Local Scour Associated with Angled Spur Dikes

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Abstract: A series of experiments were conducted in which the volume of the scour hole associated with model spur dikes was measured in a laboratory flume under clear-water overtopping flows. Spur dike models were angled at 45, 90, and 135° to the downstream channel sidewall with contraction ratios of 0.125 and 0.250. The main goals of the experiments were to evaluate the effect of the three angles on the volume of scour and potential aquatic habitat and on minimizing erosion adjacent to the streambanks. The experiments showed that of the three angles tested, the least erosion of the bed in the near bank region was associated with the spur dikes with 90° angles, while the greatest volume of the scour hole was associated with the 135° spur dikes. It was concluded that spur dikes with 135° angles showed the best potential for providing improved aquatic habitats while minimizing the potential for erosion of the channel bank.

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Introduction

A spur dike may be defined as a structure extending outward from the bank of a stream for the purpose of deflecting the current away from the bank to protect it from erosion. In addition to bank protection, spur dikes have also been used to enhance aquatic habitat by creating stable pools in unstable streams (Klingeman et al. 1984). Fish communities in warm water streams are quite sensitive to the availability of large stable pools (Schlosser 1987). Spur dikes cause pools to be created and maintained, and have been found, in general, to be more beneficial to aquatic habitat resources than other types of bank protection (Knight and Cooper 1991; Shields et al. 1995a, 2000). The magnitude of the benefit to the habitat in a disturbed stream is related to the scour hole volume. Shields et al. (1995b) documented significant increases in fish numbers, size, biomass, and number of species in an incised stream following modification of spur dikes to enlarge scour holes and increase the percentage of pools in the reach. Designers of bank stabilization structures should, where possible, select spur geometry which stabilizes the bank and provides the largest scour volume subject to cost constraints.

The volume of local scour in the vicinity of a spur dike is difficult to estimate accurately. Most investigations in this field have just measured the maximum depth of scour and not the geometry of the scour hole. Few studies have been made which measured the velocity distribution associated with spur dikes and scour holes (e.g. Rajaratnam and Nwachukwu 1983a), and none to our knowledge which measure the velocity distribution as the scour hole evolves. The physics of the interactions between the three dimensional (3D) unsteady flow and sediment in transport on the bed are poorly understood and difficult to characterize. As a result, most scour prediction algorithms are empirically based and predict only the maximum depth of scour (Raudkivi 1990; Melville 1992, 1997; Melville and Coleman 2000). The effect of alignment on the maximum depth of scour for abutments was summarized by Melville and Coleman (2000). With a few exceptions (Kwan 1984; Kandasamy 1985), the main trend in the data was for maximum scour depth to increase about 20% as the alignment angle increased from 30 to 150° for long abutments [ratio of abutment length (L) to flow depth (Y_∞) greater than or equal to 3]. For values of the length ratio less than one, no effect of alignment on the maximum depth of scour was assumed by Melville and Coleman (2000).

Experimental studies to date have predominantly used flow depths less than the height of the spur dike model (e.g., Garde et al. 1961; Gill 1972; Copeland 1983; Rajaratnam and Nwachukwu 1983b; Klingeman et al. 1984). The nature of the flow near protruding abutments has been characterized by Rajaratnam and Nwachukwu (1983a); Kwan (1988); and Kwan and Melville (1994). Prototype spur dikes in many cases, however, have been designed to be overtopped regularly (e.g., Franco 1982; Burch et al. 1984; Shields et al. 1995b; Thompson 2002). Overtopping flow has the effect to significantly impact the nature of the vortices around the structure. The primary vortex gains an upward component in the lee of the spur dikes with overtopping flows. This leads to some significant differences in the geometry of scour holes of spur dikes with overtopping flows (Kuhnle et al. 1999). This study was designed to expand on a previous study (Kuhnle et al. 1999) to determine the best angle to minimize the

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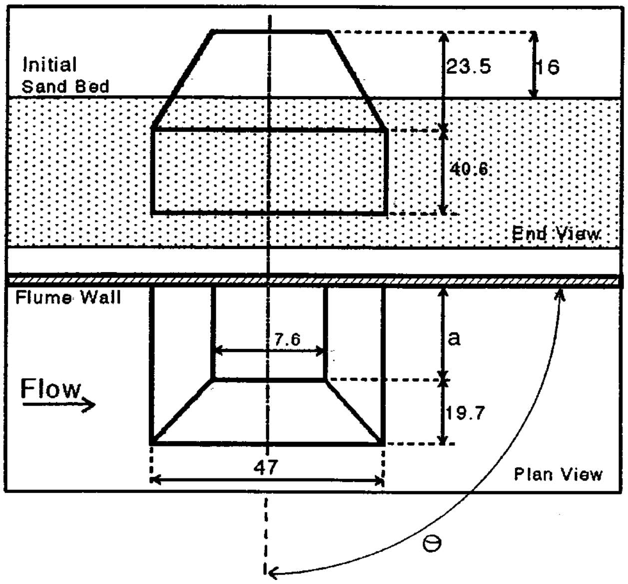

Fig. 1. Dimensions (cm) of model spur dikes used in experiments (not to scale). Length of spur dikes perpendicular to flow direction: (a) was either 0.152 or 0.305 m. Angle of spur dike to flow direction (θ) was 45, 90, or 135°.

potential of erosion of the channel bank and to maximize the volume of the scour hole for overtopping flows.

