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PREDICTION OF LOCAL SCOUR AROUND WIDE BRIDGE PIERS UNDER CLEAR-WATER CONDITIONS

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ABSTRACT: Local scour is the removal of sediment from around bridge piers due to flowing of water. A large amount of local scour is dangerous to the bridge piers and causes the structure tend to collapse and loss of life without any warning. Many researchers have already investigated the phenomenon of local scour around bridge piers. The literature search revealed that there is very little information on predictive equations or data on scour around wide piers. Most of the predictive equations in the literature are intended to apply equally well to large and small piers. Hence, this leads to a situation in which design is prioritised over prediction, which thus proves costly and economically inefficient. This study attempted to fill this gap where new experimental data from a physical model of scouring around a cylindrical and rectangular wide pier embedded in two types of uniform sediment beds are presented. The effects of sediment sizes and various pier widths on equilibrium scour depth of wide bridge piers are described. New empirical relation for the estimation of non-dimensional maximum scour depth for a wide pier were proposed as functions of the sediment coarseness. The experimental data obtained in this study and data available from the literature are used to validate the predictions of existing methods and the accuracy of the proposed method. The proposed method gives reasonable scour depth predictions and was verified with statistical methods where the root mean square error was reduced from 71% to 26%. The new empirical relation agrees satisfactorily with the experimental data.

Keywords: Local Scour, Wide Piers, Equilibrium Scour, Existing Equations, Scour Prediction

1. INTRODUCTION

Failure of bridges due to local scour has motivated many investigators to explore the causes of scouring and to predict the maximum scour depth around piers. Numerous studies have been conducted with the purpose of predicting scour and various equations have been developed [1], [2], [3], [4], [5], [6], [7], [8], [9], [11] and [22]. In addition, the equations and methodologies have been developed as well for estimating design scour depths around wide and long skewed piers. Bridge scour is the meaning of removal of soil, sand and rocks from around a bridge supports or piers as shown in Fig.1.

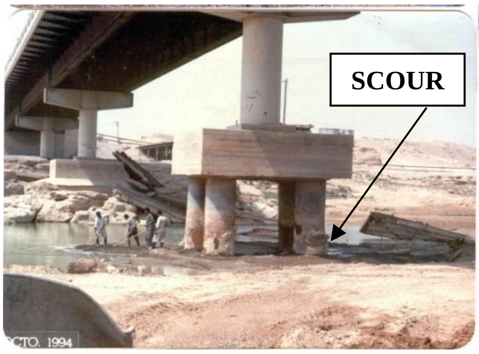

Fig. 1 Local scour at bridge pier

2. MATERIALS AND METHODS

The scour experiments were performed in a flume that was 2.0 m deep, 1.5 m wide, and 50 m long which is in the hydraulic laboratory of the National Hydraulic Research Institute of Malaysia (NAHRIM). A test section that was 10 m long and 0.4 m deep was filled with uniform sediment. The depth of flow was maintained at 0.25 m for all of the experiments. The velocity of both sediments was 0.27 m/s (d_{50}=0.23mm) and 0.36 m/s (d_{50}=0.80mm). An area velocity module (AVM) was used to measure the velocity of flow. In order to measure the depth of scour, a vertical point gauge on the vernier scale was applied. The critical shear velocity, U*c, and critical flow velocity, Uc, for entrainment of sediment, were calculated from the equations given in [13]. The experiments were performed under clear-water conditions at threshold flow intensity $U/Uc \approx 0.95$. A single pier model was fixed at the centre of the flume width. Two pier shapes– cylindrical and rectangular – were used to perform the experiment on wide piers. Each pier shape had the same pier width, b, which was tested at 60, 76, 102, 140, and 165 mm; two sizes of cohesionless uniform sediments with median particle size, d_{50} = 0.23 mm and d_{50} = 0.80 mm were also tested. Therefore, there were a total of 20 experiments conducted on wide piers. The experiments were conducted in two sizes of cohesionless uniform sediments with d_{50} = 0.23 mm and d_{50} = 0.80 mm, thus giving a total of 20 experiments.

