Hydraulic evaluation of emerged and submerged spur-dikes: temporal bed evolution and equilibrium state characteristics

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Spur dikes can be classification according to the height of the dike relative to water depth, as submerged or emerged dikes. The bed evolution criteria near the dike are studied and compared for the two dike states. The development of clear water local scour is experimentally recorded. For each state, an expression for predicting scour depth at any time is obtained by using regression analysis. In equilibrium state, the study reveals that the scour depth in a mature scour hole is asymptotically increasing. The characteristics of formed downstream sand bars are clarified. The deceleration of velocity behind the emerged spur dike is more than that behind the submerged one. New data are presented in addition to collected previous data in order to study the effective parameters on the properties of scour hole in both cases. Scour depth, width and volume for the case of emerged dikes are larger than those of submerged one. New predicting expressions for maximum scour depth of emerged and submerged dikes are presented and linked with evaluation graphs in the light of extensive data.

الرؤوس الحجرية يمكن تقسيمها من حيث الإرتفاع عن سطح الماء الى نوعين أساسيين، إما غاطسة تحت سطح الماء أو بارزة. وفى هذا البحث تم عمل دراسة مقارنة لحركة الرواسب فى القاع بالقرب من تلك الرؤوس وذلك لكل من حالتى الرؤوس الغاطسة والبارزة. فقد تم عمل دراسة معملية وافية لتطور النحر الموضعى مع الزمن وذلك لحالات الجريان المختلفة ولرؤوس حجرية ذات أبعاد هندسية مختلفة. وتم استنتاج معادلات للتنبوء بعمق النحر عند أزمنة مختلفة وذلك للنوعين السابق ذكرهما. وقد أثبتت الدراسات المعملية أن عمق النحر فى الحفرة المكتملة يتزايد بنسبة تقاربية ضئيلة ومن الصعب التحديد الدقيق لزمن التوقف للنحر. وتم أيضا مقارنة خصائص التكوينات الرملية المترسبة فى المنطقة خلف الرأس الحجرى للحالتين ومدى تطورها مع الزمن. وقد تم عمل خرائط توضح قيم ومتجهات السرعة فى المسقط الأفقى أمام وخلف الرأس الحجرى وكذلك خرائط توضح خطوط الكنتور لمناسيب القاع بعد الوصول الى حالة الإتزان مع توضيح الفرق لكل من حالتى الرؤوس البارزة والرؤوس الغاطسة. وايضا تم دراسة تأثير المتغيرات الهيدروليكية والهندسية المختلفة على مقدار عمق النحر للنوعين من الرؤوس. ويمكن إجمال القول بأن عمق وعرض النحر وكذلك حجم الحفرة المتكونة فى حالة الرؤوس البارزة أكبر من حالة الرؤوس الغاطسة. أخيرا تم تجميع البيانات المعملية المقاسة مع بيانات سابقة منشورة لباحثين آخرين، وتم الإستعانة بتلك البيانات لتقديم معادلتين مختلفتين لإستنتاج العمق الأقصى لحفرة النحر أمام الرأس الحجرى لكل من النوعين السابق ذكرهما مع المقارنة وذلك باستخدام مدخل نظرى سبق تقديمه فى بحث سابق مع الإستعانة بالطريقة الرياضية المعروفة بطريقة التحليل الترددى لربط المتغيرات وتحديد ثوابت المعادلات.

Keywords: Local scour, Bed evolution, Spur dike, Abutment, Sediment transport

1. Introduction

Spur dikes are structures constructed in rivers to maintain a suitable measures for bank protection and flood control. Recently dikes have been received more attention from the standpoint of ecosystem. The design, location, orientation and length of spur dikes are very important subjects for the hydraulic engineers in the field. Basically, it is important to have a clear picture of scour phenomenon around these structures in order to be able to make a safe and economic design. Also, hydraulic conditions such as velocity, water depth, bed shape, and bed material around dikes are so diverse to provide the ecosystem with suitable habitat.

Spur dikes can be classified as follows: (1) classification according to the method and materials of construction- permeable and impermeable (solid); (2) classification according to the height of dike relative to water depth, submerged or emerged; (3) classification according to the thickness and shape of spur cross section; (4) classification according to the function served; attracting, deflecting, repelling, and accumulating sediments; and (5) special types - Denehy's T-headed dikes, Hockey type, Burma type, etc.

In some locations dikes are constructed higher than the high water level, which are called emerged dikes. In other locations dikes are submerged under the water surface. In rivers with unsteady flow conditions, dikes can serve as emerged in ordinary state or submerged during flood. The area behind the dike is either a dead zone during emerged conditions or a slow flow zone during submerged flow conditions.

Most of previous investigators published experimental data on the various aspects of the local scour around emerged spur dikes. In their experiments, they have used flow depths that were less than the height of the spur-dike model, (Ahmed [1], Liu et al. [2], Garde et al. [3], Laursen [4], and Gill [5]). Recent studies have included Rajaratnam and Nwachukwu [6] and Melville [7]. The study of Melville [7 and 8] summarized several studies completed since the beginning of the 1980s (e.g., at Auckland University). Many prototype spur dikes, however, were designed to regularly consider overtopping flow, submerged condition. A few studies were presented for submerged dikes, such as the study of Kuhnle et al. [9], Kuhnle et al. [10], Elawady [11].

The difference in hydraulic characteristics and bed topography changes for both cases of emerged and submerged dikes is not clearly clarified yet. Two main subjects should be presented for evaluating both cases. The first subject is the time development of bed evolution around spur dike; the second is the estimation of maximum local scour depth near the tip of the dike.

