J. King Saud Univ., Vol. 19, *Eng. Sci.* (2), pp. 195-207, Riyadh (1427H./2007)

Physical Modeling of Local Scouring around Bridge Piers in Erodable Bed

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(Received 05 January 2005; accepted for publication 11 November 2006)

Abstract. The construction of bridges in alluvial channels will cause a contraction in the waterway at the bridge site. The contraction in the waterway will cause a significant scour at that site. Many bridges failed around the world because of extreme scour around piers. The vertical reduction in the riverbed measured from bed level prior to the commencement of the scour action is called a scour depth. Usually, a structural engineer checks the safety of the bridge components while an architect designs the bridge shape. The hydraulic engineer predicts the scour depth at the bridge site for a design flood before the construction and evaluates the need for scour protection at the bridge site after construction. Local scour at pier site has been subjected to many investigations throughout the world and only very limited success has been achieved by the attempts to model scour computationally, and physical model remains the principal tool employed for studying the scour at the bridges and the site of other hydraulic structures. Numerous prediction formulas and design charts have been established as a result of laboratory and field investigations. In this study, a physical model was used to simulate the local scour around piers. The main variables affecting the local scour around piers in alluvial bed of the real system were simulated and studied in the experimentation of the physical model. Dimensional analysis technique is used to get dimensionless groups for the variables governing local scour around bridge pier. Data gathered from experiments conducted on the physical model is used to study the effects of flow depth, velocity of approach, angle of pier inclination, pier shape, and pier numbers on the local scour depth.

Keywords: Bridge pier, Mobile bed, Physical model, Local scour, Governing variables.

Introduction

Scour is a natural phenomenon caused by erosive action of the flowing water on the bed and banks of alluvial channels. Scour also occurs at the coastal regions as a result of the passage of waves. The construction of bridges in alluvial channels will cause a contraction in the waterway at the bridge site. The contraction in the waterway will cause significant scour at that site. Many bridges failed around the world because of extreme scour around piers.

Total scour at the bridge site is comprised of three components, namely the aggradation and degradation, contraction scour, and the local scour. Aggradation involves the deposition of materials eroded from other sections of a stream reach, whereas degradation involves the lowering or scouring of the bed of a stream. This scour component is natural and has a long-term effect on streambed elevation changes. The contraction scour results from a reduction of the flow area at the bridge site due to the encroachment into the flood plain or the main channel by the piers, abutments and approach embankments.

Local scour involves the removal of material from around piers, abutments, spurs, and embankments. It is caused by an acceleration of the flow and resulting vortices induced by the flow obstructions. Local scour occurred at bridge piers are caused by the interference of the piers with flowing water. This interference will result in a considerable increase in the mean velocity of the flowing water in the channel section. Scouring vortex will be developed when the fast moving flow near the water surface (at the location of the maximum velocity in the channel section) strikes the blunt nose of the pier and deflected towards the bed where the flow velocity is low. Portion of the deflected surface flow will dive downwards and outwards. This will act as a vacuum cleaner and suck the soil particles at the pier site and result in a considerable increase in the scouring depth at this location. Local scour can occur as either ‘clear-water scour’ or ‘live-bed scour’. In clear-water scour, bed materials are removed from the scour hole, but not replenished by the approach flow while in live-bed scour the scour hole is continually supplied with sediment by the approach flow and an equilibrium is attained when, over a period of time, the average amount of sediment transport into the scour hole by the approach flow is equal to the average amount of sediment removed from the scour hole. Under these conditions, the local scour depth fluctuates periodically about a mean value. The interaction between the flow around a bridge pier and the erodible sediment bed surrounding it is very complex [1]. In fact, the phenomenon is so involved that only very limited success has been achieved by the attempts to model scour computationally, and physical model remains the principal tool employed for estimating the expected depths of scour. In this paper, a physical model was used to investigate the effect of the variables affecting the clear-water local scour around piers.

