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Developed Computational Methodology for the Most Effective Design of Open Channel Cross Sections

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Abstract: Open channel is the most important way to convey water for various purposes. Channels cost a lot of money to construct. The optimal design means delivering water with efficiency, safely, and economical costs of construction. The determinant of minimum cost must take into account the effect of manning coefficient variation between the sides and the bed. The proposed program is solved using the Shuffled complex evolution method developed at the University of Arizona (SCE-UA) algorithm. The results obtained in this study are compared with existing models developed by others in the past using either the complex equations or the Simultaneous Perturbation Stochastic Approximation (SPSA) technique. The result shows that the existing optimization problem formulations, when solved using SCE-UA, provided results compared to those solved using the Lagrange multiplier method. The results obtained in this study indicate that approximately 34% of cost savings can be achieved. Also, the provided results were compared to those obtained by others in the past using (SPSA) technique. The results obtained in this study indicate that approximately 36.5% of cost savings can be achieved. It was found that the (SCE-UA) technique is more accurate than (SPSA) and has the lowest total construction cost.
Keywords: Composite roughness; Minimum construction cost; Objective function; Open channel; Optimal design; Optimization problem; SCE- UA; SPSA.

1. Introduction

Open channel is the most important way to convey water for various purposes. The Channels' construction cost is very high. Therefore, it is considered the construction cost of channels normally includes excavation cost and surface lining cost. The optimal design aims to reach the most effective size to transport enough discharge with the least amount of channel construction cost along the channel. Das (2000) [1] determined the optimal trapezoidal channel cross section (using the Lagrange multiplier method with composite roughness (using Horton's (1933) equation in [2]) by using the classical optimization technique.

The minimization of channel construction costs and the maximization of channel flow rates are taken into account when determining the cross-sectional geometry of a channel [3]. It is less expensive to create composite channel cross-sections with many sides and bed lining materials than it is to do it simply [1, 4]. Freeboard was a parameter that Guo and Hughes [3] used to improve the trapezoidal channel cross-section. By including the freeboard parameter, velocity limitations, and the cross-section's geometric constraints, Loganathan [5] optimized the parabolic channel. Due to lower costs for excavation and lining, an open channel cross-section with a minimum cross-sectional area or maximum mean velocity is the most economically efficient [6].

The channel's bed and sides were considered to have a uniform roughness coefficient in these earlier studies. For computations involving uniform flow in channels with varied bed and side roughness coefficients, an equivalent roughness coefficient is taken into account [4]. The ideal cross-sectional geometry of an open channel was investigated by Swamee et al. [7] with the objective function of the channel construction costs taking consideration of the expenses of excavation, lining, and water losses.

When contrasted with the parabolic cross-section and trapezoidal cross-section, Babaeyan-Koopaei et al. [8] demonstrated that the parabolic-bottomed triangle channel cross-section (using the Lagrange multiplier approach) has a minimum wetted perimeter and a cross-sectional area for the precise parameters of discharges, side slopes and bed, and roughness coefficients. Their findings demonstrate that the costs of lining and excavation are reduced for this cross-section. As a result, the Triangle cross-sections with parabolic bottoms are the most cost-effective (when compared to the trapezoidal and the parabolic channels). The ideal formulae for designing a parabolic cross-section were presented by Chahar [9] without the freeboard. These equations, which were derived in an explicit dimension using the Fibonacci search method, were used to reduce the constructing expenses (excavation and lining costs).

Many previous studies used the genetic algorithm (GA) technique to minimize construction costs. Bhattacharjya [10], for instance, investigated the ideal stable trapezoidal composite cross-section taking the safety factor into consideration as a requirement for the side slope stability. Reddy and Adarsh [11] used the GA genetic algorithm and PSO heuristic algorithms to optimize the composite channel with a trapezoidal cross-section while accounting for the impact of uncertainty analysis and the probability concept. Using the GA genetic algorithm, Roushangar et al. [12] studied the ideal channel (trapezoidal cross-section). They looked at each limitation separately, including the impact of the flow depth, Froude number, top width, and flow velocity. The ideal composite trapezoidal cross-section for moving sediment carrier flow was created by Gupta et al. [13] by taking freeboard (constant value and depth-dependent) into account while maximizing hydraulic efficiency and minimizing construction costs.

Many literature studies used the genetic algorithm (GA) technique for solving optimization problems as mentioned previously. The SCE-UA strategy has the preference over the simple genetic algorithm for the following reasons: (i) SCE-UA performed less number of function evaluations than GA for obtaining the optimal design, (ii) the size of the executable program of SCE-UA is less than that of GA , and (iii) the simple GAs needs to convert the optimization variables to binary representation, while SCE-UA deals with those variables directly by the real number presentation, (iv) computer memory used during SCE-UA runs is less than that of GAs runs by approximately 52%, and (v) results obtained by using SCE-UA are slightly more accurate than that of GAs [14].

