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Development of Empirical Formulas for Effect of Circular Pier and Abutment on Local Scour Depth

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Abstract :

This study based on laboratory experiments for computing depth of local scour around abutment and bridge pier neighboring abutment considering the study of the effects of upstream flow conditions , pier and abutment sizes , median size of bed material and spacing between pier and abutment on the maximum scour depth and scour pattern around a pier and abutment.

The study was conducted using a physical hydraulic model of pier and abutment operated under subcritical flow , clear-water condition and using uniform cohesionless sand as bed material . Three different size models of pier and abutment were used to show the effect of the size on the local scour and two different median size (d_{50}) of sand were used in this study.

Dimensional analysis techniques and statistical analysis were used to find new formulas with help of the experimental data . One of these formula was to compute the maximum scour depth at pier neighboring abutment and the other to find the maximum scour depth at abutment.

There formula were derived to predict the maximum scour depth in terms of Froude number , diameter of pier and abutment , median size of sand , flow depth , flow velocity and spacing between pier and abutment.

Key-words : Pier , Abutment , Scour , Froude number , Bridge.

تطوير المعادلات الوضعية لتأثير الدعامة والكتف الدائريين على عمق الانجراف ألموقعي

الخلاصة:

تم في هذا البحث اعتماد التجارب المختبرية لحساب عمق الانجراف الموقعي حول الكتف والدعامة المجاورة له حيث أخذت الدراسة بنظر الاعتبار تأثير ظروف الجريان في مقدمة المنشأ و حجم الدعامة والكتف ومتوسط حجم حبيبات مادة القاع و المسافة بين الدعامة والكتف على عمق الانجراف الأعظم و نمط الانجراف حول الدعامة و الكتف.

لقد تم استخدام نماذج فيزيائية للدعامة والكتف وضعت داخل مجرى الماء في القناة المختبرية تحت ظروف الجريان الهادئ (subcritical)، والخالي من حمل الرسوبيات (clear-water condition) ، وباستخدام تربة رملية ذات جزيئات منتظمة وغير متماسكة كمادة للقاع. ثلاثة أحجام مختلفة من الكتف والدعامة استخدمت لبيان تأثير الحجم على عمق الانجراف كما استخدم في هذه الدراسة نموذجين من الرمل مختلفين في التدرج ومتوسط حجم الحبيبات (d_{50}).

استخدم التحليل البعدي والإحصائي استخدما لإيجاد معادلتين جديدتين لحساب عمق الانجراف العظم وبمساعدة التجارب المختبرية ، إحدى تلك المعادلتين لحساب عمق الانجراف حول الدعامة والأخرى لحساب عمق الانجراف حول الكتف.

أخذت كلتا المعادلتين بنظر الاعتبار كل من رقم فرويد ، قطر الدعامة والكتف، متوسط حجم حبيبات الرمل ، عمق الجريان ، سرعة الجريان ، المسافة بين الكتف والدعامة.

List of symbols

ds_p Depth of scour around the pier

ds_a Depth of scour around the abutment

D Diameter of pier or abutment

d_{50} Median size of the sediment particle

Fr Froude number ($Fr = v/\sqrt{gy}$)

g Acceleration due to gravity

ρ Water density, Re Reynolds number

V Mean approach flow velocity

V_c Critical velocity,

y Flow depth

μ Dynamic viscosity

x spacing between pier and abutment(face to face).

1- Introduction

The problem of scour around any obstruction placed in alluvial channel is of great importance to hydraulic engineers. In practice a channel is often obstructed by means or other such as bridge piers, abutment, spur-dikes and so on. To be able to design a safe and economic structure it is important to have a clear picture of scour phenomenon around these obstructions.

Scour is result of the erosive action of flowing water excavating and carrying away material from the bed and banks of streams showing figure (1).

Over the past half century, numerous studies were conducted and numerous equations were developed to predict bridge pier and abutment scour. Most of these equations were developed using laboratory data and sometimes tested using limited field data.

Many bridges over the world are destroyed or failed during a case of flow situations (Breusers,et al. 1977). Some failures were due to a damage in foundation of last pier neighboring abutment . Accordingly, due to necessity of a realistic design investigating the interference manner of local scour is extremely needed.

Analyzing the scour process by using a limited laboratory data to get two new formula , one of these formula to compute the maximum scour depth at pier neighboring abutment and the other to find the maximum scour depth at abutment.

