International Journal of GEOMATE, Oct., 2024 Vol.27, Issue 122, pp.132-139
ISSN: 2186-2982 (P), 2186-2990 (O), Japan, DOI: https://doi.org/10.21660/2024.122.g13427
Geotechnique, Construction Materials and Environment

TEMPORAL DEVELOPMENT OF SCOUR AROUND WIDE PIERS

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*Corresponding Author, Received: 16 June 2023, Revised: 09 July 2024, Accepted: 12 July 2024

ABSTRACT: Local scour depth around bridge piers is time-dependent. It develops asymptotically towards the equilibrium depth of scour under clear-water scour. Scour is the major cause of bridge pier failure. Many equations are available for predicting temporal and equilibrium scour depth. The present study discusses the phenomenon of temporal scour depth variation at wide bridge piers and deals with the techniques for its estimation. Two types of pier shapes (circular and rectangular) were used to collect the data. The rate of local scour, observed for different pier widths and sediment sizes, was recorded. The data indicates that 50% of the equilibrium scour depth (0.5dse) is achieved at a variety of times, which range from 0.7% to 11%, according to the sediment coarseness values. Similarly, 80% of the equilibrium scour depth develops in a time-varying from 10% to almost 50% of the equilibrium time. The upper limit curve for all the data is also presented.

Keywords: Temporal Development, Local Scour, Equilibrium Time, Wide Pier

1. INTRODUCTION

The variation in time of local scour at bridge foundations is a crucial aspect of hydraulic engineering [1]. Recent research has emphasized the importance of temporal scour evolution rather than equilibrium scour depth [2], [3]. Numerous studies on abutments and simple and complex structures have been conducted. Similarly, the majority of equations related to scour depth found in the existing literature primarily focus on the phenomenon of local scour occurring around typical piers.

The depth of local scour around bridge piers varies with time [4]. It approaches the equilibrium depth of scour under clear-water scour asymptotically [5]. Under live-bed conditions, equilibrium depth is reached more rapidly, and scour depth thereafter oscillates due to the movement of bed features past the pier [6]. This condition is depicted clearly in Fig. 1, along with the equilibrium time, te, for the development of the equilibrium scour depth. The dashed lines represent the temporal average scour depth under conditions of a live bed and clear water.

In order to achieve equilibrium conditions of clear-water scour depth development around bridge piers, experiments must be run for several days. Data obtained after shorter times, say 10 to 12 h, can exhibit scour depths less than 50% of the equilibrium depth [6]. Melville and Chiew presented the observation that many laboratory data describe the temporal development of local scour at narrow circular bridge piers (of diameter D) under clear-water conditions [5]. The results are shown by the curves, which indicate that local scour depths at the same point of development (t/t_e, where h_e is the time to develop the equilibrium depth of scour) decrease at lower values of U/Uc. Additionally, [7] concluded that both t_e and d_{se} are subject to similar influences of flow and sediment properties. The scour depth after 10% of the time to equilibrium is between about 50% and 80% of the equilibrium scour depth, depending on the approach flow velocity. Melville shows the dependence of a (dimensionless) equilibrium time scale t* (=U_{te}/b) on flow shallowness (y/b), flow intensity (U/U_c), and sediment coarseness (b/d_{50}) [8].

Oliveto et al. suggested incorporating the effect of the densimetric particle Froude number into the temporal development of scour depth [9]. Their equation was verified using the existing literature data from [5], [10-12]. Based on the sediment transport theory of [13-15] a method for computation of the temporal variation of scour depth around a circular pier. The mixing layer, which refers to the layer that the materials can be entrained from by the flow, was utilized to compute the ds in non-uniform sediment. The regression analysis of the time-dependent scour rate obtained from the laboratory work was used to formulate the scour depth evolution for non-uniform sediment [16]. However, the data and the formulations upon which the time-development relationships are based do not take into account shape or alignment, nor do they adequately account for values of b/y and b/d_{50} in the ranges found for wide piers, and therefore are of questionable validity when scaled, or applied, to wide and long skewed piers [8].

However, recent publications [17-20] argue that pier-scour depth must be very long to reach equilibrium. The reported subjectivity has important implications for the design of scour experiments. Assuming that equilibrium scour exists, but that it is not reached in a finite time, the question is, “How long should experiments be until the scouring rate becomes insignificant or practically null and scour depth is close enough to its ultimate value?” In an attempt to answer the previous question, [20] conducted six very long experiments on local scour at single cylindrical piers. They found that the equilibrium scour depth cannot be specified, in general, for experiments shorter than one to two weeks. The effect of sediment coarseness on long duration clear water scour also had been observed by [18] and they noticed that the equilibrium scour depth decreases with $b=d_{50}$, for $b=d_{50}>\sim100$, corroborating the findings of [21-24], which implies refuting the classical assumption according to which the equilibrium scour depth would not depend on $b=d_{50}$ for $b=d_{50}>\sim25$.

