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Optimal Economic Design of Diversion Structures during Construction of a Dam by Particle Swarm Optimization

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Abstract: ***Diverting river flow during construction of a main dam involves the construction of cofferdams, and tunnels, channels or other temporary passages. Diversion channels are commonly used in wide valleys where the high flow makes tunnels or culverts uneconomic. The diversion works must form part of the overall project design since it will have a major impact on its cost, as well as on the design, construction program and overall cost of the permanent works. Construction costs contain of excavation, lining of the channel, and construction of upstream and downstream cofferdams. The optimization model was applied to obtain optimalchannel cross section, height of upstream cofferdam, and height of downstream cofferdamwith minimum construction costs for diversion works which is solved by PSO method using MATLAB. The optimization model was applied to prepare the optimal design graphs.It can be noticed, at any design flowrate, optimalwater flow depth, bed width, and height of upstream and downstream cofferdams decrease with increase of the side-slope. Also, it can be observed, at any design flowrate, the construction cost increases with increase of the side-slope.***

Keywords: Diversion channel, Optimization, PSO Algorithm, Optimal economic design, Dam construction

1. Introduction

Controlling the river during construction of a main dam means providing one or more working areas that are free from water and safe from river floods, where the permanent works can be built in the dry. Diverting the river starts in summer when river level is low areas. This involves the constructioncofferdams, and tunnels, channels other temporary passages to take the river flow while construction proceeding in the river channel, and the subsequent closing off of these temporary passages for final river closure, when impounding begins [9].

A cofferdam on the upstream of the main damdirects water through the channel. A coffer dam on the downstream of the main dam prevents the river water from entering the construction area from below.The channel entrance is located upstream of the cofferdam, bypass the excavation site and exits below the downstream cofferdam. Diversion channels are commonly used in wide valleys where the high flow makes tunnels or culverts uneconomic. The cost of diversion works is composed of three elements, cost for channel excavation, cost for cross sectional surface lining and cost for upstream and downstream cofferdams[10].

The river diversion in channel is used for situations where it becomes economically unfeasible to carry out a tunnel or implant a conduit with sufficient size to ensure the flow of the design flow. The application of this solution is typical in sites where the topography is characterized by flattened valleys[5]. The river diversion in channel requires large earthworks for its structure construction. These moves allow the geotechnical characterization of the site where the diversion structure is required. The diversion channels lining takes a very important role in case of the very erodible soil or when safety conditions of the slopes are not guaranteed, with the possibility of collapse or slip. In the channel lining the most common materials are: concrete; stakes plank, rockfill and masonry [9]. The type of scheme used in the construction of diversion channels depends on the type of dam that the scheme operates. This solution can be used in concrete and embankment dams.As the mean flow velocity is usually less than 10 *m/s* is often necessary.

Hydraulic models are needed, in that some types of flow are not amenable to calculation. Flow conditions and scour risks are especially important, and erosion protection is essential in manycases [6]. Flow conditions at the inlet and outlet where the streamlines describe sharp turns with a very high risk of scour usually requires special study. A scale model would also show what material is deposited and where but this information is more qualitative than quantitative.

Saeed (2011) presented an optimization model to find optimum diameter of the tunnel and height of upstream cofferdam by using PSO. He found the relation between the optimum diameter of the tunnel, height of upstream cofferdam, and total diversion cost with flood discharge. While Adarsh (2010) developed optimization model for composite channel design considering slope stability constraint using particle swarm optimization. This method is applied for different soil conditions to show its practical applicability. The solutions are compared with those obtained by a hybrid optimization procedure involving generic algorithm (GA) and sequential quadratic programming (SQR).

