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RESEARCH ARTICLE

OPTIMAL DESIGN OF SYMMETRICAL BARRAGES/REGULATORS USING SHUFFLED COMPLEX EVOLUTION ALGORITHM.

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Abstract

Background: On the river Nile and its branches, there are more than 360 barrages/regulators, built from nineteenth century to control water discharges used for irrigation, industry and human needs. Barrages/Regulators, generally, consist of the main following parts: intermediate supports, edge supports, upstream and downstream wing walls, the bridge located above the regulator and the floor under the structure with its sheet piles and cut-offs. There is, however, no procedure to fix the basic barrage/regulator parameters; dimensions, material of its elements, types of bridge and hydraulic parameters in a cost-effective manner. Determination of these parameters is not dependant on any standard code; it depends on the designer's decision.

Aim: We aimed at presenting software for the optimal hydraulic and structural design of barrages/regulators based mainly on surface flow and how to reach the most cost-effective technical design. We also aimed at deducing an empirical formula to calculate the barrage elements' cost.

Materials and Methods: Our study has been illustrated using Shuffled Complex Evolution algorithm, developed at the University of Arizona (SCE-UA), as an optimization technique, in which the objective function is the construction cost and the parameters are dimensions, material types, bridge types and hydraulic parameters.

The applicability of this approach has been illustrated using seven existing regulators indicating its suitability to evolve a cost-effective design.

Results: The reductions of construction costs have been recorded for the selected seven examples and founded to be between 11% and 64% with an average value of 31%. The software illustrates that the slab type is more optimal than arch or beam type for the bridge, plain concrete for abutments and piers is more optimal than reinforced concrete; combining reinforced and plain concrete for the floor is more optimal than either one alone.

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Conclusion: The software demonstrates the pronounced performance of the developed tool; this program can help decision-makers to know the optimal hydraulic and structural design in addition to the optimal cost of the barrages.

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Introduction:-

The barrage/regulator designer must pass two stages to finish the design to the fullest; these two stages are (i) hydraulic design which based on surface flow to determine number of vents, span of vents, floor level and on subsurface flow to determine floor and cut-off lengths and (ii) structural design which focus on structural element material and dimensions.

Firstly, Hydraulic formula used for regulators is similar to a bridge crossing canal or a river (Leliavsky 1957). The formula which is often used in calculating the discharge under such a bridge is

$$Q = \frac{2}{3} C L_e \sqrt{2g}\left[(h + h_a)^{3/2} - {h_a}^{3/2}\right] + C L_e H \sqrt{2g(h + h_a)} \qquad (1)$$

Where h is the heading up, i.e. the difference between upstream and downstream water levels;

h_a is the head of approach $= \frac{v_a^2}{2g}$;

where v_a represent the velocity of approach $= \frac{Q}{a}$,

a being the sectional area of the canal upstream the regulator;

C is the coefficient of discharge,

H is the downstream water depth,

L_e is effective width of regulator,

g = gravitational acceleration, and

Q is the total discharge of water flowing through the regulator.

This formula has been simplified and becomes

$$Q = C L_e H \sqrt{2g(h + h_a)} \qquad (2)$$

Then infer the following equation:

$$h = \frac{1}{C^2} \frac{v_a^2}{2g} \left[\left(\frac{a}{A}\right)^2 - 1\right] \qquad (2.a)$$

Where A is effective water area of regulator.

Formula(2.a) is the main formula in Egypt (ECP 2001).

C= 0.72 . . . if the span of the opening ≤ 2.00 m
C= 0.82 . . . if 2.00 m < the span of the opening ≤ 4.00 m
C= 0.92 . . . if the span of the opening > 4.00 m

Note that formula(2.a) has similar forms with different value of coefficient C (Leliavsky 1957).

The main formula used in India (IS6531:1994) is:

$$Q = C_d L_e H_e^{3/2} \qquad (3)$$

Where the coefficient C_d is not constant but depends on many factors and H_e is the required head over crest.

There is another equation has been deduced (Leliavsky 1957, ECP 2001):

$$h = \alpha\beta \frac{v^2}{2g} \qquad (4)$$

where α and β are coefficients depends on the proportion between canal, regulator cross-sectional areas and on pier shape.

On the other hands, hydraulic design based on subsurface flow, there are three famous theories used to determine length of floor and cut-offs to resist scour, uplift pressure and exit gradient: (i)Bligh theory, formula(5), (6), (ii)Lane theory, formula (7) which are used in Egypt (ECP 2001) and (iii) khosla theory (Khosla 1932, Khosla, Bose et al. 1936) which is used in India (IS6966-1:1989).

$$L_s = 0.6 C_B \sqrt{h_{max}} \qquad (5)$$

$$L = C_B . h_{max} \qquad (6)$$

$$L = C_L . h_{max} \qquad (7)$$

Secondly, the structural design; (Leliavsky 1957) divided the regulators to four types:

- (i) Masonry and plain concrete regulators of moderate size, regulation by timber, which the determination of elements dimensions, depends on empirical formulas; the bridge is arch and the maximum span equal 3.00 meter.
- (ii) Mixed type including both heavy and light materials, the difference between this type and the previous one is the type of bridge and material of floor. Which the floor and bridge constructed from RC, bridge is slab type and beam type.
- (iii) Purely reinforced concrete design, which all elements of the regulator are constructed from RC, this ideology followed the American standard design.
- (iv) Regulators and barrages fitted with steal gates, which focused on the stability of piers against water pressure loaded on the gates.

According to (ECP 2001): there are no fixed conditions to help the designer make his decision of choosing materials or determining bridge type or even to decide the numbers of vents, and despite of recommends the use of plain concrete and reinforced concrete for the floor, it does not mention using reinforced concrete for abutments, wing walls and piers; it recommends to use brick and plain concrete for them; It also treats with the floor as a rigid footing.

According to Indian Standard (IS11130:1984): For piers and abutments design the (IS) recommends for using reinforced concrete but for raft design, there are two types of raft foundation: (1) gravity type which resists the uplift pressure with its weight only and it made from PC, (2) RC type which resists the uplift pressure with its weight and all loaded weight come from piers and abutment, The design of the RC raft for spans up to 6.00m may generally be done same as the theory of beams on elastic foundation while the floor shall be designed as a finite beam resting on elastic foundation and subjected to concentrated loads and moments at the pier and abutment points for spans above 6.00m. The raft, piers and abutment could be designed as reinforced concrete. It is important to take seismic load and wind load into consideration during pier design.

