Local Scour as a Result of Spur Dike Implementations

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Abstract

A2-D hydrodynamic model was developed to investigate the effect of spur dikes on the local scour where Naga Hammadi Barrage was selected as a case study. The model was verified against experimental results of a physical modeling in order to assure its validity. Confident with the verified model, simulations were executed the implementation process. It was intended by these simulations to study the geometry of scour holes presented in terms of depth and length in addition to specific energy at the region of contraction. Eighteen runs (18) were executed where three (3) effective parameters were tested. These parameters are the contraction ratio, which is defined as the spur length to the channel width (L/B), the spur orientation angle; and the spur spacing. The contraction ratio was varied between 0.1 and 0.2 while the used orientation angle were 60 , 90 and 120 (attracting, straight, and repelling spurs) and the spacing were 2, 4, and 7 times the spur length. The study concluded that, the summation of the scour depths is directly proportional to the number of groins which is a function of groin length, spacing, and the required protected length. The scour depth is directly proportional to groin length under constant orientation angle. However, for fixed groin lengths, both scour hole depth and length are directly proportional to the orientation angle. It was also concluded that the continuity of the scour hole length in front of spur dikes installed group is inversely proportional to the spacing between the groins. The groin number 2 in a group of groins consists of 0.1 contraction ratio with 4L spacing acts as a fire wall against flow from diversion channel where the peak bed morphological changes are located. However, attracting groins presents the lowest values. Thus it was recommended to use attracting groins with such specifications in order to protect the bank and reduce the impact on the bed. This should be coupled with a well designed riprap of the second groin that was experimentally tested. As for the impact of groins implementation on specific energy, the tests showed that under constant groin length and orientation angle, the specific energy is inversely proportional to spacing between groins. Also, it is inversely proportional to the groin length, and consequently to scour depth. Both straight and repelling groups showed the same performance from specific energy point of view. On the other hand, a slight increase in values for the attracting group was observed.

***Key Words**: Oriented Spur dike, scour, and mathematical model*

1. INTRODUCTION

A spur dike may be defined as a structure extending outward from the bank of a stream for the purpose of deflecting the current away from the bank to protect it from erosion. In the case of dynamic rivers, the banks often erode and move laterally, resulting in land loss, channel change, excessive sediment yield and degradation of the water quality. The use of a series of spur dikes is one of the most effective means for stabilizing the banks. For economic reasons, spur dikes are often constructed of riprap and are commonly designed to be submerged during high flows. Despite the widespread use of spur dikes, many aspects of their design are based on prior experience and are only applicable to streams of a similar nature (Copeland, 1983). An improved understanding of the complicated 3-D flow in the vicinity of spur dikes and its interaction with the entrainment and transport of sediment is needed. Unfortunately, one of the main side effects resulting in groins implementation are the local scour associated in front of spur dikes. In spite of that, they were used successfully to enhance aquatic habitat in unstable streams (Shields et al., 1995). Scour is a natural phenomenon caused by the erosive action of flowing stream on alluvial beds. Estimation of the depth of scour at groin tips is a problem that has perplexed designers for many years.

many factors affecting the scour hole geometry around groins (i.e. shape, alignment, sediment size, length, flow depth, and flow intensity) are evident. Investigations of morphological bed changes, due to spurs that are implemented to protect the bank facing a diversion channel, are rare. This research was thus initiated in order to investigate the impact of length, spacing, and orientation angles of spurs on the associated characteristics of local scour holes with the objectives of determining the optimum set that minimizes the side effects. for this reason, a two dimensional finite element mathematical model was developed (molinas and hafez 2000 and ebraheem 2005).

2. MATHEMATICAL MODEL

The governing differential equations for the developed mathematical model are in the Cartesian X-Y coordinates, along and across the main flow directions. In the other hand, the Navier Stokes equations are used to describe motion. The fluid is assumed to be incompressible and follows a Newtonian shear stress law, whereby, viscous force is linearly related to the rate of strain. In the model, the hydrodynamics governing equations are the equations of conservation of mass and momentum. Conservation of mass equation takes the form of the continuity equation while Newton's equations of motion in two dimensions express the conservation of momentum. The continuity equation is given as:

$$\frac{\partial U}{\partial X}+\frac{\partial V}{\partial Y}=0 \qquad (1)$$

The momentum equation in the longitudinal (X) direction is

$$U\frac{\partial U}{\partial X}+V\frac{\partial U}{\partial Y}=-\frac{1}{\rho}\frac{\partial P}{\partial X}+\frac{\partial}{\partial X}(2\nu_e\frac{\partial U}{\partial X})+\frac{\partial}{\partial Y}(\nu_e(\frac{\partial U}{\partial Y}+\frac{\partial V}{\partial X}))+F_X+\left(\frac{\partial}{\partial z}\left(\frac{\tau_{\mathrm{fx}}}{\rho}\right)\right)_{Z=H} \qquad (2)$$