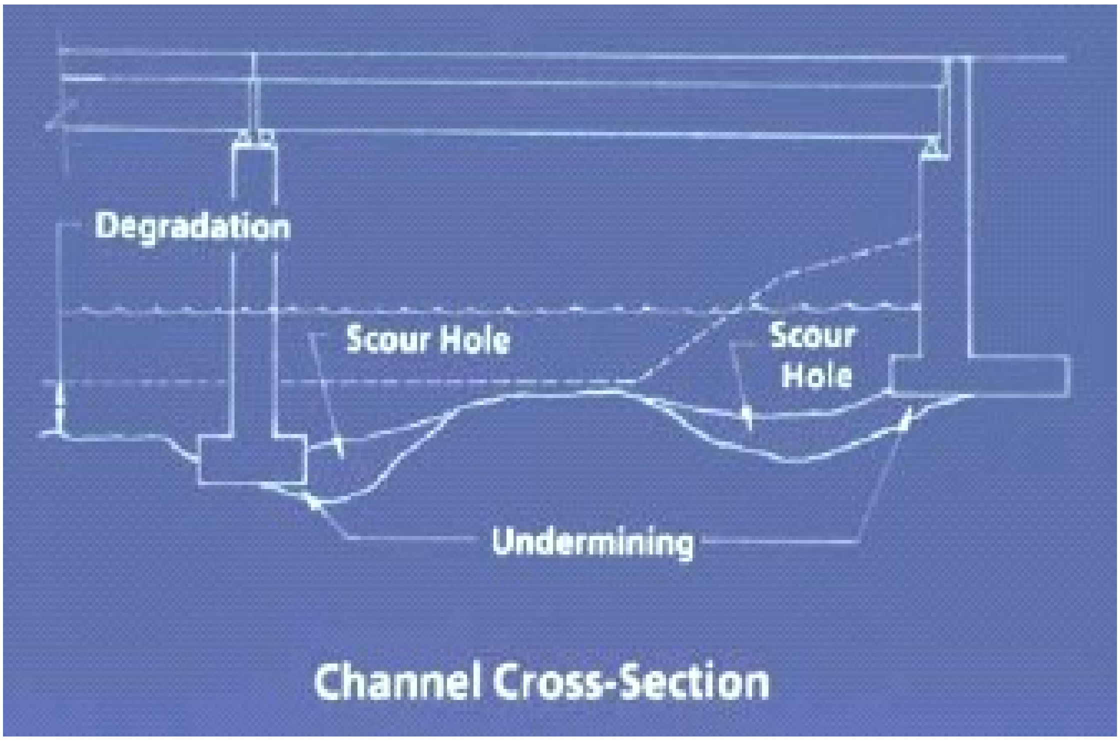


Figure (1):Gross Sectional of the Channel Showing the Scour Round Pier and Abutment (After Azlanfka University)

2- Classification of Scour Parameters

Factors affecting the magnitude of the local scour depth at piers and abutment as given by Richardson and Davies (1995), Raudkivi and Ettema (1983) and Lagasse et al. (2001) are (1) approach flow velocity, (2) flow depth, (3) pier and abutment width, (4) gravitational acceleration, (5) pier and abutment length if skewed to the main flow direction, (6) size and gradation of the bed material, (7) angle of attack of the approach flow to the pier and abutment, (8) pier and abutment shape, (9) bed configuration, and (10) ice or debris jams. According to Breusers et al. (1977) and Ansari et al. (2002) the parameters that are listed above can be grouped into four major headings.

• ***Approaching Stream Flow Parameters**:* Flow intensity, flow depth, shear velocity, mean velocity, velocity distribution and bed roughness.

• ***Pier and Abutment Parameters***: Size, geometry, spacing, number and orientation of the pier and abutment with respect to the main flow direction (i.e., angle of attack).

• ***Bed sediment parameters**:* Grain size distribution, mass density, particle shape, angle of repose and cohesiveness of the soil.

• ***Fluid Parameters***: Mass density, acceleration due to gravity and kinematic viscosity.

3- Experimental program

The laboratory flume used in this study is shown in figure (2). The main flume structure is a moulded glass fiber in steel stiffeners which has a 6.6 m length , 0.4 m wide and 0.4 m depth.

The flume consists of an inlet tank 1.0 m length at the upstream end, a working section 5.6 m . This tank consists of four screens to avoid any unwanted particles and debris in the working section of the flume.

The velocity of flow is measured by velocity meter as shown in figure (3), the velocity meter consists of control panel and micro-propeller. A micro-propeller is placed vertically in the water and the velocity is read by the control panel . The control panel measure the velocity with range of 2.5 to 100 cm/s.

1. Inlet tank
2. Water supplying pipe
3. Control gate
4. Point gauge
5. Tail control gate
6. Drain

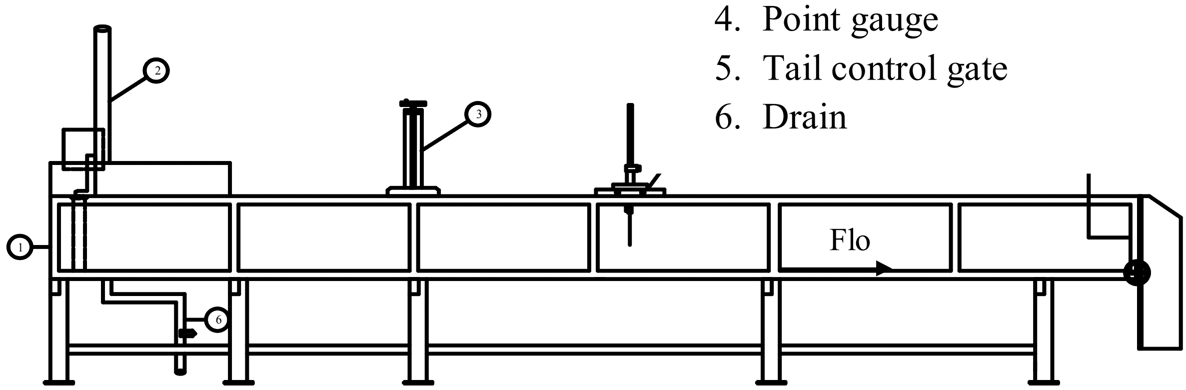


Figure (2) : Side View of the Flume

(a) Micro-Propeller (b) Control Panel Box

Figure (3): Velocity Measurement System

4- <u>Flow Conditions and Procedure</u>

All experiments were performed under steady subcritical flow with clear condition water and plain bed. The following procedure was repeated for each experimental run .