Therefore, investigation on the relationship between scour temporal and the equilibrium scour depth around wide piers is crucial and will give a better understanding on the temporal scour evolution.

The objective of this research was to clarify the effect of time on the development of scour depth at wide bridge piers under clear water conditions.

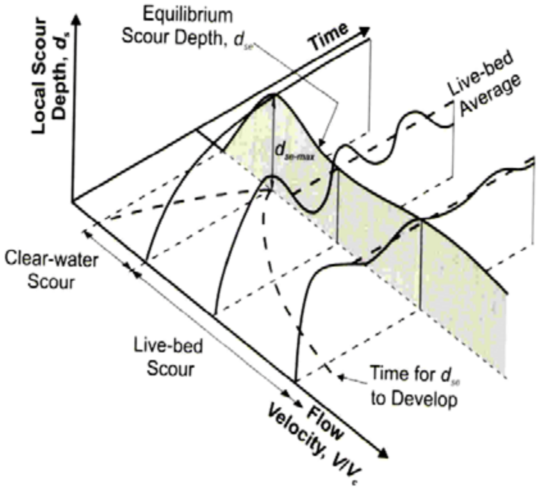


Fig. 1 Variation of local scour depth with flow velocity and time. (Source: [9])

2. RESEARCH SIGNIFICANCE

Scour at bridge piers are time-dependent. However, temporal evolution of scour at wide piers may show significantly different trends due to their sizes and the successive exposure of pier components during the scouring process. In this case, considering the limited data and lack of research on scour evolution at wide piers, it is not possible to predict the time-dependent scour pattern with confidence for prototype piers in the field, where there is typically some pier width and scour holes are not fully developed. Therefore, the significance of this study is to obtain more experimental data, speculatively describing how the scour hole forms at wide piers and investigating the relationship between scour temporal evolution and the equilibrium scour depth at two types of uniform bed cohesionless sediment.

3. EXPERIMENTAL FACILITIES

3.1 Flume Characteristics

The test channel was 50 m long, 1.5 m wide and 2.0 m deep, provided with glass and brick walls. The flume features a working section in the form of a 10-m-long recess that was filled with sediment to a uniform thickness of 0.4 m. The sand-bed recess was located 13.5 m downstream of the flume inlet, with the test models installed in the middle of the sediment recess, 17.5 m downstream of the flume inlet. An adjustable tailgate controlled the water level within the flume.

A 60-kW centrifugal variable speed pump supplied a flow rate of 0·14 m3/s through a 250 mm diameter pipe to the flume. A valve at the pipeline was used to control the discharge and water was supplied by the pumping system upstream of the flume.

Before each experiment, the sand bed was leveled and the flume carefully filled with water so as not to disturb the planar bed. The flow depth was maintained at 0.25 m for all of the experiments. Flow-velocity readings were measured using an area velocity module that was located on the streambed, upstream from the experimental area.

A vertical point gage with 0.1 mm precision on the vernier scale was used to measure scour depth. In order to get a smooth flow transition, ramps located at the beginning and end of the sand bed recess were constructed with a slope of 1:5 (vertical: horizontal).

3.2 Tested Material

Cohesionless uniform sediments were used as bed material with median particle sizes, d_{50} = 0.23 and 0.80 mm, and geometric standard deviation, σ_g = 1.3 and 1.26, respectively (Table 1). The critical shear velocity, U*c, and critical flow velocity, Uc, for sediment entrainment, were determined based on expressions given in [6].

The experiments were performed under clear-water conditions at threshold flow intensity U/Uc ≈ 0.95, i.e. the flow intensity inducing maximum local scour depth, in which U is average approach flow velocity. Two types of pier shape were selected and five different pier diameters for each pier shape, 0.06, 0.076, 0.102, 0.140, and 0.165 m, were chosen for this study.

Table 1 Sediment characteristics of the tested material

Material	d_{16} (mm)	d_{50} (mm)	d_{84} (mm)	σ	sf
S1	0.2	0.23	0.3	1.30	1.0
S2	0.65	0.80	1.1	1.26	1.0

*Note: *sf= shape factor*

3.3 Experimental Procedure

The experiments were conducted until the equilibrium local scour depth was observed, where the rate of change in the scour depth did not exceed 5% of the pier diameter in the succeeding 24-hour period [5]. Scour depth measurements were recorded at intervals of 10 minutes for 1 hour, followed by readings at intervals of 30 minutes for 2 hours and then every 1 hour for 24 hours or more.

