Effect of Erodible Bed on Backwater Rise Due to Bridge Piers Only in Case of Subcritical Flow

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Abstract: This experimental research aims to study the effect of movable bed scour on the backwater rise upstream bridge piers. The physical models were adjusted for all runs to generate subcritical flow between bridge piers using four different values of downstream Froude number equal 0.0958, 0.107, 0.277 and 0.3527. Different three nose shapes of bridge piers were used, (rectangular, triangular and circular nose), under four different values of contraction ratio (C_r) of; 0.625, 0.70, 0.75 and 0.875 using four discharge values (10 l/s., 11 l/s., 13 l/s. and 15 l/s.). The experimental work was carried out using fine sand sample with geometric mean size (d_{50}) equals 0.167 (classified according to American code). Generally, this research illustrated that the backwater rise upstream bridge piers affected directly with scour propagation around piers. It was appeared that the values of backwater rise using triangular and rectangular noses were greater than the corresponding ones using circular nose by an average percentage of 15.50% and 31.50% respectively. This means that the circular nose gave the least values of backwater rise than other nose shapes, so it is recommend to use it as the best nose shape. It was noticed that the backwater rise decreased gradually with the increasing of run time and the scour hole around piers. It was also showed that the change of Froude number, shape of pier nose and contraction ratio had a noticeable effect on the backwater rise upstream bridge.

Keywords: Backwater Rise, Movable Bed, Scour, Bridge Piers, and Subcritical Flow

1. Introduction

Thus far the discussion of backwater has been limited to the case where the bed of a stream in the vicinity of a bridge is considered rigid or immovable and, thus, does not degrade with introduction of embankments, abutments, and piers. It was necessary to obtain an experimental study under further complication of a movable bed. In actuality, the bed is usually composed of much loose material, some of which will move out of the constriction during flood flows. Nature wastes little time in attempting to restore the former regime, or the stage-discharge relation which existed prior to constriction of the stream.

For within-bank flow little changes, but for flood flows there exists an altered regime, with a potential to enlarge the waterway area under the bridge (Joseph, 1978) [4].

Usually, in high bridges that cross water ways, the bridge piers are considered as the only supports that obstruct the flow. The constriction of flow due to piers causes the water surface between piers to decrease and raise gradually the water level upstream piers.

It is important to study the backwater rise phenomenon because the cost of protective works in rivers or canals depends on the predicted flood level.

Henderson (1966) [3] stated that, Yarnell in 1934 started in studying the backwater rise upstream bridges due to contraction using piers only (Sturm, 2001) [9]. Also, Soliman (1989) [7] investigated experimentally the backwater rise upstream bridge.

In 1973, the Federal Highway Administration (FHWA) State that the failure of 383 bridges was due to of catastrophic floods showed that 75 percent involved damage in abutment and 25 percent involved damage in pier (Goswami and Barua, 2015) [2].

Mohamed (2015) [5] studied the protection of local scour using collar around multi-vents bridge piers, this collar reduce the local scour by 65%.

Nohani and Ghannad (2015) [6] studied the impact of collar on the cylindrical bridge pier by using three difference

dimensionless ratio of collar length to pier diameter, they say that the shape of oval collar have the effective impact on reducing the scour.

- Theoretical Approach

To estimate the backwater rise due to piers, energy principle is employed as follows:

Fig. (1) illustrates the backwater rise (dy) due to bridge piers. Applying Bernoulli's equation between sections (2) and (3), so:

$$\left(y_2 + \frac{V_2^2}{2g}\right).r = y_{ds} + \frac{V_3^2}{2g} \qquad (1)$$

where:

y_2 = minimum water depth at section 2;
y_{ds} = downstream water depth;
V_2 = water velocity at section 2;
V_3 = water velocity at section 3; and
r = energy residual ratio $\approx$ 0.9-1.0.
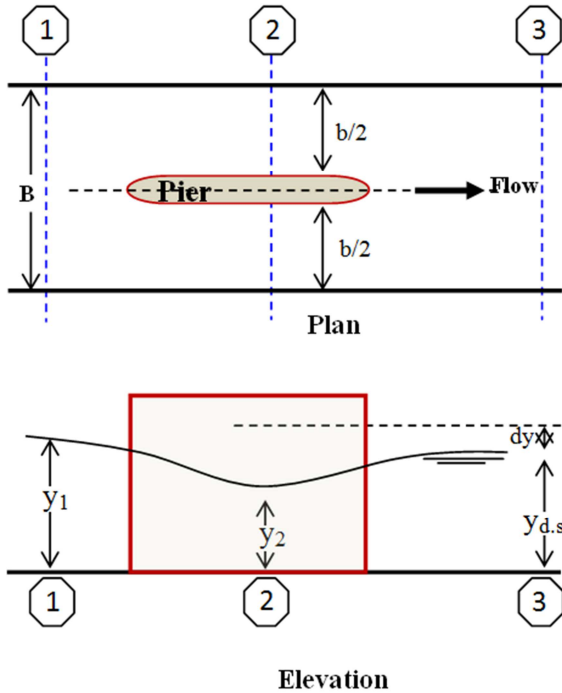[between section 2 and section 3]

