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A Parametric Study for the Optimal Design of Barrages

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Abstract— The barrage is a major diversion structure involved in canal head works and meant for local ponding and regulating river water level. The cost of a barrage will vary for different values of design parameters which address different types of soil and hydrological conditions and that govern barrage profile dimensions. In this paper a parametric analysis was conducted to investigate the effect of variation in the design parameters values on the dimensions and on overall cost of the barrage with utilization of the optimization approach to find optimal hydraulic design of the barrage. It was showed that the flood discharge have the greatest effect on the total cost of the barrage and a barrage constructed on fine grained soil is costlier than that constructed on a foundation of coarser bed material.

Index Terms— Nonlinear optimization problem, Genetic Algorithm, Hydraulic Design, Diversion Barrage, Parametric Analysis.

1 Introduction

Hydraulic structures such as weirs and barrages are costly water resources projects. A safe and economic design of hydraulic structures is always being a focus of attention to water resource researchers. Barrages on permeable soils (Fig. 1) are subjected to subsurface seepage and surface flow.

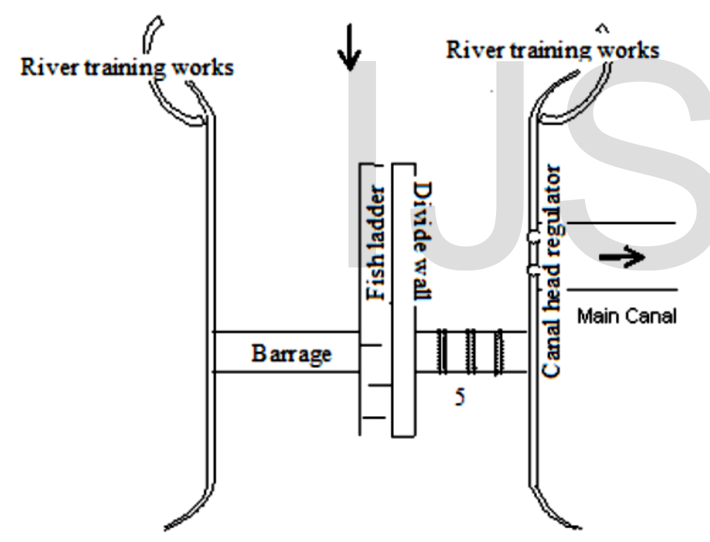

Fig. 1. Schematic of layout of Barrage [1]

The seepage head causing the subsurface seepage varies with variation in surface flows, during low flow periods in a river the gates may be closed or opened partially and thus the seepage flow will be maximum if the downstream water level was too low, but as the discharge increases the gates are raised more and more until full opening to provide unobstructed flow for the case of high flood discharge. Moreover the occurrence of Retrogression, a phenomenon that is more prominent in alluvial reaches, it causes reduction in downstream (D/S) Water Level (H_D). On account of retrogression, for a certain river discharge the d/s water level would be lesser than upstream (U/S) water level (H_U). As a result of this reduction in stages, for the same river flow a non-degraded riverbed may reveal submerged flow (Fig. 2-a) compared to a free flow (Fig. 2-b) anticipated in degraded riverbed [2].

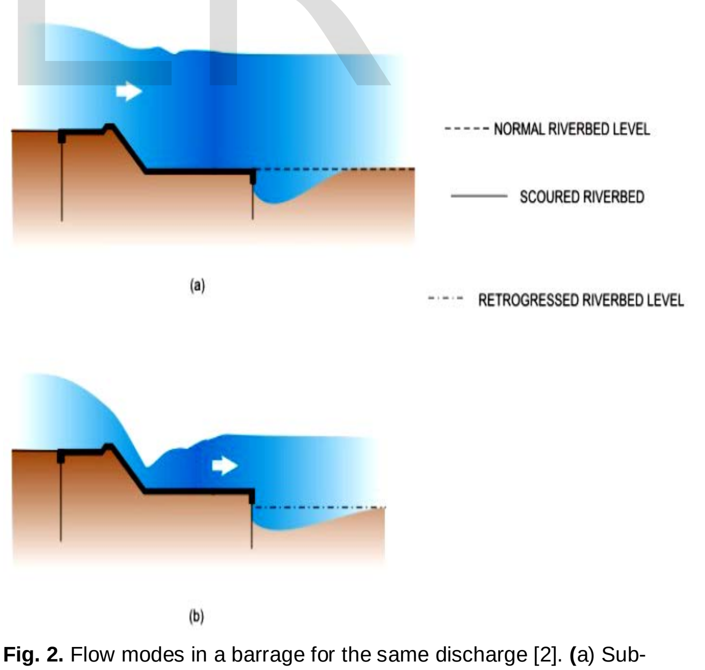

Fig. 2. Flow modes in a barrage for the same discharge [2]. **(**a) Submerged flow (b) Free flow

The design should insure safety against the flow conditions induced failure of the structure. The characteristics of surface and subsurface flows are taken into considerations while designing a barrage. Hydraulic design involves fixing the dimensions of a barrage component parts via the available formulae from a standard design code, the barrage generally in-

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cludes spillways, reinforced concrete raft floor, cut-offs, sheet-piles and protecting aprons in u/s and d/s sides. The crest level, downstream floor length, and minimum depths of upstream and downstream sheet-piles/cutoffs are mainly governed by surface flow considerations. The seepage head affects the downstream sheet-pile depth, overall length of impervious floor and thickness of impervious floor. The exit gradient, which is considered the most appropriate criterion to ensure safety against piping on permeable foundations, exhibits non-linear variation in floor length with variation in depth of downstream sheet-pile.

