MEAN FLOW AND TURBULENCE AROUND TWO SERIES OF EXPERIMENTAL
DIKES

by

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DEDICATION

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ABSTRACT

Scour around various structures obstructing flow in an open channel is a common problem; therefore a better understanding of how turbulent flow affects sediment transport is needed. Additionally, is it the mean flow or the turbulence properties that are more important in contributing to bed shear stress? To this end, an experimental study was conducted in a fixed-bed flume containing a series of dikes. Turbulence intensities and Reynold's stresses were calculated from 3-D velocity measurements gathered with a microADV. Results showed that the maximum shear stress was nearly 12-20 times that of the approach flow, while maximum turbulence intensities were about 3-5 times those of the incoming flow. Highest magnitudes of both were seen at the tip of the second dike in the three-dike series. The mean velocity appeared to have no relation to the formation of scour near the tips of the dikes but the turbulence intensities did.

1. INTRODUCTION

1.1 Background

Erosion of the banks and bed of natural and manmade channels is a common problem in water resources management. Spur dikes in rivers and streams are used to prevent bank erosion, and to keep the main channel navigable. These structures extend from the bank into the streamflow, perpendicularly, or at some angle. Most are emergent from the water surface only during low flows, becoming submerged during flood events. Scour around these and other structures such as bridge piers can cause serious problems, such as weakening structural stability. To better understand why scour occurs around such hydraulic structures, the questions of what are the mean flow and turbulence distributions around these structures and how the turbulent flow field affects sediment transport must be answered. In addition, it is important to determine if it is the mean flow or the turbulence properties that are more important in predicting the local sediment transport rate. Better understanding of these processes will aid river engineers in designing better embankments for prevention of bank erosion and local scour around bridge piers.

Knowledge gained from a scientific examination of the flow physics around structures such as spur dikes will also benefit river restoration projects, as areas around these embankments and dikes are often habitats for vegetation and fish. Dikes have been used not only to prevent erosion of the banks of a stream, but also to provide diverse bed configurations for fish spawning sites. Slow velocity zones between the dikes are areas of sediment deposition and can encourage vegetation growth, providing further stabilization

of the banks as well as habitat for fish and other aquatic species (Kuhnle, *et al.*, 2002; Biron, *et al.*, 2005; Tominaga, 2006; Haltigin, *et al.*, 2007).

1.2 Literature Research

1.2.1 Theoretical Study

Extensive research has been done to determine the mechanism of sediment transport in turbulent flow. Although several methods such as that of Shields (Julien, 1998) are accepted in practice, there is still much discussion on what exactly causes a sediment particle at rest on the bed to move (Coleman and Nikora, 2008). Recent theoretical research has focused on deriving physically-based equations that are able to describe the two dimensional flow of water over a rough bed (McLean and Nikora, 2006) and entrainment of sediment particles by the flow of water (Coleman and Nikora, 2008). Others have derived equations to describe more realistic flow, such as the equations of Dey and Lambert (2005) that describe the Reynolds stress or bed shear stress on sediment particles in nonuniform, unsteady flows.

To address turbulent flow over rough beds McLean and Nikora (2006) have proposed a double averaging approach to the classic momentum equations, and verified it with some success using an acoustic Doppler velocimeter (ADV) and a laser Doppler velocimeter (LDV) in a gravel-bed flume. The main focus of the experiment was two dimensional flows over bed forms or gravel beds; however, flow around an obstruction is highly three dimensional and would add much complexity to the equations. The advantage to using their method is that it is a rigorous approach that does not depend on

poorly defined variables, such as mean particle size, hiding factor, and so on, in some currently-used methods, but it is rather based directly on the mass and momentum conservation equations governing flow and sediment motion. Coleman and Nikora (2008) have proposed a physically-based framework for describing the hydrodynamic entrainment of sediment particles from the bed. This new method is based on Newton's second law of motion, expressed separately for sediment particles and the fluid flow, and in a spatially averaged framework. The advantage of this method is that a wide range of scales is encompassed in this framework. Another new theoretical advancement in the area of sediment transport is the novel dimensionless number proposed by Tanaka and Eaton (2008). This dimensionless parameter, the particle moment Pa , was derived from the Navier-Stokes equations for sediment-laden flow using dimensional analysis and attempts to describe the physical processes underlying the turbulence modification of the flow by the particles themselves.

1.2.2 Numerical Studies

In addition to these theoretical papers, many modeling studies have been completed to determine the location and amount of scour that will occur around embankments, abutments, dikes, piers and other obstructions to flow (Nagata, *et. al*, 2005; Zhang, *et. al*, 2005; Yossef and Rupprecht, 2006; Haltigin, *et. al*, 2007; Koken and Constantiescu, 2008; McCoy, *et. al*, 2008). These numerical studies have used the Reynolds-averaged Navier-Stokes (RANS) approach with the κ - ϵ turbulence model or large eddy simulations (LES) to obtain numerical results for the highly three-dimensional

flow around obstructions. Often these theoretical and numerical studies are validated with experimental data gathered with ADVs, LDVs, and dye tracer studies, with varying results.

Haltigin, *et al.* (2007) obtained fairly good qualitative results from their model. From flat, sand-bed flume data gathered with an ADV they were able to use the computational fluid dynamics software PHOENICS to predict with reasonable accuracy the location of maximum scour for paired dikes angled upstream 45°, downstream 45°, and perpendicular to the flow. The most significant result from this study was the area of down-welling – downward vertical velocity – in the area around the dike tips coinciding with the area of most bed scour. Since downward velocities have been associated with vortices and scour, these results indicated that there was a relationship between areas of down-welling and location of bed scour. Nagata *et. al.*, (2005) developed a RANS model to study flow and scour around a single spur dike and validated it with four sets of experimental data. The model was able to reproduce the characteristic flow patterns of down-welling at the upstream section of the structure and associated vortices, as well as the scour geometry around the dike fairly well. Their approach incorporated moving boundary conditions to simulate the dynamic processes in the formation of an equilibrium scour hole.

LES studies have also shown some success in simulating flow around obstruction in open channel flow, producing highly detailed visual results. Koken and Constantiescu (2008) applied LES to an isolated spur dike where the incoming flow encounters the entire length of the dike while Yossef and Rupprecht, (2006) and McCoy,

et. al (2008) have applied the method to large series of groynes where the incoming flow passes by the tips of the dikes. The simulation of the single dike was able to reproduce in great detail the vorticity field associated with the turbulent flow around the dike as obtained from an extensive dye tracer analysis. The simulation of the groyne fields reproduced fairly well the flow patterns and mean velocity fluctuations of the flume experiments. Because of the complexity of the experimental set-up, complete validation was not possible due to limits of measurement points. The scour geometries predicted from the numerical model did show good spatial agreement with the experiment, but consistently underestimated the depth of the scouring (Yossef and Rupprecht, 2006). Calibration and validation of these numerical simulations is an ongoing process.

1.2.3 Experimental Dike Studies

In addition to the theoretical and modeling studies, experiments have been carried out in laboratory flumes to determine the effects of engineering structures on water flow. Laser visualization techniques, particle image velocimetry (PIV), and instruments such as acoustic Doppler velocimeters (ADV), have been used extensively in recent years to determine flow fields around spur dikes, abutments, and the like (Yossef and De Vriend, 2004; Uijttewaai, 2005). Three dimensional measurements of velocity can then be used to determine turbulence intensities, Reynolds stresses and bed shear stress. Depending on the technique, or the location of the instrument, full profiles or just bed measurements can be taken. Studies using fixed, flat beds often measure

Reynolds stresses and bed shear stress in an attempt to predict where scour will take place if the bed were mobile.

Dey and Barbhuiya (2005) used an ADV to examine the turbulent flow field around a short rectangular abutment oriented 90° to the flow, starting with the fixed rough plane bed condition, and ending with the equilibrium scour hole condition. It was determined from these two experiments that the turbulent kinetic energy inside the scour hole was greater than that of the plane bed, and that the maximum bed shear stresses were about 3.2 times that of the incoming flow. Vortices and downward vertical velocities were seen in the vicinity of the dike for both the plane bed and scoured bed conditions, but were stronger for the scoured bed conditions, since the turbulence flow field in a plane bed is different from that when the scour is developed. Because the bed shear stress τ_b was greater than that of the critical shear stress τ_c of the sand forming the bed, the majority of the plane bed would have scoured had it been mobile and not fixed with resin.

A later study by Kuhnle et al (2008) used an ADV to examine the three-dimensional flow fields around a submerged spur dike with sloped sides, oriented 90° from the bank. From these time-averaged velocities the Reynolds stresses and bed shear stress were obtained. An amplification factor of three was found for the bed shear stresses around this dike, compared to earlier studies of emergent, straight-sided dikes which had amplification factors of about 3 to 5 times that of the incoming flow. A third flume experiment using similar techniques was done by Duan (2009) in which a single dike – a flat rectangular metal plate – was placed 90° to the wall of a flume with a fixed, flat bed.

