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STREAMBANK PROTECTION BY USE OF SPUR DIKES

BY

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ENGINEERING REPORT  
in partial fulfillment of  
MASTER OF SCIENCE DEGREE  
DEPARTMENT OF CIVIL ENGINEERING

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by

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ABSTRACT

The use of nearly-impermeable spur dikes made of rockfill and stone riprap as a bank protection technique is examined with a literature review, model study and field investigation.

The results of the literature review are summarized, including general design features, recommended spur dike orientation angles, spacing/length ratios and local scour prediction equations.

Local scour and streambed and streambank adjustments to a new spur dike field on the Willamette River, Oregon are documented. Flow patterns, current velocities and water depths in the dike field are reported. A scale-model study is used to evaluate several spur dike design parameters and to examine the prototype spur dike arrangement and several alternative arrangements.

The principal conclusions of the model study include: (1) the degree of bank protection provided by spur dikes is a function of the spur dike length, orientation angle and spacing; (2) as spur dike length increases, the protected distance downstream increases, but not proportionately with the increasing dike length; the model dikes could protect a bank from 2.5 to 4.5 times their own length; (3) upstream-oriented spur dikes are more efficient than downstream-oriented dikes in deflecting the river current away from the bank and thus provide bank protection farther downstream from the dike tip; and (4) upstream-oriented spur dikes cause more extensive scour holes than do downstream-oriented spur dikes.



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## 1. INTRODUCTION

This report describes the use of spur dikes as a bank protection technique at concave bends of meandering rivers. The spur dikes emphasized here involve nearly-impermeable rockfill structures. These extend outward from the bank into the river in order to prevent bank erosion and to manipulate river currents. The purpose of the report is to review spur dike design based on a comparison of available literature, a model study, and a prototype investigation.

The report is organized into six main sections. First, some important general aspects of bank erosion and erosion control are discussed. Second, the general features and effects of spur dikes are described. Third, the principles of spur dike use and design are presented, including the effectiveness of spur dikes. This section of the report is based upon a review of available literature. Fourth, the procedures and results are discussed for a model study conducted to evaluate several parameters relating to spur dike design and layout, including length and orientation angle. The model study involved a scale model of a Willamette River reach upstream of Corvallis, Oregon, where a field of eight spur dikes was constructed during the summer of 1983. Fifth, a field investigation of the spur dike field site was carried out during and after completion of the construction to determine the hydraulic affects of the spur dikes on river flow patterns and bed topography and for comparison with the model. Finally, a general comparison is made of the literature, model study and field study, together with conclusions.

## 11. GENERAL ASPECTS OF BANK EROSION AND EROSION CONTROL

### Bank Erosion

The United States has nearly 3.5 million miles of streams and rivers. The U.S. Army Corps of Engineers reports that streambank erosion is occurring on approximately 575,000 miles of these streams (24). Severe erosion is reported on two percent of the seven million bank-miles; these are in need of erosion protection. The total damage resulting from this erosion amounts to about \$250 million annually (based on 1981 figures) in losses of private and public lands, bridges, etc. The annual cost of conventional bank protection required to prevent the damage from occurring is estimated to be \$1.1 billion (24).

The removal of streambank soil particles by flowing water is one of the major mechanisms causing streambank erosion. Bank seepage provides a second important mechanism for erosion. The mechanics of streambank erosion are related to the geometry and hydraulic characteristics of the stream and to the types of sediment present.

The bends of meandering rivers are particularly significant locations for bank erosion. Figure 1 shows that the largest water velocities and deepest parts of the channel (i.e., the thalweg) in a bend shift close to the concave bank (the bank at the outside of the bend). During periods of extreme high water, the bar at the inside of the bend is more deeply covered and the largest water velocities shift closer to the convex bank, as shown in Figure 2. The most extensive streambank erosion generally occurs near the downstream end of a bend. Maximum velocities along the banks in several California rivers are reported to be as high as 1.8 times the average channel velocity (24).

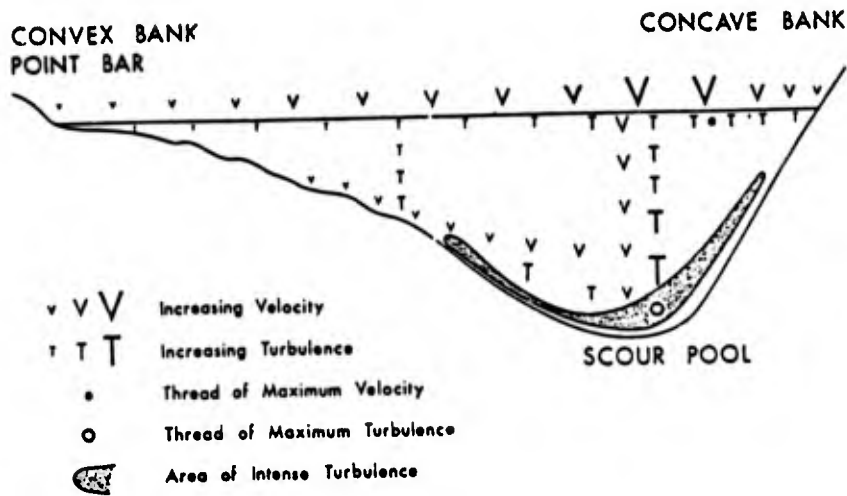


Figure 1. Velocity and Turbulence in a River Bend  
(Source: Reference 24)