Experiments

All of the experiments were conducted in a flume located at the National Sedimentation Laboratory, Oxford, Miss. The flume channel is 30 m long, 1.2 m wide, 0.6 m deep, and is supported in the center at two points and on the ends by screw jacks which allow the channel slope to be adjusted. The model spur dike was located over a 3 m long, 1.2 m wide, by 1.2 m deep recessed section of the flume 22 m downstream from the inlet section. The recessed section was filled with sediment to allow for unimpeded development of the scour hole. Flow rate in the flume was measured using a pressure transducer connected to a Venturi meter in the return pipe. Flow depth was controlled by the volume of water in the flume and measured by taking the difference in elevation of 12 m long bed and water–surface transects in the approach section. A relatively uniform-sized sand covered 24.5 m of the channel bed in all of the experiments. The bed sediment had a median size of 0.8 mm and a geometric standard deviation ($\sigma_g = [D_{84}/D_{16}]^{1/2}$) of 1.37.

Model spur dikes with two contraction ratios and three angles were used in this study. The perpendicular distance from the channel sidewall to the center of the outer edge of the crest of the spur dike was either 0.305 or 0.152 m for the six model spur dikes (Fig. 1). All spur dikes had a height of 0.16 m from the original channel bed. The models were formed of concrete and had a similar shape except for the length of the crest which was 0.152 or 0.305 m for the 90° spur dikes and 0.215 or 0.431 m for the 45 and 135° models. The angle of the spur dike (θ) is defined as the angle between the downstream stream bank and the long axis of the dike (Fig. 1). All experiments except the four "Sld90" series had flow depths that were greater than the height of the spur dikes (Table 1).

Velocity profiles were collected with a 2 mm outside diameter total head tube mounted on a point gauge at the channel centerline, 15 m downstream of the inlet section. The stagnation pressure was measured with a pressure transducer and recorded using

Table 1. Experimental Conditions

Experimental run number	Flow rate ($m^3 s^{-1}$)	Flow depth (m)	Shear velocity (u_*) ($mm\ s^{-1}$)	Shear velocity ratio (u_*/u_{*c})	Maximum depth of scour at 1,800 min (m)	Volume of scour at 1,800 min (m^3)
L45-2	0.1236	0.3020	14.20	0.71	0.1899	0.10674
L45-3	0.0659	0.1860	14.59	0.73	0.2241	0.11380
S45-1	0.1263	0.3066	13.44	0.67	0.1668	0.06763
S45-2a	0.1499	0.3070	18.92	0.95	0.2669	0.18528
S45-3	0.0767	0.1845	17.36	0.87	0.2798	0.16672
S45-4	0.0644	0.1849	14.76	0.74	0.1716	0.05569
L90-2	0.0679	0.1856	15.08	0.76	0.2215	0.13573
L90-3	0.1383	0.3001	14.21	0.71	0.2568	0.19762
S90-1b	0.0765	0.1842	18.72	0.94	0.1545	0.09916
S90-2b	0.0661	0.1863	14.23	0.71	0.0929	0.02650
S90-3	0.1283	0.3023	13.05	0.65	0.1304	0.05247
S90-4	0.1544	0.3072	18.02	0.90	0.1620	0.10913
L135-7	0.0653	0.1828	14.26	0.71	0.2513	0.14302
S135-1	0.0786	0.1838	17.85	0.89	0.3005	0.20251
S135-2	0.0650	0.1840	13.51	0.68	0.1700	0.05435
S135-3	0.1272	0.3043	14.65	0.73	0.2092	0.09553
S135-4	0.1489	0.3046	18.65	0.93	0.2847	0.26037
S1d90-1	0.0346	0.0774	19.17	0.96	0.1984	0.10005
S1d90-2b	0.0253	0.0770	13.90	0.70	0.1000	0.01776
S1d90-3b	0.0380	0.1127	13.91	0.70	0.1348	0.04565
S1d90-4	0.0448	0.1121	16.96	0.85	0.1889	0.09890

Notes: The first letter of experimental run label indicates a contraction ratio of 0.125 (S) or a contraction ratio of 0.250 (L). The "1d" after the first letter indicates the experiments had depths less than the height of the spur dike. The angle of the spur dike is contained after the letter(s). Critical shear velocity of bed sediment $= 2.0\ cm\ s^{-1}$.

an analogue to digital board on a personal computer. Water-surface and bed-surface profiles were collected using two acoustic distance measurement devices, a remote measurement unit (RMU) which operates in air, and the SedBed Monitor, which operates underwater (Kuhnle and Derrow 1994). The SedBed Monitor and the RMU were accurate to within 0.5 and 1.0 mm, respectively. These measurement devices were mounted on an instrument carriage which traveled on steel rods over the channel. The instrument carriage was equipped with a precision computer-controlled three-axis positioning system which allowed transects of the scour hole to be automatically collected using the SedBed Monitor. To characterize a scour hole, 24 streamwise transects 3.6 m long were collected at 0.05 m intervals across the entire channel width. Distances to the bed were collected at 0.01 m intervals in the streamwise transects. Measurements of the scour surface required approximately 30 min and were taken at frequent (30 min) intervals in the beginning of an experimental run, and at longer intervals (60–90 min) as changes in the scour hole slowed.