An optimization model has been formulated to minimize the barrage cost using Khosla's theory (Garg, Bhagat et al. 2002). A genetic algorithm (GA) based on embedded simulation optimization approach to design barrages with minimum cost depending on the depth of sheet piles or cut-offs and the length and thickness of floor in a cost–effective manner was studied by (Singh 2011) then he illustrates the effect of seepage head on the choosing of optimal sheet pile depth (Singh 2011). After that (Garg, Chawre et al. 2014)study the impact of heterogeneous and anisotropic soils on the uplift pressure.

In this paper, shuffled complex evolution algorithm, developed at the University of Arizona (SCE-UA) has been used as an optimization technique. It was originally developed by (Duan, Sorooshian et al. 1992). This algorithm is reported to be an efficient global optimization method that can be used to handle non-linear problems with high-parameter dimensionality (Duan, Sorooshian et al. 1992, Duan, Gupta et al. 1993, Duan, Sorooshian et al. 1994, Cooper, Nguyen et al. 1997, Kuczera 1997, Franchini, Galeati et al. 1998, Thyer, Kuczera et al. 1999, Wu, Zhu et al. 1999, Muttil and Liong 2004, Wu and Zhu 2006, Le Ngo, Madsen et al. 2007, Jiang and Gong 2012, Jeon, Park et al. 2014).

MATERIALS AND METHODS:-

A. DESIGN OF SYMMETRICAL REGULATORS

The Ministry of Water Resources and Irrigation (MWRI) of Egypt decided to carry out a feasibility study to investigate the present structural and operational conditions of most regulators and barrages in Egypt; More than one hundred structures have been inspected and presented in individual reports, these reports include photos, original drawings, hydraulic and structure information about the regulators such as types of materials used for constructing piers, abutments and floors which is brick or plain concrete or reinforced concrete, types of bridge which is arch or slab or beam type, number of vents, span of vents, levels at the top and bottom of regulator elements, levels of canal cross section such as levels of upstream and downstream water levels and discharge that the regulator passes are available; therefore, lots of constructed information have been known; there are eighty three of them are symmetric (without lock) and seventeen are not symmetric (with lock). This study concerns the symmetric regulators, i.e. for the eighty three, seven structures have been considered in this research, i.e. are to be evaluated (Photo 1), firstly the volumes of regulators elements have been calculated, secondly, determinate the cost of bridge, piers, abutment, and floor.

In every barrage, there are many types of materials and hydraulic parameters which can be changed to make the optimization design in the manner of cost. So our presented program respects the Egyptian code and then is connected with SCE-UA algorithm to optimize every regulator.

The proposed optimization program is presented in Figure 1, this program treats the results as a global optimization problem where the cost functions to be minimized is defined as the differences in inspected and computed dimensions and materials.

The optimal solution is searched in the multi-modal solution space by the SCE algorithm as described previously. Thus, for every hydraulic parameter of module solutions in the SCE search scheme, material types of the regulator's element have to be recalled to compute the resulting cost. In this research, the SCE optimization technique is connected with ODR software which designs the whole regulator dealing with parameters as inputs. This reduces the computational time of SCE during the optimization process. Thus, the resulting composed of mixing parts model; ODR-SCE combines the robustness of SCE with the computational efficiency of ODR.

The optimization technique designed by the authors was implemented in MATLAB. The variables to the toolbox are eighteen variables divided into three groups:

Group No.1:	six independent variables which are: N,S (Figure 6), M_{ab}, M_{fl}, Br_{type} (Figure 3, Figure 4, Figure 5), DBF;
Group No.2:	nine dependant variables/dimension (Figure 6, Figure 7) which are: E, T_{at}, T_{ab}, T_{1PC},T_{1RC}, T_{2PC},T_{2RC}, T_{3PC},T_{3RC};
Group No.3:	three calculated parameters (Figure 7) which are:L_1,L_2, L_3.

The choice of the SCE algorithm's parameters is crucial in achieving convergence of solution for the problem under consideration. In this research, the following guidelines proposed by Duan et al. (1992) were used for determining the SCE parameters.

A total of 364E+20 data vectors generated by modeling design equation using the Egyptian code were used for the multi-Model solution designed by the Authors.

B. OPTIMAL DESIGN METHODOLOGY

The main idea of the methodology is based on minimizing the cost of barrage elements; this cost is a function of:N, S (Figure 6), M_{ab}, M_{fl}, Br_{type} (Figure 3, Figure 4, and Figure 5), DBF.

This function can be illustrated in the form of the following equations:

$c(N, S, DBF, M_{ab}, M_{fl}, Br_{type}) = c_1(f_1)+c_2(f_2)+c_3(f_3)+c_4(f_4)$

$c_1(f_1) = Cost_{Br.} = Vol_{Br.} \times Cost_{m3(\text{arch or slab or beam})}$

$c_2(f_2) = Cost_{Pier} = Vol_{Piers.} \times Cost_{m3\ (\text{Brick or PC or RC})}$

$c_3(f_3) = Cost_{Abut.} = Vol_{Abut.} \times Cost_{m3\ (\text{Brick or PC or RC})}$

$c_4(f_4) = Cost_{Floor.} = Vol_{flPC.} \times Cos_{tm3PC} + Vol_{flRC} \times Cost_{m3RC}$

$\text{Total Cost} = Cost_{Br} + Cost_{Piers} + Cost_{Abut.} + Cost_{Floor}$

$c(N, S, DBF, M_{ab}, M_{fl}, Br_{type}) = Cost_{Br.} + Cost_{Piers} + Cost_{Abut.} + Cost_{Floor}$

$N^l<N<N^u$

$S^l<S<S^u$

$M_{ab}{}^l<M_{ab}<M_{ab}{}^u$

$M_{fl}{}^l<M_{fl}<M_{fl}{}^u$

$Br_{type}{}^l<Br_{type}<Br_{type}{}^u$

$DBF^l<DBF<DBF^u$

Where c(N, S, M_{ab}, M_{fl}, Br_{type}, DBF) is objective function represents elements cost of barrage (LE), and is a function of number of vents, N, span of vent, S, material of abutment and piers, M_{ab}, material of floor, M_{fl} and type of bridge, Br_{type}; f_1 is volume of bridge (m^3) and cost of bridge per unit volume (LE/m^3); f_2 is volume of piers (m^3) and cost of piers per unit volume (LE/m^3); f_3 is volume of abutments (m^3) and cost of abutment per unit volume (LE/m^3); f_4 is volume of floor (m^3) and cost of floor per unit volume (LE/m^3); c_1, c_2, c_3, c_4 are functions of f_1, f_2, f_3, f_4 respectively; N^l, S^l , DBF^u, $M_{ab}{}^l$, $M_{fl}{}^l$, $Br_{type}{}^l$ are lower boundaries of N, S, DBF, M_{ab}, M_{fl}, Br_{type} respectively; N^u, S^u , DBF^u, $M_{ab}{}^u$, $M_{fl}{}^u$, $Br_{type}{}^u$ are upper boundaries of N, S, DBF, M_{ab}, M_{fl}, Br_{type} respectively.