The problem of time evolution of bed has received less attention in the case of dikes and bridge abutments than in the case of bridge piers. The temporal evolution of local scour near the dike nose, and the downstream formation of sand bars have some significance, particularly to predict the scour depth at a certain moment of a flood hydrograph, and the change of channel geometrical properties in the downstream region. Several studies were carried out for depicting scour development near dikes and abutments, such as the studies of Garde [3], Gill [5], Rajaratnam and Nwachukwu [6], Zaghloul [12], Kuhnle et al. [9], Cadoso and Bettess [13], Kuhnle et al. [10], Oliveto and Hager [14].

The development of bed undulations and sand bars formation in the downstream of the dike is important for the cross sectional channel properties and the allocation of infrastructures or related waterworks such as power plants or water intakes. As far as the author knowledge, this point is not clarified yet.

The problem of estimating maximum scour depth had the attention of many investigators from several decades till now. There are basically three types of scour-depth prediction approaches in the literature: (i) the regime approach, Ahmed [1], which relates the scour depth to the increased discharge intensity or flow at the abutment location; (ii) dimensional analysis approach (Liu et al. [2], Garde et al. [3], and Melville [7], where relevant dimensionless parameters describing the phenomenon are correlated; and (iii) analytical or semi-empirical approach, such as those proposed by Laursen [4] and Gill [5], based on a sediment-transport relation for the approaching flow, or based on similarity principle such as those proposed by Oliveto and Hager [14], or based on the hydrodynamic equations such as the work of Nagy [15].

In the present study, which is exploratory and experimental in nature, the scour and flow structure around the single dike is investigated for both cases of emerged and submerged dikes. In order to clarify the effect of time of the development of the shape of scour hole, and the downstream sand waves formation, several experiments within laboratory conditions were conducted for uniform sediments and for long period of time to ensure the state of equilibrium. New expressions for scour depth development are obtained for emerged and submerged states. Velocity patterns as well as bed topography patterns for both cases are portrayed and discussed. Using a pool of extensive data sets for emerged and submerged experiments, a parametric analysis is presented. Two expressions for maximum scour depth for the two cases are given by using a semi-empirical approach and regression analysis, Nagy [15].

2. Experimental procedures

The experiments were conducted in a straight tilting plexiglass walled flume with 20 m length, 0.4 m width and having depth of 0.5 m in the Hydraulics Laboratory, Saga University, Japan. The flume has an adjustable slope. The water was supplied from an underlying sump through a re-circulating system. The water then passed through an approach tank provided with a series of baffles. These baffles distributed the flow uniformly over the entire width of the flume and also helped in dissipating the excess energy of flow. The sand bed had a thickness of 20 cm. The sand used in the experiments reported herein has mean size of d_{50}= 0.1291 mm and standard deviation of σ = 1.259. The spur dike models used in the study were made of vertical teakwood planks of thickness 30 mm and projection length of 10 cm. The spur dike nose was rounded. The spur dike was positioned with different angle of inclination of α = 30°, 60°, and 90° with the downstream. The sand bed was sited from 5.0 m upstream to 5.0 m downstream of the axis of the spur dikes. Before the beginning of each run the sand bed was leveled to give the predetermined slope. Passing a specific discharge, a constant water level was maintained by adjusting two flip and sliding gates at the tail end. The discharge was controlled by an automatic valve located in the supply pipeline and connected with electronic digital regulator to pass a certain discharge even though the pump supply is not steady. Water depths were measured by the help of a point-gauge mounted on a wooden frame. Velocity measurements were obtained by using two-dimensional elector-magnetic current-meter consisting of a 7 mm-diameter transducer probe with cable and a signal processor. Bed levels along the flume were regularly measured by using bed profile indicator connected with a digitizer. Both velocity measuring device and bed levels indicator are connected with an electronic personal computer. Two groups of experiments were conducted; the first was for single submerged dike (when the dike is totally submerged under water surface, for instance during flood), the second group was for single emerged dike (when the dike is partially submerged under water surface). Each run was ended after getting equilibrium state for local scour (72 hours). Details of experimental conditions and of selected

Table 1
Experimental conditions

Index	Series	d_{50}/h_0	I	α^0	F_n	h_1/h_0	D/h_0
A1	S-11	0,02152	1/1195	90	0,37	0,67	1,33
A2	S-12	0,01434	1/1195	90	0,27	0,44	0,67
A3	NS-11	0,0215167	1/1195	90	0,37	-	1,92
A4	NS-12	0,0143444	1/1195	90	0,27	-	1,11
A5	NS-13	0,0215167	1/1195	60	0,37	-	1,63
A6	NS-14	0,0143444	1/1195	60	0,27	-	0,98
A7	NS-15	0,0099308	1/1195	60	0,24	-	0,77
A8	S-13	0,0215167	1/1195	60	0,37	0,67	0,83
A9	S-14	0,0143444	1/1196	60	0,27	0,44	0,44
A10	S-15	0,0099308	1/1197	60	0,24	0,31	0,23
A11	S-16	0,0215167	1/1198	30	0,37	0,67	0,50
A12	S-17	0,0143444	1/1199	30	0,27	0,44	0,14
A13	NS-16	0,0215167	1/1195	30	0,37	-	0,83
A14	NS-17	0,0143444	1/1195	30	0,27	-	0,28
B1	S-01	0,021567	1/1450	90	0,37	0,17	1,67
B2	S-02	0,01291	1/1450	90	0,23	0,50	0,35
B3	NS-01	0,0215167	1/1450	90	0,37	-	1,75
B4	NS-02	0,01291	1/1450	90	0,23	-	0,75

NS : emerged dike experiments S: submerged dike experiments experimental runs are given in table 1, in which h_0 is the approaching flow water depth, d_{50}/h_0 is the sediment size ratio, I is the longitudinal slope of the channel, α^0 the angle of inclination to the downstream, F_n is the approaching flow Froude number, h_1 is the distance from the water surface to the top of the dike, which allows water to pass through it, h_1/h_0 is the overtopping ratio, D is the maximum scour depth measured from the original bed surface, and D/h_0 is the maximum scour depth ratio.

