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Scour model for circular compound bridge pier

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ABSTRACT

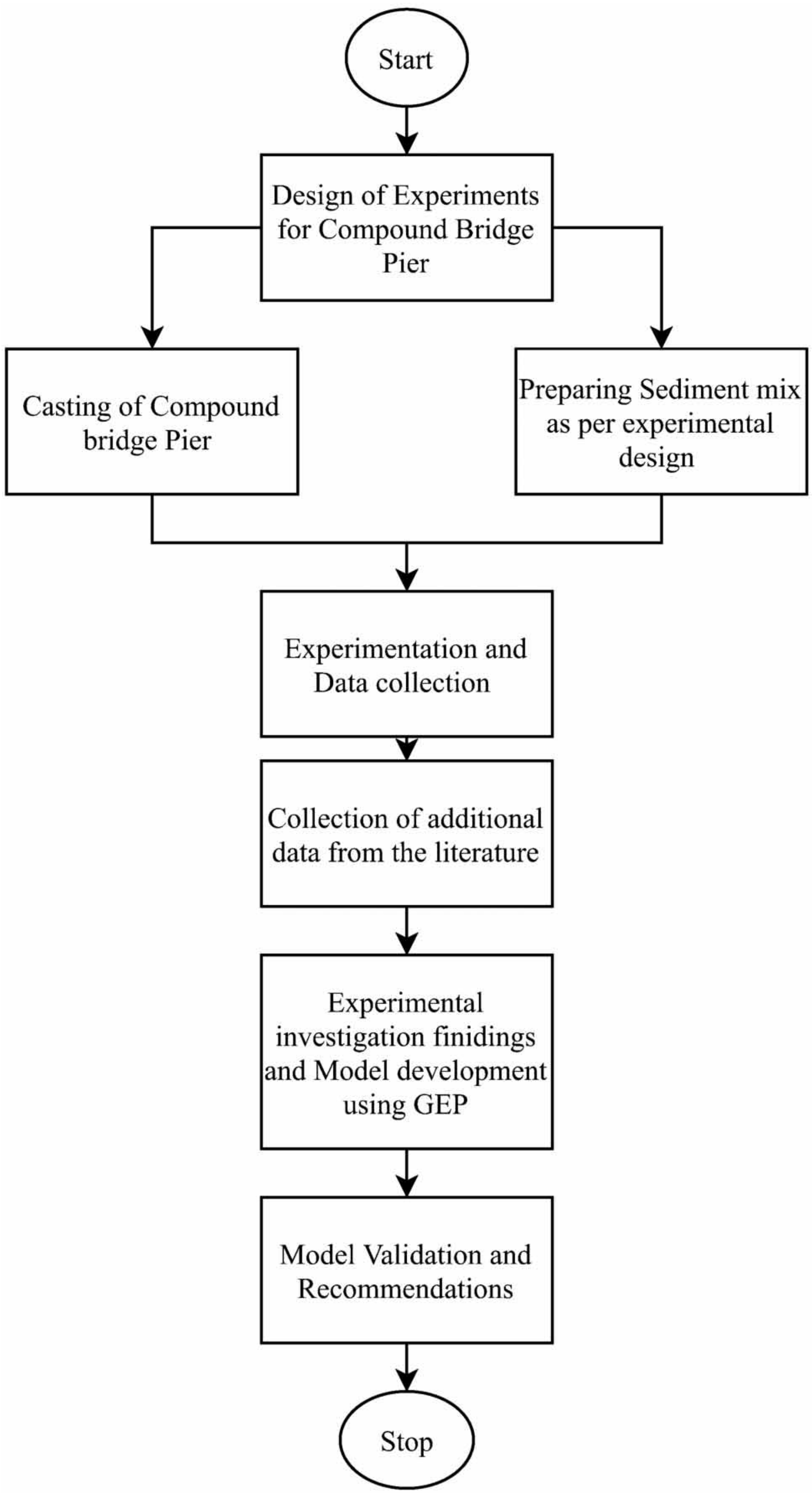
Scour is a complex phenomenon, whose complexity increases with the change in the geometry of the obstruction. Most investigations have been carried out on the scour process at a uniform pier. However, in reality, many bridge piers behave as non-uniform depending on the exposure of their foundation into the flow field. All the experimental investigations were carried out in the present study to understand the effect of pier geometry, the position of footing top with respect to bed level, and sediment mixtures (uniform and non-uniform) on local scour under clear water conditions. A total of 106 experiments were conducted in the present study with a different combination of pier models, sediment mixture, and footing top with respect to bed. A maximum scour depth model was developed using 182 data points consisting of experimental data (106) and extracted from the literature (76). To develop a model, a state-of-the-art artificial intelligence (AI) based modeling technique known as gene expression programming (GEP) was employed in this study. The GEP model was developed by using 130 data points and independent 52 data points for the model validation. The performance of the proposed scour model for the compound bridge pier was found to be satisfactory.

Key words: compound pier, GEP, non-uniform sediments, scour, uniform sediments

HIGHLIGHTS

- Experimental investigation of circular compound pier with uniform and non-uniform sediments.
- Effect of compoundness on scour.
- Development of AI-based scour model for compound bridge pier.
- Sensitivity analysis.
- Parametric study of scour.

GRAPHICAL ABSTRACT



NOTATION

The following symbols are used in this paper,

- b Diameter of the cylindrical pier
- b_* Diameter of the cylindrical foundation
- d_{50} Median sediment grain diameter
- d_s Scour depth
- d_{smin} Maximum scour depth at minimum Y
- F_p Pier Froude number
- F_{rd} Densimetric Froude number.
- U Mean velocity of approach flow
- U_c Critical mean velocity of particle motion
- y Depth of flow
- Y Depth of top of foundation below initial bed level
- σ_g Geometric standard deviation of particle size distribution