The inputs of the program are:

1. Cross section of canal (Figure 2) includes downstream bed level, DSBL, embankment level, EMB, downstream water level, DSWL, upstream water level, USWL, bed width, BedW, side slope of canal, Z, and discharge, Q.
2. Properties of soil include weight per unit volume, γ_{soil}, soil angle, Θ_{soil}, cohesion of soil, C_{soil}, allowable stresses, F_{soil}, and Bligh coefficient, C_B.
3. Properties of brick include weight per unit volume, γ_{Brick}, allowable compression strength, F_b, allowable tension strength, F_{bt}, and cost of brick per unit volume, $Cost_{m3brick}$[1].
4. Properties of plain concrete include weight per unit volume, γ_{PC}, allowable compression strength, F_c, allowable tension strength, F_{ct}, and cost of plain concrete per unit volume, $Cost_{m3PC}$[2].
5. Properties of reinforced concrete include weight per unit volume, γ_{RC}, allowable tension strength, F_s, and cost of reinforced concrete per unit volume, $Cost_{m3RC}$[3].
6. Bridge width, BrW, dead load, DL, live load, LL, and road level, RL.

- Formula (2.a), $0.00m \leq$ heading up $\leq 0.10m$, velocity through vents is between $2\times V_c$ and $3\times V_c$ are used for determinate N, S, DBF.
- The bridge is subject to Live Load, L.L.=$2.50t/m^2$ and its own weight to determinate bridge type (Br_{type}), Road level-Embankment level$\leq$0.50m (Figure 3, Figure 4, Figure 5)
- Piers are subjected to water pressure and reactions from bridge; L_{pier} is an input parameter, Pier level-USWL$\geq$0.50m; the stresses on piers checked to be less than material strength.
- Abutments are subjected to earth pressure and reactions from bridge, the stresses on abutments checked to be less than material strength, the factor of safety against sliding$\geq$2 for brick and 1.50 for plain concrete.
- Floor subjected to uplift pressure and the load comes from piers and abutments. Formula (5) used for determinate scour length, L_3; formula (6) used for determinate total length of the floor ($L_1+L_2+L_3$) providing that $0.50m<L_1<10.0m$, $L_2\geq L_{pier}$, C_B value was calculated so as not to change the floor length because the author focus on surface flow, the stresses on floor checked to be less than material strength, the factor of safety against uplift pressure$\geq$1.50, and the total loads comes from the whole structure must not exceed the allowable stresses for the soil.

N, S, DBF, L_1, L_2 and L_3 are calculated according to equations and limits mentioned above; f_1, c_1 are calculated for the three types of bridge then choose the minimum cost, c_1; f_2, c_2 are calculated for the three materials of piers after design the pier width according to each material, E, then choose the minimum cost, c_2;f_3, c_3 are calculated for the three materials of abutment after design the top thickness, Tat, and bottom thickness, Tab, according to each material then choose the minimum cost, c_3; f_4, c_4 are calculated for the three materials of floor after design the reinforced thickness, T_{1RC}, T_{2RC}, T_{3RC} and plain concrete thickness, T_{1PC}, T_{2PC}, T_{3PC}, according to each material then choose the minimum cost, c_4; after that calculate c(N, S, DBF, M_{ab}, M_{fl}, Br_{type}); then make another trial for another values of N, S, DBF; Finally, choose the minimum total cost.

Results and Discussion:-

The solution database was generated by varying the eighteen variables; the range of variables shown in Table1. For the sake of illustration, the comparison between the updated cost for an existing structure and its cost using the ODR-SCE software are presented in Table 2.

It is obviously seen that the ODR-SCE software is very effective (the ranges varies from 11% to 64%). For knowing the difference between the actual design and the optimal one Table 3, Table 4, Table 5 were performed; the optimal material for abutment and piers is plain concrete; the optimal one for floor is using two layers; the upper one is reinforced concrete and the lower one is plain concrete; the optimal type of bridge is slab type. There is very big change in choosing N, S without marked change in the multiplying of N×S (No. of vents × Span of vents), for example, the optimal program chooses N=3, S=4.00m (3×4.00=12.00m) instead of N=2, S=5.50m (2×5.50=11.00m) for ST-4 Regulator (Table 3, Table 5), which led to increase of piers numbers with reduction in the cost (29%) because the reduction caused by changing floor material from RC to PC+RC and by changing pier and abutment materials from RC to PC, N=2, S=5.00m (2×5.00=10.00m) instead of N=5, S=2.40m (5×2.40=12.00m) for ST-6 Regulator (Table 3, Table 5), which led to reduction of piers numbers and floor width, thus, 43% reduction of the cost.

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[1] $Cost_{m3brick}=200LE/m^3$

[2] $Cost_{m3PC}=500LE/m^3$

[3] $Cost_{m3RC}=2000LE/m^3$

On the other hand, the results showed very marked change in the multiplying of N×S, which illustrates very huge fault in hydraulic design. For example, the optimal program chooses N=3, S=3.00m (3×3.00=9.00m) instead of N=4, S=3.00m (4×3.00=12.00m) for ST-1 Regulator (Photo2, Table 3,Table 5), which led to reduce the floor width and the number of piers, thus, 11% reduction of the cost, N=3, S=3.00m (3×3.00=9.00m) instead of N=3, S=5.00m (3×5.00=15.00m) for ST-2 Regulator (Photo3, Table 3, Table 5),which led to reduce floor width, thus, 14% reduction of the cost, N=3, S=6.00m (3×6.00=18.00m) instead of N=6, S=5.00m (6×5.00=30.00m) for ST-3 Regulator (Photo4, Table 3, Table 5), which led to reduce the floor width and the number of piers, thus, 21% reduction of the cost, N=3, S=3.00m (3×3.00=9.00m) instead of N=4, S=3.50m (4×3.50=14.00m) for ST-5 Regulator (Photo5, Table 3, Table 5), which led to reduce the floor width and the number of piers, thus, 33% reduction of the cost, N=2, S=6.00m (2*6.00=12.00m) instead of N=6, S=3.00m (6×3.00=18.00m) for ST-7 Regulator (Photo6, Table 4[4], Table 5,

Figure 8, Figure 9[5]),which led to reduce the floor width and the number of piers, but 64% reduction of the cost comes from the change of piers and abutment material from RC to PC and the change of floor material from RC to RC+PC.