Fig. 1. *Backwater rise (dy).*

According to continuity principle between sections (2) and (3):

$$y_2\, b\, V_2 = y_{ds}\, B\, V_3 \qquad (2)$$

where:

b = Summation of clear distances between bridge piers;
B = total width of channel; and

Cr = contraction ratio = b/B \qquad (3)

Equation (4) could be resulted from the rearrangement of Eqs. (1), (2) and (3) results to the following;

$$Cr^2 = \frac{r^3 Fr^2 \left(2 + Fr_2^2\right)^3}{Fr_2^2 \left(2 + Fr^2\right)^3} \qquad (4)$$

where:

Fr_2 = Froude numbers at sections 2; and
Fr = downstream Froude number at section 3.

In case of subcritical flow, Yarnell (1934) [10] derived an empirical equation for backwater rise and could be written as:

$$\frac{dy}{y_{ds}} = CF_r^2\left[\left(C + 5F_r^2 - 0.6\right)\left(X + 15X^4\right)\right] \qquad (5)$$

where:

dy = backwater rise;
C = pier shape coefficient [it equals 0.9 for semicircular nose, 1.05 for triangular nose, and 1.25 for rectangular nose] [9];
Fr = downstream Froude number; and
X = pier thickness divided to the distance between axis of piers.

Yarnell derived the aforementioned equation for pier length-width ratio equals 4:1. He concluded that the backwater rise for ratios of 7:1 and 13:1 increased by 5% and 10%, respectively.

Skew piers with inclination angles of 10° and 20° on flow direction were experimentally investigated by Yarnell. It was appeared from his study that there was a small increase in backwater rise at 10° skew, while at 20°, it increased by 230% compared with un-skewed one. This could be concluded that due to increase of the normal projection width of the pier to the flow.

Charbeneau and Holley (2001) [1] stated that the increasing in water level upstream the bridge piers causes a negative impact on the stability of bridge and could be responsible for scouring process around piers.

Suribabu et al. (2011) [8] used different shapes of bridge piers having equal projected area to study the drag characteristics with two different contraction ratios of 0.33 and 0.40 under subcritical flow conditions. They also introduced a modification in Yarnell's equation.

For most of papers, the effect of scour hole propagation around bridge piers on backwater rise was negligible. For this reason, in this research, different experimental runs were carried out to find the effect of scour on the backwater rise due to the bridge piers only for different discharges (10 lit. /sec., 11 lit. /sec., 13 lit. /sec. and 15 lit. /sec.) with four different values of contraction ratio; 0.625, 0.70, 0.75 and 0.875 using rectangular, triangular and circular noses.

2. Experimental Work

The present experiments were conducted in a rectangular mild sloped flume of 0.40 m wide, 0.40 m deep, and 12.0 m long, with 2.0 m long Perspex sides, Fig. (2), in irrigation and hydraulics laboratory in Mansoura University.

Fig. (3) and Table (1) show the sieve analysis and characteristics of the selected used sand sample.

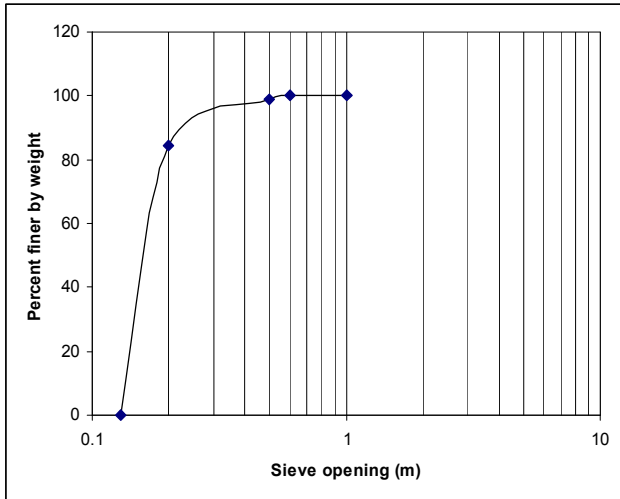*Fig. 2. Flume elevation and its 'side view'.*

Fig. 3. Particle size distribution for selected sand bed.

Table 1. Characteristics of the used sand sample.

