Optimum Analysis and Design of Curved Concrete Dams

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Abstract

This research presents an efficient strategy to find optimum analysis and shape design for arch dams. Where the design geometry is built using (Solid Work Program), which is considered as one of important programs for analysis and design of complex structures. A finite element method is used to analyze the arch dam body, which is proved to be an important method for analysis and gives accurate results according to previous researches. The design of the basic shape of the dam has been done by using horizontal curve and vertical curve equations. After conducting the analysis and design of the initial model by (SolidWork) program, it was transferred to the second phase. This is the shape optimization process by using (Genetic Algorithm) in (Matlab) program. This method is an efficient method for all optimization problems in different branches. The objective function in this research is the minimum volume of the dam, which leads to minimum weight design. There are many constraint controls the selecting of optimum shape. In this work, geometrical and structural constraints are considered. At this stage, to calculate the volume of the dam body, integration method is used to convert the volume in terms of the design variables (tc_1, tc_2, and tc_3) which represent the thickness of the dam at three levels. Then this equation has been moved to (Genetic Algorithm tools) using (m-file) to complete the optimization process.

The results show that the best design shape of the dam is with thicknesses (5.5m, 13.3m, and 19.8m) with a final optimal volume of53.75% less than the initial model and the stress is still less than the allowable limits.

Key Words: Stress; Finite element; Arch dam; Optimization; Genetic Algorithm.

التحليل والتصميم الأمثل للسدود الخرسانية المقوسة

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الخلاصة

يقدم هذا البحث استراتيجية فعالة لإيجاد التحليل والتصميم الأمثل لشكل السدود المقوسة. حيث تم تصميم الشكل الهندسي للسد باستخدام برنامج (Solid Work)، والذي يعتبر أحد البرامج الهامة لتحليل وتصميم المنشآت المعقدة. تم استخدام طريقة العناصر المحدودة لتحليل جسم السد المقوس، والذي ثبت أنه طريقة هامة للتحليل ويعطي نتائج دقيقة وفقا للبحوث السابقة. تم تصميم الشكل الأساسي للسد باستخدام المنحنى الأفقي ومعادلات منحنى عمودي. بعد إجراء تحليل وتصميم النموذج الأولي من قبل برنامج (Solid Work)، تم نقله إلى المرحلة الثانية، وهي عملية تحسين الشكل باستخدام (الخوارزمية الجينية Genetic Algorithm) في برنامج (ماتلاب Matlab). وهذا الأسلوب هو وسيلة فعالة لحل جميع مسائل الأمثلية في الفروع المختلفة. إن دالة الهدف في هذا البحث هو الحد الأدنى لحجم السد، مما يؤدي إلى الحد الأدنى من الوزن التصميمي. هناك العديد من الضوابط والقيود لاختيار الشكل الأمثل. في هذا العمل، يتم النظر في القيود الهندسية والانشائية. في هذه المرحلة، يتم حساب حجم جسم السد باستخدام طريقة التكامل لتحويل الحجم بدلالة المتغيرات التصميمية (tc1، tc2، tc3) التي تمثل سمك السد على ثلاثة مستويات. ثم تم نقل هذه المعادلة إلى (أدوات الخوارزمية الجينية) لإكمال عملية الأمثلية. وأظهرت النتائج أن أفضل شكل تصميم للسد هو بسمك (٥,٥ م، ١٣,٣ م، ١٩,٨ م) مع الحجم الأمثل النهائي بنسبة ٥٣,٧٥٪ أقل من النموذج الأولي، ولا يزال الإجهاد أقل من الحدود المسموح بها.

1. Introduction

The geometric shape of arch dam has great effect on its safety and cost. Traditionally, shape design of an arch dam depends on the experience of the designer, sample tests and trial and error

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procedures. To obtain a better shape, a designer must choose a number of alternative samples with different styles and modify them to get a several possible shapes. The best form deeming the economy of layout, construction considerations and safety is chosen as the final optimum shape. The shape of the dam selected in this method is possible, but not essentially optimal. In addition, the time of this procedure is rather long. To override these problems, special jobs were starting by researchers for generating the best shape of arch dams at the end of 1960s [14]. Nowadays, there exists a large number of methods to find the optimum shape for arch dam. However, in this study genetic algorithm method is utilized for this purpose. There are many researchers studied subjects of optimum analysis and design of arch dams for different loading types. Some of these studies, like references (1,2,3,4,5,6,7,8,9,10, and 11) studied optimum analysis and design of arch dams by different methods of analysis with different load cases. reference [8] used static load in the dam analysis while dynamic load is used in Ref [1] with different analysis programs like, ANSYS in references [2 and 8], (EACD-3D) in reference [1], and (AD Shape) in reference [7]. Some researchers studied analysis of dam body only like reference [8] while others studied the interaction between dam body and foundation like reference [11]. Some researchers studied the optimum design of arch dams, like references [12,13,14,15 ,16,17,18,19,20,21, and 22] with various methods like (SPGA) in reference [12] , (SQP) method in reference [14] and other methods used by other researchers.

2. Significance and Objectives

The aim of this study is to find a better method for analyses and best shape design for arch dams to get the optimum cross section shape with the minimum volume of concrete that leads to minimize construction cost. This process is called (optimization method) for design.

The main objectives can be summarized as follows:

1- Examining the validity of the used method for modelling and analysis of arch dam under different kind of loads.

2- Investigating the use of Genetic Algorithm encoded into Matlab for choosing the optimum shape design of arch dam aiming to get a minimum volume design, which will reduce total construction cost.

3. Initial Design Modeling:

3.1. Shape of central vertical section:

From the main perpendicular part of double-curve arch dam, as in Figure (1), one polynomial of (nth) degree is employed to select the upstream curve limit and other polynomial is selected for selecting the thickness. In this study, a parabolic function for a curve of upstream side is used as given in reference [17].

$$\mathbf{Y\ (z) = B\ (z) = -\ S\ z + \frac{S\,z^2}{(2\,\beta\,h)}} \ldots\ldots\ldots\ldots\ldots(1)$$

Where:

h= height of arch dam, ***S***=the slope at crest.

And the point where the slope of the upstream face equals to zero is $z=\beta h$ in which β is constant.

