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Optimal design of arch dams subjected to earthquake loading by a combination of simultaneous perturbation stochastic approximation and particle swarm algorithms

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ABSTRACT

An efficient optimization procedure is introduced to find the optimal shapes of arch dams considering fluid–structure interaction subject to earthquake loading. The optimization is performed by a combination of simultaneous perturbation stochastic approximation (SPSA) and particle swarm optimization (PSO) algorithms. This serial integration of the two single methods is termed as SPSA–PSO. The operation of SPSA–PSO includes three phases. In the first phase, a preliminary optimization is accomplished using the SPSA. In the second phase, an optimal initial swarm is produced using the first phase results. In the last phase, the PSO is employed to find the optimum design using the optimal initial swarm. The numerical results demonstrate the high performance of the proposed strategy for optimal design of arch dams. The solutions obtained by the SPSA–PSO are compared with those of SPSA and PSO. It is revealed that the SPSA–PSO converges to a superior solution compared to the SPSA and PSO having a lower computation cost.

1. Introduction

It is obvious that an appropriate shape design has a great influence on the economy and safety of an arch dam. In order to find an optimal shape for arch dams, optimization techniques can be effectively utilized. In the last years, some progress has been made in optimum design of arch dams. Most of them did not consider the fluid–structure interaction in their models and also used the conventional optimization methods [1–3]. Neglecting the water effects on arch dam design can lead to an unsafe design. Furthermore, conventional optimization methods are usually gradient-based algorithms.

By employing these methods for optimization of a large scale-structure such as an arch dam, much computational effort can be imposed to the process whereas trapping into local optima may be also increased [4].

It was found that some methods such as simultaneous perturbation stochastic approximation (SPSA) are computationally efficient for gradient approximations [5,6]. This method can approximate the gradient of a multi-variable function while it needs only two measurements of the function. This characteristic can significantly reduce the computational cost of the optimization process, especially in problems with a great number of variables to be optimized. Moreover, meta-heuristic algorithms, such as genetic algorithm (GA) and particle swarm optimization (PSO) due to their stochastic nature are robust tools to find the global solution in comparison with the gradient-based methods. Many successful applications of GA and PSO for engineering optimization have been reported in the literature [7–11]. However, due to a great number of function evaluations required for evolutionary algorithms, a modification on their standard algorithms seems to be necessary [12–17]. In order to overcome the computational cost involved, some soft computing techniques such as using a neural network concept have been also proposed [18,19].

In this study, a hybrid version of PSO with SPSA is introduced. An efficient approach is presented to find the optimal shapes of arch dams subjected to earthquake load utilizing a combination of SPSA and PSO methods named here as SPSA–PSO. The load cases involved here are gravity load, hydrostatic and hydrodynamic pressures and earthquake load, which is treated with the time history analysis of arch dam model. The concrete volume of the arch dam body is considered as the objective function. The design variables are the shape parameters of the arch dam. The design constraints are defined to prevent the failure of each element of arch dam under a specified safety factor using a given failure surface for concrete material.

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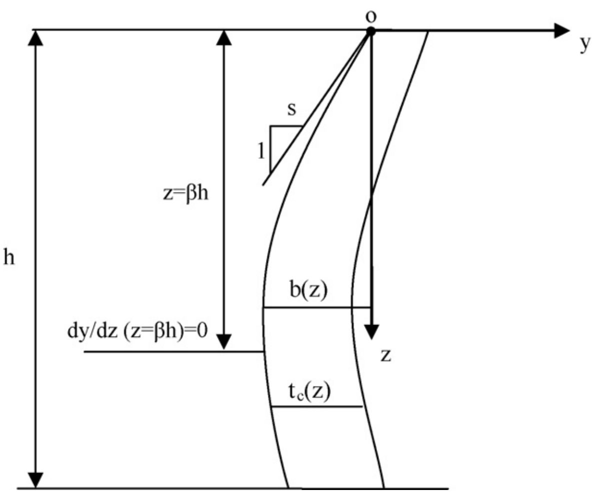

Fig. 1. Central vertical section of arch dam.

The paper is organized as follows. A brief description of the selected geometric model for arch dams is provided in Section 2. The simulation of arch dam-water system using the finite element method is discussed in Section 3. The dam optimization problem is defined in Section 4 and the proposed SPSA–PSO is presented in detail in Section 5. In order to assess the computational efficiency of the proposed optimization procedure a real test example is considered in Section 6 and finally, conclusions are presented in Section 7.

2. Geometrical model of arch dam

In order to define the geometrical model of arch dams, the shape of central vertical section is determined at first, and then by specifying the dam upstream and downstream radii of curvature at different levels, the shape of the arch dam is defined using two parabolic surfaces.

