UNIVERSITI PUTRA MALAYSIA

PHYSICAL MODELING OF LOCAL SCOUR AROUND WIDE AND SKEWED PIERS

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Abstract of thesis presented to the Senate of University Putra Malaysia
in fulfillment of the requirement for degree of Doctor of Philosophy

PHYSICAL MODELING OF LOCAL SCOUR AROUND WIDE AND SKEWED PIERS

By

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Local scour around bridge piers has been recognised as one of the major causes of bridge failure. Since the 1950s numerous studies on local scour around bridge foundations have been conducted, however the problems of scour prediction have still not been totally overcome due to the difficulties in understanding the mechanism of scour and the complexity of flow around bridge piers. The aim of this study is to investigate the temporal development, effect of sediment coarseness, and pier geometry around wide and long skewed piers with multiple sizes and shapes in a bed formed with the use of two different sizes of sediments. In this study and for wide pier analysis, ten piers with circular and rectangular shapes were tested. Furthermore, one rectangular pier was chosen for inclusion in an experiment on skewed piers at various angles of attack, α. Scour development was monitored during the initial stage, main erosion stage, and equilibrium stage around wide and skewed piers. A new relationship of scour prediction based on laboratory and field data is proposed for the purpose of improving scour prediction techniques that have a tendency to over-predict local scour depths for wide piers. Validation of the proposed scour prediction formula was conducted using a wide range of laboratory and field data. Statistical tests revealed that application of the proposed scour prediction formula produced the smallest discrepancy ratio and root mean square error value among the tested models and showed good agreement with existing scour prediction formulae. The effects of wide piers and long skewed piers on the geometry of scour holes and sediment ridges (sediment deposited at downstream near the scour holes) were also explored. The tests were performed with the pier Reynolds number (Re_p) within the range of $2.2 \times 10^4 \leq Re_p \leq 2.1 \times 10^5$. The present experimental evidence shows that the geometric characteristics of scour holes and sediment ridges (length and width) were decreases as pier Reynolds number Re_p increases. The trend of empirical relations demonstrates the effects of the studied variables, including angle of attack, on scouring and deposition volumes at different sediment sizes. It also shows that the scouring volume is much higher than the sediment ridge volume that give indication that suspended sediment transport becomes more significant as the skewness of a long pier increases. A new relationship for estimating the angle of attack factor, K_α, for shallow-water conditions is presented. The new method of estimating $K_\alpha$was compared with HEC-18 and Laursen's and Toch's curves and the superiority of the new method was verified using statistical analyses.

Abstrak tesis dikemukakan kepada Senate Universiti Putra Malaysia
sebagai memenuhi keperluan ijazah Doktor Falsafah

