

Effect of Soil Non-Uniformity on Scour for Circular Compound Bridge Piers



Abhishek Pandey, P.T. Nimbalkar

Abstract: Bridge piers having a varying foundation diameter are known as compound bridge piers. In India for the construction of road and railway bridges circular compound bridge piers are mostly adopted. In past studies it has been concluded that 60-70% of bridge failure occurs because of scour around bridge pier across a river due to flowing water. Most of the past studies were done on the uniform bridge pier and a very few studies has been carried out so far on scour around compound bridge piers. For economical design of bridge pier foundation there is a need to determine the scour depth. In the present study, an experimental investigation has been carried out for computation of time variant change of scour depth for two different models of circular compound bridge piers over non-uniform soil for all possible cases of position of footing with respect to level of the bed, i.e., I. Footing at the level of bed, and II. Footing below the level of bed (1cm, 2cm, 3cm and 4cm) for non-uniform sediments

KEYWORDS: Compound Bridge Pier, Scour Depth, Temporal Variation, Non-Uniform Sediment.

I. INTRODUCTION

Hydraulic structures such as Spurs, Bridge pairs, abutments, guide banks etc. sometime partially abstracts the alluvial streams as a result the bed level Around The structures is lowered because of the interaction between the high velocity flow and the loose bed. This is also caused because of the modification in the flow pattern and drop in the bed level, this phenomenon is known as local scour. The excessive local scour during floods causes failure of bridges and thus it is one of the challenging problems to the hydraulic engineers. In India, hydraulic factors such as stream instability, long-term streambed aggradations or degradation, general scour, local scour, and lateral resettlement are blamed for highway bridge failures. Figure 1.1 shows local scour around bridge piers and foundations, because of flood flows, is considered the primary cause of bridge failure.

Phenomena of scour at bridge location is a complex one which is caused by various agents such as localized scour combined with the general river bed degradation,

modification of flow field around Bridge structures, human interference, debris flow, etc.

Due to the three dimensional flow and sediment transport the complex nature of scour process is observed around bridge elements like piers and abutments.

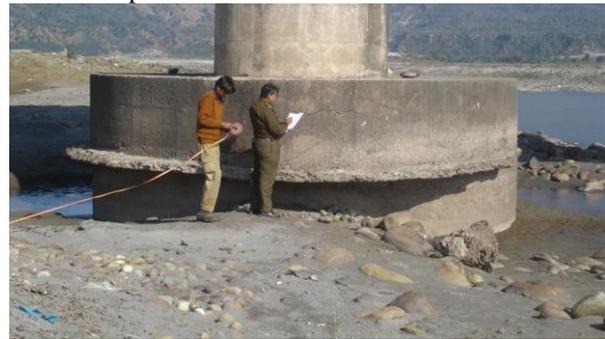


Figure 1. Local scour effects in boulder beds, Himachal Pradesh, India

With the aim of developing relationships for maximum depth of scour large number of studies has been carried out on this topic and thus on the subject of scour around the bridge pier a huge amount of literature is available. However only a few studies are conducted on the flow field around the bridge elements. Through the Laboratory experiments the flow pattern within the scour hole around circular uniform Bridge has been studied by [1] these studies have mostly focus on scar around Bridge pairs which have uniform cross section along their Heights. It also Consider the effect of foundation geometry on scour which previous researches did not considered. In practice Bridge pairs are constructed in various types of symmetries have non-uniform cross-section along their Heights.

The investigators [1-3] have shown that foundation geometry significantly affects the scour. All the above studies are carried out with uniform sediments.

The various factors affecting scour such as type of flow, depth of flow, effect of shape of pier, angle of inclination of pier with flow, opening ratio and bed material characteristics are studied in detail. Standard provisions in the country with reference to bridge pier scour are reviewed. The various relationships proposed by researchers to estimate bridge pier scour in clear water condition and live bed condition are reviewed. Temporal variation of scour around bridge pier is studied and the procedure to estimate the same is reviewed. Based on review of literature it is found that there is a need to carry out further research with respect to

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compound piers to study the aspect related to placing of top of footing and its effect on bridge pier scour in non-uniform sediments so only the effect of pier foundation diameter ratio on scour is studied in this report. Thus the research problem along with objectives and scope of study is finalized.