The impacts of every regulator element cost on the whole cost of all elements have been recorded for all the selected seven examples (Chart 1); for instant, the impact of bridge is between 4% and 11% with average value of 6%, the impact of piers is between 3% and 8% with average value of 6%, the impact of abutments is between 21% and 35% with average value of 27%, and the impact of floor is between 54% and 69% with average value of 61%.
We deduced an empirical equation to estimate the optimal cost of regulator elements (Chart 2); the equation is $0.429\times(N\times S\times H_{DS}\times L)^2-316.3\times N\times S\times H_{DS}\times L+2E6$.

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[4] ST-7 has special case whereas the abutments were covered with brick (25cm) from one side and the piers were covered with brick (25cm) from both sides.

[5] Figure 8, Figure 9 illustrates the dimensions of structure No.7 (ST-7) shown in Table 4, Table 5 as an example for the studied seven structures.

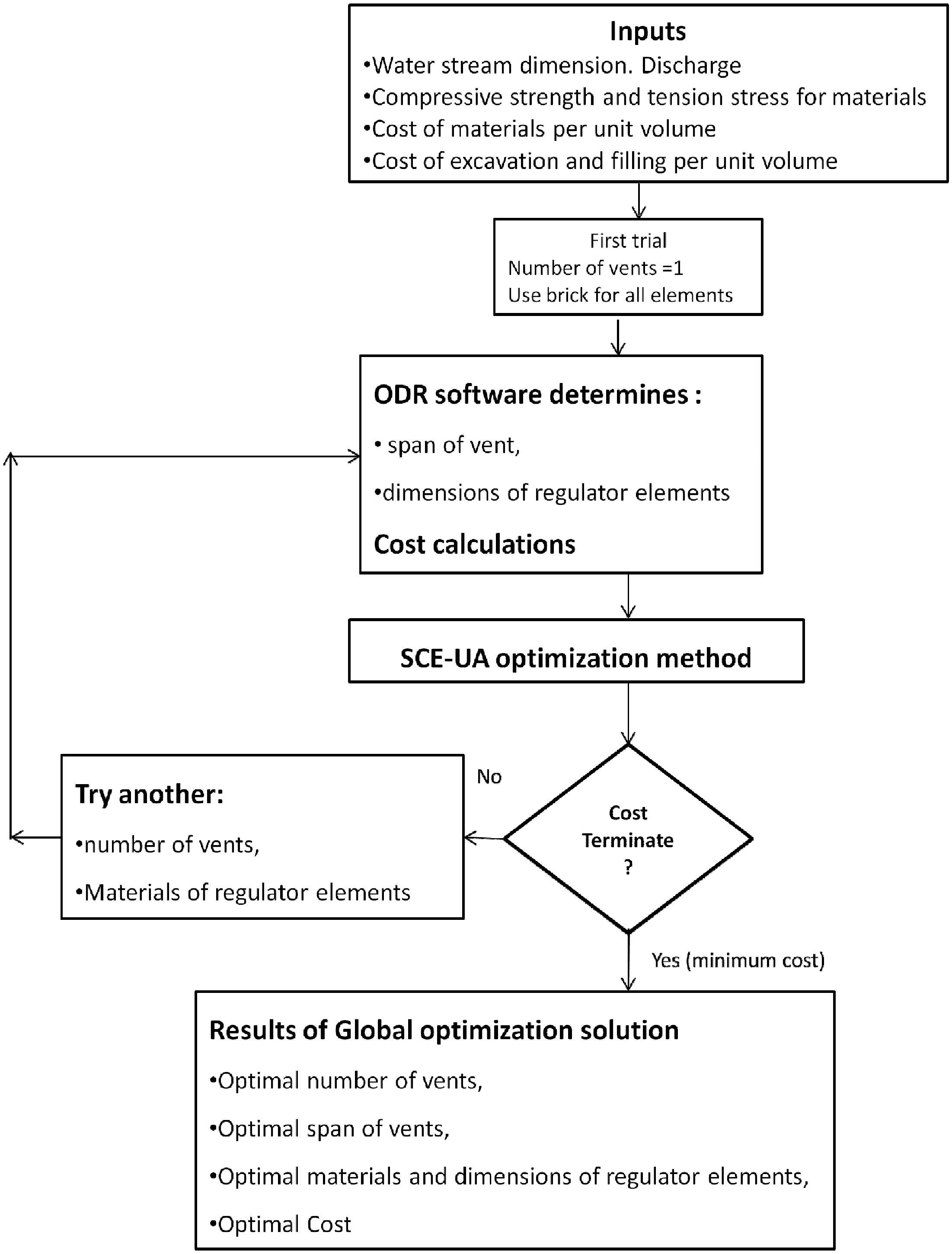

Figure 1:- Typical Flow chart designed and used in the study.

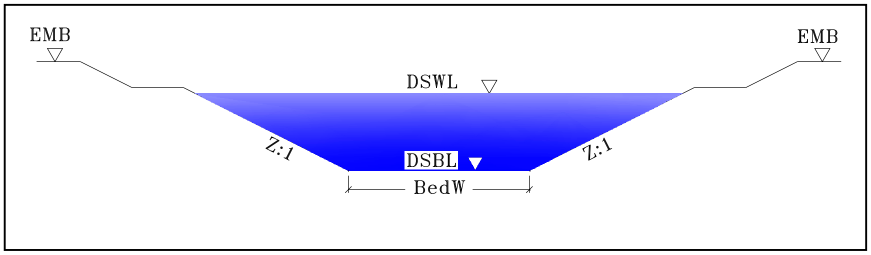

Figure 2:- Cross section of the canal

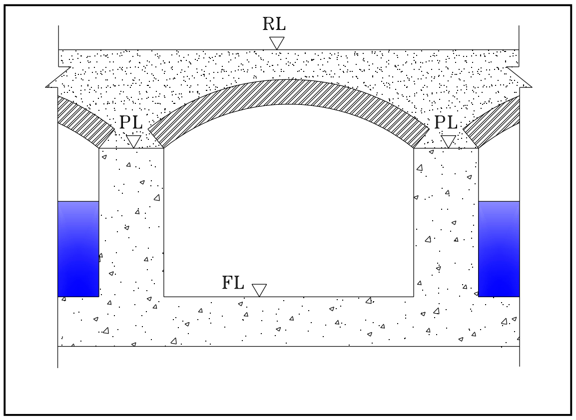

Figure 3:- Cross section of bridge type No.1 (arch bridge)

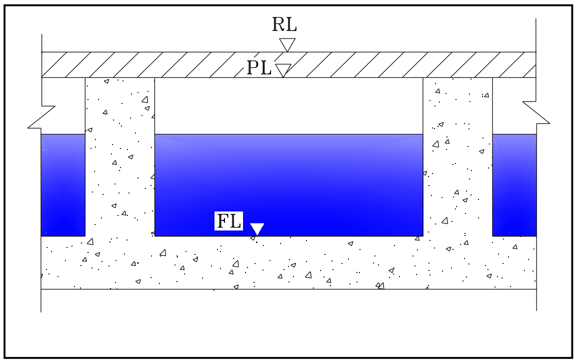

Figure 4:- Cross section of bridge type No.2 (Slab Bridge)

