A Multiple Testing Problem Analysis to Enhance the Safety Foundation Design of the Urban Integral Abutment Bridge

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***Abstract*—**Municipal organizations in cooperation with local water companies try to create a continuous flow in the urban rivers to beautify the urban landscape in correlation with the eco-tourism aspects. Re-shaping the rivers' floodplains by converting them to the landscapes, residential, complex centers have reduced the width of the rivers. This reduction the river width, increased flood intensity, greatly. Therefore, gradually weakening of the bridge foundations and high flow intensity, increase the probability of bridge failures. Bridge failure has significant effects on both the social and economic aspects of a region, and the stability of a bridge structure is closely associated with scour. Accurate prediction of the maximum depth of potential scour at a bridge foundation is important for the safe design of bridge footings. Experience has shown that insufficient attention is paid to contraction scour at Integral Abutment Bridges (IAB). Although most damage to bridges structure occur at the flooding times, undermining the bridges' foundations in a relatively long duration of time make the bridge foundation weak for the final failure at the flash flooding conditions. The current paper experimentally investigated a full-scale IAB model to estimate the clear-water contraction scour on protruding abutments in the compound channel. The tests were run to find the relationship between maximum contraction scour depth and abutment protrusion into the main-channel. The results of the validation and graphical analysis yield satisfactory predictions. Findings of the current study can help determine the footing design and depth that could minimize both construction and maintenance costs.

***Keywords*—** Urban Landscape, Integral Abutment Bridge, Compound River, Floodplain

I. Introduction

In the current decade the artistic design of the bridges is highly considered by bridge designers and engineers. Technical factors such as river width, traffic and other possible lateral loads, earthquake intensity, soil, geomorphic characteristics, and flow of the river are still the decisive factors in the selection of the structure material, number, location, and layout of the piers and abutments of the bridge, at the site of the construction. In other words, these are the technical parameters that are calculated by the bridge engineer in the initial phase of the bridge design. The bridge architects add landscape and architectural aspects to the bridge plan designs by considering the technical parameters in the final phase of the bridge design. Bridges with a total length not exceeding 60 m and with skews not exceeding 30º are more economical if designed as integral abutment bridges (IAB). These systems have full structural continuity and a smaller number of expansion joints (Lai and Greimann, 2010), and typically have high reliability, high strength, and low cost in both the construction and maintenance phases, making them feasible alternatives to conventional bridge designs. For the wider rivers (60 m< b1< 100 m), engineers also try to design IABs by locating the abutments near the banks of the main-channel or may protrude into the main-channel. However, the use of IABs is relatively new, and the design factors relating to the effects of natural hazards and environmental conditions are not well understood by bridge designers.

The society and economy of a country can be significantly affected by a bridge failure. The most common cause of bridge failure is scour around a bridge abutment. Scour is a natural phenomenon caused by the flow of water over an erodible boundary, which excavates bed materials from the bridge foundation. Although most damage to bridges structure occur at the flooding times, undermining the bridges' foundations in a relatively long duration of time make the bridge foundation weak for the final failure at the flash flooding conditions. Weakening of the bridges foundations occurs gradually by steady flow in clear-water conditions. Municipal organizations in cooperation with local water companies try to create a continuous flow in the urban rivers to beautify the urban landscape in correlation with the eco-tourism aspects. Such a continual flow of the urban river is a circulation route of the available resources like the natural capacity of rivers, semi-deep wells, or water of the near dams. Re-shaping the rivers' floodplains by converting them to the landscapes, residential, complex centers have reduced the width of the rivers. This reduction the river width, increased flood intensity, greatly. Therefore, gradually weakening of the bridge foundations ending with a high flow intensity, increase the probability of bridge failures. Bridge engineers try to increase the structure safety by over predicting the safety factor calculating the depth of bridge foundations deep. It is evident that the calculating the depth of the bridge foundations regarding to the rainfall, upstream watershed characteristics, flow rate, and geomorphic characteristics of the river bed in the bridge site lead to optimize a bridge, technically and economically. In this paper we evaluated the predictive equations of the contraction scour.

