



## Local Scour Depth at the Nose of Permeable and Impermeable Spur Dykes

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**Abstract:** Local scour for impermeable and permeable (slotted) spur dykes where tested at the lab. The experimental data were analyzed and compared for the two types of dykes. It is found that, for different sets of dykes arrangements, the local scour magnitude for permeable dykes is reduced significantly compared to that of impermeable ones. For the case of 5 spur dykes arranged on both sides of the flume the reduction in the local scour depth ranges between 16% to 51%, while for the set of 3 spur dykes arranged along one side of the flume is between 18% to 44% and for single spur dyke 30% to 62%. The generated eddy width for the case of a single spur dyke is noticed to be between 34% to 43% of the flume width  $B$  while the eddy length is found to range between 4 to 5 times the model spur length  $b$ . The contraction ratio has a significant effect in the magnitude of the local scour. The local scour depth corresponding to the middle spur of the set of five spurs (contraction ratio =60%) is equal to 2.6 times that corresponding to the same position of the set of three spurs (contraction ratio =80%) for impermeable dykes. For permeable dykes the ratio is equal to 3.

**Keywords:** *Local Scour; Spur dykes; Permeable dykes; Spur arrangement; Channel contraction.*

### 1. INTRODUCTION

An spur is an elongated structure having one end fixed to the bank of a stream and the other end projecting into the flow. Spur dykes have been widely used to protect eroding stream banks and for other river training purposes [1-5]. There are two types of spur dykes that commonly used in practice, namely; the impermeable and permeable spur dykes. Impermeable spur dykes are constructed of armoured fill. Numerous experimental studies were carried out on impermeable spur dykes. The results were used to develop empirical relations that count for the local scour depth and the pattern of flow including the shape of the generated eddies. Permeable spur dykes are constructed from piles, fences, and concrete blocks, timber cribs and slotted dykes. Limited works were done for the permeable spur dykes. All the information now availed on the behaviour of permeable spur dykes are related to direct field observations. Permeable spur dykes in application suffer greatly from local scour and loads imposed by floating objects. Generally, the permeable spurs are temporary structures used for specific purposes in river training, e.g. river bank protection by slowing down the flow current [3]. However, permanent permeable spur dykes are punctured or slotted dykes where the whole spur with slots is designed to withstand flow current and other induced hydraulic forces. The slotted dykes are the subject of this paper.

The analysis and design of spur dykes is a very complicated task. Although the use of dykes is very effective in training rivers, their construction is commonly associated with local scour and deposition that lead to complex responses of the river. This is due to the fact that the parameters controlling river responses and behavior are numerous and interrelated in a very complicated manner [6-10].

### 2. THEORY

The main factor that endangers the stability of a spur dyke is the local scour produced at the nose of the spur [11]. Upon the exposure of the foundation of the dyke nose the top structure fails followed by rapid wash out or substantial failure of the dyke body. The studies on spur dykes aim to predict the depth of the local scour in addition to the pattern of flow around the dyke, suitable dyke length, spacing between any two spur dykes, inclination angle and the shape of the spur front.

#### 2.1 Spur dykes local scour

##### *Impermeable dykes*

Following are some of the well known relations that developed from experimental studies for impermeable dykes' works.

Garde *et al.* [12] proposed that the local scour magnitude  $d_s$  is proportional to the flow Froude number  $Fr$  and the flow depth  $y$  where

$$\frac{y + d_s}{y} = \frac{K}{\alpha} Fr^n \quad (1)$$

The factors  $k$  and  $\alpha$  count for the effects of the particles sizes.

Gill [13] adopted the same variables as Garde but he introduced the median particle diameter  $D_{50}$  and a factor  $m$  that takes into consideration the effect of channel contraction i.e the ratio of the contracted width to the full channel width. He proposed a relation of the following form where  $y_0$  corresponds to the uniform flow depth.

$$\frac{d_s}{y_0} + 1 = 8.38 \left( \frac{d_{50}}{y_0} \right)^{\frac{1}{4}} \left( \frac{1}{m} \right)^{\frac{6}{7}} \quad (2)$$

