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Estimation and Optimization of the Hydrostatic Height of Waterway Embankment Using Taguchi-Based Honey Badger Algorithm

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ABSTRACT

The geometric design of a waterway embankment depends on several factors like soil and subsoil properties, loading conditions, geometric constraints, climate & weather conditions, etc. Surface wind velocity (V) and fetch length (F) are two control factors that help to determine the wave height (H) utilizing the Taguchi Factorial design method. A non-linear equation was generated by integrating optimized H with the upstream water pressure (P). In the JAVA environment, a pseudo-code was created to solve the non-linear equation and determine the resulting hydrostatic height (h_w) and crest width (b). The calculated h_w and b were validated utilizing the Honey-Badger algorithm by initializing all the control factors along with P. The outcomes from the experimental analysis of Taguchi showcase that lower control factors helped to obtain the maximum h_w along with b for the embankment. As per Analysis of Variance (ANOVA), maximum V was found to be the most significant control factor influencing the determination of H, h_w and b of the earthen embankment. The regression squared (R^2) value from the Design of Experiment (DoE) of the Taguchi method was found to be 99.21% which shows that the observed data were well fitted to the developed model for evaluating the contribution of Signal to Noise (S/N) ratio and verify the validity of optimal factor settings through confirmation experiments. The confirmatory test was piloted to check the similarity index between the two methods and the outcomes were found to be nearly similar with an error of 2.62%.

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1. Introduction

An embankment is a natural barrier or berm to construct a roadway or waterway. In general, a waterway embankment is aligned on the ridge of the river bank where the high velocity of water and climatic conditions play an important role in the determination of the cross-section of the earthen embankment. The high velocity of flow, wind speed, rainfall-runoff, etc, values are some of the essential data required for determining the high flood level [1]. Alizadeh et al. [2] and Santos and Silva [3] provided a new simulating technique for forecasting rainfall-runoff process and daily stream flow respectively by incorporating wavelet transform with artificial neural network (WANN) for a small span of the time period. A similar non-linear model was developed by Akrami et al. [4] based on wavelet-ANFIS for rainfall forecasting of Klang Gates Dam, Malaysia. It was found that the hybrid artificial neural network model gives significantly better and more accurate results than the classical artificial neural network (ANN) for a limited time period. The above past records demonstrate that even if heavy rainfall continues for a small time period, river embankments are more susceptible to seepage thereby requiring more flood control assessment for their design and construction.

Determining the time and the magnitude of the flow at a particular point in the watercourse flood routing will help to estimate storage capacity by optimizing initial inflow and outflow. Generalized reduced gradient (GRG) solver and evolutionary solver are two Excel solver techniques to estimate non-dimensional Muskingum flood routing parameters [5]. In order to prevent the overflow of flood water beyond its normal limit, flood control measures were taken into consideration. Dykes, embankments, reservoirs, and spillways are some of the flood control measures used to store and control high flood levels. However, the price of building such measures accounts for close to 20% of the overall cost of building the Dam, hence Hosseini et al. proposed [6] an optimal design of labyrinth spillways utilizing a meta-heuristic algorithm. As per IS 12094:2000 [1] design embankment height is determined based on estimated wave height and hydrostatic height on the upstream side. Therefore, surface wind velocity (V) and fetch length (L) become important parameters to predict the effect of flood and failure of slope in the embankment. To normalize this effect either we need to increase the height of the embankment or to stabilize it with higher stabilizing materials. Detailed analysis of limited factors with more complicated relationships can be easily optimized with the Taguchi Factorial methodology. A couple of investigation works have been led in the geotechnical designing field utilizing Taguchi improvement methodology. Zhang et al. [7] use a fractile-based safe, economical, and robust design framework called as Load and Resistance Factor Design (LRFD) to select the characteristic values of the uncertain soil parameters. A drilled shaft in the sand and a shallow spread base were used to demonstrate the framework. The outcomes show that strong designs can be realized by combining LRFD with the trademark values generated by the recommended fractile-based technique. Ikeagwuani et al. [8] employed Taguchi to maximize the strength of an environmentally friendly high-strength sandcrete block model. A L9 orthogonal array was adopted to evaluate the compressive strength, bulk density, and water content of the sandcrete block using end-web to center-web (E/C) ratio, water-content (W/C) ration and Coconut shell ash (CSA) as control factors. The strength of the sandcrete model was shown to be most significantly influenced by its compressive strength. Zaimoglu et al. [9] improved the

Consistency Limits and Plasticity Index of fine-grained soils amended with polypropylene fibres and additional ingredients. In this study, the Atterberg cut-off points of broad soil were examined in relation to sawdust debris, morsel elastic, and sawdust. With three variables and three levels, the Atterberg limit experiments were performed in accordance with the L9 symmetrical exhibit scheme. The analysis plan was completed using Taguchi methods and Minitab 18 software. In light of the overall dry load of the blend, nine gatherings of consistency limits were lead for each preliminary of 0-20 percent sawdust debris, 0-20 percent -piece elastic, and 0-8 percentage sawdust. According to their findings, the best-added substance materials for decreasing as far as feasible and versatile records of the instances were sawdust waste and piece elastic. Sharifi et al. [10] advances high-strength self-combining substantial blend configuration utilizing a superior Taguchi streamlining technique. Examination of change was likewise used to evaluate the compelling elements and the ideal blend plan. As it lowers the cost of analysis while improving quality and providing a strong design solution, the above records [7–10] demonstrate a good agreement between geotechnical solutions and Taguchi factorial design. But there is a gap in the implementation of the Taguchi factorial method in the design of earthen embankments.