INTRODUCTION

Scour at bridge locations is a complex phenomenon caused by various agents such as localized scour combined with general riverbed degradation, modification of flow field around bridge structures, human interference, debris flow, etc. However, the formation of a three-dimensional vortex flow field around the pier consisting of a horseshoe vortex is primarily responsible for the scour at bridge piers (Dey *et al.* 1995). Very few researchers have considered the effect of non-uniformity of the pier on scour (Parola *et al.* 1996; Kumar & Kothyari 2012). Some of the researchers who majorly contributed in this area were Jones *et al.* (1992); Parola *et al.* (1996); Melville & Raudkivi (1996). They have carried out experimental investigations on compound piers and concluded that pier non-uniformity and top of footing with reference to stream bed would significantly impact the scour around the pier. Kumar & Kothyari (2012) proposed an algorithm for computation of temporal variation of scour depth at circular compound bridge piers. Generally, bridge piers are constructed in various types of geometries, and many of them can have non-uniform cross-sections along their heights (Melville & Raudkivi 1996). Pandey *et al.* (2020) developed a scour model suitable for a non-uniform gravel bed, which is an advancement in overcoming scale effects. There are very few studies carried out considering the non-uniform sediment and bridge pier. Hence, an experimental study was undertaken to investigate the effect of non-uniformness of the pier on the scour considering uniform sediments and non-uniform sediments (three different sediment mixtures) to estimate maximum scour depth. For any kind of the modeling, type of technique being employed is very much important. An artificial intelligence (AI) technique viz. gene expression programming (GEP) was employed in the model development. The GEP technique is a new evolutionary AI-based technique developed by Candida Ferreira in 1999. Koza (1999), Ferreira (2006), Khan *et al.* (2012), Moussa (2013), Muzzammil *et al.* (2015), and Najafzadeh *et al.* (2016) have applied GEP to the estimation of scour around uniform bridge piers. GEP comes with the additional merit of providing a simple and easy-to-use empirical expression for the dependent variable to be estimated. GEP combines the advantages of both its predecessors, genetic algorithm (GA) and genetic programming (GP) while eliminating some of the limitations of these two techniques. GEP is a fully-fledged genotype/phenotype system where both are dealt with separately (Najafzadeh *et al.* 2016). The GEP method provides a simple and easy-to-use empirical expression for the modeled response function and captures the nonlinearity of the scour formation; hence, the GEP technique has been recommended among data-driven models. Najafzadeh & Oliveto (2021) found the GEP method performed better and stands at 3rd position among advanced machine learning techniques and having one of the simplest forms of the equation as compared to other. For any field engineer's or designer simple expression having power to produce good accuracy is essential hence GEP technique was adopted.

Thus, this study experimentally investigated uniform and compound bridge piers for six different elevations of top of footing concerning bed level using uniform and non-uniform sediments ($\sigma g = 1.14$, 2, 3, and 4) and develops a novel model based on GEP for the computation of maximum scour depth around compound bridge piers.

EXPERIMENTATION

The experiments were conducted on a tilting flume 10.0 m long, 0.3 m wide, and 0.5 m deep located in the Hydraulics Laboratory at Bharati Vidyapeeth College of Engineering, Pune, India. The flume has a working section of 2.5 m long, 0.3 m wide, and 0.15 m deep was located 4.5 m downstream of the flume entrance. The working section was filled with the desired sediment mixture to the level of the flume bed. The line diagram of the tilting flume is shown in Figure 1.

The discharge during the experiments was measured with a sharp-crested calibrated V-notch placed in the return channel. The flow depth in the flume was measured with the help of a Vernier pointer gauge. Before starting the experimentation, the flume was filled with water from the downstream end until the flow depth reaches the desired value, which would help in avoiding the undesirable scour by the action of sheet flow. Then the flow discharge was gradually increased to the extent where the flow velocity satisfies the clear water condition. The temporal variation of scour depth at the pier was measured using the scale attached to the pier and foundation on the outer surface. The geometry of the model tested experimentally is given below in Table 1.

One uniform model (M1) and five compound models (M2 to M6) were experimentally tested in the present study. Pier to foundation diameter ratio covered the wide range of the pier geometry ranging from 0.3 to 1. Experiments were conducted for 8 hours and 20 minutes duration.

The range of parameters set during experimentations is described in Table 2.

Experimental investigation

A bridge scour is usually studied experimentally in simplified conditions, i.e., uniform sediments, uniform flow, and clear water conditions. Thus far, cylindrical piers have been mostly tested since they are insensitive to the angle of attack of the

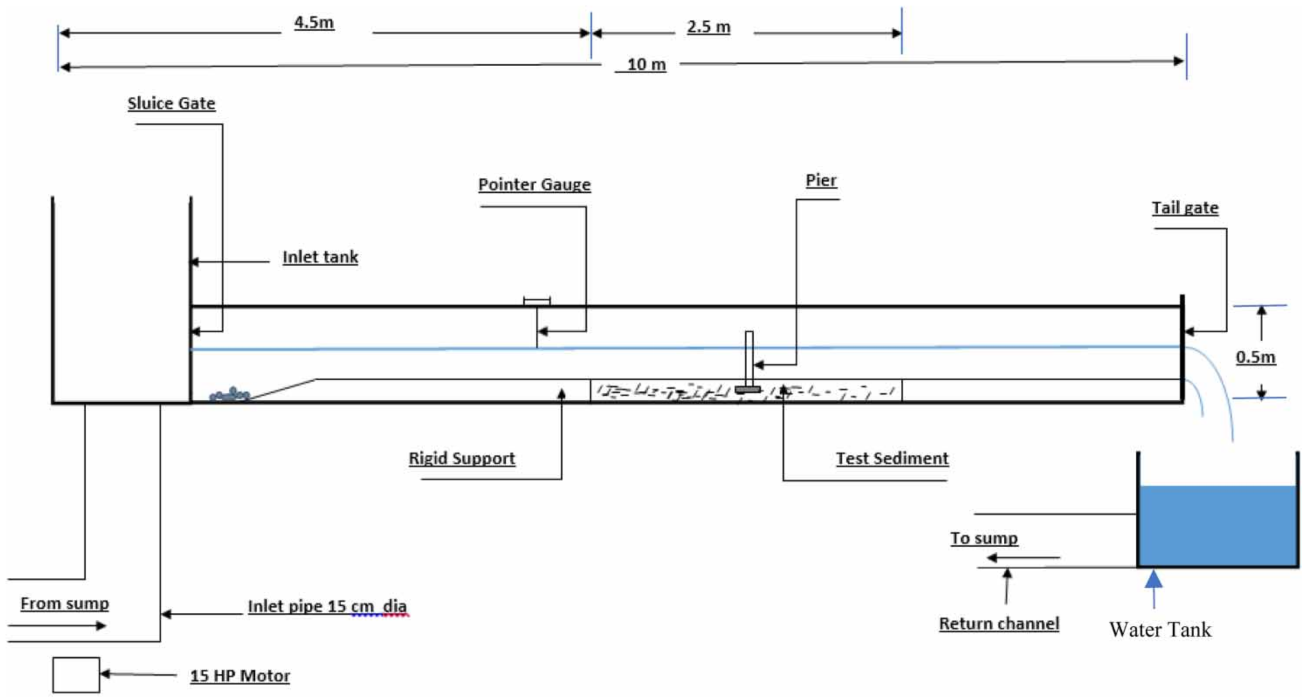


Figure 1 | Longitudinal section of tilting flume.