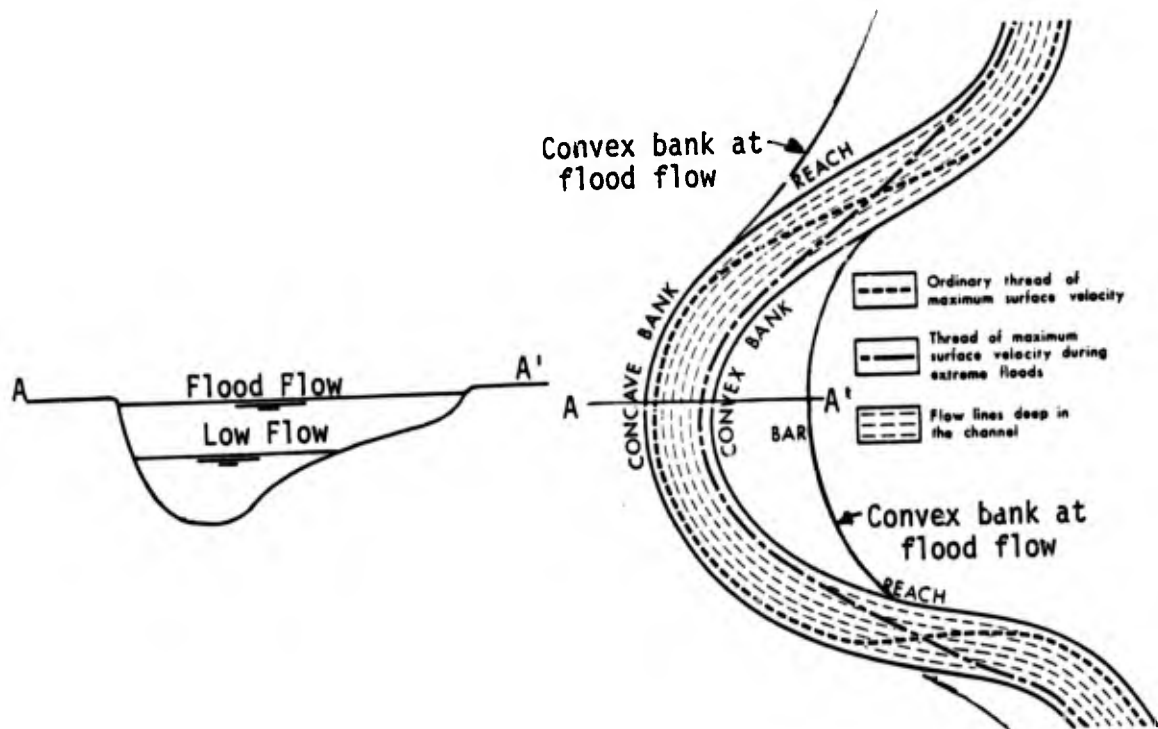


Figure 2. Paths of Maximum Surface Velocity During Normal and Flood Flows  
(Source: Adapted from Reference 24)

Meanders in alluvial rivers increase in size due to progressive erosion of concave banks of river bends. Non-uniform velocity distributions, secondary currents (crosswise to the main direction of the flow), sediment scour, and sediment redeposition also allow meanders to migrate downstream. Where general bank erosion occurs, the velocities may be well distributed. However, where the riverbank resistance to erosion increases or is variable, the flow tends to concentrate and develop locally greater velocities and depths.

### Erosion Control

The types of methods and structures used to stabilize streams vary widely and depend to a considerable extent on general experience and judgement. The state-of-the-art of streambank protection has not advanced significantly since 1950 (24). What has developed is the use of a group of methods that are favored by engineers, the most widely used being stone riprap, concrete pavement, articulated concrete mattresses, asphalt mix, jacks, vegetation, gabions, erosion control matting, bulkheads, and spur dikes.

The engineer uses basic hydraulic principles to design streambank protection structures. But because of the interrelated complex factors involved, many methods have evolved through a process of "trial and error" experience. Thus, theoretical and empirical techniques are available to determine the necessary particle size and weight to resist erosion caused by the shear or drag forces of flowing water. However, less is known about how to position various structures in the stream for most effective interaction with the flow to produce desired results; here, past experience is an important determinant of design methodology.

Streambank erosion and hydraulic conditions vary widely from one location to another. Engineering practice has been to solve each bank protection

problem independently. The development of generally applicable conclusions is difficult because of the differences in the various stream characteristics, including flow conditions, bed and bank material, and channel geometry. Even under similar erosive and hydraulic conditions, there is no single universally applicable method because of differing economic and logistic constraints, such as the availability of construction material and equipment.

### III. GENERAL FEATURES AND EFFECTS OF SPUR DIKES

#### General Features

All forms of streambank structures extending out from the bank and used for bank protection or channel current manipulation purposes, including dikes, groins and jetties, are commonly called spur dikes and are referred to as spur dikes in this report. The term "spur dike field" refers to the use of more than one dike, intermittently-spaced, at a site.

Spur dikes influence flow velocities and current patterns in a river. Spur dikes are an indirect method of bank protection, by means of which potentially eroding currents are deflected away from the bank or reduced in velocity. In contrast, direct protection methods physically isolate the bank from the eroding currents, such as by the use of a riprap revetment to blanket the bank with rock.

Spur dikes extend outward from the bank into the channel at an angle which need not be normal to the flow. Some dikes are straight (as seen in a plan view), whereas others are bent, such as "L" heads for which the outer tip turns downstream parallel to the streamflow or "J" heads for which the outer tip turns upstream or "T" heads for which outer tips turn both upstream and downstream.. Spur dikes may be constructed of various permanent materials, such as masonry, concrete, timber, earth or stone.

Spur dikes are of two principal types, permeable and impermeable. Impermeable dikes block and deflect the current away from a bank. Permeable dikes also deflect the flow but in addition slow the current passing through the dike, thereby inducing deposition of sediment in the lee of the dike near the bank. The accumulation of sediment behind a dike or between successive

dikes and the retardation of flow both cause the main channel to carry a larger proportion of the total discharge, with increased current strength and sediment transport capacity. As a result, a greater depth is maintained in the main channel. The permeable dike is most effective in a swift-flowing river carrying a substantial load of coarse sediment that can settle upon reaching a zone of reduced velocity. Timber piles are the basic component of most permeable dikes. Such dikes may also be rock-filled below some predetermined water level (e.g., low-flow level).

### Scour at Spur Dikes

Spur dikes directly influence flow velocities and patterns in a river. This has a significant effect upon sediment transport, general and local scour, and sediment deposition in the vicinity of the dike. The main current is shifted from near the bank to the center of a channel when spur dikes are built in a river bend. Channel depths must adjust to these new conditions. The effects sometimes carry downstream for some distance because of the new flow alignment due to the dike.