The following procedure was used for each experimental run. Before the experiment with the spur dike model in place, the sediment bed surface was leveled with a scraper blade mounted on a carriage that rode on the steel rods. After the bed was completely wetted and drained, a profile of the bed surface was collected with the RMU. The flume was then filled with water to obtain the desired depth. Before the pump was started an initial set of transects of the anticipated scour region was collected. Next, the pump was started and the speed adjusted to obtain a bed shear velocity (u_*) of approximately 0.7 or 0.9 times the critical shear velocity for initiation of motion of the bed sediment (u_{*_c}) for the approach flow as predicted from a modified form of the Shields curve (Miller et al. 1977). These values were chosen to maintain conditions of clear water scour. The same rate of flow and approach depth were maintained for the entire experimental run. As soon as the flow rate in the channel was stable, transects of the scour region were begun, and a velocity profile was taken 15 m downstream of the inlet region at the channel centerline. Shear velocity (u_*) was calculated by fitting a least squares regression to flow velocity and distance measurements from near the bed to 20% of the flow depth using

$$u_* = \frac{d\overline{u}}{Ad(\log_{10} y)} \tag{1}$$

where $\overline{u}$=time-mean flow velocity at a distance y, from the bed and $A(=5.75)$=constant for uniform flows over rough, flat surfaces. At least ten measurements within the inertial turbulent zone (Coleman and Alonso 1983) were used for this calculation. Transects of the scour region were initially collected at 30 min intervals. This interval increased to 60 and 90 min as the experiment progressed and changes in the scour region became slower. The experiments were all continued for at least 1,800 min (30 h). This time length (1,800 min) was used as a practical time for comparison of the scour holes as the rate of change had decreased markedly.

Twenty-one experimental runs with six spur dike models are reported here (Table 1). The experiments were designed to vary the independent variables of bed shear velocity, flow depth, spur dike length, and spur dike angle. All experiments, except the four with the prefix "Sld" (Table 1), had water depths greater than the height of the crest of the spur dike (0.16 m above the original bed surface). In the experiments, the scour hole did not reach the far sidewall of the channel during the 1,800 min measurement period for all except two (S135-1, S45-2a) of the experiments. In the experiments in which the scour hole reached the far sidewall, no

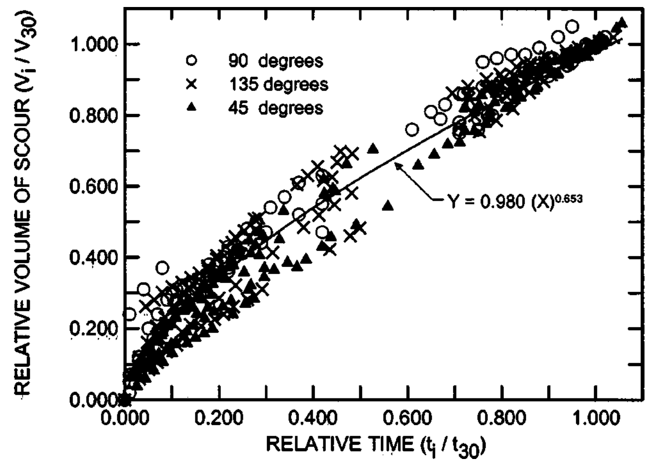

Fig. 2. Relative volume of scour versus relative time for all experiments of this study. V_{30} refers to volume of scour at a elapsed time of 30 h ($=t_{30}$).

significant changes in the rates of change of depth and volume were found after the wall was reached. On this basis, the effects of the far sidewall on the results of the experiments were assumed to be unimportant. The volume of the scour hole for each group of transects for each experimental run was calculated using Surfer from Golden Software. Volume calculations were judged to have errors of approximately 5%.

Results

The volume of the scour holes increased with time in a similar manner for all the experiments. The similarity of shape of the volume versus time relations is shown by plotting relative volume of scour against the relative time (Fig. 2). A power function was fit to the points plotted in Fig. 2

$$\frac{V_i}{V_{30}} = 0.980\left(\frac{t_i}{t_{30}}\right)^{0.653} \tag{2}$$

where V_i=volume of the scour hole at time i (t_i); and V_{30} and t_{30}=volume and time at an elapsed time of 30 h, respectively.

The shape and extent of the scour holes varied for the three different angles of spur dike used in the experimental runs (Fig. 3). To quantify the differences in the surface extent of the scour holes, dimensions as a ratio of spur dike dimensions were defined (Fig. 4) and are shown in Table 2. The width (a) and downstream (d) lengths of the scour holes were generally greater for the experiments with the 135 and 45° spur dikes as compared to the 90° spur dikes (Table 2). The distance from the left channel wall to the scour hole (b) was less for the experiments with 45° than for the experiments with 90 or 135° spur dikes. The upstream length (c) and the ratio of the volume of scour to the volume of the spur dike in most cases was higher for the 135° spur dikes than for the ones with 90 or 45° angles.