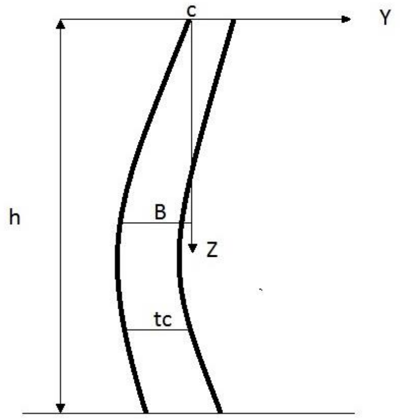


Figure (1): Middle vertical part of the curved dam [17]

➢ Thickness of the central vertical section $t_c(z)$ equals:

$$t_c(z) = N1(t_{c1}) + N2(t_{c2}) + N3(t_{c3}) \quad \text{…………..} \quad (2)$$

Where:

$$N1(z) = (z/h - \lambda)(z/h - 1)/\lambda \quad \text{……….} \quad (3)$$

$$N2(z) = (z/h)(z/h - 1)/\lambda(\lambda - 1) \quad \text{………} \quad (4)$$

$$N3(z) = (z/h)(z/h - \lambda)/(1 - \lambda) \quad \text{……….} \quad (5)$$

And

t_{c1} = thicknesses of the central vertical section at z = 0

t_{c2} = thicknesses of the central vertical section at z = λ h

t_{c3} = thicknesses of the central vertical section at z = h

λ = factor, in this study, is taken equal to 0.5(reference [17]).

3.2. Shape of central horizontal section:

The form of the horizontal part of a parabolic arch dam is selected by two parabolas as shown in Figure (2):

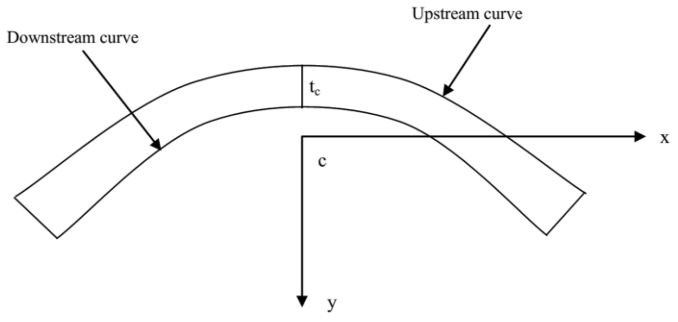


Figure (2): Horizontal curve of arch dam [17]

➢ At the upstream face of arch:

$$Y_U(x, z) = \frac{x^2}{2\,RU(Z)} + B(z) \text{………………….} (6)$$

➢ At the downstream face of arch

$$Y_D(x, z) = \frac{x^2}{2\,RD(Z)} + B(z) + tc(z) \quad \text{……………} (7)$$

Where

R_U = radius of curvature at upstream curve.

R_D = radius of curvature at downstream curve.

R_U and R_D can be calculated by the following equations:

$$R_U = N1\,(z)\,R_{U1} + N2\,(z)\,R_{U2} + N3\,(z)\,R_{U3} \quad \text{.............(8)}$$

$$R_D = N1\,(z)\,R_{D1} + N2\,(z)\,R_{D2} + N3\,(z)\,R_{D3} \quad \text{............. (9)}$$

Where

R_{U1}, R_{D1} radius at z = 0

R_{U2}, R_{D2} radius at $z = \lambda h$

R_{U3}, R_{D3} radius at z = h

The values of the basic parameters in design for initial model of the dam are chosen arbitrarily (from reference 17) and given in Table (1) .The initial 3D model is shown in Figure (3) and the volumetric properties for initial design in Table (2).

3.3 Solid Works program

The *SolidWorks* cad software is a sample of computer-aided design (CAD) and computer-aided engineering (CAE) program . It is considered as a mechanical design automation application that lets designers quickly sketch out ideas, experiment with features and dimensions, and produce models and detailed drawings [26]. *SolidWorks* program is considered as one of the most efficient programs for analysis and design for its simplicity and ability to model, analysis and design any complex structures with any type of loading. For this reason, it is used in the present study for modeling, analysis and optimum design of the double curvature arch dam.

Table 1. Design parameters for initial design

Design parameters	Value
S	0.25
β	0.80
t_{c1}	10 m
t_{c2}	30 m
t_{c3}	40 m
R_{U1}	100 m
R_{U2}	70 m
R_{U3}	25 m
R_{D1}	100 m
R_{D2}	70 m
R_{D3}	25 m

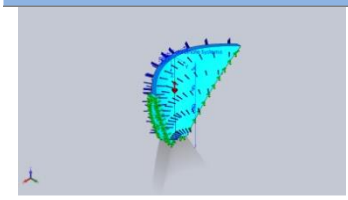
3.3.1 Modelling

The sketch in (SolidWorks program) starts with the equations for vertical and horizontal curves established in previous sections. Portions are the basic construction masses in the *SolidWorks* software. Assemblies consist of portions or other assemblies, called subassemblies. *SolidWorks* sample including 3D geometry, which selects its edges, sides, and surfaces. The *SolidWorks* software makes your layout sample, rapid and accurate. *SolidWorks* samples are [26]:

a) Selected by 3D layout. *Solid Works* uses a 3D layout approach. At first, design a part from the initial sketch to the result. It can create a 3D sample. From this sample, we can generate 2D drawing or collect elements composed of portions or subassemblies to generate 3D assemblies. It can also create 2D drawings of 3D assemblies. When designing a sample using *Solid Works*, it could be visualized in (3D).

b) Depending on the components. One of important features in the *SolidWorks* application is that any variation could be made to a portion will appear in all liked graphics or assemblies.

Table 2. Volumetric Properties for initial design

Document Name and Reference	Treated As	Volumetric Properties	Document Path	Date Modified
	**Solid Body**	**Mass:1.38511E+009 kg** **Volume:577130 m^3** **Density:2400 kg/m^3** **Weight:1.35741E+010 N**	**Initial model**	

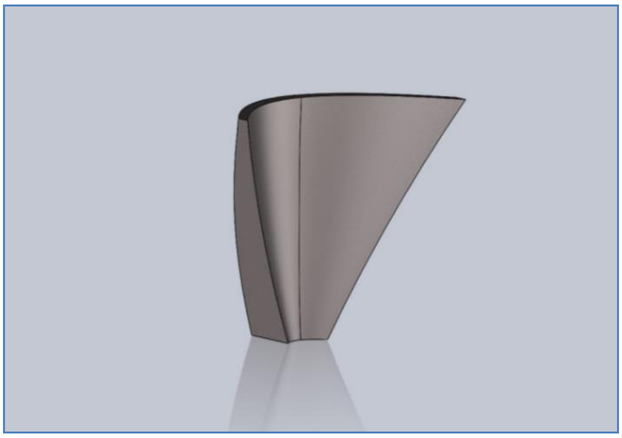


Figure 3. Initial model of the double curvature arch dam

3.3.2. Meshing

After drawing the model in *SolidWorks* program and converting to 3D body, FE meshing is generated. There are many types of elements that can be used here. In this study 3D solid element needs to be used by using a (10 node) quadrilateral tetrahedral element defined by four corner nodes, six mid-side nodes, and six edges with three degrees of freedom at each node, as shown in Figure (4). The mesh of the dam is shown in Figure (5) and meshing details in Table(3).The dam foundation is assumed to be rigid with fixed geometry to avoid the interaction between the dam and foundation, and to simplify the problem in analysis and design, where ux, uy, uz are restrained.