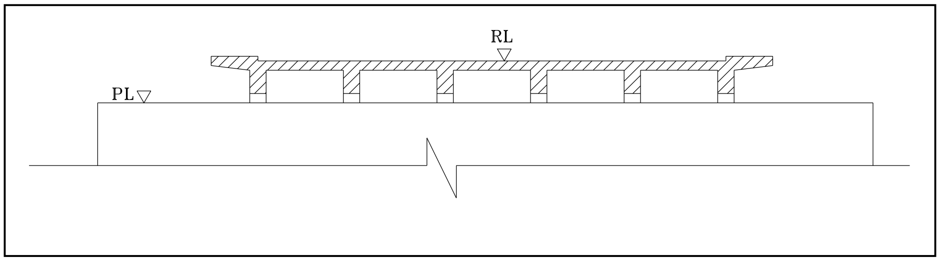

Figure 5:- Cross section of Bridge type No.3 (Beam type)

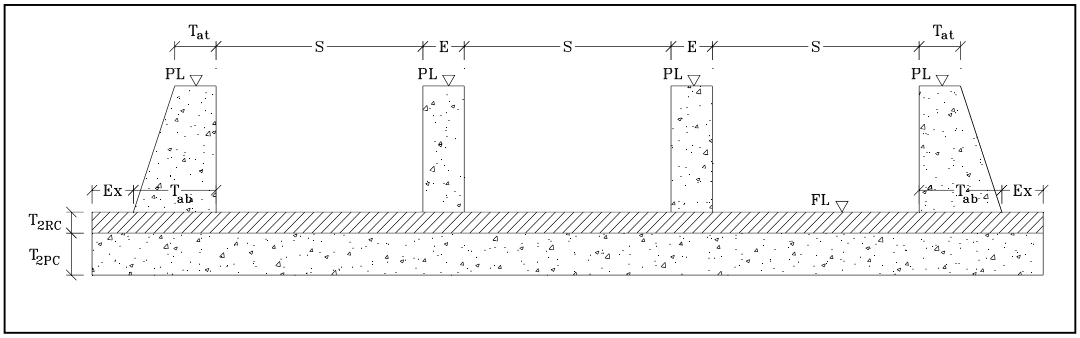

Figure 6:- Cross section of the regulator illustrates the symbols T_{at}, T_{ab}, E, S, T_{2PC} and T_{2RC}.

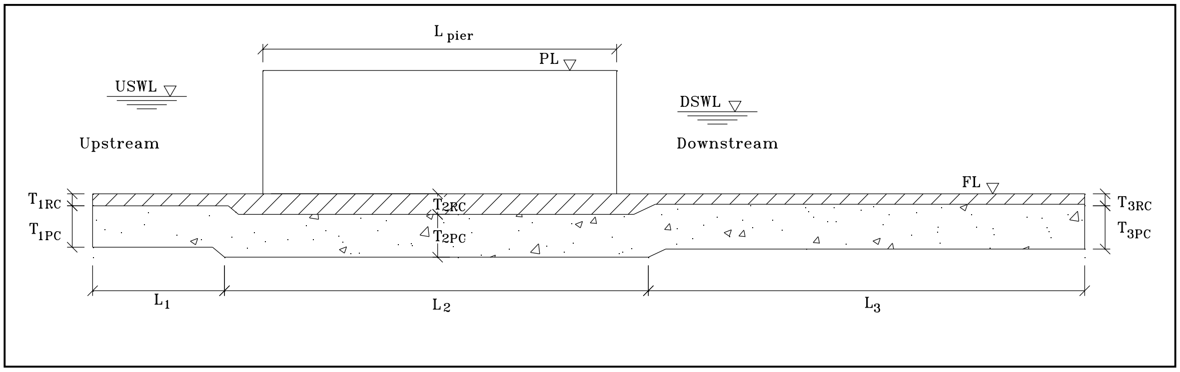

Figure 7:- Longitudinal section of the regulator illustrates symbols L_{pier}, L_1, L_2, L_3, T_{1PC}, T_{1RC}, T_{2PC}, T_{2RC}, T_{3PC} and T_{3RC}.

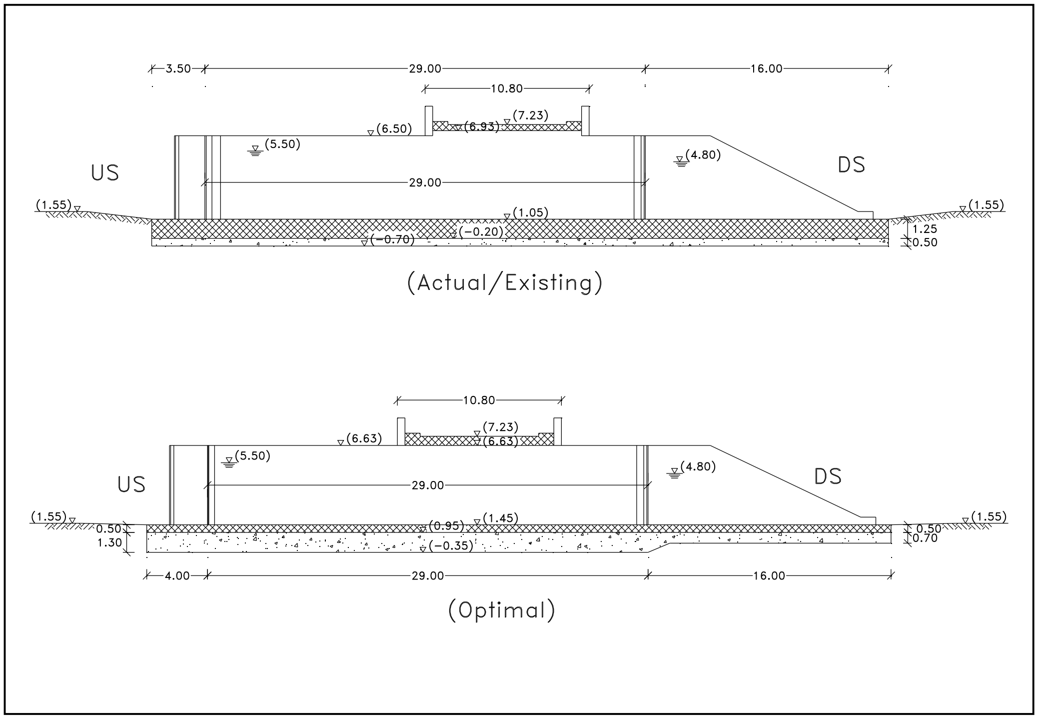

Figure 8:- Comparison between optimal and actual longitudinal sections for ST-7 (1998)

