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Shape Optimization of Concrete Gravity Dams Using Performance Criteria Rules

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Abstract

Shape optimization of concrete dams is a constraint nonlinear optimization problem. Since the failure mode of the monolith in concrete gravity dams is in tension, one of the main constraints is the tension stress limit under seismic loads. There is a new approach to check if the dam performance is safe andit is a more realistic method to observe the behavior of dams under earthquake load. According to this approach, the cumulative duration of the dam which passes the specific tension value during earthquake, should be below the allowable duration. This allowable duration is a function of the specific tension value.In this research, an innovative objective function was used to optimize the shape of concrete gravity dams by applying the new approach. This new objective function sets as one of the objective functions in multi objective method.A comparison between using this approach with multi objective and constrained optimization method in the rate of convergence reveals the advantage of employing the new objective function to find the optimal shape of concrete gravity dams under seismic loads.

Keywords: Shape optimization, concrete gravity dams, performance criteria, dynamics analysis.

Introduction

Concrete dams are designed in two stages. In the first stage, stability and stress analysis are performed to check if the dam shape is appropriate. In the next stage, stress analysis is carried out to check if dam performance is appropriate[1]. In this research assumed that the first stage is used to obtain the initial shape of the monolith and the second stage is used for the optimization. Optimization of concrete gravity dams can be economical to reduce a percentage of the enormous volume of concrete that is utilized in the body of these dams. The main concerns in optimization of an engineering problem are how to write it as a mathematical formula and which method has a satisfactory convergence for this problem. The combination of these parameters leads to several methods with different rates convergence and precision in optimization for practical problems. There are a few researches on shape optimization of concrete gravity dams especially under seismic loads. Since gravity dams are analyzed in two dimensions, thus reducing the area of monolith is one of the goals in order to reduce the cost of dam construction[2,3,4].

Researchers used allowable tension in concrete as a constraint in shape optimization problem of concrete gravity dams[4,5,6]. In this research a new approach for checking performance of dam under tension stresses, was used as a constraint and as a novel objective function to optimize the volume of dam as well.

Performance and Damage Criteria for Concrete Gravity Dams

The criteria for seismic analysis of concrete hydraulic structure, is that stresses during linear time history analysis are compared with the allowable stresses. For example in compressive stresses, the acceptance criterion is that they should be less than 1.5 times compressive strength of concrete[1]. It means, in seismic analysis of concrete dam, maximum principle compressive stresses should be less than a constant value.

One approach in seismic analysis of concrete dams is to allow the tension stress in dam during the earthquake to pass the allowable tension for five times. This criterion does not exert any magnitudes of stresses limitation on exceeding the tensile strength of the concrete[7].

The other methodology and procedure for estimation of probable level of damage which was used in this research are suggested by Ghanaat[7]. The mentioned methodology based on demand capacity ratio (DCR) and cumulative inelastic duration.

The DCR for concrete gravity dams is introduced as the ratio of the specific principal stress to tensile strength of the concrete. The maximum value of permitted DCR for linear analysis of dams is 2.

The above statement corresponds to a stress demand twice the static tensile strength of the concrete. As represented in figure-1, the stress demand associated with DCR of 2 is similar as the so-called apparent dynamic tensile strength of the concrete[8,9].

The cumulative inelastic duration of stress excursions is introduced as the total duration of stress excursions above a stress level associated with a DCR≥1. For gravity dams, a lower cumulative duration of *0.3 sec.* is considered and it is for a DCR of *1*. The cumulative duration for DCR of *2* is assumed to be zero (figure-2.)

According to this methodology, three performance levels are considered. At the first level, the dam response is evaluated to be within the linear elastic range of behavior with little or no possibility of damage if $DCR \leq 1$. It is called no damage level.

At the second or *Acceptable level*, DCR>1 is estimated; however the cumulative duration of stress excursions for whole the DCRs between 1 and 2 falls below the performance curve. The dam will exhibit nonlinear response in the form of cracking. The level of nonlinear response or cracking is assumed to be adequate with no possibility of failure if DCR<2.