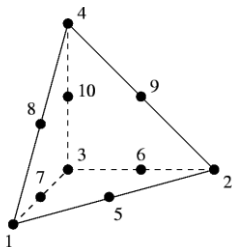


Figure 4. A tetrahedron quadratic element (10 node) [32]

Table 3. Mesh information – Details

Mesh type	Solid Mesh
Mesher Used	Standard mesh
Element Size	7.08647 m
Mesh Quality	High
Total Nodes	19146
Total Elements	12116

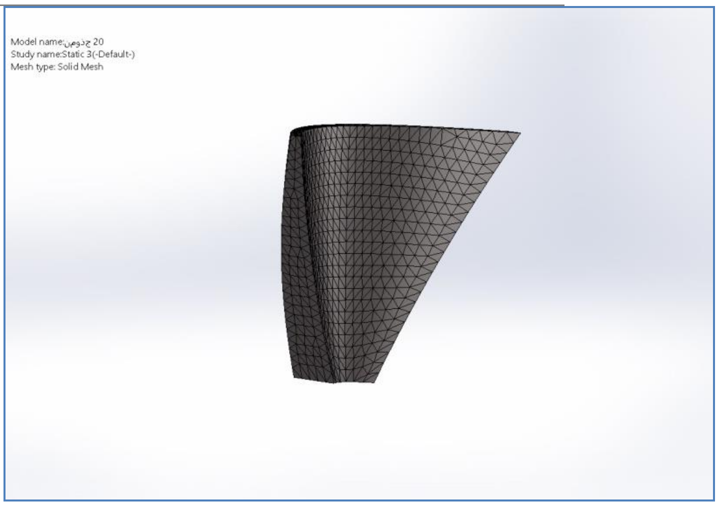


Figure 5. Arch dam mesh for initial model

3.4 Properties of the concrete used

The concrete is considered homogeneous, isotropic and linear. For analysis, there are several properties of the material which effect on the analysis of arch dams .These values are calculated according the following equation and summarized in Table (4)

1- Modulus of elasticity[30]: $E=4700\sqrt{fc'} = 4700\sqrt{40} = 29725.41$ MPa

2- Tensile strength [30] =(10% fc') = 4 MPa

3- Shear strength [30] $= 0.3\sqrt{fc'} = 1.9$ MPa

4- Shear modulus [23] $G = E/2(1+v) = 29725.41/2(1+0.2) = 12385.587$ MPa

Table 4. Properties of the concrete used in this study.

Modulus of Elasticity	29725.41 MPa
Compressive strength	40 MPa
Tensile strength [23]	4
Poison's ratio	0.2
Density of mass concrete	2400 kg / m^3
Shear modulus[30]	12385.587 MPa
Shear strength[23]	1.9 MPa
Cof. of thermal expansion	($8*10^{-6}$) per C°
Thermal conductivity	2.6 w/(M.k)
Specific heat	900 j/(kg.k)
Allowable stress in concrete	18 MPa

Other information used for the analysis is given below:

- The maximum water level 175m from the base.
- Annual temperature for air is 27 C°(from reference [8]).
- Average temperature of water layers is 19 C° (from reference [8]).
- Load combination according to references [25] and [23] that show in Figure (6) .

The load combination used in this study gravity load, water pressure and thermal load are applied on the dam body at the same time.

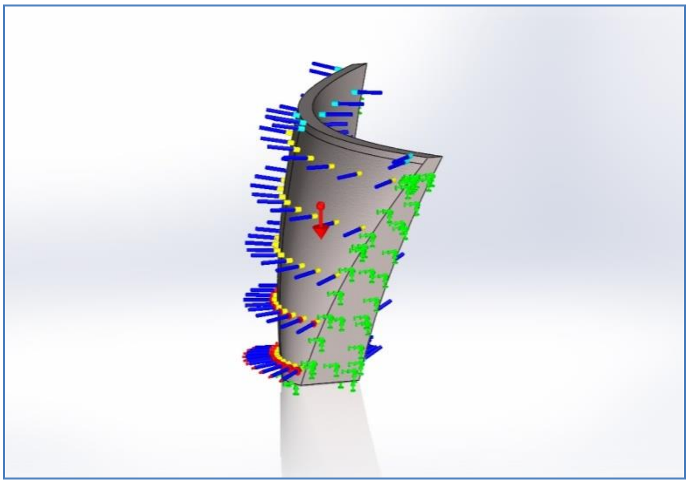


Figure 6. Load combination – up stream

3.4. Static load types

There are several types of static loads on arch dams, their importance and method of applying to the dam model are discussed below.

3.4.1 Gravity load.

Gravity loads caused by a mass of materials are calculated from the unit weight and geometry of Finite elements. A dead weight might be implemented for cantilevers without arc effect [25].

3.4.2 Reservoir Water pressure.

Most finite element programs deal with hydrostatic loads by distributing loads on the surfaces. Surface loads are then applied to the structure as concentrated nodal forces. In this way, hydrostatic change of the surface pressure could be indicated by utilizing a repertoire liquid surface and the liquid mass density as contribution as the condition shown in equation (10)[25]. The distribution only depends on the height (z). The maximum value of hydrostatic pressure occurs at the bottom of the arch dam. Water pressure is applied in a direction perpendicular to the surface and therefore a curved surface causes vertical and horizontal water pressure:

$$\mathbf{P_w = \gamma_w Z} \qquad \text{………..…….(10)}$$

Where:

$\mathbf{P_w}$ = water pressure.

γ_w = unit weight of water and $\mathbf{Z}$ = water elevation.

3.4.3 Thermal load.

Thermal loads play an important part in the design and safety evaluation of arch dams, especially when operating under severe temperature variations. Operating temperature loads are applied to the monolithic dam structure after the contraction joints are grouted [24]. Heat information needed in structural analysis came from the variance between the closure temperature and concrete temperature predicted in the dam body within its work. Temperature difference involves high and low heat limits and is usually different with the elevation of the arch in the downstream-upstream orientation [23]. In this study, determined annual temperatures are taken from literatures, which affect the downstream face and average of water temperature layers, which affect upstream.

3.4.4 Silt pressure. Arch dams are regularly subjected to silt pressure because of sedimentary materials saved in the reservoir. The saturated silt loads are treated as hydrostatically varying pressures acting on the upstream face of the dam and on the valley floor [25].

3.4.5 Ice load. Ice stress could apply noteworthy load on the dams situated at high elevations and ought to be deemed as a layout, load when the pieces of ice coverage is moderately thick. The actual ice weight is extremely hard to predict since it relies on upon various variables that are not simply accessible.