The momentum equation in the lateral (Y) direction is

$$U\frac{\partial V}{\partial X}+V\frac{\partial V}{\partial Y}=-\frac{1}{\rho}\frac{\partial P}{\partial Y}+\frac{\partial}{\partial X}(\nu_e(\frac{\partial U}{\partial Y}+\frac{\partial V}{\partial X}))+\frac{\partial}{\partial Y}(2\nu_e\frac{\partial V}{\partial Y})+F_Y+\left(\frac{\partial}{\partial z}\left(\frac{\tau_{\mathrm{fy}}}{\rho}\right)\right)_{Z=H} \qquad (3)$$

The scour depth over flow depth is

$$\frac{ds}{y}=2\ K_M\ \eta^{(1-\delta)} \qquad (4)$$

The specific energy at the region of contraction is

$$E_s=(y+d_s)+\frac{Q^2}{2g*(2.75*\frac{d_s^2}{2}+b*(y-d_s))^2} \qquad (5)$$

Where U = Longitudinal surface velocity, V = Transverse surface velocity, P = Mean pressure, ν_e = Kinematics eddy viscosity, F_x = Body force in X direction, F_y = Body force in Y direction, g = Gravity acceleration, θ = Average water surface slope, ρ = Fluid density, τ_{fx} = Turbulent frictional stresses in X-direction, τ_{fy} = Turbulent frictional stresses in Y-direction, d_s= maximum scour depth, y = depth of approaching flow, K_M= composite empirical parameter representing several factors of flow intensity, flow depth, sediment size, sediment gradation, groin shape and alignment, η = equals to groin length (L)/ flow depth (y), δ= factor depending on η, where δ ($\eta \leq 1$) = 0; δ ($1 < \eta < 25$) = 0.5; δ ($\eta \geq 25$) = 1, E_s= specific energy, Q: flow rate, b = width in contraction.

The assumptions used in the hydrodynamic model are:

- The density is constant (incompressible fluid);
- Flow conditions are constant;
- The turbulent viscosity varies with the velocity gradient;
- Surface is analyzed in a 2-D;
- Free surface is a rigid lid;
- Pressure is hydrostatic; and
- Wind stresses are neglected.

It should be mentioned that complete details about numerical solution of the model governing equations, the boundary conditions and the working flow chart is presented in Ebraheem, 2005.

3. TESTING THE MODEL

In order to make sure that the model is capable of predicting the scour in combination with velocity, the results of an experimental work (Attia, 1996) were re-simulated using the current model. The experimental work was conducted in the Hydraulics Research Institute (HRI) Ministry of Water Resources and Irrigation, Egypt as a part of PhD study. The experiment represented by a rectangular flume under re-circulated system used to simulate the flow pattern around groins in two straight reaches of the Nile River. The flume dimensions were (25.83* 0.73* 1.5m) to represent length, width and depth respectively. The spur was made of wooden rectangular plates that have a trapezoidal shape with a 15cm top width, 40cm for the bottom edge of the trapezium. The side slope was 3:2. The spur length represents about 0.15 of the channel width. The used cases are single spur dike of length 15cm and a group of three spur dikes with spacing of 45cm to represent 3L, where L is the spur length. These cases were simulated by the presented model and a comparison was hold based on the errors percentage of both depth and length of scour hole, Table (1).

It can be concluded that the maximum value of errors does not exceed 6.67%. This indicates that the model is capable to simulate new cases with reasonable results. However, 10 different experimental cases are re-simulated by the model to be more confident with its results. The simulated experiments are belongs to Kandasamy, 1989, Dongol, 1990, and Kwan, 1988) and the results are illustrated in Table (2). The table shows a comparison between the observed and computed values for the scour depth together with the percentage of errors. From the table, it could be noticed that the computed maximum percentage of errors is 8.75%.

