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A Study on the Effects of Debris Accumulation at Sacrificial Piles on Bridge Pier Scour: II. Empirical Formula

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Abstract

The major damage of bridges at river crossing occurs during floods. Damage is caused for various reasons, the main reason being riverbed scour at bridge foundations, namely pier and abutments. Debris accumulation at bridge pier provides larger obstruction to flow than an isolated bridge pier. The presence of debris causes larger scours and sediment removal compared to the absence of debris accumulation. Debris accumulation at bridge pier effects to bridge pier scour has been studied by several researchers. But the effects of debris accumulation at sacrificial piles on bridge pier scour have not been studied, yet. The aim of this study is to estimates the effects of debris accumulated at sacrificial piles to bridge pier scour and proposes a new formula for predicting bridge pier scour depth with debris accumulated at the sacrificial piles. Experiments were performed to understand the changes and interaction of scour depth over a range of flow depths, y and flow intensities, V/V_c. Experiments were conducted in single pier scour, sacrificial piles scour, single pier with debris scour and sacrificial piles with debris scour. By comparing each of the experimental results it has been found that debris effects to bridge pier scour related to its size and thickness. Several scour depth prediction methods were compared with the results of this experimental study results. Among those formulae Melville's formula was chosen to modify. The proposed modified Melville's formula depth-size factor, K'_{yb} = 1.56D was defined in this study. A new relation has been proposed to predict the effects of debris accumulation at sacrificial piles on bridge pier scour in term of relative maximum scour depth. D'_e is proposed as effective pier with debris accumulated at sacrificial piles. The new proposed formula is well fitted with the experimental results. The results of experiments from the previous paper are used to analyze and the new formula is proposed.

Keywords: *debris accumulation, sacrificial piles, bridge pier scour, single pier*

1. Introduction

Bridge pier scour has been a subject of interest and importance to people from the time of the earliest civilizations. Knowledge of predicting scour depths and countermeasures for protecting against scour problem has progressed rapidly over the past 50 years. However the effects of debris accumulation at bridge pier still not have been researched much. (Breusers *et al.*, 1977) has developed the relationship between the scour depth and the relation of V/V_c by dimensional analysis, but applied no detailed analysis into the nature of the dependency. Hancu (1971) conducted a series of scour experiments and concluded that the local scour depth is dependent of the flow velocity. This conclusion is similar to that of (Breusers *et al.*, 1977). Richardson and Davis (1995) commented that long term streambed profile changes will usually be difficult to assess. Melville (1997) presented many laboratory data that describe the temporal development of local scour at circular bridge piers under clear-water conditions. It was shown that local scour depth were reduced at lower values of V/V_c. The current pier scour design in the USA is mainly based on the CSU equation described in HEC-18 (CSU, 2001). Sheppard and Miller (2006) conducted pier scour experiments and compared their results with some of the local scour equations. Available prediction equations give widely varied results for a given flow and sediment conditions.

Sacrificial pile installation is the mechanism for reducing scour at bridge pier. Pile was installed at upstream of the pier to reduce flow approach of erosion and to weaken the eddy current motion. The scour depth at the pier was affected by sacrificial pile width upstream of the pier. If the pile width small the effect of scour reduction also small. The effects of scour reduction are number of sacrificial piles, its arrangement, pier length and various angle arrangement functions. The most recent experimental study of sacrificial piles was carried out by Hadfield (1997). Hadfield (1997) suggested that the most effective pile arrangement was found to consist of five sacrificial piles of diameter 0.167D with

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arrangement parameters X = 2.5D, e = D, and $\propto = 30^0$; where D is the diameter of the cylindrical bridge pier; X is the displacement of the forward most pile from the upstream face of the pier; e is the spacing between the piles and $\propto$ is the wedge angle. For aligned flows an alternative arrangement could reduce scour depths by 56%. The effects of debris accumulation at sacrificial piles to bridge pier scour has not been studied, recently. So the aim of this study is to estimate the effect of debris accumulation at sacrificial piles to bridge pier scour and to propose a new formula for predicting bridge pier scour depth with debris accumulated at the sacrificial piles. Experiments were performed to understand the changes and interaction of scour depth over a range of flow depths and flow intensities (Park *et al*., 2015).

2. Empirical Formula for Debris Accumulation

2.1 Analysis of Scour Depth Prediction Methods

Various scour depth prediction formulae were chosen to compare with this study experimental results. The most comment proposed methods are presented in Table 1. The comparison of single pier scour depth of this experimental study results (Sok *et al*., 2014) with various proposed scour depth prediction results are presented in Table 2.