Many of research's in open channels were presented to obtainthe optimal design by using a different techniques to solve their proposed models, as Das (2000) developed a nonlinear optimization framework to find optimal design of trapezoidal channel with composite roughness using Lagrange multipliers(LM). Jain et al. (2004) proposed a nonlinear optimization program to obtain optimal dimensions of trapezoidal channel section via genetic algorithms (GA). Bhattacharjya (2006) presented optimization model to design trapezoidal channel using sequent quadratic programming (SQP).Also, Swamee et al. (2000) proposed optimal open channel design considering seepage losses in the analysis.This study is attempted to determine the optimal height of upstream and downstream cofferdams and the characteristics of diversion channel such as their water flow depth, side-slope, and bed widthby minimizing construction costs of the diversion works

2. Study Case and Data Collection

The data obtained from the Ministry of Water Resources based on monthly flow rate in the Lower Zabduring 1961-2000. The maximum flow rate during the six months of each year (May, June, July, August, September and October) was taken to calculate the annual maximum flow rate which used to determine the design flow rate based on Gumbel's distribution method.

3. Hydrological Considerations

Flowratedata in (m^3/s) for forty water years for Lower Zab River were collected from the Iraqi Ministry of Water Resources. Figure (1)showsthe annual data for flowrate flow through the Lower Zab River from 1961 to 2000. The maximum flowrate flow of648 m^3/s was recorded in 2000 whereas the lowest flowrate flow of 100 m^3/s occurred in 1973.Gumbel's distribution is perhaps the most widely used distribution for the estimation of floods of various recurrence intervals. As per this method, the magnitude of the flood with recurrence intervals is adoptedon the design of the channel as 730.270 m^3/s.

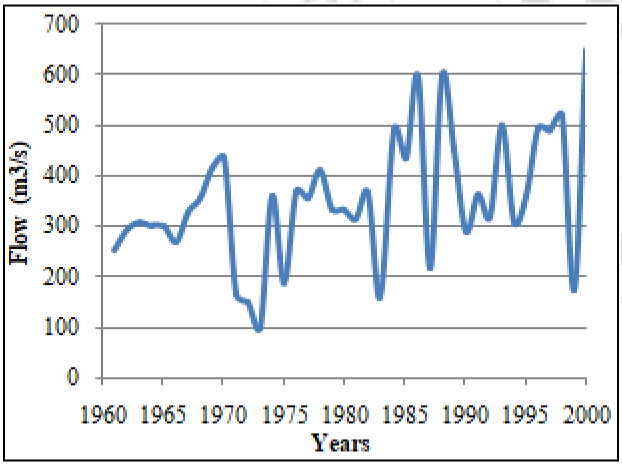


Figure 1: Annual flow rate in the Lower Zab River from 1961-2000

4. Geometric Assumptions

Figure (2) is a cross section of a trapezoidal channel with side-slope(z:1). Thewater flow depth, bed width, and free board of the channel are y, b, and f, respectively. The manning's coefficient value is represented as n of the channel. The length of channel is set depending on extend of the site required to still dry. The slope of channel is same as river bed slope. The hydraulic parameters are computed as:

1)

2)

$$A_W = b * y + z * y^2 \quad (1)$$

$$P_W = b + 2y\sqrt{1 + z^2} \quad (2)$$

$$R_h = \frac{A_W}{P_W} \quad (3)$$

$$A_T = b(y + f) + z(y + f)^2 \quad (4)$$

$$P_T = b + 2(y + f)\sqrt{1 + z^2} \quad (5)$$

Where

b = bed width, (m)

y = water flow depth, (m)

P_w=wetted perimeter, (m)

A_w = wetted area, (m^2)

Rh =hydraulic radius, (m)

z = side-slope

f = freeboard, (m)

P_T = total perimeter, (m)

A_T = total area, (m^2)

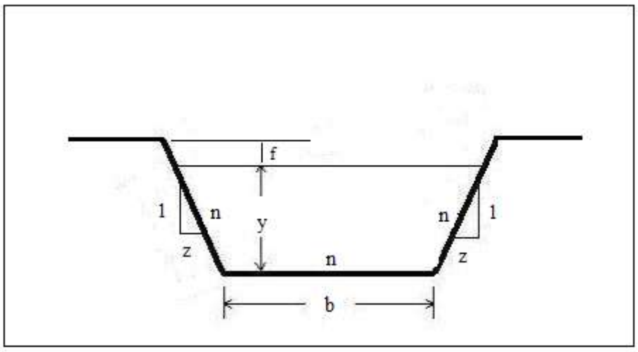


Figure 2: Cross section of trapezoidal channel

The type of cofferdams used is earth embankment dam. Figure (3) shows a cofferdam with upstream side-slope of z_u:1 and downstream side-slope of z_d:1. The crest width (top width), height of cofferdam, and freeboard are a, H, and ff, respectively.