3. Time development of bed evolution around dikes

Bed evolution starts around spur-dike when bed local shear stress exceeds the critical shear stress. Scour development in scour hole increases progressively with time in the absence of sediment supply to the scour hole from the upstream and then reaches equilibrium state. The maximum threshold velocity causes the erosive process near the dike nose. Balance between the transport capacity of the flow and bed surface resistance is accomplished when the maximum water depth over scour hole reaches a specific depth associated with the threshold shear stress. A large amount of eroded sediments from the scour hole is accumulated forming a sand bar extends somewhere in the downstream.

In all experiments, the process of temporal evolution of bed and the formation of scour hole upstream the dike and sand bar in the downstream is recorded. All experiments were conducted for a period of 72 hours for each run. It was found that the equilibrium state for sediment transport in the scour hole was attained almost after 60 hours of the beginning of experiment.

Figs. 1 and 2 show plots of bed evolution patterns for sequential time intervals for two cases of emerged and submerged dikes.

3.1. Development of scour hole

Fig. 3 shows a plot of relative temporal scour depth, D_t/D as a function of dimensionless time, $t/t_{(max)}$, for two different flow conditions; F_n = 0.272 and 0.366 and two angles of inclination; α= 90^0 and 60^0, in which

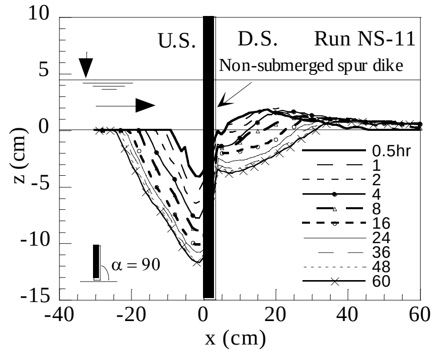

Fig. 1. Variation of bed profile with time for emerged spur dike.

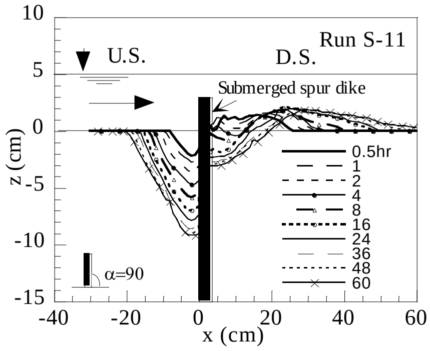

Fig. 2. Variation of bed profile with time for submerged spur dike.

$t_{(max)}$ is the maximum scour depth in each run, t is the time at a certain hour, and D_t is the scour depth at a certain time t. From the plot, three phases of scour rate is identified as follows:

i. the initial phase, which has steep slope representing high rate of scour and it takes 10 % of the elapsed time.

ii. the transition phase, which has mild slope and extends for relatively long period of time, 70% of the elapsed time, representing low rate of scour.

iii. The equilibrium phase, which has almost horizontal slope representing un-measurable rate of scour, and it takes 20 % of the elapsed time.

The plot indicates that the rate of scour for higher value of the Froude number is faster than that of lower value. Also, the rate of scour for 90^0 dike is faster than the rate for 60^0 dike.

Fig. 4 shows the rate of increase of scour depth in the scour hole for both cases; emerged and submerged dikes. It is clear from

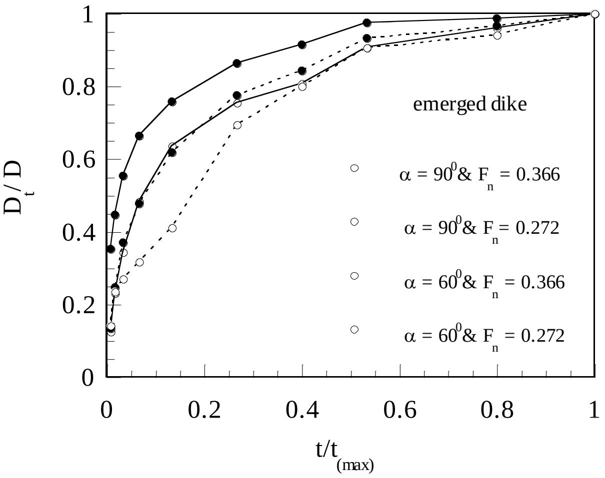

Fig. 3. Effect of F_n and α on the scour rate.

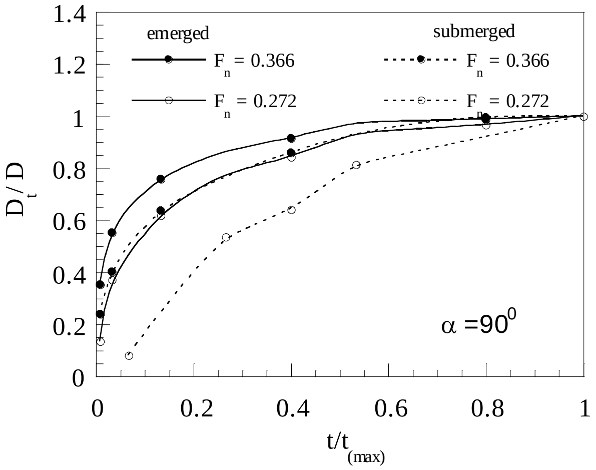

Fig. 4. Effect of dike type on the scour rate.

the graph that the scour rate is accelerating faster for emerged dike more than submerged one, especially in the initial phase of scour.