To achieve flow transition in smooth condition in the flume, ramps with a 1:5 (vertical: horizontal) slope were constructed at opposite ends of the mobile bed. Fig. 2 shows the schematic drawing for the experimental set up. Uniform sand was used in this experiment to eliminate any possibility of local scour depth reduction expected to occur in non-uniform sand. This is because in non-uniform sand, the armouring effect allowed the downflow to penetrate through the voids between the particles and then reduced the spiral action effect by dissipating some of the flow energy. The degree of uniformity of the particle size distribution of a sediment sample is defined by the value of geometric standard deviation, σ_g, which is less than 1.3 for uniform sediments [13]. The sediments used were well rounded and had a shape factor = 1.0. The Shield's function was used in the calculation of the critical shear velocity on the approach flow bed, u_{*c}, for the mean particle size, d_{50}, of each sediment. The method proposed by [13] was used to determine the critical shear velocity, u_{*c}.

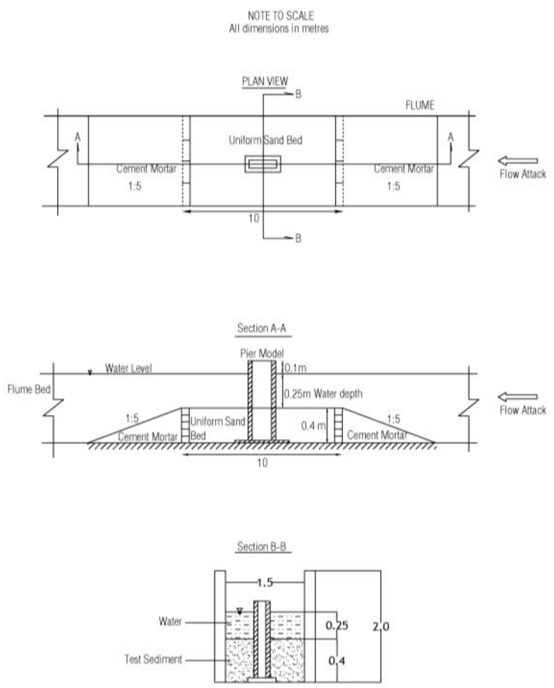

Fig. 2 Schematic drawing for the experimental setup with plan view and side view

3. RESULTS AND ANALYSES

Twenty experiments were carried out. All of them were run for a single cylindrical and rectangular wide pier with various diameters. To show the relationship of dimensionless d_s/b on b/d_{50}, all of the twenty data sets were shown in Figure 3. It was found that d_s/b reduced as b/d_{50} increased and thereafter d_s/b became constant. From the curves, it is indicate that a high value of equilibrium scour depth was achieved at b/d_{50} = 330 with b = 76 mm in fine sediment with d_{50} = 0.23 mm. The values of d_s/b for the pier sizes of 102, 140, and 165 mm show a smaller peak value compared with that observed for the smaller pier sizes at d_{50}=0.23 mm. The smaller maximum equilibrium scour depths recorded for the larger pier sizes can be attributed to greater localised scour of the bed surface around the rim of the scour hole at each of these piers compared with that occurred for the smaller pier sizes. As in [14] also noted that the reductions of scour depth for larger pier sizes were influenced by the adjustment of bed level at the upstream rim of the scour hole.