$$A_{CD} = a * H + .5(z_u + z_d)H^2 \quad (6)$$

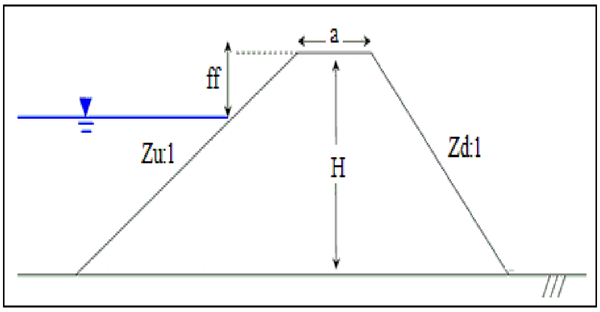


Figure 3: Cofferdam cross section

where

z_d = downstream side-slope of the cofferdam

ff = freeboard of the cofferdam, (m)

z_u=upstream side-slope of the cofferdam

a = cofferdam top width, (m)

H= height of the cofferdam, (m)

A_{CD} = area of cofferdam, (m^2)

The hydraulic assumptions adopted in model building as:

The regime of flow taking place in the channel is subcritical.

The approach velocity in the reservoir is assumed negligible.

3) The flow in the channels is uniform.

4) Local head losses.

Entrance loss at the channel inlet	$h_{l1} = k_1 \frac{V^2}{2g}$	(7)
Bend loss due to two bends	$h_{l2} = 2k_2 \frac{V^2}{2g}$	(8)
The friction loss along the channel surface	$h_f = S_f L = \frac{2g}{R}$	(9)
The Manning's equation in an open channel [16]	$\frac{nQ}{\sqrt{S_o}} - \frac{A_W^{5/3}}{P_W^{2/3}}$	(10)

The energy equation applied to this flow yields. Assume further on that the channel is long enough for the uniform flow to take place, then S_f=S_o.

$$H_e = y_e + \frac{V_e^2}{2g} + EL_e \quad (11)$$

$$H_o = y_o + \frac{V_o^2}{2g} + EL_o \quad (12)$$

$$H_e = H_o + total\ head\ loss = y_o + \frac{V_o^2}{2g} + EL_o + h_{l1} + \quad (13)$$

$$H_e = y_o + EL_o + (1 + k_1 + 2k_2) \times \frac{V_o^2}{2g} + S_o L \quad (14)$$

Upstream cofferdam crest level=$H_e + ff$

Maximum dam height of upstream cofferdam = Dam crest level-minimum Bed level.

$$H_U = H_e + ff - B.L \quad (15)$$

$$H_U = y_o + EL_o + (1 + k_1 + 2k_2).\frac{V_o^2}{2g} + S_o L + ff - B.L \quad (16)$$

Downstream cofferdam crest level =$H_o + ff$

$$H_D = H_o + ff - B.L \quad (17)$$

$$H_D = y_o + EL_o + \frac{V_o^2}{2g} + ff - B.L \quad (18)$$

Where

n = manning's coefficient

Q = design flowrate, (m^3/s)

g = gravitational acceleration, (m/s^2)

h_f = head loss friction, (m)

h_{l1} = entrance loss at the channel inlet, (m)

h_{l2} = Bend loss due to two bends, (m)

y_e = water flow depth at the entrance channel, (m)

V_e = velocity of flow at the entrance channel, (m/s)

EL_e = elevation at the entrance channel, (m)

H_e = hydraulic head at the entrance channel, (m)

H_U = height of the upstream cofferdam, (m)

