J. Indian Water Resour. Soc.,
Vol. 38, No. 4,Oct., 2018

INTERFERENCE EFFECTS AROUND BRIDGE PIERS – A REVIEW OF PARAMETERS

Rahul[1] and Baldev Setia[2]

ABSTRACT

Bridges constructed in close proximity of each other are having significant effect on local pier scouring because of their mutual interference. Bridge scour is the removal of sediment such as sand and rock around the bridge pier. For the safe and economical design of a bridge, the scour around the bridge pier is required to be controlled. Water normally flows faster around piers making them susceptible to local scour. Researchers have performed various experiments to predict and control scour. In this paper a detailed review of work on scour around the bridge pier is presented including a discussion on fundamental parameters associated with the scouring process and the variability of the experimental set-up.

Keywords: *Bridge piers, flow conditions, time variations, Interference*

INTRODUCTION

Bridges over rivers and streams are an essential part of any road and rail communication network for safe and economical movement of men and material from one place to another. The bridges, by their presence obstruct the flow passage below them and the velocity and depth of flow undergoes changes which in turn disturbs the sediment at the bed of the stream. This disturbance is most experienced by the sediment close to the bridge elements and the sediment gets dislodged from its original location at the bed around the bridge piers. Removal of sediment from the sand bed around the bridge pier results in formation of a scour hole and this phenomenon is known as scouring. The scouring process commences as a result of three dimensional separations at the upstream edge of pier. This separation results in the formation of a vortex in a vertical plane which wraps around the pier at the sediment-pier interaction junction and looks like a horseshoe in plan. This horseshoe vortex system is responsible for scraping the material from upstream of the pier and releasing it in suspension at the rear of the pier thus causing scouring around the pier, Setia (1997).

LITERATURE REVIEW

The phenomenon of scouring around a single pier has been studied by many researchers and its details have been well established. The various parameters of scouring like Mechanism, Scour depth, Depth of flow, Time variation, Velocity of flow, Froude number has been extensively studied by various researchers; i.e. Breussers et al (1977), Breussers and Raudkivi (1991), Melville and Coleman (2000), Hannah (1978) and many others. List of investigators from India includes Kothyari, Garde, and Rangaraju (1992a), Muzzammil et al. (2000), Dey and Raikar (2007), Setia (1997), Beg (2002) and others. From time to time the works have been duly reviewed by individual authors and task force committees. In the recent phase, the researchers have shown concern towards bridges constructed in close proximity and hence interfering in the flow modification zone of each other. Timonoff (1929) was perhaps the first known researcher to have worked on interfering bridge elements. He performed a model study to investigate the importance of stream wise spacing of bridge pier in the case of parallel bridges. Based on the observed sheltering effect of upstream pier on the downstream pier he recommended that new bridge piers should be located in the immediate proximity of old piers and axially aligned. Similarly, Tison (1940) carried out a model study to investigate the lateral spacing of piers, placed in side by side arrangement, on scour depths. He found no mutual interference on maximum scour depth for $Z_c > 4.3$, where in Z_c is the lateral spacing of piers measured from centre to centre.

Despite the fact that most of the works have been experimental studies carried out in the laboratory, yet the conditions and geometry of the setup is highly varying. Setia (1997) sum up some of the desirable conditions of experimental set up from the literature. The present paper analyses the works associated with interference effects and compares them on the bench mark of suggested guidelines of experimental schematic. The significant works of some of the researchers are being discussed below:

The work by Hannah (1978) is a land mark in the works associated with interference studies as the author not only presented the results based on observations but also came up with the mechanism of flow in the presence of more than one pier.

Hannah (1978)

The Author studied local scour at group of cylindrical piles with steady uniform flow and clear water conditions. A series of tests was first performed on single piles and for a oblong pier (Length: width = 6:1) with semicircular ends to provide a basis against which scour at pile groups could be evaluated. Tests showed that scour depths were 80 % of equilibrium scour depths after seven hour only minor changes occurred in scour and deposition patterns. The author, based on his experimental observation established

1 *Ph.D scholar, Civil Engineering Department, National Institute of Technology, Kurukshetra, India*

2 *Professor, Civil Engineering Department, National Institute of Technology, Kurukshetra, India (email:setia_b@rediffmail.com)*

Manuscript No. 1495

from types of mechanisms which he described as Reinforcing, Sheltering, Shed vortices and Compressed horseshoe vortex.