3.1.1. Estimation of temporal scour depth

Estimation of temporal evolution of scour near spur dikes and abutments has some significance, particularly to estimate the scour depth at any time of a flood hydrograph. Since the time of maximum scour depth, t_{max}, can not be accurately quantified, A dimensionless time scale parameter, $\sqrt{g/h_0}\,.t$, is developed particularly from measurable and effective parameters. Fig. 5 shows the relation between the time scale parameter $\sqrt{g/h_0}\,.t$ and the scour depth ratio D_t/D for emerged dikes. The plotted data shows a logarithmic trend of the relation.

The regression analysis is applied on the recorded experimental data in order to get an expression for estimating the progress of scour with time for emerged dikes. The developed expression is derived in the following form,

$$D_t / D = -1 + 0.31 \log\left[\sqrt{g/h_0} \times t + 1750\right]. \qquad (1)$$

Similarly, experimental data are plotted in fig. 6 to represent the development of scour depth with time near submerged dikes. Another expression is derived for calculating scour depth at any time, eq. (2). It is noticed in fig. 6 that the maximum scour depth for several experimental runs is not at the time of equilibrium state. The scour hole is partially refilled with sediments before getting the equilibrium state;

$$D_t / D = -1 + 0.30 \log\left[\sqrt{g/h_0} \times t + 2000\right]. \qquad (2)$$

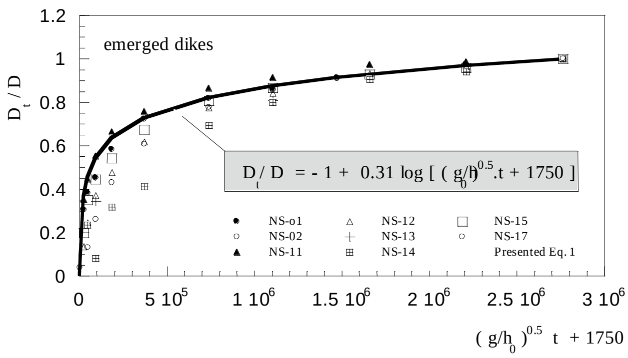

Fig. 5. Scour depth development with time for near emerged dikes.

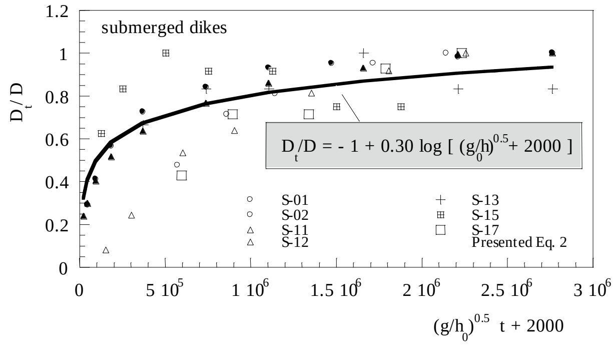

Fig. 6. Scour depth development with time for near submerged dikes.

3.1.2. Sand bar development

Development of local scour near the dike nose is congruent with the formation of bed forms in the down stream part of the channel. The removed sediments from the scour hole are accumulated in the downstream forming a sand bar or small bed forms. The plot in fig. 7 shows the relation between the relative height of downstream sand bar (H_1/h_0), and the dimensionless time (t/t_{max}) for two different flow conditions; F_n = 0.272 and 0.366, and three angles of inclination; α= 90^0, 60^0 and 30^0 for emerged dikes. where $H_1$is the height of sand bar from the original bed. From the plot, two phases of sedimentation rate can be identified as follows:

a. the initial phase, which has steep slope representing high rate of accumulation and it takes from 5% ~ 10% of the elapsed time.

b. The equilibrium phase, which has almost horizontal slope, and it takes 90% of the elapsed time.

c. for experiments with relatively high Froude number, the sand bar was partially washed out and its height had been decreased gradually.

Similar to the mechanism of the scour hole development, the plot indicates that the rate of sedimentation in the initial phase of sedimentation for higher value of Froude number is faster than the case of low value of Froude number. Also, dike with 90^0 angle of inclination is faster than the rate for dikes with 60^0 and 30^0.

Fig. 8 shows that the formation of sand bar is completed in the earlier stage for both emerged and submerged dikes. In the final

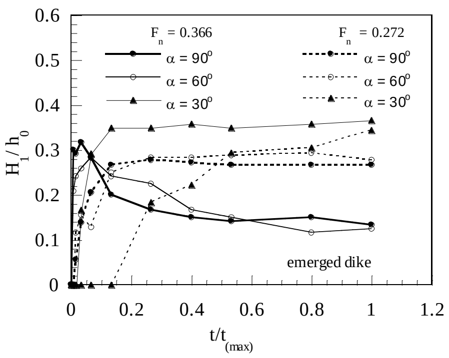

Fig. 7. Effect of F_n and α on downstream growth rate for sand bar height.

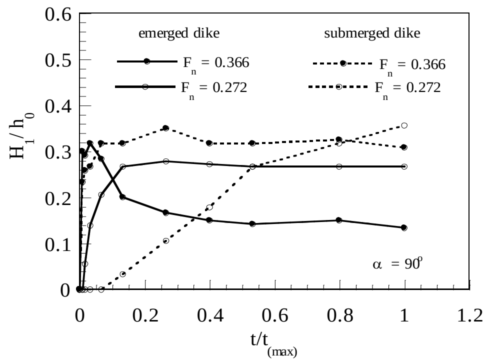

Fig. 8. Effect of dike type on the growth rate for sand bar height.

phase of sand bar formation, the relative height of sand bar for submerged dike case is higher than for the case of emerged one. For the case of emerged dike with relatively high Froude number, the sand bar has the tendency to be washed out after reaching its maximum depth.