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Furthermore, a reliable equation for predicting the maximum depth of scour at the IABs was proposed.

Scour reaches its equilibrium status when the shear erosive stress balances with the resisting stress against scouring on the streambed. Study on 503 bridges' structures failures in the United States showed that the main reasons for bridges' failures are those connected with scouring at the bridges' abutments and piers [1]. Abutments are at the two ends of a bridge transfer the loads from the superstructure to the footing bed and give support to the approach embankment. Reliability, strength, and economy are the main factors for a bridge without moving joints that are named joint-less or Abutment Bridges. Abutment Bridges are most commonly used for bridges over small channels. They have more capacities to pass the water than truss bridges. In an Abutment Bridge, abutments acquit an extra function to protect the embankment against scour as shown in Figure 1. In these situations, abutments are close to the banks of a main-channel or may protrude to the main-channel to cut the bridge construction cost. Therefore, abutments contract the flow through the waterway where, the shear stress of the bed material is closed to the threshold condition. In such a critical condition contraction scour expands [2]. Such an excessive scour leads into weakening bridge foundations at any time, without any warning [3, 4].

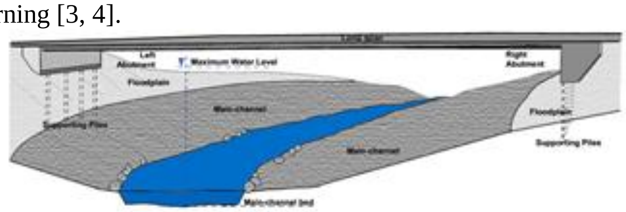

Fig. 1 View of a compound waterway with an Integral Abutment Bridge

Simple contraction attributes to the case where the riverbank is similar to geometry of the rectangular flume tests, where the contraction is long. Compound contraction scour is the case where the riverbanks and the main channel bed profile are compound. Many Abutment Bridges are found in compound channels whose geometry and hydraulic characteristics are markedly site-specific. Most of the bridge scour events are caused by live bed scour, while the maximum scour depth often resulted from clear-water flows. Maximum contraction scour represents the most severe scour that influences Abutments Bridges. Therefore, an accurate estimation of contraction scour depth is needed to design the bridge foundation safely. Over estimation will lead to unnecessary construction cost while underestimation may lead to bridge failure. That is why the bridge designers are interested in the scouring alongside the contracted section. Literature review showed insufficient attention, unreliable observations, and limited amount of empirical data from simulating the actual conditions of the contraction scour at Abutment Bridges sites [5, 6]. The major concentrations of the current study are; propose an equation; and evaluation of the equation to predict maximum contraction scour depth due to protruding Abutment Bridge in a compound channel.

II. Abutments' Categories Related With Flow Contraction

A. Review Stage

Short contraction is an ideal case in contraction scour conditions in Abutment Bridges [7]. In some earlier studies, the contraction ratio (b2/L) was detected as the main parameter impressing the scour procedure [5, 8-10], but in many other studies, it was ignored [11-14]. Contraction degree (b2/b1), directly defines the contraction severity. When b2> 0.35b1, the contraction degree strongly effect on contraction scour depth [15]. Table I summarize different classifications for Abutment and channels contraction in the scour studies. Table A.I. shows most well-known equations to predict maximum contraction scour depth in Appendix section.

TABLE I
Main Categories For Abutments And Channel Contraction

Structure	Category	Condition	Reference
Abutment	Short, Medium, or Long	$25 \geq L/y_1 \geq 1$	[16]
Contracted Channel	Long or Short	$b/b_1 \geq 1$	[17]
Contraction	Long or Short	$b/b_1 \geq 0.5$	[7]
Contraction	Norrow or Wide	$b_2/b_1 \leq 0.5$	[15]

III. Experimental Procedure

If you are using *Word*, use either the Microsoft Equation Editor or the *MathType* add-on (http://www.mathtype.com) for equations in your paper (Insert | Object | Create New | Microsoft Equation *or* MathType Equation). "Float over text" should *not* be selected.