Nouh (1986)

The author has presented the results of an experimental study on two piers placed side by side at a spacing of 0.5, 1, 2, 4 and 6 times the pier diameter. The pier diameter was changed in each test to provide a constant relative pier group size with respect to the channel width throughout the tests. The author observed that when spacing between the piers increased beyond the piers showed independent behaviour.

Vittal et al. (1995)

The authors used a solid cylindrical pier of diameter b and then replaced it by a group of small piers of diameter 0.302 b each. The piers placed at an angular spacing of 120^0. The size of the smaller piers was such that any one of them could pass through the gap between the other two. Four different sediment sizes ranging from 0.775mm to 1.844mm median diameter were used. The scour at the pier group and pier of diameter of the circumscribing circle was determined under identical flow conditions. It was found that the relative scour ratio was about 0.61.

Goddu Prasada Rao (1997)

The author has conducted an experimental study on three different arrangements, i.e. tandem, side by side and staggered. From the experimental observations it concluded that with the increasing separation between the piers the front pier experiences the maximum scour depth at X/D = 2.0 and thereafter decreases up to X/D = 5.0. The scour depth remains fairly constant for X/D > 5.0. Here X is defined as the clear spacing between the cylindrical pier arrangements. In case of equilateral or staggered arrangement the scour reaches maximum at S/D = 1, and then it decrease at S/D = 3. When S/D > 5.0, the scour depth remains constant. In second case, the scour depth of the downstream pier (left and right) was plotted against spacing between the piers (S/D) for the flow condition Fr = 0.17 to 0.18. It is found that, the scour depth in the initial stages increases from S/D = 0 to 1.0. The scour reaches maximum at S/D = 1.0, then it decrease up to S/D = 3.0 and thereafter increase up to S/D = 4.0. When S/D > 4.0, the scour depth remains constant. The scour depth on the downstream pier is more than the upstream pier.

Mubeen Beg (2002)

Mubeen Beg (2002) studied the effects of mutual interference on local scour due to the presence of a group of piers. A series of clear water scour experiments under steady uniform flow conditions had been conducted considering different configurations of pier arrangements and equations have been developed for the estimation of scour depth at a group of piers. The author observed that initially when L/D is zero the scouring rate was very high. The piers showed continuous increase in scouring depth up to a spacing (L/D) of eight times diameter of pier. After that it started to decrease meaning that the piers showed independent behavior after a spacing of eight times the diameter of pier. Here L is the spacing in between the piers and D is the diameter of pier.

Ishwar Chand (2002)

The Author observed that due to urbanization, bridges in close proximity are likely to increase. In such conditions of close proximity of bridges, if a pipeline has also to cross the alluvial river, the various structures will have a bearing on the scouring characteristics of each other. To study the effect of such interference, a set of six experiments was carried out. The author observed that as the pipeline is made to move towards the downstream, initially the scour at the downstream end of the pier is more but it goes on decreasing as the distance between the pipeline and the pier increases. When the distance between pier and pipeline reaches to about four times the diameter of the pier then both the pier and pipeline make their own zone of scour.

Neshat Movahedi; Amir Ahmad Dehghani; Mohammad Javad Aarabi and Abdul Reza Zahiri (2013)

This study focuses on temporal variation of scour depth around two side-by-side piers with varying distances between them. The results showed that good agreement exists between proposed equation and measured scour data. It is also revealed that by increasing the distance between piers, the equilibrium scour depth around side-by-side piers decreases and is close to that of a single pier and scour depth reached to the isolated pier when L/D=6. Here L is the spacing in between the piers and D is the diameter of pier.

Mubeen Beg (2014)

Mutual interference of a group of two bridge piers of unequal sizes placed in tandem arrangement at varied pier spacing under steady, uniform flow and clear water scour conditions was discussed in the study. From the experimental study, the author observed that the maximum scour depth at the 66 mm front and 33 mm rear piers were 1.86 and 1.353 times the scour depth in comparison to a 33 mm isolated pier at x/b = 10 and x/b = 0. The scour depth at 33 mm rear pier is minimum (0.57 times to that of 33 mm isolated pier) at x/b = 35. Here x is the spacing in between the piers and b is the diameter of pier.

Malik and Setia (2014)

The Authors have experimentally studied the behaviour of closely placed bridge pier models in tandem and side by side arrangement. It had been found that piers of bridges in close proximity tend to interfere with the scour behaviour of each other in both types of orientations. From the experimental observations it was concluded that when the spacing between the piers is 1.5D (D = Diameter of pier), the piers showed an independent behaviour. After that piers do not affect the behavior of each other. The effect is more noticeable in the tandem arrangement because when the spacing is up to sixteen times the diameter of bridge pier, the two piers behave like an individual pier beyond which the scour depth is equal to that of an isolated bridge pier.