Table 1: Comparison between Experimental Results and the Current Model

Reach	**Malkia**		**Gaafra**
No. of Spurs	**Single**	**Triple**	**Single**
Spur Length (m)	0.300	0.300	0.315
Flow Depth (m)	0.134	0.134	0.123
Experiment d_s (m)	0.420	0.420	0.413
Model d_s (m)	0.401	0.401	0.394
% Error for Scour Depth	4.74	4.74	4.82
Experiment Scour Length (m)	0.250	1.308	0.288
Model Scour Length (m)	0.239	1.262	0.270
% Error for Scour Length	4.60	3.65	6.67

4. SIMULATED CASES

4.1. Study Cases

A number of runs were simulated using the mathematical model; one of which represented the flow pattern without any spurs. This run was used as a reference to allocate the hydraulic performance of spur dike implementation in open channel at the opposite bank of the diversion channel.

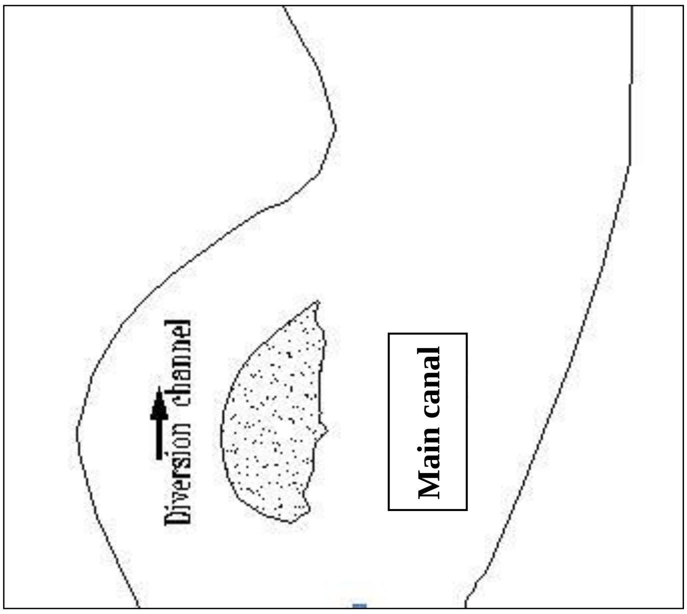

Figure 1: Sketch for The Diversion Channel

The runs names are formulated as spacing function of spur type, and contraction ratio. For example, $2A_{10}$ means that the spur spacing is equal to 2L at a 60^O (attracting spur) with 10% contraction ratio, and $4S_{20}$ means that the spur spacing is equal to 4L at a 90^O (straight spur) with 20% contraction ratio, while $7R_{10}$ means that the spur spacing is equal to 7L at a 120^O (repelling spur) with 10% contraction ratio. Table 3 shows the simulated conditions of every tested case, and figure (2) shows the alignment of spurs. The spur will cover a length of 450 m (the length needs to be protected in the diversion channel bank).

Table 2: Comparison between Measured and Computed Scour (10 Experimental Runs)

References	Spur Shape	Spur Length L (m)	Flow Depth y (m)	Measured d_s (m)	Predicted d_s (m)	Error%
Kandasamy (1989)	45° Wing Wall	1.380	0.020	0.194	0.200	3.00
		0.516	0.050	0.200	0.203	1.48
		0.125	0.125	0.179	0.188	4.79
Dongol (1990)	Vertical Wall	0.150	0.600	0.305	0.300	1.67
		0.150	0.500	0.300	0.300	0.00
		0.150	0.350	0.288	0.300	4.00
Dongol (1990)	45° Wing Wall	0.150	0.600	0.223	0.225	0.89
		0.150	0.500	0.220	0.225	2.22
Kwan (1988)	45° Wing Wall	0.475	0.150	0.365	0.400	8.75
		0.475	0.200	0.435	0.462	5.84

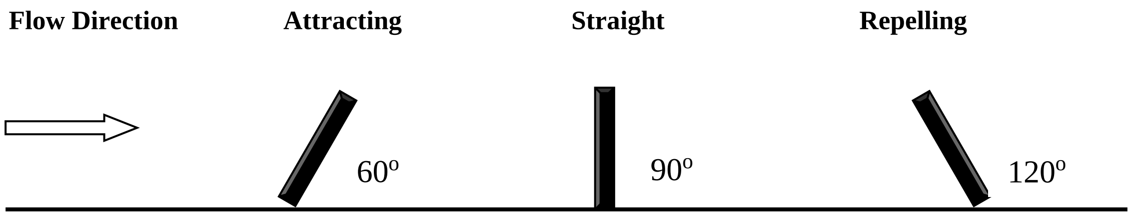

Figure 2: Shape of Oriented Spurs According to Flow Direction

5. MODEL SIMULATIONS, RESULTS AND ANALYSIS

The following section presents the results of the executed simulations, regarding the scour depth, length, and specific energy.