1. Sand was placed a long the flume with a thickness of sand was 10 cm. A scraper was used to level the sand bed, the water level was kept at 10 cm relative to flume solid bed , this might be a useful tool to scrape the sand bed to a desired level , i.e , 10 cm at any point of working section. Levels were also checked by using the point gauge and bubble level.
2. The pier and abutment models were fixed vertically in position within the second third of the working section (at 2.8m from flume entrance) .
3. The tail gates is raised and the working area was filled with water by hose from downstream portion of the flume in order to allow any air bubble to peculate out of the bed to avoid any settlement around the pier and abutment , and to prevent any abrupt high velocity which causes the disturbance in sand bed after starting pumping.
4. After starting pumping the tail gate was gradually lowered until the required water depth established in the flume. This depth is checked by a point gauge. The test was conducted over three hours which is considered as a suitable period to reach the equilibrium condition.

5. At the equilibrium time the scour depth was recorded by using a point gauge at the upstream apex of pier and abutment , at which the expected higher scour occurs. After this the flow was stopped , the flume was drained slowly to avoid any change of the scour hole , the sand is allowed to dry and the required measurements of sand bed upstream ,downstream longitudinally and transversely are recorded.

It should be noted that the maximum scour recorded at the upstream apex of pier or abutment.

5- Pier and Abutment Models

Plywood plates were used to construct different models of pier and abutment. Dimensions of these models are given in table (1).

These models were smoothly finished and painted to prevent any roughness , or changes in dimensions resulting from swelling when immersed in water for a long period of time.

The pier and abutment locations were chosen to be within the second third of flume to achieve a well-established flow. The pier and abutment were fixed by sticking in sand bed.

Table (1): Pier and abutment of test models

model No.	Circular pier model	Rectangular round nose abutment model	
	diameter	diameter	length
1	1.5	1.5	4.5
2	2.5	2.5	4.5
3	4	4	4.5

6- Sediment

The sand was spread in flume by 10 cm deep. Two types of uniform texture , cohesionless sand were used as bed material. Each type was prepared by sieving analysis , the first type was a pure finer sand with a medium particle size (d_{50}) of 0.29 mm , the second type was prepared by sieving analysis with a median particle size of 0.465 mm.

7- Equilibrium Time

In order to find the limited (equilibrium) scour time and adopt it in all tests for the purpose of eliminating the time effect , different velocities were used.

When the flow was established the pier and abutment models were introduced and bed reading at the notes were taken at various time intervals , after 1 , 2 , 3 , 4 , and 5 hours. It was noticed that almost change in scour depth occured at the notes of the pier and abutment after three hours. So that , the limited scour time in all test was taken about three hours . The scour around pier was occurred at the first of equilibrium time, while the scour in abutment was occurred at the last of equilibrium.

8- Analysis and discussion of results

Estimating the maximum possible scour depth around bridge piers and abutments is an important step in the design of bridge pier and abutment foundation. To examine such a phenomenon , sets of experiments were performed using cylindrical models .

There are several parameters which may control the scouring depth and the features of bed elevations upstream and downstream the pier and abutment.

- ***Pier and Abutment Size***

The size of pier and abutment has a direct influence on the scouring process , that is , the larger the size , the deeper the observed scour upstream of the pier and the larger the deposition at the downstream. This is due to the strength of the horseshoe vortex which is proportional to pier diameter , while the larger diameter of abutment gives smaller scour depth and smaller deposition at the downstream. This is due to the strength of the horseshoe vortex which is decreased when the flow is passing beside the abutment diameter and also because of the effects of wall flume and abutment diameter on reducing the flow velocity .

- ***Flow Depth***

The scour process is directly proportional to flow depth. Many investigators showed that the propagation of scour occurs with increasing flow depth , and the rate of this propagation decelerates up to a limiting value of flow depth at which its influence is absent.

- ***Flow Velocity***

The intensity of flow has direct influence on the scour depth regardless of flow depth and sediment size. A linear increase of scour depth with velocity is observed for velocities below the threshold value. This finding is in agreement with these of previous investigation for clear water condition and as cited in chapter three.

- ***Froude Number***

Dimensional analysis has shown that the Froude number ($Fr = v/\sqrt{gy}$) is a significant parameter for scour around pier and abutment. It was found that the scour increases with increasing Froude number since Froude number ($Fr = v/\sqrt{gy}$) is directly proportional with flow velocity and so the scour increases with increasing flow velocity.

- ***Sediment Size***

To investigate the influence of median grain size on the scouring process and hence on the depth of scour at the upstream nose of bridge pier and abutment , two different median grain sizes are used in experimental program. As can be found that the scour depth tends to decrease with increasing sediment size. Ettema (1980) explained that the reductions in scour depth for relatively large sediments are due to large particles impeding the erosion process at the base of the scour hole and dissipating some of the flow energy in the erosion zone (as cited in Melville 1997).

- ***Spacing Between Pier and Abutment***

The spacing between pier and abutment has a direct influence on the scouring process. That is , the scour depth increase with increasing the spacing between pier and abutment. Three models are used with different distances between pier and abutment in order to deduce the effect of spacing between pier and abutment on the scour depth. The Froude number remains the same for all runs.

A set of experiments of (30 runs) was conducted to evaluate the relationship between pier and abutment as shown in figures (4) and (5).