PERMODELAN FIZIKAL KEROKAN TEMPATAN SEKITAR TIANG SAMBUT LEBAR DAN SERONG

Oleh

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Kerokan tempatan di sekitar tiang sambut jambatan telah diketahui sebagai salah satu penyebab utama kegagalan jambatan. Sejak 1950, terdapat pelbagai kajian kerokan jambatan di sekitar asas jambatan telah dijalankan, walaubagaimanapun masalah dalam ramalan kerokan masih belum sepenuhnya diatasi kerana kesukaran dalam memahami mekanisma kerokan dan kerumitan aliran di sekitar tiang sambut jambatan. Matlamat kajian ini adalah untuk menyelidik perkembangan terhadap masa, kesan kekasaran sedimen dan geometri tiang sambut di sekitar tiang sambut lebar dan serong panjang dengan pelbagai saiz dan bentuk dalam dasar yang terbentuk dengan menggunakan saiz sedimen yang berbeza. Dalam kajian ini dan untuk analisis tiang sambut lebar, sepuluh tiang sambut dengan bentuk bulat dan segiempat tepat telah diuji. Juga, satu tiang sambut segiempat tepat telah dipilih untuk melaksanakan ujikaji terhadap tiang sambut serong di pelbagai sudut serangan, α. Perkembangan kerokan diawasi bermula dari peringkat awal, peringkat hakisan utama dan peringkat keseimbangaan di sekitar tiang sambut lebar dan serong panjang. Satu hubungan baru terhadap ramalan kerokan berdasarkan data di makmal dan lapangan telah dicadangkan bagi tujuan memperbaiki teknik ramalan kerokan yang mana cenderung untuk terlebih meramal kedalaman kerokan tempatan di tiang sambut lebar. Pengesahan kepada formula ramalan kerokan yang telah dicadangkan telah dijalankan menggunakan pelbagai data dari makmal dan lapangan. Ujian statistik mendedahkan bahawa penggunaan formula ramalan kerokan menghasilkan nisbah percanggahan yang paling kecil dan nilai RMSE telah menunjukkan persetujuan yang baik dengan formula-formula ramalan kerokan yang sedia ada. Kesan-kesan tiang sambut lebar dan serong panjang terhadap geometri lubang kerokan dan rabung sedimen (sedimen yang terenap di bahagian hilir kawasan kerukan) juga diterokai. Ujian-ujian tersebut telah dijalankan dengan halangan nombor Reynolds, Re_p dalam ukuran $2.2 \times 10^4 \leq Re_p \leq 2.1 \times 10^5$. Bukti ekperimen pada masa sekarang menunjukkan ciri-ciri geometri lubang kerokan dan rabung sediment (panjang dan lebar) berkurang apabila halangan nombor Reynolds, Re_p meningkat. Hala hubungan empirikal menunjukkan kesan-kesan pembolehubah yang dikaji termasuk sudut serangan pada isipadu mengeruk dan pemendapan pada saiz sedimen yang berbeza. Ia juga menunjukkan isipadu kerokan lebih tinggi dari isipadu endapan, menunjukkan pengangkutan sedimen terampai menjadi lebih penting apabila keserongan tiang sambut panjang meningkat. Satu hubungan untuk menganggar faktor sudut serangan, K_α telah dibentangkan dan ia telah dibangunkan untuk keadaan air yang cetek. Kaedah baru untuk menganggar K_α telah dibandingkan dengan HEC 18 dan lengkung-lengkung Laursen dan Toch dan keunggulan kaedah baru telah disahkan menggunakan analisis-analisis statistik.

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I certify that a Thesis Examination Committee has met on 3 December 2015 to conduct the final examination of Nordila binti Ahmad on her thesis entitled "Physical Modeling of Local Scour around Wide and Skewed Piers" in accordance with the Universities and University Collages Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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LIST OF ABBREVIATIONS

α = angle of attack

ρ = fluid density

ν = kinematic viscosity

τ_c = critical shear stress

σ_g = geometric standard deviation of particle size distribution

τ_o = shear stress

σ_r = standard deviation of discrepancy ratio

ρ_s = sediment density

Π_{Sg} = dimensionless parameter for scour geometry

$\bar{r}$ = average values of discrepancy ratio

Al = alignment of the pier

b = pier width

B = rectangular flume width

B_h = bottom width of scour hole (by Heza et al., 2007)

B_α = projected width

D = diameter

d_{50} = median diameter of the bed material, diameter which 50% of the sizes are smaller

d_{84} = diameter of the bed material of which 84% are smaller

d_s = scour depth

d_{se} = equilibrium scour depth

F_r = Froude number

g = acceleration of gravity

h_r = height of sediment ridge

K = bottom width of scour hole (by Richardson and Abed (1993)

K_α = angle of attack factor

K_θ = discharge approach angle correction

k_σ = Sediment gradation factor

K_3 = factor for mode of sediment transport

K_4 = factor for armoring by bed material

K_s = shape factor

K_w = wide pier correction factor

L = pier length

l_r = ridge length

Lr = as the longest dimension of scour hole length at skewed piers

l_s = scour hole length

Ls = as the longest dimension of sediment ridge length at

skewed piers
r = discrepancy ratio
R^2 = correlation of determination
Re_p = pier Reynolds number
Re_{pw} = object Reynolds wave number
Sh = parameters describing the shape of piers
S_g = Scour geometry
t = time
t_e = equilibrium time
U = mean approach flow velocity
u_{*c} = critical shear velocity
U_a = critical mean approach flow velocity for non-uniform sediment
U_c = critical mean approach flow velocity
U_m = amplitude of the flow velocity
V = volume
V_d = deposition volume for skewed piers
V_r = volume of sediment ridge
V_s = volume of scour hole
V_t = sum of erosion and deposition volumes ($V_t = V_s + V_d$)
w_r = ridge width
W_r = as the longest dimension of sediment ridge width
w_s = scour hole width
W_s = as the longest dimension of scour hole width
y = flow depth