However, an optimization problem may be formulated to obtain the optimum structural dimensions that minimize the cost as well as satisfy the safety requirements. The optimization problem for determining an optimal profile for the weirs or barrages normally consists of minimizing the construction cost, earth work, cost of sheet piling and protection works. The flow conditions are embedded in the optimization formulation.

Earlier work [3] discussed the optimal hydraulic design of barrage profile for single deterministic value of the design parameters. This study first solve the optimization problem using genetic algorithm (GA) which gives optimal dimensions of the barrage profile that minimizes cost of concrete work, sheet-piling, cement concrete blocks, graded gravel, stones/boulders, earth works and the gates. It searches the barrage dimensions satisfying the safety requirements. The work is then extended to characterize variation in design parameters due to different soil and hydrological conditions and hence variation in dimensions and in overall cost of the barrage.

2 OPTIMAL DESIGN METHODOLOGY

The optimization problem involving the minimization of barrage overall cost may be stated as in the following model:

$X = [x_1 \quad x_2 \quad x_3 \quad x_4 \quad x_5]$ which minimizes

$$C(X) = c_1(f_1) + c_2(f_2) + c_3(f_3) + c_4(f_4) + c_5(f_5) + c_6(f_6) + c_7(f_7) - c_8(f_8) + c_9(f_9) \quad \ldots(1)$$

Subjected to

$$h_a - x_1 \le 0 \quad \ldots(2)$$

$$d_1 - x_3 \le 0 \quad \ldots(3)$$

$$d_2 - x_4 \le 0 \quad \ldots(4)$$

$$b - x_5 \le 0 \quad \ldots(5)$$

$$v_3 - v_l \le 0 \quad \ldots(6)$$

$$x_1^l \le x_1 \le x_1^u \quad \ldots(7)$$

$$x_2^l \le x_2 \le x_2^u \quad \ldots(8)$$

$$x_3^l \le x_3 \le x_3^u \quad \ldots(9)$$

$$x_4^l \le x_4 \le x_4^u \quad \ldots(10)$$

$$x_5^l \le x_5 \le x_5^u \quad \ldots(11)$$

where C (x_1, x_2, x_3, x_4, x_5) is objective function represents total cost of barrage spillways section in unit price (U.P.), and is function of the design variables that would be optimized as follows:

x_1 : Maximum permissible afflux (m).
x_2 : Gated spillway span (m), integer variable.
x_3 : Depth of the upstream sheet-pile (m).
x_4 : Depth of the downstream sheet-pile (m).
x_5 : The impervious floor length (m).

The functional parameters ($f_1, f_2, \ldots, f_9$) involved in the objective function for a typical profile in a barrage spillways section is outlined herein:

f_1 : Total volume of concrete for a given barrage profile, (m^3).
f_2: Area of sheet-piling below concrete floor in u/s side, (m^2).
f_3: Area of sheet-piling below concrete floor in d/s side, (m^2).
f_4 : Quantity of concrete blocks for the block apron, (m^3).
f_5 : Quantity of gravel under the block apron on d/s, (m^3).
f_6: Quantity of stones/boulders for the flexible apron, (m^3).
f_7: Total volume of excavated soil, (m^3).
f_8: Total volume of soil required in filling, (m^3).
f_9 : Weight of the gates, (kg).

The prices of materials and all entries required to evaluate the cost of a barrage profile in unit price (U.P.) is explained below:

c_1 : Cost of concrete (labor and material), (unit price/m^3).
c_2 :Cost of u/s sheet-piling includes driving, (unit price/m^2).
c_3 : Cost of d/s sheet-piling includes driving, (unit price/m^2).
c_4 : Cost of cement concrete blocks, (unit price/m^3).
c_5 : Cost of graded gravel for inverted filter, (unit price/m^3).
c_6 : Cost of stones or boulders, (unit price/m^3).
c_7 : Cost of excavation with dewatering , (unit price/m^3).
c_8 : Cost of earth filling, (unit price/m^3).
c_9 : Cost of a gate, (unit price/kg).

x_1^l, x_2^l, x_3^l, x_4^l and x_5^l are lower bound on x_1, x_2, x_3, x_4, x_5 respectively; $x_1^u, x_2^u, x_3^u, x_4^u$ and x_5^u are upper bound on x_1, x_2, x_3, x_4, x_5 respectively.

Constraints used in this model are applied to ensure that the barrage constructed with minimum cost will satisfy all the necessary requirements to perform its function safely and efficiently, these constraints include:

1) The observed afflux (h_a) at the design flood shouldn't exceed the maximum permissible afflux (x_1) with consideration of 20% flow concentration, where:

$$h_a = H_s - HFL \quad \ldots(12)$$

H_s : Total head above crest.

HFL = The corresponding river water level at the design flood.

2) The provided depth for pile lines in upstream and downstream should not be less than that required from scour considerations (d_1) and (d_2). In alluvial rivers the depth of scour can be evaluated from formulae as given by Lacey's:

$$R = 0.473\left(Q/f\right) \quad \text{looseness factor} > 1 \quad \ldots(13)$$

$$R = 1.35\,(q^2/f)^{(1/3)} \quad \text{looseness factor} \le 1 \quad \ldots(14)$$

R : Measured scour depth below flood level in (m).