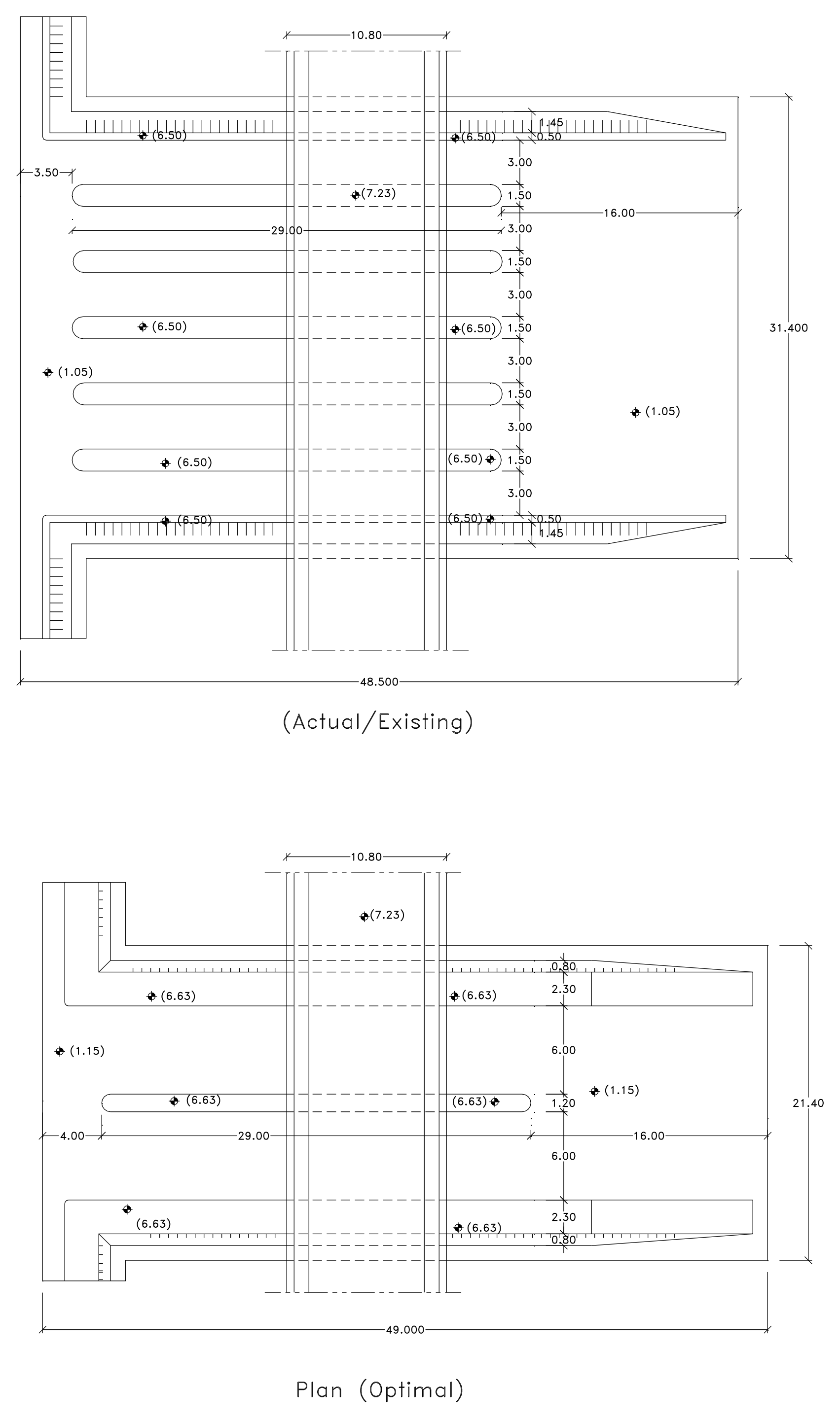

Figure 9 :- Comparison between optimal and actual plans for ST-7 (1998)

Photo 1:- Google earth photo illustrates the seven evaluated regulators

Photo2:- U.S. View of ST-1 shows all gates are fully opened (at W.L. less than the minimum designed W.L.)

Photo3:- U.S. View of ST-2 shows continuing closed third gate

Photo4:- U.S. View ST-3 shows all gates are partially opened

Photo5:- U.S. View of ST-5 shows fully closed two gates and fully opened two gates

Photo6:- U.S. View ST-7 shows continuing closed two gates

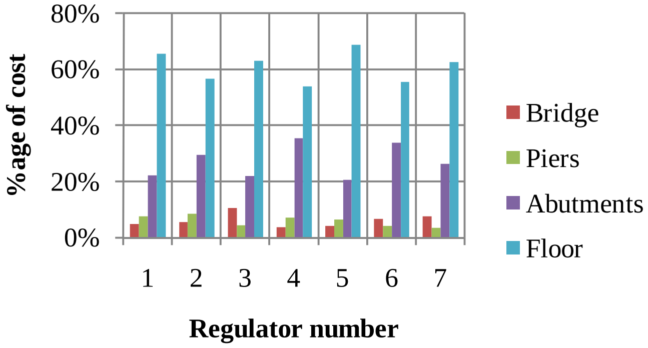

Chart 1:- The impact of regulator elements on the total cost.

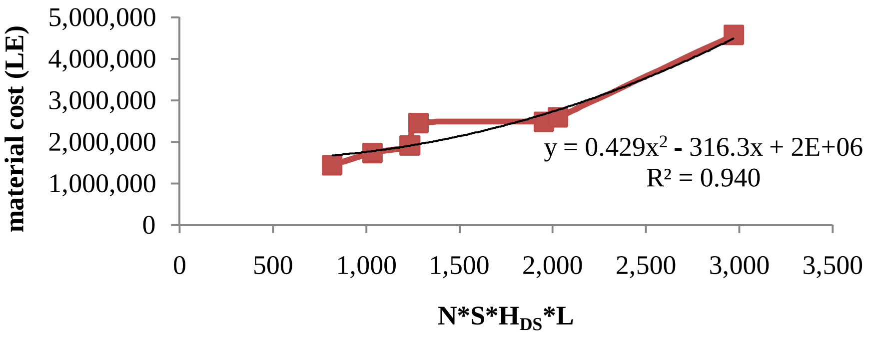

Chart 2:- The relation between $N*S*H_{DS}*L$ and material cost.