Table 1 | Geometry of pier models used in the present study

Name of the model	Diameter of the pier in mm (b)	Diameter of foundation in mm (b*)	Pier to foundation diameter ratio (b/b*)
Model 1 (M1)	32	32	1
Model 2 (M2)	32	47	0.68
Model 3 (M3)	32	62	0.52
Model 4 (M4)	32	74	0.43
Model 5 (M5)	32	90	0.36
Model 6 (M6)	32	107	0.30

Table 2 | Range of parameters used during experimentation

Parameter	Range
Diameter of the pier *b* (m)	0.032
Diameter of the foundation *b** (m)	0.047–0.107
Flow depth h (m)	0.11–0.138
Median size of the sediment d_{50} (m)	0.001
Position of top of footing with respect to bed level *Y* (m)	0–0.05
Velocity of approach flow *U* (m/s)	0.35–0.47
Discharge in the channel *Q* (m^3/s)	0.0115–0.0195
geometric standard deviation of particle size distribution σ_g	1.14–4

fluid (water) flow. However, little attention has been paid to the fact that a pier has its footing buried into the channel bed, which also affects the scour process once it is stripped. Experimental investigation shows a phenomenological perspective on the effect of compoundness on the uniform and non-uniform sediments on scour.

Effect of compoundness and sediment uniformity on scour

Six models of different geometry (Table 1) were investigated to study the effect of position of footing top with respect to bed level (Y) (tested for Y = 0 to 5 cm) and σ_g (1.14 to 4) on scour depth. Two cases can be considered to explain the scour process in the case of a compound pier: (1) in the direction of flow, outside the scour hole, and far away from the pier, the flow is unidirectional and stronger as compared to the other two directions and (2) when flow enters the scour hole, due to obstruction of the pier, the downward flow gets stronger. The accelerated downward flow above the bed causes the flow to rotate inside the scour hole. Rotating flow towards the free surface after hitting to bed results in a commonly known phenomenon known as the principal horseshoe vortex system. Visual flow patterns in the compound bridge pier can be explained by considering three different cases. Different cases are considered based on where the top of footing lies with respect to the channel bed. Figure 2 shows the hypothetical three different zones; dashed lines show the imaginary footing level.

Zone one is considered where the footing level is above the general bed level. This zone results in a large principal vortex causing a larger and wider scour hole due to the diameter of the pier. In zone two, the footing is below the channel bed. In this case, footing resists the flow to accelerate in a downward direction; flow loses its strength, which results in weak vortices. Weak vortices cause less bed material to erode, and hence, small scour depth can be seen. A similar flow pattern was also observed by Kothyari & Kumar (2012). In zone three, when the footing top is at the channel bed level, the compound bridge pier behaves very much like the uniform circular bridge pier (Kumar *et al.* 2012). In the present study, case two was investigated for scour depth *(ds)* to occur at a particular footing top position with respect to bed level (Y). The experiments were conducted separately for uniform and non-uniform sediments to examine the effect of sediment mixture under clear water conditions.

Experimental results

Scour depth (d_s) and the elevation difference between footing top and bed level (*Y*) were normalized with the pier diameter (*b*), and variation of ds */b* is shown as a function of *Y/b* for all the models (b/b_*). Figure 3 shows that each model shows minimum scour depth at a particular footing top position with respect to the bed level. In general, for all models, the normalized scour depth is observed minimum (d_{smin}/b) for *Y/b* values in the range of 0.6 to 0.9. Conversely, Model 6 $(b/b_* = 0.30)$ has shown the minimum normalized scour depth at $Y/b = 0.31$, and it is the largest footing diameter among all experimental models.

Interestingly, the model with the largest footing diameter (M6) resulted in the least value of Y (=0), which can be inferred as, to get the least value of scour depth, the footing top of model 6 could be placed at the bed level. In general, the footing top position with respect to bed level (Y) and footing diameter (b_*) are inversely related. Hence, it can be concluded that footing diameter (b_*) plays a crucial role in obtaining optimum *Y/b* at which scour will be minimum (d_{smin}/b).

Effect of compoundness on scour for non-uniform sediments

Local scour around compound bridge piers with non-uniform, cohesionless sediments under clear water conditions was studied experimentally. Variations of the particle size distribution of the bed sediment can significantly influence local

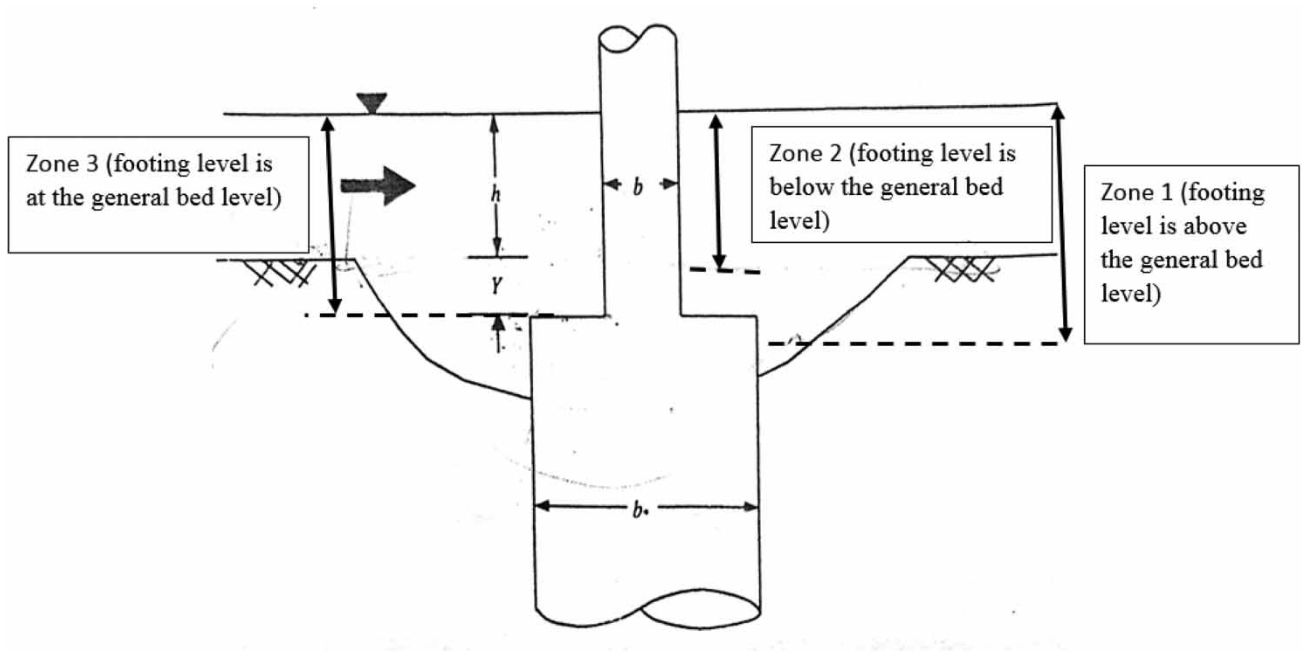


Figure 2 | Various zones of the non-uniform pier.

scour depths around bridge piers (Chiew & Melville 1989). The investigation comes out with the firm conclusion that as σ_g increases, scour depth decreases, and there is no effect of pier dimension (b/b_*) on scour depth for $\sigma_g \geq 3$. Footing width (b_*) has a more significant impact on the maximum scour depth since it holds the secondary current on top as a result, water loses the strength to remove the sand particles. At this stage, it is essential to note that for non-uniform