Malik, Ravish, and Setia (2014)

The authors studied closely placed bridge pier models using wet paint technique on rigid and mobile bed (d_{50}= 0.18mm) using 30mm and 50mm cylindrical piers. Besides the side by side and tandem arrangements, a staggered pattern in two rows of piers was studied. In staggered arrangement the piers in the second row showed fluctuating but rising trend of scour depth.

Khaple (2017)

The author had studied the local scour at a group of cylindrical piles of size, b 6cm and 8.2cm with a steady uniform flow under clear water conditions. Author observed that for three piers in staggered arrangement, the scour depth at the downstream piers for the stream wise spacing less than 8b and for narrow lateral spacing 2b is greater than that at the isolated single pier owing to the effect of wake vortices. As the radial distance between the upstream and downstream piers increases, the scour depths at downstream piers decrease. In this arrangement, as the lateral spacing L between the downstream piers increases, the equilibrium scour depths at downstream piers decrease. Further, as the center-to-center stream wise spacing S between upstream and downstream piers increases, the scour depths at the downstream piers decrease and attain approximately the same scour depths occurring at the upstream pier at a stream wise distance equal to ten times and lateral spacing twice the size of the pile.

Melville et al. (2017)

The authors studied the estimation of scour depths at upstream and downstream pier for two piers in line. They concluded that the scour at the upstream pier always exceeded that at the downstream pier and the maximum scour depths for two in line piers occurred at a spacing of L/D equal to 2.5 and it was 22% higher than that of the single pier case. For L/D > 2.5, the maximum scour depths at upstream pier decreased and become equal to that at a single pier at L/D approximately equal to 10. At L/D = 1, i.e. the two pier in tandem arrangement touching each other, the maximum scour depth at upstream pier was equal to that for the single pier. When 1 < L/D > 2.5 then the maximum scour depth at upstream pier increases rapidly as the spacing between the two in line piers increases.

A comprehensive review of the up to date studies on various scour parameters is presented below. For the sake of convenience the authors have been assigned some notations which is given in Table 1.

Table 1: Summary of the Works of Various Researchers

Author	Notation for authors	Type of work	Size of pier (D) mm	Mean sediment size (d_{50}) mm	Velocity of flow (V) m/s	Depth of flow (d) (cm)	Size of flume (l:.b:.h)	Duration of run (T) (Hours)	Non dimensional depth of flow (d/D)	Froud number (Fr)
B W. Melville & Arved J Raudkivi (1977)	B & A	Flow characteristics	50.8	0.385	0.25	15	19:4.56:4.4	-	3	0.21
Y.M Chiew & B.W. Melville (1987)	Y & B	Scour	31.8	1.45	-	17	11.4:0.44:0.38	1.6	5.3	-
U.C Kothyari et.al (1991)	U	-	-	0.71	-	-	03:0.1:0.6	-	-	-
Setia (1997)	sa	Scour protection and Mechanism	11.5 to 165	0.16	0.17 to 0.20	-	27:0.9:0.35	100	1.13 to 16.26	0.12 to 0.15
J. K Kandasamy & B.W Melville (1998)	J	Scour	-	0.9	-	30	19:045:0.44	-	-	-
Mubeen Beg (2002)	M	Tandem	33	1.0	0.226	14	75.6cm wide	-	4.2	0.19
S.A Ansari et.a) (2002)	S	Cohesion around pier	112.5	0.27	0.21 to 0.41	5 to 18	03:01:06	30	1.6	0.36
W.H Graf & Istiarto (2002)	W & I	Scour		2.1	0.45	18	-	120 to 168	1.2	0.34
Stephen E. Coleman et. al (2003)	S&C	Scour	-	0.82	0.37	-	-	-	-	0.33
Amir R. Zarrati et. al (2004)	A	Protection	50	1	0.05 m^3 Discharge	19.5	12:0.08	-	3.9	-
Zhao- Yin Wang (2010)	Z	Scour rate and inertia	12	12	-	16.5 to 19.1	10:0:0.5:0.5	-	15.9	-
Padmini Khwairakpam et.al (2012)	P & K	Scour prediction	50	0.365	-	6 to 8	10:0.81:0.60	28	1.6	-
Behzad Ataie Ashtiani (2012)	B	Single pier	91	0.71	0.354	30	15:01:03	72	3.2	0.21

