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SECTION OPTIMIZATION AND RELIABILITY ANALYSIS OF ARCH-TYPE DAMS INCLUDING COUPLED MECHANICAL-THERMAL AND HYDRAULIC FIELDS

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Abstract. *From the design experiences of arch dams in the past, it has significant practical value to carry out the shape optimization of arch dams, which can fully make use of material characteristics and reduce the cost of constructions. Suitable variables need to be chosen to formulate the objective function, e.g. to minimize the total volume of the arch dam. Additionally a series of constraints are derived and a reasonable and convenient penalty function has been formed, which can easily enforce the characteristics of constraints and optimal design. For the optimization method, a Genetic Algorithm is adopted to perform a global search. Simultaneously, ANSYS is used to do the mechanical analysis under the coupling of thermal and hydraulic loads. One of the constraints of the newly designed dam is to fulfill requirements on the structural safety. Therefore, a reliability analysis is applied to offer a good decision supporting for matters concerning predictions of both safety and service life of the arch dam. By this, the key factors which would influence the stability and safety of arch dam significantly can be acquired, and supply a good way to take preventive measures to prolong ate the service life of an arch dam and enhances the safety of structure.*

1 INTRODUCTION

Nowadays, more and more arch-dams have been built to protect from natural disaster, irrigate plants, generate electricity power, etc. The structure of an arch dam has the advantage of using upstream curvature to transfer water pressures to the basement on both sides of the valley, which means the stability of dam body relies on the reactive force from the basement of abutment instead of its own weight.

For arch dams, the main loads influencing the structure most are water loading, self-weight and fluctuation of temperature, which are main cases contributing to the deformation of arch dams. A proper method selected for shape optimization decides the efficiency of design process. With the development of heuristic algorithms [4-5], it became popular to apply this kind of optimization into shape optimization of structural design for its characters of global search.

Reliability analysis is involved to judge the structure after optimization and provides predictions of both safety and service life of the arch dam, which can supply a good way to take preventive measures to prolong, ate the service life and enhance the safety of the dam body

2 SHAPE OPTIMAL DESIGN PROCEDURES

2.1 Description of the shape of arch dam

Generally, the function of upstream curve is assumed to be a cubic equation along height direction (z coordinate direction), which can be written in form of $y(z) = a_0 + a_1 z + a_2 z^2 + a_3 z^3$ .... In order to solve this function, three height control points, $z = z_1, z_2, z_3$ are selected

$$\begin{aligned} y(z=0) &= 0 \\ y(z=H) &= -\beta_2 t_b \\ \frac{dz}{dy}(z=\beta_1 H) &= 0 \end{aligned} \tag{1}$$

Where $t_{c,}\ t_b$ are the width of dam crest and bottom; $\beta_1,\ \beta_2$ are coefficients obtained according to experiences. And the same procedure for acquiring the function of the sectional thickness, $T_c(z) = b_0 + b_1 z + b_2 z^2 + b_3 z^3$ ..., and a linear function is used to stand for the change of thickness, and the coefficients can be found by the following equations:

$$\begin{aligned} T_c(z=0) &= t_c \\ T_c(z=H) &= t_b \end{aligned} \tag{2}$$

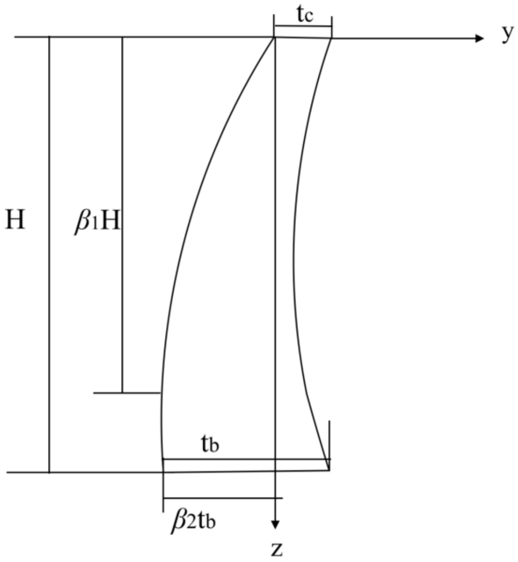


Fig1 Central Section of Arch Dam

2.2 Objective function

Generally, the objective function of the shape optimization is defined to ensure either minimal stresses of the structure or minimal volumes of dam body. In this case, for the sectional optimization, the objective function is determined by the minimum area of dam section:

$$f(\hat{\boldsymbol{x}}) = area(\hat{\boldsymbol{x}}) = \int \ |y_d(z) - y_u(z)|dz \tag{3}$$