4. RESULTS AND DISCUSSIONS

4.1 The Temporal Development of Scour Around Piers

Local scour is a dynamic process for which the time scale of scour evolution is related to the size and strength of the local flow structure that causes the local scour as well as the particle size of the bed sediment. For varying pier width and sediment size, the depths of local scour should be compared with similar stages of scour development. For given piers and sediment sizes, the developments of scour were presented in terms of time. The rate of local scour, observed for different pier widths and sediment sizes, was recorded.

To investigate the effects of scour depth on temporal variation of local scour around wide piers, different values of b (pier width) were chosen in this study. The experimental data and flow condition are given in Table 2. The shapes of the scour holes for each pier shape for the two tested sediments after the flume was drained are shown in Fig. 2 to Fig. 5. They show that the larger the pier width, the wider the scour hole width became.

4.2 Temporal Variation of Local Scour at Wide Piers

Local scour is a dynamic process for which the time scale of scour evolution is related to the size and strength of the local flow structure that causes the local scour as well as the particle size of the bed sediment. For the value of parameter U/Uc = 0.95, the temporal development of local scour, ds using different sizes of uniform bed sediment and pier shapes are shown in Fig. 6(a)–(e) and Fig. 7(a)–(e). When all the data in the present study were merged with laboratory local scour data from the literature, the temporal variations were clearly shown in different in different stages, as presented in Fig. 8. In this figure, only data that had b/d_{50}> 50 were chosen where they corresponded to the wide pier category as stated by [9]. Three stages of local scour – (i) the initial stage, (ii) the main erosion stage, and (iii) the equilibrium stage – are described separately in the following sections.