Author	Notation for authors	Type of work	Size of pier (D) mm	Mean sediment size (d_{50}) mm	Velocity of flow (V) m/s	Depth of flow (d) (cm)	Size of flume (l:.b:.h)	Duration of run (T) (Hours)	Non dimensional depth of flow (d/D)	Froud number (Fr)
Abolfazal Aslani Kordkandi (2012)	A & K	Tandem	91	0.71	0.346	26	15:01:03	72	2.8	0.22
Alessio Radice & Chau K. Tran (2012)	A & C	Scour	72	-	0.30	-	5.8:0.40:0.16	-	-	-
Gangarudraiah veerappadevaru et. al (2012)	G	Vortex	-	0.65	-	-	9.5:0.54:0.36	10	-	-
Baldev Setia & Upain Kumar (2013)	B & U	Protection	80, 82	0.16	0.31	-	27:09:0.35	10	-	
Neshat Movahedi et.(2013)	N	Side by side	20	0.9	0.24	13	12:0.6:0.6	48	6.5	0.21
Reza Mohammadpur et. al (2013)	R &M	Local scour	-	0.6	-	9.7 to 11.0	6:0.6:0.6	24	-	-
Rahul Malik & Baldev Setia (2014)	R & B	Side by side	50	0.18	0.24 to 0.26	13.4 to 14.2	12:0.6:0.7	5	2.84	0.22
Rahul Malik & Baldev Setia (2014)	R & B	Tandem	50	0.18	0.24 to 0.26	12.9 to 13.4	12:0.6:0.7	5	2.68	0.23
Rahul et. al (2015)	R	Tandem Side by side, Staggered	50, 30	0.18	0.24	12.9 to 14.2	12:0.6:0.7	5	2.84, 4.7	0.2
Khaple et al. (2017)	Ka	Tandem, Staggered	60, 82	0.96, 1.8	0.34 to 0.47	16	15.5:0.91:0.70	36	2.6, 1.95	0.27, 0.37
Melville et al. (2017)	Ma	Tandem	55	0.85	0.26 to 0.34	11 to 16	19.0:0.61:0.6	75	2.0, 2.9	0.25, 0.33
Kai Tze Kho et. a	K	Single pier	25, 50	0.002 to 0.06	0.26 to 0.52	15	0.6:0.6:0.45	-	6, 3	0.43

COMPARISON OF EXPERIMENTAL PARAMETERS

Scouring around the bridge pier have been investigate by number of researchers using different parameters like velocity of flow, depth of flow, diameter of pier and using different type of sediments. However, there is a significant variation in the parameters adopted by the researchers.

Existing literature suggests the following guidelines on good experiment test conditions the point of view of pier diameter: (i) In order to minimize the error and scale effects from laboratory to field data, laboratory experiments should be conducted on as large a size of the pier as is feasible under the available test conditions. (ii) The diameter or width of the pier should be more than 50 times the median size of the sediment (Ettema, 1980; Chiew, 1984). The constriction ratio should be desirable be 10 or greater. The acceptable values should be such so as not to cause excessive blockage effects. (iii) The flow depth ratio d/D should be greater than 2.6 so as not to introduce any correction factor for scour depth (Shen, 1966; Ettema, 1980). In light of the above guidelines, various parameters used by different researchers in the past has been discussed below:

EXPERIMENTAL RUN TIME, T

Researchers referred to in literature have used different times durations like 72 hours (Chiew, 1992), 72 hours (Ashtiani, 2012), 100 hours and 10 hours (Setia, 1997), 6 hours (Vittal et al., 1995).

Experimental runtime employed by different researchers has been presented in Figure 1. The authors listed along the x-axis have been sorted to present the run-time in an ascending order. The minimum run-time employed by Chiew and Melville is 1.6 hours (100 minutes) and the maximum run-time is very obvious. A simple arithmetic mean 'T_m' of the run-times works out to be 42.9% and has been presented on the figure as a horizontal line. 42.9% of the researchers considered in the present paper have used time duration of more than the T_m value.