Using the three dimensional time-averaged velocities, mean flow, turbulence and Reynolds stresses around the dike were determined. In this case, the bed shear stress calculated from the Reynolds stresses was 2 – 3 time that of the incoming flow. In spite of the differences in dike shape and flow Reynolds number, all three studies showed similar amplification factors of bed shear stress.

When building a spur dike or series of spur dikes for the purposes of bank protection, production of fish habitat, or for river training as part of a restoration project, the effects of the dike shape, orientation to the flow, submergence depth, and permeability must be considered. Depending on these parameters, different bed configurations, flow patterns, and amounts of scour around these structures will be seen. Permeable dikes allow flow-through, thus reducing some of the vorticity found near impermeable structures. Flow around submerged structures also shows a reduction in vorticity, as the flow passes over the structure and does not have to go around it, as in the case of emergent structures. The angle of orientation to the flow also has an effect on the amount of scour around the dike tip as well as on flow patterns around the dike. Dikes angled in the direction of flow (oriented with a downstream skew) attract the flow towards the banks. Dikes angled against the direction of flow (oriented with an upstream skew) repel the flow, directing it towards the main channel. Dikes oriented perpendicular to the flow deflect it, similar to the upstream-skewed dikes, but with less vorticity near the tip (Zhang and Nakagawa, 2008).

Several studies have been done on the effects of orientation angle on the amount of scour around a spur dike. One such study examined the effects of three different

orientation angles on scour around spur dikes (Kuhnle et al, 2002) for the purposes of creating scour holes for aquatic habitats while at the same time minimizing bank erosion. A series of flume experiments was performed using a short, angled, submerged spur dike with sloped sides. Results indicated that the least bank erosion occurred when the dike was oriented 90° from the bank, and the greatest amount of scour occurred near the 135° dikes (45° from the bank, upstream skew) with only a little more bank erosion occurring than for the 90° dikes. Similar results were seen by Tominaga and Matsumoto (2006) in an experiment using flat slabs of wood as model spur dikes in a sand bed flume. The dikes were arranged in alternating series of three, on both sides of the flume, and remaining submerged throughout the experiment. For both the 135° case and the 90° case, the maximum scour was mainly seen around the dike tips, with some deposition on the sides, with the greatest scour occurring in the upstream skew dikes. For submerged dikes in series, the maximum scour was located around the tip of the first dike. Biron et al (2005) also examined the effects of orientation angle on turbulent flow, but in this experiment, two flat Plexiglas model dikes were used, spaced across from each other in a Plexiglas flume. The study included both emerged and submerged flow, and plane bed and mobile bed to see if results obtained from plane bed flows could be used to predict mobile bed scour. As seen in the previous two studies, the maximum scour was seen with the 135° and 90° cases, but emerged flow produced the most scour in all cases, compared to submerged flow. Results also showed that the location of maximum shear stress in the plane bed runs did not spatially coincide with the location of the maximum scour in the mobile bed runs. The maximum bed shear stress was located downstream of the dikes,

with a maximum amplification factor of 12 to 15. The 90° oriented dikes produced the highest bed shear stresses, both for emerged and submerged flow, with the 135° emerged dikes having slightly smaller bed shear stress amplification.

1.3 Objective of Present Study

The present study examines the turbulence distributions at the bed around a series of three dike structures in the path of the flow to show how the turbulent flow field affects bed shear stress. It also examines the effects of discharge and dike alignment on the mean flow and turbulence fields around these series of obstructions. This is an examination of the simplest case – a fixed, flat bed channel. It is hypothesized that from this information gained from the simplest case can be applied to a more complex case, that of a mobile sand bed. The prediction is that areas of maximum bed shear stress in the plane bed will be areas of maximum scour in the mobile bed. Future experiments are planned to see if it this is indeed the case. In addition, data gathered in both experiments will be used to derive an equation that attempts to predict the depth of maximum scour.

1.4 Format of Thesis

The format of this thesis is defined by the University of Arizona Graduate College's Manual for Theses and Dissertations and is, therefore, subject to repetition of information. It includes an 'INTRODUCTION' chapter describing the relevance and uniqueness of this research, in the context of previous research, and a 'PRESENT STUDY' chapter that briefly summarizes the findings of the manuscript included in

Appendix A and discusses the results, conclusions, and potential future research of the current study. Appendix A is a scientific manuscript on determining the turbulent flow properties and bed shear stress around series of obstructions in open channel flow, and is planned for submission to the Journal of Hydraulic Engineering.

2. PRESENT STUDY

The methods, results, and conclusions of this study are presented in the paper appended to this thesis in Appendix A. The following is a summary of the most important findings in this document along with a section ‘Future Research’ which discusses potential work to extend the present study.

2.1 Methods

An experimental study was conducted in a 0.6 m wide, 12.2 m long flume with a flat, fixed bed, and a 0.1 m high weir placed 10.6 m downstream of the inlet (Figure 1). The left wall of the flume was painted metal and the right wall of the flume was painted metal with a 3 m long smooth glass observation section roughly in the middle of its length. A 10 cm high broad-crested weir was installed at the end of the flume to measure volumetric discharge by using the appropriate weir equation. A 16 MHz SonTek microADV was used to measure the instantaneous velocities in the three spatial directions, x , y , and z at a sampling rate of 25 Hz. In order to assure 1000 good measurements, 5000 measurements were taken at each point on a measuring grid (Figure 2) at a height of about 5 mm above the bed.

Figure 1: Plan view of the flume set-up.

Figure 2: Measurement grids for the straight (left) and angled (right) dikes.

To determine the effects of dike placement and angle with respect to the flow on the mean flow and turbulence flow fields, two series of experimental runs were performed: one with a series of three deflecting dikes perpendicular to the direction of flow and the other of three repelling dikes angled into the direction of flow. Each model dike was made of 40 cm tall, 4 mm thick aluminum plate; the deflecting dikes were 15 cm long, and the repelling dikes were 30 cm long. The model dikes were placed a distance of $2l$ apart, where l is the distance the dikes protrude into the flow. In both

experiments this distance l was 15 cm, about $\frac{1}{4}$ the width of the flume, which is typical in natural rivers. However, flow in the flume is fully three-dimensional so that the shallow water assumption is not valid. The first experiment consisted of three model dikes, 15 cm long, attached at a 90° angle to the left wall of the flume, and spaced 30 cm apart. The second experimental set-up consisted of three model dikes, 30 cm long, and angled 30° to the left wall with an upstream skew (i.e., 150°). As with the first experiment, the dikes were spaced 30 cm apart.

To determine the effects of flow depth and magnitude of discharge on the mean flow and turbulence flow fields, each dike series was subjected to three different flow rates. For each run, velocity profiles were measured at the undisturbed approach flow to validate the logarithmic law shown in Fig.3a and 3b. The shear velocity for each run was determined by fitting the velocity profile using the logarithmic law. Table 1 summarizes the flow properties of each experiment.

Experiment	Orientation Angle	Q_0 (m^3/s)	Mean Velocity (m/s)	Re	Fr	Flow Depth (m)	u_{*0} (m/s)
1	90°	0.065	0.420	82910	0.07	0.307	0.009
2	90°	0.035	0.262	39572	0.05	0.244	0.008
3	90°	0.013	0.114	12451	0.03	0.187	0.004
4	150°	0.065	0.403	82911	0.07	0.307	0.008
5	150°	0.035	0.233	39573	0.05	0.244	0.008
6	150°	0.013	0.100	12452	0.03	0.187	0.006

Table 1: Summary of experimental flow properties.

Figure 3a: Velocity profiles at the upstream center of channel for straight dikes.

Figure 3 b. Velocity profiles at the upstream center of channel for angled dikes.

