Evaluation of Scour around Isolated and Two Circular Piers using Semi-Empirical and Machine Learning Approaches

SYNOPSIS

For

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by

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Synopsis:

Scouring around bridge piers is caused by water flow interacting with bridge piers-like structures, causing sediment erosion. Scour is a complex process that changes over time, from initial erosion to maximum (d_{sm}) and equilibrium scour (d_{se}). This can weaken the bridge foundation and has caused approximately 50-60% of bridge failures (Wardhana and Hadipriono 2003, Xiong et al. 2023). To keep bridges safe, it is crucial to accurately predict the scour depth (d_s). While traditional methods have been used, there is a growing need to improve them or use machine learning (ML) for better accuracy, especially for single and two-pier arrangements. The d_s around two pier arrangements can create side-by-side, tandem, and eccentric combinations which are subjected to different flow phenomena such as reinforcing, sheltering, shed vortices, and compressed horseshoe vortices can be seen (Hannah 1978, Das et al. 2016). Reinforcing: When the scour holes from a downstream pier overlap with the front pier, it increases scour at the front pier. Sheltering: Upstream pier can reduce the approach velocity for downstream piers, diminishing the horseshoe vortex effect and reducing scour at those piers. Shed vortices: Vortices shed from an upstream pier are carried downstream along specific paths. If a second pier is placed near one of these paths, the vortices can help lift material from the scour hole, increasing the scour. Compressed horseshoe vortices: Scour increases when piers are placed close together across the flow. These two pier groups sometimes may be aligned, eccentrically in some cases for example Nivedita and Vivekananda bridges in Kolkata (Das et al. 2019). To address this, new models using semi-empirical methods and ML offer advantages over traditional approaches for analyzing scour in these configurations. However, only predicting d_s is not enough for this eccentric pier arrangement. Identifying areas with minimum scour is also important for safely positioning new bridge piers. Due to the complexity of real-world flow conditions, experimental studies are necessary to determine the safest locations for new pier placement. The following section will outline the significance of this study, highlight the gaps in current research, and explain the purpose of this research and the final outcomes.

- First of all, semi-empirical formulas are developed to predict d_{se} for the isolated pier over several decades (*HEC-18:* Richardson and Davis 2001, *New Zealand formula*: Melville and Coleman 2000, *Chinese formulas 65-1*: Gao 1993 and *65-2*: Hoang 2015) by different researchers. However, there is a gap in research for temporal scour (d_{st}) as well as d_{sm} estimation. During floods, scour can occur faster than in normal flow conditions in less time, so it is important to measure d_{st} in real-time (Chabert and Engeldinger 1956, Melville and Chiew 1999). Recently, Franzetti et al. (2022) proposed a semi-empirical formula for maximum scour depth (d_{sm}) based on laboratory metadata. However, such extensive metadata from different laboratory studies are often subjected to side wall effects, also known as constriction effects, the effect of such parameters assumed differently by various researchers. Considering these effects as influential parameters could enhance the accuracy of the semi-empirical formula. This study aims to address this gap by investigating how different parameters, such as sediment uniformity (σ), flow intensity (u/u_c), flow shallowness (h/d), sediment coarseness (d/d_{50}), and time (t) along with an additional influential parameter which is constriction ratio (d/W), influence the evolution of d_{st}. The main focus is given on comparing existing formulas and proposing a new formula derived from a comprehensive analysis of laboratory experimental data over 60 years. A total of 11 literature formulas were reviewed and introduced a new formula to estimate d_{st}. Analyze 329 time-series datasets from 13 studies over 70 years. Compare all formulas using multi-attribute decision-making methods for ranking. The following conclusion can be made after addressing the research gap.

- The sum of Squared Error (SSE) was reduced by ~15% than the best formula from the literature in the d_{st}/d category.
- To derive a d_{st} prediction formula that is independent of d_{se} and t_e, the present formula demonstrates the highest accuracy, outperforming Franzetti et al. (2022) and other literature formulas.
- The formula proposed by NCHRP (2011) remains the most reliable for computing d_{st}, with Melville and Chiew's (1999) formula showing accuracy that is very close to it when d_{se} and t_e are known.
- Among the 13 selected laboratory studies, the experimental data from Chabert and Engeldinger (1956), show strong agreement with both the existing and newly proposed formulas.