Q : Discharge over the crest, (m^3/sec).

q : Discharge per unit length of spillway, (m^3/sec per length).

f : Silt factor (m).

$$d_1 = RL - (H_u - R) \quad \ldots(15)$$

$$d_2 = BL - (H_D - R) \quad \ldots(16)$$

RL : Average river bed level (m).

BL : Basin level (m).

3) The total length of impervious floor in conjunction with the depth of d/s sheet-pile should cater for safety requirements against piping failure:

$b = x_4 \, [\{2(H/ \, [\pi.SEG.x_4] \,)^2 - 1\}^2 - 1]^{(1/2)}$ …(17)

b : total floor length for safety against piping, (m).

4) The d/s velocity (v_3) should be kept to a limiting value (v_1), since the increase in its value due to a high discharge intensity may initiate displacement of loose stone apron, where

$V_3 = q/R$

…(18)

2.1 Characterizing Model Design Parameters

For a specified barrage profile geometry (Fig.3) and hydrological conditions, the functional parameters f1, f2, f3,f4, f5, f6, f7, f8 and f9 involved in optimization model represented by (equations1, 2, …, 18) is computed by assuming a steady state subsurface flow below barrage floor when the gates are closed and water is ponded upstream for diversion into an off-taking canal, and a free surface flow over barrage crests in case of fully opened gates during a flood discharge. Both objective function and constraints are nonlinear; make the problem in the category of nonlinear optimization formulation, which are inherently complex. Characterization of functional parameters is available in literature [3].

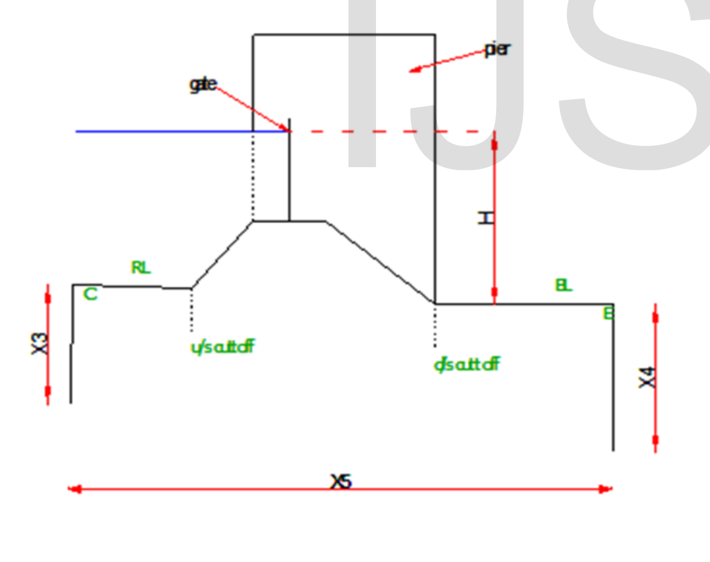


Fig. 3. Schematic of barrage profile utilized in optimization formulation.

In the optimization model of barrage hydraulic design, the following parameters represent the conditions under which the structure is to work and govern the dimensions of the barrage profile, thus govern the overall cost:

Q_{des} : Design flood discharge (m^3/sec).

H : Seepage head (m).

r : Riverbed retrogression (m).

SEG : Safe exit gradient for riverbed material.

f : Silt factor (m).

Z_{crest} : Crest level of a spillway bay (m).

w_p : Width of piers (m).

t_{min} : Minimum assumed floor thickness (m).

2.2 Optimization Process Based Genetic Algorithm

Genetic Algorithm (GA) is an optimization method that simulates the evolution of natural genes to find approximated solutions to optimization problems. It could be applied to different types of problems that could not be solved by classical algorithms, like when the objective function is discontinuous, or not differential, stochastic and/or nonlinear. The GA does sequent steps in an iterative manner to converge at an optimal solution [4]. GAs manipulate the design variables in the form of strings of binary numbers, 0 and 1. In each generation, GA creates random population of design vector components ($i.e.\ x_1, x_2, x_3, x_4$ and x_5). Then, the functional parameters (f1,….,f9) are estimated using the decimal values of design vector components so that fitness can be evaluated depending upon the objective function and constraints values. Different population is produced by means of algorithm functions (selection, cross-over, and mutation function). The first generation is ended and new points to search within are concluded, these steps are repeated iteratively till the fitness of the solution is converged or a stopping condition is achieved.

The optimization model represented by equations (1)-(18) and all the embedded expressions is applied for a hypothetical case study and solved using genetic algorithms with the aid of MATLAB software version (8.3.0.532), the basic steps employed are available in [3]. The barrage profile was designed by the conventional method based on the recommendations of Indian Standard code 6966 [5] total cost of the structure is estimated for the provided dimensions and unit prices of the materials. Table 1 shows results obtained by conventional method and GA based optimization for Fig. 3 applying the same input data and unit prices.

TABLE (1)

GENETIC ALGORITHM (GA) AND CONVENTIONAL METHOD RESULTS.

Parameters, (m)	Design method	
	Conventional method	GA optimization
x_1	1	0.38
x_2	18	10
x_3	5.2	3.79
x_4	5.7	5.15
x_5	66.1	37.33
Overall cost (U.P.)	294090	234970
Cost reduction %	-	20.103

Solving an optimization problem by GA with MATLAB software version (8.3.0.532) needs to appoint many options values and methods, it starts with the identification of the fitness and constraints functions that are the essential parameters, integer constraints impose some restrictions on the settings of the algorithm to perform well. In this study running the GA with initial population of [0.4 10 3.8 5.2 38], crossover rate of 0.8 and 100 population size gives the best results.