4. Qualitative evaluation in equilibrium state

4.1. Velocity vector pattern

Two-dimensional velocities are measured for a horizontal mesh located at the midpoint of water depth. The measurements were conducted on a grid of points in front of the region upstream and downstream the spur dike by using electro-magnetic current-meter. The grid size is 20x10cm away from the dike, and 10x5cm near the dike. The results demonstrate the differences between the nature of turbulence in the two different stages. In fig. 9, the pattern of velocity vector is portrays the emerged dike with 60° angle of inclination, while fig. 10 portrays the dike with the same angle but in submerged state. In general, the mix between main channel flow and the dike region flow creates a field of vortices in the near area. The bottom vortices cause sediment transport and morphological changes in the bottom of the channel. The dynamics of flow near spur dikes are investigated for two different dikes stages.

When dike is emerged, the flow behind the dike field shows the circulation behavior. It could be characterized by eddy vortices, which covers length of about four times the

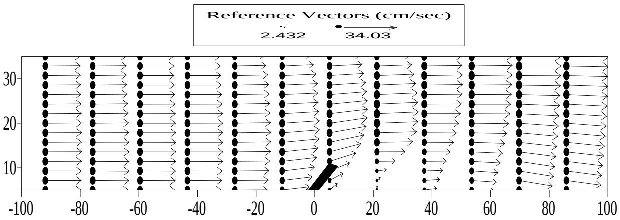

Fig. 9. Pattern of velocity vector in channel with 60° emerged dike.

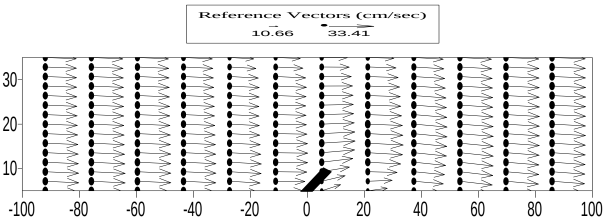

Fig. 10. Pattern of velocity vector in channel with 60° submerged dike.

projection length of the dike. The velocity is less than 10 % of the channel mean velocity, and the momentum exchanges between the circulating flow and the main flow of the channel. The separation zone downstream of the abutment is also clearly evident.

When dike is submerged the flow in the dike field does not show the circulation pattern as observed in the emerged condition. It is characterized as a slower velocity region. The momentum transfer by the water flowing over the dikes is sufficient to balance the momentum transfer through the mixing layer. The flow behind the dike shows decelerating pattern.

4.2. Bed topography pattern

After the end of each experiment, the data for bed level indicator are processed, and a contour map for bed topography is drawn by using the computer software "Surfer". A comparison between scour patterns for emerged and submerged dikes is done. Different flow conditions and different angles of inclination are examined, figs. 11-a to 11-d show two pairs of graphs representing the topography of scour holes and downstream sand bars for two angles of inclination, 90° and 30°, respectively. Each pair has similar flow conditions, dike geometry, soil properties, and angle of inclination, but one graph is for submerged dike while the other is for emerged one. The experiments for emerged dikes had the maximum depth of scour at the upstream nose of the structure, figs. 11-a and 11-c. For experiments of submerged dike the maximum depth of scour was on the upstream side of the structure, figs. 11-b and 11-d. The following conclusions may be obtained from the graphs:

1. The maximum scour depth for emerged dike is deeper than that for submerged one.
2. Scour hole width and volume for submerged dike is smaller than that for emerged one.
3. Both types of dikes formed sand bars in the down stream, however bed undulation for experiments of emerged dikes extended longer distance in the downstream.
4. Experiments for dikes with angle of inclination have less scour depth, scour volume, smaller downstream sand waves, and limited effect on the bed near the other side of the channel.

5. Evaluation based on parametric analysis

5.1. Mining of previous experimental data

A database of 235 laboratory experiments conducted under clear water scour conditions in rectangular flumes for vertical wall spur dikes has been assembled, analyzed and added to the present 18 measured data sets. The purposes are to perform a parametric analysis for a wide range of variables and conditions, and to develop a general formula for maximum local scour depth near vertical wall abutments and spur dikes under emerged and submerged states. The data are compiled from the studies of Grade et al. [3], Gill [5], Rajaratnam et al. [6], Zaghlol [12], Kwan [16], Tey [17], Lim [18], and Mamdouh [19], Elawady [11]. Table 2 shows the summary of the established database. The data ranges for each of the pertinent parameters are $0.05 \leq F_n \leq 0.75$, $0.08 \leq L/b \leq 0.68$, $0.32 \leq L/h_0 \leq 17.4$, $0.002 \leq d_{50}/h_0 \leq 0.08$, $0.00003 \leq I \leq 0.00295$, $1.0 \leq \sigma \leq 2.2$, $30^0 \leq \alpha^0 \leq 150^0$, in which b is the channel width, L/b is the contraction ratio, σ is the standard deviation of sediments size distribution. Table 2 shows the range of parameters for the previous studies.