The Root Mean Square Error (R.M.S.E) test has been performed for each prediction results versus the laboratory data. Among various proposed scour prediction method results Melville (1997) gave the lowest root mean square error rate, R.M.S.E = 0.020. So Melville formula was chosen to use for proposing a new method for predicting scour depth at bridge pier with debris accumulated at the sacrificial piles.

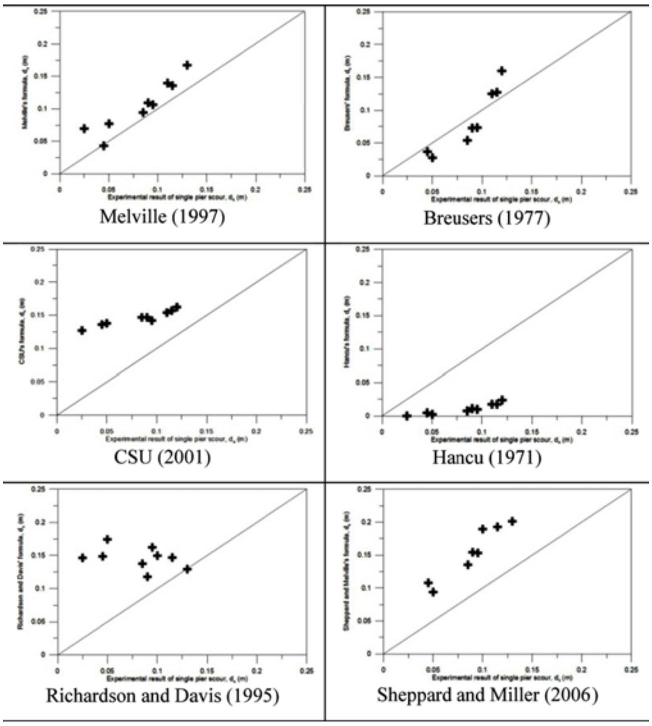
2.2 Melville's Formula

Melville (1997) has developed a design method for estimation the scour depth at bridge pier. The design method rests on the following relation for the depth of local scour:

Table 1. Various Proposed Scour Depth Prediction Methods

Author	Formula
Hancu (1971)	$\frac{d_s}{D} = 2.42\left(\frac{2V}{V_c}-1\right)\left(\frac{V_c^2}{gD}\right)^{\frac{1}{3}}$
Breusers (1977)	$\frac{d_s}{D} = f\left(\frac{V}{V_c}\right)\left[2.0\tan\left(\frac{y}{D}\right)\right]K_sK_\theta$
Richardson and Davis (1995)	$\frac{d_s}{D} = 2.0K_sK_0K_3K_4\left(\frac{y}{D}\right)^{0.35}Fr^{0.43}$
Melville (1997)	$d_s = K_{yb}K_IK_dK_sK_\theta K_GK_t$
CSU (2001)	$\frac{d_s}{y} = 2.0K_1K_1\left(\frac{D}{y}\right)^{0.65}Fr^{0.43}$
Sheppard and Miller (2006)	$\frac{d_s}{D} = 2.0K_1K_2K_3K_4K_w\left(\frac{y}{d}\right)^{0.35}Fr^{0.43}$

Table 2. Comparison of this Experimental Study Results with Various Proposed Scour Depth Prediction Method Results



$$d_s = K_{yb}K_IK_dK_sK_\theta K_GK_t$$

Where, K_d = Sediment size factor
K_G = Channel geometry factor
K_I = Flow intensity factor
K_S = Pier shape factor
K_t = Time factor
K_{yb} = Depth-size factor
K_θ = Pier alignment factor