3 PARAMETRIC ANALYSIS

There is a high degree of local variability and imprecision in the determination of soil parameters and hydrological parameters so that cost of barrages will vary for different values of design parameters, to investigate effects of variation in design parameters values on total cost and on the design dimensions a number of analyses have been worked out. The values of design parameters used in this exploration are shown in Table (2). Each analysis uses a chosen set of input values to find design dimensions values and total cost of the barrage. Each parameter was taken separately while the others persisted constant, MATLAB program version (8.3.0.532) is adapted to be able to implement this analysis.

TABLE (2)

VALUES OF DESIGN PARAMETERS USED IN THE ANALYSIS.

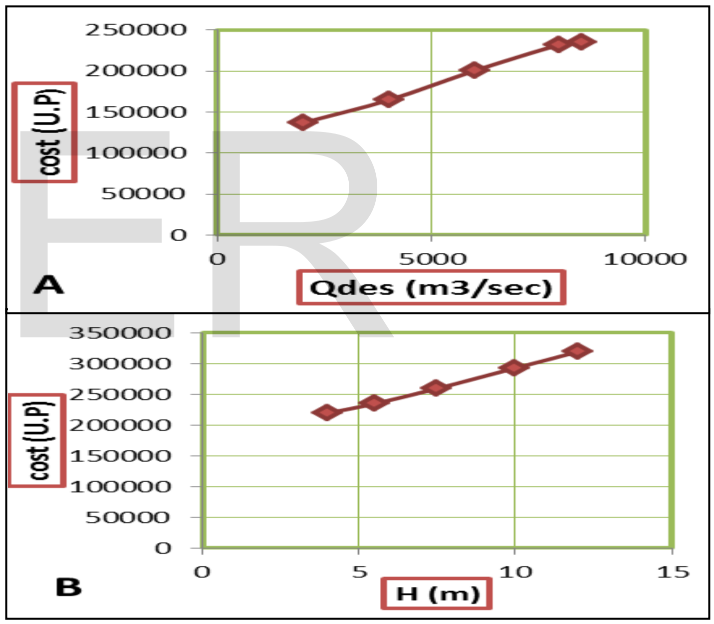
parameter	symbol	unit	Reference value*	Investigated values
Flood-discharge	Q_{des}	m^3/sec	8500	2000, 4000, 6000, 8000, **8500**
Seepage head	H	m	5.5	4, **5.5**, 7.5, 10, 12
Safe exit gradient	SEG	-	1/6	1/8, 1/7, **1/6**, 1/5, 1/4
Retrogression	r	m	0.5	0.3, **0.5**,0.8, 1, 1.25
Silt factor	f	m	1	0.6, 0.85, **1**, 1.25, 1.5
Minimum floor thickness	t_{min}	m	1	1.5, **1**, 0.75, 0.5, 0.25
Crest elevation	Z_{crest}	m	101.25	101, **101.25**, 101.5, 102, 103
Pier width	wp	m	1.5	1, **1.5**, 2, 2.5, 3
Cost of Plain Concrete	C_1	U.P. $/m^3$	2	1.2, 1.5, 1.8, **2**, 2.2
Cost of sheet-piling in u/s	C_2	U.P. $/ m^2$	10	4.5, 5.6, 7.5, 8, **10**
Cost of sheet-piling in d/s	C_3	U.P. $/ m^2$	10	5, 6, 7.5, 9, **10**
Cost of concrete blocks	C_4	U.P. $/ m^3$	1	0.15, 0.25, 0.5, **1**, 1.5
Cost of Graded gravel	C_5	U.P. $/ m^3$	0.85	0.1, 0.3, 0.6, **0.85**, 1
Cost of boulders	C_6	U.P. $/ m^3$	0.75	0.65, **0.75**, 0.86, 1, 1.25
Cost of Excavation	C_7	U.P. $/ m^3$	0.04	0.02, 0.03, **0.04**, 0.05, 0.06
Cost of Earth fill	C_8	U.P. $/ m^3$	0.1	0.06, 0.08, 0.09, **0.1**, 0.11
Cost of a radial gate	C_9	U.P. /kg	0.02	0.01, **0.02**, 0.03, 0.04, 0.05

** Design parameters values utilized for optimization process in Table 1.*

4 RESULTS AND DISCUSSION

4.1 Effect of Design Parameters Variation on the Barrage Total Cost

The effect of different design parameters values on overall cost is displayed in Fig.4. In general, it is shown that the cost of barrage increases with the increase in the flood discharge and seepage head. Also, it increases by increment in each of the river bed retrogression, silt factor, minimum assumed floor thickness and pier width. On the contrast, as the safe exit gradient value rises for a certain soil type the cost diminishes. The increment of the unit price of plain concrete, sheet-piling, concrete blocks, graded gravel, boulders, excavation and the gates lead to increment in the overall cost, while the rise in the value of earth fill price leads to a decrement. The effect of crest elevation is irregular.