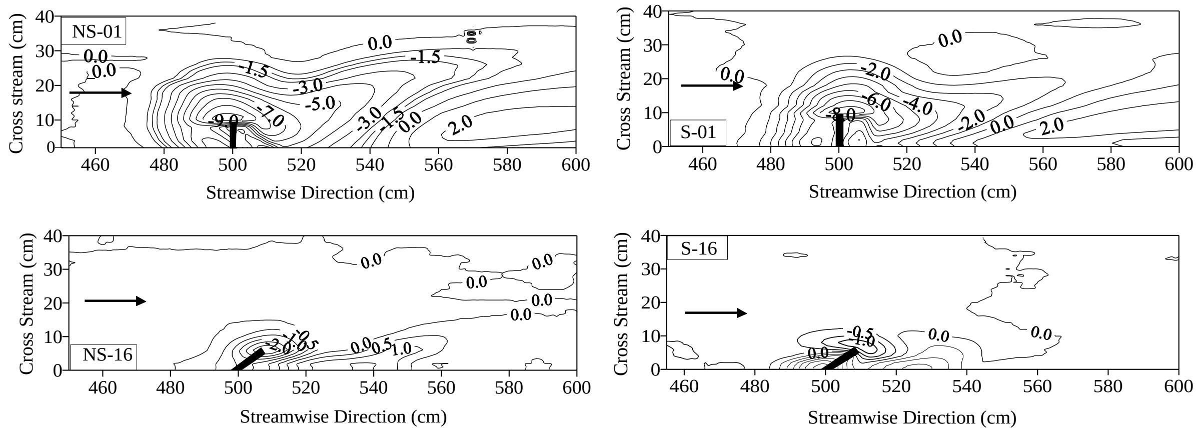

Fig. 11. Contour maps for scour holes emerged and submerged spur dikes for the cases:
(a) Emerged with 90° angle of inclination; (b) Submerged with 90° angle of inclination;
(c) Emerged with 30° angle of inclination; (d) Submerged with 30° angle of inclination.

5.3. Effect of overtopping ratio on the maximum scour depth

For submerged dike, the ratio between this distance and the water depth is called overtopping ratio, h_1/h_0. Fig. 12 shows the relation between the flow Froude number, F_n, and the maximum scour depth ratio, D/h_0, with the overtopping ratio, h_1/h_0 as a parameter and for constant value of L/b= 0.25 and angle of alignment α = 90^0. Also the figure shows that, for constant Froude number, the overtopping flow does make a significant difference in the magnitude of scour depth, in which increasing the overtopping ratio, h_1/h_0, is inversely proportional to the scour depth ratio, D/h_0. For emerged dike, the overtopping ratio, h_1/h_0, equals zero. It is concluded that, for the same flow, sediment and dike geometrical properties, the scour depth in the hole around emerged dike is deeper than that for submerged one.

5.2. Effect of dike alignment on the maximum scour depth

Spur dikes vary depending on their action on the stream flow. They may be classified as deflecting, attracting or repelling dikes. A deflecting spur-dike usually of short length perpendicular to the river/channel bank, changes only the direction of flow without repelling it, and gives only local protection. An attracting spur-dike points downstream and attracts the stream flow toward itself. This type of dikes does not repel the flow towards the opposite bank, and therefore should never be placed on a concave bank. A repelling spur-dike points upstream and has the property of repelling the river flow away from it, Prezedwojski et al. [20].

Several researches have studied the effect of spur dikes alignment on scour depth. Melville and Coleman [21] stated that the depth of scour increases by about 20% as the angle of the abutment is increased from 30° to 150° for large abutments (L/h_0> 3). Kwan [16] and Kandasamy [22] found that the scour depth decreases for alignment angles greater than 90°.

The effect of dikes alignment is investigated for both emerged and submerged dikes. In all experiments, the scour hole falls near the tip of the dike in upstream side or downstream as well. To illustrate the effect of dikes alignment on maximum scour depth, the tabulated experimental data, table 1, in addition to a group of data collected from several reliable resources, table 2, are utilized. Five angles of inclination; 30°, 60°, 90°, 120°, and 150° are presented, respectively.

Figs. 13 and 14 show the relation between the angle of inclination α and the ratio of maximum scour depth to the maximum scour depth of the dike with 90° angle of inclination, D_α/D_{90} for emerged and submerged dikes, respectively. The tested group of data represents the long dikes (L/h_0>3), intermediate dikes (1<L/h_0<3), and short dikes (L/h_0<1). From

Table 2
Summary of the assembled experimental data for local scour

Researcher	d_{50} mm	σ	F_n	L/b	L/h_0	d_{50}/h_0	α degree	Exp. Time hrs	No. of Points	Group
Garde et al. (1961)	0.029	1.66	0.11~ 0.37	0.16	0.56~2.79	0.002~0.08	90	5	18	A
Garde et al. (1961)	0.10	1.38	0.34~ 0.39	0.08~0.41	0.51~2.54	0.01 ~0.011	90	5	5	A
Gill (1972)	0.15	1.15	0.24~ 0.75	0.27	2.09~7.79	0.015~0.047	90	6	33	A
Gill (1972)	0.091	1.22	0.24~ 0.58	0.13~0.40	1.73~7.30	0.016~0.028	90	6	27	A
Rajaratnam et al(1983)	0.14	1.30	0.17~ 0.31	0.17	0.99~1.42	0.009~0.013 0.014~0.039	90	166~600	6	A
Zaghlol (1983)	0.45	1.30	0.18~ 0.40	0.33	0.47~1.30	0.017	90	2.5	12	A
Kwan (1984)	0.085	1.28	0.31~ 0.38	0.13~0.68	3.28~17.4	0.005~0.016	45~135	22 ~ 100	11	A
Tey (1984)	0.082	1.26	0.25~ 0.38	0.11~0.20	1.65~6.04	0.006	90	67 ~ 121	4	A
Siow-Yong Lim(1997)	0.094	1.25	0.15~ 0.27	0.08~0.25	0.33~1.00	0.003~0.006 0.006~0.015	90	72 ~ 193	11	A
Mamdouh (2000)	0.051	2.2	0.05~ 0.24	0.10~0.50	0.32~2.38		30~150	5	55	A
Elawady (2002)	0.075	1.0	0.32 ~0.52	0.13~0.38	0.38~3.00		30~120	5	68	B

A: emerged dikes experiments B: submerged dikes experiments

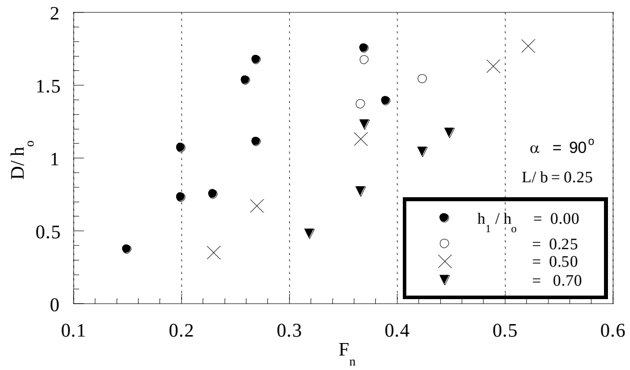

Fig. 12. Effect of overtopping ratio on maximum scour depth.