Effective diameter (d10)	0.140 mm
Geometric mean size (d50)	0.167 mm
d65	0.18 mm
Standard deviation (σ)	1.1680
Gradation coefficient (G)	1.1683
Type of sample	Fine Sand Sample

Different three nose shapes of bridge piers were used, (rectangular, triangular and circular nose). The volumetric flow meter was used to measure the discharge. It is bolted with two flanges in the supply pipeline. It was calibrated with a triangular weir (V-notch) fixed at the flume end. A movable point gauge with an accuracy of ±0.1 mm was used to measure the water depths.
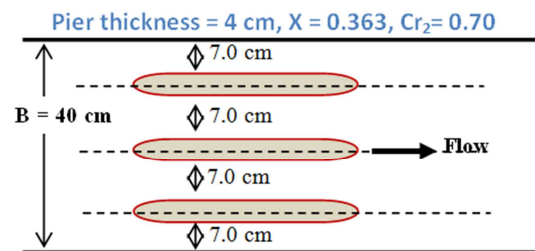
- Experimental Procedure

In each run, before putting the physical models [glass pier models], downstream water depth ($y_{d.s}$) for each discharge and the water velocity V_3 were measured. Then, for each run, after piers placing, upstream water depth y_1 and water depth between piers y_2 were measured at run times of 0.0 hr, 0.5 hr, 1.0 hr and 2.0 hrs. A test run was conducted to estimate the time that will be taken for all runs, to be sure that the scour hole depth and length are constant. The estimated time was two hours.
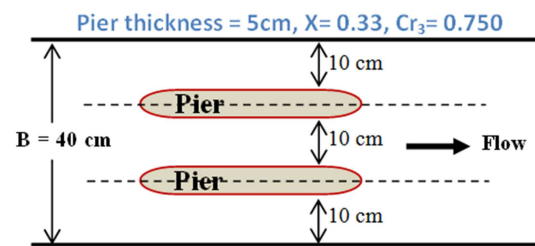
3. Models Layout

To validate the four values of contraction ratios, four scenarios of piers models were prepared as mentioned in Fig. (4). These scenarios were repeated for each nose shape.
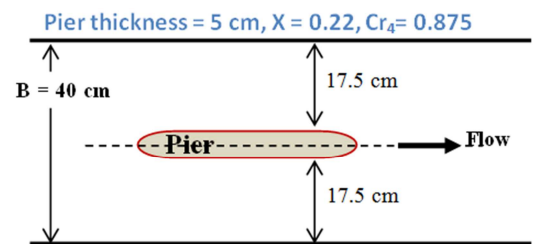

Fig. 4. Used models scenarios.

All runs were repeated with all discharges and noses shapes. For each run, the backwater rise (dy) was measured. The total number of runs was 48. It was observed that the scour hole around piers was formed through the first two hours from operating and the movement of sand particles started for stopping.

4. Results and Analysis

To explain values of backwater rise (dy) due the different affected parameters with the proceeding of scour process, this paper is consisted of three parts:-

Part (1):- Effect of Nose Shape on Backwater Rise
Part (2):- Effect of Cr on Backwater Rise
Part (3):- Effect of Run Time (t) on Backwater Rise

Part (1):- Effect of Nose Shape
All experimental runs were exerted with three nose shapes of piers; Rectangular, triangular and circular nose. Figs. (5) through (8) show the effect of three nose shapes on backwater rise ratio (dy/y_{ds}) with different run time (t) for contraction ratio (Cr) of 0.875.
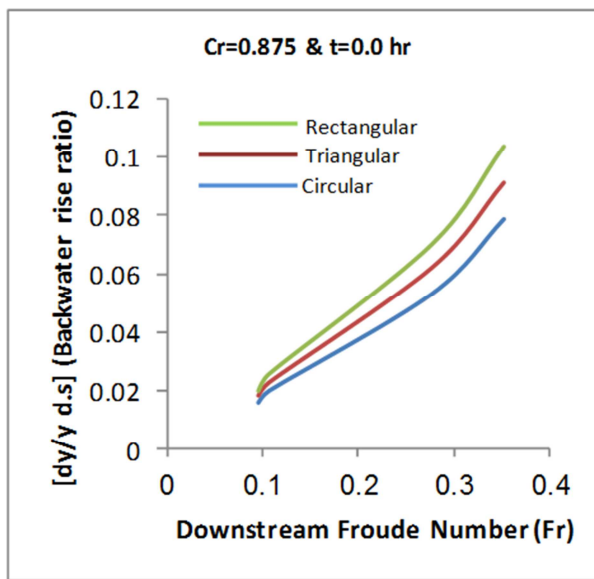