Abbass [7] assumes that there exists functional relations between the local scour depth  $d_s$ , flow depth  $y$ , Froude number  $Fr$ , length  $E_L$  and width  $E_w$  of the generated eddy, induced flow shear  $\tau_0$  in un-contracted section, median particle diameter  $D_{50}$ , width  $B$  of the channel and length  $b$  of the spur dyke. He carried out intensive experimental works resulted in the development of the following relations:

$$\frac{d_s}{y} = C_1 \left( \frac{E_w}{B} \right)^\alpha \left( \frac{E_w}{B} \right)^\beta \left( \frac{\tau_0}{\gamma_{sub} D_{50}} \right)^\lambda \quad (3)$$

$$\frac{E_L}{b} = C_2 \left( \frac{b}{B} \right)^{n_1} Fr^{m_1} \quad (4)$$

$$\frac{E_w}{B} = C_3 \left( \frac{b}{B} \right)^{n_2} Fr^{m_2} \quad (5)$$

where  $\gamma_{sub}$  = submerged specific weight, and  $n_1, m_1, n_2, m_2, \alpha, \beta, \lambda$  are constants determined from regression analysis.

The condition for bed-load motion is when  $\tau_0 > \tau_c$  where  $\tau_c$  is the critical shear stress for initiation of bed load transport. For straight channel  $\tau_0$  is equal to  $\gamma R S$ , where  $\gamma$  = specific weight of water,  $R$  = channel radius and  $S$  = channel slope. However at river bend the shear stress can better be estimated using semi-log velocity distribution where the shear velocity  $u_*$  can be used to calculate the induced flow shear stress from the relation  $\tau = \rho u_*^2$ . The critical shear stress  $\tau_c = k \gamma_{sub} D_s$  where  $D_s$  representative particle diameter (Meyer -Peter - Muller bed load equation). The parameter  $k$  ranges between 0.03 to 0.06 depending on the turbulence intensity and sediment particle size.

### Permeable dykes

As discussed above few experimental works were carried out on permeable dykes. The bulk of the information availed in this matter is related to field observations. In fact punctured (slotted) spur dykes are seldom tested at laboratory. A slotted dyke means allowing the flow to pass through slots made in the body of the dykes to the downstream side of the dyke as

demonstrated in this study. The main objective is to reduce the flow velocity at the nose of the dyke by having certain percentage of the flow passing through these slots to the downstream part of the dyke. Another effect of these slots is to reduce the strength and size of the vortex generated at the downstream by pushing them towards the main flow (central flow). These vortices have direct effect in shaping the geometry and size of the local scour hole generated at the dyke front.

Nasrollahi *et al.* [14] proposed estimating the local scour depth of permeable dykes using relations similar in form to the ones adopted for local scour estimation at bridge abutments and piers. Recently, Teraguchi *et al.* [15] carried out laboratory studies for permeable spur dykes known as Bandal-like structure where a tested spur dyke took the shape of a fence obstructing the flow with solid impermeable part of the spur capping the full length of the spur dyke. In other words, the top part of the spur is impermeable while the lower part is permeable. The test was carried for submerged and un-submerged conditions for the dykes. Slight difference was found between the magnitude of the local scour depth for the case of submerged and un-submerged conditions when testing permeable dykes. However, the difference was found to be significant when comparing the results of local scour of permeable spur dykes with those correspond to impermeable ones reported by Melville [16].

In this study local scour depth corresponding to impermeable and permeable spur dykes (slotted) were tested at the lab. The openings of the slots have area less than 10% of the wetted cross sectional area of the flume. The experiments were also carried out for impermeable dykes having the same length as the permeable ones to determine the local scour depth at the front of the dykes. The local scour depth corresponding to the types of spur dykes were analyzed and compared with other researchers' results.

### 3. EXPERIMENTS

The main purpose of these experiments is to find out the local scour depth taking place at the nose of permeable and impermeable spur dykes, for different flow condition. The experiments were carried out at the sediment flume at the Hydraulic and Fluid Mechanics Laboratory of the Civil Engineering Department, Faculty of Engineering, Khartoum University. Fig (1) shows the sediment flume and the feeding tank. The flow discharge is measured using a V- weir mounted at the inlet of the feeding tank. The spur dykes models are shown in Fig (2). Three different sets of dykes arrangements were tested. The first set consists of five dykes arranged oppositely along the flume walls. The second set consists of three dykes but set on one side of the flume wall. The third set consists of a single dyke. The experiments were carried for unsubmerged permeable and impermeable dykes. Fig (3) presents the dimension of the permeable and impermeable dykes models used in the study.

