BRIDGE MODELING ON THE BACKWATER EFFECT DUE TO ARRANGEMENT AND TYPE OF PIERS

YAP CHEE KIEN

Thesis submitted in fulfilment of the requirements for the award of the degree of

Bachelor Degree in Civil Engineering

Faculty of Civil Engineering and Earth Resources

UNIVERSITI MALAYSIA PAHANG

JUNE 2013

ABSTRACT

The existing of bridge piers in river waterways causes backwater effect where there is an increase in water level at upstream. During monsoon season at East Coast of Malaysia, the amount of water flow in upstream of bridge increases due to long duration and high intensity of rainfall that effectively increases the backwater amount. Hence, the excessive amount of backwater resulted in flooding to vicinity area. Therefore, a research was carried on the basis of laboratory experimental as to analyse the hydraulic profile and the significance of the backwater effect. The models incorporated different types and arrangements of piers for bridge model in three channel conditions (rectangular, floodplain and embankment channels) in subcritical flow. The results from this research suggested that the backwater measured was relatively higher than that computed backwater from equation where these values need to be reduced by considering the absolute surface roughness value for concrete material. In addition, it is shown that $\Delta y/y_3$ values for square pier and α of 0.167 are relatively higher than circular pier and α of 0.083, respectively. With such findings enhance the knowledge of engineer by considering backwater effect in designing bridge which eventually reduces the flood events due to excessive backwater effect.

ABSTRAK

Pembinaan tiang jambatan melintasi saluran sungai kejadian air berbalik iaitu peningkatan paras air di hulu jambatan. Semasa musim monsun di kawasan pantai timur Malaysia, jumlah aliran air di hulu jambatan semakin bertambah yang disebabkan hujan lebat yang berpanjangan dan seterusnya menambahkan jumlah air bebalik secara mendadak. Maka, jumlah air berbalik yang berlebihan ini mengakibatkan berlakunya banjir di kawasan sekitarnya. Oleh itu, satu kajian dijalankan berdasarkan ujikaji makmal bagi mengkaji profil hidraulik dan signifikasi bagi kejadian air berbalik. Model yang digunakan adalah daripada tiang jambatan yang berlainan bentuk dan susunan tiang dalam tiga keadaan saluran berlainan (saluran segiempat tepat, saluran dasar banjir dan saluran yang bertambak) bagi aliran subkritikal. Keputusan dari kajian ini mencadangkan jumlah air berbalik yang diukur adalah lebih tinggi daripada nilai air berbalik yang dihitung di mana nilai-nilai ini perlu dikurangkan dengan mengambil kira nilai permukaan kasar mutlak bagi bahan konkrit. Di samping itu, didapati nilai-nilai $\Delta y/y_3$ bagi tiang segiempat sama dan α bernilai 0.167 adalah lebih tinggi daripada nilai-nilai $\Delta y/y_3$ bagi tiang bulat dan α bernilai 0.083 masing-masing. Maka, keputusan dari kajian ini dapat memantapkan pengetahuan jurutera dalam mengambil kira kejadian air berbalik semasa merekabentuk jambatan, lantas mengurangkan kejadian banjir kerana kejadian air berbalik yang berlebihan.

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LIST OF SYMBOLS

A_1	Area of flow including backwater at section 1
A_{n2}	Gross area of flow in constriction below normal water surface at Section 2
α	Ratio of pier thickness to the distance between pier axis.
b	Width of constriction,
b	Bridge piers width
b_1	Distance between piers axis
b_2	Distance between piers face
B	Channel width
C_L	Loss Coefficient
Cr	Contraction Ratio
E_1	Total energy at Section 1 (upstream)
E_2	Total energy at Section 2
F_1p	Force of prototype at Point 1
F_1m	Force of model at Point 1
F_2p	Force of model at Point 2
F_2m	Force of model at Point 2
Fr	Force scale ratio
Fr_1	Froude number at Section 1 (upstream)
Fr_3	Froude number at Section 2 (downstream)
g	acceleration due to gravity
H_L	Head loss
hp	Height of the prototype
hm	Height of the model