The potential for bank erosion in the vicinity of the spur dike varied for the three spur dike models (Fig. 3). An evaluation of potential bank erosion was made by considering the bed surface transects collected 25 mm from the left channel wall (i.e. the side with the landward end of the spur dike) at 30 h elapsed time. It was assumed that significant erosion of the bed near the bank would lead to bank erosion in a natural stream. A representative plot of near-wall bed surface transects for experimental runs with

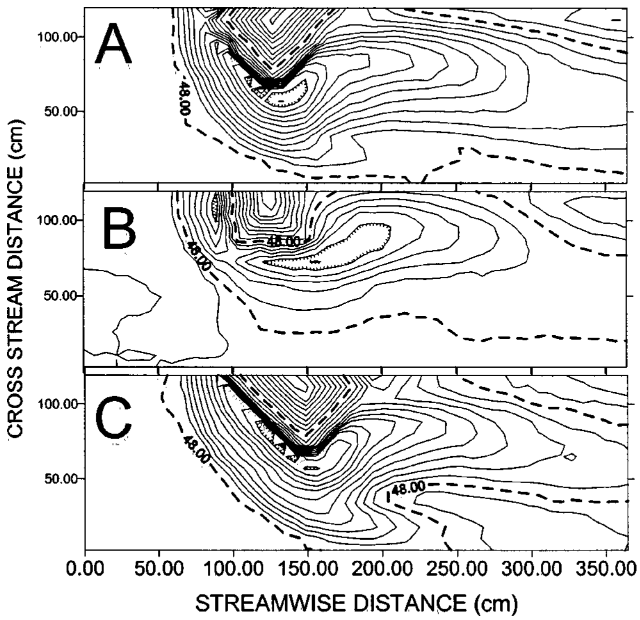

Fig. 3. Topographic maps of spur dikes and scour holes for experimental runs: (A) S135-4, $\theta=135°$, elapsed time (ET)=1,823 min; (B) S90-4, $\theta=90°$, ET=1925 min; (C) S45-2a, $\theta=45°$, ET =1,790 min. Elevations are in cm above bottom of recessed well. Initial bed elevation is approximated by 48 cm contour. Contour interval is 2 cm. Flow direction was from left to right.

the three angles of spur dike and nearly the same flow depths and shear velocity ratios is shown in Fig. 5. This indicates near bank bed scour was greatest for the 45° spur dikes. The excess scour in the 45° experiments tended to be concentrated downstream of the structure (Fig. 5). To quantify the erosion of the bed near the sidewall, a computer program was written to calculate the volume per unit length below the initial bed elevation using numerical integration. The calculated near-bank bed erosion for five groupings of experiments with similar flow depth and shear velocity are shown in Table 3. In all five groupings, the calculated near-bank bed erosion was greatest for the 45° spur dikes. The greater magnitude of near-bank bed erosion associated with the 45° spur dikes would be expected to lead to an increase in bank erosion and channel instability and be detrimental to aquatic habitat in a field situation. Spur dikes with angles of 90 and 135° would be expected to cause less bank stability problems than the 45° spur dikes, provided the channel was wide enough that the scour hole did not encroach on the opposite bank of the channel.

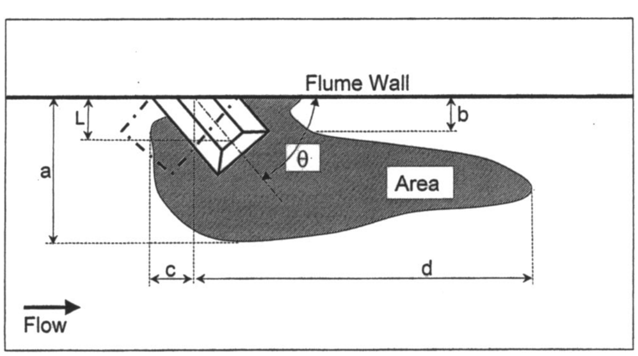

Fig. 4. Definition sketch for ratios in Table 2 (not to scale)

Table 2. Scour Hole Dimensions as Ratio of Spur Dike Dimensions. Edge of Scour Hole is Defined as 0.46 m Contour Line. Definition sketch is in Fig. 4