Table1:- Parameters, and intervals of cycles

	Symbol	Definitions	Intervals of cycles	Rate of intervals	No. of cycles
independent variables					
1	S	Span of vent	from 2.00m to 9.00m	1	8
2	N	Numbers of spans	from 2 to 50	1	49
3	DBF	The difference between bed level and floor level	from 0.00m to 0.50m	0.1	5
4	M_{ab}	Pier and abutment Materials	1 Brick, 2 PC, 3 RC	1	3
5	M_{fl}	Floor Materials	2 PC, 3 RC, 4 PC+RC	1	3
6	Br_{type}	Type of bridge	1 Arch, 2 Slab, 3 Beam	1	3
dependant variables/ dimensions					
1	E	Pier width	form 0.50m to 3.00m	0.1	25
2	T_{at}	Top width of abutment	form 0.50m to 3.00m	0.1	25
3	T_{ab}	Bottom width of abutment	form 0.50m to 10.00m	0.1	95
4	T_{1PC}	Floor PC thickness	form 0.50m to 3.00m	0.1	25
5	T_{1RC}	US floor RC thickness	form 0.50m to 3.00m	0.1	25
6	T_{2PC}	Middle floor PC thickness	form 0.50m to 3.00m	0.1	25
7	T_{2RC}	Middle floor PC thickness	form 0.50m to 3.00m	0.1	25
8	T_{3PC}	DS floor PC thickness	form 0.50m to 3.00m	0.1	25
9	T_{3RC}	DS floor RC thickness	form 0.50m to 3.00m	0.1	25
calculated parameters					
1	L_1	US floor length	form 0.50m to10.00m	0.5	19
2	L_2	Middle floor length	form 5.00m to 30.00m	0.5	50
3	L_3	DS floor length	form 5.00m to 30.00m	0.5	50
Total number of trials					364E+20

Table 2:- Comparison between the estimated costs for the existing structures and their optimal costs using the multi-model solution.

	Cost		
Name	estimated (LE)	optimal(LE)	% Age Reduction
ST-1	1,951,255	1,743,800	11%
ST-2	1,685,439	1,450,138	14%
ST-3	3,174,225	2,495,640	21%
ST-4	6,477,828	4,575,320	29%
ST-5	2,853,950	1,923,328	33%
ST-6	4,309,911	2,455,890	43%
ST-7	7,297,355	2,599,908	64%

Table 3:- The actual dimensions, materials, volumes and the updated costs for the existing structures (from ST-1 to ST-6).

Symbol	ST-1	ST-2	ST-3	ST-4	ST-5	ST-6
S	3.00	5.00	5.00	5.50	3.50	2.40
N	4	3	6	2	4	5
DBF	0.50	0.00	0.50	0.00	0.50	1.50
M_{ab}[6]	2	2	2	3	3	2
M_{fl}[7]	4	4	4	3	4	4
Br_{type}[8]	2	3	3	2	2	2
E	1.50	1.75	1.50	1.60	0.60	2.00
T_{at}	1.00	2.00	1.00	1.30	0.60	1.03
T_{ab}	2.20	3.00	3.50	1.30	0.75	5.00
T_{1PC}	1.00	0.75	0.50	0.00	0.60	2.35
T_{1RC}	0.50	0.50	0.50	1.10	0.80	0.25
T_{2PC}	1.00	0.75	0.50	0.00	0.60	2.35
T_{2RC}	0.50	0.50	0.50	2.20	0.80	0.25
T_{3PC}	1.00	0.75	0.50	0.00	0.60	2.35
T_{3RC}	0.50	0.50	0.50	1.50	0.80	0.25
L_{pier}	22.00	19.00	16.50	26.00	23.75	20.00
L_1	2.00	2.00	5.00	9.10	5.50	7.00
L_2	22.00	19.00	16.50	26.00	24.00	21.00
L_3	14.00	5.25	11.50	18.00	18.00	14.00
BrW	10.00	10.00	10.00	12.50	10.00	12.00
PL	5.35	57.40	79.60	28.95	26.20	21.35
FL	0.50	51.70	72.80	20.50	21.58	12.00
Wf	22.90	26.50	46.50	17.20	19.30	32.00
$Vol_{Br.}$	55.50	82.68	165.23	100.38	62.30	63.36
Vol_{Piers}	480.15	379.05	841.50	351.52	197.51	1496.00
$Vol_{Abut.}$	589.76	748.12	1009.80	1166.61	296.26	2367.98
Vol_{flPC}	870.20	521.72	767.25	0.00	550.05	3158.40
Vol_{flRC}	435.10	347.81	767.25	1620.41	733.40	336.00
$Cost_{Br}$	111,000	165,368	330,450	200,750	124,600	126,720
$Cost_{Piers}$	240,075	189,525	420,750	703,040	395,010	748,000
$Cost_{Abut.}$	294,880	374,063	504,900	2,333,214	592,515	1,183,991
$Cost_{Floor}$	1,305,300	956,484	1,918,125	3,240,824	1,741,825	2,251,200
Total Cost	1,951,255	1,685,439	3,174,225	6,477,828	2,853,950	4,309,911

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[6] M_{ab}=1 Brick, 2 PC, 3 RC

[7] M_{fl} = 2 PC, 3 RC, 4 PC+RC

[8] Br_{type}= 1 arch bridge, 2 slab bridge, 3 beam bridge

Table 4:- The actual dimensions, materials, volumes and the updated costs for the existing structures (ST-7).

Symbol	ST-7
S	3.00
N	6
DBF	0.50
M_{ab}	3
M_{fl}	3
Br_{type}	2
E	1.50
T_{at}	0.50
T_{ab}	1.95
T_{1PC}	0.50
T_{1RC}	1.25
T_{2PC}	0.50
T_{2RC}	1.25
T_{3PC}	0.50
T_{3RC}	1.25
L_{pier}	29.00
L_1	3.50
L_2	29.00
L_3	16.00
BrW	10.80
PL	6.93
FL	1.05
Wf	31.40
VolBr.	89.10
Vol_{Piers}	(volume of RC)852.60 (volume of Brick cover)426.30
$Vol_{Abut.}$	(volume of RC)556.10 (volume of Brick cover)142.59
Vol_{flPC}	761.45
Vol_{flRC}	1903.63
$Cost_{Br}$	178,200
$Cost_{Piers}$	(Cost of RC)1,705,200 (Cost of Brick cover)85,260 1,790,460
$Cost_{Abut.}$	(Cost of RC)1,112,202 (Cost of Brick cover)28,518 1,140,720
$Cost_{Floor}$	4,187,975
Total Cost	7,297,355

Table 5:- The optimal dimensions, materials, volumes and the optimal costs using the multi-model solution (from ST-1 to ST-7).