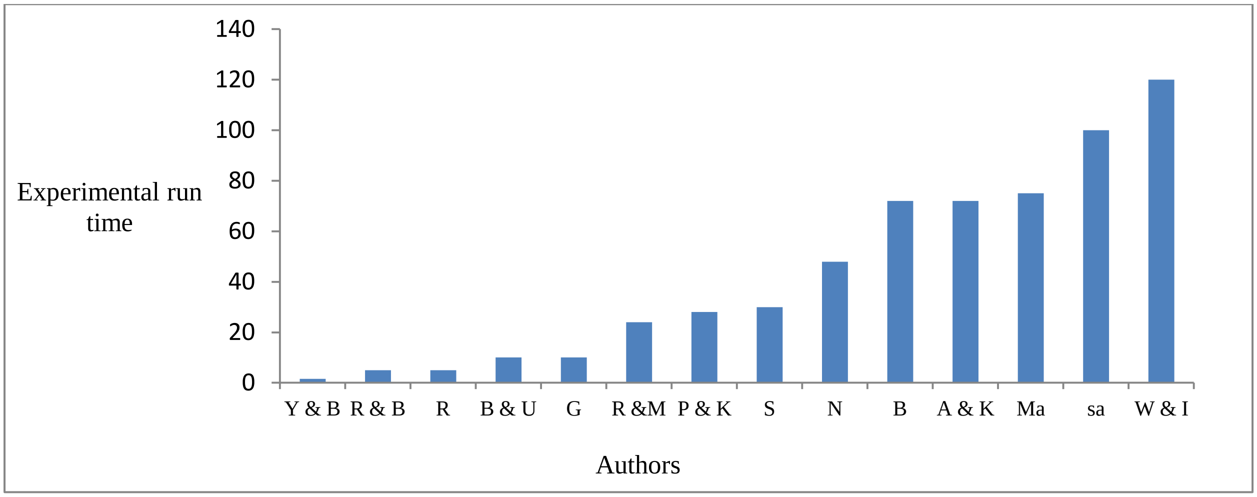

Figure 1: Variation in time of flow

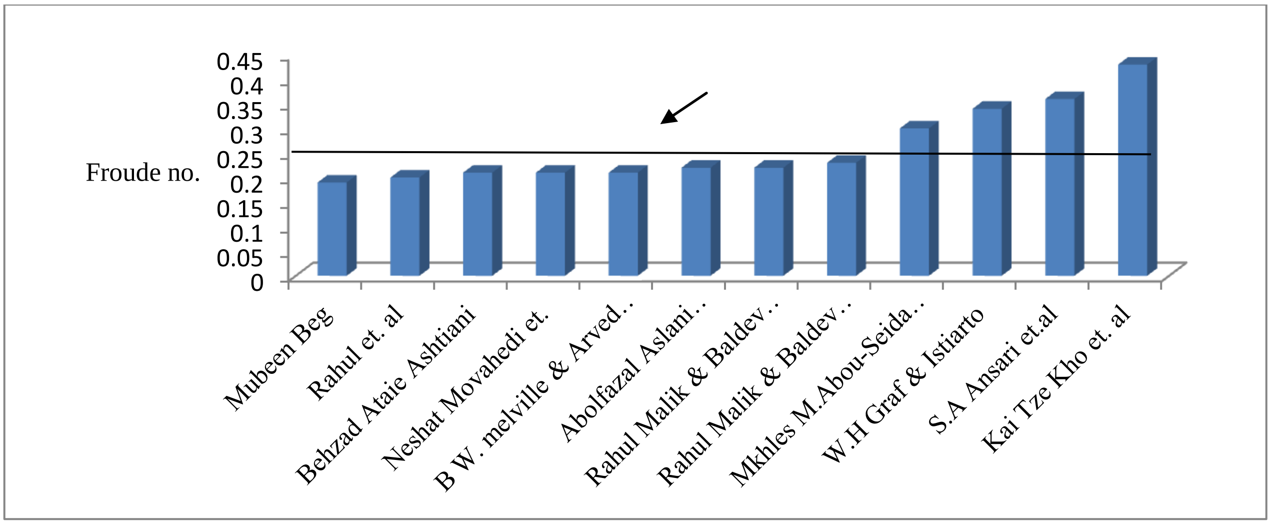

Figure 2: Variation in Froude number discussed by various researchers

FROUDE NUMBER, F_r

Froude number is also an important parameter in the fluvial hydraulics to find the type of flow whether it is critical, sub critical or supercritical. For the above discussion of froud number in the present paper, it has been computed as:

$$F_r = V/\sqrt{g\,h}$$

where V is the velocity, g is the acceleration due to gravity and h denotes the depth of flow w.r.t the average bed level. The Froud number occurring in different experimental studies of various researchers has been plotted in Figure 2.

Table 1 and Figure 2 show that researchers have worked on different Froude numbers. As per Figure 2, Kho et. al. had worked on the maximum value of Froude number (F_r = 0.43). Average value of Froude number in the present collection is 0.26, from which it can be concluded that 33% of researchers have worked above and 67% below the average value of Froude number.

