

Shape Optimization of Concrete Gravity Dams by ESO Method

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Abstract: Engineers are always after possible ways to reduce the design and construction costs of engineering structures. Due to the complexity of technical matters in design and construction of dams, special emphasis is placed in optimizing the dam shape with an eye on lowering the volume of concrete which must be used to construct it. Concrete gravity dams have been studied in this study. The aim is optimization of dam shape to reduce the utilized concrete volume. In the present paper, a finite element code was prepared by FORTRAN 90 to be used for structural optimization of gravity dams using ESO (Evolutionary Structural Optimization) method. The prepared code is capable of improving topology of an initial design into an optimized final design. To validate the results obtained by the prepared code for nodal stresses, these values are compared with the results calculated by SAP 2000. It was seen that the maximum difference is 1.5%. So the FORTRAN code presented here is considered to be adequate to produce valid results.

Key words: Concrete gravity dam . Optimization . ESO . Finite element method . FORTRAN

INTRODUCTION

Gaining a suitable plan and optimizing the considered plan are the main objectives of designers. In special structures such as gravity dams, Through considering a large number of plans which have various shapes, the best plan which has sufficient safety as well as relatively low cost in comparison with the initial and other plans must be chosen.

A gravity dam which has been studied in this research can be defined as a heavy structure constructed across the river to increase the height and volume of water at the upstream. It can be made from concrete or other constructing materials. A well-designed gravity dam must have adequate weight to be stable under the exerted forces. In some cases such as narrow or steep valleys or those valleys which have unsuitable soils to construct earth-fill dams, gravity dams are more efficient and economical in comparison with earth-fill dams. Moreover, their construction process is relatively straight-forward. The aim is of this study is optimization of dam shape to reduce the utilized concrete volume.

DESIGN OF GRAVITY DAMS

A gravity dam may collapse due to the following reasons:

- Sliding on the horizontal surface
- Rotating on the toe

- Weakness of constructing materials which can lead to increase of applied stresses [1].

Stability against rotation: Overturning induced collapse of gravity dams occurs due to either development of tensile cracks at the upstream or omission of materials due to increase of compressive stresses at the downstream. So if the tensile and compressive stresses are lower than corresponding allowable stresses, gravity dam would be safe against the overturning.

Stability against sliding: Collapse of gravity dam may occur due to sliding on the horizontal surface.

Stability against sliding can be controlled by shear friction factor which can be expressed as below:

$$SFF = \frac{\mu \sum F_v + \tau A}{\sum F_h} \quad (1)$$

Where:

SFF = Shear friction factor,

μ = Friction coefficient between the upper and lower pieces of constructing materials,

$\sum F_v$ = Total vertical forces applied to the considered section,

$\sum F_h$ = Total horizontal forces applied to the considered section,

τ = Average shear strength of the materials in the considered section and

A = Section area.

Design allowable stresses: Stresses produced inside the dam body should be lower than corresponding allowable stresses. Bearing capacity of the dam is one of the most important factors in optimization.

Allowable tensile stress: Generally, tensile strength of concrete can be neglected in design process of gravity dams. Allowable tensile stresses for normal and abnormal loading combinations are approximately 10 and 15 kgf cm⁻² respectively. It is recommended that tensile stresses greater than 5 kgf cm⁻² are not accepted for large concrete dams.

Allowable compressive stress: Maximum compressive stress for normal loading combination should not be greater than specified compressive stress (28 days strength) divided by safety factor 3.0. For abnormal loading combination, allowable compressive stress is gained through dividing the specified compressive stress by safety factor 2.0. It should not exceed 160 kgf cm⁻². For abnormal loading combination, a safety factor equal to 1.0 can alternatively be used.

Allowable shearing stress: Maximum allowable shearing stress of concrete in any internal section of dam for three different types of loading including normal, abnormal and special type are obtained through dividing the shearing strength by a suitable safety factor. Minimum corresponding safety factors are 3, 2 and 1 for normal, abnormal and special loadings, respectively.

ESO (EVOLUTIONARY STRUCTURAL OPTIMIZATION) METHOD

ESO method was firstly programming for plane stress condition in 1992-97. Research for formulating is continued for preparing softwares to cover various branches of optimization [2]. In ESO method, through gradual elimination of materials/ineffective elements from the structural model, the shape of the structure can be optimized. Different design constraints such as stress, stiffness, frequency and buckling load may be applied to the structure [3].