In the data analysis, the x , y , and z axes were oriented along the main flow longitudinally, to the left bank in the transverse direction, and toward the water surface in

vertical with velocity components denoted as u , v , and w , respectively. Post-processing of the raw data was done using the publicly-available WinADV software from SonTek. The filtering criteria used were the signal to noise ratio (SNR) and the Nikora-Goring despiking algorithm (Wahl, 2000) that has been incorporated into the software. All measurements with a SNR < 15 db were removed from the dataset by the software. For the smallest flow, a threshold of SNR > 10 db had to be used, since the flow velocity was so small that an insufficient amount of data points had SNR > 15 db. Processed data was directly used by a calculation program to output the desired information in a text file to be used by a visualization software. The measured velocities in the processed data file were used to calculate the following turbulence characteristics: (a) mean velocities in the longitudinal, transverse, and vertical directions denoted as $\bar{u}, \bar{v}, \bar{w}$, respectively; (b) Reynolds stresses, $-\overline{\rho u'v'}$, $-\overline{\rho u'w'}$, and $-\overline{\rho v'w'}$ in which $u', v',$ and w' are turbulence intensities in longitudinal, transverse, and vertical directions, respectively. The following equations were used to calculate the turbulence intensities and Reynolds stresses:

$$u' = \frac{1}{n} \sum_{i=1}^n (u - \bar{u})^2 \quad v' = \frac{1}{n} \sum_{i=1}^n (v - \bar{v})^2 \quad w' = \frac{1}{n} \sum_{i=1}^n (w - \bar{w})^2$$

$$\overline{u'v'} = \frac{1}{n} \sum_{i=1}^n (u - \bar{u})(v - \bar{v}) \quad \overline{u'w'} = \frac{1}{n} \sum_{i=1}^n (u - \bar{u})(w - \bar{w}) \quad \overline{v'w'} = \frac{1}{n} \sum_{i=1}^n (v - \bar{v})(w - \bar{w})$$

where $u, v,$ and w are instantaneous velocities in x, y, and z directions, respectively; $\bar{u}, \bar{v},$ and $\bar{w}$ are time-averaged velocities in x, y and z directions, respectively; and n is the number of total measurements.

2.2 Results

2.2.1 Mean Flow

As expected, areas between the dikes and near the banks showed relatively low horizontal and even negative velocities. Dimensionless time-averaged longitudinal velocities $\frac{\bar{u}}{\bar{u}_0}$, where $\bar{u}_0$ is the time-averaged longitudinal velocity at the center of the channel at the upstream end, were calculated. Similarly, dimensionless values of $\bar{v}$ and $\bar{w}$ were obtained by dividing each by $\bar{u}_0$. It can be seen in Figure 4 that the areas in front of the dike tips amplify the incoming longitudinal velocity by a factor of about 1.5 to 2. The time-averaged velocities in the transverse direction were much more negative than those in the longitudinal direction, and the positive transverse velocities were about a third of the positive longitudinal (downstream) velocities. In Figure 5, a strong circulation can be seen around the dikes as the flow curved away from the first dike then circulated back in towards the second dike in the case of the straight dikes, and towards the second and third dike in the case of the angled dikes. Velocities in the vertical direction were much smaller than those in both u and v directions. Figure 6 shows strong downward (negative) velocities just downstream of the tip of the first dike, in both series, and strong upward velocities just upstream of the second and third dikes in the case of the straight dikes and only the second dike in the case of the angled dikes.

Figure 4 a: Distribution of dimensionless mean longitudinal velocities; $Q = 0.065 \text{ m}^3/\text{s}$.

Figure 4 b: Distribution of dimensionless mean longitudinal velocities; $Q = 0.035 \text{ m}^3/\text{s}$.

Figure 4 c: Distribution of dimensionless mean longitudinal velocities; $Q = 0.013 \text{ m}^3/\text{s}$.

Figure 5 a: Distribution of dimensionless mean transverse velocities; $Q = 0.065 \text{ m}^3/\text{s}$.

Figure 5 b: Distribution of dimensionless mean transverse velocities; $Q = 0.035 \text{ m}^3/\text{s}$.

Figure 5 c: Distribution of dimensionless mean transverse velocities; $Q = 0.013 \text{ m}^3/\text{s}$.

Figure 6 a: Distribution of dimensionless mean vertical velocities; $Q = 0.065 \text{ m}^3/\text{s}$.

Figure 6 b: Distribution of dimensionless mean vertical velocities; $Q = 0.035 \text{ m}^3/\text{s}$.

Figure 6 c: Distribution of mean vertical velocities (m/s) for $Q = 0.013 \text{ m}^3/\text{s}$.

2.2.2 Turbulence Intensity

In both series of dikes, the turbulence intensities u' and v' were the about the same regardless of measurement location, Reynolds number, or alignment of dikes. However, the w' component was consistently nearly three times smaller than u' or v' . The averaged and extreme turbulent intensities around the dike are listed in Table 2, as well as the dimensionless values. Dimensionless values represent the ratio of the averaged and extreme turbulence intensities to the corresponding incoming flow intensity.

Q (m ³ /s)	Mean (m/s)		Dimensionless Mean		Dimensionless Extremes			
	Straight	Angled	Straight	Angled	Straight		Angled	
0.013					Min.	Max.	Min.	Max.
u'v'	-0.13	-0.35	-6.65	2.11	-41.2	10.5	19.5	-7.4
u'w'	0.02	0.06	0.93	4.81	-16.2	12.8	-27.7	69.5
v'w'	0.00	-0.02	0.43	0.73	-138.6	88.7	24.8	-12.4
0.035								
u'v'	-1.04	-1.59	25.57	5.28	126.8	-13.7	23.0	-9.0
u'w'	0.15	0.16	1.37	1.91	-3.3	9.5	-6.2	26.0
v'w'	0.03	0.02	-2.93	-2.78	27.0	-94.7	162.5	-77.1
0.065								
u'v'	-2.86	-4.09	5.80	33.94	33.9	-4.0	141.8	-97.9
u'w'	0.35	0.41	2.01	2.42	-5.9	14.2	-14.2	16.8
v'w'	-0.06	-0.11	8.67	-11.60	213.0	-265.8	-571.7	191.8

Table 2: Averaged and extreme turbulence intensities

The turbulent intensities are consistently 2-3 times larger than the corresponding turbulent intensities of the approaching flow. Figure 7 shows the plots of the ratios of turbulent intensities measured in the dike zone to those of approaching flow. It can be seen that the values are similar regardless of dike alignment or magnitude of discharge. This indicates that the increase in turbulence intensities has no direct correlation with flow Reynolds numbers and alignments of dikes. Consequently, the increases of turbulence activities due to those dikes are independent from the approach flow.

Figure 7: Distribution of dimensionless turbulence intensities; straight dikes (*top*), angled dikes (*bottom*).

From the above figures and Table 2, it can be seen that the magnitudes of u' , v' , and w' were larger for the angled dike series, but only by about 1.5 times that of the straight dike series. The increase was not primarily on any one turbulent intensity, although u' did see a slightly larger increase over v' and w' when the dikes were angled

upstream. As the Reynolds number increased, turbulence intensities u' , v' , and w' generally increased. However, when non-dimensionalized by the corresponding approaching flow turbulent intensities, the amplification of turbulence intensities around the dikes was nearly the same regardless of dike alignment as shown in Figure 7. The amplification factors around the dikes were about 4 – 5 times that of the incoming flow turbulence intensities, whereas the mean amplification factors across the domain ranged from 1.79 to 2.4. As seen in Figures 8 – 10, the spatial distribution of the turbulence intensities shows that the largest values occur near the tips of the dikes, primarily near the tip of the second dike. It is also clear from the scales in Figures 8 – 10 that the values of u' and v' are nearly the same, and much larger than those of w' .

Figure 8 a: Distributions of u' (m/s) at $Q = 0.065 \text{ m}^3/\text{s}$.

Figure 8 b: Distributions of u' (m/s) at $Q = 0.035 \text{ m}^3/\text{s}$.

Figure 8 c: Distributions of u' (m/s) at $Q = 0.013 \text{ m}^3/\text{s}$.

Figure 9 a: Distributions of v' (m/s) at $Q = 0.065 \text{ m}^3/\text{s}$.

Figure 9 b: Distributions of v' (m/s) at $Q = 0.035 \text{ m}^3/\text{s}$

Figure 9 c: Distributions of v' (m/s) at $Q = 0.013 \text{ m}^3/\text{s}$.

Figure 10 a: Distributions of w' (m/s) at $Q = 0.065 \text{ m}^3/\text{s}$.

Figure 10 b: Distributions of w' (m/s) at $Q = 0.035 \text{ m}^3/\text{s}$.

Figure 10 c: Distributions of w' (m/s) at $Q = 0.013 \text{ m}^3/\text{s}$.

2.2.3 Reynolds Stress

The Reynolds stresses increased considerably around the dike region. The averaged, maximum, and minimum Reynolds stresses compared to those of the approach flow are listed in Table 3. The averaged $-\overline{\rho u'v'}$ component is one order of magnitude larger than the other two components, $-\overline{\rho u'w'}$ and $-\overline{\rho v'w'}$. However, the averaged values did not realistically represent the relative importance of three Reynolds stresses' components at each measured point.