IV. Units

Main assumptions in the current study are; flow is uniform; flow continuity equations are satisfied; and critical velocity for equilibrium contraction scour is used. Contraction scour depth is presented as the function of contraction degree (b2/b1), abutments' protrusion (L/bf), approaching velocity (v1), and approaching water depth (y1). Therefore, the tentative form of the equation to predict the maximum contraction scour depth is:

$$Dsmax = Ks\ K\theta\ KGF\ KGC\ f(v1, b2/b1, L/bf, y1) \qquad (1)$$

Where, KS, Kθ, KGF, and KGC are the correction factors for abutment shape, transition angle, floodplain geometry, and channel geometry, respectively. In the flume tests, contraction scour was generated in a short contracted compound channel with rectangular abutments perpendicular to the incoming flow. Sediment weight and uniformity were kept constant in the channel. Therefore, the effect of the abutment shape, transition angle, and geometry on the scour process is negligible (KS, Kθ, KGF, and KGC = 1.00). Experiments were conducted in a 15 m long, 1.5 m wide, and 2 m deep circulating flume at the National Hydraulic Research Institute of Malaysia (NAHRIM) laboratory. The flume had 0.00 % slope, thus the flow hydraulic gradient was controlled by the difference in water surface elevation between the head box and the tail box. The Abutment Bridge that is in used by Public Road Department Malaysia was modeled within the compound

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river with a geometrically scale of 1:24. Uniform and non-cohesive sand with median particle size (D50) of 0.28 mm was used in the flume. The sediment section was 10 m long with at least 50 cm height at the channel centerline. The approach velocity was obtained by adjusting the inlet valve so that to produce a value of v/vc<1.00. Therefore, the experiments were conducted under clear-water scour conditions. Before running, the initial bed elevation was recorded for each experiment. Among the tests, the water depth, flow velocity, and discharge were kept constant.

In line with Coleman et al., (2003) proceedure, when the scouring rate is reduced to 5 % than the abutment length in the succeeding 24 hours period, it is assumed that an equilibrium status is reached. Afterwards, the discharge was reduced slowly to zero and water was drained from the scour hole. For determining the scour profiles, the scour depths at vertical sections were measured by a Vernier point gauge with an increment of 5~10 cm. Table II shows the characteristics of the tests. In the tests, floodplain width was kept constant but the abutments' lengths were varied.

TABLE II
CHARACTERISTICS OF EXPERIMENTAL TESTS

Test no.	b/y_1	L/y_1	L/b_f	b_1/b_2	Maximum contraction scour depth (cm)
01	2.5	1.65	1.69	2.03	4.80
02	2.5	1.62	1.65	1.98	4.76
03	2.5	1.57	1.60	1.92	4.60
04	2.5	1.52	1.56	1.88	4.35
05	2.5	1.52	1.55	1.81	4.27
06	2.5	1.21	1.24	1.69	3.79
07	2.5	1.11	1.13	1.52	2.91
08	2.5	1.08	1.11	1.46	2.47
09	2.5	1.03	1.05	1.45	2.42
10	2.5	0.98	1.00	1.43	2.39

V. RESULTS AND ANALYSIS

Table II shows that maximum contraction scour depth generally increases as the contraction degree decreases. Figure 2 presents the photographs of the selected tests that the contraction degrees are significantly are different. Figure 3 illustrates the contours' variation corresponding to the experiments shown in Figure 2. It is evident that the bed was eroded in front of the abutments and at the channel centerline. As the contraction degree decreased, sediment was accumulated in the main-channel with the local maximum 1.7 m longitudinal distance from the embankment axis. In addition, as L/bf increased erosion force becomes more severe.