The limit state method is frequently used for the design and analysis of earthen embankments. Later limit state method anticipated with other advanced techniques was implemented in the slope stability analysis. Finite element analysis coupled with Genetic Algorithm was utilized by Bhandary et al. [11] to evaluate the factor of safety (FOS) of an earthen embankment built in on a soft compacting layered soil. Mohr-Coulomb non-linear model and least FOS was estimated at a different time interval from point of construction to the complete consolidation stage using the Genetic algorithm which guides researchers to know about the suitable time period and best use of the embankments. Planning and resource management during the pre-construction stage under adverse rainfall conditions can be effectively accomplished by simulating an embankment model. Belo et al. [12] conducted a reliability analysis of an embankment built and reinforced on soft clay using limit equilibrium and finite equilibrium methods. Artificial neural networks and a genetic algorithm were used by Mamat et al. [13] to predict the slope failure surface and slope angle of an embankment. Later some surcharge was applied to study the substantial influence on slope stability. Kommu et al. [14] optimized different embankment sections with different backfill materials constructed in contrasted land for overall cost construction reduction purposes. Although evaluation times with high precision might be up to 13.8 times faster than the average. Ghali et al. [15] provided an anticipated method to stimulate an embankment construction period during heavy rainfall season by taking rainfall data set form NASA satellite imaging. Flessati et al. [16] employed a displacement-based design technique to estimate differential and average displacements at the top of an embankment. The design technique enhances the pile diameter as well as the width of the pile group. A roadway embankment was studied by Shejwal and Gaikwad [17] using optimal values of the fly ash and cost-effective geogrid reinforcement. Furthermore, the generic study and design viewpoint on employing different side slope ratios with a combination of an effective percentage of fly ash, which lowered the geogrid reinforcement length, were described. The effectiveness of a cohesive-frictional embankment built on a soft clay stratum that is reinforced by a vertical, evenly spaced granular cylindrical column was examined by Mohapatra and Kumar [18]. They carried out the performance analysis to incorporate different geomechanics reliability issues by utilizing the homogenization-based kinematic limit analysis technique. The distribution of water with the depth in a soil column was estimated by Peters and Durner [19] using the equilibrium equation. They reported the removal of systematic parameter estimation errors, which resulted in better estimations of the soil water retention function.

Distinguished investigators tried to design the embankment either by numerical methods or by material replacement. The published research works [11–19] only focused on stabilization and promoted safety measures against embankment failure. Fusion of the classical method of slope stability with optimization technique proved to be more advantageous as it provides more consistent, cost-effective, and improved quality results.

Some of the coupled optimization techniques are listed below in chronological order. *Multi-gene genetic programming* was utilized to estimate the drag coefficient of a flow around a sphere [20][and predict the performance of tunnel boring machines [21]. *Cluster-based Bayesian network* predicts longitudinal dispersion in a river stream [22] whereas a non-hydrostatic wave model requires to study of the complete dispersion of highly non-linear waves [23]. Sediment transport rate near southern shoreline of Caspian Sea was estimated by an artificial intelligence technique called a *Neuro-fuzzy interference system* [24]. In order to forecast the influence of flood embankments on agricultural revenue distribution in the coastal region of Bangladesh, a stochastic-optimization method called as *multi-objective optimization technique* was used by Barbour et al. [25]. They concluded that the upgraded drainage could lessen the negative effects of increased salinity and waterlogging, which was the outcome of the restoration of embankments leading to boosting agricultural productivity. Escalante et al. [26] created a two-layer depth-integrated non-hydrostatic model with improved dispersion correlations. *Dispersive optimized model* results with good linear wave attributes that can be enhanced for long waves.

Limited attention was given to maximize the embankment height by considering various factors like wave height, fetch length, and velocity of the wave as influencing factors. The present study considers the above factors to design the maximum height of embankment. The hybrid optimization technique is not employed by the researchers to find a suitable maximum height of embankment. Due to the negligible approach of waterway embankment design using optimization techniques, the current work centered to involve a hybrid optimization strategy for its construction purpose.

2. Methodology

In this study, an attempt has been made to optimize the hydrostatic height (h_w) of the waterway embankment. Two important control factors i.e., maximum wind velocity (V) along with the fetch length (F) have been considered for maximizing the h_w. This was achieved by hybridizing Taguchi with a nature-based Honey-Badger (HB) Algorithm. The experimental investigation initiated with the numerical evaluation of the wave height (H) using different values of F and V based on the wave's height equation derived by the Molitor [1]. The numerical solutions of H incorporated with critical steady seepage analysis to formulate a non-linear non-homogeneous equation with two variables as h_w and crest width (b). The sets of output response of H, h_w and b from Design of Experiment (DoE) were optimized under the Taguchi method and validated with the HB algorithm. Lastly, a confirmatory test was conducted with ANOVA to determine the relevance of the control factors in addition to the predicted value.