For more elucidation on the influence of spacing between pier and abutment the bed elevation sections are prepared and presented in figures (5-6a,d and c). It can be seen from these figures that the scouring process is greater when the spacing (x=10.5cm), while the other influencing parameters (flow depth and velocity) are kept constant.

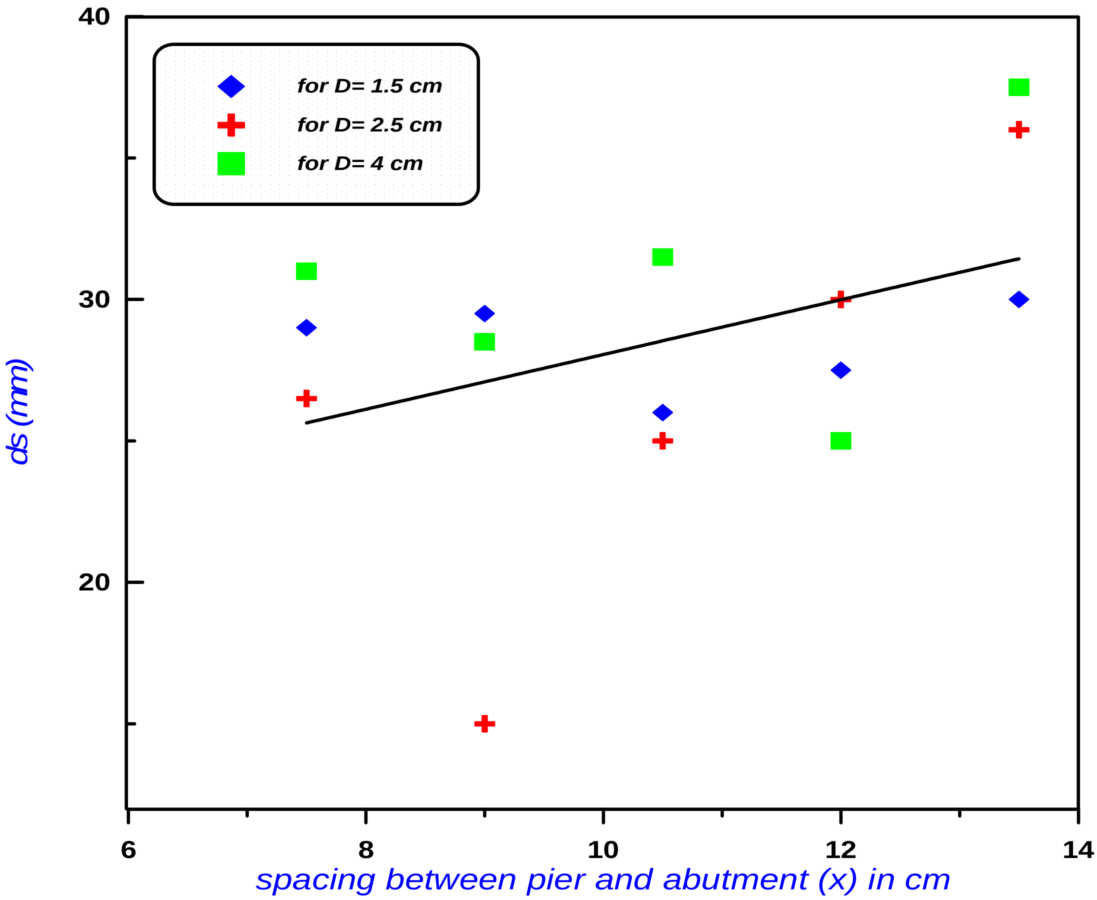


Figure (4): Development of Scour Depth with Spacing Between Pier and Abutment for Pier (d_{50}=0.29mm)

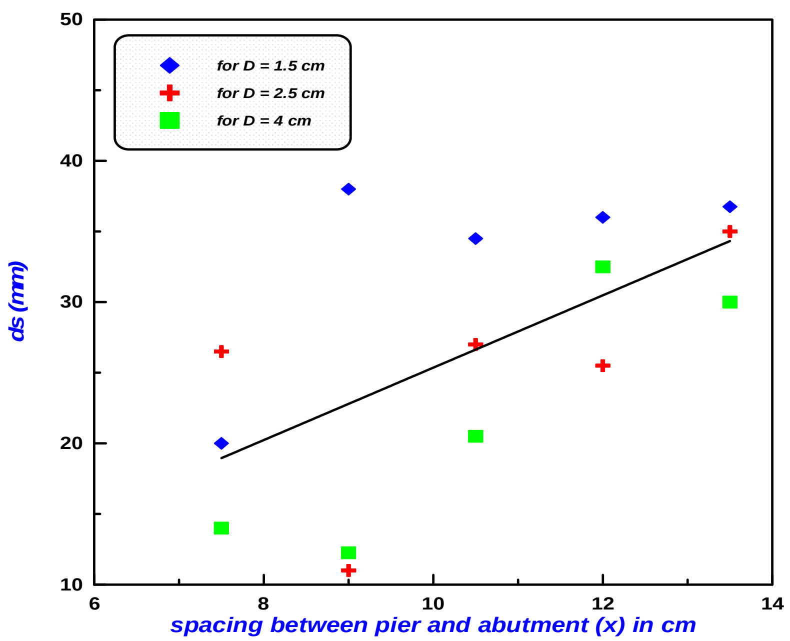


Figure (5): Development of Scour Depth with Spacing Between Pier and Abutment for Abutment (d_{50}=0.29mm) .