Whatever the materials which have lower level of the stress are eliminated from the structural model, the stress distribution in the structure would be more uniform.

Nowadays, Evolutionary structural optimization (ESO) method may be used in different fields of optimization which can be categorized as follows [4]:

- Size, shape and topology optimization of various parts of the structure. In the present paper, this category is considered.

- Using different optimization criteria for different parts of the structure,
- Optimization considering numerous load cases,
- Optimization considering various restraints,
- Optimization considering various materials used in different parts of the structure,
- Two and three dimensional optimization,
- Simultaneous optimization of linear static behavior, dynamic behavior and stability,
- Structural optimization considering geometrical and material nonlinearity,
- Frequency optimization.

Optimization steps in ESO method: Steps of ESO method can be summarized as follows:

- Using FEM to discrete the structure,
- Applying the boundary conditions and exerted loads,
- Analyzing the model,
- Extracting Von Mises stress in all elements. For three dimensional elements such as brick elements, Von Mises stress can be obtained as follows:

$$\sigma^{vm} = \frac{1}{\sqrt{2}} \sqrt{(\sigma_1 - \sigma_2)^2 + (\sigma_1 - \sigma_3)^2 + (\sigma_2 - \sigma_3)^2} \quad (2)$$

- Where σ_1 , σ_2 and σ_3 are principal stresses.
- Finding the maximum Von Mises stress (σ_{max}^{vm}),
- Eliminating all the elements which satisfy the following condition:

$$\frac{\sigma_e^{vm}}{\sigma_{max}^{vm}} < RR_i \quad (3)$$

- Where, RR_i is the current rejection ratio.
- Iterating the analysis to reach the steady state in which no more elements should be eliminated from the structural model.
- Adding the evolutionary rate (ER) to the current rejection ratio (RR_i) and iterating with updated rejection ratio (RR_{i+1}) to reach the steady state. The mentioned process can be expressed as below:

$$RR_{i+1} = RR_i + ER \quad i = 0, 1, 2, 3, \dots \quad (4)$$

- Repeating the mentioned procedure to reach the optimized topology.

With the exception of some certain conditions, it is impossible to reach a model which has quite uniform

Table 1: ESO parameters, material properties and allowable stresses

ESO parameters	
Initial rejection ratio	1%
Evolutionary rate	1%
Number of elements	480
Material properties	
Specific gravity of concrete	2.5 ton m ⁻³
Young's modulus	2 e 6 ton m ⁻²
Poisson's ratio	0.2
Allowable stresses	
Allowable tensile stress	150 ton m ⁻²
Allowable compressive stress	1600 ton m ⁻²
Allowable shearing stress	400 ton m ⁻²

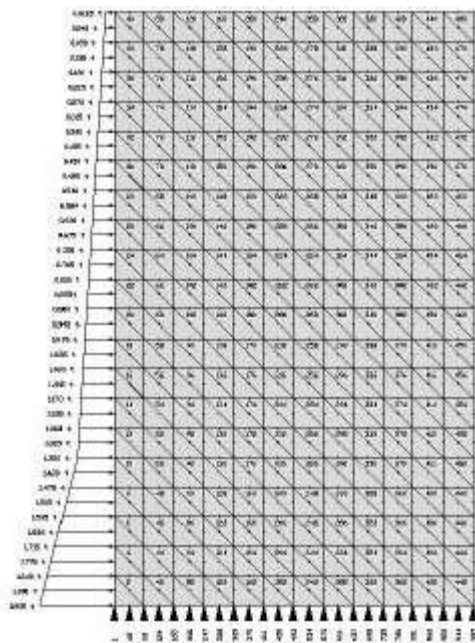


Fig. 2: Loading and boundary conditions of the considered concrete gravity dam

presented. Loading and boundary conditions are shown in Fig. 2. Assuming linear stress and strain conditions, 30*30 cm triangular 6-node elements were used to generate the mesh. ESO parameters, material properties and allowable stresses are presented in Table 1.

To validate the results obtained by the prepared code for nodal stresses, these values are compared with the results calculated by SAP 2000. It was seen that the maximum difference is 1.5%. So the FORTRAN code presented here is considered to be adequate to produce valid results. It is worth mentioning here that convergence of the method used in the prepared code to give a singular solution for different initial shapes was verified in this study.