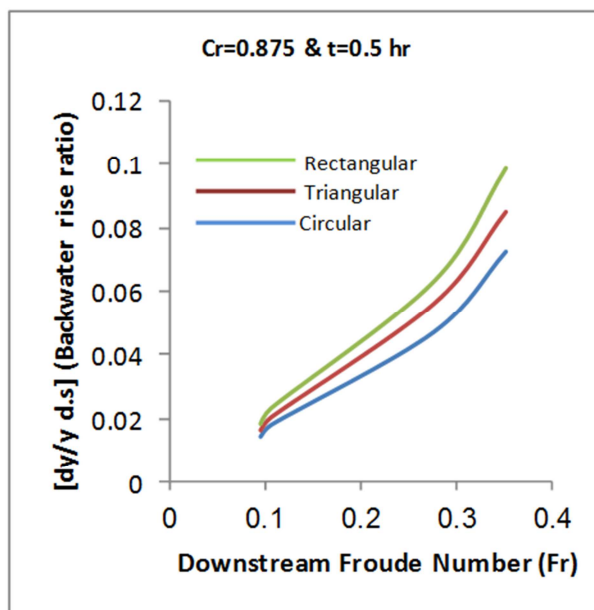*Fig. 5. Backwater rise ratio at t=0.0 hr.*
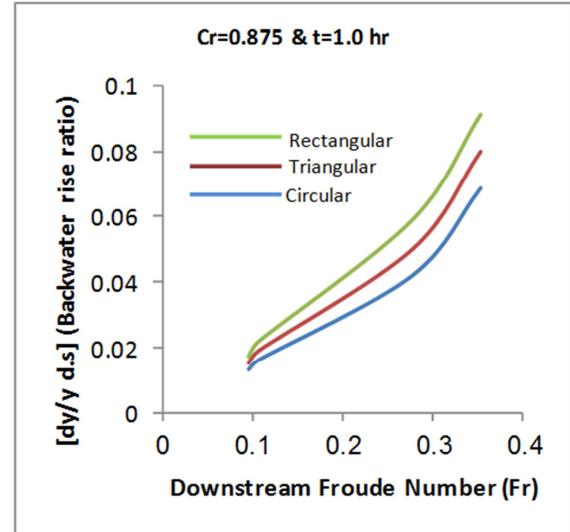

Fig. 6. Backwater rise ratio at t=0.5 hr.
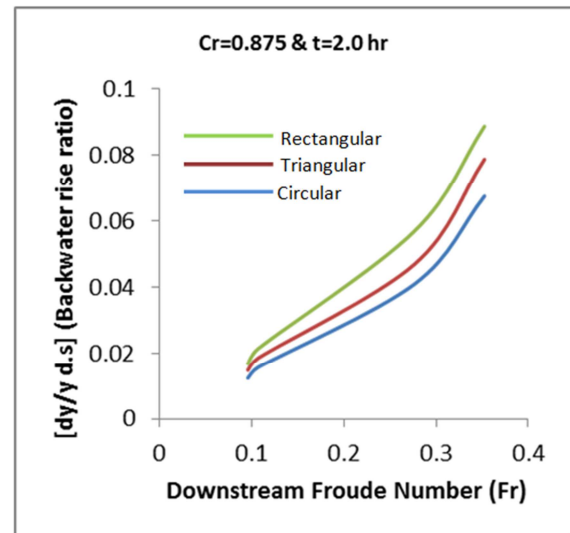

Fig. 7. Backwater rise ratio at t=1.0 hr.

Fig. 8. Backwater rise ratio at t=2.0 hr.

From the aforementioned figures, it was noticed that:-
Values of backwater rise using triangular and rectangular noses are greater than the corresponding ones using circular nose by an average percentage of 15.50% and 31.50% respectively. This means that the circular nose gives the least values of backwater rise than other nose shapes and it could be considered the best nose shape.

The effect of nose shape appears obviously with the increasing of downstream Froude number.

The backwater rise value decreases gradually for all nose shapes with the increasing of the scour hole volume around piers. This phenomenon occurs due to the increase in water depth with increasing the scour hole which causes low water velocities and small values of head losses.