Selected Local Scour Formulas

Scour around bridge piers has been the subject of many investigations throughout the world, and numerous scour prediction formulas have been published. Selected scour formulas related to the studied topic are described below. Shen [2] suggested the following equation:

$$\frac{d_s}{b} = k_1 k_2 \frac{v}{2g} - \frac{30d}{b} \tag{1}$$

where k_1 is a coefficient depending on pier dimensions, k_2 is a coefficient depending on the ratio of flowing depth to pier width and pier's Froude number, d_s is scour depth, v is the mean velocity of flow, b is pier width, g is acceleration due to gravity, and d is bed particle size. The unit of d in Eq. (1) is in centimeters, while the units of the rest of the parameters are in meters and seconds.

The scour depth is related to the Pier Reynolds number which is defined as the flow velocity multiplied by pier width divided by the kinematic viscosity of the flowing water, since the horseshoe vortex system is a function of the Pier Reynolds number. Shen *et al*. [3] used laboratory data and limited field data to develop the following clear-water scour equation:

$$d_s = 0.00022\ R^{0.619} \tag{2}$$

where R is Pier Reynolds number. Equation (2) is valid only for a bed of particle size of 0.52 mm or less. The following linear equation was given by Shen [2] to estimate the scour depth:

$$d_s = 1.4\ b \tag{3}$$

Also, there were several non-linear formulas proposed by many researchers for the purpose of estimating the local scour depth, but the following formulas are famous and given by Cheremisinoff [1]:

$$d_s = 1.05\ k\ b^{0.75} \tag{4}$$

$$d_s = 3\ b^{0.8} \tag{5}$$

where k is a coefficient depending on pier shape and the value of k is equal to 1 for cylindrical pier and 1.4 for rectangular pier.

Equations (4) and (5) are applicable for a pier which is aligned with the flow direction. For piers which are inclined by an angle θ from the flow direction (called the angle of attack), the value of this coefficient k_θ is equal to 1.1 as given by Melville and Sutherland [4]. They developed a scour model based on extensive laboratory experiments.

$$d_s = K_i K_d K_y K_\alpha K_s b \tag{6}$$

where K_i is flow intensity factor, K_d is sediment size factor, K_y is flow depth factor, K_α is pier alignment factor, and K_s is pier shape factor.

Qadar [5] studied the mechanism of the local scour around the bridge pier using physical model. The local scour depth is related to some of the basic characteristics of the scouring vortex as described by the following formula [5]:

$$d_s = 538(C_0)^{128} \tag{7}$$

where C_0 is the initial strength of the vortex. Equation (7) is applicable for sediments with a diameter up to 0.5 mm.

Colorado State University's pier scour equation is commonly used within the United States and this equation is described by the following equation [6]:

$$d_s = 2.0K_1K_2K_3\left(\frac{b}{y}\right)^{0.65}F^{0.43} \tag{8}$$

where y is the flow depth directly upstream of the pier, K_1 is the shape factor for pier, K_2 is the factor for the angle of attack for the flow, K_3 factor for bed condition, and F is Froude number.

Melville [7] proposed an integrated approach for estimating the scour in bridge sites resulting from the combined effect of piers and abutments. This approach was based on the data which was obtained from physical model for three types of piers, namely pier with a square nose, pier with sharp nose and cylindrical pier. This approach was summarized in several design charts to assist the user to estimate the scour depth based on the flow condition, sediment size, foundation shape, alignment of the bridge, and channel geometry. Ettema *et al.* [8] highlighted the importance of considering the influence of turbulence on equilibrium local scour depth. Chang *et al.* [9] developed a method for computing the equilibrium scour depth based on the mixing non-uniform sediment layer. Mia and Nago [10] proposed a designed method to predict the local scour depth with time considering sediment transport equation. Chiew and Lim [11] conducted experimental work to study the effect of using a layer of riprap to reduce local scour.

Theoretical Approach

The dimensional analysis technique using Buckingham π-theorem was applied to obtain dimensionless groups from the variables governing the local scour depth in a mobile bed resulting from constricting the flow by the bridge piers. These variables are as follows:

1) The flow characteristics in the open channels represented by the average velocity, V and the water depth, y.

2) Characteristics of the flowing fluid represented by the mass density, ρ and the dynamic viscosity, μ .

3) Geometrical characteristics of the pier which include pier length, L , pier width, b, angle of attack, θ, and the spacing between piers, x.