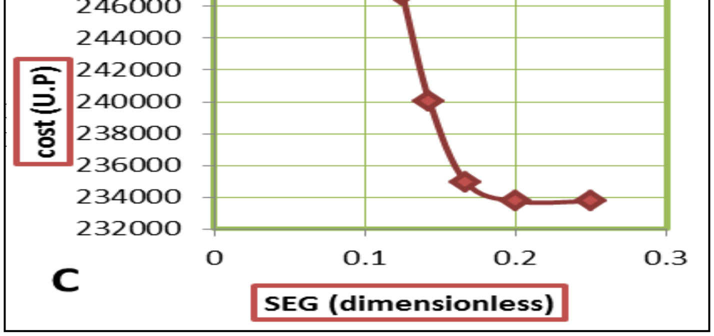
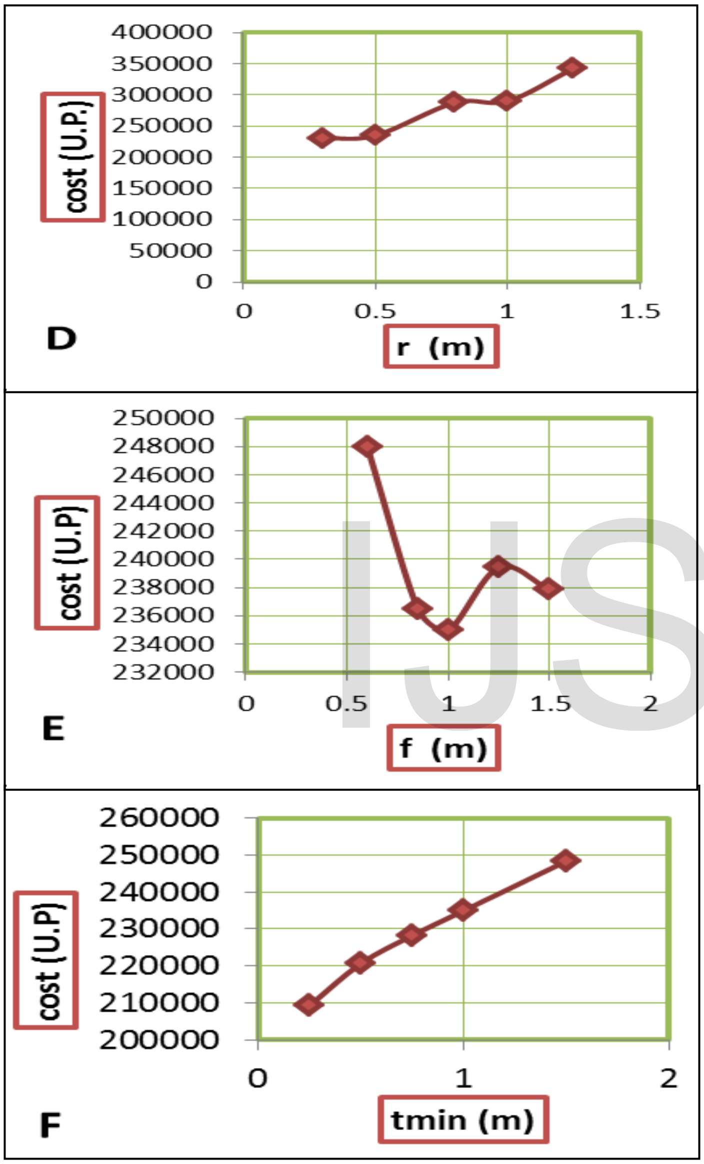
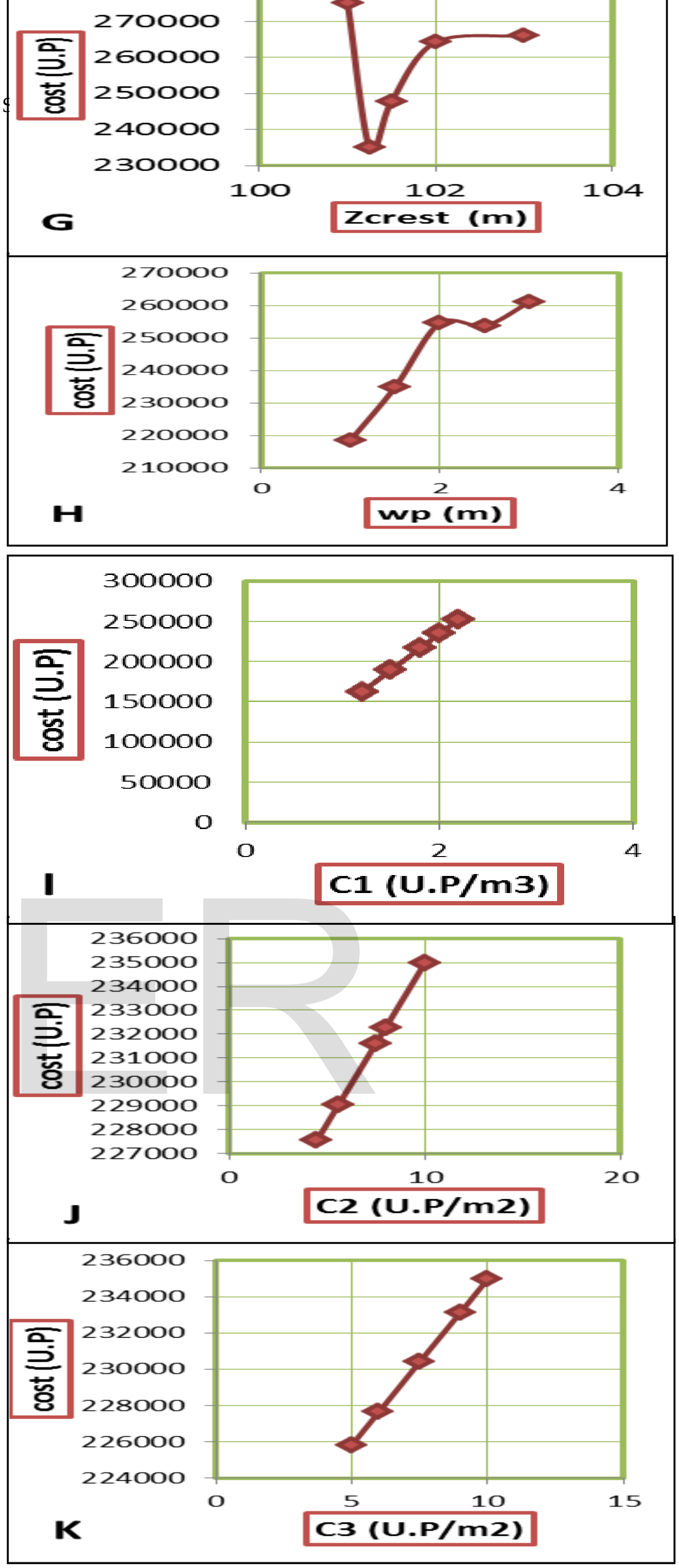
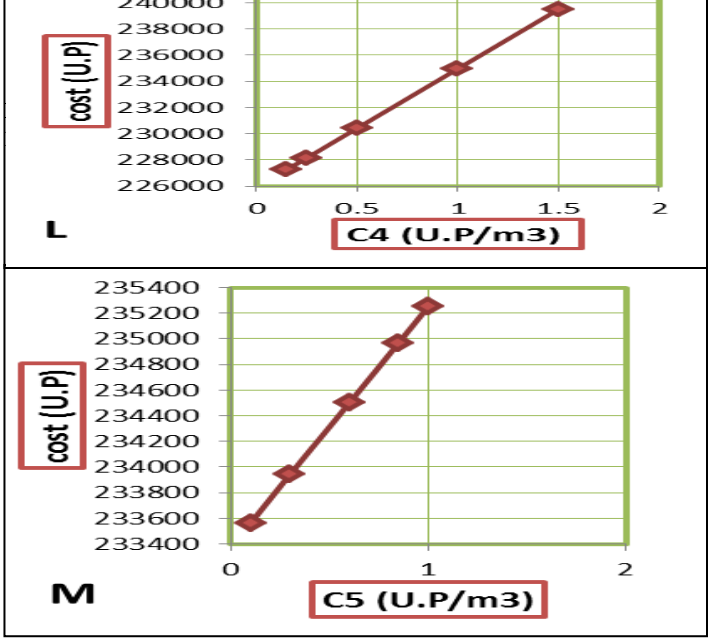