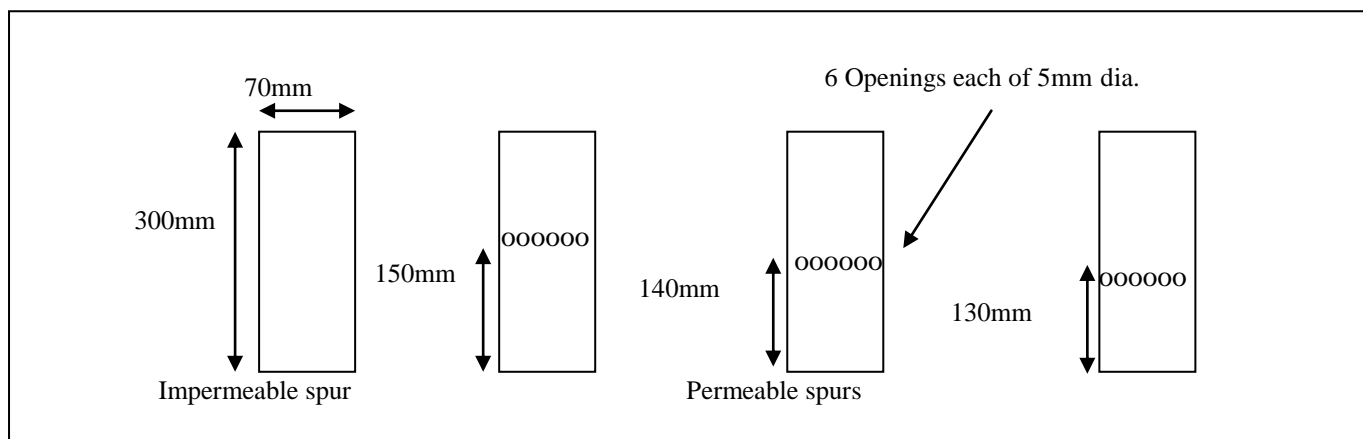
Two types of sand soil were used. The first is much courser than the second as indicated by sieve analysis curves shown Fig (4) and Table (1).