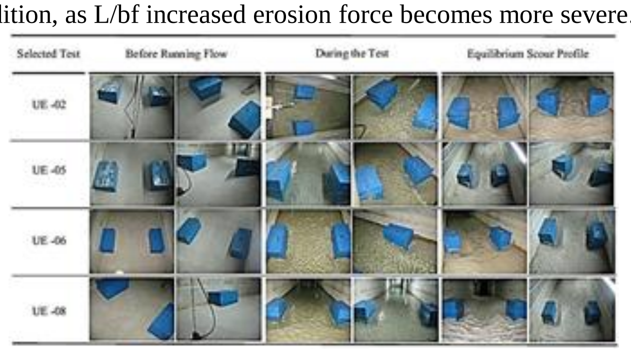

Fig. 2 Scour at the abutment; before test; during the test; and equilibrium status (The other tests' photos are not presented here because of space limitations, but they are available upon request)

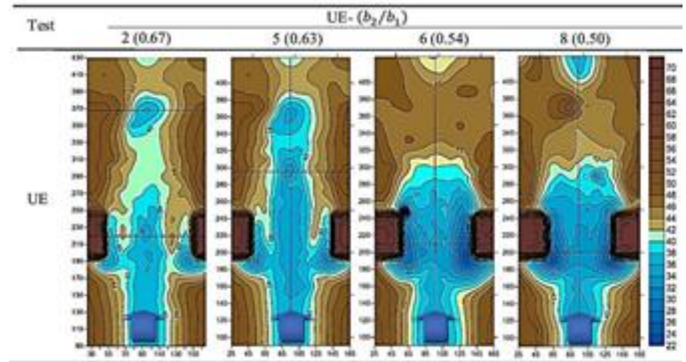

Fig. 3 Contour plot of the scour hole, in UE and UF tests of the Figure 2

Froude Number (Fr), and Reynolds Number (Re), are two widely used dimensionless terms in flow analysis. Regression analyses showed that contraction scour is irrelevant with Reynolds Number but it has a close relation with the Froude Number. Thus, contraction scour depth is likely to be a proportional of the difference between Froude Number at the equilibrium status of the test and critical Froude Number as the following equation:

$$d_{smax}/y_1 = K_1(K2\ Fr^* - Fr_c) \qquad (2)$$

Since other contraction factors may influence v2, we used nominal velocity for correlation purposes. In addition, in order to optimum fit, the nominal Froude Number needs a factor K2in front of the Fr1 (b1/b2) as:

$$v^* = v_1(b_1/b2) \qquad (3)$$

$$Fr^* = K_2 Fr_1(b_1/b_2) = K_2(v_1/\sqrt{gy_1})(b_1/b_2) \qquad (4)$$

Where, K1 and K2 as dimensionless coefficients were obtained in the multi-regression analysis. Bringing Equation (4) in to the Equation (2) and replacing the obtained amount of the dimensionless coefficients converts the contraction scour equation into the following equation as shown in Figure 4:

$$d_{smax}/y_1 = 0.38((2.47(v_1 b_1/b_2)/\sqrt{gy_1}) - ((\tau_c/\rho)0.5/gny_1^{1/3})) \qquad (5)$$

Y1 and v1 in the Equation (5) are the corresponding values when the tests are stopped.

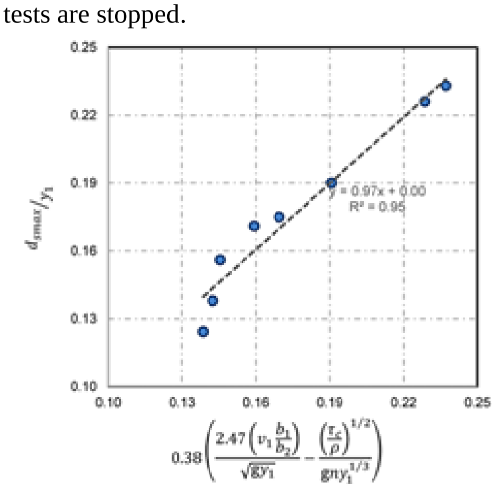

Fig. 4 Graphical determination of multi-regression analysis to obtain the dimensionless coefficients