Q (m ³ /s)	Mean (m/s)		Dimensionless Mean		Dimensionless Extremes			
	Straight	Angled	Straight	Angled	Straight		Angled	
0.013					Min.	Max.	Min.	Max.
$-\overline{\rho u'v'}$	-0.13	-0.35	-6.65	2.11	-41.2	10.5	19.5	-7.4
$-\overline{\rho u'w'}$	0.02	0.06	0.93	4.81	-16.2	12.8	-27.7	69.5
$-\overline{\rho v'w'}$	0.00	-0.02	0.43	0.73	-138.6	88.7	24.8	-12.4
0.035								
$-\overline{\rho u'v'}$	-1.04	-1.59	25.57	5.28	126.8	-13.7	23.0	-9.0
$-\overline{\rho u'w'}$	0.15	0.16	1.37	1.91	-3.3	9.5	-6.2	26.0
$-\overline{\rho v'w'}$	0.03	0.02	-2.93	-2.78	27.0	-94.7	162.5	-77.1
0.065								
$-\overline{\rho u'v'}$	-2.86	-4.09	5.80	33.94	33.9	-4.0	141.8	-97.9
$-\overline{\rho u'w'}$	0.35	0.41	2.01	2.42	-5.9	14.2	-14.2	16.8
$-\overline{\rho v'w'}$	-0.06	-0.11	8.67	-11.60	213.0	-265.8	-571.7	191.8

Table 3: Averaged and extreme Reynolds stresses

The scatter plots of all the measured data in Figure 11 show that $-\overline{\rho u'w'}$ and $-\overline{\rho v'w'}$ are the same order of magnitude, and both magnitudes are less than $-\overline{\rho u'v'}$. Therefore,

when comparing the actual values of the Reynolds stresses between the two dike series, the horizontal Reynolds stress component, $-\overline{\rho u'v'}$, had a much greater magnitude than the other two components, $-\overline{\rho u'w'}$ and $-\overline{\rho v'w'}$. The Reynolds stress components $-\overline{\rho u'w'}$ and $-\overline{\rho v'w'}$ were roughly the same magnitude as each other in each case, both for straight and angled dikes, and across all three discharges, as can be seen from Figure 11.

Figure 11 a: $u'v'$ vs. $u'w'$ for straight and angled dikes, at all three discharges.

Figure 11 b: $u'v'$ vs. $v'w'$ for straight and angled dikes, at all three discharges.

Figure 11 c: $u'w'$ vs. $v'w'$ for straight and angled dikes, at all three discharges.

The distributions of Reynolds stresses around the dikes in the individual scales, shown in Figures 12 – 14, confirmed that Reynolds stresses are nearly the same order of magnitude regardless of the alignments of dikes. The maximum and minimum values occurred at the tips of the first and the second dikes. For the 0.035 m³/s flow, however, the positive values of $-\overline{\rho u'v'}$ and $-\overline{\rho v'w'}$ were similar for the angled dikes. Again, the highest magnitudes, both extreme positive and extreme negative values of the Reynolds stresses were seen around the tips of the dikes.

Figure 12 a: Distributions of $u'v'$ at $Q = 0.065 \text{ m}^3/\text{s}$.

Figure 12 b: Distributions of $u'v'$ at $Q = 0.035 \text{ m}^3/\text{s}$.

Figure 12 c: Distributions of $u'v'$ at $Q = 0.013 \text{ m}^3/\text{s}$.

Figure 13 a: Distributions of $u'w'$ for the $0.065 \text{ m}^3/\text{s}$ flow.

Figure 13 b: Distributions of $u'w'$ for the $0.035 \text{ m}^3/\text{s}$ flow.

Figure 13 c: Distributions of $u'w'$ for the $0.013 \text{ m}^3/\text{s}$ flow.

Figure 14 a: Distributions of $v'w'$ for the $0.065 \text{ m}^3/\text{s}$ flow.

Figure 14 b: Distributions of $v'w'$ for the $0.035 \text{ m}^3/\text{s}$ flow.

Figure 14 c: Distributions of $v'w'$ for the $0.013 \text{ m}^3/\text{s}$ flow.

2.2.4 Turbulent Kinetic Energy

Turbulent kinetic energy generally increased around the dike region due to the turbulence intensities increases. The averaged TKE is about 4 – 6 times greater than the approaching flow, while the maximum and minimum ratios to the approach flow are about 20 and 12, respectively. In addition, from Figure 15, it is clear that the areas of highest turbulent kinetic energy (TKE) were around the tips of the dikes; most noticeably the second dike. In the case of the angled dikes, however, the tips of all three dikes were high-energy areas. This may be due to the dikes interacting with each other as well as the incoming flow. In both cases, the contraction ratio was the same; both series blocked 25% of the incoming flow and were the same distance apart. However the angled dikes were twice as long as the straight dikes due to the angle, and this may have caused more

between-dike interaction in the angled dike case. These distributions of TKE at different flows synchronize to the distributions of turbulence intensities (Figures 8 – 10) and Reynolds stresses (Figures 12 - 14). In contrast to the distributions of Reynolds stresses in which both positive and negative values are shown, Figure 15 clearly indicates that the areas of highest TKE are concentrated around the dikes with the maximum value at the second dike. If sediment transport and scour are initiated from high turbulent activities, the high TKE zone indicates potential sediment entrainment and consequent erosion. In this regard, the TKE distribution is a better representation of turbulence activities in a disturbed flow field and provides a better indicator of potential erosion and sedimentation.

Figure 15 a: Distribution of turbulent kinetic energy for $Q = 0.065 \text{ m}^3/\text{s}$

Figure 15 b: Distribution of turbulent kinetic energy for $Q = 0.035 \text{ m}^3/\text{s}$

Figure 15 c: Distribution of turbulent kinetic energy for $Q = 0.013 \text{ m}^3/\text{s}$.

2.2.5 Methods of Calculating Bed Shear Stress

Several methods are commonly used in calculating the bed shear stresses among which the five most commonly used ones are based on shear velocity from the logarithmic velocity assumption, Reynolds stresses (Dey et al., 2005) Reynolds stresses, w' only (Biron et al, 2005), turbulent kinetic energy (Biron, 2005), and turbulent kinetic energy from w' only. Since the logarithmic law assumption is not valid around the dike, this method was not used in this study. The mathematical expressions for the four other methods, the ones using Reynolds stress and TKE, are below:

$$\text{Reynolds stress (Dey) method: } \tau = \rho \sqrt{(u'v' + u'w')^2 + (v'w' + u'v')^2}$$

$$\text{Reynolds stress using } w' \text{ only: } \tau = \rho(\overline{u'w'} + \overline{v'w'})$$

$$\text{TKE method: } \tau = 0.19\rho[0.5(u'^2 + v'^2 + w'^2)]$$

$$\text{TKE using } w': \tau = 0.9\rho(w'^2)$$

This study calculated the bed shear stress using these four methods and compared their magnitudes. Figure 16 a – c is a summary of bed shear stress calculated using the four listed methods for each experimental run.

Figure 16 a: Bed shear stresses for straight and angled dikes at $Q = 0.065 \text{ m}^3/\text{s}$.

Figure 16 b: Bed shear stresses for straight and angled dikes at $Q = 0.035 \text{ m}^3/\text{s}$.

Figure 16 c: Bed shear stresses for straight and angled dikes at $Q = 0.013 \text{ m}^3/\text{s}$.

The methods of only using turbulent kinetic energy or Reynolds stresses from w' yielded smaller shear stresses in all the runs because flow around the dikes is highly three-dimensional; thus not only w' but also v' and u' contributed to the turbulence shear stresses. Therefore, it was not a suitable approach in calculating the bed shear stress. The Dey's method or the Reynolds stresses method in average always predicted larger shear stresses than those from the TKE method. To assess the magnitude of shear stresses calculated from TKE and Reynolds stresses methods, bed shear stresses calculated by these methods are plotted in Figure 17 for each run at each measured point, for all three discharges.

Figure 17 a: Comparisons of Reynolds (Dey) and TKE shear stresses for straight dikes

Figure 17 b: Comparisons of Reynolds and TKE shear stresses for angled dikes

Figure 17 shows that the bed shear stress calculated by the Reynolds stresses (Dey et al. 2005) method is about two times larger than those predicted from the TKE method, especially for the angled dike cases when flow discharge is above $0.035 \text{ m}^3/\text{s}$. This indicates that both methods maybe valid for calculating bed shear stresses since they yielded consistent results. However, on the other hand, many in tidal flow research (Kim, et al., 2000, Pope, et al., 2002) recommended the use of TKE method when ADV measurements are used to estimate bed shear stresses, since it is nearly impossible to align the x and y arms of the ADV probe correctly when the flow is curving around an obstruction. Since flow around the dikes is three-dimensional, and therefore all three turbulent intensities contribute to the total, both these methods may be valid for the dike series case. However, the Reynolds (Dey et al., 2005) method may place undue emphasis on the u and v components. Therefore, if there are any errors introduced into the data from difficulty in aligning the probe arms, the TKE method may be the method to use in this case, since it places less emphasis on those two components.