4) Characteristics of the bed material for the open channel represented by the average particle size, d, the local scour depth, d_s , and finally the acceleration due to gravity, g.

$$\phi_1(V, y, \rho, \mu, L, b, \theta, x, d, d_s, g) = 0 \tag{9}$$

The repeating variables chosen by the authors are the average velocity of the flow, V, the pier width, b, and the mass density, ρ. The total variables in Eq. (9) are 11 and the repeating variables are 3, and according to the π- theorem used in the analysis the dimensionless groups obtained will be 8 as shown below:

$$d_s = \phi_2 (\pi_1, \pi_2 , \pi_3 , \pi_4, \pi_5, \pi_6 , \pi_7 , \pi_8) \tag{10}$$

After the application of the dimensional analysis technique, Eq. (10) can be changed to the following form:

$$d_s = \phi_2 \ (\frac{bg}{V^2}, \frac{L}{b}, \frac{d_s}{b}, \frac{y}{b}, \frac{d}{b}, \frac{\upsilon}{Vb}, \theta, \frac{x}{b}) \tag{11}$$

where $\nu = \mu / \rho$.

After rearranging Eq. (11), we get:

$$\frac{d_s}{b} = \phi_3 (\frac{V^2}{bg}, \frac{b}{L}, \frac{b}{y}, \frac{b}{d}, \frac{Vb}{\upsilon}, \theta, \frac{x}{b}) \tag{12}$$

United States Department of Transportation [6] recommended that the pier length has no appreciable effect on scour depth. So, the effect of the dimensionless ratio b/L will be neglected. Simons and Sentürk [12] found that the size of the bed materials in the sand size range has little effect on the scour depth. So, the significance of the dimensionless ratio b/d and the dimensionless b/L will not be considered in this study. Equation (12) can be simplified to the following form:

$$\frac{d_s}{b} = \phi(F_p, \frac{b}{y}, R_p, \theta, \frac{x}{b}) \tag{13}$$

where F_p is pier's Froude number and R_p is the pier's Reynolds number.

In case of piers which are inclined (skewed) at an angle θ with the flow direction, as shown in Fig. 1, the projected dimension of the pier in the flow direction will be used for computing Reynolds number and Froude number for the pier. Ettema *et al.* [13] highlighted the effect of inclined pier on local scour and they proposed a skew factor to account for pier inclination in computing local scour depth. The skew factor depends on both the skew angle (θ) of the pier and its aspect ratio (L/b).