VI. Evaluation Of The Proposed Method

Equation (5) was proposed to predict maximum contraction scour depth in the compound channel. Generally, in evaluation a method the under predictions should be minimal and matching the predicted data with the measured ones are prerequisites as closely as possible. In engineering statistical comparison between predicted and measured data is used to evaluate validity of a new method. If its' validation be high, it means that the statistical analysis approved the method applicability. Current statistical tests consist of Correlation, Regression (R), Mean Absolute Error (MAE), Root Mean Square Error (RMSE), and Theil's coefficient (U). The closer the correlation coefficient is to either −1 or +1 the stronger correlation between the variables. Maximum value of R, minimum values of MAE and RMSE represent reasonable predictions. The closer the Theil's coefficient (U) is to 0.00; the closer the predicted contraction scour depths are to the measured depths. Table III shows the statistical test results. In addition, a method is graphically evaluated by comparing its scatter-points of measured and the predicted data with the line of perfect agreement to see whether it agrees sufficiently for a new method to replace the old. The closer the scatter-points to the line of perfect agreement means a better prediction. Figure 5 shows the graphical evaluation of the methods in Table A.I and the authors' proposed method.

According to the results of statistical and graphical analyses, the authors' method predicts a reliable contraction scour depths. Comparison the contraction scour depth predicted by authors' method with measured depths approved that defined criteria for the new method. Therefore, the outcomes show satisfactory predictions of the authors' empirical equation for maximum contraction scour depths.

Table III
Statistical Analyses Results

Equation	R^2	m	MAE	RMSE	Theil's coefficient, U
Laursen (1963)	0.98	1.88	10.25	10.29	0.48
Komura (1966)	0.98	1.35	11.60	11.61	0.51
Gill (1981)	0.98	3.02	1.86	2.03	0.09
Lim (1998)	0.98	3.45	7.74	8.11	0.32
Chang (1998)	0.01	-0.07	8.26	8.34	0.45
HEC-18 (2001)	0.25	0.47	7.95	8.00	0.43
SRICOS-EFA (2002)	0.98	0.23	2.75	2.84	0.19
Proposed Method	0.90	0.97	0.24	0.32	0.02

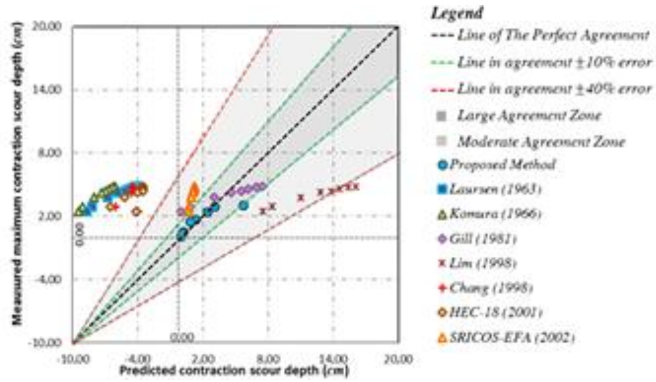

Fig. 5 Graphical comparison of measured and predicted scatter points with the line of perfect agreement

VII. Conclusion

Most of the recent predictive methods on contraction scour have the limitations of the method assumptions, simplification of the experiment geometry circumstances, space limit in laboratory flume, and the numerical simulation methods. The main deficiency of previous studies is that they do not represent contraction scour development at abutments in relation with the contraction degree (b2/b1) and the abutments' protrusion into the main-channel (L/bf). The full-scale model of the Abutment Bridge in the compound channel was tested to produce maximum contraction scour depths under clear-water conditions. The experimental data were used to estimate an equation to predict maximum contraction scour depth as a function of contraction degree and abutment protrusion. Following sub-sections summarizes the results of the current study.

The results showed that contraction scour is a function of difference between the approaching Froude Number and critical Froude Number. Based on the laboratory flume tests, authors proposed the equation to predict the maximum contraction scour depth. Authors' method showed large agreement between predicted contraction scour depths and corresponding measured depths. Over predictions were comparatively more than under predictions while the predicted contraction scour depths are adequately close to the measured depths. These conditions are in line with the two basic criteria in method evaluation. According to the graphical and statistical analysis, there is enough evidence for the reliability of the proposed method. Therefore, the authors' method gave satisfactory predictions for maximum contraction scour depth at Abutment Bridges due to protruding into the compound channel.