The experimental investigation comes up with a detailed procedure to evaluate the maximum h_w and b which are the fundamental specifications needed to build an earthen embankment. This will provide a potential benefit to the researcher and working personnel to design the earthen embankments without following tedious manual codes.

2.1. Model study

Water pressure force (P) and self-weight (W) are considered to be the main forces affecting the design and construction of the Earthen Embankment. Neglecting uplift force by considering undrained conditions in foundation soil. Adopted a country slope ratio of 2.5:1 and a river slope ratio of 2:1 for uniformly well-graded soil stated by Husain [27]. Fig. 1 represents a waterway embankment with all the expected forces acting on it.

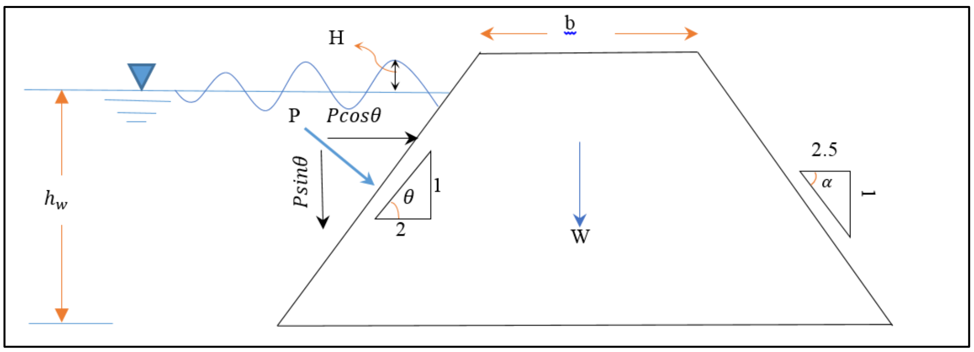

Fig. 1. Schematic diagram of an embankment with the expected forces.

David A. Molitor calculated the experimental equation for the embankment's wave height (H), which is stated in equations (1) and (2) [1].

$$H = .032\sqrt{FV} + 0.763 - 0.271\sqrt[4]{F} \quad (1)$$

where F < 32 km

$$H = 0.032\sqrt{FV} \quad (2)$$

where F> 32 km

H= wave height in meters

V = maximum wind velocity in km per hour

F = Fetch in km.

As per the US Bureau of Reclamation (USBR), the values of F and V are basic elements used for the estimation of H and subsequent calculation of h_w and b. Thereby current study considers V and F are two control factors listed in Table1 with a variation of minimum to maximum values.

Table1

Levels of the variables (control factors) used in the experiment.

Control Parameter	**Code**	**Lvl-1**	**Lvl-2**	**Lvl-3**
Maximum wind velocity (V) in km/hr	A	30	40	50
Fetch (F) in km	B	20	25	30

Additional height is provided to high flood levels in order to prevent embankment-like structures from overtopping and flooding. As per the US Bureau of Reclamation (USBR), 10-15% of the highest flood level was provided as freeboard. For extreme flood levels, a typical range of 2-3m of freeboard is provided, with a maximum fetch length of 32km and an average wind speed of 40 kmph. The crest width can be determined for such a prototype circumstance using the formulas provided by Punmia [28] and Garg [29] represented below;

$$b = \frac{h_w}{5} + 3 \qquad \text{(For embankment height} \leq 6m) \tag{3}$$

$$b = 0.55\sqrt{h_w} + 0.2h_w \qquad \text{(For embankment height} \leq 30m) \tag{4}$$

$$b = 1.65\sqrt[3]{h_w + 5} \qquad \text{(For embankment height} > 30m) \tag{5}$$

where b = crest width in meters; h_w = height of embankment in meters

Forces acting on the riverside of the embankment are estimated by normalizing the force due to the water reservoir as given by equation (6) and self-weight of the waterway embankment structure is represented in equation (7).

$$P = 0.5\,\gamma_W b(2H + h_w)^2 \tag{6}$$

$$W = 28.8h_w^2 + 66.6h_w + 83.7 \tag{7}$$

Under critical steady seepage conditions P and W are incorporated to find out the h_w subsequently calculate the crest width using equation (4) as a way to construct a stabilize the earthen embankment. The simplified equation represented in equation (8) was solved by an Object-oriented programming (OOP) approach.

$$(23.04 - 7.2b)h_w^3 + (303.36 - 81b)h_w^2 + (646.38 - 208.8Hb)h_w + 728.19 = Hb(208.8B + 28.8H) \tag{8}$$

2.2. Taguchi factorial design method

After the numerical analysis a pseudo-code has been generated in the JAVA environment for computing H, h_w, and b represented in Fig. 2. Then the computed h_w, H and b for each experimental run, were arranged as per the expected design of experiment (DOE). The DOE was generated for the three output responses using two control parameters according to Taguchi L9 orthogonal array.

2.3. Honey-badger algorithm

The obtained results have been validated by the Honey Badger algorithm which was developed by Fatma A.Hashim et al. [30] in 2021. The newly introduced optimization technique was inspired by the intelligent foraging of honey-badger. This mathematical tool provides an efficient search strategy for solving optimization problems. The current research work involves the dynamic behavior of honey badger to optimized the maximum hydrostatic height using a pseudo-code provided in the form of flowchart (Fig.3).