Part (2):- Effect of Contraction Ratio
Figs. (9) through (12) show the effect of contraction ratio on the backwater rise for rectangular nose only with different Froude numbers. Rectangular nose was chosen because it gives the largest values of backwater rise.
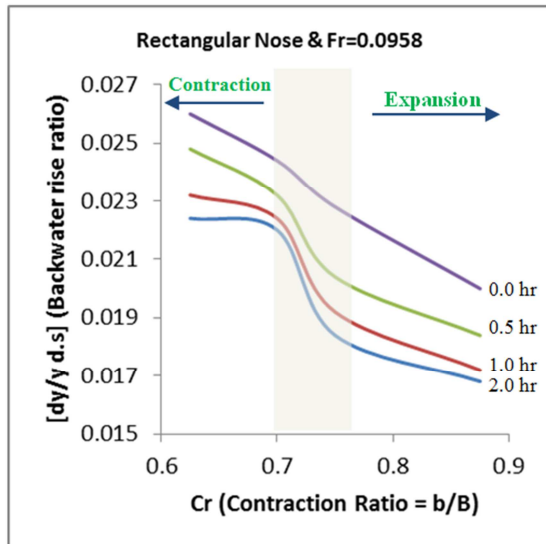
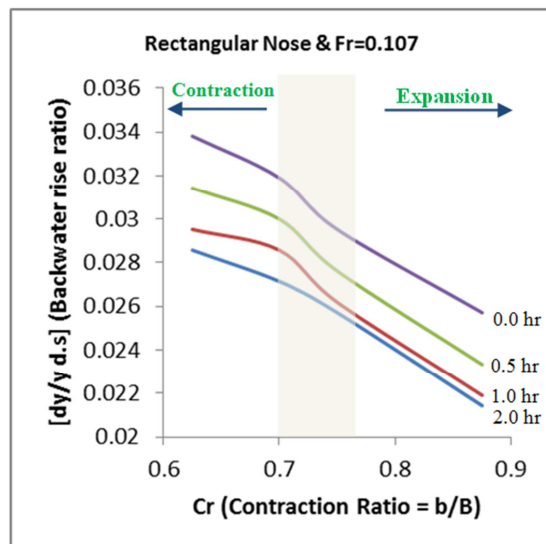*Fig. 9. Relationship between [dy/y$_{d.s}$] and Cr at Froude number of 0.0958.*

Fig. 10. Relationship between [dy/y$_{d.s}$] and Cr at Froude number of 0.107.
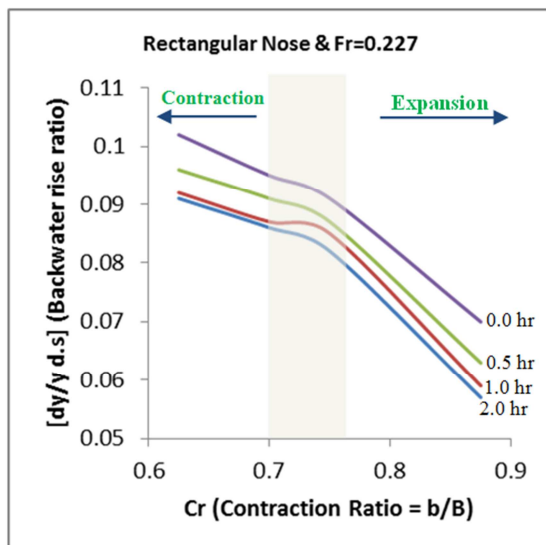

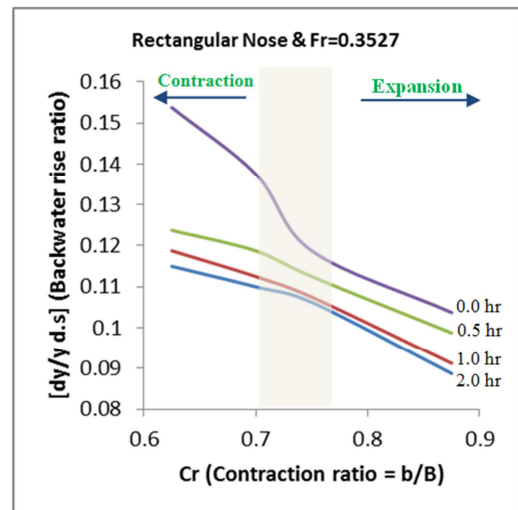*Fig. 11. Relationship between [dy/y$_{d.s}$] and Cr at Froude number of 0.227.*

Fig. 12. Relationship between [dy/y$_{d.s}$] and Cr at Froude number of 0.3527.

From the aforementioned figures, it was observed that:-
- The backwater rise values decreases gradually with the increase of (Cr) values (expansion).
- Value of backwater rise decreases by a large rate at contraction ratio from 0.70 to 0.75.

Part (3):- Effect of Run Time (t) [scour]

Constriction of a channel produces backwater at flood flows; backwater is indicative of an increase in potential energy upstream. This makes possible higher velocities in the constriction, thus, increasing the transport capacity of the flow to above normal in the channel.

The greater capacity for transport results in scouring of the bed in the vicinity of the constriction; the removed material is usually carried a short distance downstream and dropped as the stream again returns to full width. As the scouring action proceeds, the waterway area under the bridge enlarges the velocity and resistance to flow decreases, and a reduction in the amount of backwater results.