By introducing exterior penalty terms, the objective function with constraints can be transferred to an unconstraint optimization problem.

$$F_{obj} = f(\hat{\boldsymbol{x}}) + \delta_k \sum_{i=1}^{m} [\max\{0, g_i(\hat{\boldsymbol{x}})\}]^2 \tag{4}$$

where $f(\hat{\boldsymbol{x}})$ is the cost function, $g_i(\hat{\boldsymbol{x}})$ is the ith constraint condition, lb, ub are respectively lower and upper boundaries of $\hat{\boldsymbol{x}}$ and δ_k are non-negative penalty factors. In this study, the variables defining the shape of arch dams section are $\beta_1, \beta_2, t_c, t_b$ which are included in the vector

$$\hat{\boldsymbol{x}} = [\ \beta_1, \beta_2, t_c, t_b]^T. \tag{5}$$

2.3 Constrained conditions

(1) Stress constraint

For the assurance of normal working during service life, the maximum stress of arch dam must be under allowed stress. Then, the stress constraint can be expressed as follows:

$$g_1 = \frac{\sigma_1}{[\sigma_1]} \le 1 \tag{6}$$

$$g_2 = \frac{\sigma_3}{[\sigma_3]} \le 1 \tag{7}$$

in which, g_i is the constraint condition, σ_1, σ_3 are respectively the maximum strain stress and maximum compressive stress.

(2) Geometric constraint

Generally, for any convenient construction, the geometrical constraints are expressed as the degrees of overhang on the upstream and downstream side, which is represented by 's'. According to [3], the principle degree of overhang [s] is 0.3, so, the geometrical constraint is:

$$g_3 = \frac{s}{[s]} \leq 1 \tag{8}$$

(3) Stability Constraint:

Any design for an arch dam must fulfil the slope stability requirements. Consequently, stability against sliding must be taken into consideration by introducing coefficients of sliding resistance, which are given by the sliding resistance K_i. The constraint condition can be written as:

$$g_4 = \frac{[K_i]}{K_i} \leq 1, \tag{9}$$

where the $[K_i]$ is the minimum allowable coefficient of sliding resistance for the ith point, and K_i is the coefficient of sliding resistance of ith point.

2.4 GA method of unconstrained minimization

The idea of GA [9] is to realize globally optimal designs in a given search region mimicking the procedure of natural selection. After randomly generating an original population, the next generation is produced by crossing over and mutation. New generations are formed from the last generation.

2.5 Coupled Thermo-Hydro-Mechanical Field Analysis

As the structural behavior of dams is visibly dominated by three fields - thermal, hydraulic and mechanical – we choose a coupled-analysis approach here. A coupled-field analysis is an analysis that takes into account the interaction between two or more disciplines of engineering. The procedure for a coupled/field analysis depends on which fields are being coupled, but two distinct methods can be identified: direct and sequential.

The couplings between the procedure of heat transfer, fluid flow and stress/deformation in porous geological media like concrete has become an increasingly important subject in many engineering disciplines. The two-way coupling process reveals continuing reciprocal interaction among different processes in a complex way, see Figure 2.

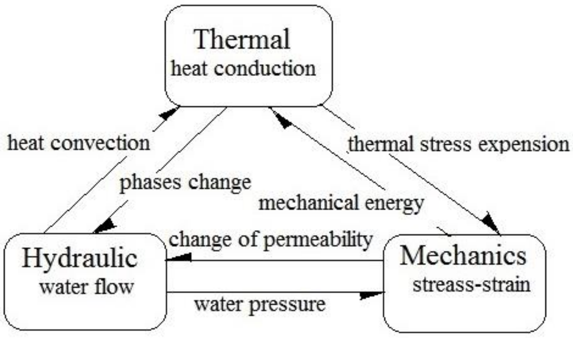


Fig2. Reciprocal Interaction among Different Process

3 NUMERICAL EXAMPLES FOR ARCH DAM SECTIONAL OPTIMIZATION COUPLING THERM–HYDRO -MECHANICS FIELDS

The example used in this paper is an arch dam with the height of 88m, density of 2355kg/m^3, Young's modulus of 2.6e+10 Pa, and the Poison's ratio of 0.25.