Experimental run number	L	a/L	b/L	c/L	d/L	V_{30}/V_{sp}
L45-2	0.305	3.4	0.0	1.0	4.1	4.6
L45-3	0.305	3.5	0.5	0.9	5.3	4.9
S45-1	0.152	5.5	0.0	3.2	8.1	4.9
S45-2a	0.152	7.6	0.0	4.8	15.8[a]	13.5
S45-3	0.152	7.0	0.0	3.5	14.7	12.2
S45-4	0.152	5.3	0.0	1.7	8.0	4.1
L90-2	0.305	4.0	0.7	2.3	5.7	7.7
L90-3	0.305	3.4	0.0	2.4	8.5[a]	11.2
S90-1b	0.152	5.4	0.5	3.9	9.2	9.1
S90-2b	0.152	4.0	1.0	3.0	6.3	2.4
S90-3	0.152	4.5	0.7	3.3	7.4	4.8
S90-4	0.152	5.4	0.0	3.8	11.1	10.0
L135-7	0.305	3.8	0.5	2.5	4.3	6.2
S135-1	0.152	7.5	0.1	4.6	12.3	14.8
S135-2	0.152	5.6	0.8	3.1	7.0	4.0
S135-3	0.152	6.3	0.7	4.0	8.8	7.0
S135-4	0.152	7.1	0.0	4.5	18.6[a]	19.0

Notes: Volumes of the spur dikes above the bed (V_{sp}) were as follows: $V_{sp}=0.0109\ m^3$ for the 0.152 m long 90° spur dike; $V_{sp}=0.0176\ m^3$ for the 0.305 m long 90° spur dike; $V_{sp}=0.0137\ m^3$ for the 0.152 m long 45 and 135° spur dikes; $V_{sp}=0.0231\ m^3$ for the 0.305 m long 45 and 135° spur dikes.

[a]Extrapolated beyond measurement area.

Depth of Scour and Spur Dike Alignment

Several researchers have conducted experiments documenting the effect of spur dike alignment on the depth of scour associated with abutments (see Melville and Coleman 2000, Fig. II-13). The general trend of the data of these studies summarized by Melville and Coleman (2000), is that the depth of scour increases by about 20% as the angle of the abutment is increased from 30 to 150°. Two studies (Kwan 1984; Kandasamy 1985), in contrast with the others, found that scour depth decreases for alignment angles

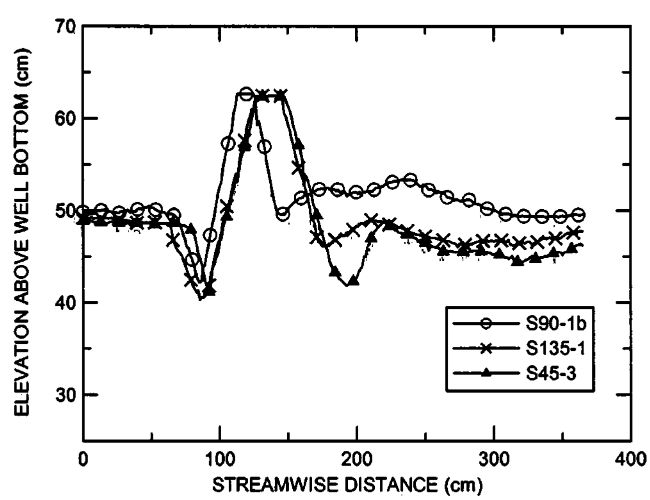

Fig. 5. Near bank (25 mm) bed surface transects for 0.18 m flow depth and shear velocity ratio=0.9. Every tenth point plotted with symbol.

Table 3. Near Bank Bed Erosion and Volume of Scour Hole

Experimental run number	Near bank bed erosion (cm^3/cm of bank)	Volume of scour at, 1800 min (m^3)
Flow depth = 0.18 – 0.19; shear velocity ratio = 0.7		
S90-2b	30.0	0.02650
S135-2	50.0	0.05435
S45-4	135.0	0.05569
Flow depth = 0.18; shear velocity ratio = 0.9		
S90-1b	147.0	0.09916
S135-1	582.0	0.20251
S45-3	702.0	0.16672
Flow depth = 0.30 – 0.31; shear velocity ratio = 0.7		
S90-3	187.0	0.05247
S135-3	131.0	0.09553
S45-1	304.0	0.06763
Flow depth = 0.30 – 0.31; shear velocity ratio = 0.9		
S90-4	802.0	0.10913
S135-4	534.0	0.26037
S45-2a	844.0	0.18528
Flow depth = 0.18 – 0.19; shear velocity ratio = 0.7		
L90-2	139.0	0.13573
L135-7	366.0	0.14302
L45-3	444.0	0.11380

greater than 90°. The relative change in depth of scour with alignment angle using the data reported by Melville and Coleman (2000) and the data from this study is shown in Fig. 6. All of the data used by Melville and Coleman (2000) was for intermediate ($1 < L/Y_\infty < 3$) or long abutments ($L/Y_\infty \geqslant 3$), while four of the five sets of data from this study (S1–S4) were for short spur dikes ($L/Y_\infty < 1$) with the other (L1) for an intermediate length ($L/Y_\infty = 1.7$). The scour depths from the intermediate spur dikes of this study follow closely the trends of the long structures. However, the short spur dikes show significantly larger scour depths for the 45 and 135° angles as compared to the 90° case (Fig. 6). This does not agree with the equations from Melville and Coleman (2000) that show the effect of alignment on scour depth decreases for intermediate abutments ($1 < L/Y_\infty < 3$) and disappears for short abutments ($L/Y_\infty \leqslant 1$). This discrepancy may result from the lack of data on short abutments, or alternatively may be due to the trapezoidal shapes of the spur dikes and the overtopping flows used in this study.