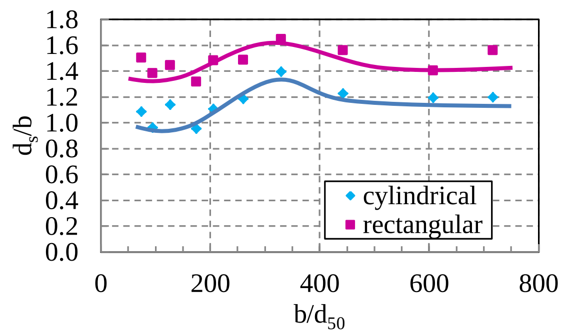

Fig 3 Equilibrium-normalised scour depth versus b/d_{50}

To show more specific patterns and a wider range of applicability for the relationship between d_s/b and b/d_{50}, laboratory data in the present study were merged with the data from the researchers as listed in Figure 4 [15], [14], [16], [17], [18] and [19]. The range of the data up to 4,000. The equilibrium scour depth versus b/d_{50} for large ranges of sediment coarseness (b/d_{50}) was plotted and is shown in Figure 4. These plots evidently demonstrate that d_s/b values were reduced as values of b/d_{50} increased. A least-squares regression analysis using a fitting criterion of mean square error was applied to all data and found the optimum coefficients which minimised the mean square error between the experimental and predicted values. The best fit relationship between d_s/b and b/d_{50} is described by Equation (1).

$$\frac{d_s}{b} = 3.4 - \frac{30}{\left(\frac{b}{d_{50}}\right)} exp\left[0.088\left(ln\left(\frac{b}{d_{50}}\right)\right)^2\right]$$
(1)

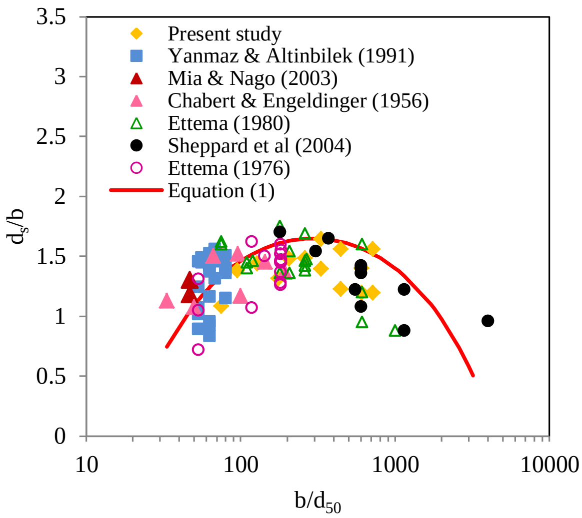

Fig 4. Effect of b/d_{50} on the equilibrium local scour depth around piers

3.1 Assessment of existing equations for estimating the depth of maximum local scour at wide piers

In this section, the laboratory data sets from the present study and literature were used to validate the predicted maximum scour depth at wide piers using equations proposed by [5], [20] and [21]. Statistical
analysis was carried out to assess the performance of each predictive equation. The discrepancy ratio (r), the standard deviation of the discrepancy ratio (σ_r), and the root mean square error (RMSE) were determined. The formulae for the statistical analysis are described below:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{N}\left(d_s/b_{predicted,i} - d_s/b_{measured,i}\right)^2}{N-1}} \quad (2)$$

$$r = \frac{(d_s/b)_{predicted}}{(d_s/b)_{measured}}$$
(3)

$$\sigma_r = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(r_i - \bar{r})^2} \quad (4)$$

Where $\bar{r}$ is the average of the discrepancy ratio. A value of unity for $\bar{r}$ shows perfect agreement between the dimensionless scour depths of the predicted and measured values. σ_r represents an evaluation of the scatter in the predictions relative to the average value.

The results of the statistical analysis for each predictive equation are given in Table 1. By using the laboratory data sets, the average values of the discrepancy ratio, $\bar{r}$, showed that the [5], [20] and [21] equations over-predict the d_s/b values by 19% to 47%, while Equation (1) gave an average value of a 4% over-prediction. Next, the smallest standard deviation of the discrepancy ratio, σ_r, was obtained by applying Equation (1) where the average value was found to be±1.06 and the RMSE value was ±0.26.

Table 1. Summary of the discrepancy ratio, r, and root mean square error, RMSE, for each predictive equation

	Laboratory data		
	r		
	$\bar{r}^1$	σ_r^2	RMSE^3
Jones and Sheppard (2000)	1.19	1.27	0.52
HEC-18 (2012)	1.26	1.30	0.53
Sheppard et al. (2014)	1.47	1.47	0.71
Present study	1.04	1.06	0.26

$\bar{r}^1$= average discrepancy ratio, σ_r^2 = standard deviation of discrepancy ratio, RMSE^3 = root mean square error

Visual comparison (scattergrams) is another method that can be used to evaluate the predictive equations using the predicted and measured scour depths at wide piers. Figures 5 demonstrate the dimensionless scour depth for laboratory and field data sets. The plots indicate how much the predicted values of normalised scour depth deviate from the line of perfect agreement.