Fig. 4. Overall cost (Unit Price) vs. different input parameters.







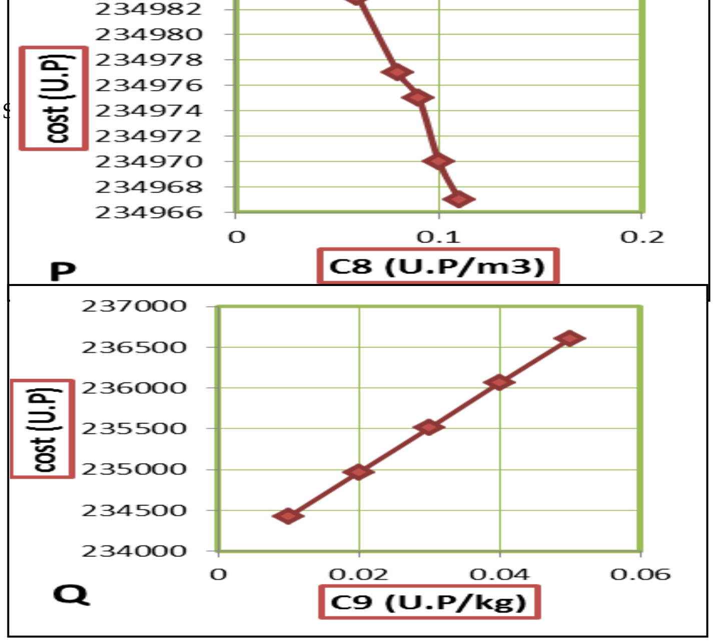
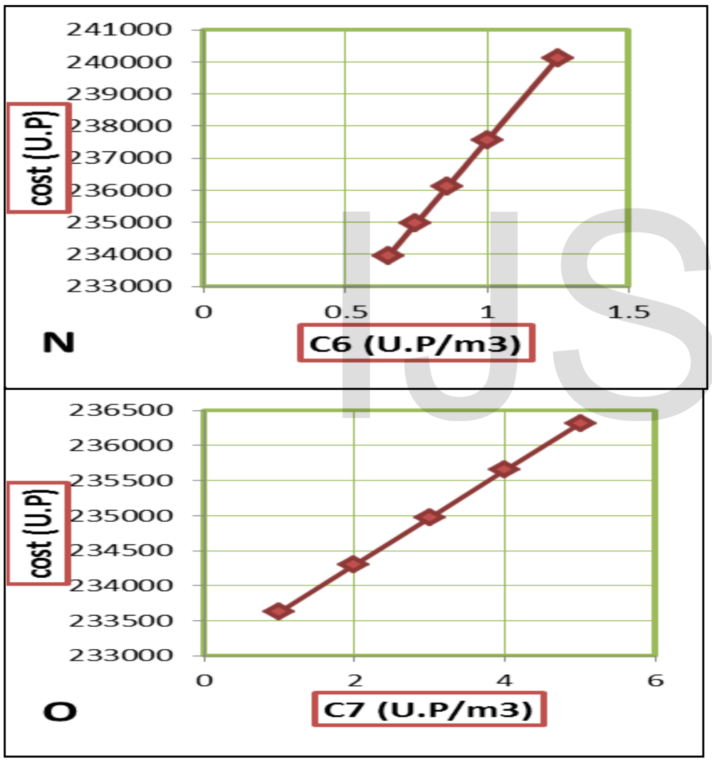