Table 3: The Conditions of the Simulated Cases

Run Name	**L/B**	**Angle of Orientation**	**Spur Name**
Basic	-----	-----	No spur
$2A_{10}$	0.10	60^0	Attracting
$4A_{10}$	0.10		
$7A_{10}$	0.10		
$2A_{20}$	0.20		
$4A_{20}$	0.20		
$7A_{20}$	0.20		
$2S_{10}$	0.10	90^0	Straight
$4S_{10}$	0.10		
$7S_{10}$	0.10		
$2S_{20}$	0.20		
$4S_{20}$	0.20		
$7S_{20}$	0.20		
$2R_{10}$	0.10	120^0	Repelling
$4R_{10}$	0.10		
$7R_{10}$	0.10		
$2R_{20}$	0.20		
$4R_{20}$	0.20		
$7R_{20}$	0.20		

5.1 The Scour Hole Depth

To investigate the geometry of scour holes under the tested simulated cases, a finite element mesh was created. It consisted of more than 7200 measuring nodal points. This required a long time in running the model, however it will increase the accuracy of the obtained results. The computed results were obtained, analyzed, and presented on figures (3) to (8). From figure (3) it could be noticed that, as the number of the groins increases (the number of groins increase as the spacing decrease to cover the required length of 450 m) , the summation of scour depths increases. (The smaller spacing together with the smallest contraction ratio, e.g., $2A_{10}$, $2S_{10}$, and $2R_{10}$). This is clarifying that the closer the spurs in the group specification the continuous action is extended to cover the entire length of the group. Therefore, it can be concluded that this type of specification of the group is suitable for bank protection. On the other hand, it was noticed that using fixed groin lengths, the group of attracting groins has the lowest values for scour depth. The group of repelling groins has the highest scour depth values. In other words it can be summarized that the scour depth is directly proportional to the angle of orientation. These results show good agreement with Milville conclusion in 1992 that the orientation angle is very effective in controlling the shape of scour holes, in addition to their depths and lengths. Figure 3 is established to confirm these results. It illustrates the relation between the number of groin location and scour depth over the flow depth for a group of groins with 45m length (0.1 contraction ratios) and 4L spacing at different orientation angles, (i.e. runs $4A_{10}$, $4S_{10}$, and $4R_{10}$). It was clear from the figure that the tested orientation angles showed the same trend with a peak value at the 2nd groin. Using attracting groins decrease the scour depth by 21.27% and 36.67% less than straight and repelling groins respectively. The attracting groins decrease the summation of scour depths at all groins by 19.80% and 37.69% less than straight and repelling groups respectively.

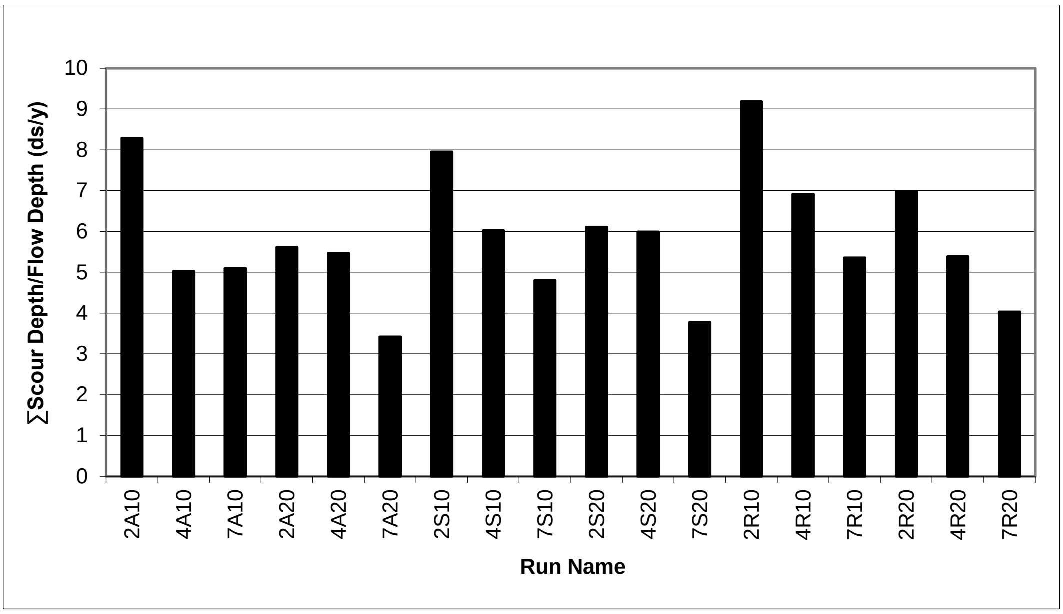

Figure 3: Summation of Scour Depth over Flow Depth for the Simulated Cases

5.2 The Scour Hole Length

The produced scour hole with the groin installation was found to have an inverted cone shape (has a depth and top length). Figure (5) shows the max scour length and width for the different simulated cases. The figure indicated that, for fixed orientation angle, the scour length is directly proportional to the groin length. Also, as the number of groins increase, the summation of scour lengths increase. Consequently, the closer spacing shows higher values for scour lengths.