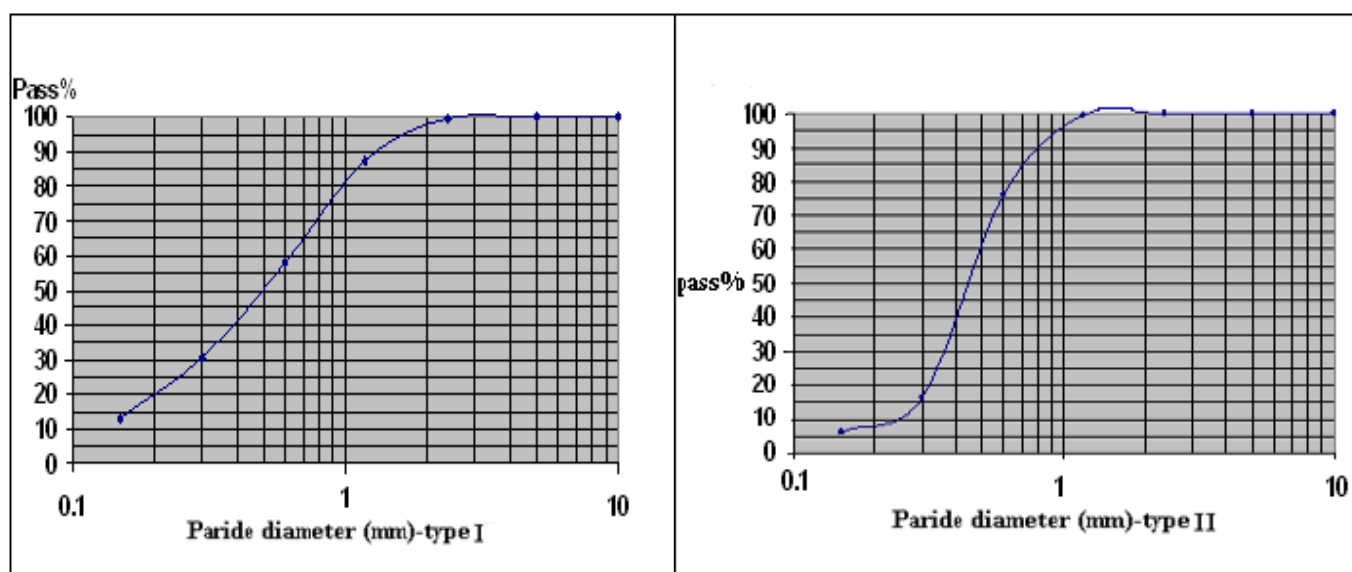
**Fig. 1.** Sediment flume



**Fig. 2.** Impermeable and permeable dykes



**Fig. 3.** Permeable and impermeable spur dykes dimensions



**Fig. 4.** Sieve analysis charts for soil type I and type II

**Table 1.** Sand properties

Soil properties	$D_{50} = 0.28 \text{ mm}$	$D_{50} = 0.28 \text{ mm}$
$\rho \text{ (Kg/m}^3\text{)}$	2.48	2.24
$\gamma \text{ (KN/m}^3\text{)}$	24.4	22

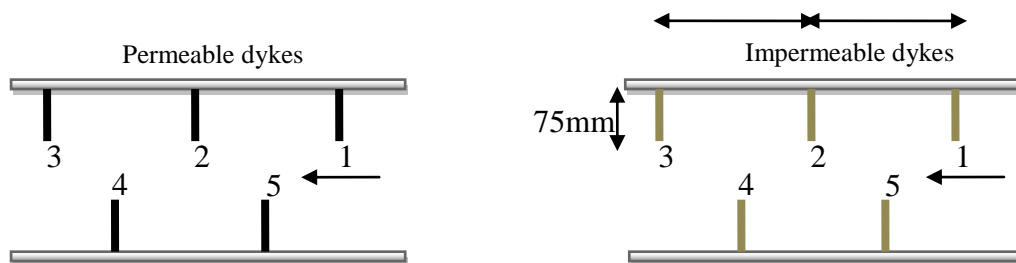
### 3.1 Experimental Procedure

The local scour tests were carried out at the open channel flume described before. The tests were carried out for different sets of spur dykes with different arrangements as shown in Fig (5) and Fig (6). Gravel pack at depth 100mm and length 600mm was first furnished at the inlet of the flume to break out the flow energy and ensure uniform flow approaching the spur dykes model. Then, the sand was levelled on the flume bed extending from the transition zone to the end of flume. A sand depth of 100mm is kept throughout the experiments. Tap water is allowed first to enter

the supply tank then allowed to seep gradually into the testing flume. When the water reached the level of the tail gate the models were fixed in the required arrangements with the space of 350mm between each two spurs. Then, the pump is operated.

For each set of the dykes arrangements, the following variables were measured: flume flow depth, length and width of the generated eddies Fig (7), and height of the openings of permeable dyke model above the bed and the head for the V-notch weir. On next day the scour depth at the nose of each model and the geometry of the scour hole Fig (8) were recorded after the water drained out of the flume.

The above procedure was repeated for different sets of spur dykes with different arrangements as shown in Fig (5) and Fig (6).