The present study describes the details of experimental investigations carried out in the laboratory on compound bridge pier for five different elevations of top of footing below bed in non-uniform sediments with σ_g value 2.11, analysis of the results of all the experimental data is presented

II. EXPERIMENTATION

Test run of 300 minutes for two pier models was carried out and observations were noted at different time intervals throughout the run in a tilting flume. Non-uniform Sediment of standard deviation ($\sigma_g = 2.11$) was used for the experimentation.

A. Flume

A tilting flume 10.0 m long, 0.3 m wide and 0.55 m deep located in the Hydraulics laboratory of Bharati Vidyapeeth Deemed University College of Engineering, Pune, India is used to conduct all the experiments. The flume has an acrylic false bed of 0.1 m height, 0.3 m wide placed inside for the entire length of the flume except the working section. The working section of the flume which is 1 m long, 0.3 m wide and 0.1 m deep and is located 4.5 m downstream of flume entrance. The working section is filled with desired sediment to the level of flume bed. Some extra sediments 0.25 m in length and 0.05 m deep is also placed over the false bed for an extension of working section. The discharge in the flume was measured with the help of sharp crested calibrated V notch placed in the return channel. The flow depth in the flume was measured with the help of vernier pointer gauge.



Figure 2. View of Tilting Flume

B. Sediment sample

Non cohesive sand will be used as sediment in the experimental work. The Geometric standard deviation (σ_g) of sample is kept greater than 1.5 for non-uniform sediment. Different sizes of sieve (4.75mm, 3.35mm, 2.60mm, 2.36mm, 1.60mm, 1mm, 0.6mm, 0.3mm and 0.15mm) including Pan and Lid were used for sediment sampling along with Weight balance with accuracy up to 0.01gm.

Percentage finer differences between two consecutive sieve sizes were obtained from grain size distribution curve. That percentage multiplied by total weight of sample required is computed. The procedure is repeated for all consecutive sieve sizes

Properties of sample are as follows:-

- Type of sediment = Uniform sand
- Median size of sediment, $d_{50} = 0.8\text{mm}$
- Geometric standard deviation, $\sigma_g = 2.11$
- $\sigma_g = \sqrt{d_{84}/d_{16}}$

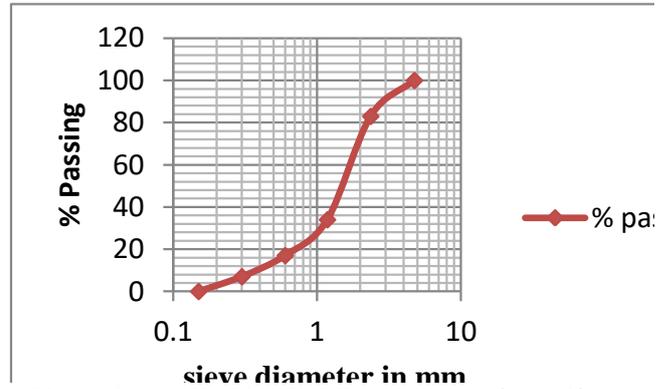


Figure 3. Particle size distribution curve for uniform sediments ($\sigma_g = 2.11$, $d_{50} = 1.5\text{mm}$)

C. Models of compound piers.

The models of compound circular pier were made up of PVC pipes. Two different cases were considered for observing the scour around the pier. The footing top of bridge pier models were placed at various elevations Y with respect to general bed level. First observation was taken with footing top 1 cm below the bed level, second observation with footing top at 2 cm below the bed level, third observation with footing top 3 cm below the bed level, fourth observation 4 cm below bed level and fifth observation was taken when foundation top was at same level with the bed.

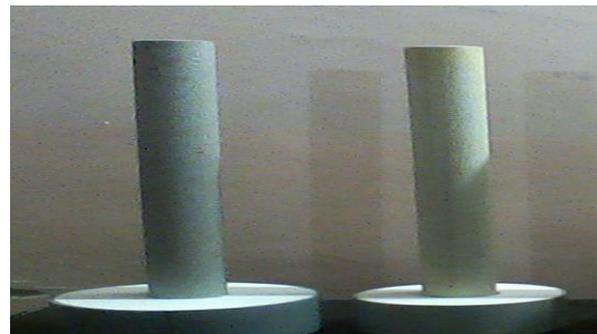


Figure 4. Photograph showing two models of bridge pier

Table I. Dimensions for pier models used for experimentation work

Name of the model	Diameter of pier in mm	Diameter of foundation in mm
Model 1 (compound circular pier)	32	90