The initial stage corresponds to the formation of

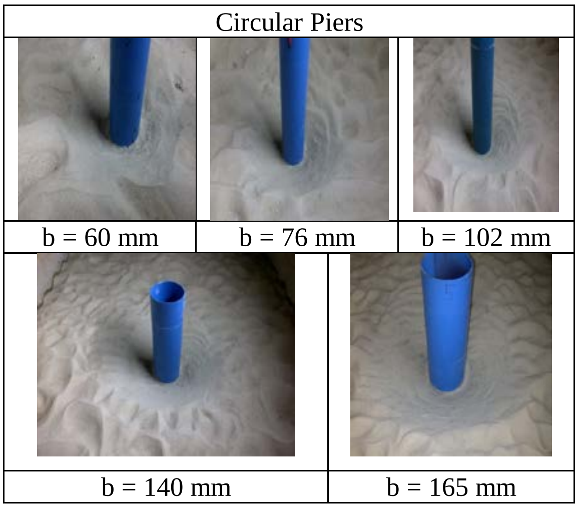

Circular Piers
b = 60 mm
b = 76 mm
b = 102 mm
b = 140 mm
b = 165 mm

Fig.2 Scour around the circular piers for d_{50} = 0.23 mm

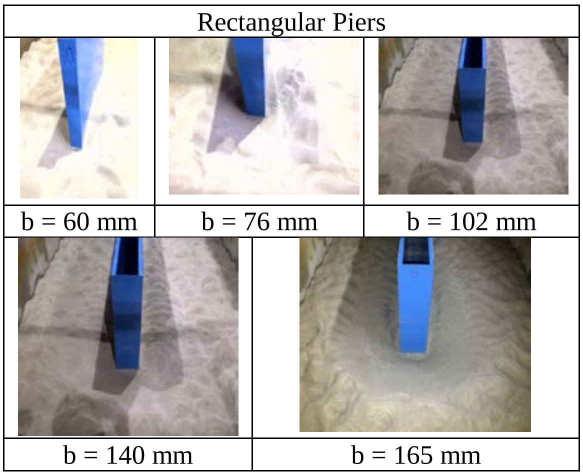

Rectangular Piers
b = 60 mm
b = 76 mm
b = 102 mm
b = 140 mm
b = 165 mm

Fig. 3 Scour around the rectangular piers for d_{50} = 0.23 mm

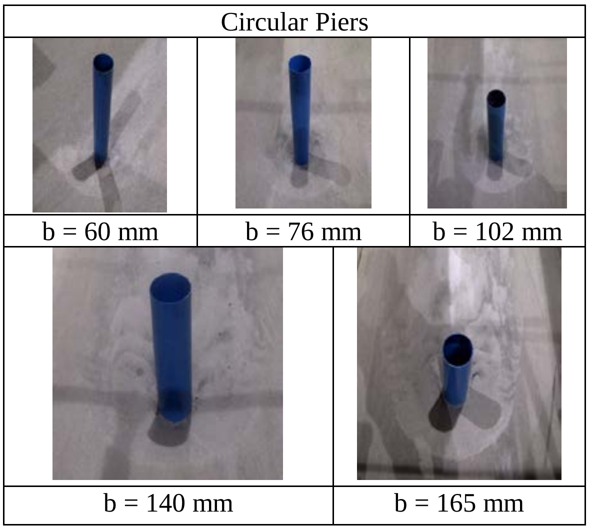
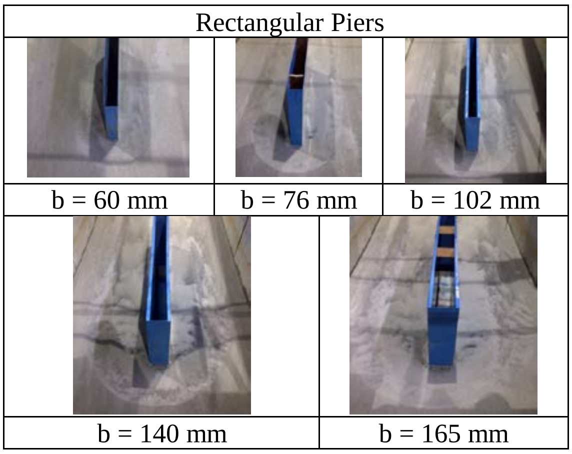

Circular Piers
b = 60 mm
b = 76 mm
b = 102 mm
b = 140 mm
b = 165 mm

Fig. 4 Scour around the circular piers for d_{50} = 0.80 mm

Table 2. Experimental data for wide piers

Run	Pier width	Sediment d_{50}		Water Depth	Flow		Test Duration	Eq. scour depth	Dimensionless parameter		
					Velocity	Critical Velocity					
	b (m)	mm	σ_g	y (m)	U (m/s)	U_c (m/s)	(h)	d_s (m)	b/d_{50}	ds/b	Sh
1	0.165	0.23	1.30	0.25	0.27	0.285	23	0.197	717	1.19	C
2	0.140	0.23	1.30	0.25	0.27	0.285	23	0.167	609	1.19	C
3	0.102	0.23	1.30	0.25	0.27	0.285	22	0.125	443	1.23	C
4	0.076	0.23	1.30	0.25	0.27	0.285	22	0.106	330	1.39	C
5	0.060	0.23	1.30	0.25	0.27	0.285	13	0.071	261	1.18	C
6	0.165	0.80	1.26	0.25	0.27	0.285	18	0.182	206	1.10	C
7	0.140	0.80	1.26	0.25	0.27	0.285	20	0.133	175	0.95	C
8	0.102	0.80	1.26	0.25	0.27	0.285	19	0.116	128	1.14	C
9	0.076	0.80	1.26	0.25	0.27	0.285	17	0.073	95	0.96	C
10	0.060	0.80	1.26	0.25	0.27	0.285	13	0.065	75	1.08	C
11	0.165	0.23	1.30	0.25	0.36	0.380	21	0.257	717	1.56	R
12	0.140	0.23	1.30	0.25	0.36	0.380	20	0.196	609	1.40	R
13	0.102	0.23	1.30	0.25	0.36	0.380	20	0.159	443	1.56	R
14	0.076	0.23	1.30	0.25	0.36	0.380	20	0.125	330	1.65	R
15	0.060	0.23	1.30	0.25	0.36	0.380	13	0.089	261	1.48	R
16	0.165	0.80	1.26	0.25	0.36	0.380	25	0.244	206	1.48	R
17	0.140	0.80	1.26	0.25	0.36	0.380	21	0.185	175	1.32	R
18	0.102	0.80	1.26	0.25	0.36	0.380	21	0.148	128	1.45	R
19	0.076	0.80	1.26	0.25	0.36	0.380	20	0.105	95	1.38	R
20	0.060	0.80	1.26	0.25	0.36	0.380	14	0.090	75	1.50	R

Note: Sh = pier shape


Rectangular Piers

b = 60 mm
b = 76 mm
b = 102 mm
b = 140 mm
b = 165 mm

Fig. 5 Scour around the rectangular piers for d_{50} = 0.80 mm

the scour hole from the flat-bed condition. From the observation, the maximum depth of local scour initially formed at the sides and gradually moved to the leading edge or pier nose as the scour hole formed. The main erosion stage is characterized by the straight-line sections (on the log-normal plot) which describe the development of the scour hole up to its equilibrium stage. The equilibrium stage occurred when little or no change in scour depth was recorded with time. The analysis of the data is accompanied by some photographs which illustrate the development of local scour for two types of piers in two sizes of uniform sediments as shown in Fig. 2 to 5. Those experiments were run within the same duration as the present study. The durations ranged from 24 to 29 hours.