**Fig . 5a.** Arrangement of 5 spurs dykes  
(Flow depth=100 ,80 ,60,30,20mm)



**Fig. 5b.** Arrangement of 3 spurs dykes  
(Flow depth=100 ,80 ,60,30,20mm)



**Fig. 5c.** One spurs dike  
(Flow depth=100 ,80 ,60,30, mm)





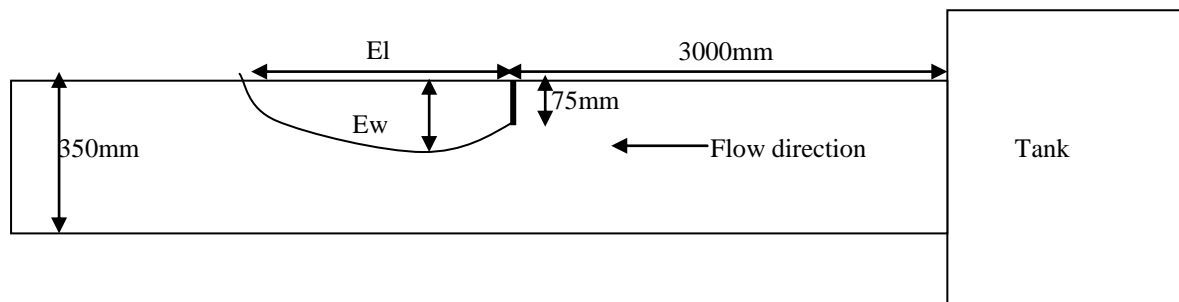
**Fig. 6a.** Case of five spurs



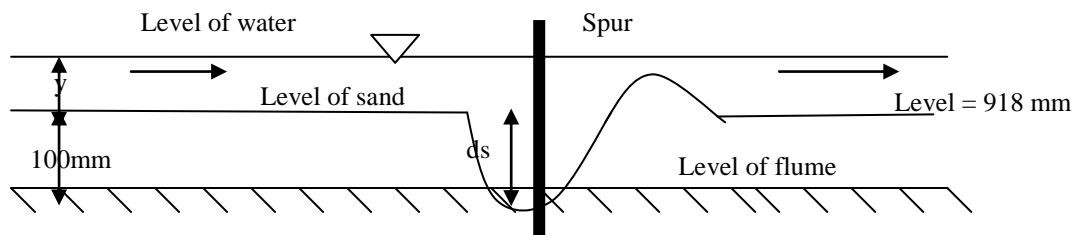
**Fig. 6b.** Case of three spurs



**Fig. 6c.** Case of single spur



**Fig. 7.** Experiment sketch



**Fig. 8.** Local scour sketch

#### 4. RESULTS AND DISCUSSION

The data and experimental results of the laboratory work were analyzed. First the discharge, velocity and Froude number were computed for all runs. Then sand particle characteristics and properties such as bed shear stress and critical shear stress were determined. This is followed by developing the functional relationships among the variables including local scour depth at the nose of spur dyke. The effects of flow contraction and the way the dykes were arranged are also reflected in the relations. The results are presented in the forms of equations, curves and charts.

For sand bed with  $D_{50} = 0.45\text{mm}$ , Manning coefficient = 0.02 the particle critical shear stress is calculated as  $\tau_c = 0.258\text{N/m}^2$  while for  $D_{50} = 0.28\text{mm}$ , Manning coefficient = 0.016,  $\tau_c$  is equal to  $0.192\text{N/m}^2$ . For a discharge of  $0.0045\text{m}^3/\text{s}$  the induced flow shear  $\tau_o$  is found as  $0.364\text{N/m}^2$ . It is clear; that the induced flow shear exceeds that of particle resisting shear stress and therefore one should expected particle removal to take place especially when strong vortex develops.

The experiments were run for discharge values in the range 4.2 l/s to 9.3 l/s and velocity ranges between 0.6m/s to 0.265m/s and Froude number 0.27 to 0.74.

The induced flow shear stress value is computed and is between  $1.55\text{N/m}^2$  to  $12.09\text{N/m}^2$  which greatly exceeds the particle critical shear stress resisting the motion as computed above. Therefore, the material at the nose of the dyke will subject to larger shear stresses combined with strong vortices causing scouring and removal of this material.

The maximum local scour depth  $d_s$  is measured at the nose of the dyke. For the arrangement of five spur dykes a maximum scour value of 42mm is recorded at dyke No 5 for the set of impermeable dykes while it is 30mm corresponding to the dyke No 5 for the set of permeable dykes. Obviously for the arrangement of three spur dykes the maximum local scour depth should occur at dyke No 1 facing the flow. For the impermeable dyke the maximum scour depth recorded is 27mm while it is 20mm for the permeable one. For a single dyke the maximum scour depth is 27mm for the case of an impermeable dyke while it is 15mm for the permeable one.

The length  $E_l$  of the eddy is compared to the length of the dyke  $b$  (case of a single dyke). For impermeable dyke the maximum ratio  $E_l/b$  came to be 6.84 while it is 5.71 for a permeable one. On the other hand, the width  $E_w$  of the eddy is compared to the flume width  $B$ . For impermeable dyke the maximum ratio  $E_w/B$  came to be 0.43 while it is 0.34 for a permeable one.