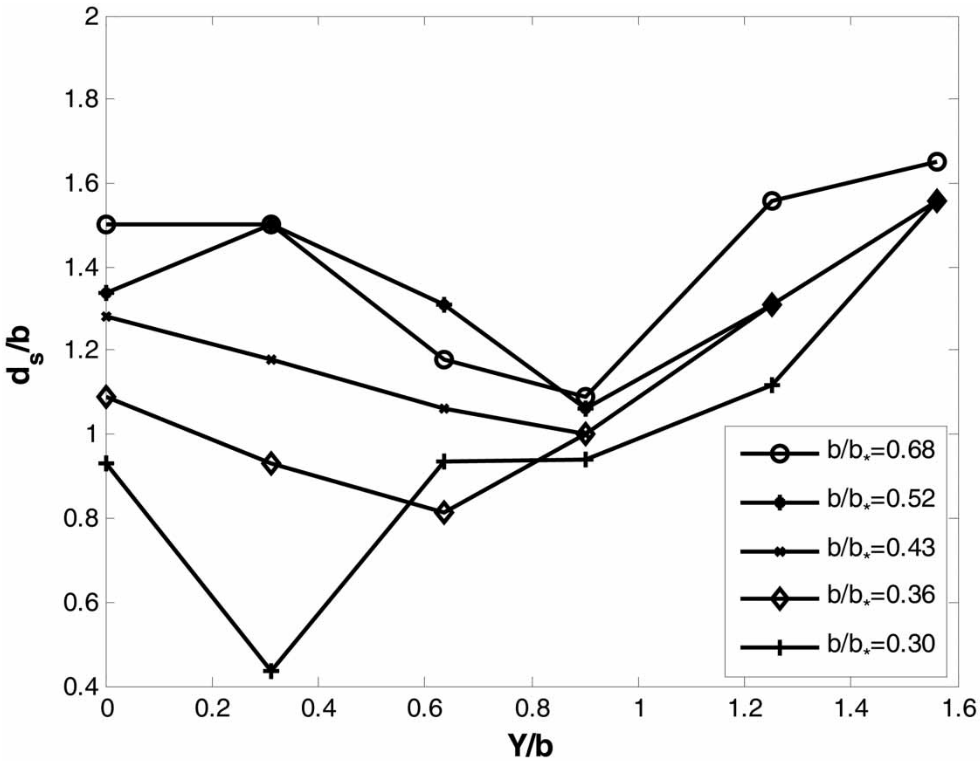


Figure 3 | Scour related to the position of footing top (uniform sediment).

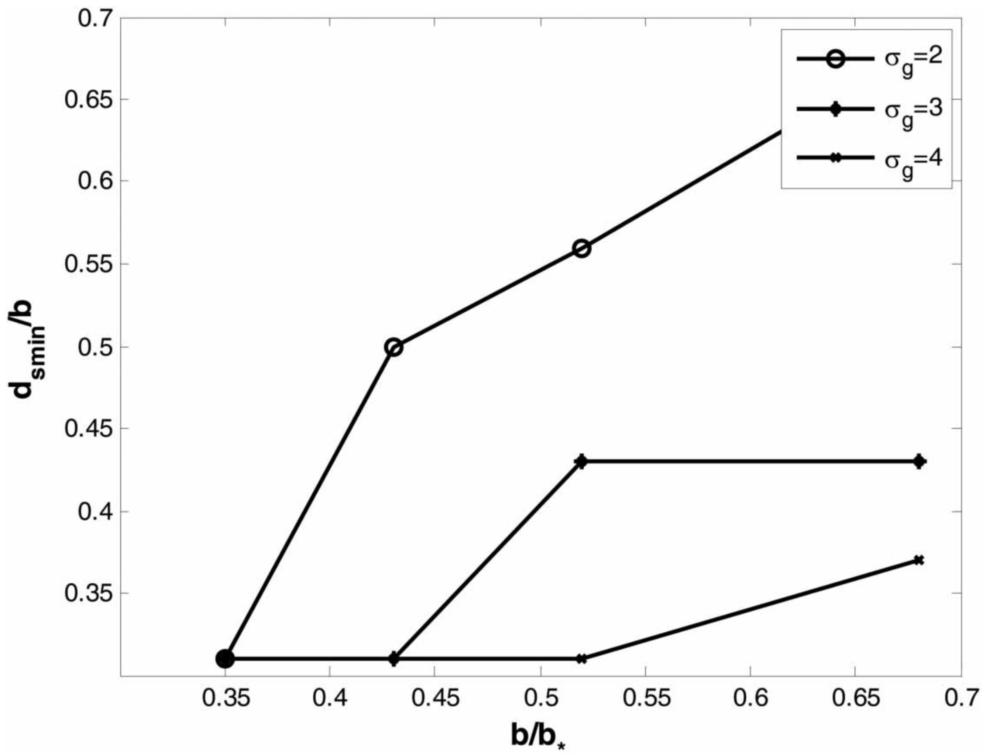


Figure 4 | Pier geometry for minimum scour.

sediments, Y has little or no effect on the maximum scour depth of the compound bridge pier. Figure 4 depicts the effect of footing width (b_*) and σ_g. Investigations were carried out for minimum scour depth and associated footing top level for different compound pier models (b/b_*). d_{smin}/b represents the normalized scour depth corresponding to minimum Y/b (footing top with respect to bed level). In other words, if footing top placed at Y, there is highly likely to get minimum scour depth, i.e., d_{smin}. Figure 4 shows the variation of normalized scour depth for four compound pier models (M2 to M6) for sand mixture ($\sigma_g = 2,\ 3,\ and\ 4$).

From the above Figure 4, it is observed that the minimum normalized scour (d_{smin}/b) occurring for any model was equal to 0.35. In general, d_{smin}/b increases as compoundness (b/b_*) and non-uniformity (σ_g) of sediment decreases.

Temporal variation

Temporal variation of scour depth considering non-uniform sediments was observed and reported in this study. Typical recorded observations of temporal variation of scour depth for the compound circular pier of Model 4 (M4) is shown below in Figure 5 as a representative variation. More or less similar patterns were observed for the remaining models.

It is observed from the experimental investigations on temporal variation of scour depth in the context of a compound bridge pier is that the scour depth varies greatly due to the position of the footing top with respect to bed level (Y) and geometric standard deviation of the particle size distribution. In the case of uniform sediments ($\sigma_g \leq 1.14$), it is observed that minimum scour depth was obtained at the position of footing top 3 cm below the bed level. The same pier model (M4) using $\sigma_g = 2, 3,$ and 4 (non-uniform sediment) showed minimum scour depth for the case when the footing top was at the bed level. This result was expected because of the armoring effect. Similar kinds of results were observed for all other models mentioned in Table 1.