The obstruction caused by a spur dike generates an intense and complicated system of vortices. The primary vortex impinges on the bed immediately in front of the spur dike, erodes bed material, entrains the eroded material in the flow, and allows it to be carried away downstream by the main flow (3). Intermittent vortices of lesser strength occur along both the upstream and downstream faces of the dike, as shown in Figures 3 and 4. The deepest point of the main scour hole is located close to the tip of the spur dike. If the spur dike is oriented downstream, the primary vortex is deflected downstream and the main scour hole may be positioned some distance downstream of the dike tip (20). An upstream-oriented dike may cause greater scour than a downstream-oriented dike (2, 11, 19, 23).

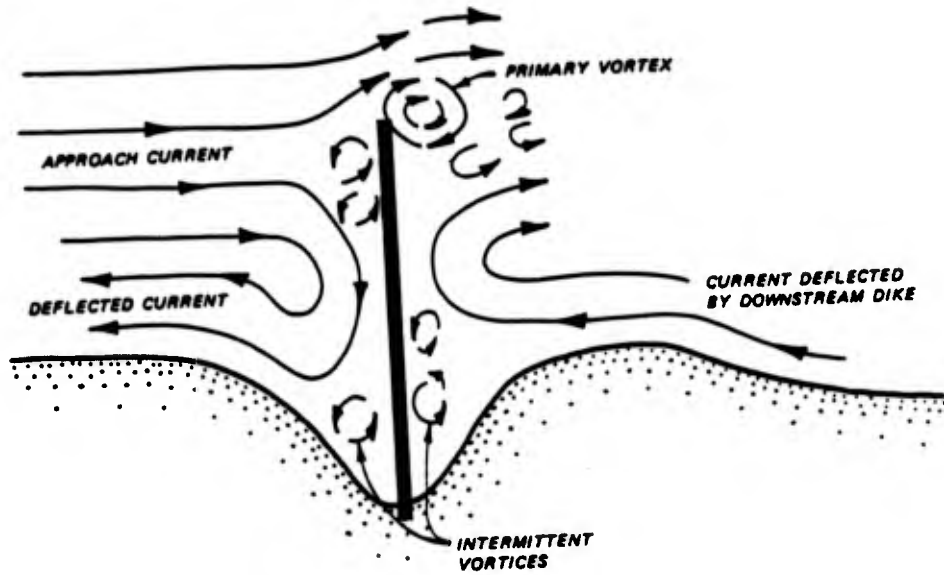


Figure 3. Plan View of Flow Patterns at a Spur Dike  
(Source: Reference 7)

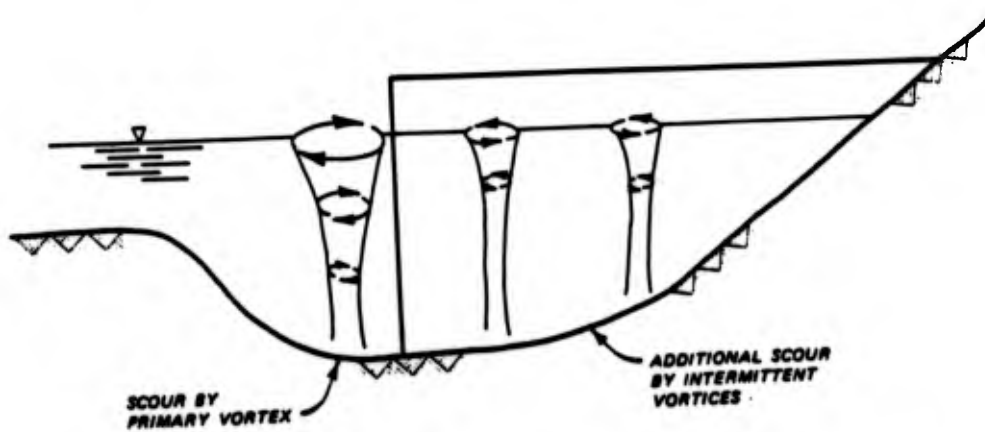


Figure 4. Front Profile of Scour Hole Along a Spur Dike  
(Source: Reference 7)

The size, depth, and extent of the scour hole generated by a spur dike and the angle of repose for bed material forming the sides of the scour hole are all of concern with respect to possible bank erosion in the vicinity of the dike. The anticipated scour adjacent to the spur dike is also of concern in dike design, so that the base elevation of the spur dike is set below that of the scour hole.

Much research has been done on scour depth at a dike. Samide (20), identifies several parameters that must be considered in order to determine the depth of scour. These include water parameters, channel flow parameters, dike parameters, and sediment parameters. These are shown in the following equation:

$$d_s = f(\rho_w, \mu, g, h, V, B, b, \theta, \beta, D_{50}, \sigma_{gd}, C, \rho_s) \dots \dots \dots (1)$$

In which  $d_s$  = limiting depth of scour below original bed level;  $\rho_w$  = specific density of water;  $\mu$  = absolute viscosity of water;  $g$  = acceleration due to gravity;  $h$  = average depth of flow in approach channel;  $V$  = average velocity in approach channel;  $B$  = average width of approach channel;  $b$  = average width of contracted channel;  $\theta$  = dike orientation angle,  $\beta$  = dike side-slope angle;  $D_{50}$  = median grain size of bed sediment;  $\sigma_{gd}$  = term describing the size gradation of bed sediment;  $C$  = sediment concentration by weight; and  $\rho_s$  = specific density of bed sediment. (All symbols used are listed in Appendix 2.)