K	Shape coefficient
k	Absolute surface roughness value for concrete
Lr	Length scale ratio
lp	Length of the prototype
lm	Length of the model
M_2	Momemtum at Section 2
M_3	Momemtum at Section 3 (downstream)
Q	Flow rate (Discharge)
r	Residual ratio of energy between Sections 2 and Section 3
v	Average velocity at downstream
V_1p	Velocity of prototype at Point 1
V_1m	Velocity of model at Point 1
V_2p	Velocity of prototype at Point 2
V_2m	Velocity of model at Point 2
v_1	Flow velocity at Section 1 (upstream)
v_2	Flow velocity at Section 2
v_3	Flow velocity at Section 3 (downstream)
Vr	Velocity scale ratio
Vp	Velocity of prototype
Vm	Velocity of model
Wp	Width of the prototype
Wm	Width of the model
$\bar{y}$	Mean depth of flow under bridge, referenced to normal depth level
y_n	Normal Flow depth

y_1	Flow depth at Section 1 (upstream)
y_2	Flow depth at Section 2
y_3	Flow depth at Section 3 (downstream)
Δy	Backwater generated by the bridge pier

LIST OF ABBREVIATIONS

EQN	Equation/Theoretical
EXP	Experimental
FEMA	Federal Emergency Management Agency
MoDOT	Missouri Department of Transportation
NFIP	National Flood Insurance Program
TxDOT	Texas Department of Transportation
UMP	Universiti Malaysia Pahang

CHAPTER 1

INTRODUCTION

1.1 RESEARCH BACKGROUND

Over the years, bridge had been significantly important as an infrastructure that served as communication links between population areas based on the ever-increasing rate. This is due to the increase in demand of river infrastructure such as bridge that caused by the rapid development and urbanization near the river area.

In order to ensure the safety and design efficiency of the bridge, it is important to understand the hydraulics and hydrology of waterways thus include the factors that will affect and be affected by the bridge structure. Besides that, confining flood waters critically by the bridges can cause to backwater damage suits, overtopping of water on roadways, excessive scour to bridge piers, high cost of maintenance or even loss of a bridge. In addition, the presence of bridges that produced excessive backwater could result in flooding to surrounding area such as upstream of the river during the monsoon season of the area. Therefore, it is important to avoid the disaster caused by the flood to the property in the upstream river area with the increasing property values over the years.

Although most bridge sites were selected where channels were straight, banks were stable and square cross-section to avoid all these hydraulic and hydrological waterways issues. But it is a necessary condition to consider the effect of backwater by the presence of bridge across the river. However, there was no precise method in determining the amount of backwater of a bridge that would be produced after the bridge was in place thus cause difficulty to forecast the worse backwater effects by the bridges. Therefore, it is required that the backwater produced by bridges should be kept within a knowledgeable and reasonable limits. Hence this place demands on hydraulic engineer to promote and develop more scientific approach to the bridge waterways problem (Bradley, 1978).

Progress of bridge designs always kept in pace with the times. With various researches done bridge's structure this induced in the achievement of bridge structural achievement. Structural engineers are well aware of the economic factors which can be considered in the proper type, selection and design of a bridge with given overall length and height. On the other hand, the role of hydraulic engineer is to establish lengths and vertical clearance for the bridge that should be in placed. But with the lack of hydraulic and hydrological information on the waterways such as backwater effect, it is difficult for hydraulic engineers to establish such clear distances. Hence, this could effect in the over-design of bridges, making the bridge longer than necessary due to safety factor.

1.2 PROBLEM STATEMENT

Backwater effect is a natural hydraulic effect that is unavoidable. This phenomenon occurs when the water flow of a river is obstructed by an object. The water level in the upstream will increase to above normal level of river. The increase in the water level is called backwater effect.