3.4.6 Uplift forces. An impact for uplift pressure on stress distribution in thin curved dam is immaterial and may be disregarded. However, uplift could affect the strength of a thick arch dam and ought to be considered in the analysis. Uplift or pore weight is created when water enters the interstitial spaces inside the body of a curved dam the foundation joints, cracks, and creases. The impact of uplift pressure is to decrease the typical compressive stresses on level segments inside concrete and for building a relating tensile stresses [25].

In this paper, three types of loadings are selected, namely (gravity, water pressure and thermal) for their important and high effect on dam stresses and displacements. The load combination on dam body and their distribution are as in Figure (6).The dam section are actually consists of steel reinforcements to support the dam body and reduce the tensile stresses in the dam which create cracks in dam body, but this is not considered in this study.

3.5 Static linear elastic analysis of arch dams

Static loads are loads that don't change with time. The reaction to static load is represented by the stiffness of the structure. In linear analysis, the relation between stress and strain in elastic materials can be described by the stress-strain diagram. There is a linear relation between stress and strain in small stresses, and a linear approximation of the stress-strain relation is frequently used to describe the structural behavior. Hooke's law is applied:

$$\boldsymbol{\sigma = E\epsilon} \qquad \text{............(11)}$$

Where:

σ = static stress.

E = modulus of elasticity and ϵ = strain in the model.

3.6 Von Mises Stress

Von Mises stress is referred to a hypothesis called the Von Mises-Hencky basis. In an elastic body that is interesting to an arrangement of loads in (3D) analysis, a complex (3D) arrangement of stresses is created. That is anytime inside the body there are stresses affecting in various orientations. The orientation and value of stress vary from point to another. A Von Mises hypothesis is a recipe for figuring if the stress combination at any point may cause failure [31].The general formula for Von Mises stress is given by [31]:

$$\sigma_v = \frac{1}{\sqrt{2}}\left[(\sigma_1-\sigma_2)^2+(\sigma_2-\sigma_3)^2+(\sigma_3-\sigma_1)^2\right]^{1/2} \text{..........(12)}$$

According to Von Mises failure criterion, the material under multi-axial loading will yield if the "Von Mises stress" exceeds the yield stress, then the material is thought to be at the failure condition [31].

$$\sigma_v \geq \sigma_y \ldots\ldots\ldots\ldots\ldots\ldots(13)$$

Where

$\sigma_1, \sigma_2, \sigma_3 =$ principal stresses. And σ_y =yield stress.

In this study σ_y is taken equal to ($0.45f_c' = 18$ MPa) reference[30].

3.7 Analysis results for initial design of arch dam

3.7.1 Stresses results

An initial design for double curvature arch dam with initial dimensions is analyzed by the *SolidWork* program, for combinations of design loads (gravity, hydrostatic pressure and temperature). Results show that the maximum *Von Mises* stress is (5.7467 MPa) at node no. 368(near the abutments) which is less than the allowable stress for concrete which is equal to (18 MPa). That leads to make this design feasible. A minimum stress is (2.10977E-006 MPa) at node no. 16546(at the up crest). The volume of the dam body for initial design is (577130 m^3).This is considered as the objective function to be minimized as the aim of the optimization process. Figure (7) below shows these values.

ame	Type	Min	Max
Stress1	VonMises Stress	2.10977E-006 MPa (Node: 16546)	5.74675MPa (Node: 368)

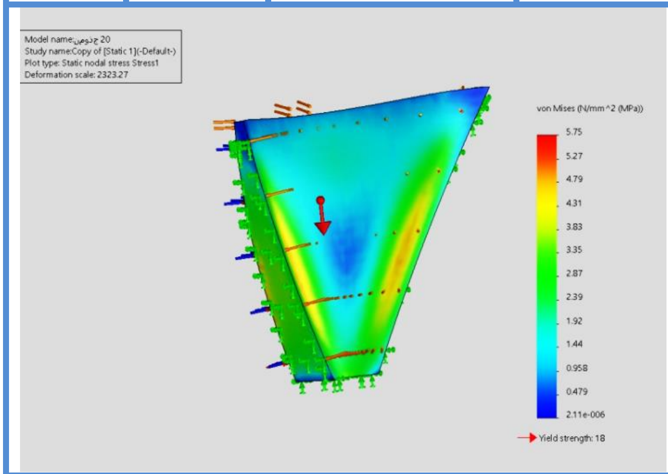


Figure 7. Analysis results for initial design of arch dam

3.7.2. Displacements results

For the same initial design, check for maximum and minimum displacements in the arch dam and their locations has been done. From the results of analysis, it is found that maximum displacement is (9.89 mm) at node (861) in the middle part of dam body ,then displacement decreases toward supports (fixed ends) and the base reaching to (0.00) at node (1) at the base and sides of the dam. Displacement results are shown in Figure (8).

Name	Type	Min	Max
Displacement	Resultant displacement	0 mm Node: 1	9.89 mm Node: 861

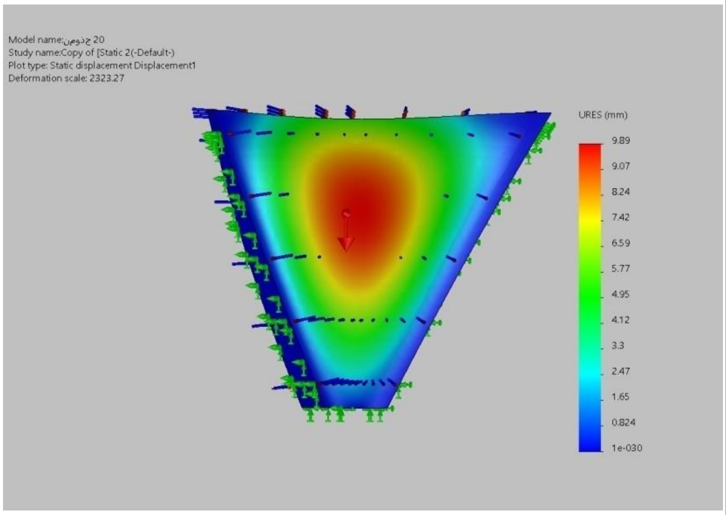


Figure (8): Displacements in the initial model of arch dam

4. Optimization of the Arch Dam

Optimization is the way toward altering the contributions to or attributes of scientific operations, or examination to locate the maximum or minimum product. The informations comprises two factors; a procedure or function is defined like the cost function, goal function, or wellness work. Briefly optimization is the investigation of how to locate the "best" (ideal) answer to an issue. Phrasing "best" arrangement suggests that there are more than one answer and the answers are not of equivalent amount [29].