As, the authors' method provides critical information of the contraction scour at Abutment Bridge. After evaluation by the field verification, it can be applied in depth calculating process of the Abutment Bridges foundations. Current study outcomes allow promoting the economical Abutment Bridges' design by decreasing the bridges' construction cost and saving additional maintenance charges. The findings indirectly rises bridges' stability that prevents loss of lives and cut economic risk in transportation.

Appendix

Appendixes, if needed, appear before the acknowledgment.

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NOTATIONS

The following symbols are used in this manuscript:

b = Contraction length, [L];

bf = Floodplain width, [L];

dsmax= Maximum contraction scour depth [L];

Dm = Effective mean diameter of the bed material in the bridge = 1.25D50, [L];

D50= Median particle diameter (50 % of the particles by weight are finer), [L];

Fr = Froude number, dimensionless;

Frc = Critical Froude number, dimensionless;

Fr* = Nominal Froude number, dimensionless;

g = Gravitational acceleration force, [LT-2];

KS = Correction coefficient for abutment shape, dimensionless;

KGC = Correction coefficient for channel geometry, dimensionless;

KGF = Correction coefficient for floodplain geometry, dimensionless;

Ku = Constant coefficient in HEc-18 equation, dimensionless;

Kθ = Correction coefficient for transition angel, dimensionless;

K1 = Correction constant coefficient in contraction scour equation, dimensionless;

K2 = Correction constant coefficient for optimum fit in contraction scour equation, dimensionless;

L = Length of abutment, [L];

MAE= Mean Absolute Error, dimensionless;

n = Manning coefficient, dimensionless;

q = Unit discharge, [LT-1];

Q = Total discharge in compound channel, [L3T-1];

Re= Reynolds number, dimensionless;

RMSE= Root Mean Square Error;

U = Theil's coefficient, dimensionless;

v = Flow velocity, [LT-1];

*v*c = Critical velocity for sediments, [LT-1];

*v** = Nominal velocity, [LT-1]; y = Flow depth, [L];

β1 = 0.59 ~ 0.69.

β2 = 0.066 ~ 0.367.

θ = Transition angle, [°];

ρ = Mass density of water, [ML-3];

σg = Geometric standard deviation of the sediment, dimensionless;

τc = bed shear stress; the subscript "c" symbolizes the condition for initial sediment motion [L2T2];

Subscripts

1= Uncontracted (approach) section and;
2= Contracted section

Appendix

TABLE A.I
EQUATIONS FOR UNIFORM CONTRACTION SCOUR UNDER CLEAR-WATER CONDITIONS

Reference	Eq. No.	Equation	Applicability/ Supplementary Equation
Laursen (1960)	(A.1)	$y_2/y_1=(Q_2/Q_1)^{6/7}(b_1/b_2)^{a}(n_2/n_1)^{b}$	Depth predicting
Komura (1966)	(A.2)	$y_2/y_1=1.6Fr_1^{0.2}(b_1/b_2)^{0.67}\sigma_g^{-0.5}$	Depth predicting $\sigma_g=(d_{84}/d_{16})^{0.5}$
Gill (1981)	(A.3)	$y_2/y_1=(b_1/b_2)^{6/7}(\tau_c/\tau_1)^{-3/7}$	Depth predicting
Lim et al. (1998)	(A.4)	$y_2/y_1=(b_1/b_2)^{0.75}$	Depth predicting
Chang (1998)	(A.5)	$d_{smax}=\left(q/\left(4.16d_{50}^{0.33}\right)\right)\left(1/\left(1+0.125/d_{50}^{0.40}\right)\right)$	Depth predicting $0.03 > d_{50} > 0.0003$
HEC-18 (Richards on & Davis) (2001)	(A.6)	$y_2=\left(K_uQ^2/d_m^{2/3}b^2\right)^{3/7}$	Depth predicting $d_{smax}=y_2-y_1$; $d_m=1.25d_{50}$ $K_u=0.025$ in SI and 0.0077 in English
SRICOS-EFA (Li) (2002)	(A.7)	$d_{smax}=1.9y_1\left[1.38(b_1/b_2)(v_1/\sqrt{gy_1})-\left((\tau_c/\rho)^{0.5}/\right.\right.$	Depth predicting $\tau_c=(\rho g n^2 v_c^2)(y_1)^{0.33}$