The third and last level is severe damage level. The damage is assumed severe when DCR>2, or cumulative overstress duration for all DCRs in the range of 1–2 falls above the performance curves. In these cases, a nonlinear time-history analysis is required, especially if the fundamental period of the dam falls in ascending region of the response spectra[10].

Linear analysis for the gravity dam is sufficient, if the diagram of the cumulative duration of the dam is below the performance curve (figure-2)[11].

In this study, linear analysis was used to improve the shape of concrete gravity dam monolith using performance based on second level criteria.

Proposed Approach

Generally, a multi optimization matter can be represented as the following mathematical form:

Optimize $$F(\mathbf{x}) = \{f_1(\mathbf{x}), f_2(\mathbf{x}), ..., f_n(\mathbf{x})\} \quad (1)$$

Where $g_i(\mathbf{x}) \leq 0$ $i = 1, 2, ..., n$

That F is the set of objective functions and g_i's are the constraints of the problem [12]. An optimization problem can be considered as constraints satisfaction and multi objective optimization problem.In optimization process, the objective function can be cost of the structure in the form of minimizing the weight or volume of the structure. The constraints can be geometry, stability or stress constraints.

Concrete gravity dams are constantly analyzed in 2 dimensions thus the area of the monolith has a direct relation with the weight of the dam and its cost of construction. It means it is not irrational to consider it as objective function.

On the other hand, in constrained optimization problem, usually the optimal points are on the surface of some constraints in optimization space. In other words, optimum point usually violates some constraints. For example we can expect the optimum shape of the concrete gravity dams passes the allowable tension during earthquake but still remains in acceptable level. Moreover for the optimum shape, one can expectthe area between diagram of the cumulative duration and performance curve (represented by A_1 in figure 3) be less than other shapes.By using this idea, the new objective function is represented as this area.

Optimize $$F(\mathbf{x}) = \{f_1(\mathbf{x}), f_2(\mathbf{x})\} \quad (2)$$

Where $g_i(\mathbf{x}) \leq 0$

That f_1 is area of dam and f_2 is the area between performance curve and cumulative duration line which is represented in figure 3 by A_1.

New objective function can be written as a constraint as below for all demand capacity ratios:

$$(cumulative\ duration)_k - performance\ curve_{(DCR)} \leq 0 \quad (3)$$

Where index k is representative of the number of constraint and performance curve is a function of DCR.

Optimization procedure

Interior penalty method was used to alter the constrained optimization problem to unconstrained problem and then steepest descent method is applied to solve the unconstrained issue.

Interior penalty method is one of the common methods to solve a constrained optimization problem. The original form of the interior penalty function, ψ_{int} is as follows [13]:

$$\psi_{\text{int}}(\mathbf{x}, r) = f(\mathbf{x}) - r_{\text{int}}\left(\sum \frac{1}{g_i(\mathbf{x})}\right) \quad r_{\text{int}} \to 0 \quad (4)$$

where r_{int} reduces gradually from a high value to *0*. This equation does not allow any constraint to be violated; thus it requires a feasible staring point.

Raohas proposed the following function to select r_{int} at the start of the optimization procedure[14]:

$$r_{\text{int},1} = (0.1 \sim 1) \times \frac{f(\mathbf{x}_1)}{-\sum \frac{1}{g(\mathbf{x}_1)}} \quad (5)$$

where x_1 is a vector which represents the initial point in the feasible region. In the optimization procedure r_{int} reduces gradually to *0* as follows [14]:

$$r_{\text{int}_{i+1}} = c \times r_{\text{int}_i} \quad (6)$$

Where c is a coefficient less than 1. Figure 4 summarizes the optimization procedure of the interior penalty method[15].

To find the unconstrained minimum x_k^* in each step of optimization, the steepest descent method was used.