Symbol	ST-1	ST-2	ST-3	ST-4	ST-5	ST-6	ST-7
S	3.00	3.00	6.00	4.00	3.00	5.00	6.00
N	3	3	3	3	3	2	2
DBF	0.00	0.20	0.00	0.00	0.00	0.00	0.10
M_{ab}	2	2	2	2	2	2	2
M_{fl}	4	4	4	4	4	4	4
Br_{type}	2	2	2	2	2	2	2
E	1.40	1.00	1.00	1.40	1.20	1.40	1.20
T_{at}	2.00	1.10	1.90	1.70	1.40	1.90	2.30
T_{ab}	2.60	4.00	2.90	5.00	2.50	3.60	3.10
T_{1PC}	1.30	1.20	1.60	1.50	1.30	1.40	1.30
T_{1RC}	0.50	0.50	0.50	0.50	0.50	0.50	0.50
T_{2PC}	1.30	1.20	1.60	1.50	1.30	1.40	1.30
T_{2RC}	0.50	0.50	0.50	0.50	0.50	0.50	0.50
T_{3PC}	0.70	0.20	0.70	1.00	0.60	0.70	0.70
T_{3RC}	0.50	0.50	0.50	0.50	0.50	0.50	0.50
L_{pier}	22.00	19.00	16.50	26.00	23.75	20.00	29.00
L_1	3.00	2.00	6.00	10.00	6.00	4.00	4.00
L_2	22.00	19.00	16.50	28.00	25.00	23.00	29.00
L_3	14.00	5.00	12.00	17.00	16.00	15.00	16.00
BrW	10.00	10.00	10.00	12.50	10.00	12.00	10.80
PL	5.30	57.96	79.90	29.30	26.40	20.70	6.63
FL	1.00	51.50	73.30	20.50	22.08	13.50	1.45
Wf	19.00	21.00	27.80	26.80	18.40	20.60	21.40
VolBr.	41.40	39.00	132.00	84.00	40.20	80.40	98.50
Vol_{Piers}	264.88	245.48	217.80	640.64	246.24	201.60	180.26
$Vol_{Abut.}$	771.42	856.60	1092.96	3242.80	791.86	1663.20	1370.63
Vol_{flPC}	803.70	550.20	1234.32	1983.20	918.16	994.98	1157.74
Vol_{flRC}	370.50	273.00	479.55	737.00	432.40	432.60	524.30
$Cost_{Br}$	82,800	78,000	264,000	168,000	80,400	160,800	196,992
$Cost_{Piers}$	132,440	122,740	108,900	320,320	123,120	100,800	90,132
$Cost_{Abut.}$	385,710	428,298	546,480	1,621,400	395,928	831,600	685,314
$Cost_{Floor}$	1,142,850	821,100	1,576,260	2,465,600	1,323,880	1,362,690	1,627,470
Total Cost	1,743,800	1,450,138	2,495,640	4,575,320	1,923,328	2,455,890	2,599,908

Conclusions:-

The presented methodology of the design is a process to determine materials and dimensions of regulator elements, number of vents, and vent span by matching an existing structure with the newly calculated parameters with iteration/ optimization schemes. This research focuses on the development of a new design method for symmetrical regulators based on surface flow and material types of elements and coupled with a hybrid evolutionary global optimization algorithm, namely Shuffled Complex Evolution (SCE). The SCE algorithm developed at the University of Arizona is reported to be an efficient global optimization method that can be used to handle non-linear problems with high-parameter dimensionality. This approach treats equations as a global optimization problem where the cost function to be minimized is defined as the differences in measured and computed dimensions and materials. The optimal solution (materials and dimensions of regulator elements, number of vents, and vent span) is searched for in the multi-model solution space by the SCE algorithm.

Seven regulators are used to evaluate the prediction accuracy of the developed ODR-SCE tool. The results demonstrate the pronounced performance of the developed tools; this software can help decision-makers to know the optimal hydraulic and structural design in addition to the optimal cost of the barrages. It also illustrates that the slab type is more optimal than arch or beam types for the bridge, plain concrete for abutments and piers is more optimal than reinforced concrete; combining reinforced and plain concrete for the floor is more optimal than either one alone.

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List of Symbols

BedW	Bed Width
Br_{type}	Type of Bridge
BrW	Bridge Width
C_B	Bligh coefficient
C_L	Lane coefficient
θsoil	Soil angle
C_{soil}	Cohesion of soil
$Cost_{Abut.}$	Cost of abutments
$Cost_{Br}$	Cost of bridge
$Cost_{Floor}$	Cost of floor
$Cost_{m3brick}$	Cost of brick per unit volume
$Cost_{m3PC}$	Cost of plain concrete per unit volume
$Cost_{m3RC}$	Cost of reinforced concrete per unit volume
$Cost_{Piers}$	Cost of piers
DBF	The difference between bed level and floor level
DS	Down Stream
DSBL	Down Stream Bed Level
DSWL	Down Stream Water Level
E	Pier width
ECP	Egyptian code of practice
EMB	Embankment level
F_b	Allowable compression strength of brick
F_{bt}	Allowable tension strength of brick
F_c	Allowable compression strength of plain concrete
F_{ct}	Allowable tension strength of plain concrete
FL	Floor Level
F_s	Allowable tension strength of steel
F_{soil}	Allowable stresses
γ_{Brick}	Weight of brick per unit volume
γ_{PC}	Weight of plain concrete per unit volume
γ_{RC}	Weight of reinforced concrete per unit volume
γ_{soil}	Weight of soil per unit volume
H_{DS}	Down Stream head of water
h_{max}	Difference between USWL and FL
H_{US}	Up-Stream head of water
IS	Indian Standard
L_1	Up-Stream floor length
L_2	Middle floor length
L_3	Down-Stream floor length
L	$L_1+L_2+L_3$ (floor length)
L_{pier}	Pier Length
Ls	Scour length
M_{ab}	Pier and Abutments Materials
M_{fl}	Floor Materials
N	Numbers of spans
ODR	Optimal Design of Regulator

PC	Plain Concrete
PC+RC	Lower layer of plain concrete + above layer of reinforced concrete
Q	Discharge
RC	Reinforced Concrete
S	Span of vent
ST	Structure
T_{1PC}	Floor PC thickness
T_{1RC}	US floor RC thickness
T_{2PC}	middle floor PC thickness
T_{2RC}	middle floor PC thickness
T_{3PC}	DS floor PC thickness
T_{3RC}	DS floor RC thickness
T_{ab}	bottom width of abutment
T_{at}	top width of abutment
US	Up Stream
USWL	Up Stream water level
V_c	Velocity throw canal.
Vol_{Abut}	Volume of abutments.
$Vol_{Br.}$	Volume of bridge.
Vol_{flPC}	Volume of plain concrete part of floor.
Vol_{flRC}	Volume of reinforced concrete part of floor.
Vol_{Piers}	Volume of Piers.
W.L.	Water level
Z	Side slope of the canal

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