□ Furthermore, in recent years, ML techniques have been widely used to predict d_{sm} at bridge piers. These data-driven approaches, such as Artificial Neural Networks (ANNs), Adaptive Neuro-fuzzy Inference Systems (ANFIS), and evolutionary algorithms, offer significant advantages over traditional formulas (Bateni et al. 2007, Cheng et al. 2014). Similarly, genetic programming and Support Vector Machines (SVMs) have shown good performance in improving d_{sm} predictions by accounting for nonlinear relationships between input variables (Choi et al. 2017). However, recent research suggests that the integration of ensemble learning techniques, which combine multiple ML models, could further improve the accuracy and robustness of d_s predictions (Chou and Nguyen 2022, Kumar et al. 2023, Baranwal et al. 2024). Moreover, there has been an emphasis on sensitivity analysis and uncertainty quantification to account for the variability of input parameters and their influence on d_{sm} predictions (Singh et al. 2022). There is a gap in combining the strengths of both base and meta-learning models to predict d_{sm} under clear water scouring conditions. Therefore, this research aims to develop ensemble models that integrate various standalone base models with different meta-learners to improve the accuracy of d_{sm} predictions using 634 data points from 35 different literature sources and compare them with the six most promising d_{sm} formulas from the literature. The following conclusion can be made after the analysis using the ensemble method.

- The best parameters input found using best subset regression followed by k-nearest neighbors (KNN) are flow intensity (u/u_c), flow shallowness (h/d), sediment gradation (σ), sediment coarseness (d/d_{50}), dimensionless time ($ut/d\Delta^{0.5}$), constriction ration (d/W) and Froude number (Fr) to predict d_{sm}/d.

- Stochastic Gradient Boosting using Reduced Error Pruning Tree SGB(REPTree) model shows the best performance using compromise programming (CP), considering training and overall data (Rank 1).
- However, when considering the testing dataset, the Boosted Regression Trees using Support Vector Machine Regression with Pearson VII Universal Kernel BRT(SVMR-PUK) model show the best (Rank 1).
- Sensitivity analysis in training and testing phases: σ and u/u_c are the most important variables to predict d_{sm}/d in clear water.
- However, it can be seen that SGB (RFR) has great efficiency in terms of Correlation Coefficient (CC) and Persistence Index (PI) but it has a high bias in terms of Absolute Normalized-Mean Bias Error (ANMBE) and low efficiency in terms of Modified Kling-Gupta Efficiency (MKGE)
- When we compared the model across the testing data, the BRT(SVMR-PUK) model has MKGE ~15% (↑), CC and PI ~ 6%(↑), ANMBE~74%(↓), then Nandi and Das (2023), which is the highest performing model from the literature. The ensemble model predicts d_{sm} more accurately than both standalone models and traditional formulas.

□ In addition, it was reported that the d_{se} near bridge piers theoretically takes an infinite time to occur (Franzetti et al. 1982). Therefore, the equilibrium time (t_e) considering experimental data from different research was calculated using an established formula by Sumer et al. (1992) and Melville and Chiew (1999). Here, Chabert and Engeldinger (1956) defined equilibrium as the point where d_s increases very little over a certain period of time. Ettema (1980) described t_e as the time when less than 1 mm of d_s is added in 4 hours. Melville and Chiew (1999) stated that equilibrium is reached when the d_s increases by less than 5% of the pier diameter (d) in 24 hours. Grimaldi (2005) defined equilibrium as a scour rate of less than (0.05×width of the channel)/3 in 24 hours, Lança et al. (2010) suggested using long-term data and a six-parameter polynomial function to estimate d_{se} at circular piers. Different research groups have different definitions to estimate t_e, creating ambiguity in considering a single formula. However, a quasi-equilibrium state can be reached in a stipulated period. To address this research gap, new formulas are needed to more accurately calculate quasi-equilibrium scour time (T_e). Previous laboratory data consisting of 69 data points for calibration, and 24 data points for validation including eight additional laboratory experiments, are used to validate and assess the accuracy of the developed formula. The following findings can be highlighted from this chapter.