– Depth-size factor

$$K_{yb} = 2.4D, \frac{D}{y} < 0.7$$

$$K_{yb} = 2\sqrt{yD}, 0.7 < \frac{D}{y} < 5$$

$$K_{yb} = 4.5y, \frac{D}{y} > 5$$

– Flow intensity factor

$$K_I = \frac{v-(v_a-v_c)}{v_c}, \frac{v-(v_a-v_c)}{v_c} - 1$$

$$K_I = 1, \frac{V-(V_a-V_c)}{V_c} \geq 1$$

$K_I = \frac{v}{v_c}$ for clear-water condition, uniform sediment

– Sediment size factor

Table 3. Shape Factors for Uniform Piers and Shorter Abutments

Foundation type	Shape	K_s
Uniform pier	Circular	1.00
	Round nosed	1.00
	Square nosed	1.10
	Sharp nosed	0.90
Abutment	Vertical-wall	1.00
	Wing-wall	0.75
	Spill-through 0.5:1 (H:V)	0.60
	Spill-through 1:1	0.50
	Spill-through 1.5:1	0.45

$$K_d = 0.57\log\left(2.24\frac{D}{d_{50}}\right), \frac{D}{d_{50}} \le 25$$

$$K_d = 1, \frac{D}{d_{50}} > 25$$

– Pier shape factor

The shape factor K_s is defined as the ratio of the scour depth for a particular foundation shape to that for the standard shapes, namely circular piers and vertical-wall abutments. Table 3 shows the shape factors for uniform piers and shorter abutments.

– Pier alignment factor

$$K_\theta = \left(\frac{b_p}{b}\right)^{0.65} = \left(\frac{1}{b}\sin\theta + \cos\theta\right)^{0.65}$$

for circular piers $K_\theta = 1$

– Channel geometry factor

The approach channel geometry factor K_G is the ratio of the local scour depth at a bridge pier foundation to that at the same foundation sited in the equivalent rectangular channel. The local scour at bridge piers is considered not to be affected by approach channel geometry as long as approach values of y and V are used to estimate the scour depth. If value of y and V are selected to be representative of the flow approaching the particular pier, $K_G = 1.0$

– Time factor

$$K_t = \exp\left\{-0.03\left|\frac{V}{V_c}\ln\left(\frac{t}{t_2}\right)\right|^{1.6}\right\}$$

$$t_e(days) = 48.26\frac{D}{V}\left(\frac{V}{V_c} - 0.4\right), \frac{y}{D} > 6, \frac{V}{V_c} > 0.4$$

$$t_e(days) = 30.89\frac{D}{V}\left(\frac{V}{V_c} - 0.4\right)\left(\frac{y}{D}\right)^{0.26}, \frac{y}{D} \le 6, \frac{V}{V_c} > 0.4$$

2.3 Modified Melville's Formula

Melville and Dongol (1992) have developed a design method for scour depth estimation with debris accumulation. Local scour depth estimation based upon the largest possible scour depth that can occur at a cylindrical pier, which is 2.4D.

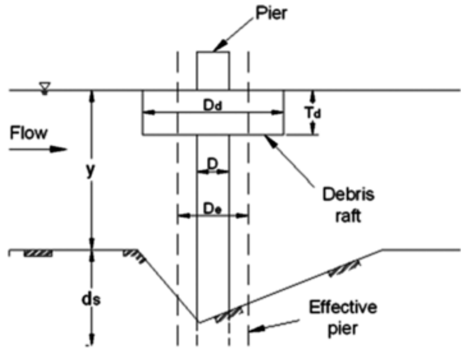


Fig. 1. Idealized Floating Debris Raft Diagram (Melville and Dongol, 1992)

$$D_e = \frac{0.52T_dD_d + (y - 0.52T_d)D}{y}$$

Where, D = Pier diameter
D_e = Effective diameter
D_d = Width of floating debris raft
T_d = Thickness of debris
y = Flow depth

After calculated effective diameter, D_e, the local scour depth can be estimated by using the following relation:

$$d_s = K_{yb}K_IK_dK_sK_\theta K_GK_t \text{ in with, } K_{yb} = 2.4D_e$$

The results of single pier with debris scour of this experimental study (Park *et al*., 2014) were compared with Melville's formula as shown in Fig. 2.

It was seen that Melville's formula over-predicted the scour depth compared with this study experimental result. Koopaei and Valentine (2003) has studied on the bridge pier scour in self-formed laboratory channels. The result showed that Melville's design method over-predicted the scour depth. The over-prediction of the scour depth due to the fact that the equation is intended to be used for design purposes and therefore is based on an envelope curve for scour depth prediction.

In this study $K'_{yb} = 1.56D$ was modified on Melville's formula.