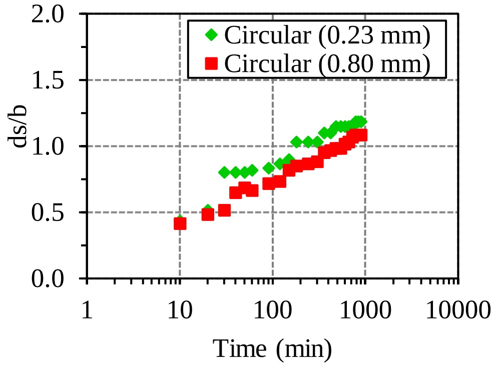
4.3 The Effect of Equilibrium Time on Local Scour Depth

To clarify the effect of equilibrium time on the development of scour depth around circular and rectangular piers under clear-water conditions, the results for twenty experiments with different pier widths and two types of uniform bed cohesionless sediment are presented. Fig. 9 shows the temporal development of the scour hole plotted for ds/dse versus t/te, with the sediment coarseness as a third parameter. In this plot, dse represents the scour depth at a particular time, t, while te is the equilibrium time. It shows a group of curves with the value of sediment coarseness, b/d_{50}, with a range from 75 to 717 for two types of uniform sediments around circular and rectangular piers. The data indicates that 50% of the equilibrium scour depth ($0.5d_{se}$) is achieved in a variety of times which range from 0.7% to 11% of te, according to the sediment coarseness values.

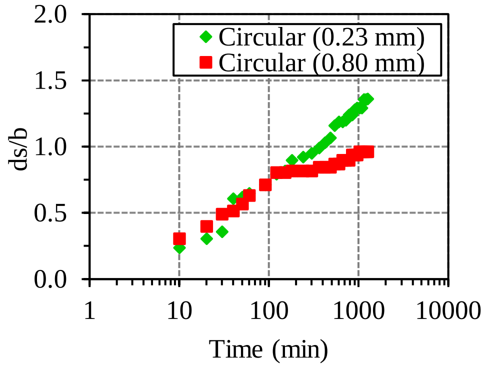
Similarly, 80% of the equilibrium scour depth develops in a time varying from 10% to almost 50% of the equilibrium time. The data depicts the significance of time in the estimation of scour depth. The data in Fig. 9 can also be represented by the following equation:

$$ds/dse = 0.067 * \ln(t/te) + 1.023 \quad (1)$$

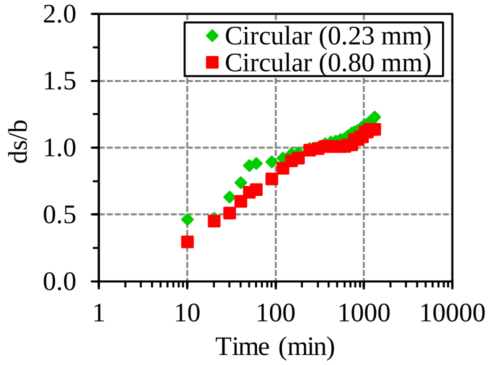
which is plotted in Fig. 10 and represents the upper limit curve or general equation for all the data.