4.1 Genetic algorithms (GA)

Genetic Algorithm (GA) is a technique which is discovered as a very useful tool which could be used in search and optimization problems. Today, GAs are used to solve complicated optimization problems in different branches of technology [33].

In this study, it is implemented particularly, in the optimum design of the arch dam.

4.2. Optimization steps in (GA)

The general optimization process using GA involves as follows[34]:

1) Production of starting populace: arbitrary populace ought to be produced to serve as the initial populace. Starting populace specifies a population size. In this study initial population is contained twenty solution all one represented volume of dam with different dimensions and that volume is an objective function.

2) Calculation of the best individuals: objective function value ought to be characterized to assess the individual fitness. The fitness (objective) function in this study represents the dam body volume, that is shown in equation (23) below. The best solution is that which gives us a minimum value for the objective function.

3) Selection: best people ought to be chosen as parents that will add to the number of next generation. In this study is used Tournament selection

4) Use of genetic operators, for example, crossover and mutation: crossover point and transformation point must be created to produce a new generation or new person.

- Crossover combines two individuals, or parents, to form a new individual, or child, for the next generation. Crossover in this study is a single point. Single point chooses a random integer n between 1 and a number of variables, and selects the vector entries numbered less than or equal to n from the first parent, selects genes numbered greater than n from the second parent, and concatenates these entries to form the child. For example:

P1 = [1 2 3 4 5 6 7 8] , P2 = [A, B, C, D, E, F, G, H]

Random crossover point = 3

Child = [A, B, C, 4 5 6 7 8]

- Mutation functions make little arbitrary improvements in the people in the populace, which give genetic assorted qualities and enable the genetic algorithm to look a more extensive space. In this study mutation rate is 0.01.

5) Providing stopping criteria: Termination conditions must be determined. In this study, it is selected equal to (100) generate as default and stall generations equal to (50) as default too.

- The parameter of GA techniques is given in Table (5).

Table (5): Parameters of GA

Parameters GA	Value
Population size	20
Crossover rate	0.9
Crossover method	Single point
Mutation rate	0.01
Maximum generation	100

4.3 Optimization problem

The problem in this study is to find a minimum volume of concrete. This aim is leading to a minimum cost for the dam. The optimization problem can be formulated as follows:

$$\text{Minimize} \quad V(x)$$

$$\text{Subject to:} \quad \{g_j(x) \leq 0,\ j=1\ 2\ 3\ldots..n\}\ldots\ldots\ldots..(14)$$

where

x = vector of design variables.

g_j = constraints.

$V(x)$ = volume of the dam body (The objective functions that need to be minimized).

4.4 Design variables

There are a number of variables, which affect directly the shape design of the arch dam. These variables define the shape and size of the dam. Therefore, in this study it is aimed to find the best values for these variables to get the optimum shape satisfying the design constraints and without failure. These variables in this study are chosen as follows:

$$D_v = \{ t_{c1}, t_{c2}, t_{c3} \} \qquad \text{.....................(15)}$$

Where:

D_v = design variable vector

4.5 Design constraints

The constraints represented some of functional relationship among the design variables and other design parameters satisfying certain physical phenomenon and certain resource limitations. The nature and number of constraints to be included in the formulation depend on the user. Constraints may have exact mathematical expressions or not [33].

There are three types of constraint sets for determining the shape of concrete arch dams. These constraints are required for the design control and construction. In this study, these constraints are:

1. Variable bounds: In this problem, the constraints surround the feasible region. Other problems may require the search algorithm within these boundaries. In general, all (N) design variables are restricted to lie within the minimum and the maximum limits as given below:

$$x_{iL} \leq x_i \leq x_{iU} \qquad \text{................(16)}$$

$$\text{for } i = 1, 2, 3, \ldots N$$

x_{iL}=lower bound to variable, and x_{iU}=upper bound to variable.

In this study the lower and upper bounds are selected from literatures as follows: [17]

$$4m \leq t_{c1} \leq 8m \quad , \quad 8m \leq t_{c2} \leq 30m \quad , \quad 12m \leq t_{c3} \leq 40m \qquad \text{.............. (17)}$$

2- Geometrical constraints.

A) The most important geometric constraint is that to avoid the increase of the dam volume for final design more than $V_{initial}$:

$$V_{final} < V_{Initial} \qquad \text{..................... (18)}$$

Where

V_{Final} = volume of final design.

$V_{Initial}$ = Initial volume of the dam.

B) Structural Constraints: In this study, the behavior constraints are defined to prevent stress failure in any element in the dam body frame:

$$\sigma_v < \sigma_{all} \qquad \text{.................(19)}$$

where:

σ_v = maximum Von-Mises stresses from all design load combinations.

σ_{all} = allowable stresses.

3- Stability restrictions: This restriction is to make sure of sliding stability of the dam. This is not considered in this study since the dam foundation is assumed rigid.

4.6 Objective function

The objective function is a math representation of the issue to be minimized in terms of design variables. The aim is to get the amount of these variables such that the objective function is a minimum.

In this study, the objective function represents the volume of arch dam. The volume V(x) is defined by number of equations calculated in (Matlab program) as follows:

$$V(x) = \iint_{Area} \left| Yd\,(x,z) - Yu\,(x,z)\right| dxdz \qquad \ldots\ldots(20)$$

Where

Area = area produced by projecting on xz plan.

Yu = equation for upstream curve as defined by equation (6).

Yd = equation for downstream curve as defined by equation (7).

Equation (20) is solved by Matlab and found to be:

$$Yu = \frac{x^2}{\left(\frac{z}{180}-0.5\right)*\left(\left(\frac{z}{180}-1\right)*4*m3\right)-\left(4*\left(\frac{z}{180}\right)\left(\frac{z}{180}-1\right)*m4\right)+\left(2*\left(\frac{z}{180}\right)*\left(\frac{z}{180}-0.5\right)*m5\right)+} - m1*z + \frac{m1*z^{\wedge}2}{360*m2} \qquad \ldots\ldots(21)$$

$$Yd = \frac{x^2}{\left(4*\left(\frac{z}{180}-0.5\right)*\left(\frac{z}{180}-1\right)*m6\right)-\left(\left(4*\frac{z}{180}\right)*\left(\frac{z}{180}-1\right)*m7\right)+\left(2*\left(\frac{z}{180}\right)*\left(\frac{z}{180}-0.5\right)*m8\right)} - (m1*Z) + \frac{m1*z^{\wedge}2}{360*m2} + \left(\left(\frac{z}{90}-1\right)*\left(\frac{z}{180}-1\right)*m9\right) - \left(\left(\frac{z}{45}\right)*\left(\frac{z}{180}-1\right)*m10\right) + \left(m11*\left(\frac{z}{180}\right)*\left(\frac{z}{90}-1\right)\right) \qquad \ldots\ldots\ldots(22)$$

