Optimum Design Program for Shape of Arch Dams

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ABSTRACT

This paper presents an applicable and practical computer program (ODPSAD) and suggests a new algorithm for geometry of concrete arch dams. In this program shape optimization of arch dams for static and dynamic loads and enhancement of its seismic behaviour is carried out. Abutment excavation and dam body volumes have been considered as the objective function and in order to increase the consistency with practical conditions, a great number of geometrical and behavioural constraints have been included in the mathematical model. Three loading cases i.e., gravity loading, static loading and dynamic loading have been accounted for analysis. In seismic loading, longitudinal component of the OBE2 spectrum have been considered. For finite element analysis the base of program FEAPpv3 is used and extended for this purpose. Sequential nonlinear approximation (SQP) procedure is used for the optimization analysis. Results show that the modification and optimization of shape can be very versatile and professional leading to considerable reduction in the dam body volume and costs in regular cases.

1. Introduction

In concrete arch dams, geometry of the structure has a great influence on the safety and economy of design. Geometry is also an important factor in the stability of dam. Nowadays, a high number of arch dams are constructed in seismic zones and despite their acceptable performance under dynamic loading, there is still overmuch need to improve their behaviour and to increase their safety during strong ground motion events. Generally, shape design of an arch dam is based mainly on the experience of the designer, model tests and trial and error procedures. In trial and error procedures, an initial scheme is selected or given and then analyzed. If it satisfies the demands of the design specifications, the scheme is adopted. Otherwise, the shape of the dam is modified and reanalyzed. This process continues until the whole demands of the design specifications are satisfied. To get a better shape, the designer should select several alternative schemes with various patterns and modify them such as the first scheme to obtain a number of feasible shapes. The best shape considering economy of design, structural considerations, safety, etc. is selected as the final shape. The shape of the dam obtained in this way is feasible but not necessarily optimal or even good. Moreover, the time of design is rather long. To overcome these difficulties, special efforts have begun by researchers for optimal shape design from the late 1960's. In the search of arch dams with optimal shape, early research did by (Fialho (1955) & Serafim (1966)) [1,2]. Later, Rajan, M.K.S. (1968) [3], Mohr, G.A.

1. Optimum Design Program for Shape of Arch Dams

2. Operating Basis Earthquake

3. Finite Element Analysis Program for Personal Version

4. Sequential Quadratic Program

1, 2, 3

In this research new algorithm for modelling geometry of arch dams is used [24,25].As a high number of design variables and large dimensions of shape optimization of concrete arch dams’ problem, make its nature very complicated, preparing a suitable method for this problem is highly demanding. This research employs Bofang’s dam body geometrical expression but is quite improved in modelling the Dam-Foundation system, dynamic load definition, stress constraints, numerical analysis method and method of optimization. The main aim has been an attempt to develop a practical and professional program for shape optimization of arch dams.[26]

2. Design Variables

Site geometry is described in the Cartesian site coordinate system $t_0,t_1,t_2$. This global coordinate system is chosen at the beginning of the project and remains unchanged throughout the design procedure. The axes $t_0$ and $t_1$ lie in a horizontal plane. The axis $t_0$ points to the right side of the dam body. The axis $t_2$ points vertically upward. The geometry of the arch dam is described in the cartesian dam coordinate system $x_0,x_1,x_2,\theta_c$ whose origin and orientation change for each design with the location of the dam and the orientation of the axis of the dam. Fig (1). For crown shape It is assumed that design variables are the dam thicknesses $T_{b}, T_{m}, T_{u}, T_{c}$ and the overhang parameters $p_{b}, p_{m}, p_{u}, p_{c}$ at the interpolation stations. Shape of crown is defined via cubic Spline equations of upstream and downstream faces. The thickness variation in the crown is specified by $T_{b}, T_{m}, T_{u}, T_{c}$ design variables. The upper and middle levels are specified relative to $H_c$ with the level ratios $h_b = 0.75, h_m = 0.4$. The thickness is interpolated with Splines over the height of the dam. The upstream face of the dam is divided into a central zone of constant thickness, which will be denoted by $Z_c$, and zones of variable thickness at the left and right abutments, which will be denoted by $Z_L$ and $Z_R$. The zones are shown in Fig.3. In zone $Z_c$, the thickness of the dam body in each horizon equals the thickness in the crown joint. In the zones $Z_L$ and $Z_R$, the thickness in each elevation varies parabolically from the thickness of $Z_c$ to the abutment thickness. The start points of variable zone in 4 stations at right and left is defined with 8 design variables, i.e. $t_b, t_m, t_u, t_c, s_b, s_m, s_u, s_c$. The thickness of the dam body at the abutment is specified by the thicknesses $T_{r_b}, T_{r_m}, T_{r_u}, T_{r_c}$ and $T_{r_l}, T_{r_m}, T_{r_u}, T_{r_c}$ which are design variables. The thickness is interpolated with Splines over the height of the dam. Consider the elevation of a dam body at level $x_2$ as shown in Fig.4. The upstream edge of the horizon is a parabola whose vertex lies on the upstream edge of the crest joint profile. The radius of curvature $r$ of the parabola is specified at levels $H_b, H_m, H_u, H_c$ by the $R_b, R_m, R_u, R_c$ design variables. It is interpolated between these levels with the cubic Splines.
Fig.1. Site & Dam Coordinate Systems

Fig.2. Crown Cantilever Profile

Fig.3. Thickness Zones of the Dam Body

Fig.4. An elevation Arch of the Dam Body

Fig.5. Shape of the Dam and Its Foundation
3. Objective Function

The objective function is the volume of the dam and foundation excavation, which expressed as follows:

\[ f(x) = V_1(x) + V_2(x) \]  

(1)

In which \( f(x) \) = the sum of volumes, \( V_1(x) \) = volume of concrete in the dam body, \( V_2(x) \) = volume of foundation excavation and the \( x \) is the vector of design variables. The volume of the dam is the sum of volumes of the elements. The foundation excavation is computed from mathematical formulation that is depended to design variables.