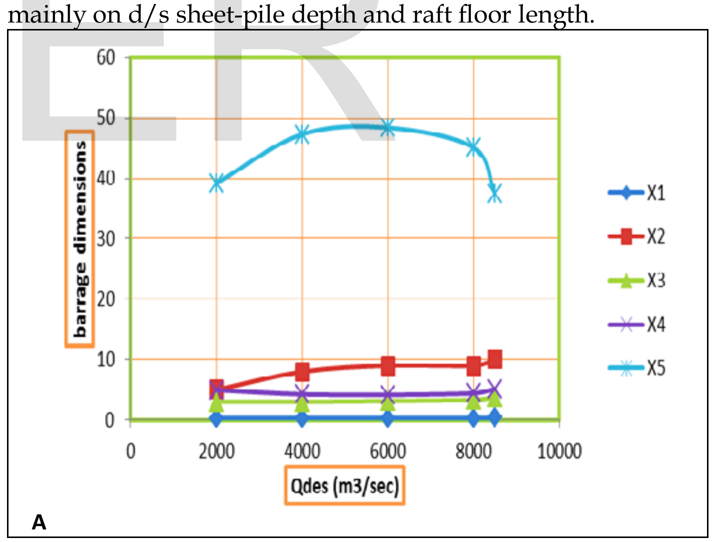
Fig. 4. Overall cost (U. P.) vs. different input parameters (continued).

Fig. 4. Overall cost (U. P.) vs. different input parameters (continued).



4.2 Effect of Design Parameters Variation on the Barrage Profile Dimensions

The design parameters effect on barrage profile dimensions for the same parameters values given in (table 2) is shown in fig.5. It is obvious that the flood discharge (Q_{des}), silt factor (f), crest elevation (Z_{crest}) and pier width (w_p) affect relatively on all the barrage dimensions, while the safe exit gradient of bed material (SEG), seepage head (H), retrogression of d/s river bed (r) and minimum assumed floor thickness (t_{min}) affect mainly on d/s sheet-pile depth and raft floor length.



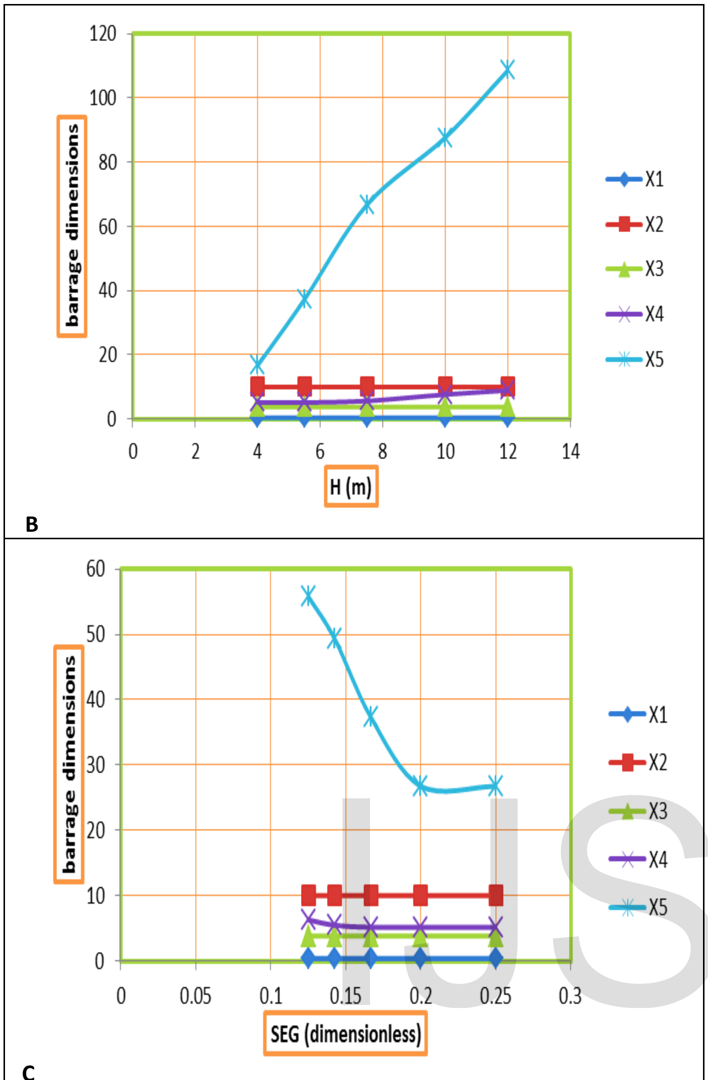
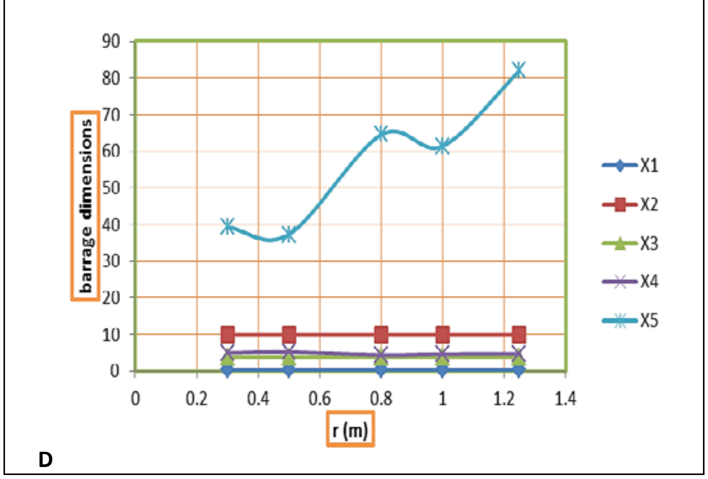