CHAPTER I

INTRODUCTION

1.1 Background

Scour is a natural process induced by the erosive activity of a flowing stream on alluvial beds. Rivers are active agents of erosion, transport and deposition which adjust their boundaries throughout the course of their development, in the duration of which the greatest adjustments occur in times of flood. Thus it is important for the designers to have reliable methods for estimating and controlling local scour. In the United States, bridge scour is one of the three main causes of bridge failure (the others being collision and overloading). It has been estimated that 60% of all bridge failures result from scour and other hydraulic-related causes (Marks, 1992).It is the most common cause of highway bridge failure in the United States, where 46 of 86 major bridge failures resulted from scour near piers from 1961 to 1976 (USGS, 2010)).

Currently, although the scientific basis for the structural design of bridges is well established, the design of bridge foundations in alluvial rivers remains a challenge due to the need for solutions to unpredictable problems. The complexities of the flow and sediment transport processes attendant to a pier's presence seem to be enduring barriers to progress in developing a reliable analytical design procedure. In wide pier aspects, over-prediction of scour depths is a problem that engineers have long been aware of. Several studies (Melville and Sutherland 1988; Melville and Coleman, 2000) have found that the relation between the depth of local scour around a bridge pier depends on three dimensionless elements: (i) flow intensity (average flow velocity divided by the critical flow velocity for initiation of sediment motion, U/U_c); (ii) flow shallowness (flow depth divided by pier width, y/b); and (iii) sediment coarseness (pier width divided by the median diameter of the sediment particles, b/d_{50}). Most of the dimensionless parameters from (i) and (ii) can be kept constant between field and laboratory results, however large differences in the values of sediment coarseness are found in most field situations and laboratory models. This phenomenon greatly impacts the predictions of scour depth for prototype-scale structures, especially when the structures are located in fine sand. In fact, if the sediment coarseness is not correctly calculated in the predictive equations, problems will appear as the equations are implemented in situations different from the laboratory conditions in which they were developed.

The main cause of bridge failure is stream channel instability resulting in river erosion and changing angles-of-attack can contribute to bridge scour. Debris can also have a substantial impact on bridge scour in several ways. On the other hand, scour-induced bridge failure usually occurs in flood flows, which are inherently unsteady and may also produce changes in approach channel bathymetry as channel thalweg and morphology change. This makes river flow interact with varied mixtures of sediments, ranging from alluvial sands to stiff clays, and weathered rocks, which may erode at different rates. These situations often lead to shifts in channel alignment. Nowadays, bridge designers have overcome their design problems by using a large variety of pier and abutment shapes, which are not always aligned with the predominant flow direction or with the flow direction during a flood. The latter situation becomes more complicated due to the fact that it introduces the complication of skewness. Skewness can cause maximum scour depth to increase dramatically. The scour depth around a rectangular pier with an aspect ratio of 10 at a skewness of 30° may increase scour depth several times compared with that occurring around the same pier when it is aligned with the flow direction (Mostafa, 1994). In terms of design aspects, skewness effects can determine the foundation design depth, thereby emphasising the importance of an accurate determination of likely flow pier alignment. The scour mechanism at skewed piers is complex not only because the scour depth increases but also because the width of scour holes increases and the lateral extent of the scour may become so large that the adjacency of the pier can be affected, thus depicting prediction of local scour depths complicated.