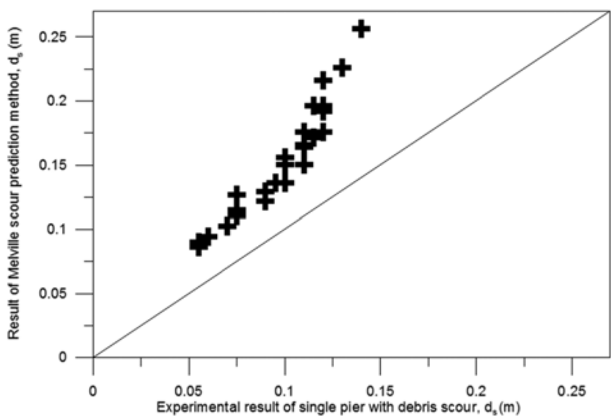


Fig. 2. Comparison Results of Single Pier with Debris Scour with Melville's Formula

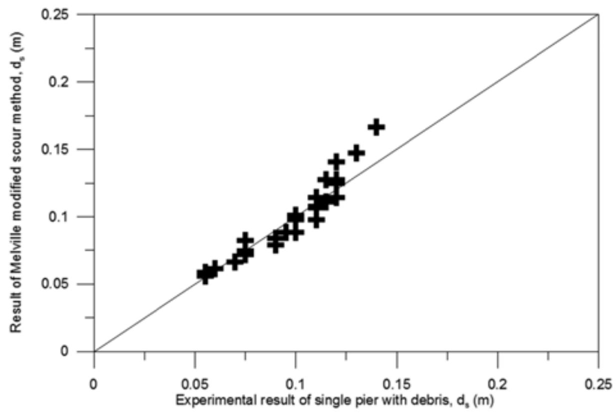


Fig. 3. Comparison Results of Single Pier with Debris Scour with Melville's Modified Formula

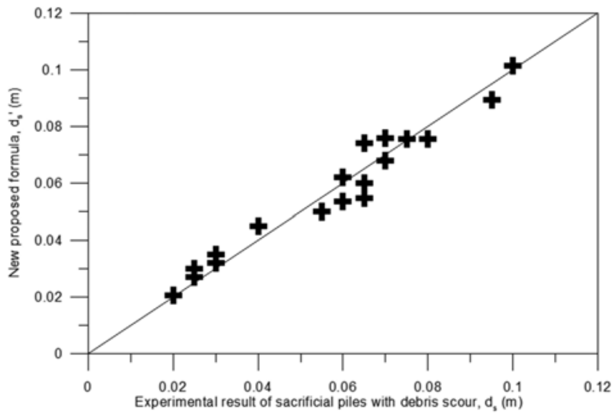


Fig. 5. Comparison Results of Sacrificial Piles with Debris Scour with the New Proposed Formula

It was proper with the experimental data. The results of single pier with debris scour of this experimental study were compared with Melville's modified formula. It was seen that the results of Melville's modified formula was well fitted with the results of the experiments as shown in Fig. 3.

3. New Formula for Sacrificial Piles with Debris

3.1 Derivation of New Formula

Sacrificial piles are piles placed upstream of the bridge pier for the purpose of protecting it from scour. The piles, which themselves may be subject to substantial scour, protect the pier from scour by deflecting the high velocity flow and creating a wake region behind them. The effectiveness of this method as a pier scour countermeasure is dependent on the number of piles and the geometric arrangement of the piles in relation to one another and the bridge pier. The scour depth at bridge pier decrease by using sacrificial piles placed upstream of the bridge pier. However debris accumulation at sacrificial piles also effected to the scour depth at bridge pier (Sok *et al*., 2014). The aim of this study is to estimates the effects of debris accumulated at sacrificial piles to bridge pier scour and proposes a new formula for predicting bridge pier scour depth with debris accumulated at the sacrificial piles. Fig. 4 showed the idealized floating debris raft at sacrificial piles diagram.

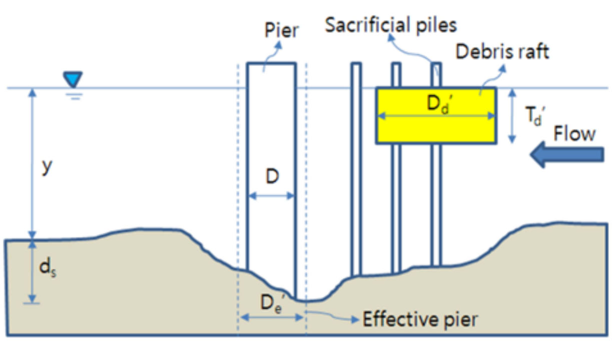


Fig. 4. Idealized Floating Debris Raft at Sacrificial Piles Diagram

D_e' was defined as effective pier diameter with debris accumulation at sacrificial piles. The relation is come as the following:

$$D_e' = \frac{0.52T_d' D_d' + (y - 0.52T_d')D}{y} \times K_{ds}$$

Where, D = Diameter of bridge pier
D_d' = Debris diameter at sacrificial piles
K_{ds} = Distance factor
T_d' = Debris thickness at sacrificial piles
y = Approach flow depth

Where, l = distance of sacrificial piles from the bridge pier. a,b,c and d are coefficients of debris size from empirical which a = 0.58, b = 0.55, c = 4.5 and d = 3.5.