From the observation, the selected scour prediction equations over-predict the scour depth, while the results obtained from applying Equation (1) are found to be in agreement and close to the measured values. As a factor of safety, 25% can be added to the value obtained from Equation (1) in order to consider the value of the maximum scour depth for all data sets used. Meanwhile, it needs to be stressed that the applicability of Equation (1) is limited to values of b/d_{50} from 50 – 4200, to skewed piers with angle of attack, α< 45°, to piers in shallow flows and to graded sediments with σ_g less than 7.

4. CONCLUSION

In conclusion, the result showed the relative scour depth d_{se}/b decreased with increasing values of sediment coarseness b/d_{50} and this was found to be in agreement with experiments in very large flumes as well as with the data points from the previous researchers. Overall, the validation of experimental results and analysis of the effects of pier width and bed sediment size on scour depth verifies the theory of wide piers for the most part. However, the results of the present study are limited to clear-water

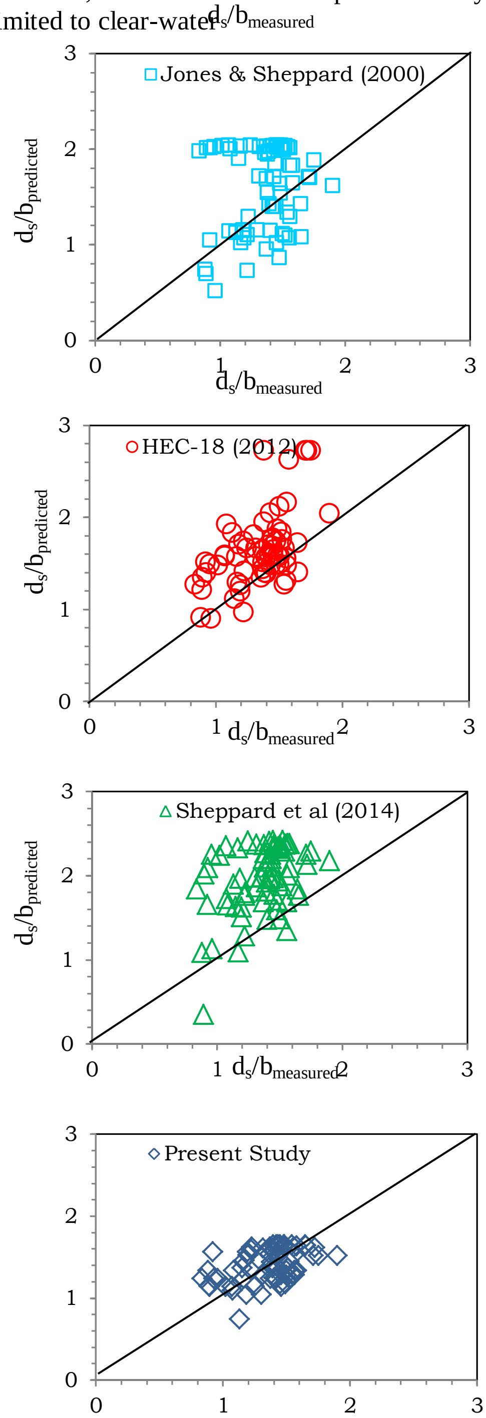

Fig. 5 Comparison of the predicted and measured normalised scour depths from laboratory experiments including Chabert and Engeldinger (1956), Ettema (1980), Yanmaz and Altinbilek (1991), Mia and Nago (2003), and Sheppard et al. (2004) data with selected existing scour depth predictive equations

conditions, steady flow, non-cohesive sediments, and subcritical flow conditions. An important practical limitation of laboratory experiments on pier configuration is flume width; the size of the flume is not wide enough to facilitate scour experiments for large values of b.

5. ACKNOWLEDGEMENTS

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