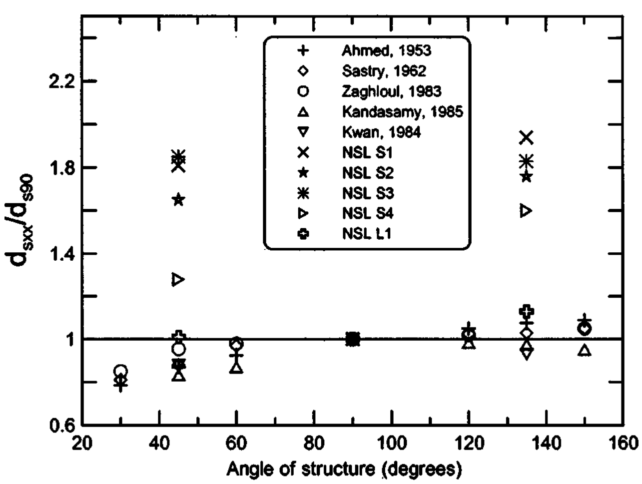

Fig. 6. Scour depth versus angle of structure. Scour depths for given angle (d_{sxx}) are scaled by depth of scour for structure with 90° angle (d_{s90}). L/Y_∞ ratios for the data from Melville and Coleman (2000) ranged from 2.7 to 16.2.

Table 4. Depth of Scour and Volume Prediction

Experimental run number	d_s calculated (Melville 1992)	Ratio d_s calculated/ d_{s30} measured	Ratio V_{30}, calculated/V_{30}, measured Eqs. (3), (4)
L45-2	0.431	2.27	3.25
L45-3	0.340	1.52	1.50
S45-1	0.203	1.22	0.54
S45-2a	0.288	1.08	0.56
S45-3	0.264	0.94	0.48
S45-4	0.225	1.31	0.89
L90-2	0.362	1.64	1.56
L90-3	0.430	1.67	1.69
S90-1b	0.286	1.86	2.27
S90-2b	0.216	2.32	4.54
S90-3	0.198	1.52	1.25
S90-4	0.274	1.69	1.72
L135-7	0.352	1.40	1.32
S135-1	0.270	0.90	0.42
S135-2	0.206	1.21	0.70
S135-3	0.222	1.06	0.50
S135-4	0.282	0.99	0.37
S1d90-1	0.208	1.05	0.39
S1d90-2b	0.151	1.51	0.84
S1d90-3b	0.183	1.36	0.58
S1d90-4	0.222	1.17	0.48

Depth of Scour Hole Prediction

Being able to predict the depth and volume of the scour hole associated with a spur dike for a given set of boundary conditions is a valuable tool for design of spur dikes and evaluation of potential effects on the aquatic habitat. Toward that end the relations of Melville (1992) were used to calculate the maximum depth of scour for each of the experimental runs of this investigation. The Melville relations were developed using laboratory data from several shapes of model bridge abutments and model spur dikes and are standardized to the threshold condition for the bed sediment. In all cases the flow depth of the water was less than the height of the model structures. These equations can be expressed by

$$\frac{d_s}{Y_\infty} = 2K_M \eta^{(1-\delta)} \tag{3}$$

where $\eta = L/Y_\infty$; $\delta(\eta \leqslant 1) = 0$; $\delta(1 < \eta < 25) = 1/2$; and $\delta(\eta \geqslant 25) = 1$. In these expressions, d_s = maximum scour depth; Y_∞ = depth of the approaching flow; L = length of the dike crest measured perpendicular to the flow; and K_M = composite empirical parameter representing several factors. K_M represents the effect of flow intensity, flow depth, sediment size, sediment gradation, abutment length, abutment shape and alignment, and approach flow geometry on the maximum depth of scour. Values of K_M used in this study were calculated as the product of the flow intensity variable (K_I) for which the shear velocity ratio was used, and the alignment variable of the dikes (K_θ), which was determined for the three angles using the relations of Melville (1992). The results of applying Eq. (3) to the experiments of this

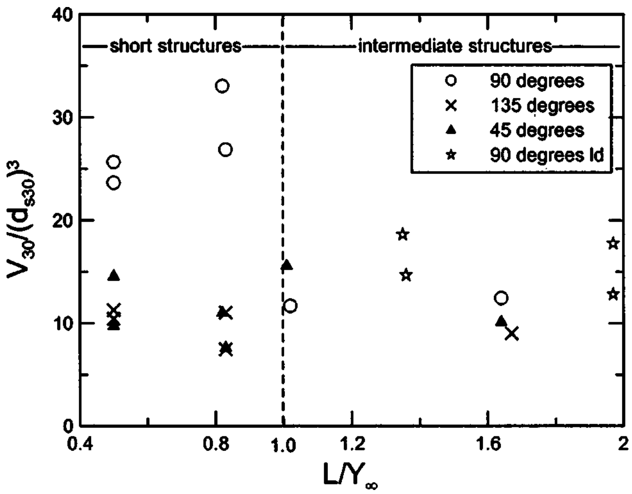

Fig. 7. Dimensionless volume at 30 h for all experiments. Ratios for all experiments tend to constant value of about 12, except S90 experiments

