of concrete gravity dams is considered as an important problem in design approach of dams. To achieve this purpose, several alternative schemes with various patterns should be selected and modified to obtain a number of feasible shapes. Therefore, the proper shape of dam considering the economy and safety of design, structural considerations, etc. is selected as the final shape [1]. In order to reliably achieve an optimal shape for dams instead of this try and error procedure, optimization techniques have been effectively utilized.

Several interesting researches on the design optimization of arch dams under static and dynamic loads have been carried out and reported in [2–9]. Although the conventional mathematical models have been utilized for analysis approximation and optimization task in these studies, the effects of arch dam–water–foundation rock interaction have been neglected. In recent years, the optimal shape design of arch dams including dam–water–foundation rock interaction has been developed by few researchers [1,10–14]. Recently, a study has also been introduced by Salajegheh et al. [15] so that the shape optimal design of concrete gravity dams including hydrodynamic effects is achieved using hybrid of gravitational search algorithm (GSA) and particle swarm optimization (PSO). A study as updated and revised version of the conference paper [15] has also been introduced by Slajegheh and Khosravi [16] so that shape optimal design of concrete gravity dams including hydrodynamic effects is achieved using the hybrid of GSA and PSO.

Recently, gravitational search algorithm (GSA) as a new meta-heuristic optimization method has been proposed by Rashedi et al. [17]. In GSA, the agents as a collection of masses interact with each other based on the Newtonian gravity and the laws of motion. To find the best solution in the search space, the agents share information using the gravitational force. The high performance and the global search ability of GSA in solving various nonlinear functions have been demonstrated by Rashedi et al. [17]. The GSA method suffers from slow searching speed in the last iterations. Due to this

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fact, the convergence rate of GSA decreases. To eliminate this drawback of GSA, an improved gravitational search algorithm (IGSA) was introduced by Li and Zhou [18]. The IGSA method is based on the idea of memory and social information of PSO. Although IGSA has the characteristics of high accuracy and stability, it has the shortcomings of premature convergence, low searching accuracy and iterative inefficiency. When an agent in the population finds its current optimal position, the other agents will gather close to it rapidly. Thus, the IGSA algorithm traps into local optimum.

This study proposes a hybrid approach based on IGSA and an orthogonal crossover (OC) operator [19], which is called IGSA-OC. This hybrid approach is introduced to eliminate drawbacks of IGSA, and improve the performance of IGSA. The optimal shape of gravity dams with consideration of dam–water–foundation rock effects is investigated using the proposed IGSA-OC. To find the optimal shape of concrete gravity dams, the interaction effects of dam–water–foundation rock subjected to earthquake loading are considered.

In order to reduce the computational cost of optimization process subjected to earthquake loading, many methods of forecasting equipped with the techniques have been utilized as metamodel. Support vector machine (SVM) proposed by Vapnik [20] as an efficient metamodel has been used for modeling the high non-linear system based on small sample. This metamodel has been applied in many classification and regression problems successfully. SVM based on the structural risk minimization (SRM) rules is superior to artificial neural networks (ANNs), which have been developed the traditional empirical risk minimization (ERM) inductive principle [21]. Also, the problems as over learning, dimension disaster and local minimum are eliminated in SVM [21]. Weighted least squares support vector machine (WLS-SVM) regression was introduced by Suykens et al. [22] to decrease the training computational effort of SVM in the large-scale problem. According to the practice, WLS-SVM is more robust and precise than that of SVM and least squares version of SVM (LSSVM) [21,22]. In this study, the WLS-SVM regression is utilized to predict the time history response of gravity dams. WLS-SVM can significantly reduce the computing effort of optimization procedure.

To demonstrate the high performance and the global search ability of the proposed IGSA-CO, first, four well-known benchmark functions in literatures are optimized using IGSA-CO. The results of IGSA-CO are compared with the standard GSA and the other modified GSA methods. The numerical results demonstrate the efficiency and robustness of the proposed IGSA-CO. Then, the optimal shape of concrete gravity dams is found using IGSA-CO. Furthermore, the optimal solutions obtained by the proposed IGSA-OC are compared with those of the standard GSA, IGSA and PSO. The optimal results revealed that the proposed IGSA-OC can create a robust tool for effectively optimizing concrete gravity dams.