So the new proposed formula for sacrificial piles with debris scour is come as the following:

$$d_s' = K_{yb}' K_I K_d K_s K_\theta K_G K_t \text{ in which, } K_{yb}' = 1.56 D_e'$$

The results of sacrificial piles with debris scour from this experimental study were compared with the new proposed formula. The results are shown in Fig. 5 and it was seen that the new proposed formula is well fitted with the experimental results.

3.2 Prediction Accuracy and Formula Calibration

The root mean square error (R.M.S.E) test has been performed for each prediction results versus the laboratory measured data. It was defined that the new proposed formula was well accurate with the R.M.S.E = 0.005.

$$R.S.M.E = \sqrt{\sum \frac{(Y_M - Y_S)^2}{N}}$$

In which,
Y_M = Measured scour depth in the laboratory experiments
Y_S = Calculated scour depth by any of the selected prediction
N = Total number of observations

According to the literature reviews the effective of sacrificial

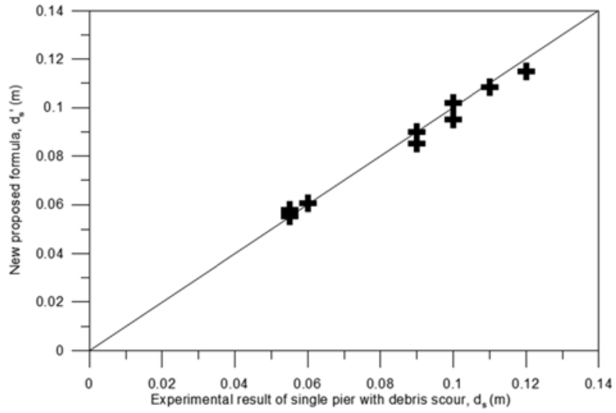


Fig. 6. Comparison Single Pier with Debris Experimental Results with News Proposed Formula

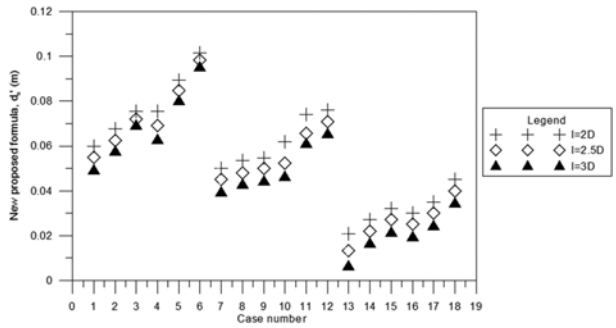


Fig. 7. Calculated Scour Depth with Different Distances for Sacrificial Piles from the Bridge Pier

piles depend on the number of piles, its arrangement, the wedge angle and the distance from the bridge pier. As recommended by Hadfield (1997) the effective distance from the bridge pier was 2D for aligned flow and 2.5D for non-aligned flow. So the new proposed formula is limited to use for distance more than 3D. If the distance of sacrificial piles with debris, l = 0, the effective pier diameter with debris accumulated at sacrificial piles, $D'_e = D_e$. It means that the scour depth of sacrificial piles with debris is about the same to the single pier with debris scour. The results of sacrificial piles scour experiments showed that the scour depth increased when the sacrificial piles come closer to the bridge pier and decreased when the sacrificial piles in a distance from the bridge pier.

In physically if the distance of sacrificial piles with debris, l = 0, the scour depth at bridge pier should be the same as single pier with debris scour. If l = 2.5D or 3D, the scour depth at bridge pier should be decreased. So the new proposed formula has been calibrated with l = 0, l = 2D, l = 2.5D and l = 3D. Table 2 showed the comparison results of new proposed formula with experimental results when l = 0. Fig. 6 showed that the new proposed formula was well fitted with the experimental results when l = 0. Fig. 7 showed the results of new proposed formula when l = 2D, l = 2.5D and l = 3D. It was seen that the scour depth at l = 2D is higher than the scour depth at l = 3D. So it can be concluded that the new proposed formula is well accurate.