Model 2 (compound circular pier)	32	75
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III. THEORITICAL APPROACH

A. Flow intensity under clear water conditions for non-uniform sediments:

V is the mean velocity of flow calculated from the known discharge and depth of flow for a single discharge value. During the experimental work discharge is adjusted by inlet valve and outlet gate. Discharge measurement is done using a Calibrated V notch. The discharge is calculated from the V notch equation as given below,

$$Q = \frac{8}{15} \sqrt{2g} C_d H^{\frac{5}{2}} \tag{1}$$

Where

- Q = Discharge (m³/sec)
- C_d = Coefficient of discharge (0.61)
- H = Head over a weir

Depth of flow is measured in the tilting flume for particular discharge values and the approach velocity of flow is calculated by using the continuity equation given below,

$$V = \frac{Q}{A} \tag{2}$$

$$A = B \times D \tag{3}$$

Where,

- A=Area of flow cross section
- B= Width of flume in m
- D = Depth of flow in m

The ratio V/V_c is the measure of flow intensity and determines whether sediment motion occurs on the channel bed. For $V/V_c < 1$, clear water scour condition exists for both uniform and non-uniform sediments. For non-uniform sediments ($\sigma_g > 1.5$) armoring occurs on the channel bed and in the scour hole. [4] used the ratio V/V_a as the measure of flow intensity for scour with non-uniform sediments. If $V/V_a < 1$, as scour proceeds armoring of the bed occurs and clear water scour conditions are considered to exist. The method to determine V_a is given in [4], Thus $V_a = 0.8 V_{ca}$, where V_{ca} is the mean flow velocity beyond which armoring of the non-uniform sediments bed is impossible. The critical velocity V_{ca} can be determined from logarithmic form of velocity profile

$$\frac{V_{ca}}{u_{*ca}} = 5.75 \log \left(5.53 \frac{D}{d_{50a}} \right) \tag{4}$$

In this u_{*ca} is critical shear velocity for d50a size and d_{50a} is median armor size. Shear velocity is determined from Shields diagram for respective sizes. The particle size d_{50a} is found using the equation (5).

$$d_{50a} = d_{max}/1.8 \tag{5}$$

d_{max} is the maximum particle size determined from particle size distribution.

Table II shows the experimental data for uniform sediment and Table III shows the experimental condition for test series on tilting flume for uniform sediment.

Table II. Experimental data for uniform sediment

Variable	Quantity
Geometric standard deviation σ_g	2.11
Median size of sediment , d_{50}	1.5 mm
Flow depth D	110 mm
Average approach velocity (calculated) V m/s	0.4242 m/s
Critical velocity of sediment motion (calculated) V_{ca} m/s	0.49392 m/s
Footing elevation w.r.t. Bed level Y mm	1 cm, 2 cm, 3cm, 4 cm, same as bed level
Slope of the flume	0.001
Discharge Q m ³ /s	0.014 m ³ /s
critical shear velocity for d50a (u_{*ca})	0.045
V/V_c	0.9443

For experimental studies, the width of an experimental flume should be at least 8 times the size of the bridge pier for clear-water scours conditions to minimize the blockage effects [5-6] and the pier diameter should not be more than 10% of flume width to avoid wall contraction effect on scouring [7].

IV. EXPERIMENTAL OBSERVATIONS AND RESULTS

The computed temporal variation of scour depth is graphically represented in the present study figure 4 to figure 13. Test run for two pier models was carried out and observations were noted at different time intervals throughout the run in a tilting flume. Non-uniform Sediment of standard deviation ($\sigma_g = 2.11$) was used for the experimentation. Scour depths were measured with the help of vernier pointer gauge for 5 hours i.e. 300 minutes duration and scour depths were noted down at different time interval. Figure 4 to Figure 8 shows the graphical representations of temporal variations of scour depth for 75 mm pier foundation diameter and from Figure 9 to Figure 13 shows the graphical representations of temporal variations of scour depth for 90 mm pier foundation diameter at different positions of pier foundation with respect to bed level. Scour depths were observed at upstream, downstream, left face, and right face of the compound piers. The scour depths were observed for two different cases:-

- When the pier foundation top is same as the bed level.
- When the pier foundation top is below the bed level at 10mm, 20mm, 30mm, and 40mm.