Since river flows are highly turbulent when scour occurs, the effects of fluid viscosity can be neglected compared to inertial forces. Assuming  $h$ ,  $V$  and  $\rho_w$  as the repeating variables, a dimensional analysis yields:

$$\frac{d_s}{h} = f\left(\frac{gh}{v^2}, \frac{B}{h}, \frac{b}{h}, \theta, \beta, \frac{D_{50}}{h}, \sigma_{gd}, C, \frac{\rho_s}{\rho_w}\right) \dots \dots \dots (2a)$$

or, rearranging slightly,

$$\frac{d_s}{h} = f\left(\frac{V}{\sqrt{gh}}, \frac{B-b}{h}, \frac{b}{h}, \theta, \beta, \frac{D_{50}}{h}, \sigma_{gd}, C, \frac{\rho_s}{\rho_w}\right) \dots \dots \dots (2b)$$

This illustrates that the scour depth is related to the Froude number ( $F_n = \frac{V}{\sqrt{gh}}$ ), contraction ratio ( $\alpha = \frac{B-b}{h}$ ), sediment and sediment transport characteristics ( $D_{50}, \sigma_{gd}, C, \frac{\rho_s}{\rho_w}$ ), geometry of main channel flow at the dike ( $\frac{b}{h}$ ), and the spur dike itself ( $\theta, \beta$ ).

Garde et al. (11) also using dimensional analysis obtained:

$$\frac{D + d_s}{D} = f(F_n, \alpha, \theta, C_D) \dots \dots \dots (3)$$

In which  $D$  = average flow depth and  $C_D$  = the drag coefficient.

Investigators disagree as to which parameters are most important in determining scour depths at spur dikes. Early investigators considered the stream velocity and waterway contraction ratio to be the most significant factors. Laursen (14) maintained that the scour depth is primarily a function of the dike length and the upstream depth and is independent of the contraction ratio if sediment movement occurs upstream of the dike. Liu et al. (16) and Cunha (8) also determined that the contraction ratio was not important once sediment motion was established. However, Liu et al. considered velocity to be an important factor with or without sediment movement. Garde et al. (11) and Gill (12) determined that the contraction ratio was an important parameter. Gill reported that velocity was not an important factor, but Garde et al. stated that it was. There is also controversy regarding the importance of bed material size. Garde et al (11) and Gill (12) found grain size to be important while Laursen (14), Liu et al. (16) and Ahmad (3) did not believe it to be a major determinant of scour depth.

Several equations proposed for predicting scour depths at spur dikes are presented in Table 1. The equations are primarily based on laboratory testing of a single spur dike in a straight flume, with limited prototype verification. More prototype data are needed to resolve disagreements as to main prediction parameters and conflicting predictions given by the equations.

Table 1. Summary of Published Scour Depth Prediction Equations

1.	$y_s = k \left( \frac{Q}{F} \right)^{0.33}$ k varies between 0.8 and 1.8	Inglis (7)
2.	$y_s = k \left( \frac{q^2}{F b_0} \right)^{0.33}$ k varies between 2.0 and 2.75	Blench (5)
3.	$y_s = k(q)^{0.67}$	Ahmad (2)
4.	$\frac{h + d_s}{q^{2/3}} = 1.616 - 0.908 \left( \frac{2}{3} \right)^{15}$	Ahmad (2)
5.	$y_s = yK \left( \frac{B_1}{B^2} \right) (F_n)^n$	Garde et al. (11)
6.	$y_s = y + 1.1y \left( \frac{L}{4} \right)^{0.4} (F_n)^{0.33}$	Liu et al. (16)
7.	$y_s = 8.375y \left( \frac{D_{50}}{y} \right)^{0.25} \left( \frac{B_1}{B^2} \right)^{0.83}$	Gill (12)
8.	$\frac{L}{y} = 2.75 \left( \frac{y_s - y}{y} \right) \left( \left[ \frac{1}{r} \cdot \frac{(y_s - y)}{y} + 1 \right]^{1.70} - 1 \right)$	Laursen (14)
9.	$h + d_s = \frac{10.4 (S_{ing})^{1/4} (\cos \beta)^{1/2} U_m (hm)^{1/2}}{(1-m) \left( \frac{S}{85\%} \right)^{1/6} (1+0.09C) q^{1/2} (1+135F)^{3/2}}$	Mukhamedov et al. (19)
10.	$\frac{d_s}{s} = 0.30 + 1.60 \log_{10} \left( \frac{\tau_{ns}/N_{ns}}{\tau_{ns}^*/N_{ns}^*} \right)$ where $\frac{\tau_{ns}^*}{N_{ns}^*} = \frac{82.6 \tau_c}{(3.69m + 0.84)^2}$	Awazu (4)

See Appendix 2 for Definitions of Symbols

### Some Environmental Effects

Spur dikes impact the local environment encompassing the stream banks, streambed, and flow zone. These effects extend from a short distance upstream to several river widths downstream. Some impacts have already been described as part of the general behavior of spur dikes.

Spur dikes have local aesthetic impacts which vary with river level. Spur dikes have limited impact on upper bank vegetation; only minor land clearing is required for construction work and to anchor the dike root in the bank. The disturbed bank and the structure surface may be revegetated above the normal water level so as to blend into the natural surroundings. A short low-elevation overflow section can be included in the structure to allow some water to flow behind the structure and improve the riverine environment in the backwater area behind the structure. For some rivers, such areas have been identified by fish and wildlife biologists as a critical and scarce type of riverine aquatic habitat; the water warms up faster and submerged aquatic plants have a chance to become established.

### Cost Effectiveness

Recent (1981) costs of spur dikes are about \$26-\$65 per linear foot (24). This is greater than the unit cost for many other types of erosion control structures. However, spur dikes protect a downstream bankline length that is several times the length of the structure itself. Therefore, on the basis of cost per linear foot of protected bankline the overall cost is relatively favorable for spur dikes compared to other techniques.

#### IV. DESIGN OF SPUR DIKES

##### General Considerations

Although spur dikes are used extensively, there are no definitive hydraulic design criteria to follow. Design is based primarily on experience and judgement, due to the wide range of variables affecting the performance of the spur dikes. Parameters affecting spur dike design include channel width, water depth, water velocity, channel sinuosity, bed material size, sediment transport rate, bank cohesiveness, spur dike length, dike width, dike profile, dike orientation angle, and dike spacing if more than one dike is present (15).