S_o = slope of the channel

V = velocity of flow, (m/s)

EL= Bed level, (m)

S_f=friction slope

k_1 = loss coefficient at the channel inlet

k_2 = loss coefficient at the bends

y_o = water flow depth at the exit channel, (m)

V_o = velocity of flow at the exit channel, (m/s)

EL_o = elevation at the exit channel, (m)

H_o = hydraulic head at the exit channel, (m)

H_D = height of the downstream cofferdam, (m)

5. Optimization Analysis

The optimization analysis was applied to obtain the optimal channels dimensions, height of upstream and downstream cofferdams with minimum construction costs for diversion works .Construction costs contain of excavation,lining of the channel, and construction of upstream and downstream cofferdams. The optimization model can be written as,

$$minC_T = C_{11}\, L\, A_T + C_{22}\, L\, t\, P_T + C_{33} W\, A_{CD\,(U/S)} + C_{33}\, W\, A_{CD\,(D/S)} \quad (19)$$

Subject to (20)

$$G1 = \left| \frac{nQ}{\sqrt{S_o}} - \frac{A_W^{5/3}}{P_W^{2/3}} \right| - \varepsilon \le 0 \quad (21)$$

$$G2 = \left| H_U - y_o - EL_o - (1 + k_1 + k_2).\frac{V_o^2}{2g} - S_o L - ff + B.L \right| - \varepsilon \le 0 \quad (22)$$

$$G3 = \left| H_D - y_o - EL_o - \frac{V_o^2}{2g} - ff + B.L \right| - \varepsilon \le 0 \quad (23)$$

$b, y_o, z_1, H_U, H_D \ge 0$

where

C_T=construction cost of channel and cofferdam, (US $)

C_{11}=excavation cost per unit volume of the channel, (US $ /m^3)

C_{22}=lining cost perunit volume of the channel, (US$ /m^3)

C_{33}=full cost per unit volume of the cofferdam; (US $ /m^3)

t=lining thickness, (m)

W= length of the cofferdam, (m)

$A_{CD(U/S)}$=area of upstream cofferdam, (m^2)

$A_{CD(D/S)}$=area of downstream cofferdam, (m^2)

ε =error tolerance

PSO methodwith MATLAB softwareis used to solve the optimization model.

6. Particle Swarm Optimization Algorithm (PSO)

The Particle Swarm Optimization algorithm (PSO) is an algorithm depends on stochastic search method for solving the nonlinear optimization problem. Kennedy and Eberhart in 1995developed the PSO algorithm. PSO algorithm, all particles are initialized randomly, calculated initial fitness, and selected the personal best and global best. In the next step, the particle velocity is calculated by the personal best and global best, and the particle position is calculated by the present velocity. Evaluate fitness of each particle and update personal best and global best. The steps are ended with a stopping criterion predetermined in advance. The velocity equation of the particles is:

$$V_{i,j}^{k+1} = \omega * V_{i,j}^{k} + c_1 * rand(\,) * \left(Pbest_{i,j}^{k} - X_{i,j}^{k}\right) + c_2 \quad (24)$$

$$X_{i,j}^{k+1} = X_{i,j}^{k} + V_{i,j}^{k+1} \quad (25)$$

Where
V = velocity vector
j = number of dimensions (variables)
i = particle in the population
k = iteration
ω = inertia coefficient
c_1 = personal acceleration coefficient
c_2 = social acceleration coefficient
P_{best} = personal best position vector
G_{best} = global best position vector
X = position vector

7. Results and Discussion

Table (1) contains the basic assumptions used in this study to determine optimal design of trapezoidal channels cross section and height of upstream and downstream cofferdams.The proposed model was used to find optimal cross section of channels (the optimalwater flow depth,side-slope, and bed widthof channel), and as well as the optimal height of upstream cofferdam and the optimal height of downstream cofferdam at any value of design flowrate. Table 2 shows the MATLAB software results from optimization models after adopting the design flowrate is 730.270 m^3/s. The choice of side-slope is due to the designer and the site conditions, so, the Table 2 shows for each side-slope imposed by the designer there is the optimal bed width, water flow depth, and the optimal height of upstream and downstream cofferdams.