VELOCITY OF FLOW, V

Under the clear water condition, the local scour increase almost linearly with the velocity to a maximum at critical velocity Shen et al (1966). Melville (1988) shown that as the velocity exceeds the threshold velocity, the local scour depth first increase and then decrease again. Melville and Coleman (2000) have defined the flow intensity as the ratio of the free stream flow velocity, *V*, to the critical flow velocity of the sediment; *Vc*. Based on the flow intensity, the local scour at piers can be classified as local scour under the clear water condition and local scour under the live bed condition.

Clear water scour occurs for the velocities up to the threshold condition, i.e. $V/Vc \approx 1$. In this condition, there is no supply of sediment to the scour hole; movement of the sediment materials occurs only around the obstruction like bridge piers. However, in the live bed scour condition, sediment is continuously supplied to the scour hole from upstream side. In live bed scour condition, the ratio *V/Vc* is greater than 1.

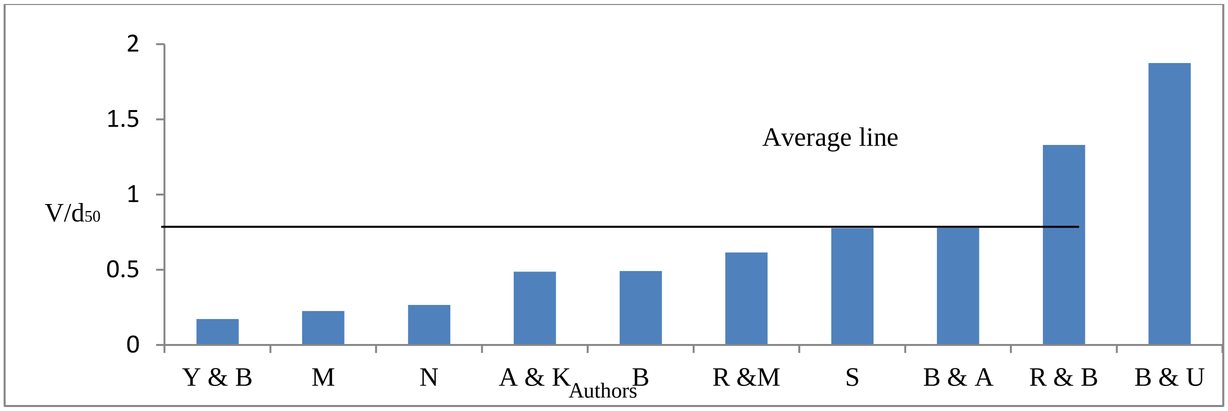

Figure 3: Variation in velocity of flow observed by the various researchers.

Table 1 and Figure 3 show that number of researchers has worked on different velocities to find the mechanism of scouring. Average value of velocity of flow non-dimensionalised with mean size of the sediment in present collection is 0.57, from which it can be concluded that 50% of researcher have worked above and 50% working below the average line as shown in Figure 3.

DEPTH OF FLOW, d

Depth of flow has been discussed under two subheads:

a) Depth of flow non-dimensionalised with diameter of pier (d/D).
b) Depth of flow non-dimensionalised with mean size of the sediment (d/d_{50}).

a) Depth of flow non dimensionalised with diameter of pier (d/D)

In order to minimize the effect of depth of flow on scouring, the ratio of depth of flow to the diameter of pier, d/D is to be kept more than 2.5 times diameter of pier (Chiew, 1984). The depth of flow non-dimensionalised with diameter of pier has been plotted and shown in Figure 4.

Figure 4 shows that there is a significant variation in non-dimensional depth of flow adopted by researchers during the experiments. The average value of non-dimensional depth of flow w.r.t diameter of bridge pier was found to be 4.2. From the observation presented in the Table 1 the 26.6% of researchers had worked above and 73.3% of the researchers worked below the average non dimensional depth of flow. So it can be concluded that 46.7% more researchers worked under the average value of non-dimensional depth of flow (d/D) in comparison to the other (D= Diameter of the pier). According to the suggested values of d/D 53.4% researcher were worked below and 46.6% above the suggested line.

b) Non-dimensional depth of flow, d/d_{50}

Number of researchers i.e. Movahedi (2013), Graf and Istiarto (2002), Melville and Chiew 1987), Zarrati et. al. (2004), Malik and Setia (2014), Malik et. al. (2015) and Wang (2010) have worked on bridge piers with different scouring depths. Laursen (1963) influenced by the lacey regime theory insists that for constant velocity, the depth of scour increase with increasing water depth. The depth of flow non-dimensionalised with mean size of the sediment has been plotted and shown in Figure 5.