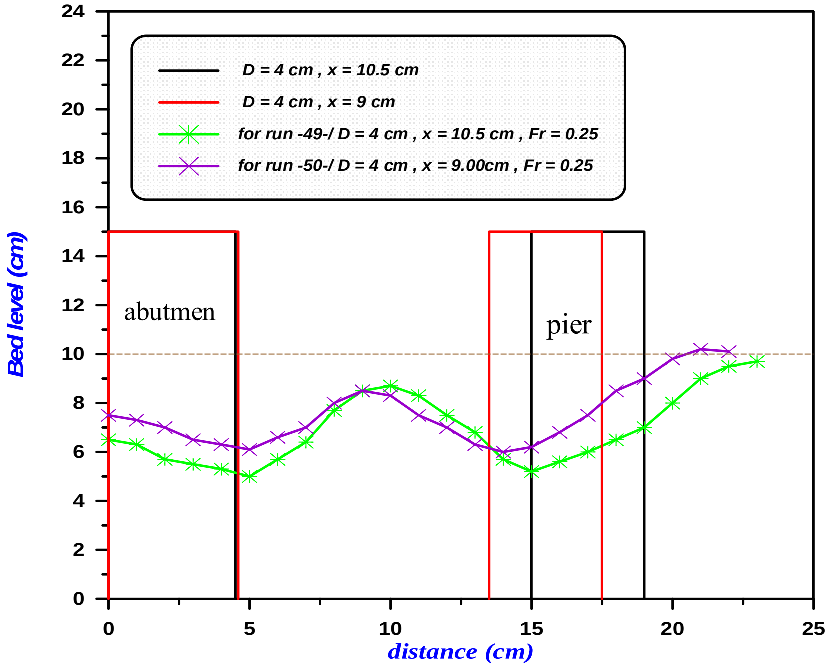
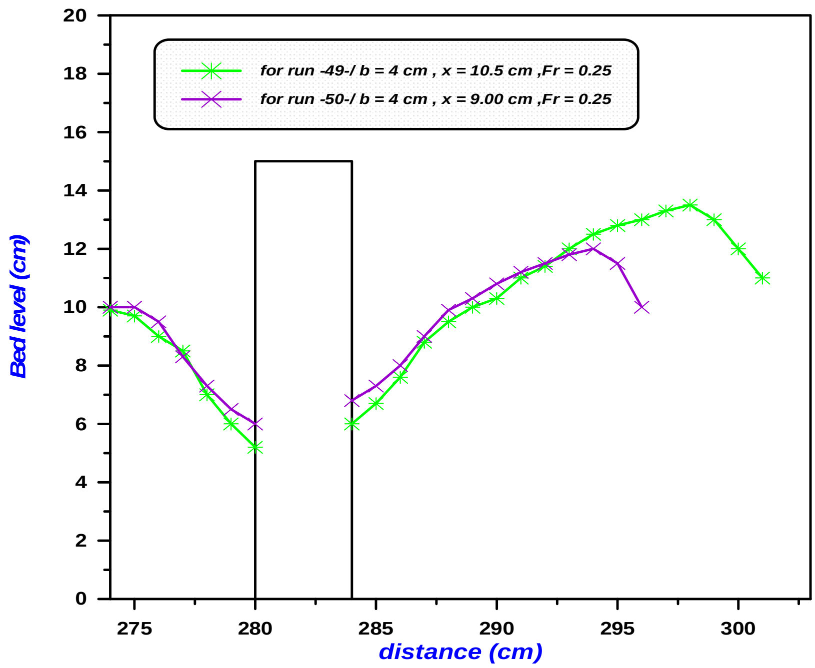
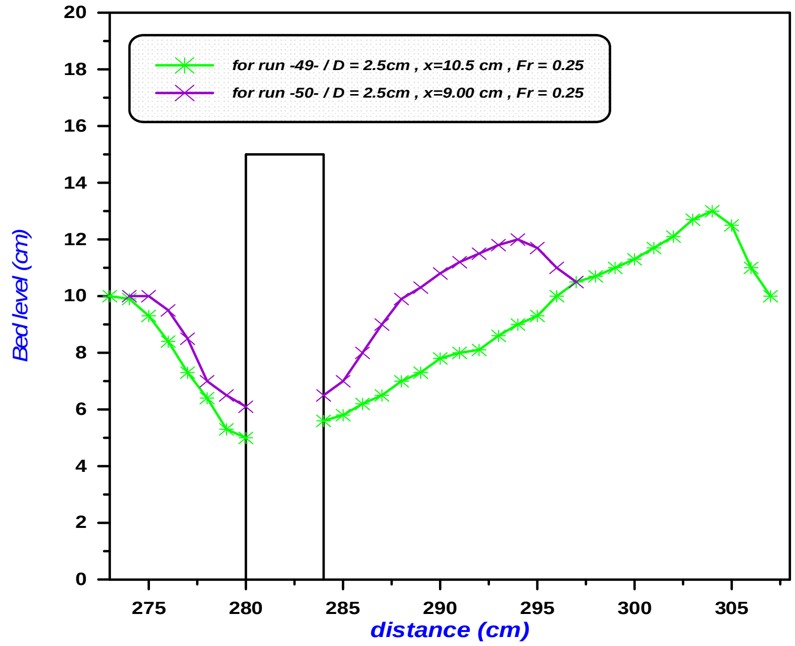


Figure (6a):Upstream Vertical Sections of the Bed Across the Flow Showing the Effect of Spacing Between Pier and Abutment on Scour Depth (d_{50}=0.465mm)