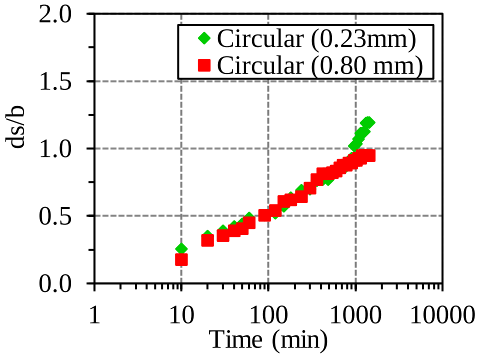
(a) Scour depth with time; b = 60 mm



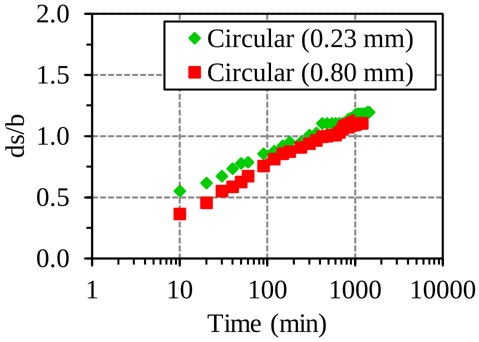
(b) Scour depth with time; b = 76 mm



(c) Scour depth with time; b = 102 mm

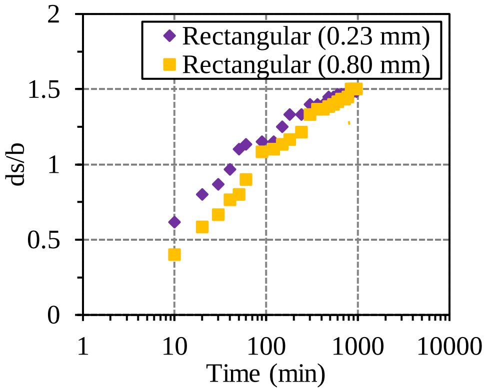


(d) Scour depth with time; b = 140 mm

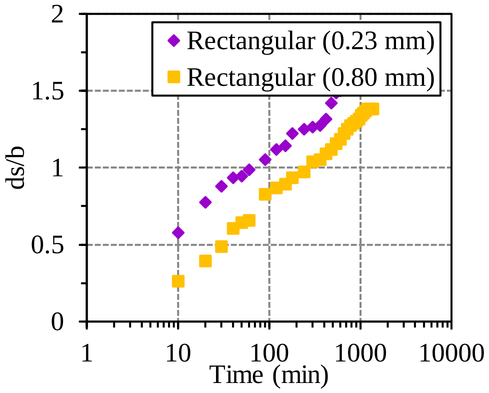


(e) Scour depth with time; b = 165 mm

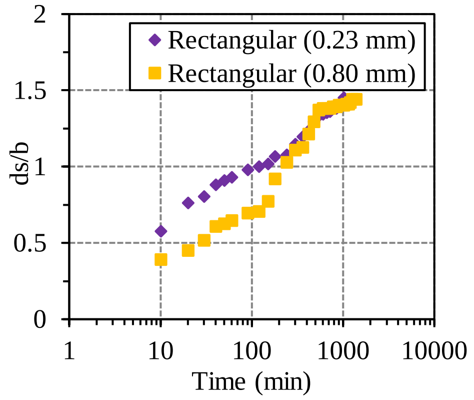
Fig. 6 Normalised local scour depth (d_s/b) versus time (circular piers) in a sediment bed of d_{50}=0.23 mm and d_{50}=0.80 mm



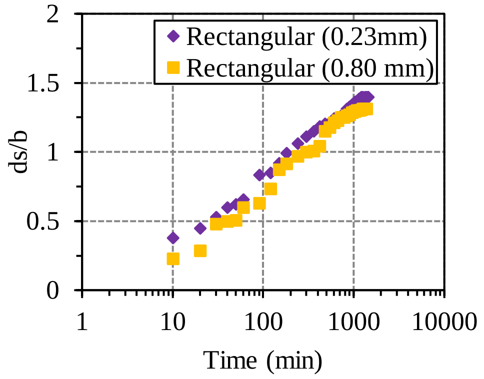
(a) Scour depth with time; b = 60 mm



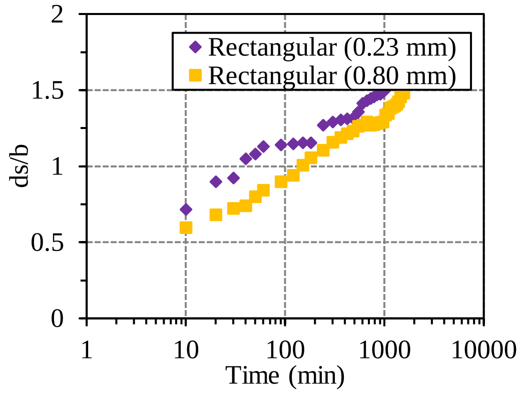
(b) Scour depth with time; b = 76 mm



(c) Scour depth with time; b = 102 mm



(d) Scour depth with time; b = 140 mm



(e) Scour depth with time; b = 165 mm

Fig. 7 Normalised local scour depth (d_s/b) versus time (rectangular piers) in a sediment bed of d_{50}=0.23 mm and d_{50}=0.80 mm