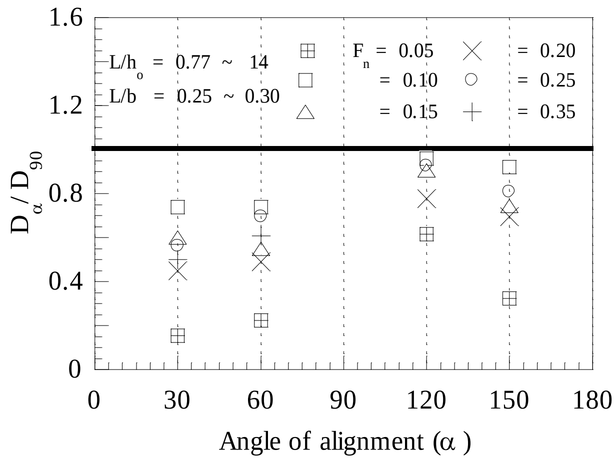

Fig. 13. Effect of angle of inclination for emerged dikes.

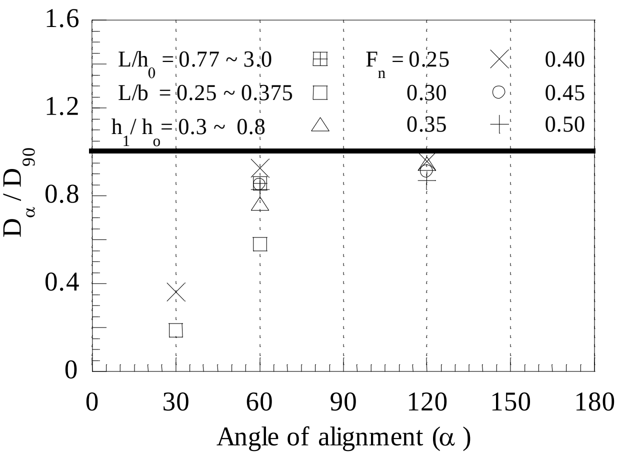

Fig. 14. Effect of angle of inclination for submerged dikes.

the presented figures, it is concluded that:
1. The maximum scour depth for emerged dikes is larger than submerged ones for the same flow and dike geometric conditions.
2. Perpendicular dikes to the sidewall of the channel cause deeper scour depths more than the attracting or repelling dikes.
The dike with inclination angle $\alpha < 90^{o}$ produced the least scour depth at all times.

5.4. Effect of dike intrusion length ratio

For a constant value of sediment size ratio and for the same angle of inclination ($\alpha = 90^{0}$), the relation between Froude number, F_n

and the maximum scour depth ratio D/h_0 is shown in figs. 15 and 16 with L/bas a parameter for both cases emerged and submerged dikes, respectively. For both states of flow the scour depth ratio increases with the increase of the intrusion length ratio.

6. Quantitative evaluation of maximum scour depth

Based on the flow continuity equation, the generalized form of the momentum equation, the bed scour geometry and the Karman-Prandtl logarithmic law for flow resistance, an expression for maximum scour depth near emerged spur dike obstructing the flow direction is developed, Nagy [15]. The analytical analysis proved that maximum scour depth ratio is in direct proportional to the square of the Froude number. The obtained expression involves various flow, sediment and geometrical properties, which have significant effect on the local scour criteria.

$$\frac{D}{h_0} = f\left(d_{50}/h_0\,,\, L/h_0\,,\, h_1/h_0, \alpha\right) F_n{}^2 . \qquad (3)$$

For emerged dikes, a group of 193 experimental data sets on clear-water scour depth is utilized to develop a discrete form for the expression of maximum scour depth through a statistical nonlinear regression analysis. For submerged dikes, a group of 78 data sets were utilized. The range of variables in both flow conditions is shown in table 3.

The presented expression for emerged dikes yields, [15]

$$\frac{D}{h_0} = 3.0 \; \frac{\left(L/h_0\right)^{0.42} (sin\alpha)^{0.717}}{\left(d_{50}/h_0\right)^{0.277}} \; F_n^2 \; . \qquad (4)$$

Similarly, a regression analysis is used to develop the new expression for submerged dikes,

$$\frac{D}{h_0} = 1.7 \; \frac{\left(L/h_0\right)^{0.42} \left(h_1/h_0\right)^{0.025} \; (sin\alpha)^{0.717}}{\left(d_{50}/h_0\right)^{0.277}} F_n^2 \; . \qquad (5)$$

Table 3
Range of data used fin regression analysis for emerged and submerged dikes

Parameter	Emerged data ranges	Submerged data ranges
F_n	0.05 ~ 0.75	0.23 ~ 0.52
L/h_o	0.32 ~ 17.4	0.38 ~ 3.0
L/b	0.07 ~ 0.68	0.13 ~ 0.38
d_{50}/h_0	0.002 ~ 0.08	0.006 ~ 0.022
h_1/h_0	---------	0.06 ~ 0.81
D/h_0	0.022 ~ 5	0.231 ~ 2.50

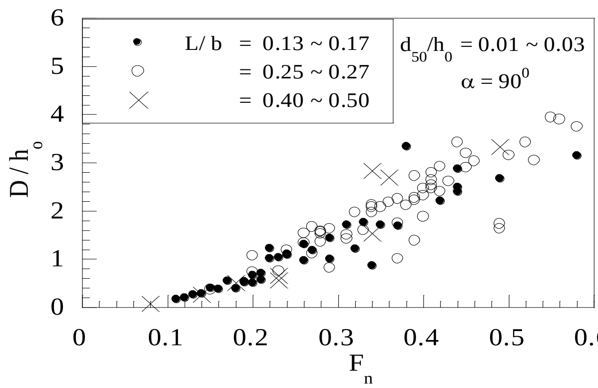

Fig. 15. Effect of intrusion length on scour depth for emerged dikes.