Han et al.'s [15] use of the Lagrange Multiplier optimization approach led to the most cost-effective cross-section. The optimization issues were resolved via the SPSA (Simultaneous Perturbation Stochastic Approximation) algorithm. Their Result indicates that the construction costs increase with increasing the water depth, equivalent roughness coefficient, left side slope, and freeboard [16].

There are several different trails and methods to reach the optimum design of composite open channel, namely the bat algorithm (BA), their hybrid (HBP), and particle swarm optimization (PSO), which are applied for designing trapezoidal open-channel cross-sections in [17]. By adjusting the discharge and slope angle, Saplioglu et al. [18] established an ideal design for a trapezoidal cross-section.

In this study, conceptual analytical models and mathematical functions are used to more precisely describe the optimization of a trapezoidal composite channel cross-section.

The optimal design concept, the required discharge is taken into account while designing the channel cross-section, and the construction expenses are kept to a minimum Moreover, a comparison of the current study and different studies for the optimum design of the trapezoidal composite channel cross-section was conducted. The methodology of the conceptual and analytical models that are applied in this current study differs from that in earlier publications. This comparison considers one of the most innovations of this study.

2. Problem description

The optimum design of a trapezoidal composite channel for uniform flow state is presented. In the present study, the equivalent Manning's roughness coefficient was determined using Lotter's equation from [19]. Its derivation was established from the concept that total channel discharge equals the sum of sub-area discharges. This approach is normally used for irregularly shaped open channel such as natural floodplain. As seen in [20], vertical lines that extend from each point where the channel's roughness breaks up to the water's surface are used to define the segmental areas.

3. The channel's geometrical parameters

The channel's geometrical parameters of the design cross-section are shown in Fig. 1. The flow wetted perimeter consists of bed width and the two wetted side slopes of the cross-section. The Manning roughness coefficient values for side faces having slopes z1(H):1(V) and z2(H):1(V) and bed width (b) are n1, n2, and n3, respectively. y is the water depth, f is the freeboard, T is the top width of the channel and S is the longitudinal bed slope.

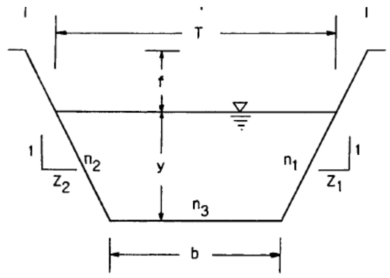

Figure 1. The geometric dimensions for a trapezoidal cross section

4. Optimization method - SCE-UA algorithm

The shuffled complex evolution method developed at the University of Arizona (SCE-UA) is an evolutionary programming technique that combines the Strengths of the simplex procedure [21] with (i) the concept of controlled random search [22]; (ii) competitive evolution [23]; and (iii) the concepts of complex shuffling [24]. The synthesis of these concepts makes the SCE algorithm not only effective and strong but also efficient and flexible.

Using deterministic strategies lets the SCE algorithm make functional use of the response surface data to drive the research. Strength and flexibility are taken into account by using random elements. Concentrating a search in the most promising zone of the search space is oriented by the implicit clustering strategy. The use of the systematic complex strategy makes a relatively robust search that is governed by the structure of the objective function. Basically, this approach starts with a group of points (population) sampled randomly from a suitable region. It is split into communities, each of which is permitted to evolve, in other words, to generate offspring independently. Geometrically on the framework of a statistical replication program which uses of the complicated shapes to guide the research in a more precise manner.

To facilitate the sharing of information from the various complexes, the points are reassigned to communities and the population is shuffled in the evolutionary process' direction. If the population's starting size is large enough, repeated application of this method leads the population to converge toward the area surrounding the global optimum [25]. During the investigations of [24], the competitive complex evolution (CCE) algorithm is considered one of the basic components of the shuffled complex evolution procedure. It is one of the main requirements for the evolution of each complex of the SCE methodology. (See Fig.2)