Ideally, a bridge should be designed so that its piers are aligned with the flow direction. However, external constraints may necessitate skewed piers, such as in the replacement of a bridge with an existing road alignment. In addition, lateral shifting of the main flow channel can cause skewness at a previously aligned bridge pier, meaning that alignment changes may happen at different river stages and may be un avoidable. This situation can also be called thalweg movement. The Bulls Road Bridge failure in New Zealand is an example of bridge failure caused by thalweg movement. The local scour was aggravated by the obliqueness of the flow on the pier, while debris accumulated immediately downstream of the bridge pier and thus led to flow constriction. The maximum scour depth measured below the armoured bed level was about 12.2 m (Coleman and Melville, 2001).

The most common cause of bridge failure is attributed to scouring around foundations during floods. The reasons for bridge collapse were evaluated in Columbia based on the study of 63 real cases of reported bridge failures since 1986(Diaz et al., 2009). According to the analysis of each failure event, 64% of the cases studied corresponded to concrete bridges that mainly collapsed due to scour effect and overload; the remaining 36% corresponded to steel structures that failed due to structural deficiencies. Elsewhere, a study of 503 bridge structural failures in the United States from 1989 to 2000 indicated that the main reasons for the failure or damage of the examined bridges were interconnected with scouring around the piers and abutments of the bridges (Whardana and Hadipriono, 2003). Extensive local scour around a pier was found during the Great Flood of 1993 in Missouri, where a more than 20-m-deep scour hole formed around the piers. Another bridge failure caused by flood flow is the Tangiwai Rail Bridge, New Zealand, where a 6-m flood rose at the bridge travelling with a velocity of 6 m/s (Melville, 2014).

In Malaysia, while bridge failure due to structural damage is very rare, bridge failures are very often caused by scouring of the footing structure during major floods (Ng and Razak, 1998). Since the 1920s, Malaysia has experienced major floods during seasonal monsoons, causing a large concentration of surface-water runoff that exceeds the capacities of most rivers. States located on the east coast of Peninsular Malaysia such as Kelantan, Terengganu, Pahang, and Johor are affected significantly by massive, seasonal floods (Akib et al, 2011). The government agency that is responsible for bridge construction and maintenance is the Public Works Department (Jabatan Kerja Raya, JKR). Table 1.1 shows the statistics on bridges in Malaysia, while Figure 1.1 presents the number of bridges constructed along federal roads under the responsibility of JKR based on construction material (Heng and Hamid, 2009; Nazri, 2011).

Table 1.1. Statistics on bridges in Malaysia (Source: Heng, 2008)

Department	Bridges
JKR Federal	7,133
JKR State	7,000
JKR Sabah	1,730
JKR Sarawak	1,540
Toll Concession Roads	560
Malaysian Railways Department	920

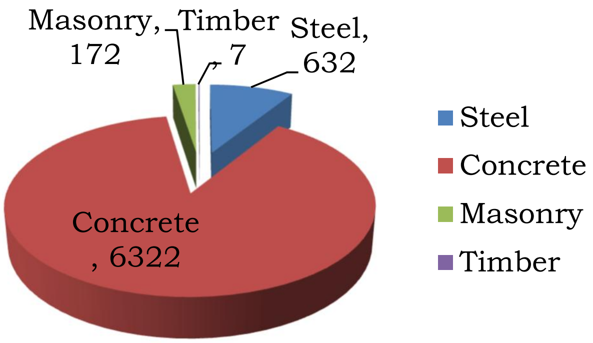

Figure 1.1. Types of Bridge in Malaysia by construction material
(Sources: Heng and Hamid, 2009; Nazri, 2011)

Malaysia is located in the equatorial zone and has an average monthly temperature ranging from 23°C to 34°C throughout the year and relative humidity as high as 90%. Malaysia experiences very high rainfall intensity, especially during the monsoon seasons. The annual rainfall varies between 2,000 mm and 2,500 mm and the mean monthly rainfall between 133 mm and 259 mm. A number of bridges are currently affected by scouring problems. Over the last few years, some bridges in Selangor, Sabah, Perak, Pahang Kelantan, and Kedah have experienced scouring of their bridge piers and structural damage. A lot of remedial action and maintenance has been carried out to protect and solve this problem. Chiew et al. (2000) presented their experience of facing hydraulic problems in Malaysia. Revetment of the Pukin River bridge, the Plentong River bridge, and the Keratong River bridge were cited as case studies. It was later learned that the Pukin River bridge was badly scoured around both abutments and piers during heavy flooding in December 2006. The most scour hazards to the piers of bridges in Malaysia are shown in Table 1.2.