Previous studies in the literature have shown bed shear stress amplification factors of around 3 (Kunhle, 2002; Dey and Barbhuiya, 2005; Duan, 2009) for a single dike to as much as 12 - 15 (Biron et. al, 2005) for two dikes across from each other. The present study found amplification factors of 12 to 20 for dikes in series. The larger amplification of bed shear stress seen here may be due to interactions between the dikes as well as the incoming flow.

2.2.6 Distribution of Bed Shear Stress

Bed shearing stress was calculated using four different equations to determine which method was the most suitable, and from this study the TKE method was adopted. Dimensionless bed shear, $\frac{\tau_b}{\tau_0}$, was then found by dividing by the bed shear stress at the undisturbed upstream end, thus obtaining the amplification factor of bed shear stress.

Figure 18 a: Distribution of bed shear stress for $Q = 0.065 \text{ m}^3/\text{s}$.

Figure 18 b: Distribution of bed shear stress for $Q = 0.035 \text{ m}^3/\text{s}$.

Figure 18 c: Distribution of bed shear stress for $Q = 0.013 \text{ m}^3/\text{s}$.

From Figure 18 it can be seen that the areas of highest shearing stress at the bed are around the tip of the second dike. For the angled dikes there may be more interaction between the dikes than for the straight dikes, causing areas of high shearing stress to be seen around the tips of all three dikes, as well as higher magnitudes of shear stress for the angled dike set-up. The bed shear stress amplification around the dikes ranged from about 12 to 20 times that of the incoming flow; Figure 19 shows the amplification of bed shear stress for all three flows.

Figure 19 a: Distribution of bed shear stress amplification for $Q = 0.065 \text{ m}^3/\text{s}$.

Figure 19 b: Distribution of bed shear stress amplification for $Q = 0.035 \text{ m}^3/\text{s}$.

Figure 19 c: Distribution of bed shear stress amplification for $Q = 0.013 \text{ m}^3/\text{s}$.

2.3 Summary and Conclusions

This study conducted a series of experimental measurements of turbulent flow field around two three-dike series with 90° and 30° angles to the side bank. Measurements showed that the mean flow velocities do not seem to be as important as the turbulence properties in determining whether or not scour will occur. However, the turbulent intensities, Reynolds stresses, and TKE have increased considerably around the dikes. The turbulence intensities in all three dimensions were 4-6 times larger than those of the approach flow, while the maximum increments that occurred near the dike tips were 5-6 times larger. Of the three turbulence intensities, u' and v' were the most significant. As a result, the turbulent kinetic energy around the dikes has increased to 10-15 times of that of the approach flow. All three components of Reynolds stresses were also increased to 8-10 times of the approaching flow.

The effect of change in discharge (Q) on the mean flow and turbulent flow fields was mainly that of change in magnitude. Overall, the larger the Q , the higher were the magnitudes of mean velocities and turbulence intensities in the channel. The effect of dike angle on the mean flow and turbulent flow fields was mainly that of spatial distribution, although in some cases, the angled dikes showed slightly larger magnitudes than did the straight dikes. In general, the angled dikes showed a much wider distribution of the maximum values of the mean flow velocities and turbulence intensities than did the straight dikes. Maximum values were spread out around all three angled dike tips, whereas they were found mainly around the second dike tip in the straight dike case.

Bed shear stress is crucial in determining sediment transport and local scour around the dikes. The increase in turbulence activities is reflected in the amplification of bed shear stresses. This study adopted the TKE method to calculate bed shear stresses because the ADV measurements can not be aligned exactly with the streamlines in the complex 3D flow fields around the dikes. The highest magnitude of bed shear stress and turbulent kinetic energy was consistently seen around the second dike in the series. Previous studies observed the first dike with the largest magnitudes of shear stresses, since that is the dike that the incoming flow first encounters. However, in all flows, but most noticeably the largest flow, and for both angled and straight dikes, the highest magnitudes were seen around the second dike. Given the magnitudes of the bed shear stress around the dikes in the plane bed case and the velocities of the incoming flow, it may be possible to predict the depth of the resulting scour hole when it reaches equilibrium if the bed were mobile.

It would seem that there would be a spatial correlation between the area of highest bed shear stress and where the maximum scour will occur. Further study needs to be done, using sediment in the flume, to test whether the location of highest shear stresses in a flat, fixed bed channel can be used to predict the location and even depth of the equilibrium scour hole formed in the same channel but with a mobile bed. It is expected that there may be some correlation and that the plane bed case can be used in some way to predict the location of the maximum scour.

2.4 Future Research

A mobile bed flume experiment is planned for the near future. The experimental set up will remain the same except that 10 cm of sand will be added to the flume. The same Q of $0.035 \text{ m}^3/\text{s}$ that was used for the intermediate flow in the plane bed experiment will be used in the mobile bed experiment. The experiment will be run for several hours to allow the bed scour to reach equilibrium, at which time the flume will be carefully drained, and the location of the maximum scour depth will be determined. The bed will then be measured at each point on the plane bed measurement grid to determine the magnitude of scour and deposition seen in the mobile bed case. This experiment will be carried out for both the straight and angled dike cases. Flow over the equilibrium scoured bed will then be measured with an ADV in the same way as for the plane bed case, and the resulting mean velocity and turbulent flow fields, and Reynolds stress and bed shear stress distributions will be compared.

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APPENDIX A – DISTRIBUTIONS OF BED SHEAR STRESSES AROUND SERIES
OF STRAIGHT AND ANGLED DIKES

Distribution of Bed Shear Stresses around Series of Straight and Angled Dikes

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Abstract

Predicting scour around a series of dike structures in open channel flow has challenged river engineers for decades. Flow turbulence has amplified the bed shear stresses around structures and consequently initiated erosion. However, no consensus has been reached on the amplification factor, method of calculating bed shear stress and location of maximum shear stresses. Therefore, an experimental study of near-bed turbulence and bed shear distributions around a series of three dikes was conducted in a flat, fixed-bed laboratory flume. A micro acoustic Doppler velocimeter (ADV) was used to measure velocities near the bed in all three spatial directions and then the turbulence intensities and Reynolds' stresses were calculated from these measurements. Results showed that bed shear stress should be determined either by the turbulent kinetic energy (TKE) or the Reynolds stresses. The maximum shear stress, occurring at the tip of the second dike in the three-dike series, is nearly 6-8 times that of the approaching flow. Turbulence intensity, u' , was the largest with highest values around the second dike in the series. Magnitudes of the turbulence intensities around the dikes were about 3 to 5 times that of the incoming flow.

Subject headings: Reynolds stress; Spur dike, Turbulence, Bed Shear Stress

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1. Introduction

Erosion of the banks and bed of natural and manmade channels is a common problem in water resources management. Spur dikes in rivers and streams such as the Mississippi River are used to prevent bank erosion and to keep the main channel navigable. These structures extend from the bank into the streamflow, perpendicularly or at some angle. Most are emergent from the water surface only during low flows, becoming submerged during flood events. Scour around these and other structures such as bridge piers can be a serious problem, weakening structural stability. To better understand the mechanism of scour around such hydraulic structures, the questions of what are the turbulence distributions around these structures and how the turbulent flow field affects sediment transport must be answered. In addition, it is important to determine which turbulence properties are more important in predicting the local sediment transport rate. Better understanding of these processes will aid river engineers in designing better embankments for prevention of bank erosion and scour around bridge piers. This knowledge will also benefit river restoration projects, as areas around these embankments and dikes are often habitats for vegetation and fish.