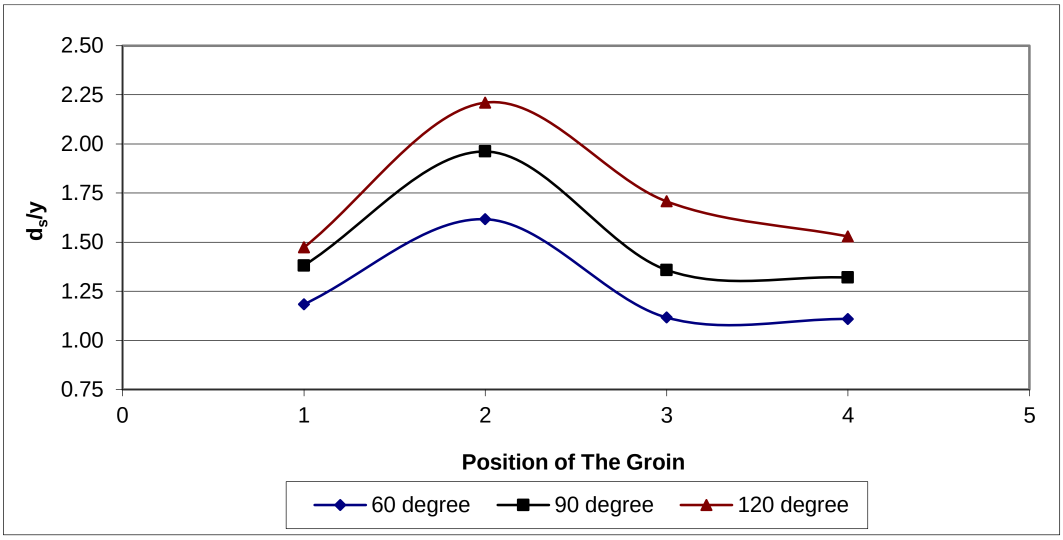

Figure 4: Effect of Orientation Angle on Scour Depth at Different Groins

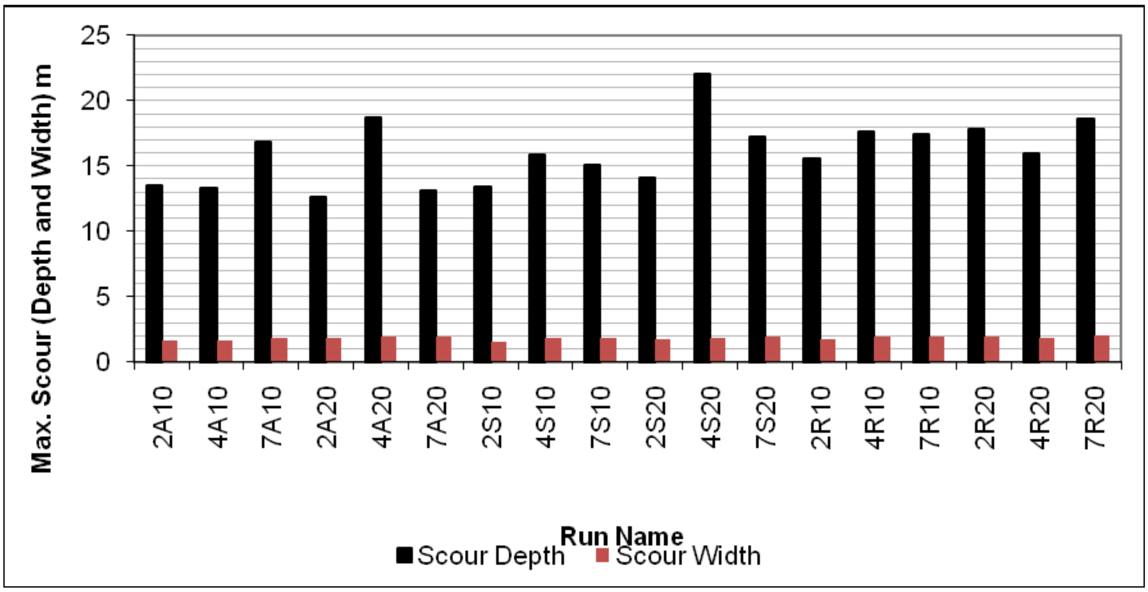

Figure 5: Maximum Scour Depth and Width for the Simulated Cases

Figure (6) reveals the effectiveness of the angle of orientation on the scour hole length. The relation between scour length over flow depth (b_o/y) for a group of groins with 67.5m length (0.1 contraction ratios) and 4L spacing at different orientation angles. (i.e. runs $4A_{10}$, $4S_{10}$, and $4R_{10}$) is given. From the figure it could be noticed that the curves have the same trend of (d_s/y) but with different values, as the lengths of scour hole are directly proportional to orientation angle. The peak value was found to be at the 2nd groin where attracting groin decreases the scour length by 10.01% and 16.91% for straight and repelling groins, respectively. Moreover, the attracting groins decrease the summation of scour lengths for all groins by 9.43% and 17.33% for straight and repelling groups respectively. Thus it was concluded that, the impact of orientation angles on scour depth is greater than their impact on scour length.