Recent floods in Kelantan, Malaysia, have caused serious damage and bridge failures. The National Security Council (NSC) confirmed that the massive flood that hit Kelantan was the worst in the history of the state. Heavy rain from the 26th to the 30th December 2014 caused the river to rise above Sultan Yahya Petra Bridge. According to the council's report, the water level of Kelantan River at Tambatan DiRaja, which has a danger level of 25 meters, reached 34.17 meters

Table 1.2. Malaysian experiences: Failure due to scour hazards
(Source: Heng, 2008)

No.	Bridge location	Date of failure	Problems
1	A bridge over the Buloh River, Selangor	1989	Collapsed due to local scour around the upstream pier after a large flood

2	The Larut River Bridge, Matang, Perak	1993	Collapsed due to local scour around the upstream pier after a large flood
3	A bridge over the Labong River, Johor	1993	Collapsed due to local scour around the upstream pier after a large flood
4	A bridge over the Salor River, Kelantan	1996	Local scour occurred around an exposed pile
5	A bridge over the Salor River, Kelantan	2008	Local scour occurred around an exposed pile

on 27th December 2014, compared with29.70 meters in 2004 and 33.61 meters in 1967. Figures1.2 to 1.4 show the aerial view of the flooded area in Kota Bharu and some bridge damage at Kelantan River and Stelu River in Gua Musang, Kelantan.

Figure 1.2. This aerial view shows houses and plantations submerged in floodwaters in Pengkalan Chepa, near Kota Baru, Kelantan, on 28th December 2014. (Source: Malay Mail, 2015)

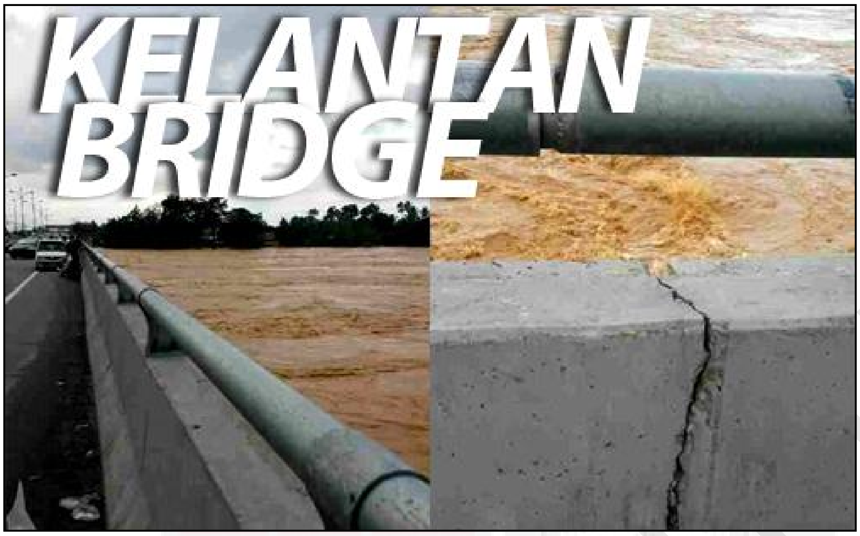

Fig. 1.3. Flooding at Sultan Yahya Petra Bridge, Kota Bharu, Kelantan caused some part of the structure to crack
(Source: Bernama, 2014)

Fig.1.4: Stelu River Bridge at Gua Musang, Kelantan, collapsed due to scouring during floods

1.2 Problem statement

Many researchers have already investigated the phenomenon of local scour around bridge piers. As a consequence of these studies, a large number of design relationships have been published for bridge designers. However, many bridges still suffer damage caused by scour. A conclusion that can be drawn is that the phenomenon of local scour of the bed sediment around a pier is still not adequately understood. This is not surprising, as local scour involves the complexities of the two and three-dimensional turbulent flow fields around a pier together with the mechanics of sediment transport.