2. Optimization problem of concrete gravity dam

The optimization problem of concrete gravity dam subjected to earthquake loading is expressed as follows:

$$\begin{aligned} &\text{Minimize} \quad f(\boldsymbol{X}) \\ &\text{Subject to} \quad g_i(\boldsymbol{X}, t) \le 0 \qquad i = 1, 2, \ldots, m, \quad t = 0, \ldots, T \\ &\boldsymbol{X}^L \le \boldsymbol{X} \le \boldsymbol{X}^U \end{aligned} \tag{1}$$

where f, g_i and t are the objective function, ith constraint from m inequality constraints and the time, respectively. $\boldsymbol{X}^L$ and $\boldsymbol{X}^U$ are the lower bound and the upper bound of the design variables, $\boldsymbol{X}$, respectively. T is the earthquake duration.

Constraint handling approaches in conjunction with meta-heuristic optimization methods have been proposed to deal with constrained search spaces. A comprehensive overview of the most popular constraint handling approaches was presented in the literature review by Coello [23]. In the present study, the external penalty function method as one of the most popular forms of the penalty function in the structural optimization is utilized as follows [24–26]:

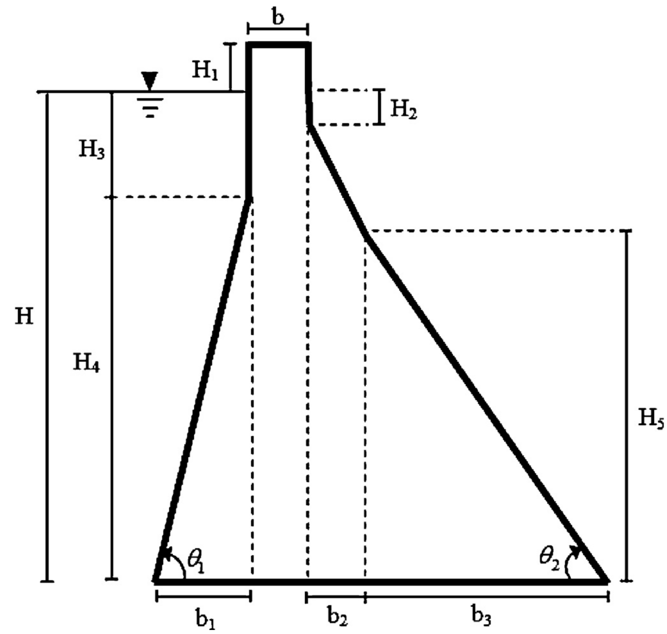

Fig. 1. Geometrical model of concrete gravity dam.

$$\tilde{f}(\boldsymbol{X}) = f(\boldsymbol{X})(1 + R_p P_f) \tag{2}$$

where $\tilde{f}(\boldsymbol{X})$, P_f and R_p are the modified function (fitness function), the penalty function and an penalty factor, respectively. The penalty function is expressed as the sum of all active constraints violations as [23]:

$$P_f = \sum_i \max\,(g_i(\boldsymbol{X}, t), 0.0)^2 \tag{3}$$

2.1. Design variables

In order to assign the geometrical model of concrete gravity dams, the shape of concrete gravity dams can be defined using seven parameters. As depicted the model of concrete gravity dam in Fig. 1, a concrete gravity dam can be modeled by a vector $\boldsymbol{X}$ that has seven components including the shape parameters of the concrete gravity dam as:

$$\boldsymbol{X} = \{b\, b_1\, b_2\, b_3\, H_2\, H_4\, H_5\} \tag{4}$$

where $\boldsymbol{X}$ is design variable vector.b and H_1 are two parameters required to defined crest and free board of gravity dam, respectively. H_3 depends on H_4 and reservoir water level (H). The upstream slope, θ_1, is defined by the b_1 and H_4 design variables. Also, the downstream slope, θ_1, is specified by the b_3 and H_5 design variables.

2.2. Objective function and design constraints

In the optimization problem of concrete gravity dams, the concrete weight of gravity dam body is considered as objective function, $f(\boldsymbol{X})$, that should be minimized. The weight of concrete gravity dam can be determined as follows:

$$f(\boldsymbol{X}) = W = \rho_c g V \tag{5}$$