study are shown in Table 4. For most of the experiments of this study, Eq. (3) predicts a value greater than the measured one. Average values of the discrepancy ratio (predicted/measured scour depth) were 1.78, 1.39, 1.27, and 1.11, for the 90° with over-topping flows the 45°, the 90° with flow depths less than the spur dike height, and the 135° spur dikes, respectively. The mean discrepancy ratio for all of the experiments was 1.41. The reasons for the over prediction of the Melville (1992) equation are likely related to the fact that over-topping flows were used in all of the experimental runs of this study except for the ''ld'' series (Table 1). The discrepancy ratios for the ''1d'' series experiments were significantly lower than for the experiments conducted with the same model spur dike but with over topping flows. The remaining difference between the predicted and measured scour depths may be due to effects related to the shape of the model spur dikes and to the effect of the time to reach full equilibrium.

Volume of Scour Prediction

The ratio of the volume of scour to the cube of the maximum scour depth was found to be well represented by a constant value for most of the experimental data of this study (Fig. 7).

$$\frac{V_{30}}{(d_{s30})^3}=C \qquad (4)$$

With the exception of the four points from the S90 experiments, a value of $C=12.11$ does a reasonable job of representing the measured ratios of the volume of scour to the cube of the maximum scour depth (Table 4). The use of Eq. (3), with the constant changed from 2 to 1.41 to allow for the probable effect of over-topping flows, coupled with Eq. (4) can be used to predict the maximum depth of scour and volume of scour for spur dikes. The change in the volume of scour with time (up to 30 h) can also be calculated using Eq. (2). Due to the limited range of conditions used to develop this procedure [Eq. (2)–(4)], the range of applicability of this technique is unknown. This technique may be seen as providing information for a method to compare the relative volume of scour to be expected for different spur dike designs, not as a means to quantify the volume of scour expected.

Summary and Conclusions

Experiments were conducted to test three spur dike angles to determine the one which yielded the maximum volume of the associated scour hole and minimum potential for bank erosion. This would have the effect of maximizing the beneficial effects to aquatic habitats and still afford a reasonable degree of near bank protection. For the three angles of spur dikes and two contraction ratios considered in this study, spur dikes with 45° angles had the highest bed erosion in the vicinity of the channel bank, while 135 and 90° spur dikes split between intermediate to the lowest value for the five cases (Table 3). The volume of local scour was greatest in four out the five cases (Table 3) for the spur dikes with 135° angles. Thus for over-topping flows, and as long as the opposite bank is not threatened by the scour hole, the spur dikes with 135° angles were judged to be the best design of the three considered because the potential near-bank erosion was minimized, while the volume of scour was maximized. Significant differences in the trend of scour depth and alignment angle were found between the experiments of this study for short $(L/Y_\infty<1)$ spur dikes and the data for abutments presented by Melville and Coleman (2000). This discrepancy may have resulted from the lack of data available for angled short structures, or because the spur dike shape and overtopping flow used in this study were different from other studies considered by Melville and Coleman (2000).

Acknowledgment

The use of trade and company names is for the benefit of the reader; such use does not constitute an official endorsement or approval of any service or product by the U.S. Department of Agriculture to the exclusion of others that may be suitable.

Notation

The following symbols are used in this paper:

A = constant for velocity profiles (=5.75);
C = constant from Eq. (4);
D_{xx} = diameter of grain which is finer than xx%;
d_s = maximum depth of scour;
d_{sxx} = maximum depth of scour for structures with xx° angle to bank;
d_{s30} = maximum depth of scour at elapsed time of 30 h;
d_{s90} = maximum depth of scour for structures with 90° angle to bank;
K_I = parameter from relation of Melville (1992) to represent effect of flow intensity; K_θ=parameter from relation of Melville (1992) to represent effect of angle;
K_M = composite empirical parameter from relation of Melville (1992), which represents several factors;
L = length of dike crest measured perpendicular to flow direction;
t_i = elapsed time;
t_{30} = elapsed time of 30 h;
$\overline{u}$ = time mean flow velocity at given depth;
u_* = shear velocity;
u_{*c} = critical shear velocity for initiation of movement of bed material sediment;
V_i = volume of scour hole at ith time (t_i);
V_{sp} = volume of material contained in spur dike;

V_{30} = volume of scour hole at elapsed time of 30 h;
Y_∞ = depth of approaching flow;
y = distance above bed;
δ = variable whose value depends on η;
η = L/Y_∞;
θ = angle of spur dike measured from downstream bank; and
σ_g = standard deviation of bed material sediment.

References

Burch, C. W., Abell, P. R., Stevens, M. A., Dolan, R., Dawson, B., and Shields, F. D., Jr. (1984). ''Environmental guidelines for dike fields.'' *Tech. Rep. No. E-84-4*, U.S. Army Corps of Engineers, Environmental and Water Quality Operational Studies, Hydrologic Engineering Center, Davis, Calif.

Coleman, N. L., and Alonso, C. V. (1983). ''Two-dimensional channel flows over rough surfaces.'' *J. Hydraul. Eng.,* 109(2), 175–188.