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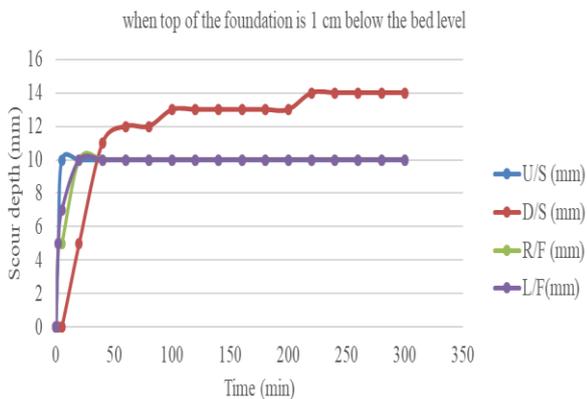


Figure 4: Time v/s scour depth graph for compound pier when foundation top is 10mm below the bed level (model 1)

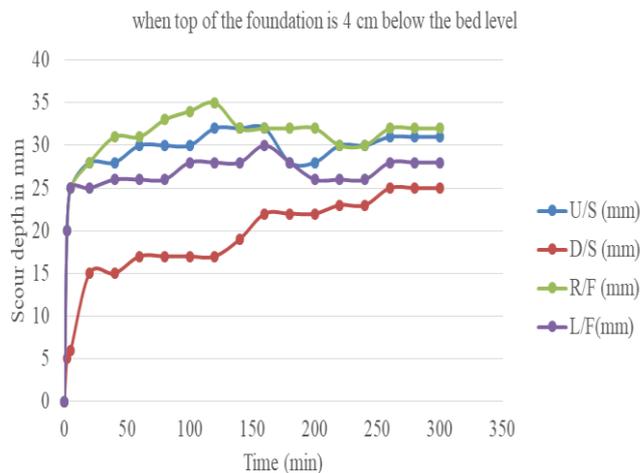


Figure 7: Time v/s scour depth graph for compound pier when foundation top is 40mm below the bed level (model 1)

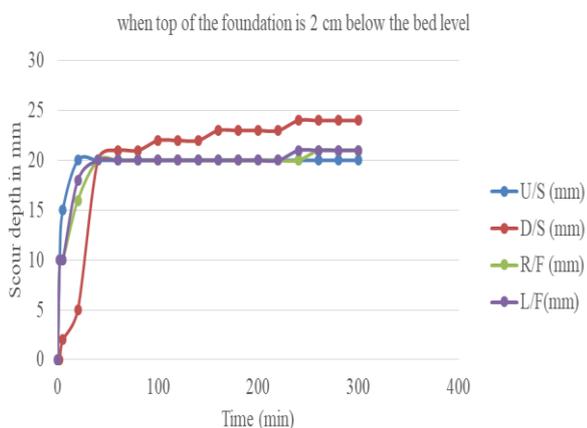


Figure 5: Time v/s scour depth graph for compound pier when foundation top is 20mm below the bed level (model 1)

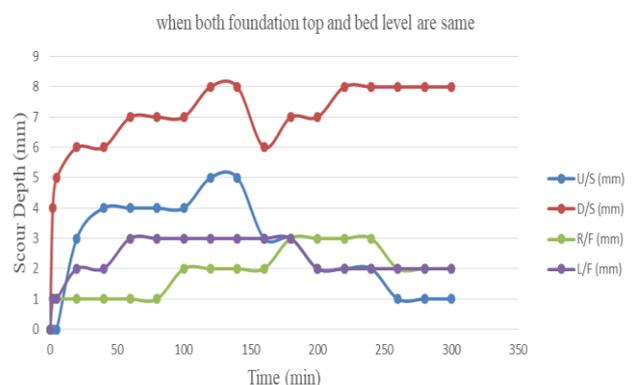


Figure 8: Time v/s scour depth graph for compound pier when foundation top is same as bed level (model 1)