5. CONCLUSIONS

This study is limited to local scouring at wide bridge piers with values b/d_{50} from 75 – 717 in uniform bed sediments. The following conclusions are drawn in this study – (a) the shape of scour hole show that the larger the pier width, the wider the scour hole width became; (b) when all the data in the present study were merged with laboratory local scour data from the literature, the temporal variations were clearly shown in different stages: (i) the initial stage, (ii) the main erosion stage, and (iii) the equilibrium stage. Those experiments were run within the same duration as the present study. The durations ranged from 24 to 29 hours; and (c) scour depth 10% to almost 50% of the time to equilibrium, the scour depth values vary between about 50% and 80% of the equilibrium depth, depending on the sediment coarseness. The data can be represented in Equation (1) and is plotted in Fig. 8, which represents the upper limit curve or general equation for all the data.

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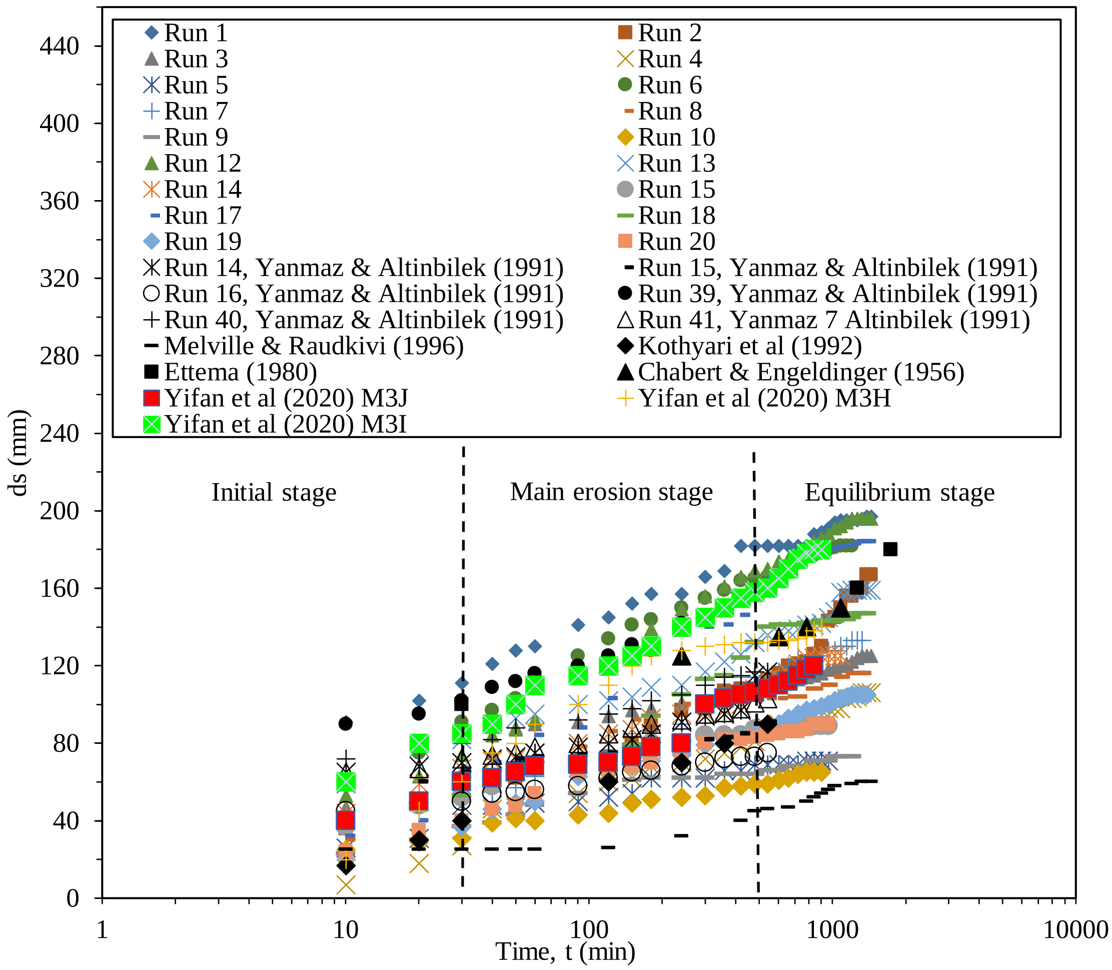