The use of the negative of the gradient vector as a direction for minimizationis first proposed by Cauchy [15-20]. This method is started from initial trial point x_1 and iteratively moves towards the optimum point according to the rule:

$$\mathbf{x}_{i+1} = \mathbf{x}_i + \lambda_i^* S_i = \mathbf{x}_i - \lambda_i^* \nabla f_i \qquad (7)$$

Where λ_i^* is optimal step length along the search direction $S_i = -\nabla f_i$ .f is the objective function and its index represents the number of steps in optimization procedure. The flowchart for this method is given in figure 5.

Results and Discussion

Interior penalty function was used to change the constrained to unconstrained optimization problem; moreover, the steepest descent method is applied to find the minimum of unconstrained problem. In addition, Newton method is employed to minimize the one dimensional optimization problem.

Figure 6 indicates the change of the area of the dam under dynamic loads for single and multi-objective method. Shape of dam in final step was further presented in Figure 7. There is a meaning different between using performance criteria as objective function or as a constraint in optimization rate as demonstrated in figure 8.

In addition, the change in design variables values (x_i) through optimization was presented in figure 8. The slope of the upstream and downstream increased during optimization.

Performance criteria chart presented figure 9 reveals that the final shape is in a feasible region. This chart was created by using the data of change the stresses during earthquake which is illustrated in figure 10.

Conclusion

The results reveals the effectiveness of the new approach in shape optimization of concrete gravity dams. Using area between performance curve and cumulative duration as an objective function leads to an optimum shape of dam under seismic load. Moreover using multi objective form of problem increases the rate of convergence considerably. The comparison between single and multi-objective function forms indicate that the precision is increased by ten percent and the rate of convergence is improved by 40%.

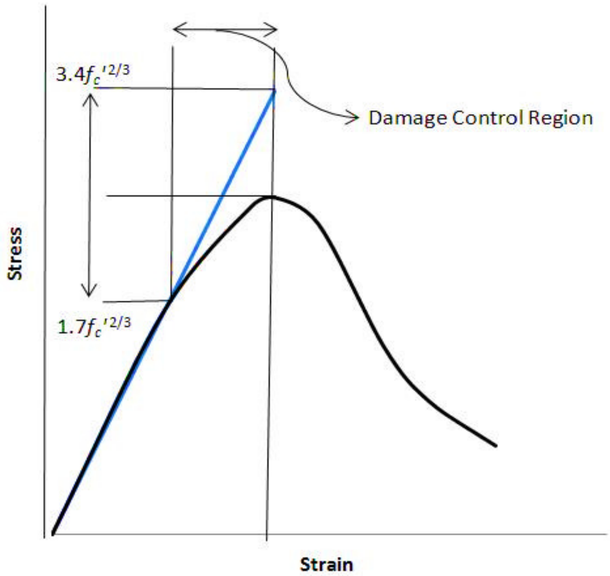


Figure-1
Stress–strain relation for concrete [8]