In bridge condition, the backwater effect is normally produced by the obstruction of bridge piers. The amount of water flow in the upstream of the bridge increase as the backwater effect increase drastically with the heavy rain season lasted for a long period. This season usually occurs around the area in East Coast area of Malaysia in the monsoon season around the month of November to March. Thus cause flooding to area nearby the area that not only cause destruction to property of nearby vicinity area but also destruct the natural habitat of the wild life surrounding the river area. In addition, the over flow of backwater on the road or bridge surface will also cause to structural defect to the bridge including excessive scour around the bridge piers. Thus, this will contribute to the increase in the cost of reparation or maintenance to the bridge that burden to the public. Therefore, it is an important issue in bridge design to investigate on the effect of pier shape on the channel obstruction and hydraulic efficiency (Charbeneau and Holley, 2001).

One of the flooding issues by the river in East Coast area of Malaysia is in Galing River, Kuantan. For many years, the vicinity of the area had been badly affected by the flash floods although Kuantan town that has been significant changes with many developments and infrastructure projects carried out as planned in the past years. Hence, this caused severe property damages and losses to the vicinity of the area. One of the reason in this flooding issue is the effect of backwater was not significantly taken into consideration when building bridge across the river. Since this flooding issue had been raised up for many years and there are many effects caused by the excessive backwater produced by the bridge structure. Therefore, an intensive research should be carried out as to find solution to avoid such issue. Figure 1.1 illustrates the bridge located in the Galing River, Kuantan where bridge piers act as the structural element caused to backwater in the river.

Figure 1.1: Bridge of Galing River, Kuantan

1.3 RESEARCH OBJECTIVES

This research outlines the following objectives::

i. To analyze the backwater effect at upstream due to different arrangement and type of bridge piers.

ii. To understand the relationship between backwater rise in the fraction of $\Delta y/y_3$ and Froude number at downstream.

iii. To understand the significance and importance of consideration on the backwater effect in bridge designs.

1.4 SCOPE OF RESEARCH

The research is on the analysis hydraulic flow profile at upstream of the bridge caused by backwater effect using model of bridge in the laboratory. The model of bridge is of different arrangement and type of piers

The research will be focused on a number of experiments for subcritical flow condition only as to collect the data required such as normal depth, the increase in depth and velocity of the water flow in the upstream of the bridge as to achieve the objectives. The flow rate is adjust to level the desired normal depth that set as the manipulated variable which effects in the increase in depth and velocity of water at upstream due to the backwater effect by different arrangement and types of bridge piers. The research will be focused on rivers with rectangular channel, slope embankments and channel with floodplain in region of Malaysia only.

1.5 EXPECTED OUTCOMES

From this research, the experimental data collected will enhance the knowledge in consideration of backwater effect during the bridge design hence avoid issues such excessive backwater that cause flash floods, overtopping of water on roadways or even excessive scour under the bridge. The backwater effect experimental data can be taken into consideration as the model is scaled of modelling laws derived from dimensional analysis. Hence, backwater effect by the bridge structure could be determined in advanced for design factor just by using appropriate scaling of the design bridge into bridge model for laboratory experiment.

1.6 SIGNIFICANCE OF RESEARCH

In most bridge design process, the clear distances for both horizontal and vertical distance are difficult to be determined by hydraulic engineer due to lack of hydraulic and hydrological information for selected river site. Therefore, with the laboratory experimental results gained using the scaled model, the engineer could obtain more precise backwater effect of the bridge that enhances the consideration during the bridge design.

CHAPTER 2

LITERATURE REVIEW

2.1 BACKWATER EFFECT BY BRIDGE

The construction of bridge across a wide channel of river is not encouraged as the cost of construction is high. To reduce the cost of construction, embankments on the both side of the river will be filled that creates floodplains that serve as a platform for the piers. These piers that act as the main support for the bridge will caused obstruction to the water flow within through a reduced cross section. As mentioned by Rahman (2010), backwater is the increase in the water surface level relative to the level occurred under unobstructed channel. MoDOT (2000) also stated that the backwater is induced by a bridge opening that obstructed the free flow of water in the channel. MoDOT (2000) also added that the backwater is measured above the normal water level and the water surface elevation resulted from obstruction of flow as shown in Figure 2.1.