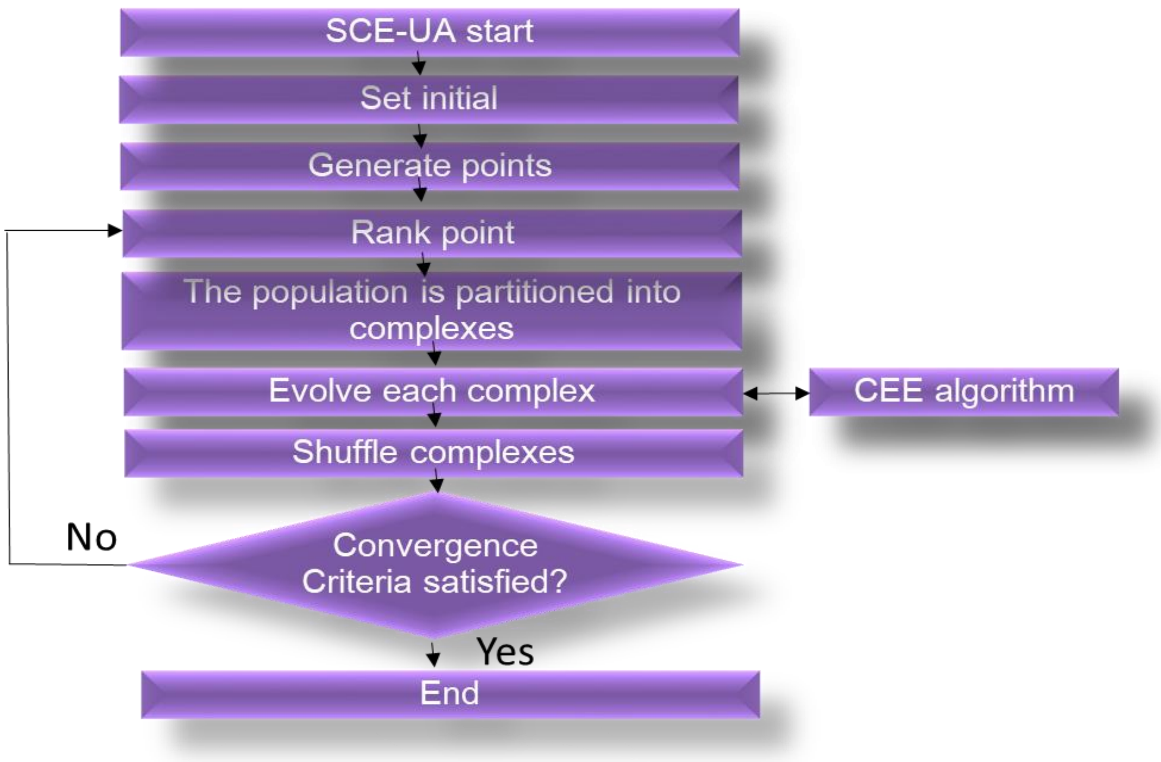

Figure 2. Flow chart of SCE-UA algorithm

A competitive evolution process is ensured during recognition of the fact that parents with higher probabilities contribute more to the generation of offspring than those with lower probabilities. Such competitiveness is guaranteed by using a triangular probability distribution. The processes of competitive evolution and complex shuffling in the SCE algorithm ensure that the data of the samples is efficacy and completely exploited. They also help to guarantee that the data set does not become degenerate. These features provide the SCE process with excellent global convergence properties over a wide range of problems. On the other hand, given a predefined number of function evaluations, the SCE approach should have a high probability of succeeding in its objective of obtaining the global optimum [24]. In the SCE algorithm, different algorithm parameters are selected as the most recommended values from the literature. Those parameters are: (i) number of complex (nc), (ii) number of complex population (ncp), (iii) number of sub-complex population (nscp), (iv) generated offspring (ntp), and (v) number of generation inside the extermination room (maxgene) [14].

5. Objective function

The constraints in Manning's equation, the total cost of channel construction (surface lining and excavation costs per unit length of the channel(1m)), and positive values of the design variables namely channel water depth and bed width formed the objective function. To calculate the equivalent manning roughness coefficient, Lotter's equation was applied. The total cost of constructing a 1 m channel, taking into account surface lining and excavation expenditures, is the study's objective function. Equation can be used to represent either the cost function or the objective function:

$$\text{Minimize } C_t\,(y, z_1, z_2, b) = c_1A_{total} + c_2P_1 + c_3P_2 + c_4P_3 \tag{1}$$

where, Right side slope, left side slope, and channel bed, respectively, are denoted by the subscripts 1, 2, and 3, respectively. A total is the total cross-sectional area (m2), P is the lining length (m), y, z1, z2, and b are four decision variables, and Ct is the objective function. It is the sum of the excavation and lining costs for the channel in currency units; c1 is the excavation cost per square meter for a length of the channel of one meter (currency units/m2); and c2, c3, and c4 are the lining costs per one meter for the perimeter, including the freeboard, of segments one, two, and three of the trapezoidal channel cross section, respectively (currency units/m).