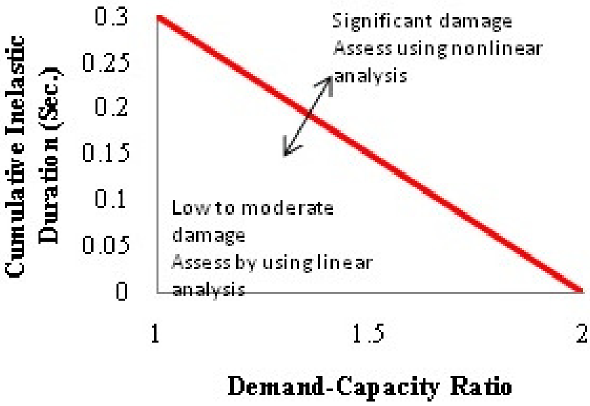


Figure-2
Performance curve for concrete gravity dams

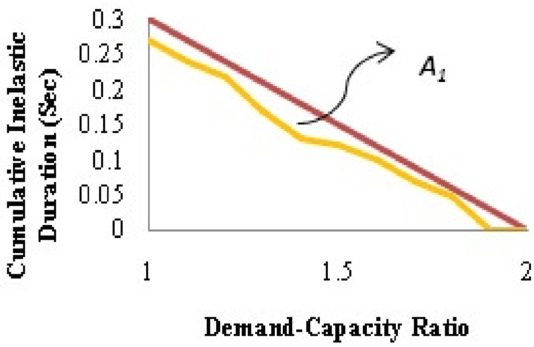


Figure-3
New objective function

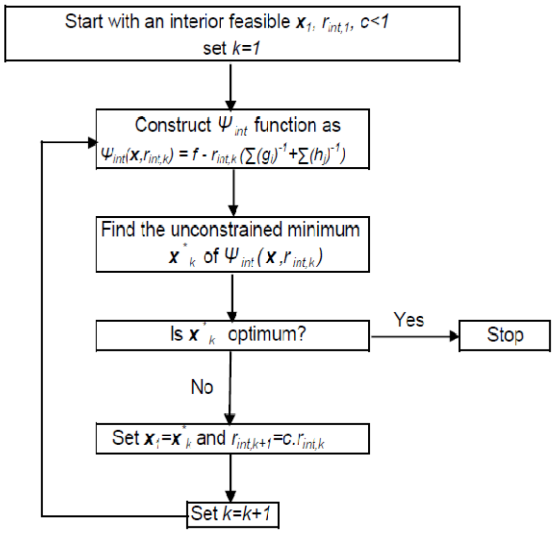


Figure-4
Flowchart for interior penalty function method

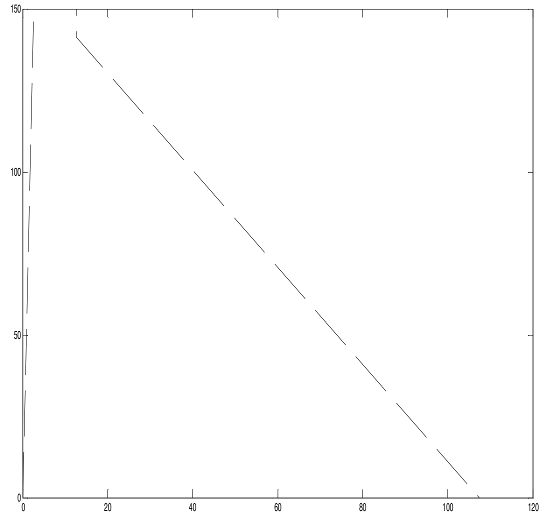


Figure-7
Final shape of dam (Multi Objective Method)

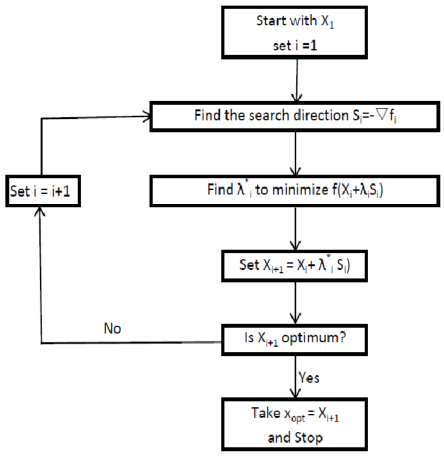
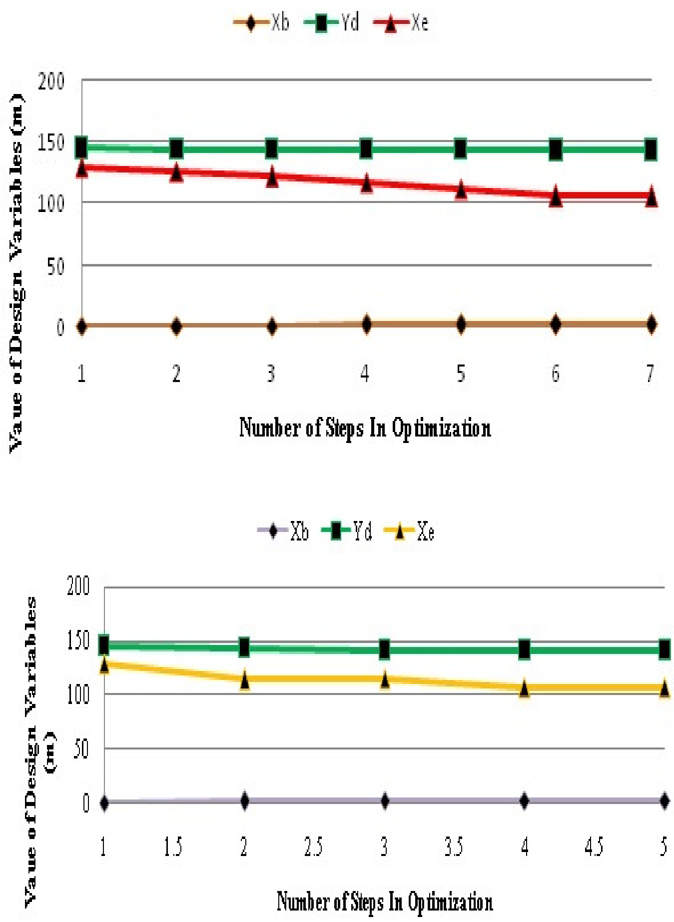