Theoretical studies have derived equations describing the bed shear stress in turbulent flows (Dey and Lambert, 2005; McLean and Nikora, 2006; Coleman and Nikora, 2008; Tanaka and Eaton, 2008). Many modeling studies using large eddy simulations (LES) have determined the location and amount of scour that will occur around embankments, abutments, dikes, piers and other obstructions to flow (Nagata, et al, 2005; Zhang, et al, 2005; Yossef and Rupprecht, 2006; Haltigin, et. al, 2007; Koken

and Constantiescu, 2008; McCoy, et al, 2008). Often these theoretical and numerical studies are validated with experimental observations using dye tracers. LES simulated results shed light on detailed turbulence vorticity field near structures, which has not been measured in the laboratory. In addition, experiments have been carried out in laboratory flumes to determine the effects of engineering structures on the flow (Yossef and De Vriend, 2004; Uijttewaai, 2005). Laser visualization techniques, particle image velocimetry (PIV), and instruments such as acoustic Doppler velocimeters (ADV), have been used extensively in recent years to determine flow fields around spur dikes, abutments, and the like. Three dimensional measurements of velocity can then be used to determine turbulence intensities, Reynolds stresses and shear stress. Studies using fixed, flat beds often measure Reynolds stresses and bed shear stress in an attempt to predict where scour will take place if the bed were mobile. Dey and Barbhuiya (2005) used an ADV to examine the turbulent flow field around a short rectangular abutment oriented 90° to the flow, starting with the fixed rough plane bed condition, and ending with the equilibrium scour hole condition. It was determined from these two experiments that the turbulent kinetic energy inside the scour hole was greater than that of the plane bed, and that the maximum bed shear stresses were about 3.2 times that of the incoming flow. Because the bed shear stress τ_b was greater than that of the critical shear stress τ_c of the sand forming the bed, the majority of the plane bed would have scoured had it been mobile. A later study by Kuhnle et al (2008) used an ADV to examine the three-dimensional flow field around a submerged spur dike with sloped sides, oriented 90° from the bank. An amplification factor of three was found for the bed shear stresses

around this dike, compared to earlier studies of emergent, straight-sided dikes which had amplification factors of about 3 to 5 times that of the incoming flow. A third flume experiment using similar techniques was done by Duan (2009) in which a single dike – a flat rectangular metal plate – was placed 90° to the wall of a flume with a fixed, flat bed. In this case, the bed shear stress calculated from the Reynolds stresses was 2 – 3 times that of the incoming flow. In spite of the differences in dike shape and flow Reynolds number, all three studies showed similar amplification factors of bed shear stress.

Dikes angled in the direction of flow (oriented with a downstream skew) attract the flow towards the banks. Dikes angled against the direction of flow (oriented with an upstream skew) repel the flow, directing it towards the main channel. Dikes oriented perpendicular to the flow deflect it, similar to the upstream-skewed dikes, but with less vorticity near the tip (Zhang and Nakagawa, 2008). Several studies have been done on the effects of orientation angle on the amount of scour around a spur dike. One such study examined the effects of three different orientation angles on scour around spur dikes (Kuhnle et al, 2002) for the purposes of creating scour holes for aquatic habitats while at the same time minimizing bank erosion. A series of flume experiments was performed using a short, angled, submerged spur dike with sloped sides. Results indicated that the least bank erosion occurred when the dike was oriented 90° from the bank, and the greatest amount of scour occurred near the 135° dikes (45° from the bank, upstream skew) with only a little more bank erosion occurring than for the 90° dikes. Similar results were seen by Tominaga and Matsumoto (2006) in an experiment using flat slabs of wood as model spur dikes in a sand bed flume. The dikes were arranged in

alternating series of three, on both sides of the flume, and remained submerged throughout the experiment. For both the 135° case and the 90° case, the maximum scour was mainly seen around the dike tips, with some deposition on the sides, with the greatest scour occurring in the upstream skew dikes. For submerged dikes in series, the maximum scour was located around the tip of the first dike. Biron et al (2005) also examined the effects of orientation angle on turbulent flow. The study included both emerged and submerged flow, and plane bed and mobile bed. Results also showed that the location of maximum shear stress in the plane bed runs did not spatially coincide with the location of the maximum scour in the mobile bed runs. The maximum bed shear stress was located downstream of the dikes, with a maximum amplification factor of 12 to 15. The 90° oriented dikes produced the highest bed shear stresses, both for emerged and submerged flows, with the 135° emerged dikes having slightly smaller bed shear stress amplification.

In the present experimental study, the flow field was measured around a series of three spur dikes installed at an open, flat-bed channel by using a SonTek 25-MHz MicroADV. Time histories for velocities in all three spatial dimensions were recorded near the bed at cross sections perpendicular to the walls of the flume. These measurements can be used to study the impacts of the dikes on flow structures. These impacts, which include flow convergence and locally increased bed-shear stress, may then be used to explain the initiation of scour holes and the sorting of sediment as scouring evolves.

2. Experimental Set-up

An experimental study was conducted in a 0.6 m wide, 12.2 m long flume with a flat, fixed bed and a 10 cm high weir inserted into the flow 10.6 m downstream of the inlet (Figure 1). The left wall of the flume was painted metal and the right wall of the flume was painted metal with a 3 m long smooth glass observation section roughly in the middle of its length. A 10 cm high broad-crested weir was installed at the end of the flume to measure volumetric discharge. The weir equation $Q = K L H^{1.5}$, where L is the crest length, H is the height of water flowing over the weir, and K is some constant, was used. For this study, $K = 6678$ (for units of m^3/hr). Since many recent experiments of turbulent flow have been measured using the acoustic Doppler velocimeter (ADV) either in flume studies as mentioned earlier or in the field (Stone and Hotchkiss, 2007; Tritico and Hotchkiss, 2005; Nikora and Goring, 2000) to examine three dimensional flow properties, a 16 MHz SonTek microADV was used to measure the instantaneous velocities in the three spatial directions in the flume at a sampling rate of 25 Hz. The sampling volume was about 5 cm below the probe tip, thus allowing for unimpeded sampling of the flow.

To study the effects of dike placement and angle with respect to the flow, two experimental runs were performed: one with a series of three deflecting dikes perpendicular to the direction of flow and the other of three repelling dikes angled into the direction of flow. Each model dike is made of 40 cm tall, 15 cm long, and 4 mm thick metal plate. The model dikes were placed a distance of $2D$ apart, where D is the distance the dikes protrude into the flow. In both experiments this distance D was 15 cm, about $\frac{1}{4}$ the width of the flume. The second experiment was for three upstream skewed

dikes aligned at 30° to the left wall, which are modeled as three metal plates 40 cm tall, 30 cm long and 4 mm thick. As with the first experiment, the dikes were spaced 30 cm apart but protruding into the channel the same distance $D = 15$ cm as the straight dikes.

The accuracy of ADVs for various turbulence applications has been well-documented (Voulgaris and Trowbridge, 1998; Nikora and Goring, 1998; Gratiot et al, 2000; McLelland and Nicholas, 2000; and Garcia et al, 2005). Research into new data filtering methods to assure ADV data quality is ongoing. Goring and Nikora (2002) proposed a phase-space de-spiking algorithm for ADV data, and this method has been incorporated into the publicly-available WinADV data processing program used in this study (Wahl, 2000). Recently, Cea et al (2007) developed a new filtering process for ADV data gathered in highly turbulent flows, but after comparing the method to available ones and found the SNR as a filter is not good because it varies with the flow properties. Finelli et al (1999) evaluated the spatial resolution of the ADV for near-bed flows and found that the system incorrectly calculated the transmitter-to-bed distance and therefore underestimated the near-bed velocities. Therefore, careful monitoring of signal quality is required to assure proper placement of the ADV probe for near-bed applications. In this study, about 5000 measurements were taken to ensure at least 1000 good measurements for the near bed nodes. The main criteria used for determining a good measurement was the signal to noise ratio (SNR). According to the manufacturer, the signal to noise ratio is a function of turbidity, i.e. the amount of particulate matter in the flow. For high-frequency measurements ($> 25\text{Hz}$) an $\text{SNR} > 15$ decibels (db) is recommended. In addition, when the three-dimensional velocity measurements are to be used to determine

turbulence properties, an SNR > 15 db is required. The manufacturer also recommends a correlation score (COR) between 70% and 100%. However, highly turbulent or aerated flows can cause the COR to be much lower than this recommended range. This phenomenon was noticed in this study, especially at nodes around the dikes and when the flow was particularly aerated at the highest flow. When only the mean velocity properties are desired, a COR of near 30% is considered sufficient (SonTek ADV Technical Documentation Manual, 2001).

To determine the effects of flow depth and magnitude of discharge on bed shear stress and turbulence properties, each dike series was subjected to three different flow rates. The lowest flow corresponding to $h = 0.15$ m depth at the downstream end was calculated to be $0.013 \text{ m}^3/\text{s}$; the highest flow corresponding to 0.25 m flow depth at the downstream end was $0.065 \text{ m}^3/\text{s}$. An intermediate flow depth of $h = 0.20$ m at the downstream end, where $Q = 0.035 \text{ m}^3/\text{s}$, was used complete the experiment.

3. Experimental Procedure

A full velocity profile consisting of 5 verticals starting about 5 mm from the bed and extending at 1 cm intervals to 5 cm from the water surface was measured a distance greater than $2l$ upstream of the first dike, where l is the length of a dike. This was 33 cm for the 90° dikes and 63 cm for the 150° dikes. This was done in order to establish the mean and unaffected flow properties in the flume. The mean flow velocity and the shear velocity of the center vertical, obtained through a linear regression analysis, were then

used to non-dimensionalize the near-bed velocities, turbulence intensities and Reynolds stresses.