6. Results and discussion

A comparison among several analytical and mathematical models of the existing formulations used by Das (2000), Somayyeh (2021), and the proposed model (2022) is presented in this study. These models are used for solving composite channel optimization problems. Results from Das (2000), who utilized the Langrage multipliers approach, and Somayyeh (2021), who applied the Simultaneous Perturbation Stochastic Approximation (SPSA) algorithm, are compared to those from the SCE-UA technique.

The design discharge of 100 m/s, the constant bed longitudinal slope = 0.0016; the values of Manning's roughness coefficients in different parts n1= 0.02, n2= 0.018, and n3= 0.015; This study has adopted the freeboard parameter of 0.5 m and the cost parameters (c1, c2, c3 and c4) of 0.6, 0.2, 0.25, and 0.3 respectively as same as in Das (2000) and Somayyeh (2021). To certify the efficacy of the study's approach. The outcomes of Das's (2000) approach, Somayyeh (2021), and the proposed model (2022) solved by using SCE-UA are represented in the following Table 1. to compare with them.

Table 1. Outcomes of the existing formulation used by Das (2000), Somayyeh (2021), and the proposed model (2022)

Formulations by	Technique	Bed width (m) (B)	Side slop (Z_1)	Side slop (Z_2)	water depth (m) (Y)	Total cost (currency units) (C)
Das (2000)	(Classical)	5.826	0.247	0.265	4.052	22.958
Somayyeh (2021)	(SPSA)	5.550	0.236	0.254	4.889	23.731
Proposed model (2022)	(SCE-UA)	3.50	0	0.404	4.00	15.068

Table 1 shows that the costs required to construct the composite channel determined by Das (2000) with the classical technique is 22.958, by Somayyeh (2021) is 23.731 and the Proposed model (2022) with the SCE-UA technique is 15.068. Clearly, the proposed Model result has the lowest costs of all the models examined in this study.It is clear from table 1 that the results obtained by Das (2000) compare very well with the Model by Somayyeh (2021). But the classical technique is based on differential equations that have many difficulties because of the complexity of the relationship between the control variables in the objective function.

It should also be highlighted that the total construction costs of the composite channel determined by the proposed model using the (SCE-UA) technique are more accurate and faster than (SPSA) and the least in total construction costs.

When compared to the Das (2000) and Somayyeh (2021) models, the suggested model (2022), which was solved using SCE-UA, performs well. When SCE-UA was used to address existing optimization issues, it proved that the outcomes were superior to those obtained by earlier researchers using the Lagrange multiplier method (Das 2000). The study's findings show that it is possible to save money by about 34%. Furthermore, Somayyeh (2021), who applied the (SPSA) technique, contrasted the outcomes with those of this study. The findings of this study show that a cost reduction of about 36.5% is possible. Therefore, the conceptual and analytical models used in this work differ from those used in past publications in terms of technique. One of the most novel aspects of the study is this contrast.

7. Conclusions

The Results of an examination regarding the optimum design for composite channels using the SCE-UA technique are presented in this work. Additionally, it presents other researchers who have investigated two different optimization problem formulations in the past and it gives a comparison among them results.

To help practicing engineers understand how the SCE- UA methodology functions, a flow chart of the technique is also produced and provided in this research.

The proposed model (2022) that is solved using SCE-UA compares very well with the Models by Das (2000) and Somayyeh (2021). It was found that the results produced by the existing formulations of optimization problems when solved by SCE-UA were superior to those achieved by previous researchers applying the Lagrange multiplier approach (Das 2000). According to the study's findings, a cost savings approximately 34% can be achieved. Additionally, Somayyeh (2021) who utilized the (SPSA) technique compared the results to those achieved by this study. The results obtained in this study indicate that approximately 36.5% of cost savings can be achieved.

The significant reductions in the total construction cost of the composite channels are due to using the SCE-UA technique and using a distributed approach (The advantage of Lotter's equation over Horton's is that it accounts for the fact that the velocity changes in the channel bed and on side slops with various roughness coefficients.) that allows permits fluctuations in the velocity that let the velocity to vary in channel bed and side slopes with various roughness coefficients. Additionally, it came out that setting lower and upper boundaries for the variables using the SCE-UA technique, results in a smaller search space for the optimization solution strategy to achieve, which could speed up the convergence of the optimization technique to the optimal design. The adoption of the non-linear optimization issues raised in this study along with the SCE-UA solution methodology technique can lower the construction expenses of most of composite channel's projects worth many millions of dollars, making this a significant finding of the study presented in this paper.

For designing compound channels with floodplains on either side that have differing Manning roughness coefficients, the approach suggested in this work may be more preferable. It is anticipated that future research would concentrate its efforts in this direction to enhance the efficiency of issues relating to channel optimization.

8.References

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