The literature search conducted for this thesis revealed that there is very little information on predictive equations or data on scour around wide and long skewed piers. Most of the predictive equations in the literature are intended to apply equally well to large and small piers. Hence, this leads to a situation in which design is prioritised over prediction, which thus proves costly and economically inefficient. Additionally, equilibrium scour time data for wide and long skewed piers is still lacking, while available laboratory data is not sufficient and is limited to a circular pier shape only. The studies presented by Ettema (1980) and Melville and Chiew (1999) are examples of those conducted on time equilibrium fora circular pier. Comparison of scour development around a circular and a noncircular pier at different stages of time (initial stage, main erosion stage, and equilibrium stage) is thus necessitated and can give a better understanding of scour processes.

Pier size and shape represent important parameters that exert significant influences on the depth of local scour. The diameter of circular piers is perhaps the main factor affecting the scour depth around such piers. However, when the pier is noncircular in shape, pier shape should be taken into consideration. There are very limited findings on local scour depth for wide piers, particularly piers with a noncircular shape. The nose of the noncircular pier shape will influence scour depth. The more streamlined the nose of a pier, the less the maximum scour depth produced by the pier is. This advantage of streamlining quickly decreases once a noncircular pier is skewed in relation to the flow direction. Hence, the comparison of local scour around different pier shapes is important because it will help engineers to reasonably estimate local scour.

Investigations related to the formation of scour holes and sedimentary structures are relevant to a variety of scientific disciplines, including hydraulic engineering, fluid mechanics, oceanography, and geomorphology. Engineering research up to now has concentrated on flow fields around bridge piers (e.g. Ettema et al., 2006; Kirkil et al., 2008), but none of these were aimed at investigating the formation and geometry of frontal scour holes and downstream deposition, especially for wide and long skewed piers. Field observation reveals that the width of a scour hole may be several times the projected width of the skewed pier (Laursen and Toch, 1956). Furthermore, the height of the sand deposited downstream of a skewed pier can be a big problem for the navigation through the bridge. As the angle of attack increases, the height of the sand deposited downstream of the pier increases. Therefore, understanding the characteristics of scour morphometry and the volume of erosion in the scour hole and deposition in the sediment ridge is crucial in order to estimate the ratio of scoured and deposited material around such a pier, which would enable the result to be used for scour countermeasures.

Next, regarding scour prediction for skewed piers, most predictive methods for the effects of the flow skew angle on local scour use some form of projected width, B_α, of the pier (i.e. the horizontal dimension of the projection of the pier onto a plane normal to the flow) in their analysis (Sheppard and Renna 2005; Sheppard et al., 2011; Arneson et al., 2012). None of the investigators recommended a definite relationship for prediction of the angle of attack factor, K_α.The earliest research on how skewness effects scour depth was from Laursen and Toch (1956). They proposed extensive empirical family curves to estimate K_α for rectangular piers at different angles ($0° \leq \alpha \leq 90°$) and different aspect ratios ($2 \leq L/b \leq 16$). However, as Mostafa (1994) remarked, they never adequately explained either the theoretical or the experimental basis for estimating values of K_α. Moreover, it has been suggested that they may underestimate maximum scour depth at large angles (Mostafa (1994).

Therefore, in light of the reasons discussed above and also due to the fact that extensive scour can reduce the stability of bridge piers and lead to the bridge failure, a credible prediction of maximum scour depth around wide and long skewed piers is crucial for their safe design. In addition, research is needed to assess current techniques for estimating local scour and their appropriateness for wide bridge piers and long skewed piers. This research would aid the development of improved methods in bridge design, maintenance, operation, and bridge scour countermeasures.