Figs. (13) through (20) show the effect of sour hole propagation around piers on the backwater rise with time at all contraction ratios for circular and triangular nose shape.
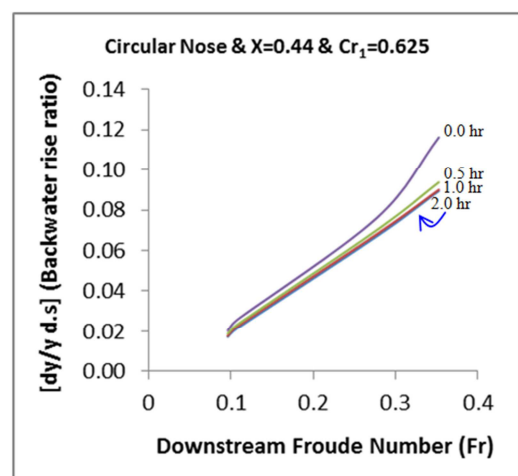

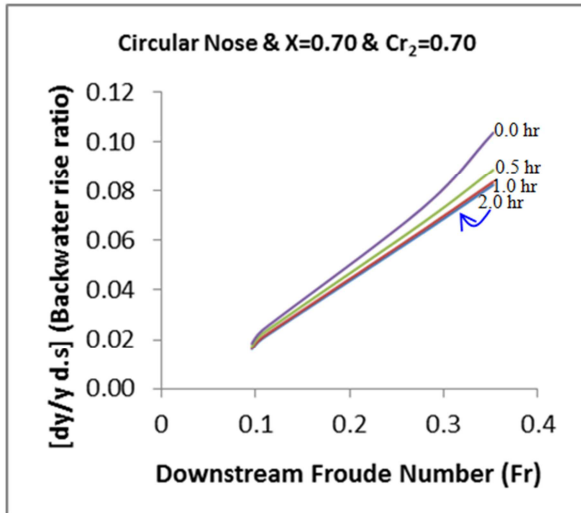*Fig. 13. Effect of run time on backwater rise ratio for circular nose at Cr=0.625.*

Fig. 14. *Effect of run time on backwater rise ratio for circular nose at Cr=0.70.*

Fig. 17. *Effect of run time on backwater rise ratio for triangular nose at Cr=0.625.*

Fig. 15. *Effect of run time on backwater rise ratio for circular nose at Cr=0.75.*

Fig. 18. *Effect of run time on backwater rise ratio for triangular nose at Cr=0.70.*

Fig. 16. *Effect of run time on backwater rise ratio for circular nose at Cr=0.875.*