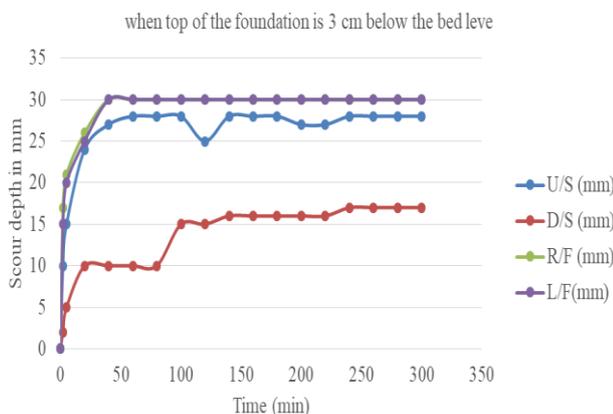


Figure 6: Time v/s scour depth graph for compound pier when foundation top is 30mm below the bed level (model 1)

Table IV. Length of scour spread for 90 mm pier foundation diameter

Position of the pier footing w.r.t. bed level	Length of scour spread (mm)	
	U/S to D/S	R/F to L/F
Same as bed level	220	180
10 mm below	230	180
20 mm below	250	190
30 mm below	260	220
40 mm below	260	200

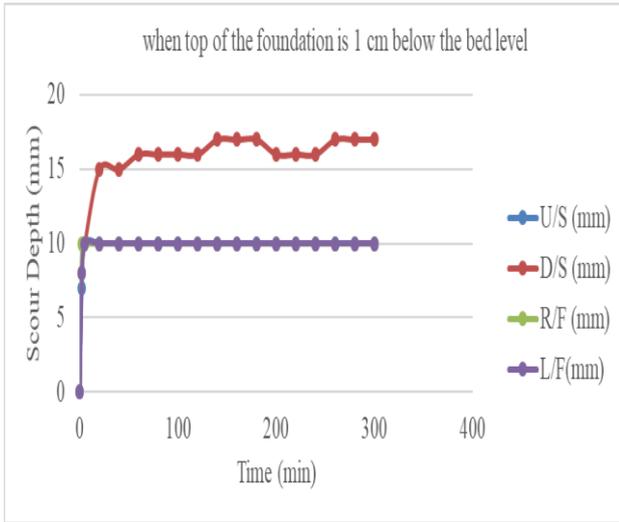


Figure 9: Time v/s scour depth graph for compound pier when foundation top is 10mm below the bed level (model 2)

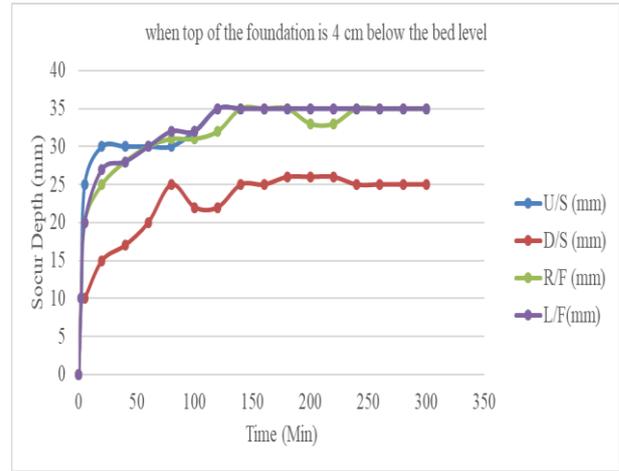


Figure 12: Time v/s scour depth graph for compound pier when foundation top is 40mm below the bed level (model 2)

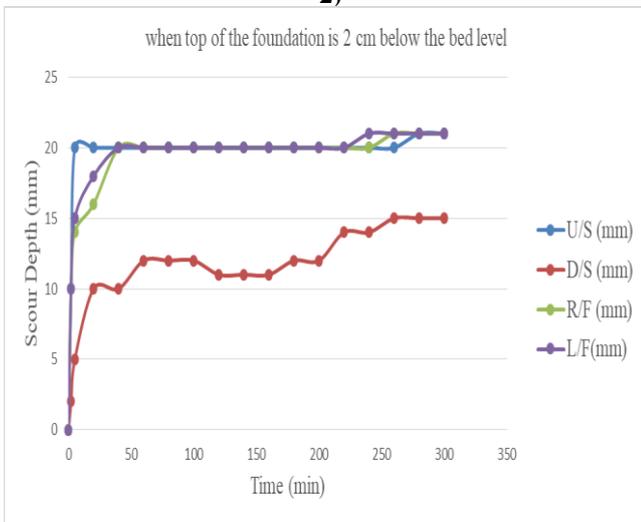


Figure 10: Time v/s scour depth graph for compound pier when foundation top is 20mm below the bed level (model 2)