4. Constraints

In shape optimization of concrete arch dams, the three following types of constraints should satisfy the demands of design and construction requirements:

1) Geometrical constraints
2) Stress constraints
3) Stability constraints

The constraints are shown by a set of \( g_j(x) \leq 0 \) conditions

5. Optimization Problem

The shape optimization problem of an arch dam can be expressed as a nonlinear constrained optimization problem of the form:

Minimize : \( C = f(x) \)

Subject to : \( g_j(x) \leq 0 \), \( (j=1,2,...,q) \) 

(2)

In which \( q \) is the total number of constraints. Because there is not any explicit formulation between design variables and the above functions, these functions are approximated in \( x_0 \) via Taylor expansion series, so the nonlinear functions replaced with sequential approximated quadratic and linear function as equations (3),(4)

\[ f(x) = f(x_0) + (x_i - x_0_i) \cdot \nabla f + 0.5 \cdot (x_i - x_0_i) \cdot H_{df} \cdot (x_i - x_0_i) \]  

(3)

\[ g_j(x) = g_j(x_0) + (x_i - x_0_i) \cdot \nabla g_j(x_0) \]  

(4)

where \( f(x) \) is approximated objective function, \( f(x_0) \) is objective function in \( x_0 \), \( \nabla f \) is objective function gradients in \( x_0 \), \( H_{df} \) is quasi Hessian matrix of objective function, \( g_j(x) \) is \( j^{th} \) linear approximated constraint, \( g_j(x_0) \) is value of \( j^{th} \) constraint in \( x_0 \) design point and \( \nabla g_j \) represents gradient of \( j^{th} \) constraint in \( x_0 \).

6. Case Study

The proposed method is applied to shape optimization of the 130 m-high concrete arch dam. The canyon has trapezoidal shape with 100 m base and slopes 1:1 at left and right. The main characteristics of the dam and the considerations related to its shape optimization process are described at tables (1),(2),(3). Also seismic input load is illustrated in Fig(6).

<table>
<thead>
<tr>
<th>Height(m)</th>
<th>( f_c ) (Mpa)</th>
<th>( E_c ) (Gpa)</th>
<th>( E_r ) (Gpa)</th>
<th>( \gamma_c ) (kN/m3)</th>
<th>( v_c )</th>
<th>( v_r )</th>
</tr>
</thead>
<tbody>
<tr>
<td>130</td>
<td>35</td>
<td>22</td>
<td>8</td>
<td>24</td>
<td>.18</td>
<td>.22</td>
</tr>
</tbody>
</table>
### Table 2. Allowable value of Constraints

<table>
<thead>
<tr>
<th>$S_{u}^{U.S}$ (degree)</th>
<th>$S_{b}^{U.S}$ (degree)</th>
<th>Undercut $a_{u}$ (m)</th>
<th>$\theta_{a_{u}}$ (degree)</th>
<th>$SF_{st}$</th>
<th>$SF_{dy}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>20</td>
<td>6.5</td>
<td>70</td>
<td>3</td>
<td>1</td>
</tr>
</tbody>
</table>

### Table 3. Initial Values of Design Variables

<table>
<thead>
<tr>
<th>$p_u$</th>
<th>$p_m$</th>
<th>$p_b$</th>
<th>$T_c$</th>
<th>$T_u$</th>
<th>$T_m$</th>
<th>$T_b$</th>
<th>$R_c$</th>
<th>$R_u$</th>
<th>$R_m$</th>
<th>$R_b$</th>
<th>$T_{rc}$</th>
<th>$T_{ru}$</th>
<th>$T_{rm}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.75</td>
<td>0.65</td>
<td>0.55</td>
<td>8.00</td>
<td>14.0</td>
<td>19.0</td>
<td>28.0</td>
<td>205</td>
<td>145</td>
<td>110</td>
<td>85</td>
<td>8.80</td>
<td>15.4</td>
<td>20.9</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$T_{rb}$</th>
<th>$T_{lc}$</th>
<th>$T_{lu}$</th>
<th>$T_{lm}$</th>
<th>$T_{lb}$</th>
<th>$t_c$</th>
<th>$t_u$</th>
<th>$t_m$</th>
<th>$t_b$</th>
<th>$s_c$</th>
<th>$s_u$</th>
<th>$s_m$</th>
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<tbody>
<tr>
<td>30.8</td>
<td>8.80</td>
<td>15.4</td>
<td>20.9</td>
<td>30.8</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
<td>0.50</td>
</tr>
</tbody>
</table>

### Fig. 6. Seismic Input Load

7. Typical Results

The optimization process of an arch dam according to the proposed methodology, converged after 12 iterations. Convergence rate of the objective function in the optimization process is illustrated in Fig. (7). Notwithstanding the value of the objective function at the end of the 11th optimization cycle is minimum, but due to a partial violation of stress constraints in this cycle, results obtained from the 12th iteration is considered as the valid optimum solution. Also In the Fig. (8) initial and optimum shape of crown cantilever presented. After performing the optimization process, dam volume has decreased by 37% in comparison with the initial design.
8. Conclusion

In this paper a program (ODPSAD) is used to shape optimization of an arch dam. It suggests a new algorithm for geometry of concrete arch dams. Abutment excavation and dam body volumes have been considered as the objective function and in order to increase the consistency with practical conditions, a great number of geometrical and behavioural constraints have been included in the mathematical model. Three loading cases i.e., gravity loading, static loading and dynamic loading have been accounted. Results show that the optimization of shape can reduce the dam body volume 37%.

References