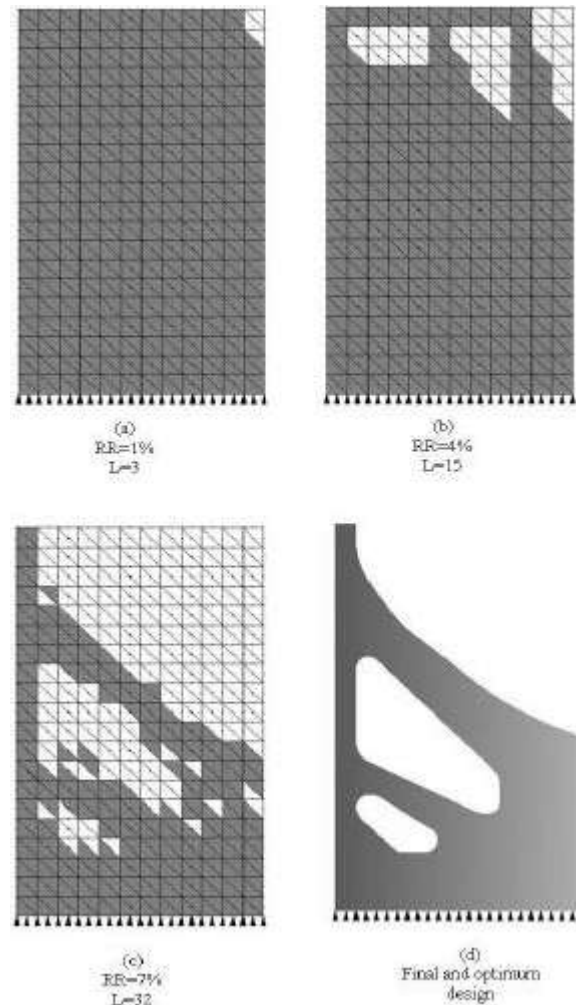


Fig. 3: Evolutionary process of dam structural optimization

Figure 3 shows the evolutionary process of dam structural optimization. In Fig. 3, RR is rejection ratio and L is the number of iterations done to reach the optimum shape.

It can be seen from Fig. 3 that for $RR=7\%$, no more elements should be eliminated from the structural model after 32nd loop. So the iteration must be stopped. If the iteration is continued, the stresses exceed the allowable values.

It was found that the value of initial rejection rate RR_0 and the ratio of eliminated elements to total number of elements must be limited to suitable values in order to obtain an appropriate optimization process.

Since the values of ER and RR have significant role in the results obtained by ESO method, it is suggested that a number of different values are assigned for both RR and ER during the analysis process to reach a reliable optimum solution.

CONCLUSION

In the present study, a finite element code was prepared by FORTRAN 90 to be used for structural optimization of gravity dams using ESO method. This code uses 6-node triangular elements assuming plane stress and plane strain conditions. The prepared code is capable of improving topology of an initial design into an optimized final design.

To validate the results obtained by the prepared code for nodal stresses, these values are compared with the results calculated by SAP 2000. It was seen that the maximum difference is 1.5%. So the FORTRAN code presented here is considered to be adequate to produce valid results.

Convergence of the method used in the prepared code to give a singular solution for different initial shapes was verified in this study.

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The FORTRAN code is prepared in such a way that if the final optimum solution becomes larger than

the initial grid dimensions, the prepared code proposed an alternative optimum solution.

REFERENCES

1. U.S.B.R., 1976. Design Manual for Concrete Gravity Dams. U.S. Government Printing Office, Washington DC.
2. Xie, Y.M. and G.P. Steven, 1997. Evolutionary Structural Optimization. Springer.
3. Bendsoe, M.P., 1997. Optimization of Structural Topology Shapes and Materials. Springer.
4. Hassani, B. and E. Hinton, 1998. Homogenization and Structural Topology Optimization: Theory, Practice and Software, Springer.
5. Xie, Y.M. and G.P. Steven, 1993. A Simple Evolutionary Procedure for Structural Optimization. Computers and Structures, Elsevier.
6. Mustoe, G. and J. Vanlaanen, 2004. Computer Aided Engineering. School of Mining, Colorado.
7. Jennings, A. and J.J. Mc Keonwn, 1992. Matrix Computation. Wiley.
8. Bathe, K.J., 1996. Finite Element methods. Prentice-Hall Inc.