Figure(6b):Longitudinal Profile of the Bed for Pier Showing the Effect of Spacing Between Pier and Abutment on the Scour Depth (d_{50}=0.465mm)



Figure(6c):Longitudinal Profile of the Bed for Abutment Showing the Effect of Spacing Between Pier and Abutment on the Scour Depth (d_{50}=0.465mm)

The scour decreases when decreasing the spacing between pier and abutment, due to the interference between horseshoe vortex for pier and abutment. The interference between horseshoe vortex causes filling of sediment particle for pier and abutment as shown in (7)

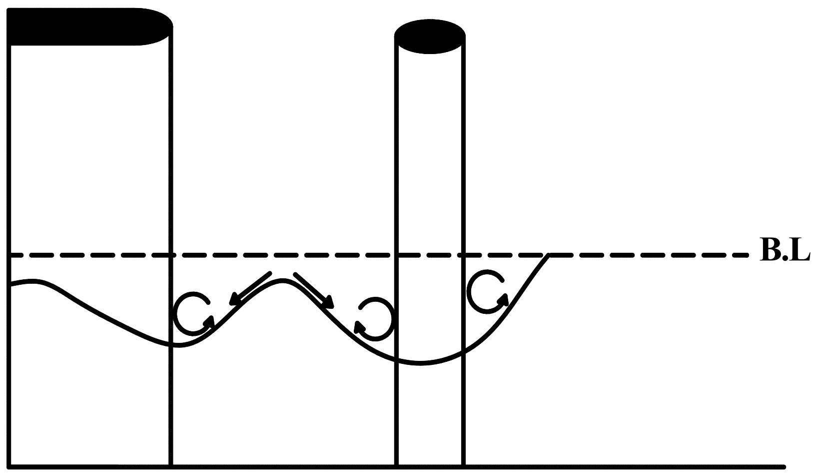


Figure (7):Mechanism of Scour When Decreasing the Spacing Between Pier and Abutment

9- Development of a New Formula

Local scour at piers and abutment , figure (8) ,is a function of many variables. Scour depth at a pier, depends on variables characterizing the fluid , flow , bed sediment , pier and abutment. Thus , the following functional relationship can be describe scour depth (Ettema et al 1998):

$$ds = f(\rho, \mu . v, y, g, d_{50}, v_c, D) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

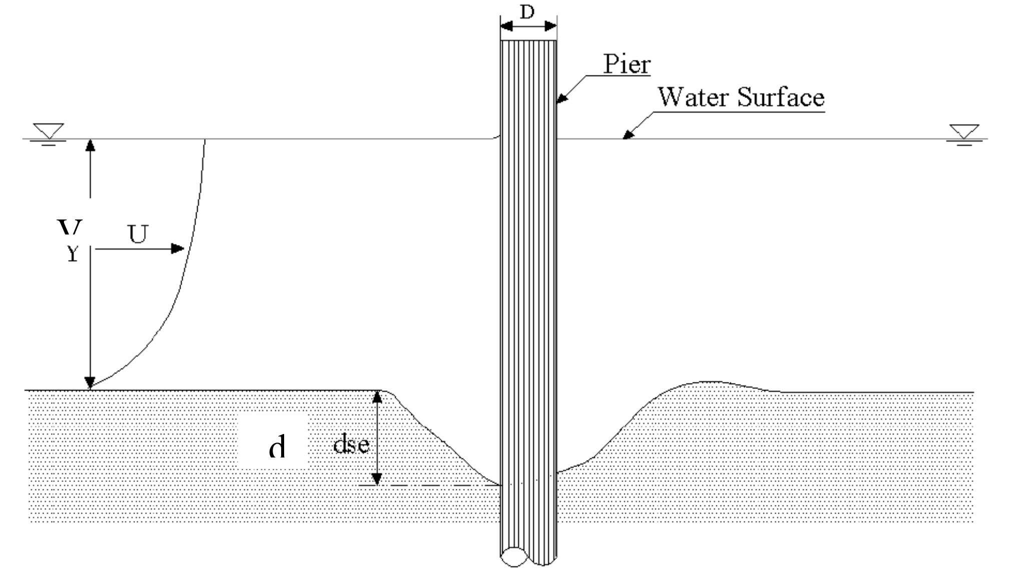


Figure (8): Flow and Local Scour Around a Circular Pier (at Bateni et al.2007)

The dimensional analysis technique was utilized by using Rayleigh method in order to formulate the experimental data which can be used to predict scour depth around pier and abutment.

$$ds = f(\rho, \mu . v, y, g, d_{50}, v_c, D, x) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

To obtain dimensionless groups from these parameters their dimensions in terms of (M, L, T) are written as:

$$\therefore \frac{ds}{D} = f\left(Fr, \frac{v}{v_c}, \frac{y}{D}, \frac{d_{50}}{D}, \frac{x}{D}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

The computer package (STATISTICA) was used to make analysis for the equation through a non-linear regression analysis using the data in table (2-9) for pier and abutment.