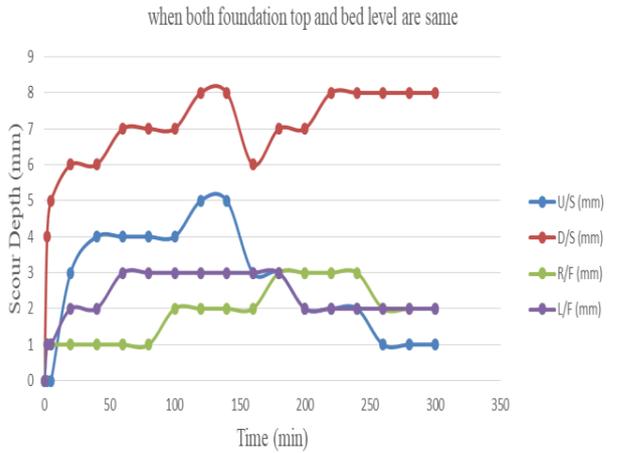


Figure 13. Time v/s scour depth graph for compound pier when foundation top is same as bed level (model 2)

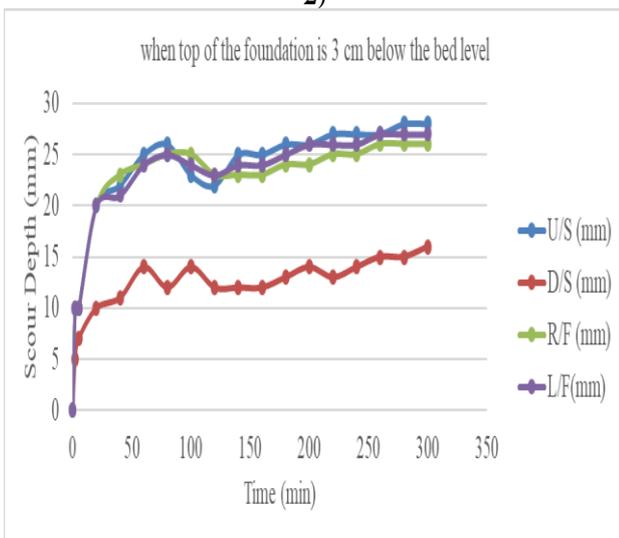


Figure 11: Time v/s scour depth graph for compound pier when foundation top is 30mm below the bed level (model 2)

Table V. Length of scour spread for 90 mm pier foundation diameter

Position of the pier footing w.r.t. bed level	Length of scour spread (mm)	
	U/S to D/S	R/F to L/F
Same as bed level	230	180
10 mm below	250	180
20 mm below	260	190
30 mm below	285	220
40 mm below	300	150

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(a)



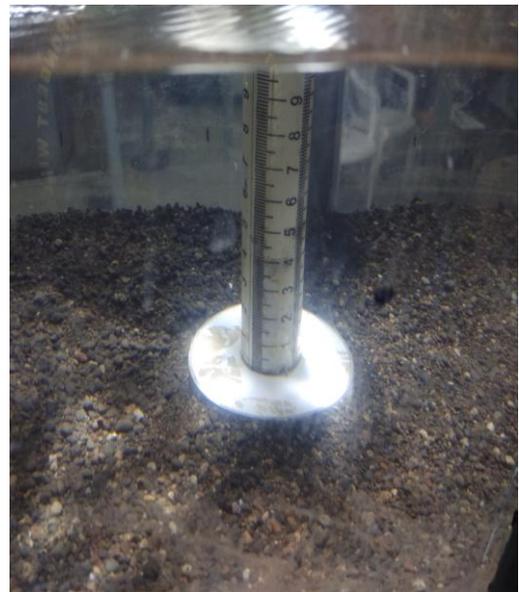
(b)



(c)



(d)



(e)



(f)

Figure. 14. (a) & (b) scour spread after achieving equilibrium depth for 75mm diameter pier foundation; (c) and (d) scour spread after achieving equilibrium depth for 90mm diameter pier foundation; (e) and (f) scour depth during different test runs.