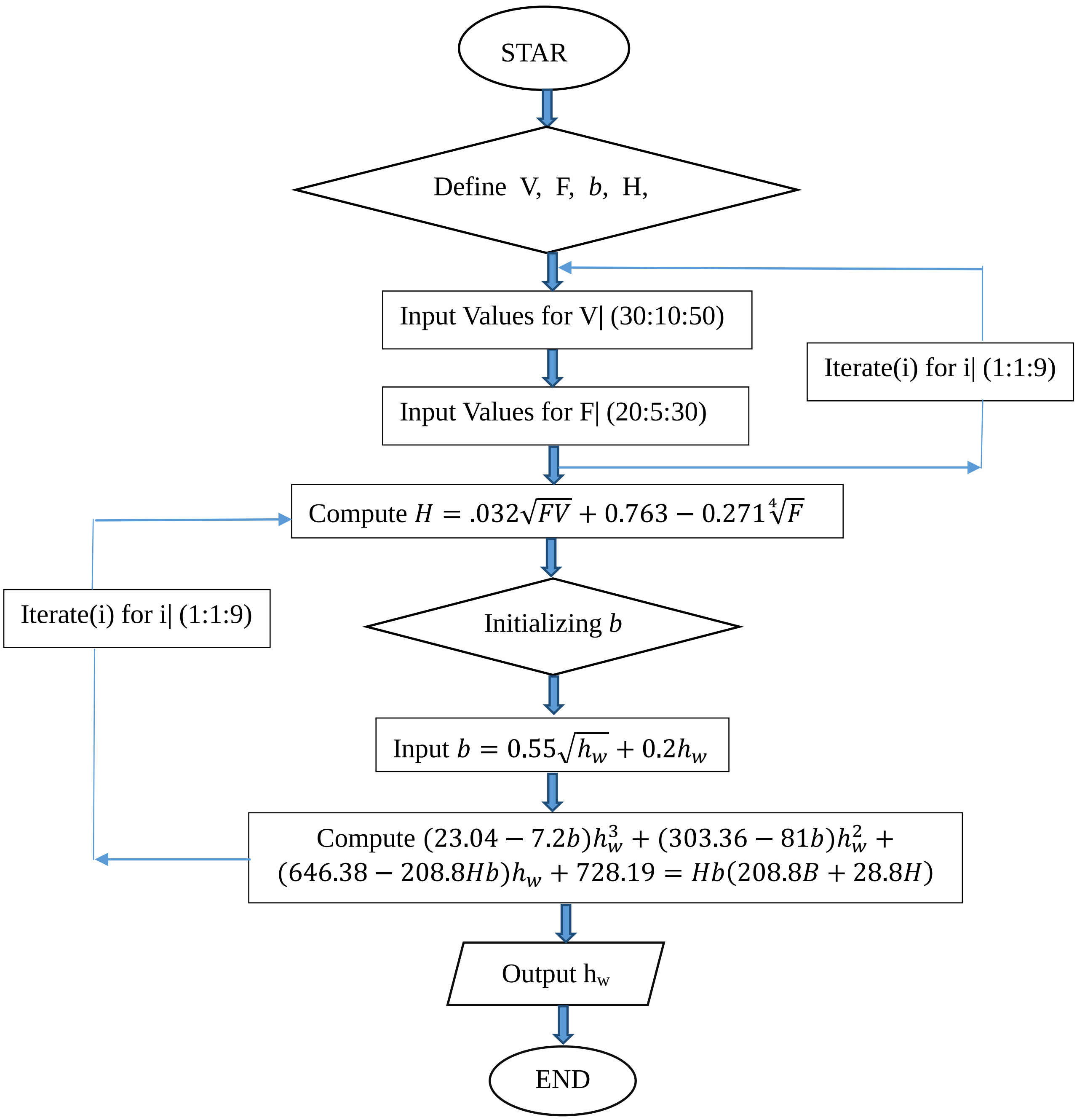

Fig. 2. Flow chart depicting hydrostatic height under JAVA environment.