Methodology: GEP model

To understand GEP, some basic terms have to be understood. A chromosome consists of one or more genes. The number of genes in a chromosome is a parameter for the analysis. If there are more than one gene in a chromosome, then a linking function is used to join them. A gene is made of two parts: the head and the tail. The head is used to encode functions for the expression. Thus, the head can contain functions, variables, and constants, but the tail can contain only variables and constants (i.e., terminals). The number of symbols in the head of a gene is specified as a parameter for the analysis. There are five

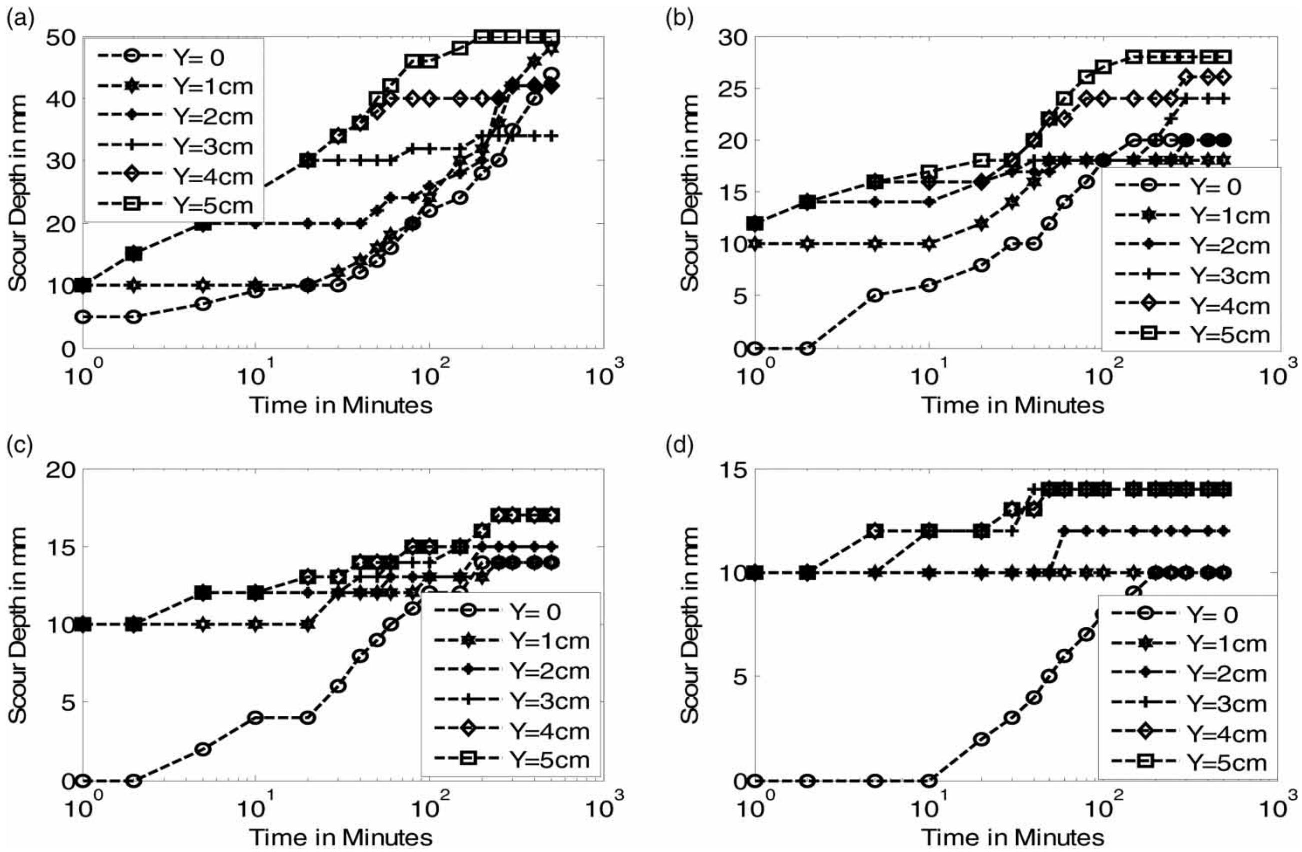


Figure 5 | Temporal variation of scour depth for M4. (a) $\sigma_g = 1.14$, (b) $\sigma_g = 2.0$, (c) $\sigma_g = 3.0$, (d) $\sigma_g = 4.0$.

major steps to use GEP (Ferreira 2001). The first step is to select the fitness function and initialize the population. Figure 6 shows the flow diagram for the development of the equilibrium scour model using the GEP technique. Data preparation is the prime important step for any modeling. Before proceeding to modeling, data quality has to be checked. Data quality can be checked by using the outlier technique. An outlier can be removed if found. GEP requires defining the predictors and predictand for the modeling. In the present study, predictors were the parameters influencing scour depth such as V, Y, etc. and the predictand was the scour depth.

The next step is to select the fitness function and initial population. Like most other evolutionary algorithms, GEP starts with an initial population of individuals. The population of individuals consists of chromosomes of fixed length. The chromosome may be uni-genic (single gene) or multigenic. In the current study, multigenic chromosomes (consisting of three genes) were used. Any number of population sizes can be used while initializing the population in GEP, but Najafzadeh *et al.* (2016) and Khan *et al.* (2012) recommended that population size in the range of 30–100 chromosomes will give good results. In the present study, a population size of 30 was adopted.

For the present problem, the fitness *fi* of an individual program i is measured by the following expression (Equation 1):

$$f_i = \sum_{i=1}^{c_t} (M - |C_{ij} - T_j|) \tag{1}$$

where M the data range, $C_{i,j}$ is the value returned by the individual chromosome, i for fitness case j, and T_j is the target value for fitness case j. C_t is the total number of fitness cases. The advantage of this kind of fitness function is that the system can find the optimal solution for itself (Ferreira 2001). The significant fourth step is to choose the linking function. In this study, multiplication was used as a linking function. The final step is to choose the set of genetic operators. A combination of all genetic operators (mutation, transposition, and crossover) is used for this purpose (Table 3). Once all the parameters are fed into the algorithm, combinations of different genes and chromosomes are tried to evaluate the data fit, and a model that satisfies the fitness criteria will be printed, followed by algorithm termination.