Using regression analysis the following relations among scour depth  $d_s$ , flow depth  $y$  and Froude number  $Fr$  were developed from the 39 runs.

– Set of 5 spur dykes :

$$\frac{d_s}{y} = 1.2799 Fr^{1.1512} \quad (6a)$$

( impermeable spurs)

$$\frac{d_s}{y} = 0.8959 Fr^{1.1249} \quad (6b)$$

( permeable spurs)

– Set of 3 spur dykes :

$$\frac{d_s}{y} = 1.1282 Fr^{1.5623} \quad (7a)$$

( impermeable spurs)

$$\frac{d_s}{y} = 0.9937 Fr^{1.8271} \quad (7b)$$

( permeable spurs)

– Single spur dyke :

$$\frac{d_s}{y} = 1.0563 Fr^{1.6396} \quad (8a)$$

( impermeable spurs)

$$\frac{d_s}{y} = 0.8309 Fr^{1.9487} \quad (8b)$$

( permeable spurs)

The plotting of  $d_s/y$  vs  $Fr$  is shown in Fig (9), Fig (10) and Fig (11).

Clearly, the local scour depth  $d_s$  is reduced when using permeable dykes compared to the same set but for impermeable dykes. The correlation coefficient  $R^2$  is noticed to be in the range 0.73 to 0.90 for permeable dykes while it is more than 0.92 for impermeable dykes.

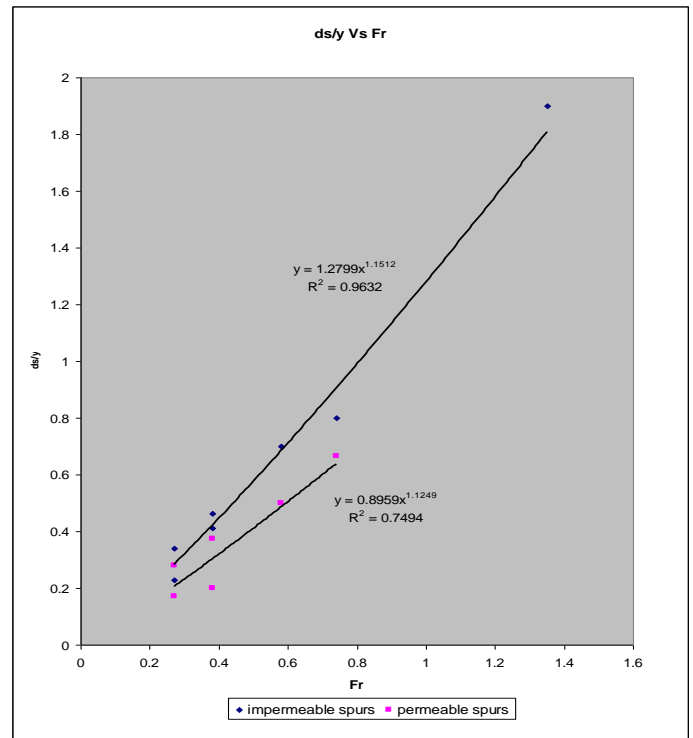
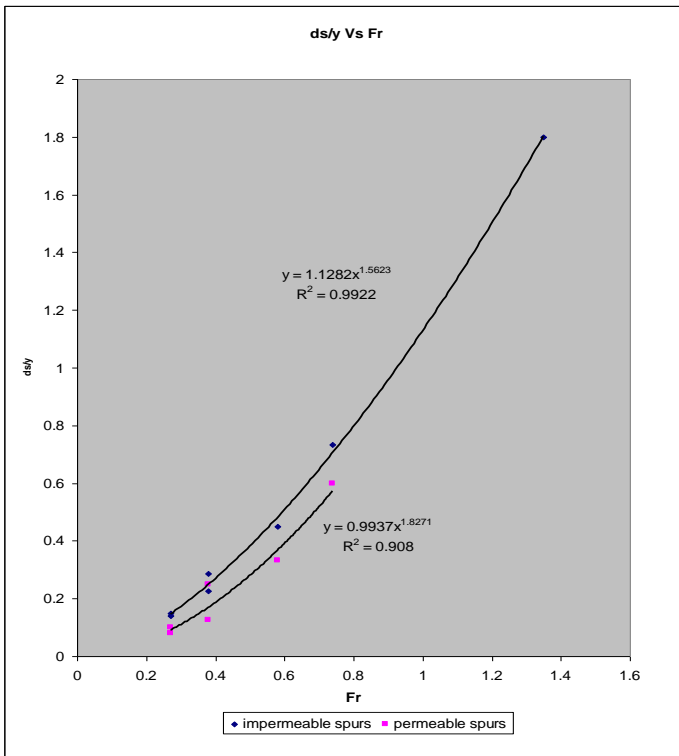
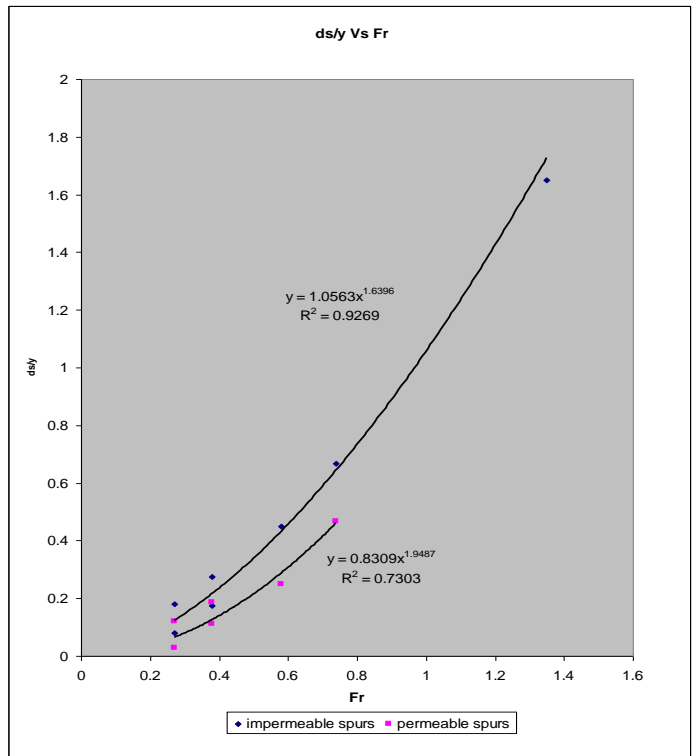