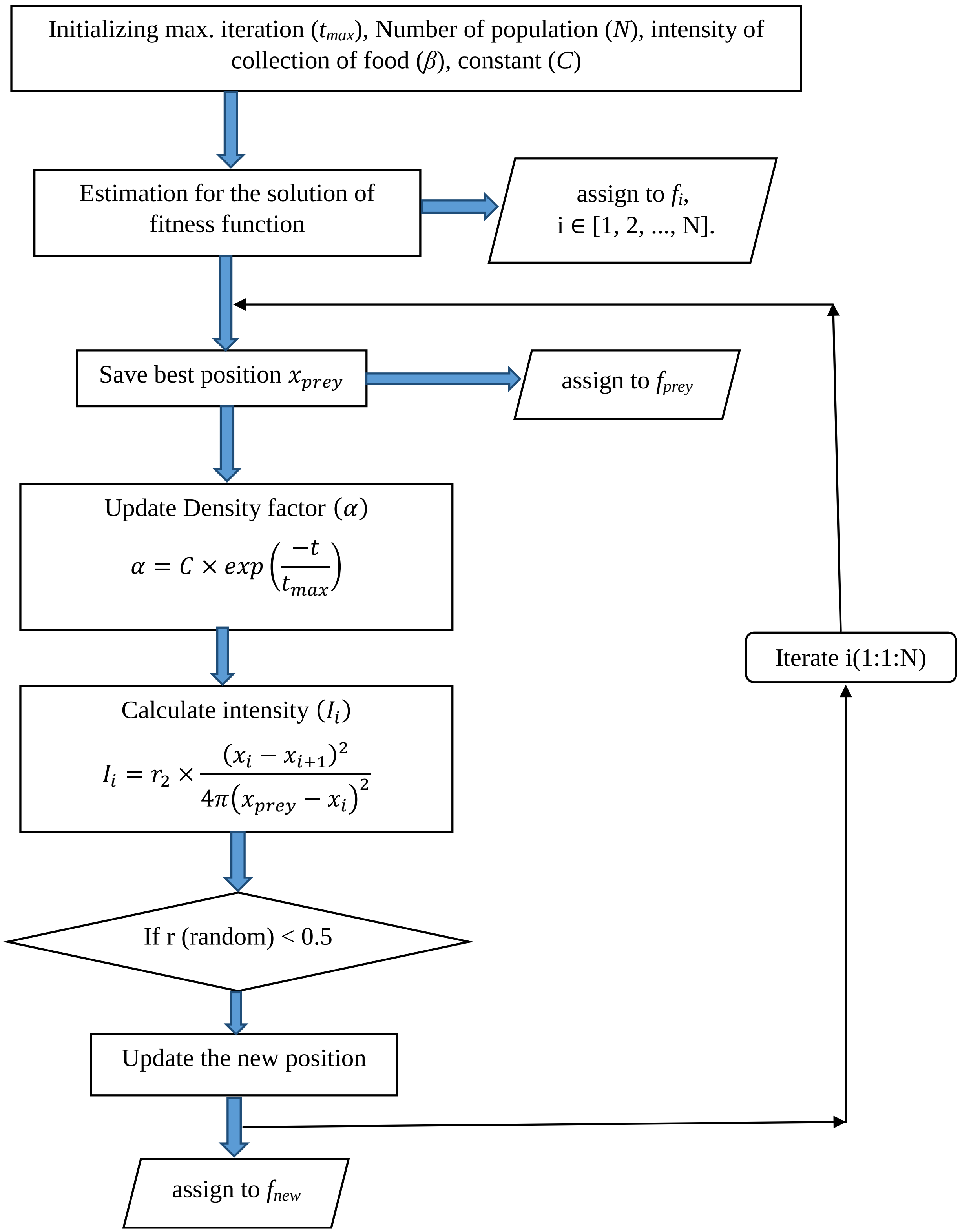

Fig. 3. Flow chart for Honey-badger Algorithm.

The adjustment parameters of the optimization algorithm are presented in Table 2.

Table 2
Adjustment parameters of the HB algorithm.

Parameters	**Values**
Number of populations (N)	30
Number of iterations (t_{max})	100
The intensity of collection of food (β)	6
Constant ‘C’	2
Random (r)	0~1

3. Results

3.1. Taguchi analysis

In order to get the optimum values of h_w and b for the geometric design of earthen embankment, maximum and minimum values are arranged from level 1 to level 3 as control factors. The Taguchi factorial design approach was utilised to design the experimental run and get optimal values for h_w and b. Taguchi examination is performed with MINITAB 18 to maximise hydrostatic height incorporate with wave height and fetch length by taking best criteria using signal to noise (S/N) ratio (9).

$$S/N = -10 * \log\left(\frac{1}{n}\sum\left(\frac{1}{x^2}\right)\right) \tag{9}$$

For the Taguchi factorial design approach, the factors affecting the best values of the h_w and b are arranged from low to high levels in Table 1 at three levels.

The L9 orthogonal array for maximum wind speed and fetch length is shown in Table 3 along with the results, which include H, $h_{w,}$ and b. All the output responses are obtained by employing the algorithm developed using the equations (1)-(8) adjacent to their respective trials as shown in Table 2. The hydrostatic height of the embankment must be optimized among the three output responses in order to tackle wave height as well as the crest width.

Table 3
L9 array with output responses.

Experiment No.	**A**	**B**	**H (m)**	**h_w (m)**	***b* (m)**
1	30	20	0.97	11.42	4.14
2	30	25	1.03	11.41	4.12
3	30	30	1.088	11.39	4.13
4	40	20	1.095	11.39	4.11
5	40	25	1.16	11.37	4.13
6	40	30	1.23	11.36	4.12
7	50	20	1.20	11.36	4.13
8	50	25	1.28	11.34	4.12
9	50	30	1.36	11.32	4.12

4. Discussion

Fig. 4. signifies the signal-to-noise ratio curve for maximum V and F coded as A and B respectively. The optimal factor setting for achieving maximal hydrostatic height is the pair of the A1B1 response, which offers higher factors with a maximum V of 30 km/hr and F of 20 km.