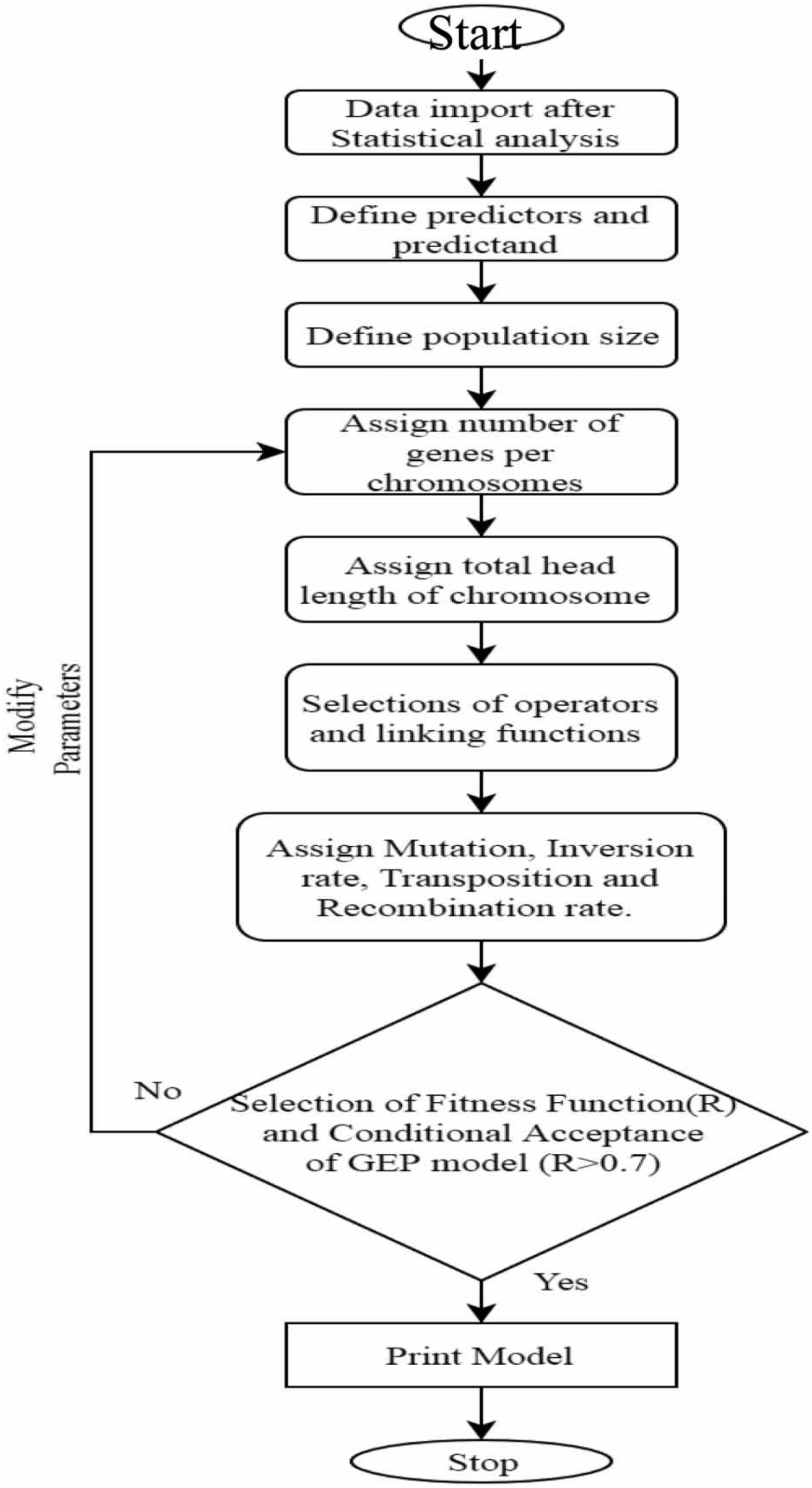


Figure 6 | Flow chart for GEP scour model.

RESULTS AND DISCUSSIONS ON THE GEP MODEL

This study aimed to develop a scour model to predict maximum scour depth for uniform and non-uniform sediments for circular compound pier using the GEP technique. Before modeling, a sensitivity analysis was carried out to understand the

Table 3 | Summary of GEP parameters

Sr. No.	GEP parameters	Descriptions
1	Population size	30
2	Genes per chromosome	3
3	Gene head length	9
4	Functions	+, −./, *,^
5	Gene tail length	12
6	Mutation rate	0.05
7	Inversion rate	0.1
8	Gene transposition rate	0.1
9	One point recombination rate	0.3
10	Two point recombination rate	0.3
11	Gene recombination rate	0.1
12	Fitness function	R ≥ 0.7

relationship between dependent and independent parameters. A simple regression technique was employed in judging the relationship.

Selection of parameters based on sensitivity analysis

From the literature (Melville & Raudkivi 1996; Parola *et al.* 1996; Kumar & Kothyari 2012) it is found that maximum scour depth mostly depends on the pier diameter *(b)*, foundation diameter *(b*)*, velocity *(U)*, the median size of the sediment (d_{50}), the geometric standard deviation of the sediment (σ_g), densimetric particle Froude number (F_{rd}), Froude number (F_r) and location of footing with respect to bed level (Y). The functional form of the maximum scour depth equation can be expressed as given in Equation (2).

$$d_{se} = f(U,\ b,\ b^*,\ Y,\ d_{50},\ F_{rd}, F_r,\ \sigma_g, h) \tag{2}$$

Sensitivity analysis helps determine how much independent variables will affect a dependent variable under given conditions and a given set of assumptions. It can be used for any phenomenon or system. A simple principle used in a

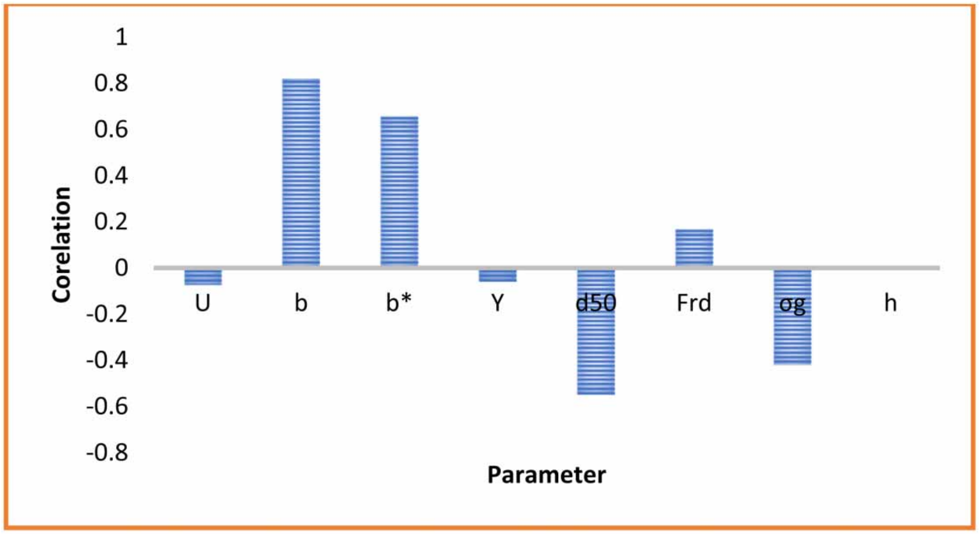


Figure 7 | Sensitivity analysis of scour parameter.

sensitivity analysis is observing the behavior of model aspects while doing systematic changes in the model parameters. The correlation coefficient, R, between dependent variables such as scour depth d_s and other independent variables, is computed to carry out sensitivity analysis. Bateni *et al.* (2019) reported in their study that the use of data in dimensional form performs better than non-dimensional form. The sensitivity analysis of the compound geometry pier on scour is shown below in the Figure 7.