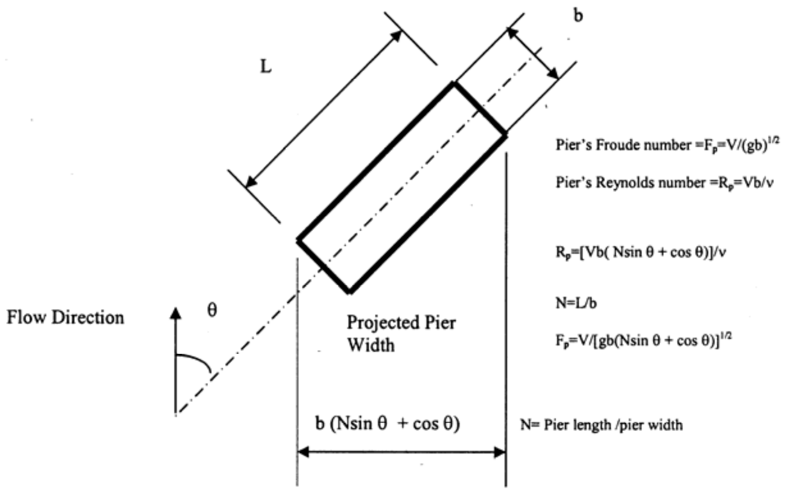
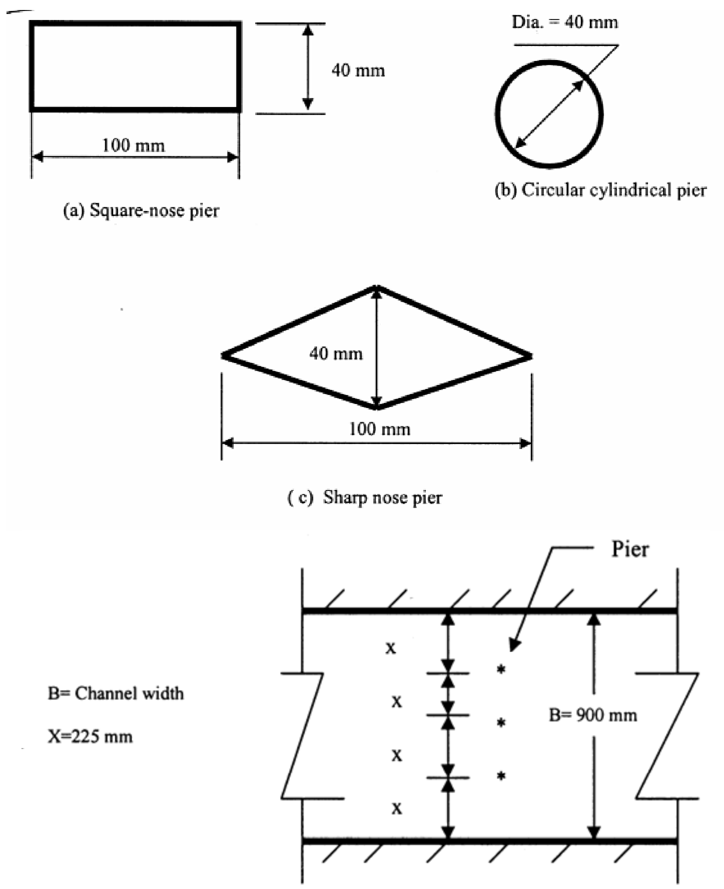


Fig. 1. Geometry of square nose skewed pier.

The Physical Model

The physical model used for simulating the local scour around piers consisted of a 20-m glass-sided tilted flume which has a rectangular cross-section (90 cm wide and 60 cm high). To simulate bed materials, compacted sand with 0.45 mm average particle size (d_{50}) is used in the flume bed. Hard teak wood was used to simulate the piers and three pier shapes were used. These shapes were squared nose (Fig. 2(a)), circular cylindrical

(Fig. 2 (b)), and the sharp nose (Fig. 2(c)). The physical model has 1/100 horizontal scale and 1/25 vertical scale. For a specified discharge, the effects of pier shape and number were investigated using single pier, two piers, three piers, four piers, and five piers from the same shape (Fig. 2 (d)). The scour depth was measured for each run after it was reached to the equilibrium condition (no change in scour depth with the time). After completing one run, the sand removed by the flowing water was replaced. The runs were repeated for other shapes as well. The effect of the flow on the local scour depth was studied by using different values of the discharge starting from 10 l/s up to 26 l/s, the discharges were measured using a V-shape weir which was calibrated before use. For fixed discharge, the effect of pier inclination or angle of attack was studied using the squared nose pier with an inclination angles of 0, 15, 30, 45 and 60 degrees. Table 1 shows the data collected from the experimentation conducted on the physical model.



(d) A sample of three piers arrangement

Fig. 2. Shapes, dimensions and arrangements of the piers used in the physical model.

Table 1. Results from the experiments conducted on the physical model

Pier Shape	Number of Piers	Discharge (l/s)	Diameter of Particle (mm)	Angle of Attack (degree)	Local Scour Depth (cm)	Local Scour Area (cm^2)
Rectangular	1	10	0.45	0	7.6	168
Rectangular	2	10	0.45	0	8.0	192
Rectangular	3	10	0.45	0	8.4	224
Rectangular	4	10	0.45	0	9.0	240
Rectangular	5	10	0.45	0	9.8	248
Circular	1	10	0.45	0	7.0	144
Circular	2	10	0.45	0	7.5	164
Circular	3	10	0.45	0	8.0	186
Circular	4	10	0.45	0	8.6	192
Circular	5	10	0.45	0	9.2	202
Streamlined	1	10	0.45	0	6.6	150
Streamlined	2	10	0.45	0	7.0	185
Streamlined	3	10	0.45	0	7.7	192
Streamlined	4	10	0.45	0	8.2	200
Streamlined	5	10	0.45	0	8.8	210
Rectangular	1	10	0.45	15	7.8	320
Rectangular	1	10	0.45	30	8.0	315
Rectangular	1	10	0.45	45	8.8	353
Rectangular	1	10	0.45	60	9.6	368
Rectangular	1	16	0.45	0	8.6	175
Rectangular	1	19	0.45	0	9.2	208
Rectangular	1	22	0.45	0	9.8	230
Rectangular	1	26	0.45	0	10.5	240