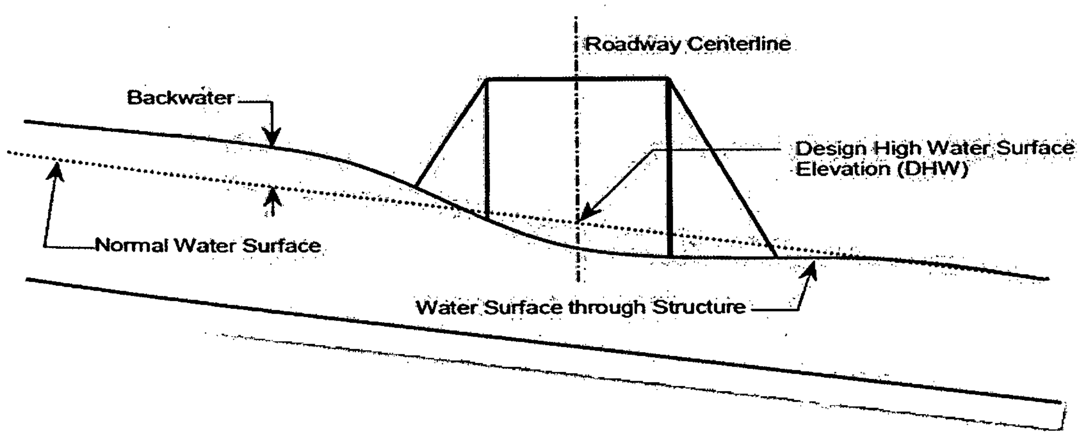
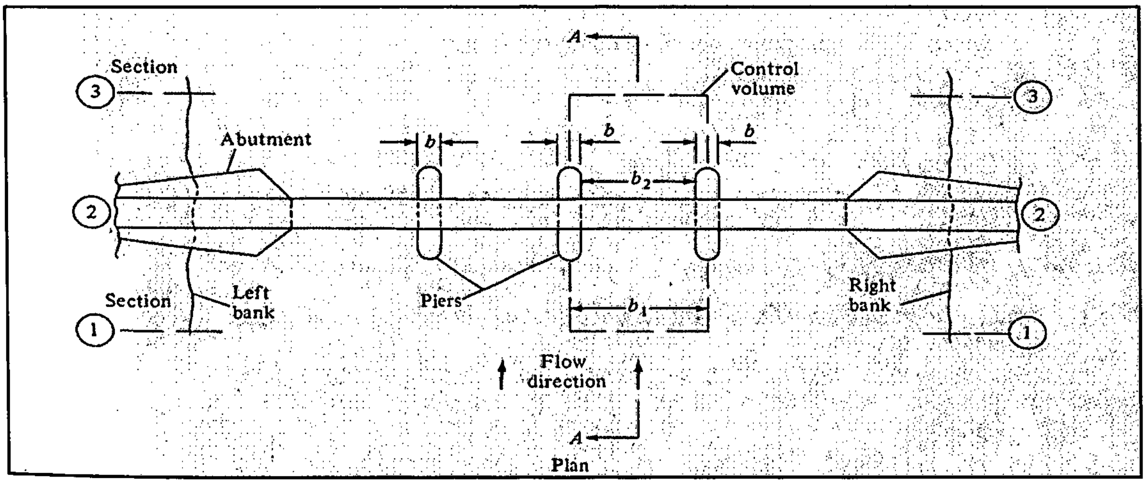


Figure 2.1: Measurement of backwater

(After MoDOT, 2000) as footnot

These backwater definition also supported by Yarnell (1934) with the statement stated that the phenomenon of backwater occurrence is the obstruction by bridge piers that cause elevation in water surface level on the upstream of the piers that produced the contraction area. The elevation in water surface level is due to the higher velocity acquired by the water when passing through the obstructed channel. Besides the contraction and expansion of water flow as it enters and leaves the bridge section that effect in the elevation of water surface level, Prasuhn (1987) also added, the increase in water surface level, Δy is due to other factors such as the impact and change in momentum caused by piers and abutments and the conditions that make the bridge opening to perform as a choke.