From Figure 6, it can be observed that the parameters b, b_*, d_{50} and, σ_g are relatively more sensitive than U, Y, and F_{rd}. Therefore, in the development of scour predicting models for the compound pier with non-uniform sediments, pier geometry (b and b_*) and sediment characteristics (d_{50} *and* σ_g) parameters were included. This information could be useful to scour modelers, field engineers, and practitioners.

GEP model calibration

To develop a model, data from the present study and available in the literature are used. Data used for calibration and validation are so segregated that each set consists of a similar data range. A total of 182 data points were used in this

Table 4 | Performance of GEP model while training

Performance Indicator	Results of calibration	Results of validation
Correlation between actual and predicted scour	0.905	0.813
RMSE (root mean squared error)	0.032	0.030
MSE (mean squared error)	0.001	0.0009
MAE (mean absolute error)	0.022	0.022

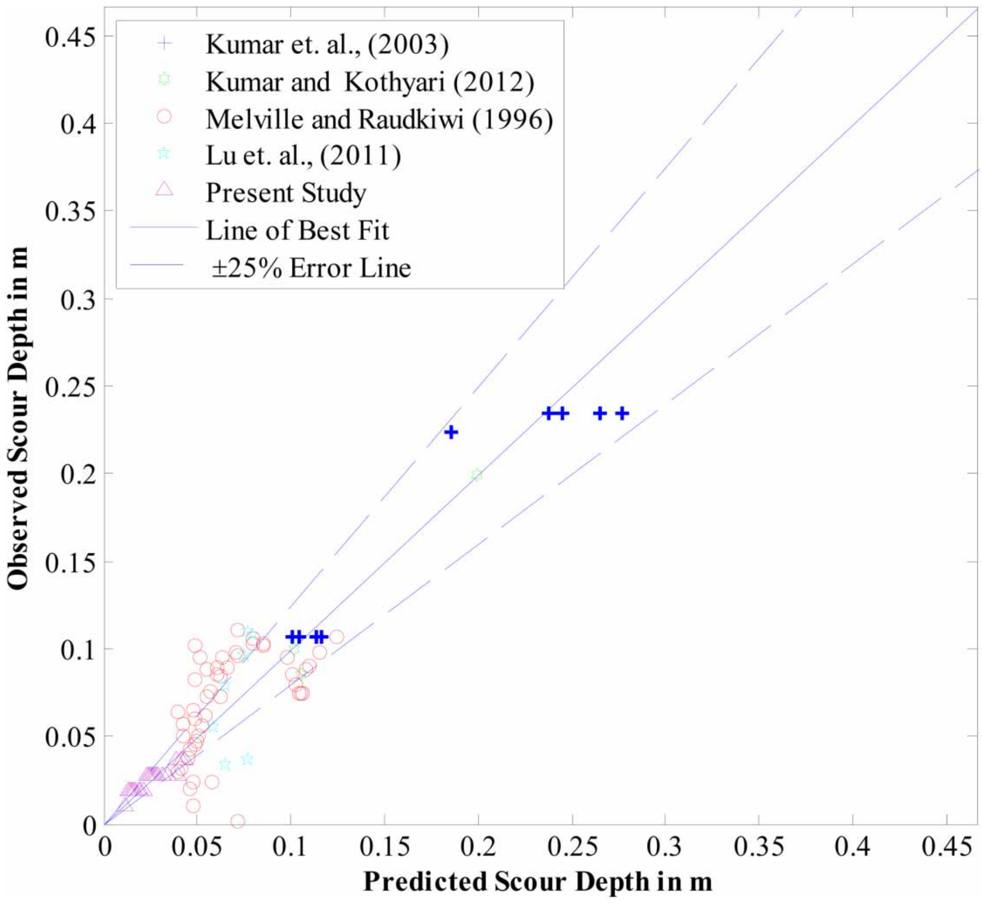


Figure 8 | The plot of observed and predicted scour depths for GEP scour model while validating.

study, out of which uniform sediment data points were 112, and non-uniform sediment points were 70. A total of 106 data points were generated through experimentation (uniform sediment; 36 and non-uniform sediment; 70) and extracted from the literature (76) used in the analysis. Total 76 data points were collected from the literature studies of other authors; all are uniform sediments (Melville & Raudkivi (1996); 49, Kumar *et al.* (2003); 12, Lu *et al.* (2011); 11, and Kothyari & Kumar (2012); 04). GEP model was developed by using 130 data points and independent 52 data points were used for the model validation. Popularly used performance indicators such as correlation coefficient, root mean squared error (RMSE), mean squared error (MSE), and mean absolute error (MAE) are employed to assess the developed GEP model.

Since F_{rd} itself includes d_{50} and F_r (Sarathi *et al.* 2008), d_{50} and F_r are not considered in the modeling. Initially, all data points and the variables are imported as input, out of which predictors and predictand are defined. In this case, d_{50} is a predictand, and all independent variables are predictors. The GEP scour model obtained is shown below in Equation (3).

$$d_{se} = \left[\left(\frac{b}{b_*}\right) * (\sigma_g - F_{rd})^2\right]^Y * \left[\frac{b}{\sigma_g\ (Y+U)}\right] \qquad (3)$$

The performance of the GEP scour model (Equation (2)) under calibration and validation is as shown below in the Table 4. The developed scour model (Equation (2)) is validated using independent data set consisting of experimental data of the present study and data from the literature. The proposed model earned very good values for the four criteria given while training (calibration) and testing (validation).

The correlation coefficient $R^2 \geq 0.8$ and the remaining error parameters ≈ 0 indicate the developed GEP model's excellent performance. The validation plot of the GEP model is shown below in Figure 8. It is found that 70% of the data points lie within a $\pm 25\%$ error band. Obtained statistical values provide sufficient evidence to support the efficacy of employing the proposed model on the compound bridge pier-scour-depth problem.

The performance of the scour model was further checked under the uniform and non-uniform sediments separately.