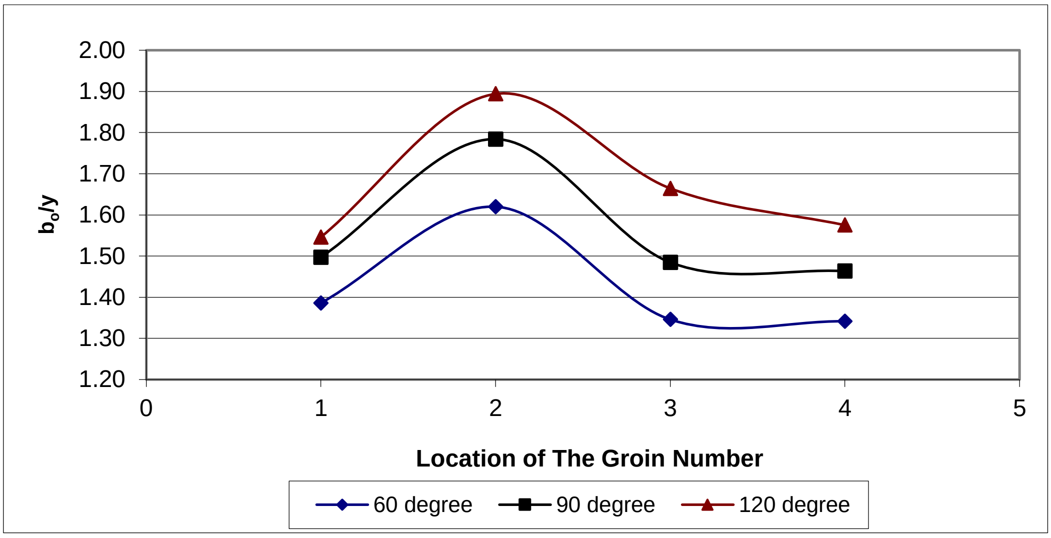

Figure 6: Effect of Orientation Angle on Scour Length for Different Groin Locations

5.3 The Specific Energy

The total energy of water in any stream line passing through a channel section is expressed as the total head of water in meters, which is equal to the sum of the elevation above a datum, the pressure head, and the velocity head, while the specific energy in a channel section is defined as the energy per unit weight of water at any section of a channel measured with respect to the channel bottom. Groin installation in any channel affects its bottom from scour holes point of view according to their installation. This affects the specific energy especially at the region of contraction. Figure (7) illustrates that for fixed groin length and orientation angle, the specific energy is inversely proportional to spacing between groins. Moreover, on contrary the scour depth, for a single groin, the specific energy is inversely proportional to groin length. It could thus be said that the specific energy is inversely proportional to scour depth due to groin installation.