Figure-5
Flowchart for the steepest descent method



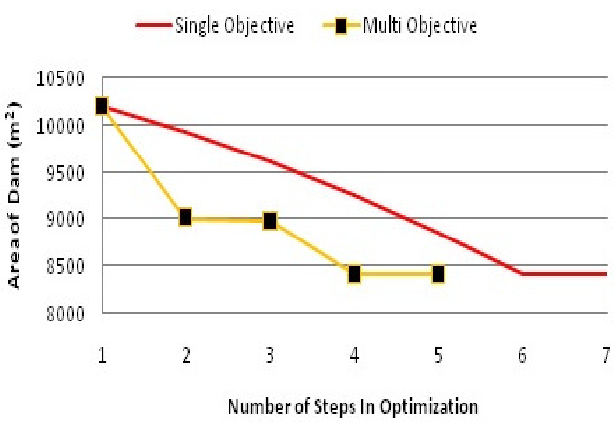


Figure-6
Area of Dam through optimization procedure, using performance criteria approach method

Figure-8
Change in values through optimization: (a) Single Objective, (b) Multi Objective

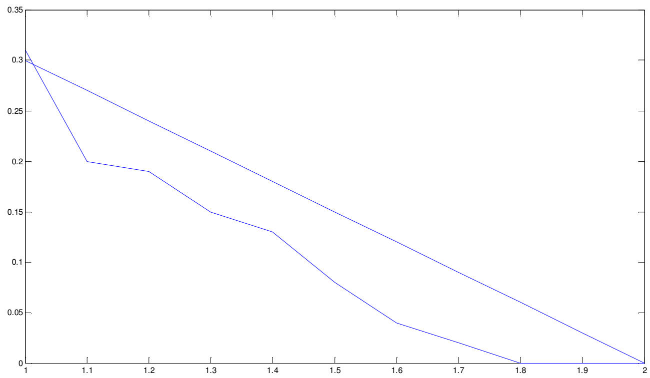


Figure-9
Final Performance Criteria chart (Multi Objective Method)

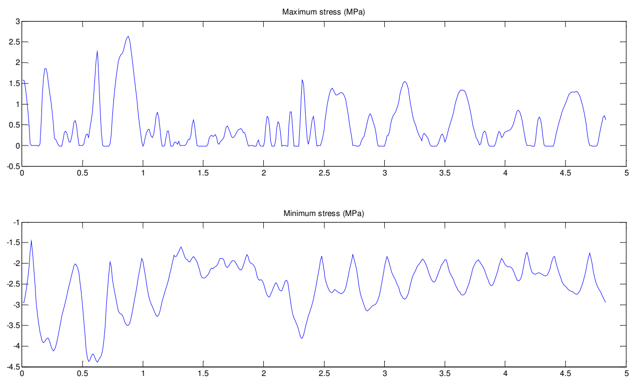


Figure-10
Maximum and minimum principal stresses in controlling points during earthquake for final shape (Multi Objective Method)

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