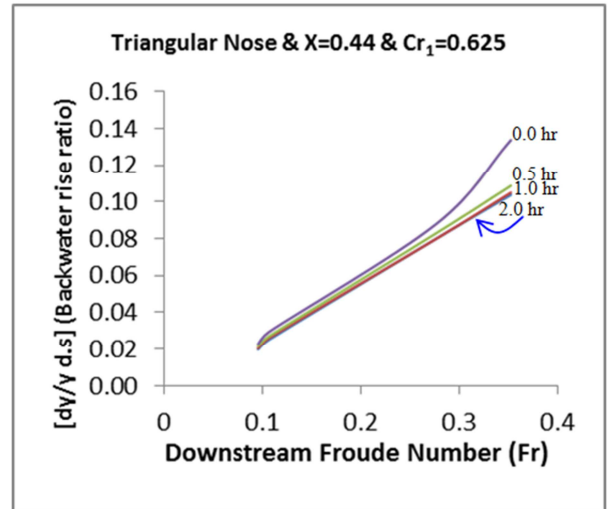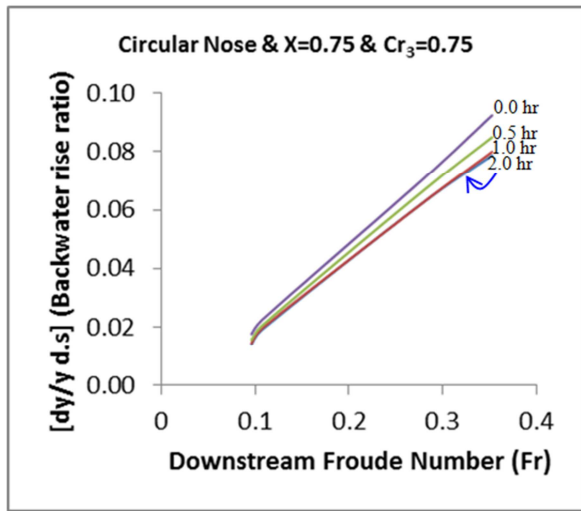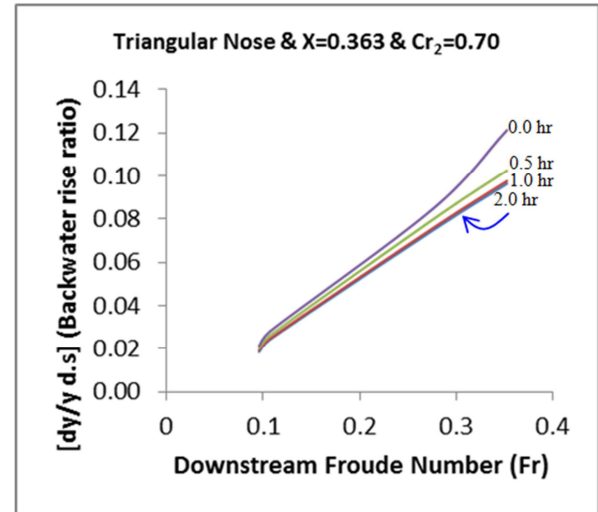**Fig. 19.** *Effect of run time on backwater rise ratio for triangular nose at Cr=0.75.*
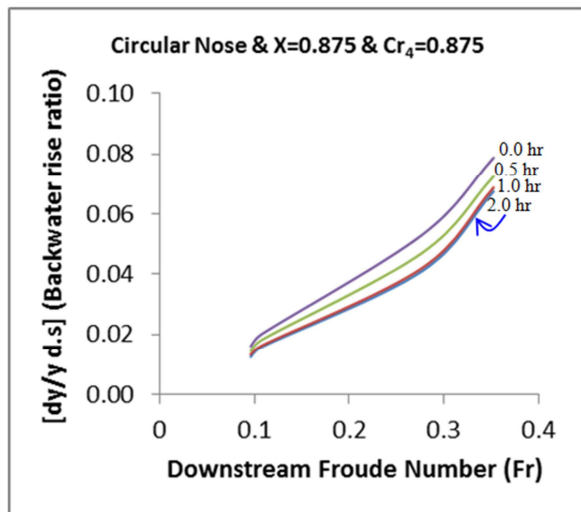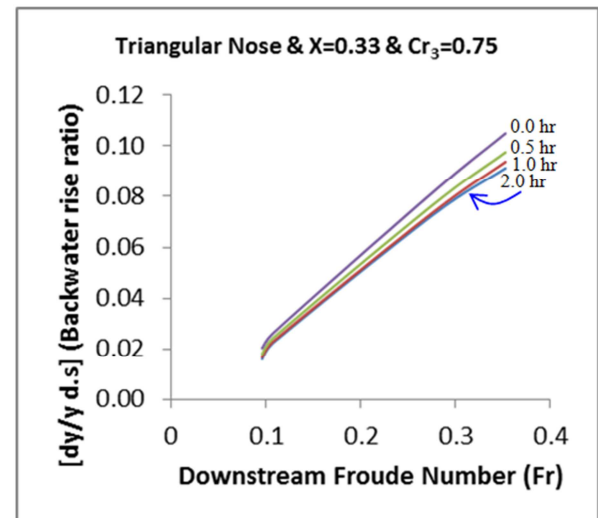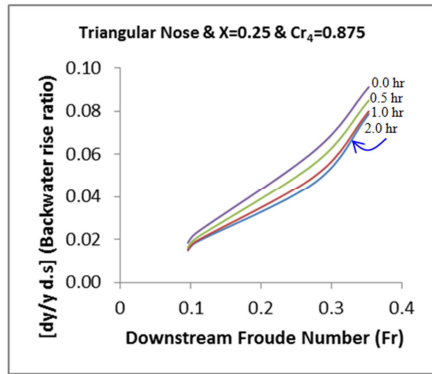
Fig. 20. *Effect of run time on backwater rise ratio for triangular nose at Cr=0.875.*

From the aforementioned figures, it was deduced that:-

- Backwater rise ratios decreases with the increasing of the scour hole depth by different rates with time. The result of increasing scour hole depth around piers is the decrease in water velocity and consequently decrease in head loss.
- The decreasing rates of backwater rise with run time differentiate with contraction ratio and nose shape.
- With the large values of contraction ratios [expansion] the difference between decreasing rates of backwater rise with run time is noticeable than the corresponding rates with small contraction ratios [contraction].
- With the increasing of downstream Froude number, the difference between backwater rise rates with time increases.
- There is no noticeable difference between backwater rise ratios after one hour from starting run time.

From Figs. (5) through (20) it was concluded that the backwater rise affects obviously by nose shape, contraction ratio and propagation of the scour hole with time.