Spur dikes must redirect the flow away from an erosion-prone bank. This affects flow patterns and sediment movement. Permeable dikes induce sediment deposition which helps redirect the flow. Impermeable dikes do not depend on sediment deposition to redirect the flows; they rely upon the reduced width of the river to alter flow conditions. Where the river is contracted by a new dike, the water slope and energy gradient initially become steeper and the velocity becomes greater, increasing the scour potential of the flow. The river may attempt to regain its original cross-sectional area through bank and bed erosion. But, if the dike and the opposite bank are stable, the main flow may only be able to scour out the river bed in order to increase the cross-sectional area and reduce the velocity and scour potential. The size and stability of the bed material will determine the extent to which this can occur. For flow contraction to continue along the entire length of a dike field, the dikes must be closely spaced or sediment deposition must occur between the dikes. The possible depth of main-channel scour caused by dikes and dike fields must be considered in spur dike design.

Spur dikes affect sediment deposition patterns (15). While most deposition occurs in the lee of permeable dikes, deposition in the vicinity of impermeable dikes and dike fields can also occur upstream of the dike because of greater flow retardation and decreased velocity. When impermeable dikes in a spur dike field are built to an elevation above the high water level, deposition between dikes can only occur if sediment is brought in by eddy action of currents from the main channel. When impermeable dikes are overtopped by water carrying coarse sediment, deposition can occur on and between the spur dikes, especially with L-head dikes. Unless the stream carries a large amount of coarse material in suspension when the water overtops impermeable dikes, the rate of such deposition will be slow. To increase this rate, it may be necessary to divert the bed load into the dike field. One way to accomplish this is by stepping-down the top elevation of successive dikes in a dike field, from upstream to downstream dike (15).

As an alternative to inducing deposition, it may be desired to prevent the area between dikes from accumulating sediment. For example, this might be desired so as to maintain a fish habitat there. In such cases, the spur dike elevations and L-heads may be designed to prevent overtopping and to allow eddy currents to keep the area scoured out.

#### Angle of Spur Dike to Bank

The orientation of a spur dike describes the direction the dike points into the flow from the bank where it is rooted. The orientation angle is defined as the angle between the downstream bank and the axis of the dike. There is considerable controversy as to whether spur dikes should be oriented upstream, perpendicular to the bank, or downstream (3, 7, 9, 11, 13, 15, 19,

23, 25). Proponents of upstream orientation claim that flow is repelled from dikes oriented upstream while flow is attracted to the bank by dikes oriented downstream. They also claim that sedimentation is more likely to occur behind spur dikes oriented upstream, so that less protection is required on the banks and on the upstream face of the dike. Proponents of downstream-oriented spur dikes claim that turbulence and scour depths are less at the end of a spur dike oriented downstream and that the smaller the orientation angle, the more the scour hole is angled away from the dike. They also claim that an upstream alignment promotes flow towards the base of the dike which endangers the integrity of the root of the dike and may cause a channel to form along the bank in the dike field and that debris and ice are less likely to accumulate on downstream oriented dikes.

Franco (10) tested dikes angled normal to the flow, 30 degrees upstream of normal, and 30 degrees downstream of normal. He rated the 30-degree downstream alignment best in performance (based on scour, deposition, channel depth and alignment). The upstream-angled dikes produced the least amount of scour but the scour area was greater, extending along the upstream face of the dike. Upstream dikes produced more disturbance to flow.

Copeland (7) recently determined that larger eddies are present on the upstream side of upstream-oriented spur dikes than of downstream-oriented spur dikes. This may afford some protection by displacing the currents away from the spur dike root. However, since scour depths are also greater for upstream-oriented spur dikes, the potential benefits of the upstream eddy may be cancelled out by the increased size of the scour hole. Copeland claims that the effective length of a dike (its projected length perpendicular to the bank) is a more significant factor than the spur dike angle, and dikes

should therefore be oriented perpendicular to the bank. Spur dikes placed at an orientation angle other than 90 degrees would cost more than dikes placed normal to the flow because of the greater required length, but they would also produce less disturbance.

It is often recommended to align spur dikes perpendicular to the flow direction rather than at any other angle because test results have been inconclusive to settle the dispute between upstream and downstream orientations.

The United Nations (25) several years ago recommended an orientation angle of between 100 and 120 degrees. More recently, the U.S. Army Corps of Engineers has generally oriented its spur dikes perpendicular to the bank or slightly downstream (15). Another practice has been to angle the first dike downstream and the remaining dikes normal to the flow. The trend among designers in selecting dike orientation appears to be shifting from upstream-oriented to downstream-oriented spur dikes.

Table 2 summarizes spur dike orientations that have been used in several geographic areas or recommended by different references.

#### Length and Spacing of Spur Dikes

The length of a spur dike is selected so that it is sufficient to shift the eroding current away from the bank. However, the dike length must not unduly restrict the channel and must not cause unacceptable velocities.

The spacing of spur dikes in a spur dike field has generally been based on the length of the spur dike. If the dikes are spaced too far apart, the current may return to the bank before reaching the zone of influence of the next dike; as a result, bank erosion may occur between the dikes and, if unchecked, may cause and the loss of the downstream dike. If the dikes are

Table 2. Recommended Spur Dike Orientation Angles

Recommended or Generally Used Angle of Dike to Bank*, In degrees	Reference
100-120	United Nations, 1953 (25)
100-120	Indian Central Board of Irrigation and Power, 1956 (6)
100-110	Mamak, Poland, 1964 (17)
Downstream	Lindner, 1969 (15)
Upstream	Neill, 1973 (7)
90	Richardson and Simons, 1973 (7)
70-90 (30 for sharp curves)	Alvarez, Mexico (7)
90 or downstream	U.S. Army Corps of Engineers, 1970 (7)
75	U.S. Army Corps of Engineers, Los Angeles District, 1980 (7)
90	U.S. Army Corps of Engineers, Memphis and Vicksburg Districts (7)
90 or downstream	Missouri River (15)
75-90	Red River, Arkansas River (15)
Downstream	Franco (10)
90	Copeland, U.S. Army Corps of Engineers, 1983 (7)

\*Measured from downstream bank line to major axis of spur dike.

spaced too close together, the dike field would be less efficient and more expensive in preventing bank erosion than a correctly designed system (20).