The loads considered in the optimal procedure are: dead load, hydrostatic pressure on the upstream face and uplift pressure on the foundational interface. Besides, a realistic assessment of loading from water flow and temperature loading are also considered for the coupled response of shape optimization.

In order to create the shape of the arch dam, 4 proper shape design variables are selected to model the dam:

$$\begin{cases} \hat{\boldsymbol{x}} = [\,\beta_1, \beta_2, t_c, t_b]^T \\ 0.6 \le \beta_1 \le 0.9 \\ 0.3 \le \beta_2 \le 0.6 \\ 3m \le t_c \le 10m \\ 10m \le t_b \le 55m \end{cases} \tag{10}$$

The first principal stress and third principal stress results of initial structure and optimized structure are shown in Figure 3a-d, and the summary of the comparison between initial and optimal structures are tabulated in the Table1. It can be observed that the area is reduced by 14.58% compared with the initial structure.

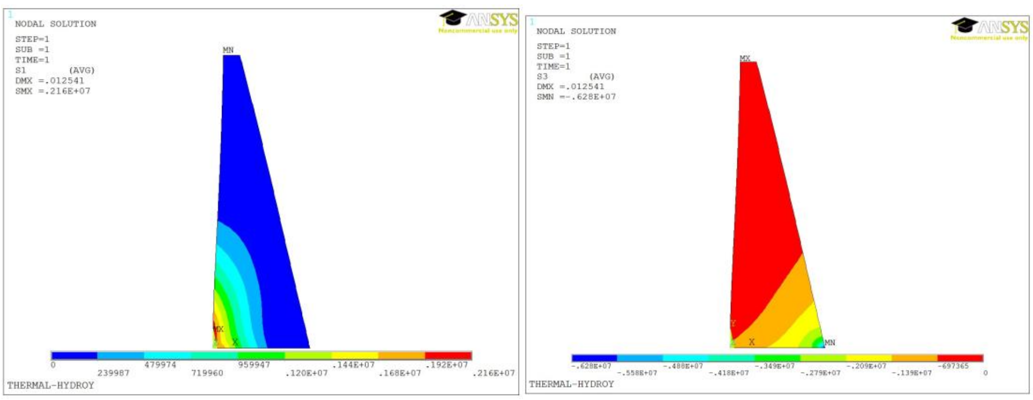
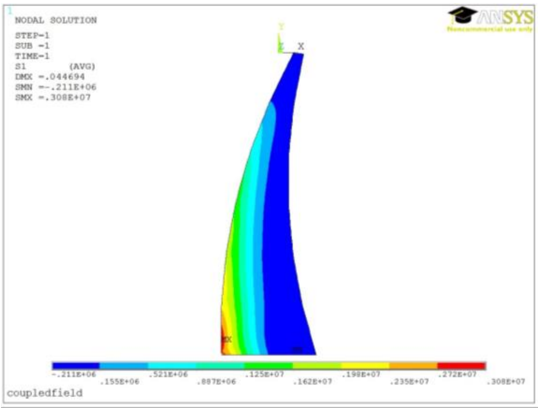


Fig3a. The First Principal Stress of Initial Dam

Fig3b. The Third Principal Stress of Initial Dam



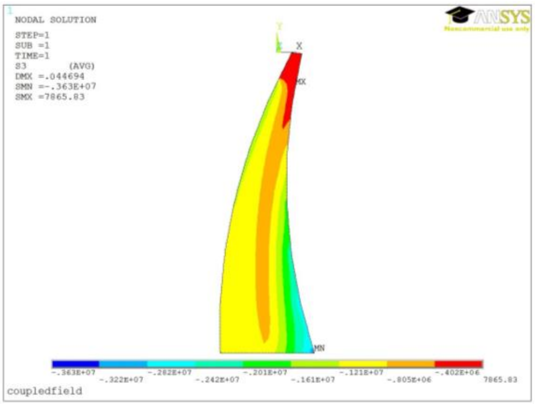


Fig3c. The First Principal Stress of Optimal Dam

Fig3d. The Third Principal Stress of Optimal Dam

Table 1. The Comparison of initial structure and optimal structure

	Height (m)	Width of dam crest (m)	Width of dam bottom (m)	Sectional area (m^2)	Max principal tensile stress (MPa)	Max principal compressive stress (MPa)
Initial	88	5	30	1540	2.16	6.28
Optimal	88	3	27.564	1344.826	3.08	3.63