The measurements were obtained in a grid around the dikes, at 5 mm from the bed and starting 10 cm from the left wall and extending to 10 cm from the right wall, as seen in Figure 2. The ADV was mounted on an instrument carriage, held in place by a specially made milled-aluminum vise. The size of the vise was such that measurements closer than 10 cm to the walls of the flume were prohibited. The vise was raised and lowered and moved side to side manually to allow for proper placement of the ADV at each of the nodes. The carriage itself was mounted on wheels on a track that extended most of the length of the flume, thus allowing for movement of the ADV in the x, y, and z directions. The measurement grid was arranged such that the nodes were denser around the dikes and becoming sparser away from the dikes (Figure 2). A total of 167 near-bed nodes for the 90° dikes and 295 near-bed nodes for the 150° dikes were arranged around the dikes so that from around the dike tips, 10 cm from the wall to the center of the flume the resolution was 3 cm by 3 cm, with two lower resolution rectangular arcs of 5 cm by 5 cm and one of 10 cm by 10 cm at the outskirts of the area of interest. One measurement was taken at each node at a depth z of about 5 mm from the bed. Raw data was collected using the ADV probe and the Horizon ADV software. Time series of velocities in three spatial directions were measured at each node at a depth $z = 5\text{mm}$ from the bed and used to calculate the turbulence intensities and Reynolds stresses.

4. Data Processes

In the data analysis, the x , y , and z axes were oriented along the main flow longitudinally, to the left bank in the transverse direction, and toward the water surface in vertical with instantaneous velocity components denoted as u , v , and w , respectively. Post-processing of the raw data was done using the publicly-available WinADV software from SonTek. The filtering criteria used was $\text{SNR} > 15$ db, as well as the Nikora-Goring despiking algorithm (Wahl, 2000) incorporated into the software. For the smallest flow, $\text{SNR} > 10$ had to be used, since the flow velocity was so small that an insufficient amount of data points had $\text{SNR} > 15$. Processed data was directly used by a calculation program to output the desired information in a text file to be used by visualization software. The measured velocities in the processed data file were used to calculate the following turbulence characteristics: (a) mean velocities in the longitudinal, transverse, and vertical directions denoted as $\bar{u}, \bar{v}, \bar{w}$, respectively; (b) Reynolds stresses, $-\rho \overline{u'v'}$, $-\rho \overline{u'w'}$, and $-\rho \overline{v'w'}$ in which $u', v',$ and w' are turbulence fluctuations in longitudinal, transverse, and vertical directions, respectively.

From the measurements of the complete velocity profile of unaffected flow, the mean horizontal velocity, where $V_x = \sqrt{\bar{u}^2 + \bar{v}^2}$, and vertical ($\bar{w}$) velocities at each node were calculated; $\bar{w}$ was orders of magnitude smaller than V_x . The mean horizontal velocity was plotted against $\log(\frac{z}{h})$ where z is distance from the bed surface, and h is the flow depth. Linear regression analysis was then used to fit the data in a semi-logarithmic scale plot and from this the friction velocity for each vertical profile, u_{*} , was obtained.

5. Experimental Results

Mean flow

For the high flow $Q = 0.065 \text{ m}^3/\text{s}$ at the weir, corresponding to a 0.25 m flow depth at the weir, the near-bed mean flow velocity V_x was about the same for the straight and the angled dikes. The straight dikes showed a patch of high velocity near 0.7 m/s directly across from the first two dikes. Upstream and downstream of the dikes, the velocity was about 0.45 m/s. The angled dikes showed this pattern as well, but to a lesser degree, only reaching a maximum of about 0.6 m/s. As expected, areas between the dikes showed relatively low velocities. Reynolds numbers for these flows ranged from about 84000 for the $0.065 \text{ m}^3/\text{s}$ flow to about 13000 for the $0.035 \text{ m}^3/\text{s}$. The Reynolds number for the intermediate flow was about 42000. The time-averaged velocities in the transverse and vertical directions were nearly zero with the maximum $\bar{v}$ at the front of the first dike, and the maximum $\bar{w}$ near the tip of the second dike.

Turbulence intensities

In both series of dikes, u' and v' were the about the same regardless of measurement locations, Reynolds number, or alignment of dikes. However, the w' component was consistently nearly three times smaller than u' or v' . Figure 3 showed w' was even smaller for the angled dikes at the lowest Reynolds number; however, this may be a result of measurement errors. There was little difference at the bed between the turbulence intensities for the straight and angled dikes, except in the spatial distribution shown in Figure 3 where the maximum values were much more spread out in the angled

dike case. In general, the magnitudes of u' , and w' were larger for the angled dike series, but only by about 1.5 times that of the straight dike series. The increase was not primarily on any one turbulent intensity, but u' did see a slightly larger increase over v' and w' when the dikes were angled upstream.

As the Reynolds number increased, turbulence intensities u' , v' , and w' generally increased. However, when non-dimensionalized by the corresponding approaching flow turbulent intensities, the amplification of turbulence intensities around the dikes was nearly the same regardless of Reynolds number. The amplification factors around the dikes were about 4 – 5 times that of the incoming flow turbulence intensities. The mean amplification factors across the domain ranged from 1.79 to 2.4. In addition, dimensionless values of u' , v' , and w' were obtained by dividing the individual turbulence intensities by the shearing velocity of the incoming flow, u_{s0} . The mean amplification across the domain was nearly the same for both the straight and angled dike series. The dimensionless turbulence intensities in both cases ranged from 2.1 to 10.9. The maximum values of dimensionless u' were located just upstream, at and slightly downstream of the tip of the second dike whereas the area of highest dimensionless v' was just downstream of the second dike.

Reynolds stresses

As the Reynolds number increased, $-\overline{\rho u'v'}$, $-\overline{\rho u'w'}$, and $-\overline{\rho v'w'}$ in general increased as well. Again, as was seen with the turbulence intensities, when non-dimensionalized by the corresponding Reynolds stresses of the approach flow, the mean

amplification of the time-averaged Reynolds stresses was nearly the same for both angled and straight dikes. These mean amplification factors had a much larger spread, ranging from 1.3 to 34.

When comparing the actual values of the Reynolds stresses, the horizontal Reynolds stress component, $-\overline{\rho u'v'}$, had a much greater magnitude than the other two components, $-\overline{\rho u'w'}$, and $-\overline{\rho v'w'}$. The Reynolds stress components $-\overline{\rho u'w'}$ and $-\overline{\rho v'w'}$ were of roughly the same magnitude as each other in each case, both for straight and angled dikes, and across all three discharges.

When looking at the spatial distributions of the different dimensionless Reynolds stress components in Figure 4, it can be seen that the angled dikes had higher magnitudes of both positive and negative values of the Reynolds stresses than the straight dikes. For the straight dikes, the area of highest $-\overline{\rho u'v'}$ was concentrated at the tip of the second dike; for the angled dikes, the largest magnitude of $-\overline{\rho u'v'}$ was seen just downstream of it. In both cases, the highest magnitudes were negative, which indicates that sweeps and ejections are the dominant turbulent burst events. Among the four burst events, sediment transport is closely associated with sweeps, and less sediment entrainment was observed in outward and inward interaction events (Nelson *et al.* 1995). Interestingly, in the case of the angled dikes, a strong negative $-\overline{\rho u'v'}$ cell was seen just downstream of the tip of the second dike, while a cell of strong positive $-\overline{\rho u'v'}$ circulated just downstream of the tip of the first dike. This distribution of burst events indicated sediment transport may be most active near the tip of the second dike rather than the first one. For $-\overline{\rho u'w'}$, for both

the straight and angled dikes, the highest magnitudes were positive, and each series showed a strong positive cell circulating near the tip of the first dike. This observation further showed that the $-\rho \overline{u'w'}$ component contributed less than $-\rho \overline{u'v'}$ to sediment transport. For the straight dike series, the positive cell was located just upstream of the first dike, while for the angled dikes it was located just downstream of the tip of the first dike. More concentrated negative cells circulated between the straight dikes, while for the angled dikes these negative cells were more spread out.

Bed Shear Stresses

In non-uniform and unsteady flows in open channels or natural rivers bed shear stress is important for estimating sediment transport rate. However, many methods to calculate bed shear stresses are available in the literature. Among them, civil engineers often adopt the Reynolds stresses method in Dey and Barbhuiya (2005). If using the near-bed Reynolds stresses to approximate bed shear stress, τ_b , the mathematical equation is $\tau_b = \sqrt{(\tau_b^x)^2 + (\tau_b^y)^2}$, where $\tau_b^x = -\rho \left(\overline{w'u'} + \overline{v'u'} \right) \Big|_{bed}$ and $\tau_b^y = -\rho \left(\overline{w'v'} + \overline{v'u'} \right) \Big|_{bed}$, ρ = density of water. An alternate method to calculate bed shear stress uses only the w' component, and the equation becomes simply $\tau_b = -\rho (\overline{u'w'} + \overline{v'w'})$ if both streamwise and transverse turbulence velocities are considered. Since turbulence intensity in the transverse direction is significant, this form was used instead of the one in Biron (2005) where $\tau_b = -\rho \overline{u'w'}$.