Equation (23) results from substituting equations (21) and (22) into equation(20).

$$V(x) = \iint_{Area} \frac{x^2}{4m6\sigma2\sigma1 - \frac{2m7z\sigma2}{45} + \frac{m8\,z\,\sigma1}{45}} - \frac{x^2}{4m3\,\sigma2\sigma1 - \frac{2m4\,z\,\sigma2}{45} + \frac{m5\,z\,\sigma1}{45}} + 2m9\sigma2\sigma1 - \frac{m10\,z\sigma2}{45} + \frac{m11\,z\,\sigma1}{90}\,dxdz \qquad \ldots\ldots\ldots\ldots(23)$$

where

$$\sigma1 = \frac{z}{180} - 0.5 \quad \text{and} \quad \sigma2 = \frac{z}{180} - 1$$

{m1, m2, m3, m4, m5, m6, m7, m8, m9, m10 and m11} are symbols for design variables equivalent to {S, β, t_{c1}, t_{c2}, t_{c3}, R_{U1}, R_{U2}, R_{U3}, R_{D1}, R_{D2}, R_{D3}}. The objective function is coded and solved in Matlab program, then go to genetic algorithm tool in Matlab by m-file to apply (GA) process.

5. Optimization results

5.1. General:

After application the optimization process by the GA in Matlab and their options, which are mentioned before, a number of possible optimum solutions have been found. All of these solutions represented new shape for the design of the double curvature arch dam. Twenty of those solutions models have been chosen according to their suitability to dam shape and other samples are neglected. All these twenty samples are analyzed by finite element method by using (SolidWork program) and are checked against stress constraints. Finally, one of these samples is chosen with the minimum volume of the dam and minimum stresses (below the allowable limits of stresses).That final model represents the optimum shape design for the arch dam. The parameters of Genetic Algorithm are given in Table (5) and the optimal results are given in Table (6).

From the analysis results it can be noted that in all samples the maximum stresses are less than allowable stress. That makes all the samples to be successful (or feasible); but it is wanting to get a minimum volume and minimum stress, which is achieved in sample 9 where the volume is 266908.07 m^{3}and stress is 14.7 MPa.

The Plot for best fitness function in the genetic algorithm program is shown in Figure (9).

Table (6):Results of the twenty models for arch dam selected by Genetic Algorithm

Models	t_{c1} (m)	t_{c2} (m)	t_{c3} (m)	Volume(m^3)	Maximum Stress (MPa)
1	4.5	24.38	32.44	449779.13	8.49
2	4.6	22.86	28.9	415702.56	12.4
3	8.9	19.2	22.94	382592.92	7.95
4	4.7	13.6	26.44	276830.39	11.3
5	5.53	18.4	27.55	354787.16	14
6	8.34	12.34	26.4	284133.52	15.1
7	12	18.2	22.6	389365.01	8.12
8	5.8	15.18	23.67	303060.19	9.42
9	5.5	13.3	19.8	266908.07	14.7
10	6.2	12	28	268693.72	17.2
11	7.44	11.23	27.17	267820.20	16.4
12	4	18	21	327040.54	15.6
13	4.5	10.34	22.77	281541.72	16.4
14	6.3	13	25	276965.25	15.1
15	6	16.7	24.97	328901.73	8.78
16	5.4	13.56	23.94	276987.95	11.2
17	7	17.1	23.3	338515.00	14.5
18	5	20	25	370128.26	7.75
19	4.5	24.38	34.44	446572.63	11.2
20	5	15	20	288564.75	16

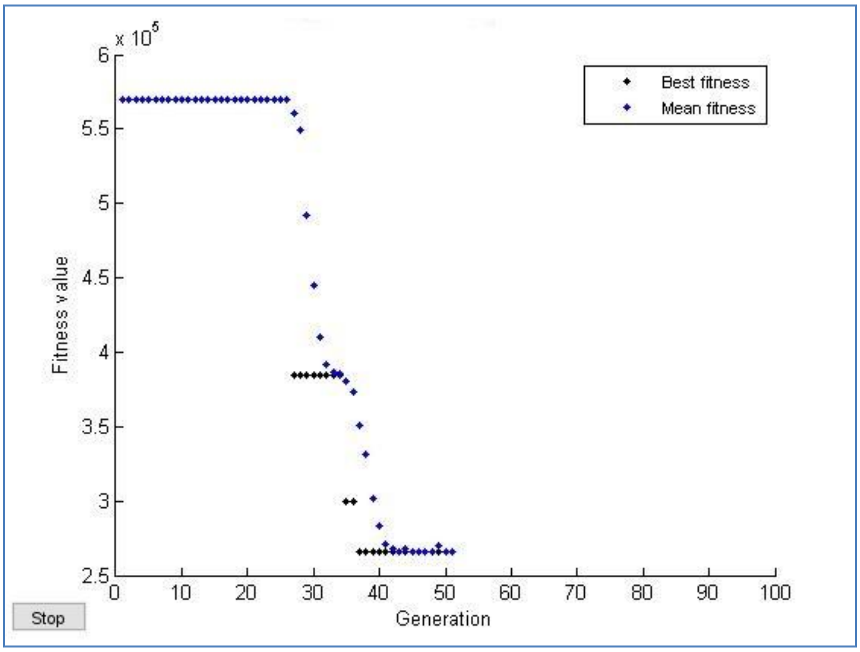


Figure (9): Plot for best fitness function in (GA)

From Figure (9) it is noted that there are a number of values of the fitness function in the diagram; but the last one is chosen from down because, it represents the global optimum and the others represent local optima.

5.2 Volumetric properties of optimum design

Volumetric properties for optimum shape shows that volume of concrete is reduced from (577130 m^3) in initial design to (266908.07 m^3) in the final design. This represents the objective function or aim of optimization process, which reduces the concrete volume keeping the maximum stress under the allowable limits as shown in Figure (10) and Table (7).