2.1. Shape of central vertical section

As shown in Fig. 1, for the curve of upstream face of central vertical section a polynomial of 2nd order is considered as:

$$y(z) = b(z) = -sz + \frac{sz^2}{2\beta h} \tag{1}$$

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.

By dividing the height of the dam into n segments containing $n+1$ levels, the thickness of the central vertical section can be expressed as:

$$t_c(z) = \sum_{i=1}^{n+1} L_i(z) t_{ci} \tag{2}$$

where t_{ci} is the thickness of the central vertical section at ith level. Also, in the above relation $L_i(z)$ is Lagrange interpolation function associated with ith level given by:

$$L_i(z) = \frac{\prod_{k=1}^{n+1} z - z_k}{\prod_{k=1}^{n+1} z_i - z_k} \quad k \neq i \tag{3}$$

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

2.2. Radii of curvature at different levels

For radii of curvature correspond to upstream and downstream boundaries, denoted by r_u and r_d, two functions of nth order with respect to z can be utilized as:

$$r_u(z) = \sum_{i=1}^{n+1} L_i(z) r_{ui} \tag{4}$$

$$r_d(z) = \sum_{i=1}^{n+1} L_i(z) r_{di} \tag{5}$$

where r_{ui} and r_{di} are the values of r_u and r_d at ith level, respectively.

In this stage, the shape of a parabolic arch dam can be determined by the following two parabolic surfaces [1,2]:

$$y_u(x, z) = \frac{1}{2r_u(z)} x^2 + b(z) \tag{6}$$

$$y_d(x, z) = \frac{1}{2r_d(z)} x^2 + b(z) + t_c(z) \tag{7}$$

where y_u and y_d are the upstream and downstream surfaces of the dam, respectively.

3. Finite element model of arch dam-water system

In fluid–structure problems the discretized dynamic equations of structure and fluid need to be considered simultaneously. The governing equation in the fluid domain is the acoustic wave equation, shown in Eq. (8) [20–23].

$$\frac{1}{c_w^2} \frac{\partial^2 p}{\partial t^2} - \nabla^2 p = 0 \tag{8}$$

where c_w is the speed of pressure wave, $p = p(x, y, z, t)$ is acoustic pressure and t is time. Furthermore, ∇^2 is three-dimensional Laplace operator.

Some boundary conditions are imposed on Eq. (8), from which the following boundary condition must be considered on the interface:

$$\boldsymbol{n}^T \nabla p = -\rho_w \boldsymbol{n}^T \frac{\partial^2 \boldsymbol{u}}{\partial t^2} \tag{9}$$

where $\boldsymbol{n}$ is a unit normal vector to the interface, $\boldsymbol{u}$ is the displacement vector of the structure at the interface and ρ_w is the mass density of water. At the fluid boundaries, a condition is required to account for the dissipation of energy due to damping as:

$$\frac{\partial p}{\partial \boldsymbol{n}} = -\frac{1-\alpha}{c_w(1+\alpha)} \frac{\partial p}{\partial t} \tag{10}$$

where $0 \leq \alpha \leq 1$ denotes wave reflection coefficient.

At the free surface, when the surface wave is neglected, boundary condition is easily defined as:

$$p = 0 \tag{11}$$

Eqs. (8)–(11) can be discretized to get the matrix form of the wave equation as:

$$\boldsymbol{M}_f \ddot{\boldsymbol{p}}_e + \boldsymbol{C}_f \dot{\boldsymbol{p}}_e + \boldsymbol{K}_f \boldsymbol{p}_e + \rho_w \boldsymbol{Q}^T (\ddot{\boldsymbol{u}}_e + \ddot{\boldsymbol{u}}_g) = 0 \tag{12}$$

where $\boldsymbol{M}_f$, $\boldsymbol{C}_f$ and $\boldsymbol{K}_f$ are fluid mass, damping and stiffness matrices, respectively and $\boldsymbol{p}_e$, $\ddot{\boldsymbol{u}}_e$ and $\ddot{\boldsymbol{u}}_g$ are nodal pressure, nodal acceleration and ground acceleration vectors, respectively. Also, $\rho_w \boldsymbol{Q}^T$ in the above relation is often referred to as coupling matrix.

The discretized structural dynamic equation subject to ground motion can be formulated using the finite elements as:

$$\boldsymbol{M}_s \ddot{\boldsymbol{u}}_e + \boldsymbol{C}_s \dot{\boldsymbol{u}}_e + \boldsymbol{K}_s \boldsymbol{u}_e = -\boldsymbol{M}_s \ddot{\boldsymbol{u}}_g + \boldsymbol{Q} \boldsymbol{p}_e \tag{13}$$