4. Conclusions

The purpose of this experimental study is to estimate the effect of debris accumulation at sacrificial piles to bridge pier scour and to propose a new formula for predicting bridge pier scour depth when debris accumulated at sacrificial piles.

In this study, four different types of experiments were conducted, single pier scour experiments, sacrificial piles scour experiments, single pier with debris scour experiments and sacrificial piles with debris scour experiments.

Single pier scour experiments were conducted in various discharges and flow depths to understand scour characteristics. The results showed that the scour depth increased with the flow intensity. The experimental condition of case A2, A5 and A8 were selected for applying in sacrificial piles scour experiments. Sacrificial piles scour experiments were conducted in eleven cases with different arrangements, pile numbers, and distances. The results showed that using sacrificial piles can reduce the scour depth at bridge pier. By installing the sacrificial piles the scour depth decreased from 39% to 60% compared to isolated pier.

For analyzing the effects of debris to bridge pier scour, single pier with debris scour experiments and sacrificial piles with debris scour experiments were conducted. The debris raft are made by acrylic in a diameter of 0.2 m, 0.3 m and 0.4 m and thickness of 0.1 m, 0.15 m and 0.2 m respectively for single pier with debris scour experiments. In sacrificial piles with debris scour experiments the debris raft diameters are 0.1 m and 0.2 m and thickness 0.1 m, 0.15 m and 0.2 m respectively. The results of single pier with debris showed that the scour depth increased from 10% to 60% compared to single pier without debris. In sacrificial piles with debris the results showed that scour depth decreased from 10% to 50% compared to isolated pier. It was seen that the effectiveness of sacrificial piles with debris is smaller than without debris. So it can be concluded that debris accumulation effects to bridge pier scour. Sacrificial piles are used as flow alternative method to reduce the scour depth. In case of debris accumulation at sacrificial piles the bridge pier scour should be considered.

In order to predict the effects of debris accumulation at sacrificial piles to bridge pier scour the formula was proposed by using the data from this study experimental result. Several scour depth prediction methods were analyzed and compared with this study experimental result. The depth-size factor of Melville's formula, K_{yb} was modified. The proposed depth-size factor, K'_{yb} = 1.56D was proposed with this experimental study results. The new formula for predicting bridge pier scour depth with debris accumulated at sacrificial piles was proposed that used D'_e as the effective pier diameter when debris accumulated at sacrificial piles. The results of new proposed formula are compared with this study experimental result. It was found that the results of new proposed formula were well fitted with the experimental study results. The new proposed formula is good for predicting the bridge pier scour with debris accumulated at sacrificial piles.

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Notations

b = Pier width
D_p = Effective pier width
D = Pier diameter
D_d = Width of floating debris raft
D'_d = Width of floating debris raft at sacrificial piles
D_e = Effective pier
D'_e = Proposed effective pier
d_s = Depth of scour
d_{50} = Median size of bed material
e = Spacing between the pile
F_r = Froude number
g = Acceleration of gravity
K_d = Sediment size factor
K_{ds} = Distance factor
K_G = Channel geometry factor
K_I = Flow intensity factor
K_s = Pier shape factor
K_θ = Foundation alignment factor
K_t = Time factor
K_{yb} = Depth size factor
K'_{yb} = Modified depth size factor
K_w = Factor for very wide pier
K_1 = Pier shape factor
K_2 = Foundation alignment factor
K_3 = Factor for model of sediment transport
K_4 = Factor for amouring by bed material
l = Distance of the first sacrificial pile from the pier
L = Abutment length
L_m = Model length ratio
L_p = Prototype length ratio
L_r = Geometric ration
Q = Discharge
R = Reynold number
t = Time
T_d = Thickness of debris
T'_d = Thickness of debris at sacrificial piles
t_e = Time for equilibrium scour depth develop
V = Mean flow velocity
V_a = Armour peak velocity
V_c = Threshold velocity
X = Displacement of the forward most pile from the upstream face of the pier
y = Approach flow depth
y_M = Measured scour depth in the laboratory experiments
Y_s = Calculated scour depth by any of the selected prediction
α = Angle of the pier to the approach flow
β = Angle of flow to the pier
ν = Kinematic viscosity of water

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