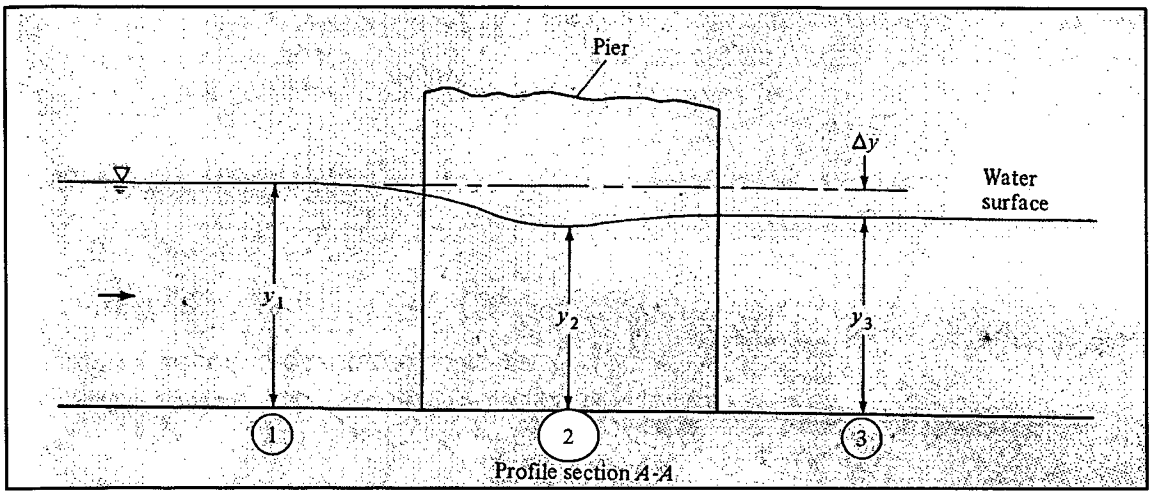
In addition, Yarnell (1934) explained that as the water enters the contracted area, there is a drop in the water surface level with the increase in velocity. However, as the contracted area expands again into unobstructed channel in the downstream of the pier, the water surface level fails to rise to the water surface level of the upstream of the pier. Hence, Figure 2.2 presents an illustration of the bridge definitional sketch while Figure 2.3 shown the water surface profiles at section A-A obstructed by bridge pier.



Where;

b	the bridge piers width
b_1	the distance between piers axis
b_2	the distance between piers face

Figure 2.2: Bridge definitional sketch.



Where;

y_1	flow depth at upstream
y_2	flow depth through vents
y_3	flow depth at downstream
Δy	the backwater generated by the bridge pier.

Figure 2.3: Water surface profiles at section A-A obstructed by bridge pier.

(After Prasuhn, 1987) as footnote

Prasuhn (1987) on the other hand, stated that it is the head loss due to contraction and expansion that occurs from river cross section to cross section caused to the changes on the water surface profiles. The changes in area of the channel caused to inability of the water to completely follow the boundary changes thus leads to flow separation. The head loss, H_L between any of two channel sections is expressed in Equation (2.1).

$$H_L = C_L \left| \frac{v_1^2}{2g} - \frac{v_3^2}{2g} \right| \qquad (2.1)$$

In which

C_L	loss coefficient
v_1	flow velocity at upstream

v_3 flow velocity at downstream

g acceleration due to gravity

Similar, El-Alfy (2006) used the application of energy principle to estimate the backwater level due to the obstruction by bridge piers in the steam. By applying the Bernoulli's equation for horizontal bed between section 2 (section at bridge pier) and section 3 (section at downstream) as shown in Figure 2.3, the equation is expressed in Equation 2.2.

$$\left(y_2 + \frac{v_2^2}{2g}\right) r = y_3 + \frac{v_3^2}{2g} \quad (2.2)$$

In which

r the residual ratio of energy between Section 2 and Section 3

v flow velocity at Section 2

v_3 flow velocity at Section 3 (downstream)

y_2 flow depth at Section 2 (minimum flow depth)

y_3 flow depth at Section 3 (downstream)

g acceleration due to gravity

Followed by continuity principle between section 2 and section 3 based on Figure 2.1a as used by El-Alfy (2006) with equation as expressed in Equation 2.3.

$$y_2 b_1 v_2 = y_3 B v_3 \quad (2.3)$$

In which

b_1 the distance between pier axis.