A. Scour depth as a function of top elevation of foundation:

Figure 15 shows the equilibrium relative depth of scour represented as a data series model of compound bridge as a function of Y/b . The both axes in Figure 15. are normalized with the pier diameter. The trend in data set is similar each showing a increase in scour depth with increase in the footing elevation and scour depth is minimum for Y/b values in the range of 0.31 and the values are increasing with the increase of Y/b value. Table VI gives values of Y/b and ds/b for present studies.

Table VI: Scour depth as a function of top elevation of foundation (non-uniform sediment)

Y/b	ds/b (Model 1)	ds/b (Model 2)
0	0.25	0.3125
0.31	0.4375	0.531
0.625	0.625	0.656
0.957	0.875	0.875
1.25	1.031	1.093

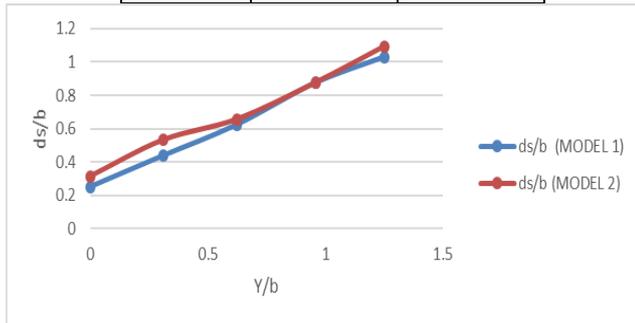


Figure 15. Scour depth as a function of top elevation of foundation (non-uniform sediment)

Y is footing elevation from bed level they are: same as bed level, 10mm, 20mm, 30mm and 40mm below the bed level. b is diameter of pier which is 32mm in all the cases. ds is maximum scour depth observed for each case from figure 4 to figure 8 for model 1 and figure 9 to figure 13 for model 2.

In Figure 16 the minimum scour depth ds_{min} are plotted as function of b/b^* also the level of Y_{min} at which the minimum scour depth occurs for a particular b/b^* are also shown in the figure. Table VII gives the values of ds_{min}/b and Y_{min}/b for different values of b/b^* .

Table VII Pier geometry for optimum protection of scour in non-uniform sediments:

b/b^*	ds_{min}/b	Y_{min}/b
0.426 (Model 2)	0.46	0.625
0.355 (Model 1)	0.312	0.312

data excluded when foundation top is same as bed level.

b is the diameter of pier which is 32mm in all the cases and b^* is pier foundation diameter which is 90mm for (model 1) and 75 mm for (model 2) ds_{min} is the minimum scour depth observed for the given dimension of the pier footing for all figure 4 to figure 8 for model 1 and figure 9 to figure 13 for model 2 and Y_{min} is that footing elevation for with the ds_{min} is observed for a given dimension of pier footing.

The observed ds_{min} for model 1 is 10mm depth at 300 min for 10mm elevation and thus for this case Y_{min} is 10mm, similarly for model 2 ds_{min} is observed 15mm depth at 300min for 20mm elevation so Y_{min} for model 2 is 20mm. Table VII only comprises the data when top of pier footing is kept at certain depth (10mm, 20mm, 30mm and 40mm) it does not includes the data when foundation top is same as bed level as for that case Y_{min} value will always remain 0.

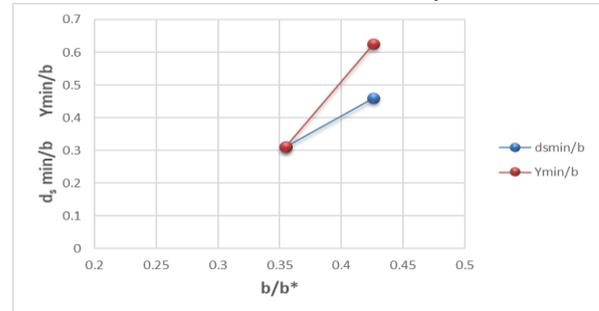


Figure 16. Pier geometry for optimum protection of scour

B. RESULTS AND DISCUSSIONS

The change in scour depth around the circular compound piers with respect to time was measured for the two models having b/b^* ratio as 0.355 and 0.426. Five different test runs were conducted by varying the position of the top surface of the footing and the same was placed at 10mm, 20mm, 30mm, 40mm below the channel bed level and same as the level of bed. The following features of the scour process were noticed.