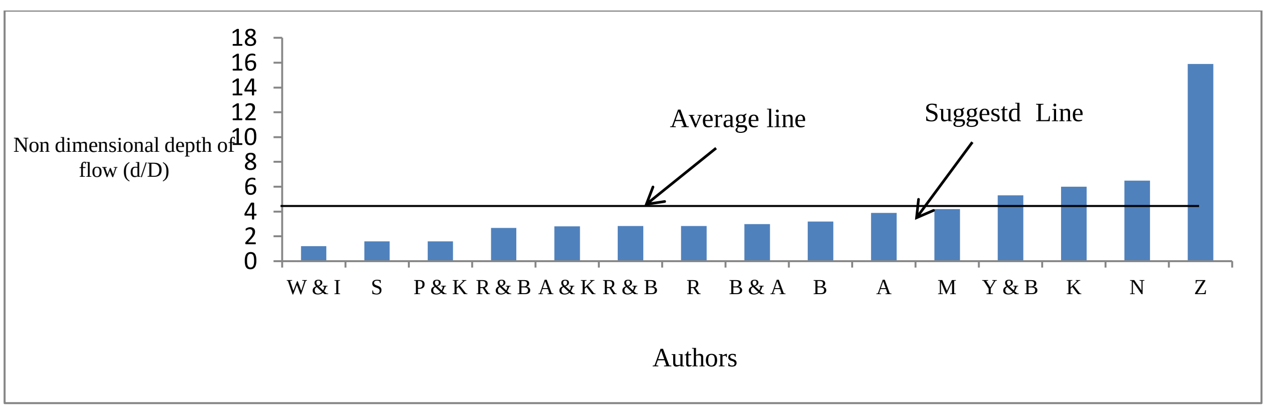

Figure 4: Variation in non- dimensional depth of flow w.r.t to diameter of pier (d/D)

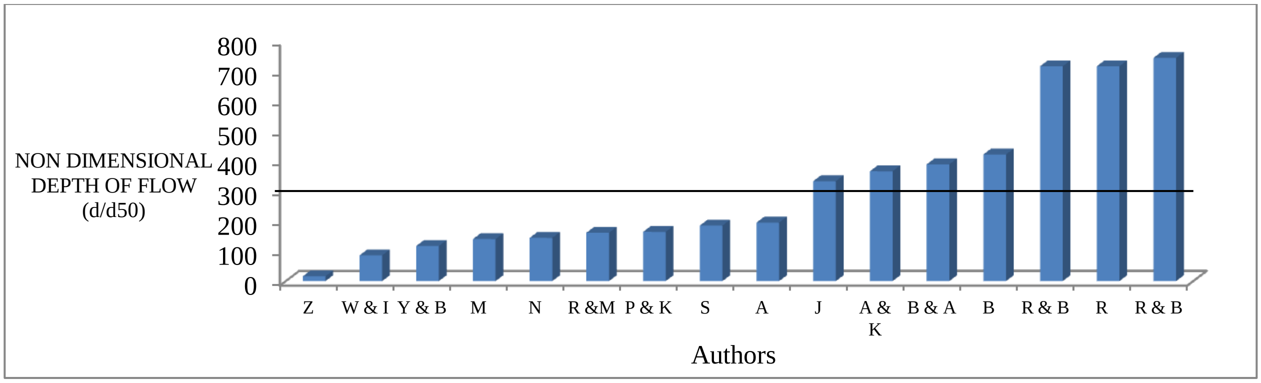

Figure 5: Variation in non-dimensional depth of flow observed by various researchers' w.r.t d_{50}

Table 1 and Figure 5 show that researchers have worked on different non-dimensional depth of flow w.r.t mean size of the sediment. Average value of non-dimensional depth of flow w.r.t mean size of the sediment was found to be 300.08. Thus, 43.75% of researchers have worked above and 56.25% researchers below the average value of depth of flow non-dimensionalised with mean size of sediment.

SEDIMENT SIZE, d_{50}

There is a suggested value of the size of the sediment in relation to the size of the pier. It has been suggested that the ratio of the size of the pier and the mean size of sediment should not be less than 75. Figure 6 shows the variations of diameter of the pier w.r.t mean size of the sediment in ascending order for different researcher on the subject.