Results and Discussion

The dimensional analysis technique is performed to get the variables affecting the local scour depth around bridge piers in dimensionless groups. Data from the physical model is used to describe the variation of these dimensionless groups with the local scour. As discussed earlier, the width of pier has a direct effect on local scour depth and Eqs. (1) to (6) described this variation. The flow depth has a direct effect on scour depth. Data from physical model showed that doubling the flow depth resulted in local scour depth by more than 200% as shown in Fig. 3. Data from the physical model showed that velocity of approach has a direct effect on local scour depth. The effect of the velocity of approach is considered by studying the effect of pier's Reynolds number with local scour depth and pier's Froude number with local scour depth. Figures 4 and 5 showed this variation. The angle of attack has an appreciable effect on local scour depth. The local scour depth increases by 15% when the angle of inclination of the pier was changed from 0^o to 45^o as shown in Fig. 6. Simons and Sentürk [12] showed the local scour depth increases by 10% when the angle of the attack of the flow increases to 45^o and the length of the inclined pier will increase the scour depth up to 33%. Pier shape and number has a significant effect on local scour depth. The pier number is described by contraction ratio (summation of the openings between piers divided by total channel width). Figures 7 and 8 showed the effect of the pier shape and number on the local scour depth and local scour area respectively. Data from physical model showed that local scour depth for square-nose pier was 9% and 15% larger than the measured local scour depth for the circular cylindrical pier and sharp nose pier respectively. Simons and Sentürk [12] showed that the local scour caused by using square-nose piers in the bridge is 10% and 20% larger than the scour caused by using the round nose piers and sharp nose piers respectively. The reduction in local scour depth and local scour area by using the piers of cylindrical shape and piers of sharp nose shape in bridges is attributed to the streamlining of the front end of these piers which certainly reduce the strength of the horseshoe vortex. As a result, the local scour depth and area are also reduced.

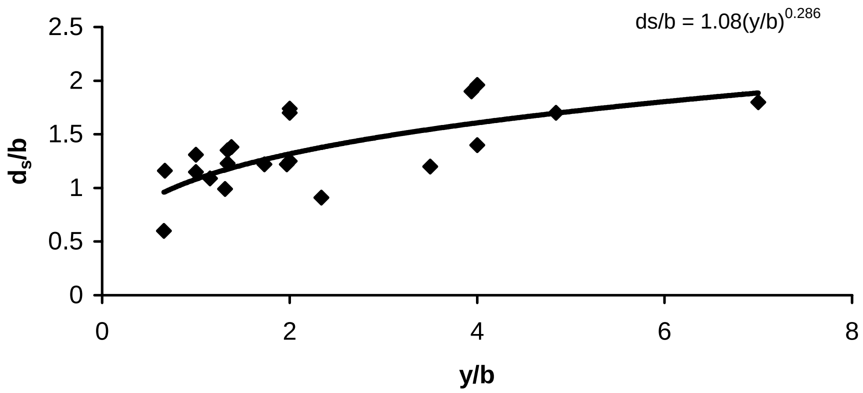


Fig. 3. Variation of flow depth with local scour depth.