1. Typical plots showing the development of scour depth with time for compound bridge piers are given in Figure 4 to Figure 13, reveal the effect of the foundation in reducing and limiting the scour depth development when the foundation is at a particular level in comparison with scour around the tow different geometry of the foundation, the scour depth rapidly developed to the level of the top of the foundation.
2. With the action of scour around the pier structure, the removal of particles from the vicinity of piers are also taking place and these sediments can be see accumulating at the downstream side, resulting in formation of hump. This hump is seen growing in size initially but with the flow of time as the scouring rate decreases the size of hump is also seen getting reduced.
3. For non-uniform sediments in the beginning scour is maximum as the finer fractions are scoured rapidly but later on coarser particles are deposited in the scour hole due to the armoring and further scouring is reduced.
4. With increase in the diameter of the foundation there was reduction in the scour depth as principal vortex is unable to scour further as the vortex supporting ability is increased with increase in diameter of foundation top.
5. it was observed that as the position of the foundation top under the bed level is increased there was increase in the scour depth in all the models of the compound pier this is due to the fact that, the process of scour continues until the foundation top is exposed and after that this process stops.

V. CONCLUSION

The following conclusions are drawn from this study.

- i. Scour depth at non-uniform cylindrical piers founded on large cylindrical foundations are dependent on top elevation Y of the lower cylinder, pier and foundation diameter ratio b/b^* .
- ii. With the increase of Y i.e. position of pier footing with respect to bed level there is increase in the scour depth.
- iii. With increase in the diameter of the foundation there was reduction in the scour depth.
- iv. For both of compound models the minimum scour was observed when pier foundation was placed at same level of bed.
- v. With increase in the ratio of footing elevation to pier diameter (Y/b) value the ratio of scour depth to pier diameter (d_s/b) is also increased.
- vi. It is observed that for both the models when the footing elevation is 30mm and 40 mm below the bed level the top of the foundation is not exposed whereas for rest of the footing elevation i.e. 10mm, 20mm and same as bed level the scour depth exposes the foundation and the foundation top lies within the scour hole.

NOTATIONS

Q = The discharge [m^3/s];
 Cd = Coefficient of discharge [0.61];
 g = acceleration due to gravity [m/s^2];
 H = Head over a weir [m];
 h = Height of weir [m];
 V = Approach velocity of flow [m/sec];
 A = Area of flow cross section [m^2];
 B = Width of flume [m];
 D = Depth of flow [m];
 Vc = Critical velocity [m/s];
 U*ca = Critical shear velocity [m/s];
 d50 = Mean diameter of particle [mm];
 σ_g = Geometric standard deviation;
 b = Pier diameter [mm];
 b* = Pier foundation diameter [mm];
 ds = The scour depth [mm];
 dsmin = The minimum scour depth [mm];
 dsmax = The maximum scour depth [mm];
 Y = The footing elevation [mm];
 U/S = Upstream face of pier to the flow;
 D/S = Downstream face of pier to the flow;
 R/F = Right face of pier to the flow;
 L/F = Left face of pier to the flow.

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 10. Shekhar Kumbhar, P.T.Nimbalkar, “Study on Anantpur community micro irrigation project – Design and preparation of project philosophy” International Journal of Civil Engineering and Technology (IJCIET) Volume 9, Issue 6, June 2018
- WorkShop/Seminar/Conference attended**
1. National conference on Hydraulics and water resources with special Emphasis on “Interlinking of Rivers” A National conference at BVDUCOE Pune, 2006
 2. ISTE Sponsored STTP On “Recent advances inPCT” at BVDUCOE Pune ,2006 TTTIR Academic Monitoring Program, B.V.U.College of Engineering Pune,2007 Foundation Problems in Geotechnical Engineering – One Day Workshop,
 3. TEQIP II Sponsored Workshop on “ Leadership Development” B.V.D.U. College of Engineering, Pune dated 22nd August 2013
 4. Training Course on “Modeling Techniques for Sediment Transport in Coastal Engineering, Central Water and Power Research Station, Pune during 9th –10th October 2013
 5. Two days’ workshop on Sediment Control in Hydro Power Plants in Himalayan ranges, CW & PRS, Pune on 29 and 30th September 2015

Extra Activity:

1. Pursuing Ph.D. at NIT Surat