Another common method of calculating the bed shear stress involves the turbulent kinetic energy (TKE). This method uses the turbulent fluctuations in the three

spatial directions, u' , v' , and w' . In this case, $\tau_b = C_1 [\frac{1}{2} \rho(u'^2 + v'^2 + w'^2)]$ where C_1 is a proportionality constant equal to 0.19 (Kim, *et al.*, 2000, Pope, *et al.*, 2002). Because the instrument noise error associated with vertical velocity fluctuations is smaller than that associated with the horizontal fluctuations, it has been suggested in the literature (Biron, 2005, Kim *et al.*, 2000) to use only w' in the calculation of bed shear stress, which then becomes simply $\tau_b = C_2 \rho(w'^2)$ and where $C_2 = 0.9$. The total bed shear stress τ_b can be expressed in dimensionless form as $\tau_b^+ = \tau_b / \tau_0$, where τ_0 = the bed shear stress of approaching flow by the log law, ρu_{*0}^2 .

These four methods of calculating bed shear stress were used in this study to determine which one would give the most satisfactory results. At first, the bed shear stress calculated by using the method in Dey and Barbhuiya (2005) was compared to the one calculated by using the TKE method as shown in Figure 5. Dey's and Barbhuiya's method yielded a bed shear stress nearly 2 – 4 times of those from the TKE method. As the Reynolds number increased, the correlation of bed shear stresses from these two methods became worse. Secondly, bed shear stresses obtained from only considering the Reynolds stresses associated with w' were also compared with the bed shear stresses from TKE method in Figure 5. The Reynolds stress method that only considers the w' component yielded much smaller bed shear stresses than the TKE method. Because turbulent flow around the dikes is highly three-dimensional, this excludes the use of this method. Since accurate ADV measurements require the primary receiver pad to be aligned with the streamwise line, measurements collected around the dike apparently

were not able to be aligned with the curved streamlines. Many applications of ADVs in tidal flows (Kim, *et al.*, 2000; Huthnance, 2002; and Pope, *et al.*, 2006) concluded that the TKE method is the most reliable to estimate the bed shear stress. Therefore, this study employed the TKE method for calculating bed shear stress.

Bed Shear Stress Distributions around Straight and Angled Dikes

Dimensionless bed shear stress $\hat{\tau}_b$ was obtained using the bed shear stress τ_{b0} of the incoming flow, also calculated using the TKE method. The magnitudes of $\hat{\tau}_b$ around the straight dikes reached a maximum of about 19.46 times that of the incoming flow at the tip of the second dike for the high Reynolds number flow as seen in Figure 6. As the Reynolds number decreased, so did the bed shear stress, although for all three flows the bed shear stress was of the same order of magnitude. For the lowest Reynolds number, the maximum amplification factor of bed shear stress was about 12.63, nearly half that for the highest Reynolds number case. However, for all three flows, the maximum bed shear stress was found at the tip of the second dike.

As to the angled dikes, for the highest Reynolds number, the dimensionless bed shear around the angled dikes was slightly larger than that around the straight dikes. The highest magnitude of bed shear stress was again seen near the tip of the second dike, although for the angled dikes it was located slightly downstream of the tip of the second dike. There was also a small area of high bed shear stress near the tip of the first dike. The bed shear stress near the tip of the second dike was 21.37 times that of the incoming flow for the highest Reynolds number. The same patterns of shear stress were seen for the

two higher Reynolds number flows. The low Reynolds number flow had a maximum amplification of about 11.88 times that of the incoming flow. A patch of high bed shear was seen just downstream of the first dike in this experimental run, not around the second dike as was seen with all other runs, both angled and straight. There were also patches of high bed shear in the main flow, which was not seen in other experiments. This may be due to errors with the instrument at low flow depth and velocities.

6. Conclusions

Of the three turbulence intensities, u' and v' are the most significant, with w' being much smaller than either of the other two. In the case of the Reynolds stresses, the horizontal component $-\overline{\rho u'v'}$ was the largest, with the other two components being roughly equal to each other, and much smaller than the horizontal component. These patterns were consistently seen in all cases, both for straight and angled dikes, and all three discharges.

The highest magnitude of bed shear stress and turbulent kinetic energy was consistently seen around the second dike in the series. It was expected that the largest magnitudes would be located around the first dike that the incoming flow first encounters. However, in all flows, but most noticeably the largest flow, and for both angled and straight dikes, the highest magnitudes were seen around the second dike. Given this information, we predict that in the mobile bed case, under clear water scour conditions, the location of maximum scour will be around the second dike in the series. In addition, given the magnitudes of the bed shear stress around the dikes and the

velocities of the incoming flow from the plane bed case, it may be possible to predict the depth of the resulting scour hole when it reaches equilibrium.

Further study will be done, using sediment in the flume, to test whether the location of the highest shear stresses in a flat, fixed bed channel can be used to predict the location of the maximum equilibrium scour hole formed in the same channel but with a mobile bed. It is expected that the location of maximum scour may be predicted using the location of the maximum bed shearing stress and turbulent kinetic energy. Future work will also include derivation of an equation to predict the depth of maximum equilibrium scour based on turbulence data obtained from the plane bed case, as well as information obtained from the mobile bed case.

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Notations

The following symbols are used in this paper:

x = horizontal longitudinal direction

y = horizontal transverse direction

z = vertical direction

h = depth of water at the weir (m)

H = height of water flowing over the weir (m)

D = distance between two dikes at the base (cm)

Q = volumetric discharge ($\text{m}^3 \cdot \text{s}^{-1}$)

K = weir constant for discharge units $\text{m}^3 \cdot \text{hr}^{-1}$

L = weir crest length (cm)

l = dike length (cm)

V_x = velocity in horizontal direction ($\text{m} \cdot \text{s}^{-1}$)

u, v, w = instantaneous flow velocities ($\text{m} \cdot \text{s}^{-1}$)

$\bar{u}, \bar{v}, \bar{w}$ = mean flow velocities ($\text{m} \cdot \text{s}^{-1}$)

u', v', w' = turbulence intensities ($\text{m} \cdot \text{s}^{-1}$).

$-\rho \overline{u'v'}, -\rho \overline{u'w'}, -\rho \overline{v'w'}$ = Reynolds stresses ($\text{N} \cdot \text{m}^{-2}$)

τ_b = bed shear stress ($\text{N} \cdot \text{m}^{-2}$)

τ_{b0} = bed shear stress of the incoming flow

τ_b^* = dimensionless bed shear stress

u_* = shear velocity ($\text{m} \cdot \text{s}^{-1}$).

u_{*0} = shear velocity of the incoming flow

ρ = density of water ($\text{kg} \cdot \text{m}^{-3}$)

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Figures

Figure 1: Plan view of the flume set up.

Figure 2: Measurement grid for the straight (*left*) and angled (*right*) dikes.

Figure 3a: Dimensionless turbulence intensities $\frac{u'}{u_{*0}}$ (top), $\frac{v'}{u_{*0}}$ (center), and $\frac{w'}{u_{*0}}$ (bottom) for straight dikes at $Q = 0.35 \text{ m}^3/\text{s}$.

Figure 3b: Dimensionless turbulence intensities $\frac{u'}{u_{*0}}$ (*top*), $\frac{v'}{u_{*0}}$ (*center*), and $\frac{w'}{u_{*0}}$ (*bottom*) for angled dikes at $Q = 0.035 \text{ m}^3/\text{s}$.

Figure 4a: Dimensionless Reynolds stresses $\frac{-\overline{\rho u'v'}}{\rho u_{*0}^2}$ (top), $\frac{-\overline{\rho u'w'}}{\rho u_{*0}^2}$ (center) and $\frac{-\overline{\rho v'w'}}{\rho u_{*0}^2}$ (bottom) for straight dikes at $Q = 0.035 \text{ m}^3/\text{s}$.

Figure 4b: Dimensionless Reynolds stresses $-\frac{\overline{\rho u'v'}}{\rho u_{*0}^2}$ (*top*), $-\frac{\overline{\rho u'w'}}{\rho u_{*0}^2}$ (*center*) and $-\frac{\overline{\rho v'w'}}{\rho u_{*0}^2}$ for angled dikes at $Q = 0.035 \text{ m}^3/\text{s}$.

Figure 5: Comparison of different methods of calculating τ for straight and angled dikes.

Figure 6a: Spatial distribution of dimensionless bed shear stress by the TKE method for straight dikes at $Q = 0.035 \text{ m}^3/\text{s}$.

Figure 6: Spatial distribution of dimensionless bed shear stress by the TKE method for angled dikes at $Q = 0.035 \text{ m}^3/\text{s}$.