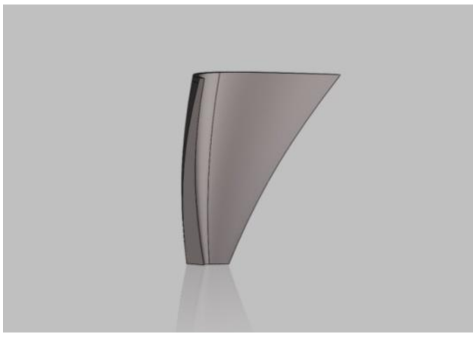
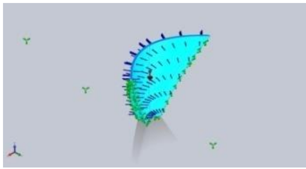


Figure (10): Optimum design for arch dam

Table (7): Volumetric properties o optimal design

Document Name and Reference	Treated As	Volumetric Properties	Document Path/Date Modified
	Solid Body	Mass:6.40579E+008 kg Volume:266908 m^3 Density:2400 kg/m^3 Weight:6.27768E+009 N	Optimum design

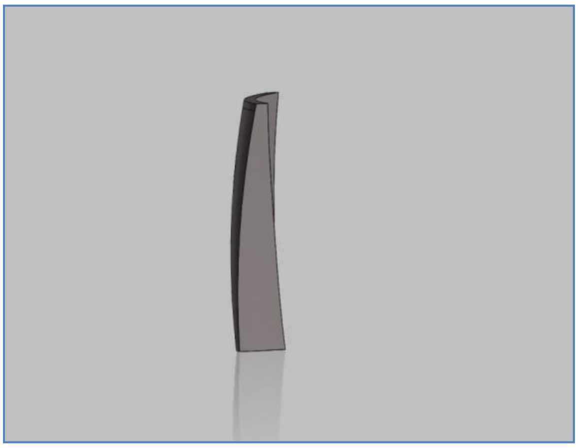


Figure 11. Central vertical section for initial model

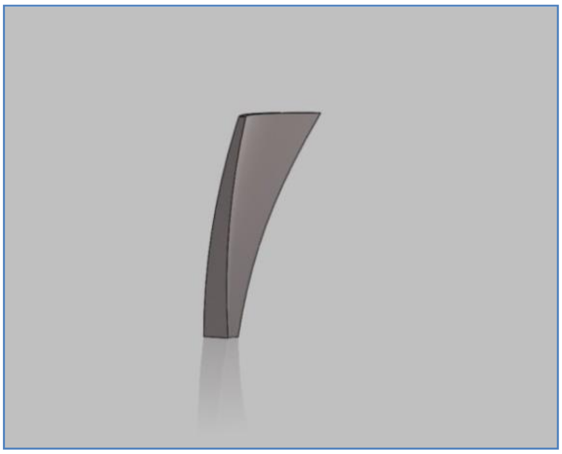


Figure 12. Central vertical section of optima model

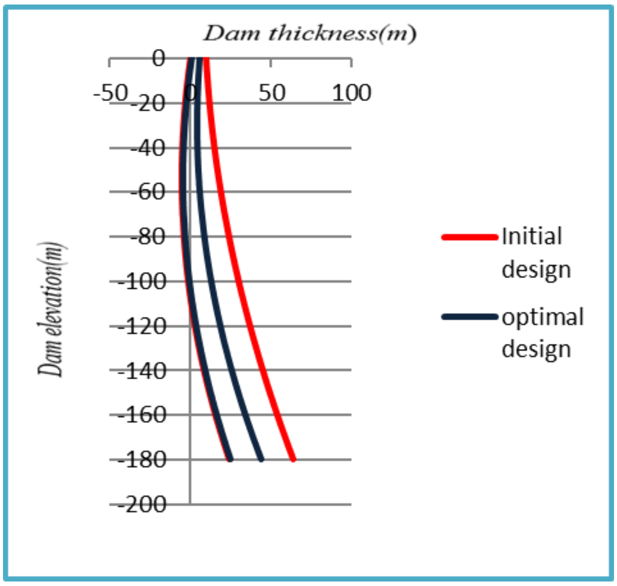


Figure (13): Initial and optimal vertical section.

From Figures 11,12 and 13 it can be noted the decreasing in thickness of a central vertical section of the arch dam and changing in the shape of the section, that lead to decreasing the total volume of the dam by (53.75%) with respect to initial design. The reducing in the dam volume helps to reduce the quantity of concrete used in dam construction and finally reduces the total cost of construction. This represents the aim of all optimization processes in most engineering projects. However, in this study the cost of construction is disregarded because the cost of concrete work changes with time and conditions. Therefore, the optimization study is based on volume of concrete only.

Table (8):Dimensions of arch dam in the initial and the optimum design.

Variables	Initial design	Optimum design	Percentage of reduction
t_{c1}	10	5.5	45 %
t_{c2}	30	13.3	55.6 %
t_{c3}	40	19.8	50.5 %
Volume	577130	266908	53.75 %

If we compare optimization results in (GA) in this study with optimization results in reference[17] where the shape optimization of the same arch dam with a height of 180 m is considered. The width of the valley in its bottom and top is 40 m and 220 m, for both studies. This reference made the optimization process in (GA) also but, by using (11) design variables while in this study only (3) variables are used and the other variables are chosen as constants or prescribed parameters. Although researcher in reference [17] used a much higher number of variables more than this study, but the optimum solution is rather converging as shown in Table (9). It is noted that the maximum stress in the two solutions is below the allowable limit and the volume of the two designs is rather converging where the percentage of the volume difference between the two solutions is only 3.99%. This result gives a confident to the present study by using only a small number of design variables, which represent the general shape of the arch dam quite accurately.

Table (9): dimensions of initial, optimal and Ref.[17] for arch dam.

Design variables	Valueinitial	Optimum	Ref. [17]
S	0.25	0.25	0.2254
β	0.8	0.8	0.8172
t_{c1}	10 m	5.5 m	4.43 m
t_{c2}	30 m	13.3 m	14.14 m
t_{c3}	40 m	19.8 m	23.2672 m
R_{U1}	100 m	100 m	129.39 m
R_{U2}	70 m	70 m	95 m
R_{U3}	25 m	25 m	39 m
R_{D1}	100 m	100 m	129.39 m
R_{D2}	70 m	70 m	95 m
R_{D3}	25 m	25 m	39 m
Volume(m^3)	577130	266907	277990.31
Max stress (MPa)	5.9	14.7	14.1

5.3 Analysis of final optimum design

5.3.1 Stress Results.

A final design for the double curvature arch dam is performed by SolidWork program for the design loads (gravity, hydrostatic pressure and temperature). The results show a maximum stress of (14.7277 MPa) at node no. 2650at downstream face, which is considered less than the allowable stress for concrete (which is taken as 18 MPa).The minimum stress is ($4.1468x10^{-7}$MPa) at node no. 2601 at downstream face near the base. Figure (14) below shows these values.

- From Fig. (14), it can be noted that the maximum stress is on the sides of the dam at abutments, and this value is less than the allowable stress. This value keeps the dam body without failure or cracking. The minimum value of stress occurs at the crest of the dam as it is expected.
- In spite of increasing in the stresses in final design, it is still within limitations and less than the allowable stresses, the minimum volume of the dam controls the final optimum design.

5.3.2 Displacement Results

In the final design, maximum and minimum displacements and their locations in the dam body have been checked. Figure (15) shows the results of displacements from which it is found that the maximum displacement is (25.5142 mm) at nodeno.2734 in the middle of dam body. Displacement is decreasing toward supports (fixed ends) and the base.