Table 1: Assumptions employed in the optimization model

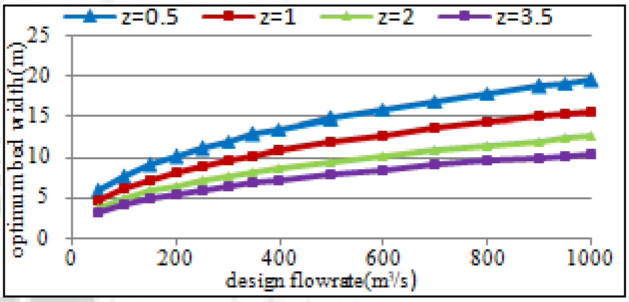
	Item	Description and assumptions
Channel	Side-slope, z	0.5 to 3.5
	Bed width, b (m)	1 to 20
	Water flow depth, y(m)	1 to 20
	Freeboard, f(m)	.5
	Lining thickness,t(m)	.2
	Manning's coefficient, n	0.025
	Bed slope, S_o	0.0025
	Flowrate ,Q(m^3/s)	50 to 1000
	Length, L (m)	1200
	Elevation U/s, EL_e (m)	137
	Elevation D/s, EL_o (m)	140
cofferdam	Type	Embankment dam
	Top width, a (m)	8
	Average length, W(m)	100
	Free board, ff (m)	2
	U/s slope, Z_u	2.5:1
	D/s slope, Z_d	2:1
Cost	Channel excavation, C_{11}	10 \$ /m^3[8]
	Channel lining, C_{22}	250 \$ /m^3[8]
	Fill for cofferdam, C_{33}	10 \$ /m^3[8]
PSO parameters	Population size, n	100
	Inertia coefficient, ω	.9
	personal acceleration coefficient, c_1	2
	social acceleration coefficient, c_2	2

Table 2: Results from optimization models

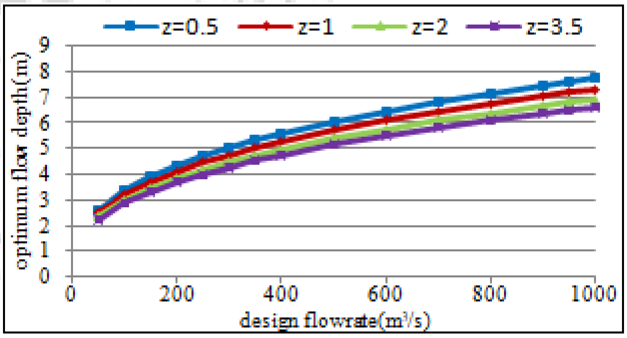
Q (m^3/s)	Z	b optimal	y optimal	H_U optimal	H_D optimal	Cost $*10^6$ \$
730.27	.5	17	6.8	16.6	13.1	5
	1	14	6.7	16.5	13	5.1
	1.5	12.5	6.5	16	12.7	5.4
	2	12	6.2	15.7	12.3	5.7
	2.5	9.8	6.2	15.5	12.2	6
	3	8.7	6	12.3	12	6.3

The optimization model was used to prepare optimal design graphs.For each value of side-slope, the proposed model runs with different design flowrate to determine the optimalwater flow depth, bed width,and height of upstream and downstream cofferdams.

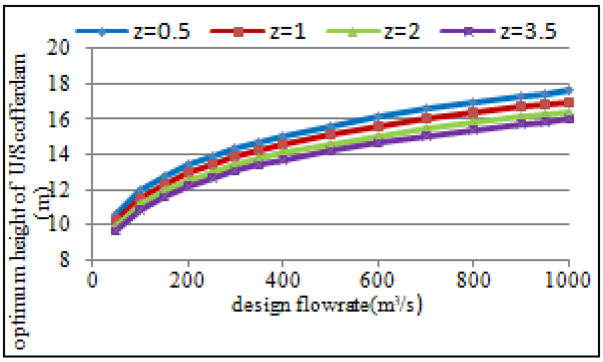
The first graph (Figure 4-a) can be utilized to find the optimal bed width, the second graph (Figure 4-b) can be utilized to find the optimal water flow depth, the third graph (figure 4-c) can be utilized to find the optimal height of upstream cofferdam, and the fourth graph (Figure 4-d) can be utilized to find the optimal height of downstream cofferdam, at any design flowrate, and side-slope of the channel.