The spacing/length ratio of a spur dike field is a function of the river's approach velocity and discharge. As the spacing/length ratio increases, the effectiveness of the dike field to prevent bank erosion decreases. In the following discussion, length is taken to mean effective length (component of true dike length perpendicular to bank).

Spacing/length ratios have been developed largely from experience. The United Nations (25) states that it is general practice for spur dikes at convex banks to be spaced at 2 to 2 1/2 times the length and for spur dikes at concave banks to be spaced at a distance equal to the length of the dike. The United Nations also states that a larger ratio is used for a wide river than for a narrow one if both have similar discharges. According to Tiefenbrum (22), dikes on the middle Mississippi River were originally spaced at two times the dike length and are now designed to be about 1 1/2 times. Ahmad (2), based on model studies, gives spacing/length ratios of 4.29 for straight reaches and 5 for curved channels. A design manual used in India (6) recommends a spacing of 2 to 2 1/2 times the dike length. Mathes (18) states that a spacing ratio of 1 1/2 should be used and that values of 3/4 to 2 are generally used on European rivers. For rivers in New Zealand and Australia, Strom (21) gives spacing ratios ranging from 3 to 5. Acheson (1) gives ratios ranging from 3 to 4, depending on the degree of curvature. Some authors recommend that the spacing should not exceed the width of the open channel remaining between the dike tip and the opposite bank. Van Ornum (26) states that the European practice is to fix the spacing between half the width of the contracted channel and the full width; within this range,

typical spacing is about half the channel width at concave sections, seven-tenths of the width in straight sections, and approximately equal to the width at convex sections.

The recommended spacing/length ratios from different sources are presented in Table 3.

Copeland (7) describes six current and eddy patterns that develop between spur dikes as the spacing/length ratio between them increases. These are presented in Figure 5, where for convenience the dike length is varied and the dike root spacing is kept constant. The type 1 and type 2 dikes have a small ratio, types 3 and 4 have an intermediate ratio, and types 5 and 6 have the largest ratio.

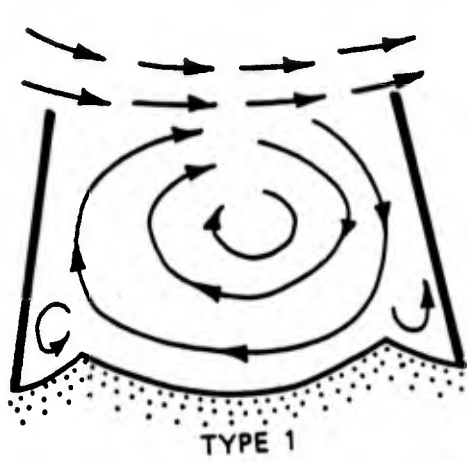
In the type 1 field, the main current is deflected outside the spur dike field and maintains a continuous deep channel there. In the type 2 field a second eddy appears but the main current is still deflected outside the spur dike field. In the type 3 field the main current is directed at the spur dike itself, creating a stronger eddy behind the dike and greater turbulence along the upstream face and lower tip. In the type 4 field, a single strong reverse current develops and the stability afforded to the upstream dike is washed out. In the type 5 field the flow diverted by the upstream spur dike is directed to the bank between the dikes and eddies form on both sides of the flow, providing some protection to the bank. In the type 6 field, the current attacks the bank directly, as the downstream eddy no longer provides protection to the bank.

#### Spur Dike Configuration

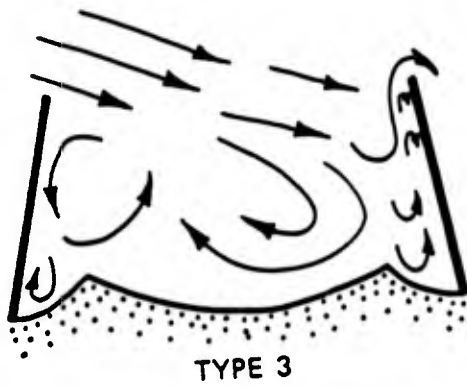
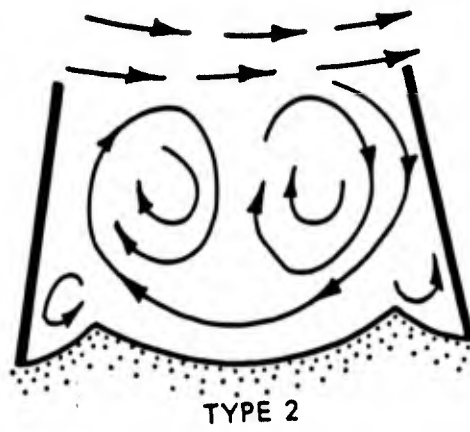
Spur dikes often include segments built at different alignments than is the main portion of the dike. Such configurations include L-head dikes, J-head dikes, and T-head dikes.