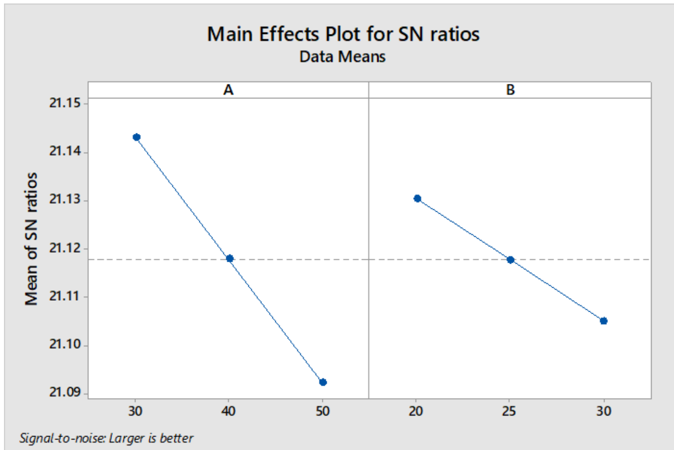

Fig. 4. Main effective plot for the maximum wind velocity and fetch length.

Fig. 5 to 7 shows the residual plots for high hydrostatic height (h_w), wave height (H), and crest width (*b*) of the earthen embankment respectively. From these figures, it was observed that the experiential values from DoE were well fitted to the regression line (red line), which will later help examine the variance analysis (ANOVA). More convergence of the results in standardized residual curves provide more well fitted values. The significance of DoE is well depicted from the normal probability plot or bar chart as it provides the fitness of experimental data.

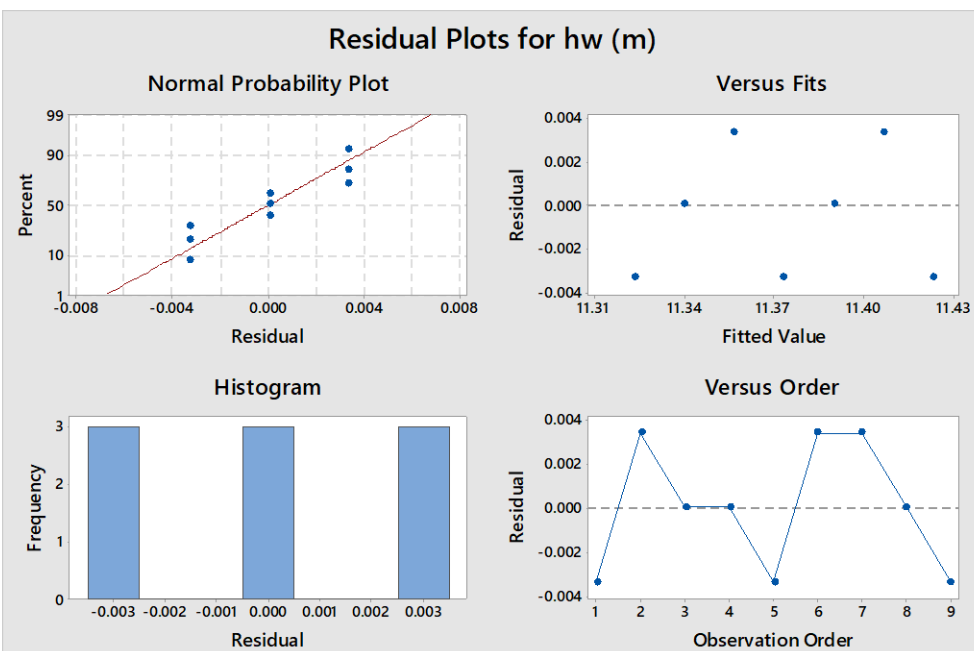

Fig. 5. Residual plot for hydrostatic height.

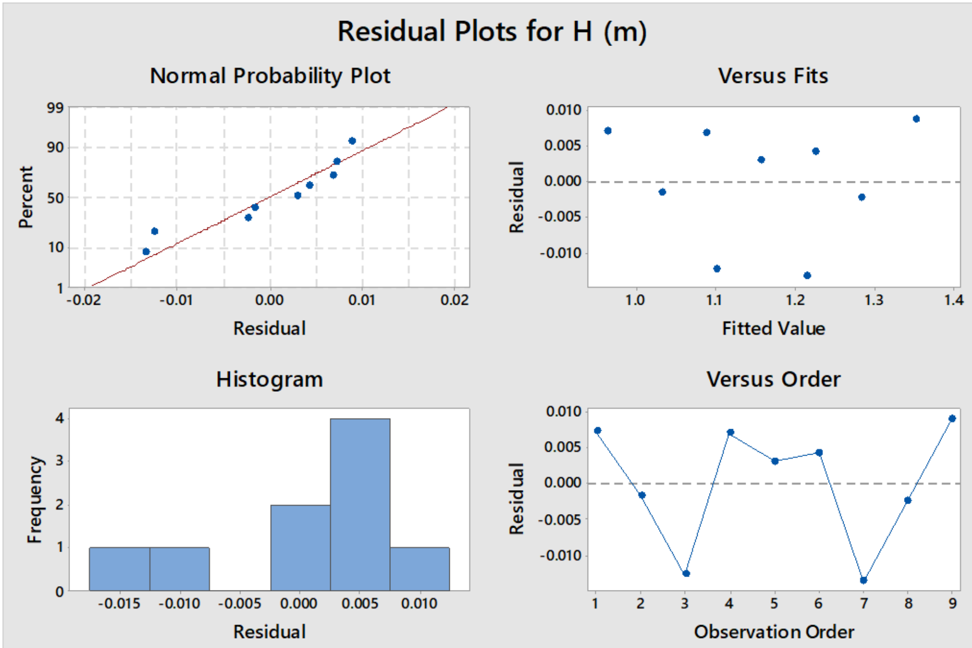

Fig. 6. Residual plot for wave height.