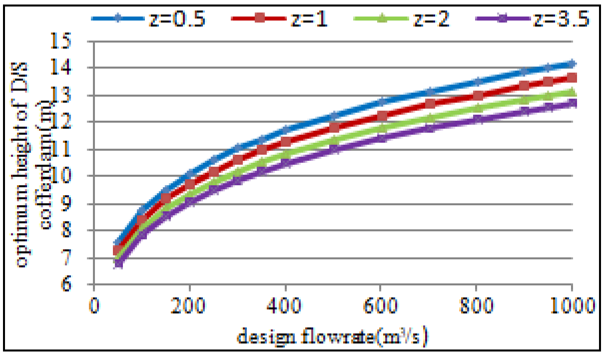
(a) Design flow rate versus bed width



(b) Design flow rate versus water flow depth



(c) Designflowrate versus height of upstream cofferdam



(d) Designflowrate versus height of downstream cofferdam

Figure 4: Optimal design graphs

It can be noticed from this figure that, at any design flowrate, the optimalwater flow depth, bed width, height of upstream and downstream cofferdams decrease with increase of the side-slope.The optimal design graphs are used to find the optimalbed width, water flow depth, cofferdam height and construction cost instead of using the proposed model direct application.

Figure (5) shows the relation between the construction costs anddesign flowrate for different values of side-slopes. It can be noted from this figure, at any design flowrate, the values of construction cost increases as the values of side-slope increases.

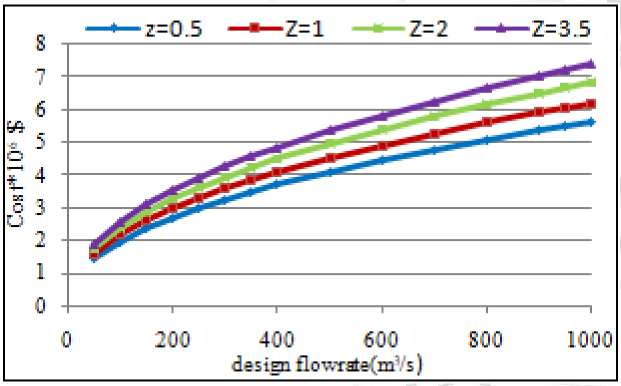


Figure 5: Design flow rate versus construction costs

By applying regression technique to optimization results the following equations were reached:

Optimal equation		R^2
$b_{(optimal)} = .918\ z^{-0.325}\ Q^{.41}$	(26)	0.972
$y_{(optimal)} = .601\ z^{-0.082}\ Q^{.362}$	(27)	0.981
$H_{U(optimal)} = 5.294\ z^{-0.049}\ Q^{.169}$	(28)	0.977
$H_{D(optimal)} = 3.193\ z^{-0.057}\ Q^{.21}$	(29)	0.979
$Cost = .264\ z^{.138}\ Q^{.457}$	(30)	0.983

The results of the proposed model were used in the SPSS software to find these equations, which are used to find the optimalbed width, water flow depth, cofferdam height and construction cost instead of using the proposed model direct application.

8. Conclusions

In this paper the optimization model was presented to investigate the optimal design parameters of the diversion structure, water flow depth, bed width of channel, andheight of upstream and downstream cofferdam which is solved by PSO method using MATLAB and predicated the optimal design graphs. It can be noticed, at any design flowrate, optimalbed width, water flow depth,height of upstream and downstream cofferdams decreasewith increase of the side-slope. Also, it can be observed, at any design flowrate, construction cost increase with increaseof the side-slope.

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