It is a complicated process to associate between all of affected parameters theoretically to find an equation of resulted backwater rise. It is recommended to use more than two soil samples to add the effect of soil properties on backwater rise.

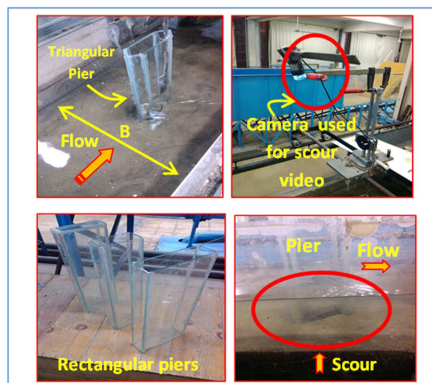Some photos through the experimental work runs are given in Fig. (21).

Fig. 21. *Some of physical models and scour around triangular pier through run process.*

Samples of experimental results in the form of tables are listed below:

Table 2. *Rectangular nose results.*

(1) at Cr = 0.625

		t= 0.0	t= 0.5 hr	t= 1 hr	t= 2 hr
Fr	y $_{d.s}$ (cm)	dy1 (cm)	dy2 (cm)	dy3 (cm)	dy4 (cm)
0.0958	25	0.65	0.62	0.58	0.56
0.107	21	0.71	0.66	0.62	0.60
0.277	10	1.02	0.96	0.92	0.91
0.3527	8	1.23	0.99	0.95	0.92

(2) at Cr = 0.70

		t= 0.0	t= 0.5 hr	t= 1 hr	t= 2 hr
Fr	y $_{d.s}$ (cm)	dy1 (cm)	dy2 (cm)	dy3 (cm)	dy4 (cm)
0.0958	25	0.61	0.58	0.56	0.55
0.107	21	0.67	0.63	0.60	0.57
0.277	10	0.95	0.91	0.87	0.86
0.3527	8	1.1	0.95	0.90	0.88

Table 3. *Triangular nose results.*

(1) at Cr = 0.75

		t= 0.0	t= 0.5 hr	t= 1 hr	t= 2 hr
Fr	y $_{d.s}$ (cm)	dy1 (cm)	dy2 (cm)	dy3 (cm)	dy4 (cm)
0.0958	25	0.51	0.45	0.42	0.40
0.107	21	0.55	0.51	0.48	0.47
0.277	10	0.82	0.77	0.74	0.73
0.3527	8	0.84	0.78	0.75	0.73

(2) at Cr = 0.875

		t= 0.0	t= 0.5 hr	t= 1 hr	t= 2 hr
Fr	y $_{d.s}$ (cm)	dy1 (cm)	dy2 (cm)	dy3 (cm)	dy4 (cm)
0.0958	25	0.46	0.41	0.38	0.37
0.107	21	0.48	0.43	0.40	0.39
0.277	10	0.62	0.56	0.50	0.47
0.3527	8	0.73	0.68	0.64	0.63

Table 4. *Circular nose results.*

Cr=0.625					
		t= 0.0	t= 0.5 hr	t= 1 hr	t= 2 hr
Fr	y $_{d.s}$ (cm)	dy1 (cm)	dy2 (cm)	dy3 (cm)	dy4 (cm)
0.0958	25	0.51	0.47	0.44	0.43
0.107	21	0.54	0.49	0.47	0.45
0.277	10	0.76	0.70	0.68	0.67
0.3527	8	0.93	0.75	0.72	0.715

5. Conclusion

This experimental study was carried out to study the effect of movable bed scour on the backwater rise upstream bridge piers in case of subcritical flow.

Three different nose shapes of piers; rectangular nose, triangular nose and circular nose were used. All runs were exerted with four different values of contraction ratio (C_r); 0.625, 0.70, 0.75 and 0.875 using four discharge values (10 lit. /sec., 11 lit. /sec., 13 lit. /sec. and 15 lit. /sec.). The experimental work was carried out using fine sand sample with geometric mean size (d_{50}) equals 0.167 (classified according to American code).

From this study, it was concluded that values of backwater rise using triangular and rectangular noses were greater than the corresponding ones using circular nose by an average percentage of 15.50% and 31.50% respectively. This means that the circular nose gave the least values of backwater rise than other nose shapes and it could be considered the best nose shape.

The backwater rise values decreases gradually with the increase of (Cr) values (expansion) and *vice versa*. This means, it can be seen that any means of increasing the waterway area under a bridge can be effective in reducing the backwater.

Backwater rise ratios decreases with the increasing of the scour hole depth by different rates with time. The result of increasing scour hole depth around piers is the decrease in water velocity and consequently decrease in head loss.

Acknowledgments

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