For pier:

$$\frac{ds_p}{D} = 60\left(\frac{x}{D}\right)^{0.08}\left(\frac{v}{v_c}\right)^{6.74}\left(\frac{d_{50}}{D}\right)^{0.97}\left(\frac{y}{D}\right)^{-0.24} Fr^{-1.89} \ldots\ldots\ldots\ldots\ldots (4)$$

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The coefficient of determination (R^2) for this formula is (0.862)

For abutment:

$$\frac{ds_a}{D} = 81.41\left(\frac{x}{D}\right)^{0.37}\left(\frac{v}{v_c}\right)^{10.04}\left(\frac{d_{50}}{D}\right)^{1.8}\left(\frac{y}{D}\right)^{-1.06} Fr^{-5.18} \ldots\ldots\ldots\ldots\ldots (5)$$

It is found that the coefficient of determination of this formula (0.92)

In:

ds_p is the depth of scour around the pier, ds_a = Depth of scour around the abutment, D Diameter of pier or abutment, d_{50} Median size of the sediment particle, Fr Froude number, g Acceleration due to gravity, ρ Water density, Re Reynolds number, V Mean approach flow velocity, V_c Critical velocity, y Flow depth, μ Dynamic viscosity, x spacing between pier and abutment(face to face).

Another data was used to test the equations of pier and abutment, a statistical comparison of equation is used to show the convergency of the predicted to the observed records , the values of R^2 are given good agreement for all data as shown in figures (9) and (10).

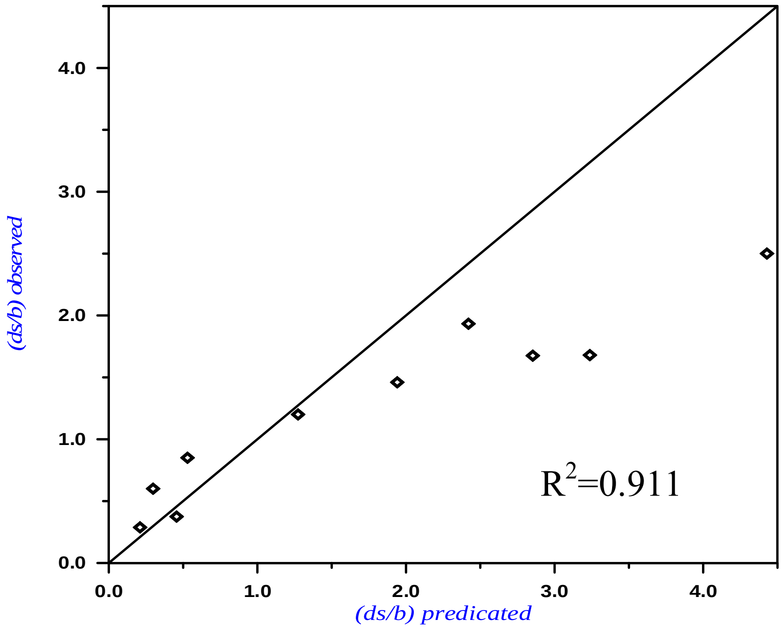

Figure (9) : Comparison of Equation (4) with Experimental Data for Pier

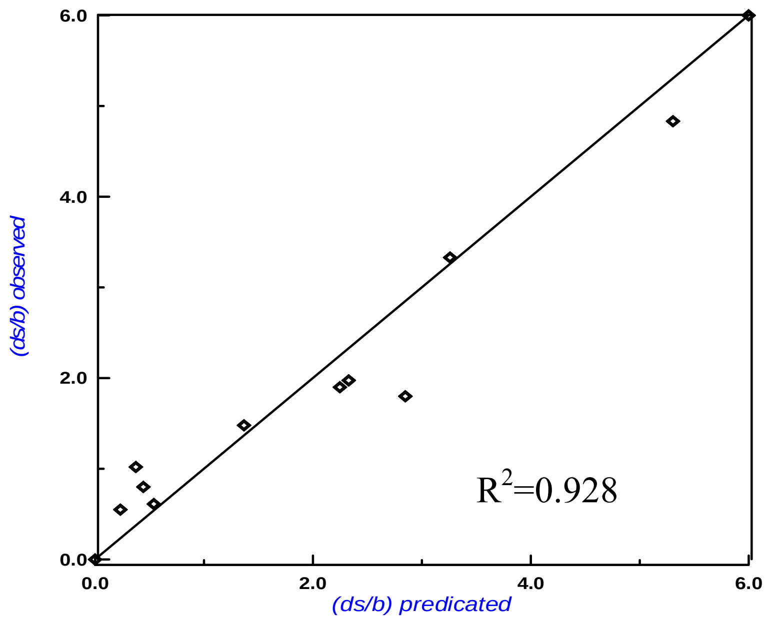

Figure (10) : Comparison of Equation (5) with Experimental Data for Abutment

Table (2): Development of scour depth (ds mm) with (Fr) for pier (d_{50}=0.29 mm, x=13.5 cm).

D (cm) / Fr		1.5	2.5	4
0.178	V=0.13m/sec Y=5.45cm	6	26	9
0.181	V=0.17m/sec Y=9.00cm	26	40	38.5
0.188	V=0.15m/sec Y=6.5cm	11.5	20	18.5
0.219	V=0.16m/sec Y=5.45cm	29	34	35.5
0.250	V=0.17m/sec Y=4.7cm	30	36	37.5

Table (3): Development of scour depth (ds mm) with (Fr) for abutment (d_{50}=0.29 mm, x=13.5 cm).