4 RELIABILITY ANALYSIS

After optimization, a newly designed dam under constraint conditions is obtained to fulfill the requirements of structural safety. Therefore, a reliability analysis is taken to offer a decision supporting for matters on predictions of both safety and service life of arch dam. The most general method to solve stochastic problems in structural mechanics is the Monte Carlo method. The sampling selects the values of uncertain variables randomly according to their probability distribution functions. For a simple approach in structural reliability analysis, the sampling includes each random variable assigned randomly to a given sample value x_i and the limit state function Z=g(**x**) is then checked. If the number of simulations is n, and among them, there are n_f times failed, according to Bernoulli theory, the frequency of random event Z<0 in the n-times independent experiments, $\frac{n_f}{N}$, converges to the failure probability. Therefore, the failure probability can be expressed as

$$\widehat{P_f} = \frac{n_f}{N} = \int_{-\infty}^{+\infty} I[g_X(x)]f_X(x)dx = E\{I[gX(x)\} \quad (11)$$

where the I(x) is indicator function, and when x<0, I(x)=1, x>0,I(x)=0. With this, the estimated value of failure probability is:

$$\widehat{P_f} = \frac{1}{N}\sum_{i=1}^{N} I[gX(x)]. \quad (12)$$

4.1 Reliability analysis results:

For the reliability analysis of the dam, the material properties values are used as random variables. The material properties will give the resistance to the structure. As the structure gets old there will be deterioration in structure due to change in the properties. The reliability analysis results are carried out respectively with Monte Carlo direct simulation and second order reliability method from the normal distribution with mean μ and standard deviation σ. The Table 2 shows the mean, standard deviation and probability distribution considered in this case, and Figure 4, 5 show the distribution of random variables.

Table 2. The Mean Standard Deviation and Probability Distribution

Description	Density of concrete ($kg/\boldsymbol{m^3}$)	Modulus of Elasticity (MPa)	Probability distribution
Mean	2400	26000	Normal
Standard Deviation	240	2600	Normal

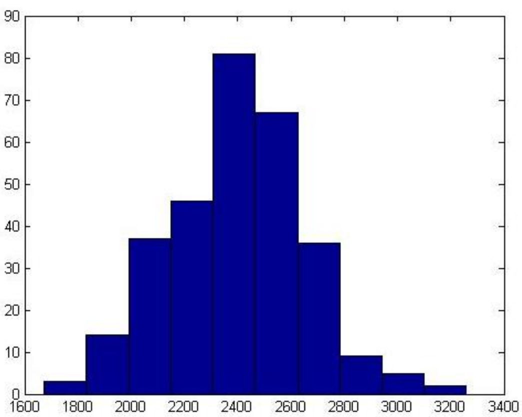


Figure 4. The Normal Distribution of Density

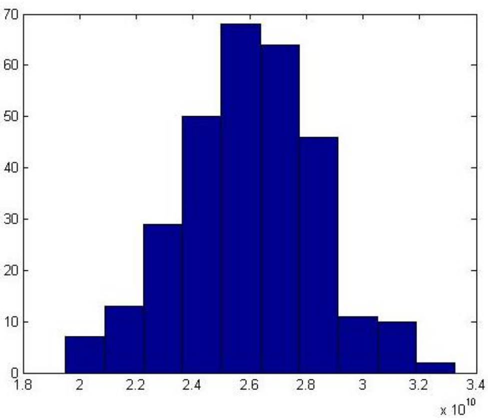


Figure 5. The Normal Distribution of Young's Modulus

Table 3. Reliability Analysis Results

	Reliability index β	Probability of failure $\boldsymbol{P_f}$
Monte Carlo direct simulation	2.67	0.0036
Second Order Method	2.905	0.0033

5 CONCLUSIONS

A sectional optimization of an arch-type dam is carried out. The optimization is processed under a thermal-hydraulic-mechanical field analysis with the application of GA method. The area of the arch dam section was visibly reduced. The problem with the chosen GA method is that is a global search method, which would be very time consuming when the number of variables is raised. More suitable optimization techniques need to be applied and tested w.r.t their suitability.

The variation of temperature provides significant stresses due to thermal expansion. This effect may be taken stronger into consideration in further analyses. Due to the low permeability of concrete, the seepage field has very little effect on stress and deformations of structure. However seepage can cause significant stresses if the concrete is deteriorated.

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