1.3 Objectives of the study

The main goal of this study is to improve previous laboratory-based scour relationships and to suggest formulae for local scour around wide and long skewed piers using experimental data of current study. This goal is achieved by addressing the following set of specific objectives:

i) to investigate the temporal development, effect of sediment size, and pier geometry on local scour around wide and long skewed piers with multiple sizes, shapes and multiple angles of attack, α, using two different sizes of uniform cohesionless sediments;

ii) to evaluate the existing equations for predicting maximum local scour depth around wide piers;

iii) to investigate the geometry of scour (scour morphometry) and to determine the relationships between the scour hole and the sediment ridge around wide and long skewed piers at equilibrium conditions; and

iv) to develop a relationship for the angle of attack factor, K_α,for skewed bridge piers that can be used to predict local scour depth with reasonable accuracy.

1.4 Scope of study

Local scour around wide and long skewed piers under steady clear-water conditions were studied. The experiments were conducted in a rectangular flume, 50 m long, 1.5 m wide, and 2.0 m deep, located in the hydraulic laboratory of the National Hydraulic Research Institute of Malaysia (NAHRIM). Two pier shapes – rectangular and circular – with five different widths or diameters were tested. There were five pier widths, b, for each pier type, (60, 76, 102, 140, and 165 mm). The wide pier tests were conducted with two sediment sizes, i.e. d_{50} = 0.23 mm and d_{50} = 0.80 mm, giving a total of 20 experiments. For skewed pier analysis, the experiments were performed at nine different of angles of attack (α = 0°, 5°, 15°, 25°, 30°, 45°, 60°, 75°, and 90°) for each sediment size, giving a total of 38 experiments. A rectangular pier model with pier width b = 60mm and pier aspect ratio L/b = 10 was used in order to investigate the effect of pier skewness on maximum local scour depth. All experiments used similar bed material sizes and the same flow conditions.

The analyses included the influences of the applied bed sediment characteristics and the pier geometry on the process of local scour around wide and long skewed bridge piers. The scour mechanisms were presented in the initial stage, main erosion stage, and equilibrium stage for the different sediments, pier shapes, and angles of attack. Next, the effects of wide and long skewed piers on the morphology of the scour hole and the sediment ridge were analysed. The relationship between the geometric characteristics of the scour hole and the sediment ridge (width and length) at pier Reynolds number, Re_p, were evaluated. The effect of the variation in the angle of attack on the scour morphometrics with different sediment sizes was also investigated. The empirical relations that demonstrate the effects of the study variables were presented. Next, a new equation for estimating the angle of attack factor, K_α, was also developed using data from experiments in addition to data available from the literature which covered different angles of attack, different pier aspect ratios (l/b), different sediment sizes (both uniform and non-uniform), and different flow depths. To investigate the effectiveness of the new equation, a comparison was made between the K_α from the present study, the K_α from Laursen's and Toch's (1956) curves, and the K_α relationship in the current version of the US guidance document, HEC-18 (Arneson et al., 2012). The accuracy of the equations is assessed using statistical analysis.

1.5 Significance of the study

This study gives a deep understanding of the scour mechanism around wide and long skewed piers from the initial stage of the scouring process until an equilibrium time is achieved. In addition, this research also intends to provide new insights into sediment transport at bridges, exploring the features of migrating sediment particles at the bedform, especially in the scour hole and deposition area which are generated immediately around piers by local scour processes. The new relationship of the angle of attack factor, K_α, proposed in this study aim to give an accurate estimation of skewness effects on maximum scour depth, d_s, around skewed bridge piers.

1.6 Thesis outline

The thesis is divided into five chapters. A review of the conducted literature study is presented in Chapter II. The review is divided into subtopics that cover the mechanism of local scour around bridge piers, the components of scour, the types of scour, the parameters affecting maximum scour depth around wide and long skewed piers, and the literature on scour holes and sediment ridges. Furthermore, in Chapter II the available equations previously proposed by different researchers for the prediction of K_α and d_s are presented. Chapter III presents the methodology of the research, including the experimental work and procedures, carried out in the hydraulic laboratory of NAHRIM. The laboratory results that were obtained are discussed in Chapter IV, in which all the data on local scour around wide and long skewed piers are analysed according to the sequence of objectives in this study. Conclusions and recommendations for future research are presented in Chapter V.

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