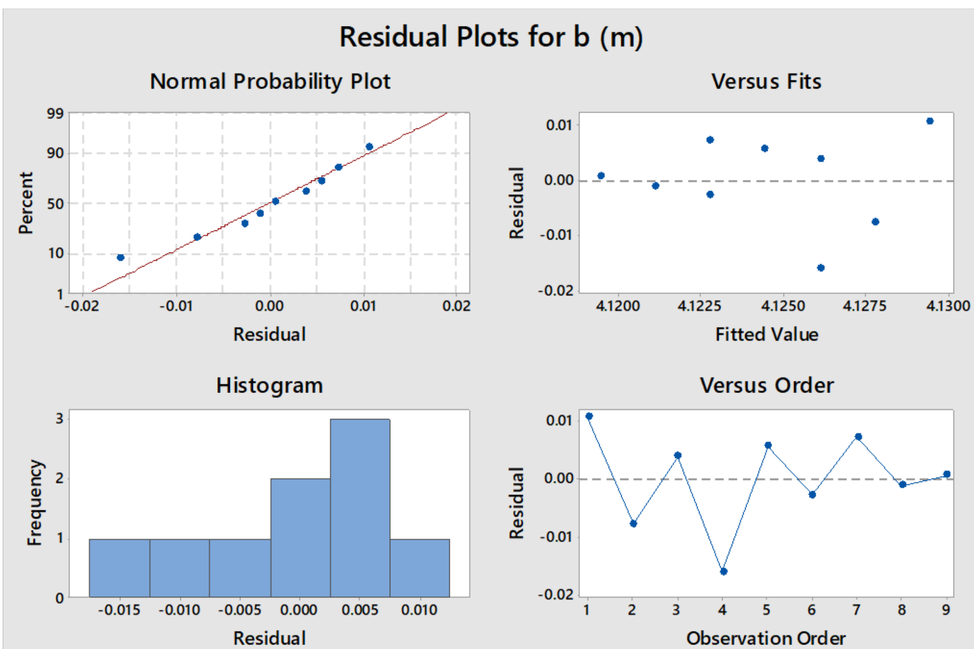

Fig. 7 Residual plot for crest width.

4.1. Analysis of variance

A quantifiable statistical approach called analysis of variance examines the speculative results for at least two equivalent populations. By using various level components for the response of the relevant mean variable, it evaluates at least two variables. The absolute squared deviation from the all-out mean of the S/N proportion was used to calculate the rate contribution of each variable.

Table 4 conveys the ANOVA for the control factors. The maximum V was discovered to be the most critical and influential control factor for reaching the maximum h_w, b, and H for the waterway embankment. But a large percentage of residual error was obtained from b as its calculation depends on the estimation of h_w. Although F was also a significant factor but less contributing as compared to the maximum V. Furthermore, the regression squared values for H, h_w, and b are 99.55, 99.21, and 13.39 percent, respectively demonstrating the relevance of the DoE.

Table 4.
Influence value (%) as obtained from ANOVA.

	Source	DF	Adj SS	% Influence	Adj MS	F-value	P-value
Height of wave (H)	Maximum wind velocity	1	0.094251	76.48	0.094251	1029.75	0.000
	Fetch	1	0.028428	23.06	0.028428	310.60	0.000
	Residual Error	6	0.000549	0.44	0.000092		
	Total	8	0.123228				
Hydrostatic height (h_w)	Maximum wind velocity (A)	1	0.006667	79.36	0.006667	600.00	0.000
	Fetch (B)	1	0.001667	19.84	0.001667	150.00	0.000
	Residual Error	6	0.000067	0.8	0.000011		
	Total	8	0.008400				
Crest width (b)	Maximum wind velocity (A)	1	0.000067	10.77	0.000067	0.74	0.422
	Fetch (B)	1	0.000017	2.73	0.000017	0.19	0.682
	Residual Error	6	0.000539	86.47	0.000090		
	Total	8	0.000622				

4.2. Honey-badger algorithm

A Meta-heuristic optimisation approach was also used to anticipate the best factor for achieving the maximum h_w. The maximum V and F are the two control factors also initialised to generate the fitness in HB algorithm utilizing the following regression squared equation:

Maximize:

$$h_w = 11.5400 - 0.00208x_1 - 0.00133x_2 + 0.000000x_1x_1 + 0.000000x_2x_2 - 0.000050x_1x_2 \quad (10)$$

Subject to:

$30 \leq x_1 \leq 50$ for maximum V

$20 \leq x_2 \leq 30$ for F

As per the requirement of problem statement, h_w maximised to get the design height of waterway embankment. In the HB method, a set iteration criterion has been established to obtain the optimal embankment design parameter. Fitness curve for hydrostatic height using HB algorithm is shown in Fig 8.