Table 3. Recommended Spur Dike Spacing/Length Ratios

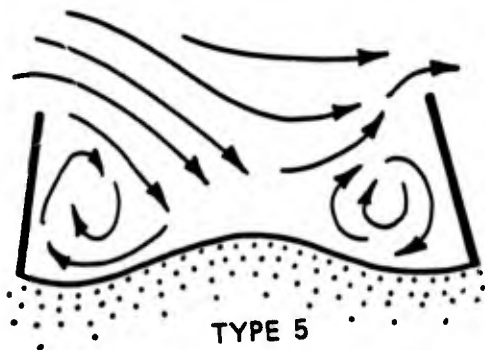
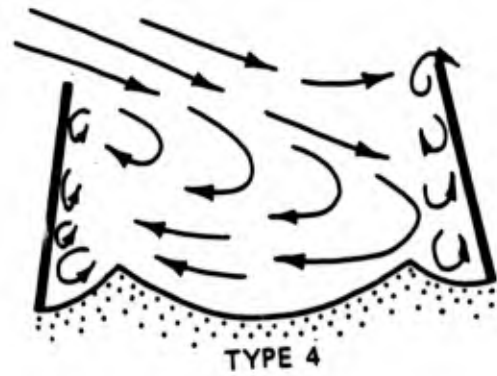
Spacing/Length Ratio	Type of Bank	Reference	Comment
1	Concave	United Nations, 1953 (25)	General practice
2 to 2.5	Convex	United Nations, 1953 (25)	General practice
4 to 6	Concave	Richardson and Simons, 1973 (7)	Bank may need riprap
3	Concave	Grant, 1948 (7)	
5.1 to 6	Straight	Alvarez (7)	
2.5 to 4	Curves	Alvarez (7)	
2 to 2.5		CBIP, 1956 (6)	
1.5	Concave	Los Angeles, District, 1980 (7)	Levee protection with riprap
2.0	Straight	Los Angeles, District, 1980 (7)	
2.5	Convex	Los Angeles, District, 1980 (7)	
2		Neill, 1973 (7)	
4		Neill, 1973 (7)	
3 to 5		Strom, 1941 (21)	
2 to 2 1/2		Indian Design Manual (6)	
2		U.S. Army (20)	
1 1/2		Mathes, 1956 (18)	
3 to 4		Acheson, 1968 (1)	
2 to 2 1/2	Convex	Bandegom (20)	
1.0	Concave	Bandegom (20)	
4.29	Straight	Ahmad, 1951 (2)	
5	Curved	Ahmad, 1951 (2)	
			If two or more dikes



MAIN CURRENT DEFLECTED OUTSIDE SPUR DIKE FIELD



MAIN CURRENT DIRECTED AT DIKE



MAIN CURRENT DIRECTED AT BANK

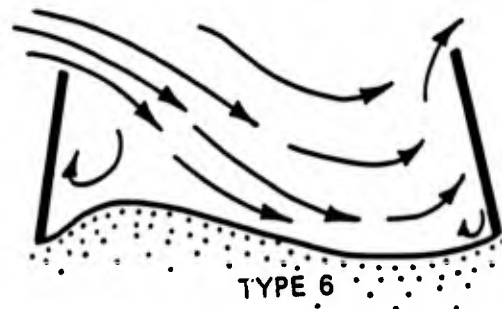


Figure 5. Effect of Spur Dike Spacing/Length Ratio on Current and Eddy Patterns  
(Source: Reference 7)

The L-head structure was developed on the Missouri River to improve protection of the concave banks of curves over that provided by straight spur dikes (15). The L-head has a downstream-angled segment added to the end of a straight spur dike. This segment is usually parallel to the channel.

Franco (10) performed tests with the length of the L-head equal to half the distance between the ends of adjacent dikes. He found that the L-head tended to prevent sediment-carrying bottom currents from moving into the areas between the dikes. Also, flow over the top of an L-head segment which is lower than the main spur dike tended to produce scour along the landward face of that section of the dike. Maximum scour at the ends of the dikes was reduced appreciably as was the elevation of deposition between the spur dikes. L-heads reduce scour at the end of the dike, reduce eddy disturbances and cause the flow contraction to persist continuously along the dike system, thus producing a more uniform bed configuration and consistent depths.

In a series of tests by Lindner (15) it was determined that the L-head should close 45 to 65 percent of the gap between dikes in a spur dike field. He also showed that little benefit was gained from building the L-head above the water surface. His results indicate that the L-heads provided protection to the bank, increased deposition between the dikes, and decreased the scour around the ends of the spur dike. Variations in the river curvature and spacing of the spur dikes would call for corresponding variations of the percentage of closure of the gaps for optimum results. Any degree of closure will give added protection to the concave bank, when compared with no closure at all.

The L-head dike possesses advantages over straight dikes when installed to protect a bank that is caving as a result of the impingement of the current. At such locations, spur dikes should either be angled downstream or be built with L-heads.

Dikes having the head segment pointing upstream are called J-head dikes. T-head dikes have segments pointing both upstream and downstream. J-head dikes and the upstream leg of T-head dikes are reported to have the same disadvantages as a dike angled upstream (15). Other shapes such as hockey-stick shapes are simply variations of the L or J-head. There has not been sufficient investigation of these various shapes to ascertain whether they offer any advantages over the L-head. It is believed that the J-head and T-head would possess disadvantages over the L-head and that their use would be unwise; but if used, the upstream leg should not be as high as the straight section of the spur dikes.

#### Elevation of Spur Dike Crest

The general practice in design of spur dikes in a dike field has been to place all dike crests at about the same height with respect to low water level. However, the crest or crown of a dike need not be horizontal. There are often situations where a variable-height crown is advantageous.

The height of the spur dike crest with respect to the water surface depends upon the effect desired of the dike upon the flow. The sloping-crown or stepped-down crown, in which the dike crown slopes downward or is stepped downward from the bank towards the channel, appears to have an advantage where mid-channel shoal erosion is needed over a wide range of stages but where a gradually diminishing channel contraction with increasing stage will suffice. Such a crown design may be required where a level-crown spur dike would produce objectionable velocities as the stage rises. Even if high velocities were not a concern, if the sloping or stepped down spur dike can produce the shoal erosion desired, it often will be less costly to build than a level crown dike (15).

Stepped-down crown spur dikes are used on the middle Mississippi River and on portions of the lower Mississippi to control meander patterns and to provide the varying degrees of contraction required. The dikes are designed to control and contract stages at mid-bank discharge. They are stepped down for an additional length to confine the low-water channel.

Where deposition of sediment in a dike field is required, the stepping down of the crowns progressively from one dike to the next may be advantageous to cause a continuous and comparatively uniform contractional effect along the entire dike field (15). By the stepped-down arrangement, bed load material moving in the channel beyond the spur dikes is diverted into the spur dike field during stages which overtop progressively each of the dikes from the downstream to upstream spur dike. The flow pattern associated with stepped-down dikes is shown in Figure 6. Flow from the channel moves around the end of the high dike into the area behind it and towards the next lower dike. The faster-moving surface currents continue in a relatively straight line while the slower sediment-carrying bottom currents move into the dike field. For this arrangement to be the most effective, the downstream dike of any two successive dikes should be overtopped for a sufficient length of time before the next upstream dike is overtopped so that there will be enough time for bed load to be diverted to the area between the two dikes.