Fig. 5. ***Barrage profile dimensions vs. different design parameters values.***



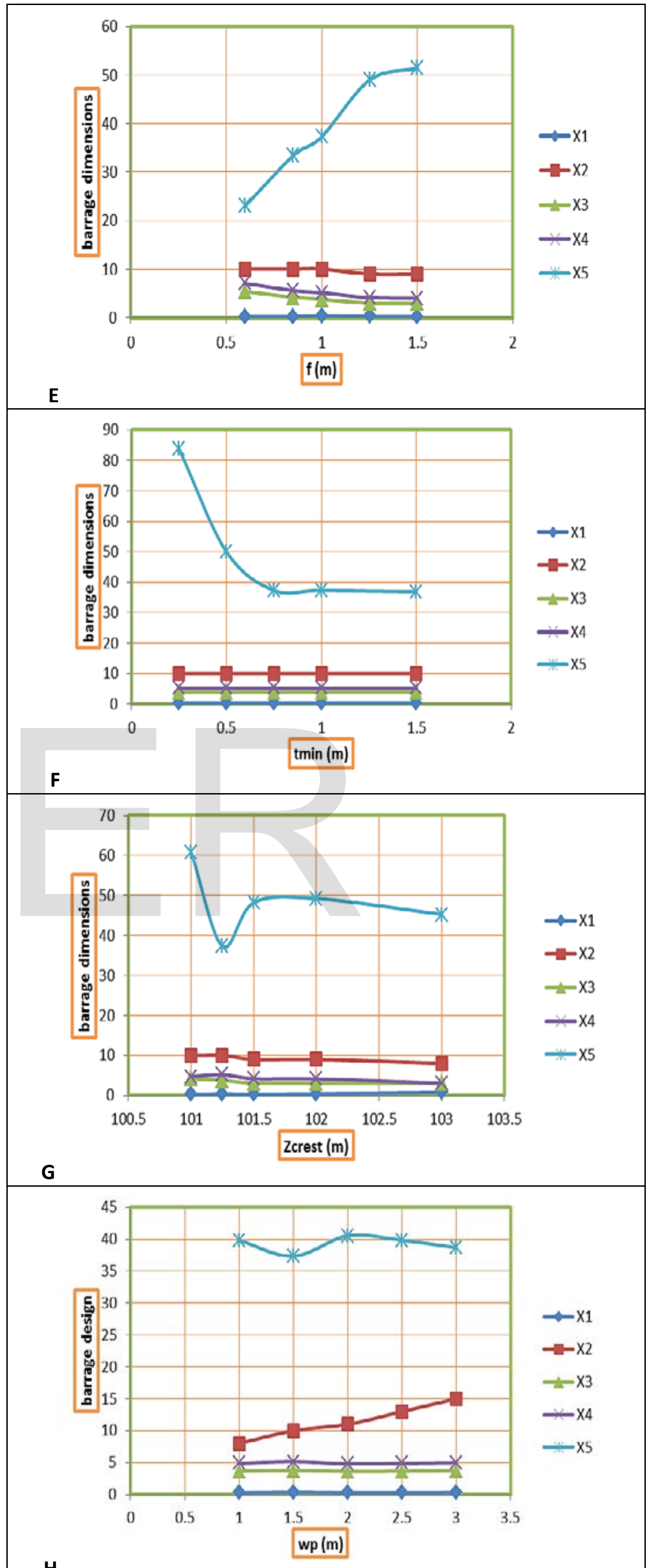


Fig. 5. ***Barrage profile dimensions vs. different design parameters values*(continued).**

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5 CONCLUSIONS

The present work shows that the optimization approach is capable of finding economic and safe design of the barrage on impervious foundation subjected to different constraint functions for design variables which are based on safety and functionality requirements, the relative sensitiveness of the barrage overall cost and dimensions to the design parameters was conducted by the parametric analysis which gives an indication about the importance of each design parameter. Among the design parameters, the flood discharge (Qdes) proved to have the greatest effect on the total cost of the barrage, also it showed that a barrage constructed on fine grained soil is costlier than that constructed on a foundation of coarser bed material.

For the different values of design parameters considered in the study, the total floor length is mainly governed by the seepage head and the safe exit gradient of soil while the upstream and downstream sheet-piles depth is governed by the value of the silt factor.

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