- The new formula performed significantly better than the literature formulas, with improvements in CC and Mean Absolute Percentage Error (MAPE) by ~51 and 20%, respectively. During training and validation, with ~36% more calibration data and 27% more validation data falling within ±80% accuracy compared to the previous best formula.
- A numerical example demonstrated to calculate T_e for 38 problem statements from the literature, achieving 89.47% of predictions within ±20% deviation.
- The new formula had the smallest uncertainty band compared to other formulas, and Taylor diagrams showed its superior performance, followed by Melville and Chiew's (1999) formula.

□ Studies have shown the importance of flow patterns and structures around piers, such as vortices, in determining d_s and patterns for single and two piers in eccentric arrangements (Das et al. 2016, Das and Mazumdar 2018). Research on scouring around side-by-side, tandem, and eccentric pier arrangements highlights the complexities of flow structures and sediment movement (Wang et al. 2016, Malik and Setia 2020, Devi and Kumar 2022). Existing studies on these configurations have not fully captured the dynamics in natural river environments, emphasizing the need for further research (Namaee and Sui 2019, Sahu et al. 2023). Tandem pier studies have explored mutual interference effects and developed empirical formulas for d_{se}, but further validation is required (Beg and Beg 2015, Liu et al. 2018). There is scope for improvement to estimate d_{sm} accurately incorporating time using semi-empirical methods.

- The proposed formula for side-by-side piers outperforms the literature formula and the new formula is based on the influenced mainly by u/u_c, h/d, pier spacing (r/d), and dimensionless time (ut/d). This formula improved by ~20% (↑) than the best literature formula in this category in terms of P_{in} (within the, ±20% error band).
- Key factors for tandem piers include u/u_c, h/d, d/d_{50}, r/d, and ut/d. In the case of the formula for Pier-1 in tandem arrangement, the P_{in} improved by ~6% (↑) than Wang et al. (2016) (best literature formula). Whereas, the Pier-2 form tandem arrangement shows an improvement in P_{in} ~160% (↑) than Malik and Setia (2020).
- Key influential parameters are for eccentric pier u/u_c, h/d, d/d_{50}, r/d, flow skew angle (φ) and ut/d. The formula for Pier-1 in eccentric arrangements has a P_{in} ~ 42% (↑) than Malik and Setia (2020), and for Pier- 2 the P_{in} ~ 74% (↑) than Malik and Setia (2020)

□ On the other side, Baranwal et al. (2024) showed that Extreme Gradient Boosting (XGBoost) outperforms SVM using Particle Swarm Optimization (PSO) for the isolated d_s estimations. The different ensemble ML models have demonstrated better performance in d_s for a single pier than the standalone model, but more research is needed to apply these methods to complex pier groups (Kumar et al. 2023, Nandi et al. 2024). Eini et al. 2023, considering SHapley Additive exPlanations (SHAP) to evaluate contributing parameters using XGBoost. However, there is a research gap in predicting using ML model around such two piers combinations. The main focus is given to Ensemble ML models, using Random Forest (RF) and XGBoost. Given the limitations of existing formulas, there is a need for a robust d_{sm} prediction model that integrates data from such pier configurations. More than 12 studies are selected for the initial data collection. A total of 431 data samples are gathered for side-by-side, tandem, and eccentric piers for developing the ensemble model and visualising the feature importance using Partial Dependence Plots (PDPs). Based on this following finding can be stated:

- For the feature selection sequential forward selection with RF and XGBoost applied and the set selected feature for Pier-1 are [u/u_c, h/d, d/d_{50}, $ut/d\Delta^{0.5}$, r/d]; [u/u_c, d/d_{50}, $ut/d\Delta^{0.5}$, φ, r/d] and for Pier-2 are [u/u_c, d/d_{50}, $ut/d\Delta^{0.5}$, φ, r/d]; [u/u_c, h/d, d/d_{50}, $ut/d\Delta^{0.5}$, φ, r/d].