References

[1] Wardhana, K. and F.C. Hadipriono, Analysis of Recent Bridge Failures in the United States. Journal of Performance of Constructed Facilities, 2003. 17(3): p. 144-150. http://dx.doi.org/10.1061/(ASCE)0887-3828(2003)17:3(144)

[2] Melville, B.W. and S.E. Coleman, Bridge scour. 2000, Colorado, USA: Water Resources Publication, LLC.

[3] Alabi, P.D., Time Development of Local Scour at a Bridge Pier Fitted with a Collar. 2006, University of Saskatchewan: Saskatoon, Saskatchewan, Canada.

[4] Duc, B.M. and W. Rodi, Numerical Simulation of Contraction Scour in an Open Laboratory Channel. Journal of Hydraulic Engineering, 2008. 134(4): p. 367-377. http://dx.doi.org/10.1061/(ASCE)0733-9429(2008)134:4(367)

[5] Hong, S., Interaction of Bridge Contraction Scour and Pier Scour in a Laboratory River Model. 2005, Georgia Institute of Technology: Georgia.

[6] Taherei Ghazvinei, P., et al., Scour Hazard Assessment and Bridge Abutment Instability Analysis. Electronic Journal of Geotechnical Engineering Geology, 2012. Vol.17(0): p. 2213- 2224.

[7] Yorozuya, A., Scour at bridge abutment with erodible embankments. 2005, University of Iowa: Iowa.

[8] Garde, R.J., K. Subramanya, and K.D. Nambudripad, Study of Scour Around Spur-Dikes. Journal of the Hydraulics Division, 1962. 88(3): p. 225-228.

[9] Gill, M.A., Erosion of sand beds around spur dikes. Journal of Hydraulic Devision, 1972. 98: p. 1587-1601.

[10] Hahn, E.M. and D. A. Lyn, Anomalous Contraction Scour? Vertical-Contraction Case. Journal of Hydraulic Engineering, 2010. 136(2): p. 137-141. http://dx.doi.org/10.1061/(ASCE)0733-9429(2010)136:2(137)

[11] Coleman, S.E., C.S. Lauchlan, and B.W. Melville, Clear-water scour development at bridge abutments. Journal of Hydraulic Research, 2003. 41(5): p. 521 -531.

http://dx.doi.org/10.1080/00221680309499997

[12] Kothyari, U.C. and K.G.R. Raju, Scour around spur dikes and bridge abutments. Journal of Hydraulic Research, 2001. 39(4): p. 367-374. http://dx.doi.org/10.1080/00221680109499841

[13] Melville, B.W., Pier and Abutment Scour: Intergrated Approach. Journal of Hydraulic Engineering, 1997. 125(2): p. 125-136. http://dx.doi.org/10.1061/(ASCE)0733-9429(1997)123:2(125)

[14] Oliveto, G., W.H. Hager, and F.Asce, Temporal Evolution of Clear-Water Pier and Abutment Scour. Journal of Hydraulic Engineering, 2002. 128(9): p. 811 -820. http://dx.doi.org/10.1061/(ASCE)0733-9429(2002)128:9(811)

[15] Ballio, F., A. Teruzzi, and A. Radice, Constriction Effects in Clear-Water Scour at Abutments. Journal of Hydraulic Engineering, 2009. 135(2): p. 140-145. http://dx.doi.org/10.1061/(ASCE)0733-9429(2009)135:2(140)

[16] Melville, B.W., Local scour at bridge abutments. Journal of Hydraulic Engineering, 1992. 118(4): p. 615-631. http://dx.doi.org/10.1061/(ASCE)0733-9429(1992)118:4(615)

[17] Komura, S., Equilibrium depth of scour in long constrictions. Journal of the Hydraulics Division, 1966. 92(5): p. 17-37.