Name	Type	Min	Max
Stress1	*Von Mises stress*	*4.14682e-007 (MPa)Node: 2601*	*14.7277 MPa) Node: 2650*

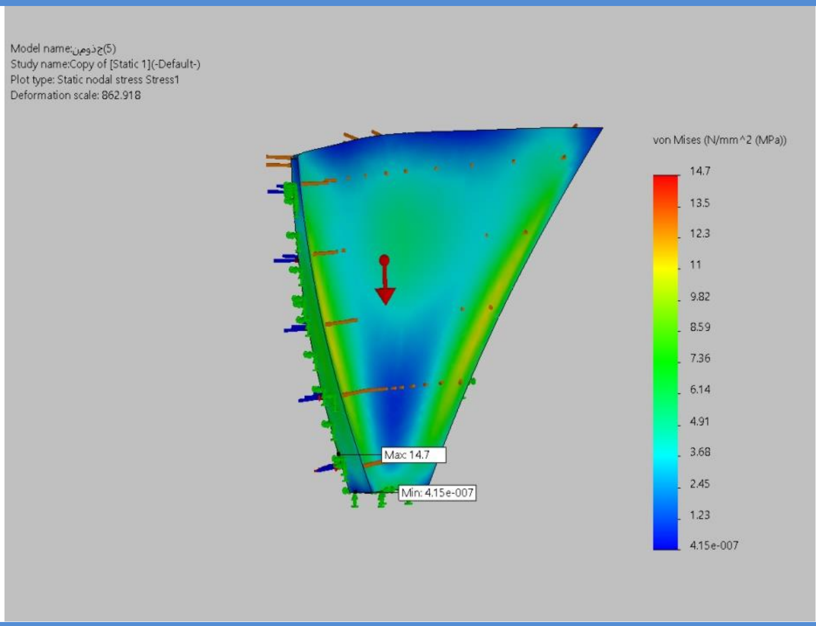


Figure (14): Von Mises stresses in optimum design

Name	Type	Min	Max
Displacement	URES: Resultant Displacement	*0.00 mm Node: 1*	*25.5142 mm Node: 2734*

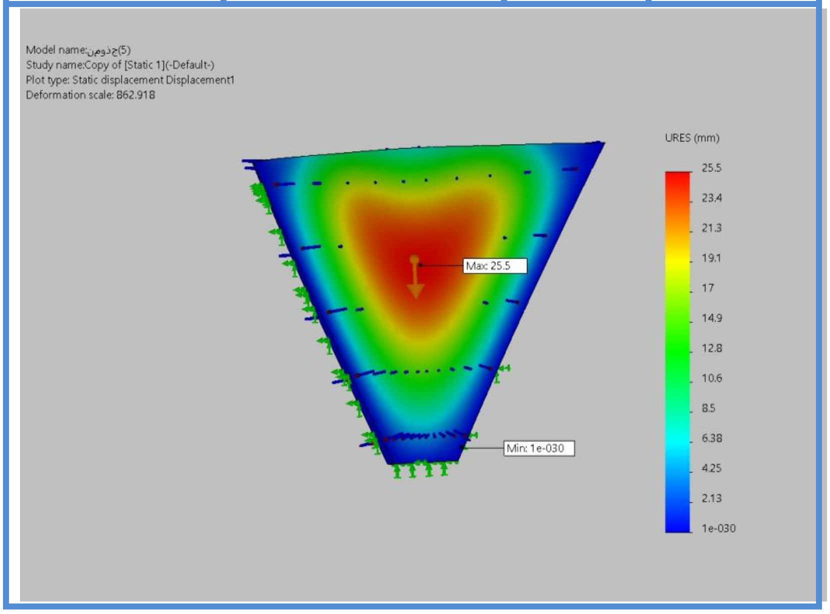


Figure (15): Displacements in the optimum design of arch dam.

6. Conclusions

1- Finite element applications with *SolidWorks* program is shown to be one of the best technique for modeling and analysis of large scale double curvature arch dams with different types of loading and different boundary conditions.

2- Using (GA) tool in Matlab program is shown to be efficient method to get an optimal design for double curvature arch dams to reduce the total volume of concrete and hence reducing the total cost of construction.

3- The results of optimization processes in (GA) gave minimum thickness for double curvature arch dam that has led to minimum volume subjected to functional design and allowable stress constraints.

4- Numerical results show that increasing in dam volume does not always lead to decreasing stresses in dams or keep the dam in safe side. Therefore, an optimization strategy must be followed in such a way to increase the thickness in places of high-expected stresses while reducing the thickness in low stress regions aiming to keep the total volume as a minimum.

5- The total volume of the dam body for initial design is 577130 m^3 and the corresponding weight is (1.35741E+007 kN). While for final optimum design model, the total volume is found to be (266908 m^3) and the corresponding weight is (6.27768E+006 kN). The percentage decrease in volume and weight in the final optimum design is (53.75%) with reference to initial design.

6- The maximum Von Mises stress for combined loads in initial model is (5.74675 MPa) at node (368) on the sides near the abutment and minimum stress is (2.1e-006 MPa) at the Node (16546) on the crest. While the maximum stress in optimal model is (14.7277 MPa) at node (2650) on the sides near the abutment and minimum stress is ($4.1468*10^{-7}$ MPa) at the node (2601) on the crest.

7- Maximum displacement in initial design is (9.89 mm) at (node 861) in the center of dam body and minimum displacement is (0) at node (1) at the supports. While the maximum displacement in optimal design is (25.51 mm) at (Node 2734) in the center of dam body and minimum displacement is (0) at node (1) at the supports.

8- Through comparing optimization results in this study with optimal results in Ref. [17],where the optimum volume in Ref. [17] equal to (277990.31 m^3*)* while in this study it is equal to (266908 m^3). It is noted that the maximum stresses in the two solutions are below the allowable limit and the volume of the two designs is rather converging. The percentage of the volume difference between the two solutions is only 3.99%. This result gives a confident to the present study by using only a small number of design variables (only three variables) which can define the general shape of the arch dam quite accurately, although Ref. [17] used a bigger number of design variables (11 design variables).

7. Recommendations for future researches

A number of suggestions to be investigated in future works presented as follows:

1- Using another method for optimizing processes and compare the results with (GA) to study the efficiency of tools in the kind of structures.

2- Study the effect of other loading types like earthquake, uplift forces and dynamic loads, and then find the optimum shape under combinations of these loads.

3- Study the effect of foundation type of the analysis and optimum shape design, then study the interaction between the two parts.

1- Select dam body with gates, spillway and study behavior of stress distribution on dam body.

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