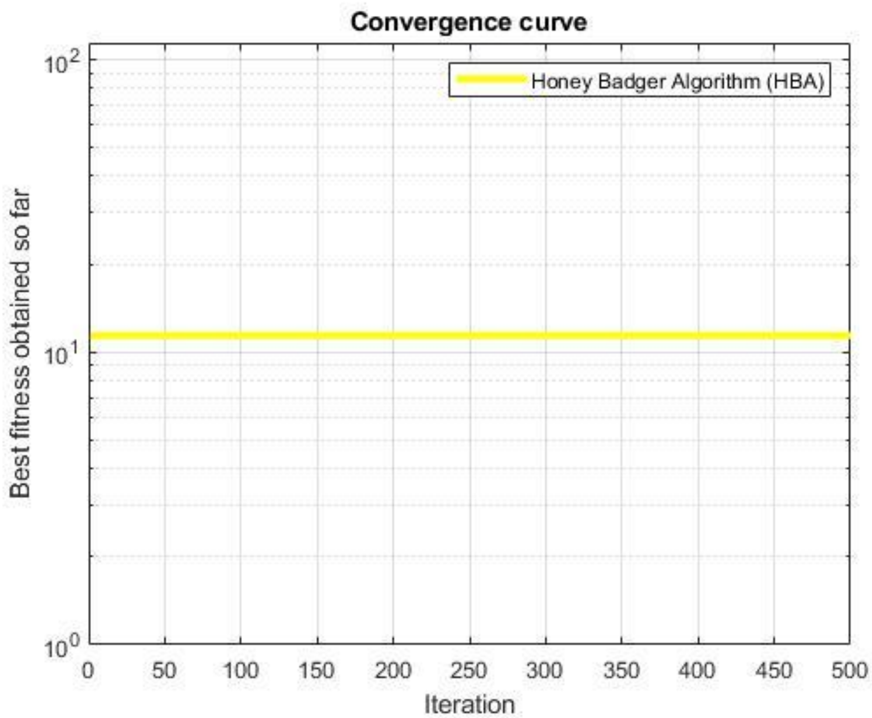

Fig. 8. Fitness plot for hydrostatic height (h_w).

4.3. Confirmatory test

To ascertain the significance of the predicted value produced from the optimisation technique, which would help in the development of optimal factor setting in maximisation of h_w for planning a waterway embankment, a confirmation experiment was conducted. It is important to note that the results obtained by the HB Algorithm match up well with the estimates given by the Taguchi technique, which are shown in Table 5. The experimental results are nearly identical to the hydrostatic height's expected value. Additionally, the higher level of factor setting has led to the h_w being maximised for the best waterway embankment design.

Table 5
Confirmatory test outcomes for h_w (m).

Method	**Maximum wind velocity (km/hr)**	**Fetch length** (km)	**Predicted value**	**Experimental value**
Taguchi Method	30	20	11.423	11.42
Honey Badger Algorithm	30	20	11.421	11.42

5. Conclusions

Prediction of the maximum h_w of a waterway embankment was conducted under the influence of variation of V and F. It was assessed with the help of the Taguchi method and a recently formulated Meta-heuristic algorithm namely the Honey Badger algorithm. According to the analysis of the Taguchi method, the best factor setting for attaining the highest h_w for the waterway embankment is a factor combination of a maximum V of 30 km/hr and F of 20 km.

From the outcomes of ANOVA, it was found that maximum surface wing velocity have the maximum influence in the design of h_w of waterway embankment. Although, Fetch length was also a significant factor but less contributing as compared to maximum wind velocity. The regression squared value was found to be 99.21% for h_w which shows the significance of the performed DoE.

The result obtained from Honey Badger Algorithm is also in good agreement with the outcomes obtained by the Taguchi method. The outcomes of the confirmatory experiment are nearly identical to the expected value of h_w. The optimal design of the waterway embankment was achieved by the lower level of factor setting of hydrostatic height. After implementing the optimal factor setting, the height of the wave, crest width, and hydrostatic height was found to be 0.97m, 4.14m, and 11.42 m respectively becoming the most appropriate design parameter for the high-rise waterway embankment to divert and confine stormwater. The resulting wave height from the proposed method was found to be more in contrast with the Bayesian model averaging (BMA) of Adnan et al. [31] to predict the significant wave height of Chabahar Port, Iran.

Results from Taguchi factorial design approach and HB method were found to be almost equal with an inaccuracy of 2.62% when back-calculating the crest width by applying anticipated values of h_w using equation (4) published by Punmia [28] and Garg [29].

The present investigation also opens the door for further model analysis using optimized height and crest width with the percolation pit in the countryside in order to recharge groundwater without affecting the designed value and underground artesian. The present study includes two control factors to decide the maximum height of the embankment, however more additional control factors may be considered to refine the results.

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Conflicts of interest

The authors declare no conflict of interest.

Authors contribution statement

FA: Investigation, Conceptualization, and Visualisation. SA: Supervision, Validation and Drafting of Manuscript. TA: Review and editing.

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