Copeland, R. R. (1983). ''Bank protection techniques using spur dikes.'' *Miscellaneous Paper HL-83-1*, U.S. Army Engineer Waterways Experiment Station, Vicksburgh, Miss.

Franco, J. J. (1982). ''Summary report: Model-prototype comparison study of dike systems, Mississippi River.'' *Tech. Rep. No.* HL-82-11, U.S. Army Engineer Waterways Experiment Station, Vicksburg, Miss.

Garde, R. J., Subramanya, K., and Nambudripad, K. D. (1961). ''Study of scour around spur-dikes.'' *J. Hydraul. Div., Am. Soc. Civ. Eng.,* 87(HY6), 23–37.

Gill, M. A. (1972). ''Erosion of sand beds around spur dikes.'' *J. Hydraul. Div., Am. Soc. Civ. Eng.,* 98(HY9), 1587–1602.

Kandasamy, J. K. (1985). ''Local scour at skewed abutments.'' *Rep. No. 375*, School of Engineering, Univ. of Auckland, Auckland, New Zealand.

Klingeman, P. C., Kehe, S. M., and Owusu, Y. A. (1984). ''Streambank erosion protection and channel scour manipulation using rockfill dikes and gabions.'' *Rep. No. WRRI-98*, Water Resources Research Institute, Oregon State Univ., Corvallis, Ore.

Knight, S. S., and Cooper, C. M. (1991). ''Effects of bank protection on stream fishes.'' *Proc., 5th Federal Interagency Sedimentation Conf.*, Vol. 13, Subcommittee on Sedimentation of the Interagency Advisory Committee on Water Data, Las Vegas, Nev. 34–39.

Kuhnle, R. A., Alonso, C. V., and Shields, F. D., Jr., (1999). ''Geometry of scour holes associated with 90° spur dikes.'' *J. Hydraul. Eng.,* 125(9), 972–978.

Kuhnle, R. A., and Derrow, R. W., II (1994). ''Using the SedBed monitor to measure bed load.'' *Proc., Fundamentals and Advancements in Hydraulic Measurements and Experimentation*, ASCE, Buffalo, New York, 129–138.

Kwan, T. F. (1984). ''Study of abutment scour.'' *Rep. No. 328*, School of Engineering, Univ. of Auckland, Auckland, New Zealand.

Kwan, T. F. (1988). ''A study of abutment scour.'' *Rep. No. 451*, Dept. of Civil Engineering, Univ. of Auckland, Auckland, New Zealand.

Kwan, T. F., and Melville, B. W. (1994). ''Local scour and flow measurements at bridge abutments.'' *J. Hydraul. Res.,* 32(5), 661–673.

Melville, B. W. (1992). ''Local scour at bridge abutments.'' *J. Hydraul. Eng.,* 118(4), 615–631.

Melville, B. W. (1997). ''Pier and abutment scour: integrated approach.'' *J. Hydraul. Eng.,* 123(2), 125–136.

Melville, B. W., and Coleman, S. E. (2000). *Bridge scour,* Water Resources Publications, LLC, Highlands Ranch, Co.

Miller, M. C., McCave, I. N., and Komar, P. D. (1977). ''Threshold of sediment motion under unidirectional currents.'' *Sedimentology,* 24, 507–527.

Rajaratnam, N., and Nwachukwu, B. A. (1983a). ''Flow near groin-like structures.'' *J. Hydraul. Eng.,* 109(3), 463–480.

Rajaratnam, N., and Nwachukwu, B. A. (1983b). ''Erosion near groyne-like structures.'' *J. Hydraul. Res.,* 21(4), 277–287.

Raudkivi, A. J. (1990). ''Erosion and deposition.'' *Loose boundary hydraulics*, 3rd Ed., Chap. 9, Pergamon P, Oxford, U.K., 237–299.

Schlosser, I. J. (1987). ''A conceptual framework for fish communities in small warmwater streams.'' *Community and evolutionary ecology of north American stream fishes*, W. J. Mathews, and D. C. Heins, eds., University of Oklahoma Press, Norman, Okla, 17–24.

Shields, F. D., Jr., Cooper, C. M., and Knight, S. S. (1995b). ''Experiment in stream restoration.'' *J. Eng., ASCE*, 121(6), 494–502.

Shields, F. D., Jr., Cooper, C. M., and Testa, S. (1995a). ''Towards greener riprap: environmental considerations for micro- to macroscale.'' *River, coastal and shoreline protection: erosion control using riprap and armourstone*, C. R. Thorne, S. R. Abt, F. B. J. Barends, S. T. Maynord, and K. W. Pilarczyk, eds., Wiley, Chichester, U.K., 557–574.

Shields, F. D. Jr., Knight, S. S., and Cooper, C. M. (2000). ''Warmwater stream bank protection and fish habitat: a comparative study.'' *Environ. Manage. (N.Y.),* 26(3), 317–328.

Thompson, D. M. (2002). ''Channel-bed scour with high versus low deflectors.'' *J. Hydraul. Eng.*, 128(6), 640–643.