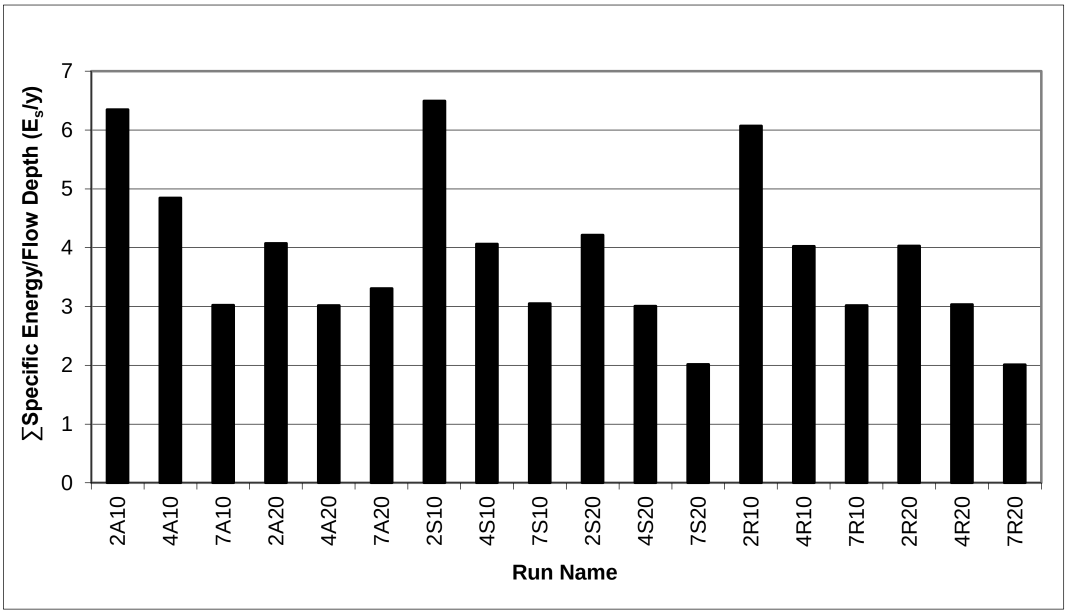

Figure 7: Summation of Specific Energy over Flow Depth for the Simulated Cases

As the orientation angles have an impact on both scour hole lengths and depths, they also have an effect on specific energy.

Figures (8) and (9) illustrate the relation between specific energy and flow depth, groin length respectively at the 2nd groin in a group of groins with fixed spacing 4L with varied length and orientation angle. The length to be 45m and 90m (presents 0.1 and 0.2 contraction ratios respectively). The orientation angles were 60^{O}, 90^{O}, 120^{O} (presents attracting, straight, and repelling groins respectively). The figures illustrate the inverse relationship between groin lengths over flow depth (L/y) versus specific energy over flow depth (E_s/y). Moreover, the attracting groins presents the peak values on contrary the repelling groins, they show the minimum values. The relationship was clear between flow depths over groin length (y/L) versus specific energy over groin length (E_s/L). It was noticed that the change in the angle of orientation does not show a noticeable difference in values. However, the attracting groins still keep the peak values. On the other hand; the repelling groins produce the minimum value. The illustrated results are in good agreement with the results of Eduardo, 1998.