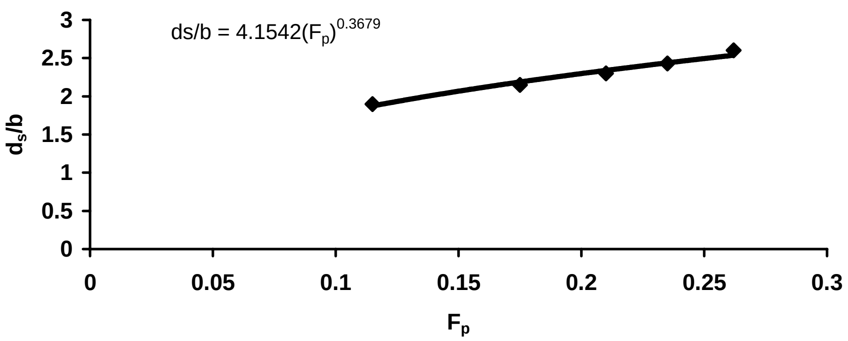


Fig. 4. Variation of Pier Froude number withlocal scour depth.

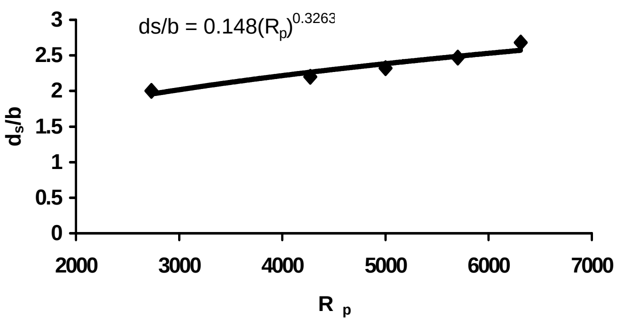


Fig. 5. Variation of pier's Reynolds number with local scour depth.

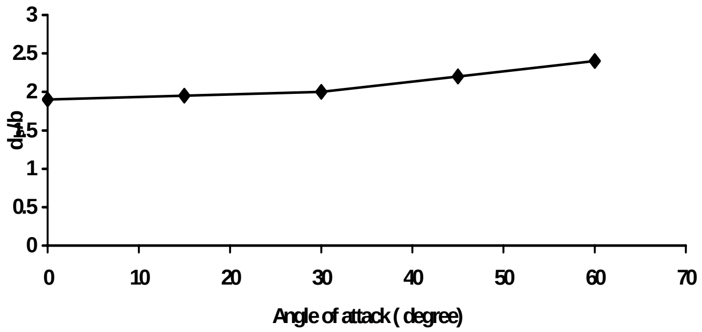


Fig. 6. Effects of pier inclination on local scour depth.

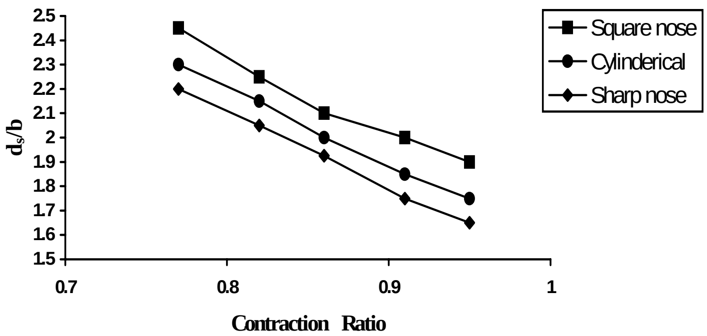


Fig. 7. Effect of the contraction ratio on the local scour depth.

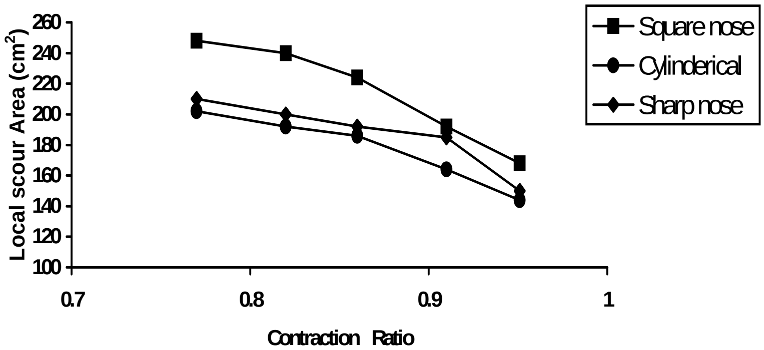


Fig. 8. Effect of the contraction ratio on the size of local scour area.