Fig. 9.  $d_s/y$  for five spurs



**Fig. 10.**  $d_s/y$  for three spurs



**Fig. 11.**  $d_s/y$  for single spurs

**Table 2.** Tests range for Abbass and Gill experiments

Model	Flow depth (mm)	Fr	$D_{50}$ (mm)
Abbass	120 - 150	0.18 - 0.30	0.30 - 0.52
Gill	30 - 600	0.30 - 0.42	0.91 - 1.5
This study	20 - 100	0.27 - 0.74	0.28 - 0.45

The eddy length  $EL$  and width  $E_w$  are not defined for the sets of 5 and 3 spur dykes. For the case of single spur dykes the generated eddy width  $E_w$  is noticed between 34 % to 43 % of the flume width  $B$  depending on the length of the spur and approaching flow velocity and Froude number. The eddy length  $EL$  is 4 to 5 times the model spur length  $b$ . From practical point of view this means that in order to have effective arrangements of dykes the spacing between any two adjacent dykes should be less than 4 times the spur length  $b$ .

When applying equations of Gill [12] and Abbass [7] to the set of experimental data obtained in this study they gave smaller values of the local scour depth than the ones measured at the lab. The reason behind this is the fact that both equations were developed for smaller values of Froude number as shown in Table (2) below. Nevertheless, the results of this study can be looked at as complementary work that bridges certain gaps corresponding to the experimental studies carried in this area.

#### 4.1 Effects of arrangements of spur dykes on scour values

It is very important to figure out how does the arrangement of the spur dykes along the banks of the river affect the scour magnitude for each dyke. The adopted arrangements for experiments were as follows:

**For the set consists of five dykes arranged along the two sides of the flume;** the highest local scour depth value did occur at the nose of the most upstream dyke in the fully contracted section of width  $= B - 2b$ . This condition is valid for both permeable and impermeable dykes. The location of dyke No (1) caused the flow to deflect towards dyke No (5) on the opposite side hence resulted in increasing the approach velocity in the contracted section and consequently the scour depth value for dyke No (5) is increased. Table (3) gives the ratios of the largest local scour depth to that of other dykes for five dykes arrangements.