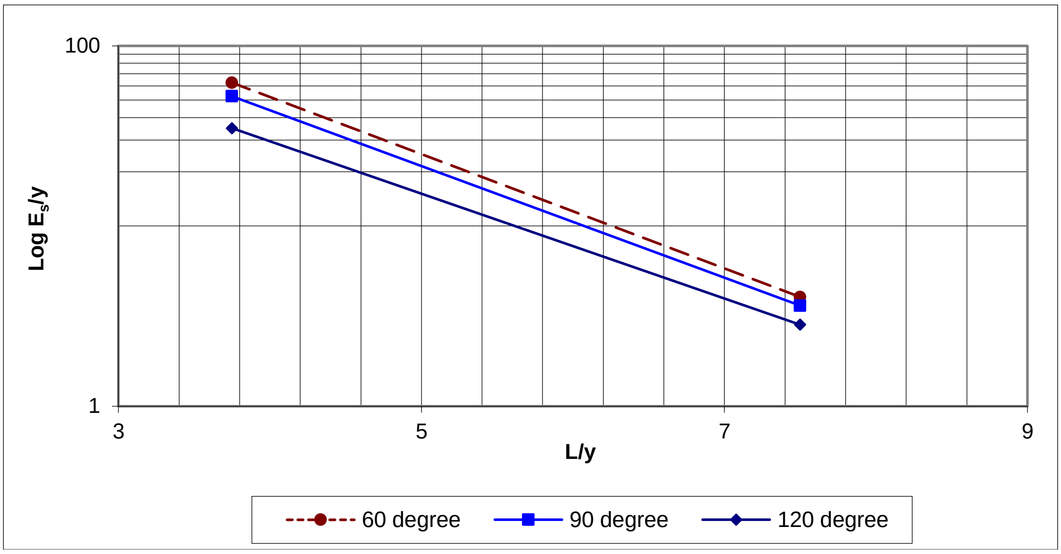

Figure 8: Effect of Flow Depth on the Specific Energy at the 2nd Groin

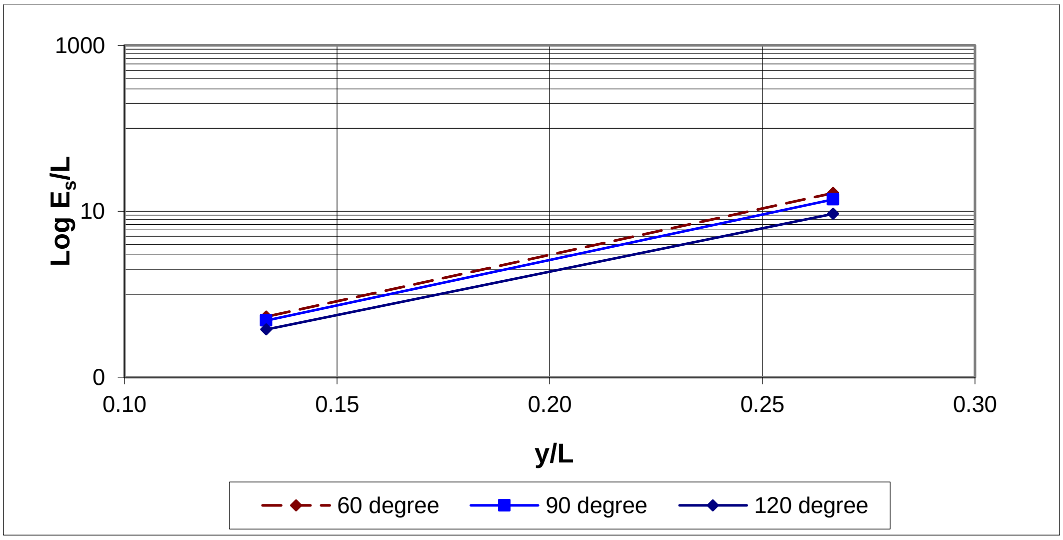

Figure 9: Effect of Groin Length on the Specific Energy at the 2nd Groin

6. CONCLUSION AND RECOMMENDATIONS

From the investigations, it was concluded that:

- The produced scour hole depth and length were found to be maximum in case of using 45m repelling groins with 2L spacing. However, the minimum values were found in case of 90m attracting groins with 7L spacing.

- For fixed orientation angle, both depth and length of the scour holes are directly proportional to groin length.
- For fixed groin length, both scour hole depth and length are directly proportional to orientation angle.
- At 2nd groin location, in a group of 45m length and 4L spacing, the peak changes in bed morphology were found, from both scour hole depth and length point of view at different orientation angles.
- Using an attracting group of 45m length and 4L spacing gave the minimum impact on bed, provided that the second groin is cared by special attention by designing its riprap cover and testing it experimentally.
- The maximum changes in specific energy were found in case of using 45m straight groins with 2L spacing. However, the minimum values were found in case of 90m straight groins with 7L spacing.
- For fixed groin length and orientation angle, the specific energy is inversely proportional to spacing between groins.
- For fixed orientation angle and spacing, the specific energy is inversely proportional to groin length, consequently to scour depth.
- Both straight and repelling groups show the same performance at all groins with a slight increase in values for the attracting group.

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8. LIST OF SYMBOLS

The following symbols are used in this paper:

L = Spur length [m]
U = Longitudinal surface velocity [m/s]
V = Transverse surface velocity [m/s]
P = Mean pressure [kg/m^2]
ν_e = Kinematics eddy viscosity [m^2/s]
F_x = Body force in X direction = g sin θ [kg.m/s^2]
F_y = Body force in Y direction = 0.0 [kg.m/s^2]

g = acceleration due to gravity [m/s^2]
s = spacing between spurs [m]
S = straight spur of 90^0
R = Repelling spur of 120^0
A = Attracting spur of 60^0
θ = Average water surface slope [degrees]
ρ = Fluid density [kg/m^3]
τ_{fx} = Turbulent frictional stresses in X-direction [kg/m^2]
τ_{fy} = Turbulent frictional stresses in Y-direction [kg/m^2]
K_M= Composite empirical parameter representing several factors of flow intensity, flow depth, sediment size, sediment gradation, groin shape and alignment
η= Equals to groin length (L)/ flow depth (y)
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Q= Flow rate [m^3/s]
b= Width in contraction [m]