- RF-RSCV delivers the best results for predicting d_{sm} in both Pier-1 and Pier-2 considering the testing data.
- Taylor diagram shows that among the models, RF-RSCV demonstrates the best performance for both Pier-1 and 2 compared to the correlation but the deviation is high for RF-RSCV, while RF-GSCV is performing better in the case of Pier-1. The models without tuning perform the closest to RF-GSCV for Pier-1, while for Pier-2 it does not perform well.
- These SHAP reveal that the parameter u/u_c has the greatest influence on the prediction for both the pier for the best model in testing data (RF-RSCV). The second most influential parameter is d/d_{50} and the least important one is φ for both piers.
- PDPs quantitatively depict each parameter which is consistent with flow physics. The u/u_c shows increasing trends in all plots, while d/d_{50}, decreases across models.

□ Urban growth increases traffic congestion, which often requires building new bridges next to existing ones, creating eccentric pier combinations (Das et al. 2016, Das et al. 2019, Nandi and Das 2024). The scouring process around such pier groups creates complex interactions, making it challenging to predict the d_{sm}. Some studies examined the impact of longitudinal spacing (l) variations (Das et al. 2016, Khaple et al. 2017), but fewer have studied variations in eccentric spacing (e) (Beg 2004). So, there is a need for rigorous experiments considering e to find the minimum scour location for safe placements of the bridge pier. After different studies on such pier groups, a complete understanding of scour geometry around piers with eccentric arrangements is also limited. There is a gap in studies on eccentric piers with varying e when it comes to identifying the minimum scour locations. The main aim is to find the position with the least scour for eccentric piers at various e. To identify the minimum scour location 24 laboratory experiments considering two pier groups arranged eccentrically along with additional single pier experiments are conducted. The d_{st} and d_{sm} analysis of the experimental study leads to the following findings:

- The minimum d_{sm} for eccentric pier arrangements can guide the construction of safe and cost-effective bridge piers. The minimum Pier-1 scour was observed at $e = 3.5d$ and $h = 1.65d$, while the maximum depth for the Pier-2 was 25% higher at the same location. However, the minimum scour at Pier -2 occurred at $e = 2d$ and $h = 1.65d$, with the scour at Pier -1 being 14% lower at the same position.
- The single pier (d_{ss}) is used to assess the increase or decrease in d_s for both piers of eccentric arrangements. The lowest scour, suitable for safe bridge design, is found at $e = 2.5d$ and $h = 1.2d$ for the eccentric pier, with a minimum scour at Pier -2 is 94% lower than the maximum scour at Pier -2 at $e = 2.25d$ and $h = 1.65d$.
- Single-pier arrangements are simpler and environmentally less impactful but may not support all spans and are prone to scour. Eccentric pier arrangements offer better load distribution and stability but increase complexity and environmental impact. The study shows that single-pier arrangements have lower d_s.

- For the eccentric pier, the MLR equation improves R^2 by 2 %, with MBE, MSE, and RMSE decreasing by 93, 76, and 51%. The MNLR equation improves R^2 by 2 %, with MBE, MSE, and RMSE decreasing by 95, 75, and 50%.
- The comparison between the MLR equation and Beg (2004) for the front pier shows a 1.36% increase in R^2, with MSE and RMSE decreasing by 66 and 42%, though MBE is higher for MLR. For the MNLR equation versus Beg (2004), R^2 and MBE increased by 0.52 and 50%, while MSE and RMSE decreased by 56 and 34%.

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Publications Related to the Ph.D. Thesis

1. List of journal publications

Nandi, B., and Das, S. (2025). Predicting Max Scour Depths near Two-Pier Groups Using Ensemble Machine-Learning Models and Visualizing Feature Importance with Partial Dependence Plots and SHAP. *Journal of Computing in Civil Engineering*, 39(2), 04025007. https://doi.org/10.1061/JCCEE5/CPENG-6150. (SCIE, Scopus)

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2. List of conference publications

Nandi, B., Das, S., Paul, S. (2025). Estimation of Clear Water Flow Induced Maximum Scour Depth Using Random Forest and XGBoost. Mukhopadhyay, A., Ghosh, K. (eds). In: *Advances in Thermo-Fluid Engineering. INCOM 2024. Lecture Notes in Mechanical Engineering.* Springer, Singapore. https://doi.org/10.1007/978-981-97-7296-4_6.

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