Conclusions

Local scour around bridge pier located in an erodible bed is a complicated problem and only very limited success has been made to model the local scour computationally. Physical model remains the principal tool employed to estimate local scour depth. The data collected from the physical model showed that flow, pier geometry and the contraction ratio have an appreciable effect on local scour at the bridge site. The selection of the pier width and shape can help in the reduction of the local scour depth. A reduction of 15% in local scour depth can be obtained by using a streamlined pier shape instead of using a squared nose pier. The local scour depth increased by 6%, 10%, 20% and 30% by using two piers, three piers, four piers and five piers respectively. The alignment of the bridge piers bridge with the flow also affects the local scours depth, such that local scour depth increases to 15% when the angle of inclination of the pier was changed from 0^o to 45^o . The flow depth and velocity have an appreciable effect on the local scour and the data from the physical model showed that doubling the flow depth will result in more than 200% increase in the scour depth. It is necessary to involve the hydraulic engineers in the design stage for bridges to take care of hydraulic effects of the flow on these bridges. Many methods were proposed for estimating the local scour around piers at the bridge site, but these methods were based mainly on the data collected from physical models and field data need to be collected to verify these methods.

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النمذجة الفيزيائية لتأث ا تغ ات ا تحكمة با ت ا وفعى حول دعامات ا سور فاع قابل للتآكل

تامر أ د مد ، ومكت جوهري مكت مد نور، وعبد ا ليم غزا ، وبدر النساء يوسف، وكاتيون سعيد

قسم الهندسة المدنية ، كلية الهندسة ، جامعة بترا الماليزية ، ٤٣٤٠٠ سالنكور ، ماليزيا

(قدِّم للنشر في ٠٥/٠١/٢٠٠٥م ؛ وقبل للنشر في ١١/١١/٢٠٠٦م)

ملخص البحث. إن إنشاء الجسور في القنوات الرسوبية سوف يسبب تقلص في مسار الماء في موقع تلك الجسور، وإن هذا التقلص يؤدي أيضا إلى زيادة ملحوظة في عمق الحت في مواقع الجسور. ومما تجدر الإشارة إليه أن كثير من الجسور حول العالم قد انهارت بسبب الحت الموقعي عند دعامات هذه الجسور. ويعرف الحت الموقعى بأنه النقص العمودي في منسوب قاع النهر مقارنة مع المنسوب الأصلي قبل الحت. إن المهندس الإنشائي يهتم بسلامة أجزاء الجسر بينما يصمم المهندس المعماري شكل الجسر وينصب اهتمام مهندس المياه بحساب الحت الموقعي قبل إنشاء الجسر مستخدما أعظم فيضان متوقع وكذلك لمعالجة مشكلة الحت عند موقع الجسر بعد الإنشاء.

تمت دراسة الحت الموقعي عند الجسور بواسطة عدد من الباحثين حول العالم، لكن هناك نجاح محدود لنمذجة الحت حسابيا، وإن النموذج الفيزيائي ظل الوسيلة الوحيدة لدراسة الحت الموقعي عند الجسور والمنشآت الهيدروليكية. وقد اقترحت معا دلالات ورسوم بيانية ناتجة عن معلومات مختبرية لغرض استخدامها في تخمين عمق الحت عند الجسور.

تم استخدام نموذج فيزيائي في هذه الدراسة لغرض تشبيه الحت الموقعي حول دعامات الجسور. وقد تم اعتبار المتغيرات الأساسية التي تؤثر في الحت الموقعي في القاع قابلة للتآكل خلال التجارب علي النموذج الفيزيائي. واستخدام التحليل البعدي لغرض الحصول على مجاميع لا بعدية تحتوي على المتغيرات التي تتحكم بالحت الموقعي حول دعامات الجسور. تم الحصول على بيانات أثناء إجراء التجارب على النموذج الفيزيائي بهدف دراسة تأثير عمق ماء الجريان, وسرعة الاقتراب, وزاوية ميل الدعامة عن اتجاه الجريان, وشكل الدعامة وعدد الدعامات على عمق الحت الموقعي .