B the channel width.

Also, as stated by El-Alfy (2006), Cr is the contraction ratio as indicated in Equation 2.4.

$$Cr = \frac{b_1}{B} \quad (2.4)$$

By rearranging of Equations 2.2, 2.3 and 2.4, this results to the following Equation 2.5.

$$Cr^2 = \frac{r^3 Fr_3^2 (2+Fr_2^2)^3}{Fr_2^2 (2+Fr_3^2)^3} \tag{2.5}$$

In which Fr_2 and Fr_3 are Froude numbers at section 2 and 3 (downstream), respectively.

Hence, the critical value of downstream (Fr_{3c}) is the value of Froude number corresponded to the value of Froude number at section 2 is equal to one (El-Alfy, 2006). This followed by the limitation value of contraction ratio, Cr to distinguish between class A (unchoked flow or also known as subcritical) or class B (choked flow or also known as supercritical) as stated by Henderson (1966). Distinguishing between classes of flow was used by Yarnell (1934) according to two approaches. One is the principle of energy conversation, $E_1 = E_2$ and the other approach is principle of momentum conservation, $M_2 = M_3$. By assuming critical flow at section 2, that is $Fr_2 = 1$, the assumptions approach $E_1 = E_2$ leads to equation as expressed in Equation 2.6.

$$Cr^2 = \frac{27 Fr_1^2}{(2+Fr_1^2)^3} \tag{2.6}$$

In which Fr_1 is the Froude number at section 1 (upstream). While the second assumption approach $M_2 = M_3$ leads to following equation as given in Equation 2.7.

$$Cr = \frac{\left(2+\frac{1}{Cr}\right)^3 Fr_3^4}{(1+2\,Fr_3^2)^3} \tag{2.7}$$

In which

E_1	total energy at Section 1 (upstream)
E_2	total energy at Section 2
M_2	momemtum at Section 2
M_3	momemtum at Section 3 (downstream)

The corresponding value of Froude number at section 3 (downstream), Fr_{3C} and Equation 2.5 can be in following form as expressed in Equation 2.8, when the Froude number value at section 2 equals to one where the flow at section 2 is critical flow.

$$Cr^2 = \frac{27r^3 Fr_{3C}^2}{\left(2+Fr_{3C}^2\right)^3} \tag{2.8}$$

The classification of type of flow based on the Froude number value as compared to critical value of Froude number, Fr_{3c} is explained later in the discussion.

In general, backwater effect or also can be known as afflux phenomenon is the increase in water level at upstream of the bridge caused by successive contraction and expansion that results in local head loss. The water levels at upstream are rose by Δy relative to downstream levels. This Δy value is equivalent to the head loss caused by contraction and expansion of flow at the bridge.

2.2 TYPES OF FLOW IN BACKWATER

There are various types of flow that may be encountered during bridge waterway design. Yarnell (1934) and Henderson (1966) both used and classified type of flow in backwater into two classes, which are Class A and Class B. Class A is the unchoked flow while Class B is the choke flow. The unchoked flow is as described by Bradley (1978) as subcritical and chokes flow as supercritical. Later, in Bradley (1978) own research, the type of flows in backwater are labelled as Type I, Type II and Type III. The Type I flow is the subcritical flow whereas Type II flow is the flow passes through critical. There are two variations of Type II flow will be described here under Type IIA and Type IIB. And the remaining is Type III flow which is the supercritical flow. In Figure 2.4, Figure 2.5, Figure 2.6 and Figure 2.7 for Type I, Type II and Type III flows water profile respectively, the normal water surface abbreviated as N.W.S in the figures or also known as the design flow level that would be assumed prior to placing obstruction in the channel is represented by the long dash lines. The solid lines on the other hand represented the configuration of the water surface on the centreline of channel for each case after the bridge in placed. Then, the short dash lines in the figures