It may be observed in Figure 6 that the values of D/d_{50} range from 10 for Zhao (2010) to 5000 for Setia and Bhatia (2013). Two horizontal lines have been introduced in the figure, one for the desired values of D/d_{50} equal to 75 and the other for average value of 1600. The average value of non-dimensional diameter of pier w.r.t to mean sediment size (D/d_{50}) is found to be 1600. Results showed that 31% of the researchers have worked above and 69% below the average line. According to the suggested values of D/d_{50} = 75, only 7.6% researchers have worked below and 92.4% above the suggested line. Figure 7 showed that the velocity of flow depends upon the diameter of pier.

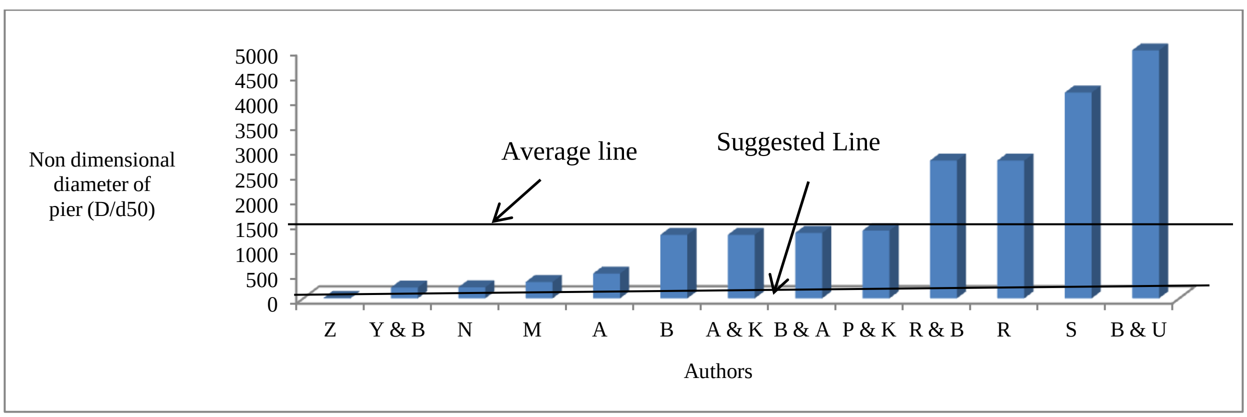

Figure 6: Variation in non-dimensional diameter of bridge pier w.r.t d_{50} (D/d_{50})
D= diameter of pier model, d_{50}= Size of the sediment

CONCLUSION

Broadly it may be seen and appreciated that though a significant quantum of work has been done on the subject of scouring around bridge piers, a relatively much lesser work has been done regarding their interference with each other. Further, there is a large variation in the use of different parameters adopted for experimentation. That makes it difficult to generalize the results obtain through such experiments. The other major conclusions of the study are:

- In case of experimental run time 38.5% of the researchers considered in the present paper have used time duration of more than the T_m value.
- Average value of Froude number in the present collection is 0.26, from which it can be concluded that 33% of researchers have worked above and 67% below the average value of Froude number.

- Average value of velocity of flow non-dimensionalised with mean size of the sediment in present collection is 0.57, from which it can be concluded that 50% of researcher have worked above and 50% working below the average line
- In case of depth of flow non dimensionalised with diameter of pier, 26.6% of researchers had worked above and 73.3% of the researchers worked below the average non dimensional depth of flow and according to the suggested values of d/D 53.4% researcher were worked below and 46.6% above the suggested line.
- In case of depth of flow non-dimensionalised with mean size of the sediment, 43.75% of researchers had working above and 56.25% researchers below the average value of non-dimensional scouring depth.
- When the diameter of pier non-dimensinalized with the mean size of the sediment results showed that 31% of the researchers had worked above and 69% below the average line and according to the suggested values of D/d_{50} 7.6% researcher had worked below and 38.4% above the suggested line.

From the above discussion the interference study around bridge pier models is in underdeveloped stage and future works in the laboratory as well as in the field should be planned and directed towards interference studies. Efforts should also be made towards suggesting and recommending guidelines for good experimental setup.

LIST OF SYMBOLS

h_s	Scour depth
D	Diameter of pier
Fr	Froude number
d_{50}	Sediment Size
V	Velocity of flow
T	Time of interval
d	Depth of flow
D/ d_{50}	Diameter of the pier w.r.t mean size of the sediment
d/d_{50}	Depth of flow w.r.t mean size of the sediment

Acknowledgements

First author would like to thank the Human Resource Development Group (CSIR) Ministry of Science and Technology, India for providing financial support for the doctoral programme.

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