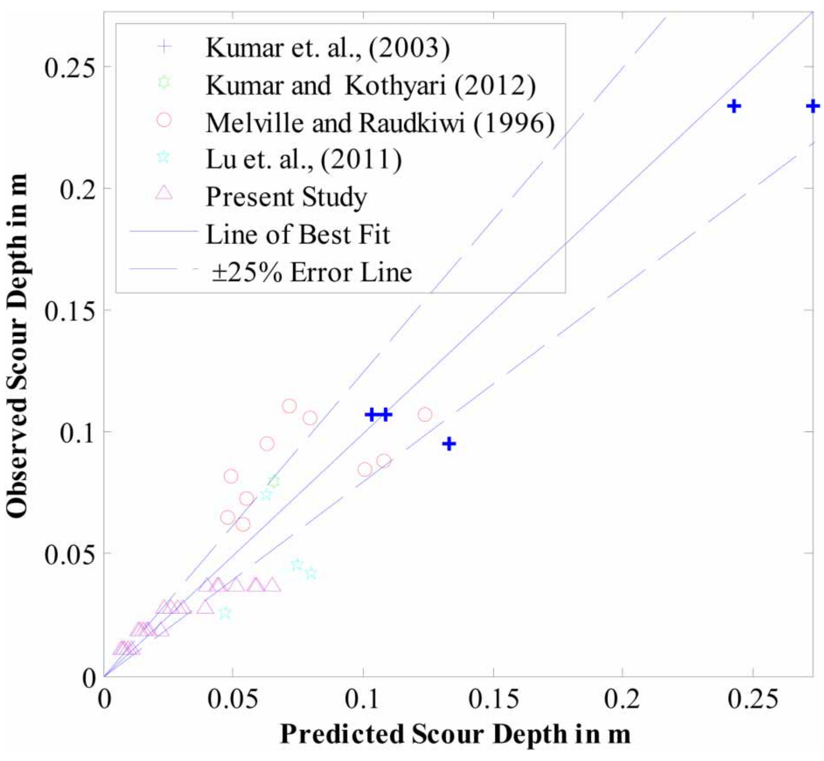


Figure 9 | Observed and predicted scour depth using GEP scour model Equation (2) for uniform sediments.

Performance of GEP scour model for uniform and non-uniform sediments

All the data of uniform sediments from the present study and literature are used for carrying out the performance analysis under uniform sediments and non-uniform sediments. The plot of observed and predicted scour depth using scour model Equation (2) is shown below in Figure 9.

Figure 9 shows that more than 60% of the data points lie within a $\pm 25\%$ error band. Figure 10 shows the performance GEP scour model Equation (2) for non-uniform sediments.

Figure 10 shows that 37% of the data points lie within a $\pm 25\%$ error band. Further, the statistical performance of the developed scour model Equation (2) is presented in Table 5 for uniform and non-uniform sediments.

Quantitative and qualitative results of a developed GEP model (Equation (2)) show that the model performs satisfactorily well under uniform and non-uniform sediments.

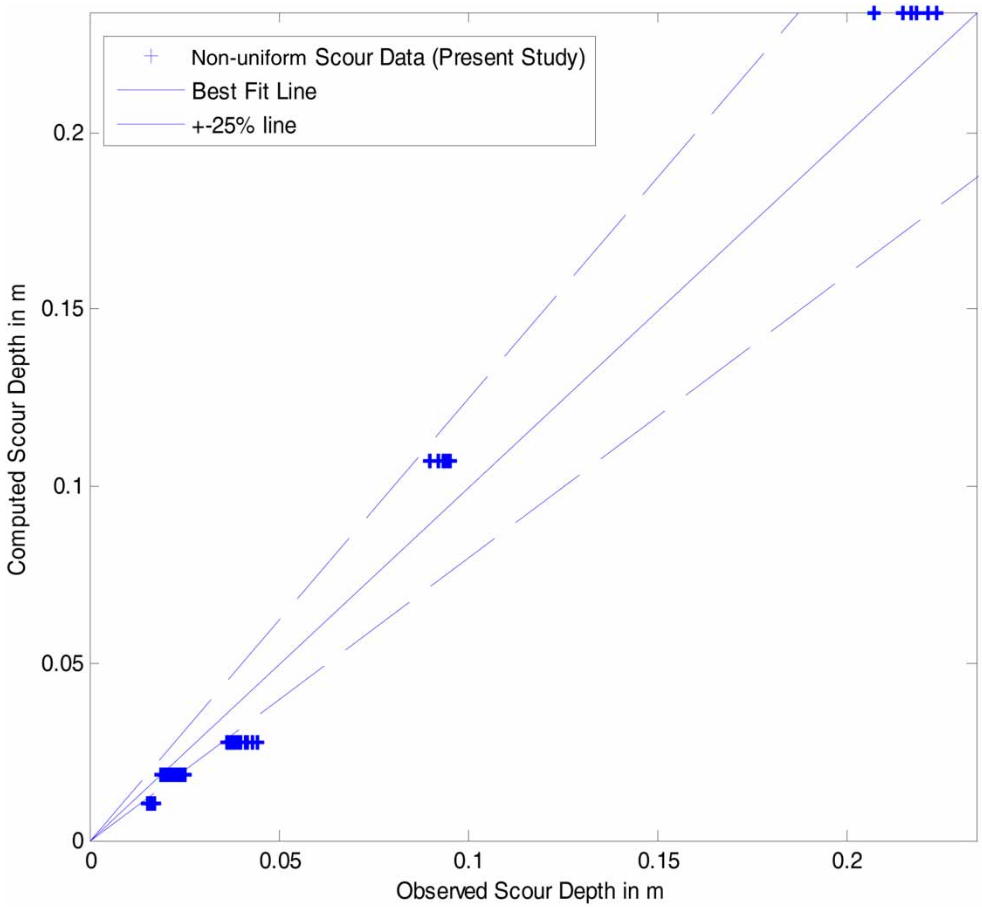


Figure 10 | Observed and predicted scour depth using GEP scour model Equation (2) for non-uniform sediments.

Table 5 | Performance of GEP scour Equation (2) during validation using uniform and non-uniform sediments

	Model (Equation (2)) Performance under	
Performance indicator	**Uniform sediment**	**Non- uniform sediment**
Correlation between actual and predicted	0.61	0.71
RMSE (root mean squared error)	0.037	0.037
MSE (mean squared error)	0.001	0.001
MAE (mean absolute error)	0.037	0.034

CONCLUSIONS

This paper investigated the use of GEP for modeling of scour around a compound bridge pier. This study tried to explore the utility of the developed model under uniform and non-uniform sediments. Performance of the proposed GEP scour model (Equation (2)) under training and testing stages were evaluated using experimental and literature data sets. The study also validates the ability of GEP as an effective modeling tool for applications in complex phenomenon modeling. GEP comes with the added advantage of providing a simple and easy-to-use empirical expression for the response function modeled. To assess the impact of scour parameters on equilibrium scour, regression-based sensitivity analysis was carried out and found that the dimensional parameters b, b^*, d_{50}, and σ_g are more sensitive than U, Y, and F_{rd}. This information could be useful to the scour modelers, field engineers, and practitioners. Quantitative results of a developed scour model (Equation (2)) during the calibrating and validating stages were encouraging, and the model has performed well. Hence, the developed model (Equation (2)) can be recommended to the design/practicing engineers for its use.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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