Fig. 17 shows the line of perfect agreement between measured and calculated maximum scour depth near emerged dikes for the 193 data sets which were used in estimating the formula. The mean error is 0.137 and the average standard error is 0.058. Almost 80% of the data points within the $\pm 50\%$ limit lines. Fig. 18 shows the same plot but for submerged dikes data. The mean error is 0.006 and the average standard error is 0.03. Almost 84% of the data points within the $\pm 50\%$ limit lines.

7. Conclusion

This study is focused on characterizing the diversity in behavior of the flow and bed topography near emerged and submerged spur dikes. The following conclusions are outlined from the study:

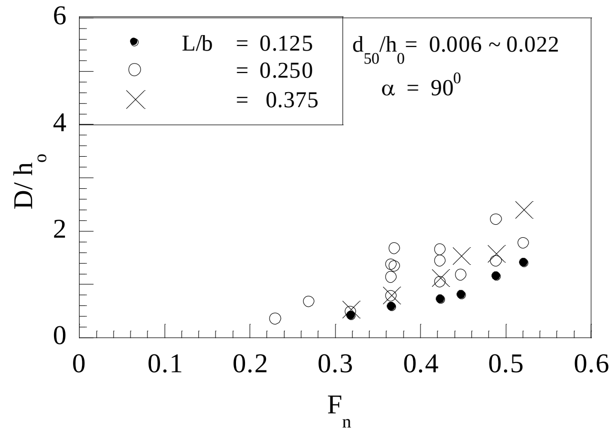

Fig. 16. Effect of intrusion length on scour depth for submerged dikes.

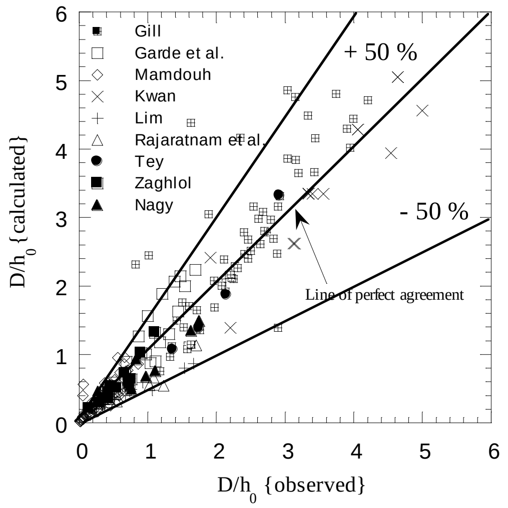

Fig. 17. Validation of eq. (2) for emerged dikes.

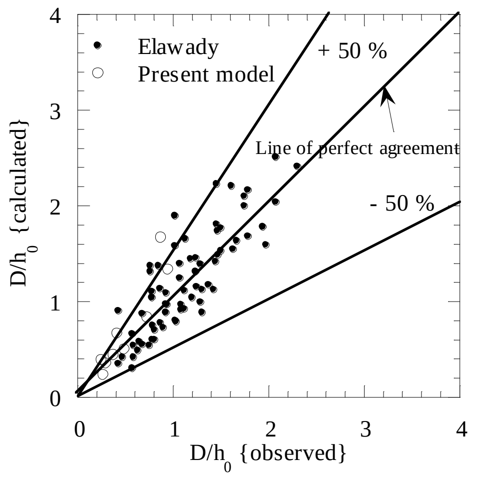

Fig. 18. Validation of eq. (3) for submerged dikes.

1. Evolution progress

- The initial phase of scour, which has steep slope representing high rate of erosion, takes 10% of the elapsed time.
- The transition phase, which has mild slope and extends for relatively long period of time, takes 70% of the elapsed time representing low rate of scour.
- The equilibrium phase, which has almost asymptotic approach representing un-measurable rate of scour, takes 20% of the elapsed time.
- The plot indicates that the rate of scour for higher value of the Froude number is accelerating faster than that of lower value of the Froude number. Also, the rate of scour for 90^0 dike is accelerating faster than the rate of lower angled dike.
- In the final phase of sand bar formation, the relative height of sand bar for submerged dike case is higher than for the case of emerged one. For the case of emerged dike with relatively high Froude number, the sand bar has the tendency to be washed out after reaching its maximum depth.
- The depth of scour progresses linearly with the logarithm of time during the development of the hole. Two equations are presented to postulate the relation between the time and scour depth development for emerged and submerged dikes.

2. The flow pattern for submerged dikes has less turbulence than that of emerged one, and the flow velocity behind the dike decelerates for emerged case more than submerged one.
3. The maximum scour depth for emerged dike is deeper than that for submerged one, and scour hole width and volume for submerged dike is smaller than that for emerged one.
4. Both types of dikes formed sand bars in the down stream, however bed undulation for experiments of emerged dikes extended longer distance in the downstream.
5. Experiments for dikes with angle of inclination have less scour depth, scour volume, smaller downstream sand waves, and limited effect on the bed near the other side of the channel the 90^0 dike.
6. A new expression for estimating the maximum scour depth is obtained from regression analysis of the experimental data.

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Received November 22, 2004
Accepted March 17, 2005