Fig. 8 Temporal variation of local scour depth at piers

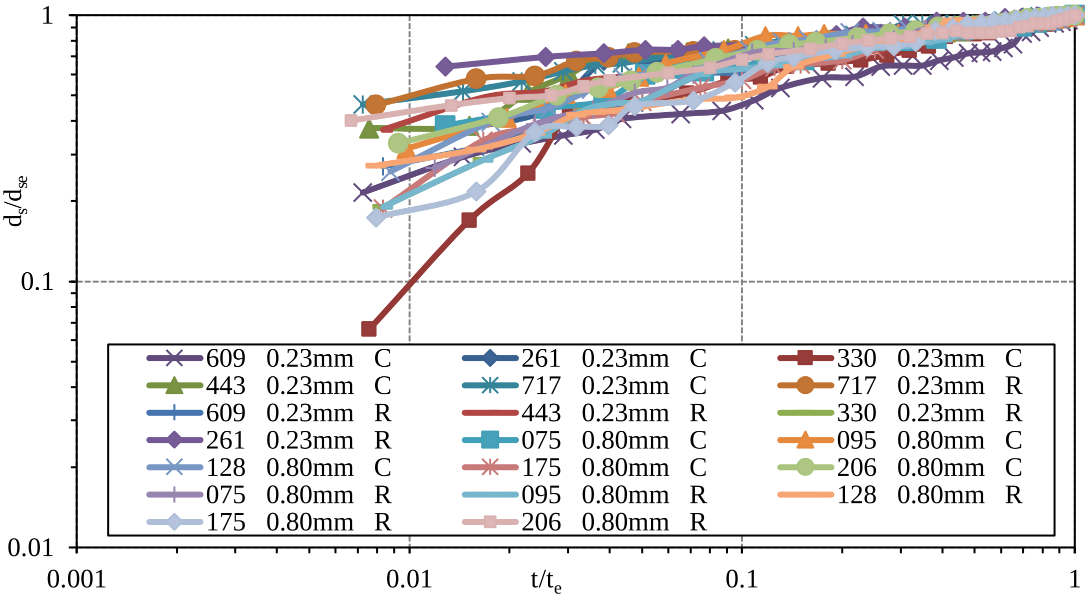

Fig. 9 New laboratory data showing the temporal development of scour depth

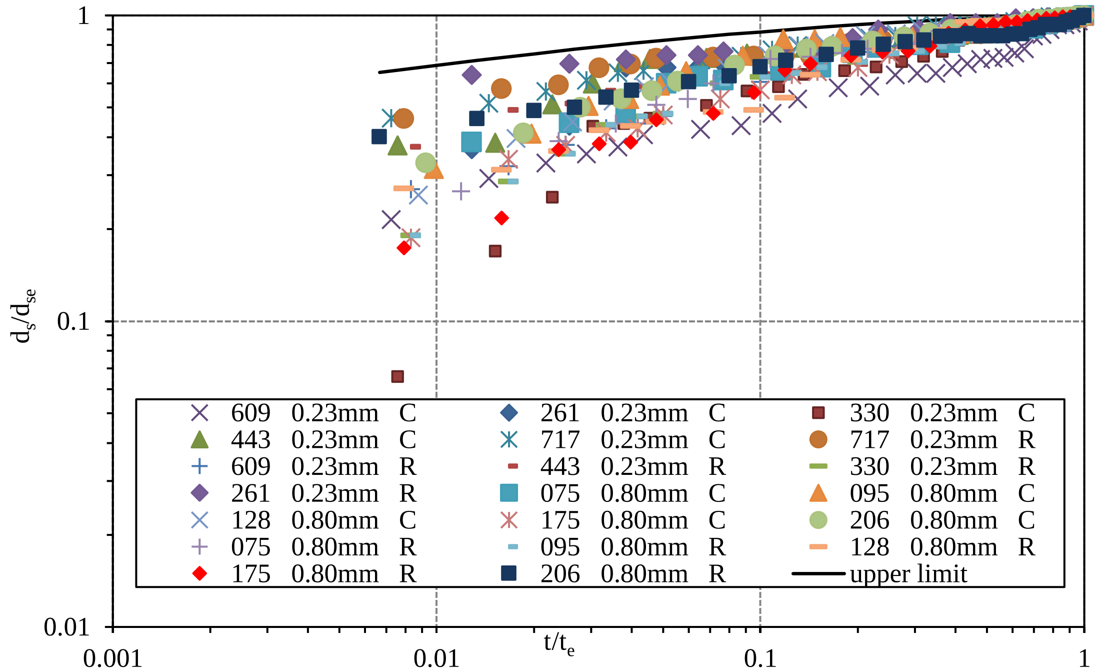

Fig. 10 Plot of Equation (1) indicating temporal development of local scour depth for flow intensity U/Uc=0.95

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