D*b(cm) / Fr		1.5*4.5	2.5*4.5	4*4.5
0.178	V=0.13m/sec Y=5.45cm	5	13	0.5
0.181	V=0.17m/sec Y=9.00cm	48	52.5	51
0.188	V=0.15m/sec Y=6.5cm	21	29	11.5
0.219	V=0.16m/sec Y=5.45cm	35	40	29.75
0.250	V=0.17m/sec Y=4.7cm	36.75	35	30

Table (4): Development of scour depth (ds mm) with (Fr) for pier (d50=0.465 mm, x=13.5 cm).

D (cm) / Fr		1.5	2.5	4
0.178	V=0.13m/sec Y=5.45cm	4	5	8.5
0.181	V=0.17m/sec Y=9.00cm	16.5	24.5	24
0.188	V=0.15m/sec Y=6.5cm	12	16.5	13.5
0.219	V=0.16m/sec Y=5.45cm	13	18.5	24
0.250	V=0.17m/sec Y=4.7cm	26	29	23

Table (5): Development of scour depth (ds mm) with (Fr) for abutment (d50=0.465 mm, x=13.5 mm).

D*b(cm) / Fr		1.5*4.5	2.5*4.5	4*4.5
0.178	V=0.13m/sec Y=5.45cm	11	5.5	5
0.181	V=0.17m/sec Y=9.00cm	30.5	36	54
0.188	V=0.15m/sec Y=6.5cm	28	33	34.5
0.219	V=0.16m/sec Y=5.45cm	27.5	31	28
0.250	V=0.17m/sec Y=4.7cm	48	39	21

Table (6): Development of scour depth (ds mm) with distance between pier and abutment (X) for pier (d_{50}=0.29 mm, Fr=0.25).

D (cm) / X(cm)	1.5	2.5	4
13.5	30	36	37.5
12	27.5	30	25
10.5	26	25	31.5
9	29.5	15	28.5
7.5	29	26.5	31

Table (7): Development of scour depth (ds mm) with distance between pier and abutment (X) for abutment (d_{50}=0.29 mm, Fr=0.25).

D*b(cm) / X(cm)	1.5*4.5	2.5*4.5	4*4.5
13.5	36.75	35	30
12	36	25.5	32.5
10.5	34.5	27	20.5
9	38	11	12.25
7.5	20	6.5	14

Table (8): Development of scour depth (ds mm) with distance between pier and abutment (X) for pier (d_{50}=0.465 mm, Fr=0.25).

D (cm) / X(cm)	1.5	2.5	4
13.5	26	29	23
12	29	34	38
10.5	27.5	31.5	48
9	34	34	40
7.5	31.5	36.5	32.5

Table (9): Development of scour depth (ds mm) with distance between pier and abutment (X) for abutment (d_{50}=0.465 mm, Fr=0.25).

D*b(cm) / X(cm)	1.5*4.5	2.5*4.5	4*4.5
13.5	48	39	21
12	37	37	46
10.5	43.5	41.5	50
9	43	36	39
7.5	42	37.5	36

10- Conclusions

The problem of local scour around the circular pier and abutment has been studied experimentally.

Under the limitations(subcritical flow , clear-water condition and using uniform cohesionless sand as bed material) imposed on this investigation the following conclusions can be drawn.

1. The scour in pier occurred at the first of equilibrium time, while in the abutment the scour occurred at the last of equilibrium time.
2. The increase of pier diameter was increase the scour depth, while in the abutment the increasing at diameter of abutment was given decreasing of the scour depth.
3. Experiments showed that the increase of the scour depth around pier and abutment with decreasing median size of bed martial (d_{50}).
4. The scour depth increased for pier and abutment by increasing the spacing between them.
5. The formula developed for the maximum depth of scour Eqs (4)and (5) were derived by using the dimensional analysis techniques. These formulas were restricted to the laboratory data. The scour depth was represented as a function of Froude number , spacing between pier and abutment , flow velocity , flow depth , sediment size and Pier and abutment size. The formulas gave a good determination coefficient between the measured and predicated data, and gave an idea to evaluate the maximum scour depth for similar conditions to those covered in this study.

11-References

1) Breusers, H.N.C., Nicollet, G. and Shen, H.W, (1977) “Local scour around cylindrical piers” , Journal of Hydraulic Research, Vol. 15, No. 3 , pp.211-252.
2) Khsaf , S. I, (2010) “A study of scour around Al-Kufa bridge piers” , Kufa Engineering Journal.Vol.1,No.1,2010, University of Kufa / College Engineering / Civil Department.
3) Lagasse, P.F. and Richardson, E.V, (2001), “ASCE compendium of stream stability and bridge scour papers”, Journal of Hydraulic Engineering, ASCE, Vol.127,No. 7,pp.531-533.
4) Maatooq , J.S, (1999) “Evaluation analysis and new concepts of scour process around bridge pier” ,Ph.D. Thesis ,The University of Technology.
5) Melivlle, B.W,(1997), “Pier and Abutment Scour: INTEGRATED APPROACH” ”, Journal of Hydraulic Engineering, ASCE, Vol.123, No.2,February, 1997, pp.125-136.
6) Raudkivi,A.J. and Ettema, R, (1977), “Effect of Sediment Gradation on Clear-Water Scour and Measurement of Scour Depth”, Journal of the Hydraulics Division, ASCE, Vol.103, No.HY10,pp.1209-1213.
7) S. A. Ansari, U. C. Kothyari and K. G. Rangaraju ,(2002) “Influence of Cohesion on Scour Around Bridge Piers” , Journal of Hydraulic Research , Vol. 40, 2002, No. 6 , pp.717-729, Dept. Of Civil Engineering, Aligarh Muslim University, Aligarh, INDIA