**For the set consists of three dykes arranged in one side;** the highest scour depth value did occur at the nose of dyke No (1) in the contracted section of width  $= B - b$ . Table (3) gives the ratios of the largest local scour depth to that of other dykes for three dykes arrangements.

One can notice that the local scour value corresponds to the case of a single dyke are almost similar to that corresponds to dyke No (1) for a set of three dykes. This is due to the fact that the two cases have similar contraction ratio and dyke No (1) behaves independently from the other dykes located downstream.

**Table 3.** Ratios of largest local scour depth to other scour values for five and three dykes arrangements

Spurs arrangements	Ratios of scour depths	Impermeable	Permeable
5 Spurs	$d_{s1}/d_{s5}$	0.7	0.9
	$d_{s2}/d_{s5}$	0.5	0.7
	$d_{s3}/d_{s5}$	0.2	0.3
	$d_{s4}/d_{s5}$	0.1	0.25
3 Spurs	$d_{s2}/d_{s1}$	0.3	0.5
	$d_{s3}/d_{s1}$	0.2	0.4

**Table 4.** Effects of contraction of channel in scour

Spurs arrangements	Ratios of scour depths	Impermeable	Permeable
5 spurs	$d_{s51}/d_{s31}$	1	1
	$d_{s52}/d_{s32}$	2.6	3
	$d_{s53}/d_{s33}$	1.5	2

The importance of such ratio comes from the fact that one needs to figure out the best arrangements of dykes and the initial cost of foundations in the early stage of river training project using spur dykes.

#### 4.2 Effects of channel contraction on scour values

To find out the effects of channel contraction on scour magnitude a comparison is made between the two cases of dykes arrangements. In Table (4) below  $d_{s51}/d_{s31}$ ,  $d_{s52}/d_{s32}$ , and  $d_{s53}/d_{s33}$  represent the ratios of scour depths between the set of 5 dykes to the set of 3 dykes. The ratios are given only for dykes No 1, 2 and three for both permeable and impermeable dykes.

As expected with increasing contraction ratio the local scour is increased for dykes being set oppositely each other. In the experiments carried out in this study the width of the contracted section *B-2b* is equal to 60% of the flume width. While for set of three dykes the contracted section width *B-b* is equal to 80% of the flume width.

#### 4.3 Effects of dykes openings in scour magnitude

In the experiments every permeable dykes is provided with six openings each of diameter 5 mm. The dyke is immersed in sand such that the row of openings is always located at half the flow depth.

For the case of 5 spur dykes the contracted flow section is calculated as

$$Ac = (B - 2b) * y \quad (9a)$$

And for the case of three dykes and single dyke arranged on one side we have

$$Ac = (B - b) * y \quad (9b)$$

The total area of openings for two opposite dykes is  $0.000236m^2$  and for three and single dykes  $0.0001179m^2$ .

The percentage relative reduction in the scour depth DSR between impermeable and permeable spur dykes is calculated from

$$DSR = \frac{d_s(impermeable)}{d_s(permeable)} \quad (10)$$

Figs (9-11) confirm the fact that the openings made in the dykes helped reducing the scour magnitudes. Although the total area of the openings is very small compared to the cross section but the presence of these openings cause a reduction in the pressure difference and vortex intensities generated at the nose of a dyke. The results require future verifications to be carried out for different arrangements and openings sizes. The values presented in this study should be looked at as an indication to one of the means that can be used to reduce the magnitude of the local scour depth at the nose of a dyke. Future quantitative analysis based on wide data is required to achieve better results.

#### 5. CONCLUSIONS

Laboratory studies were carried out to determine the local scour depth at the nose of permeable and impermeable spur dykes. The results from laboratory tests were used for developing charts and equations for engineering uses and application in the fields of river training. The study was carried out for three sets of spur dykes arranged in different manners along the walls of the flume. The study also considers the effects of arrangement patterns of spurs dykes and contraction of the channel on the scour values. The study recommended carrying out further laboratory studies for better understanding of the local scour and flow pattern for permeable (slotted) spur dykes under different flow conditions.

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