Franco (10) concluded that stepped-down spur dike fields are more effective than fields with all dikes level and that level dike fields are more effective than stepped-up fields (see Figure 6). He also says that level-crested dikes should be placed normal to the flow or oriented downstream and sloping crested dikes should be normal to the flow or oriented upstream. The reduction in shoaling is almost directly proportional to the

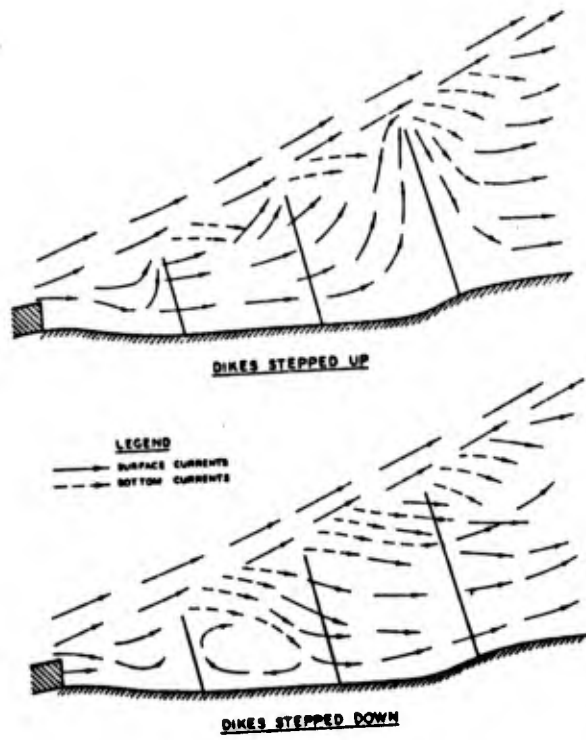


Figure 6. Currents Through Dike Field  
 (Source: Reference 10)

elevation of the dikes. The area downstream of the dikes covered by deposition generally increases in size with a decrease in dike elevation. Franco found that dikes placed normal to the flow were the most effective in reducing the amount of shoaling. The angle of the dikes is therefore related to the elevation of the dikes. In a stepped-up spur dike field where each successive downstream dike is higher, at least some of the flow over the top of the lower dike must move towards the channel, producing disturbances because of its direction. The flow also tends to prevent sediment-carrying bottom currents from moving into the area between the dikes.

#### Spur Dike Side Slopes and Root

The side slope of the spur dike at its head end affects the scour near the head. With a flatter head, the base of the dike tip extends farther away from the exposed crown. Hence, the scour hole will be more distant from the head and will be longer and shallower (20). Tison (23) tested trapezoidal-shaped dikes and found that a sloped head reduced the diving motion of the water near the upstream face and reduced the scour depth. Mamak (17) suggests using a head slope of 3:1 or flatter, up to 5:1. Mukhamedov (19), in calculating scour, uses a factor  $K_{\beta} = (\cos\beta)^{\frac{1}{2}}$  to take into account the effects of varying dike head slope, where  $\beta$  is the angle between the sloping side of the dike and the vertical plane.

For the main body of the dike, it has been recommended that the upstream face be inclined at a slope of 1.5:1 to 3:1, and that the downstream face have a slope of 2:1 to 4:1 (20).

The root of a spur dike must be protected against the risk of flood waters cutting into the bank around the main body of the dike. Mamak (17) recommends that the root be embedded into the bank 4 to 10 meters. He also recommends that short bank revetments be constructed on each side of the root.

### Spur Dike Location in River Reach

The location within the river reach at which the spur dikes should be placed is ultimately determined by the location of the erosion area and by appropriate dike spacing ratios. Water velocity and shear distributions within the stream should also be considered when placing dikes (20). For the positioning of dikes along the outside of a meander loop, Varshney (27) recommends that single dikes be placed at 0.55 of the loop length, that if two dikes are used they be placed at 0.5 and 0.6 of the loop length, and that the 0.4, 0.5 and 0.65 positions be used for a field of three dikes.

When a dike field is to be placed upstream of a bridge crossing, Blench (5) recommends that the first dike upstream of the bridge be placed at 0.4 of the loop length.

## V. MODEL STUDY OF SPUR DIKES

### Purpose

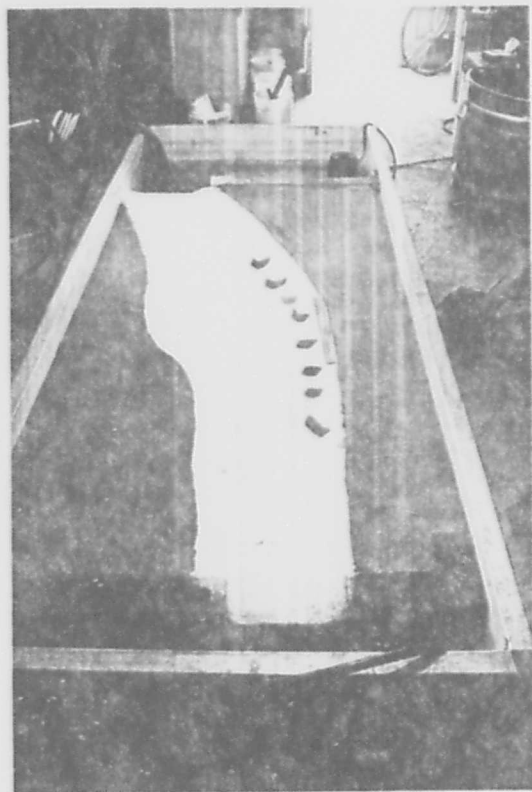
The general purpose of the scale-model study was to qualitatively investigate scour patterns and the degree of bank protection resulting from various spur dike configurations and arrangements, including that of the prototype spur dike field. Several design parameters were tested and evaluated, such as spur dike length, shape, orientation angle and spacing between dikes.

### Experimental Equipment

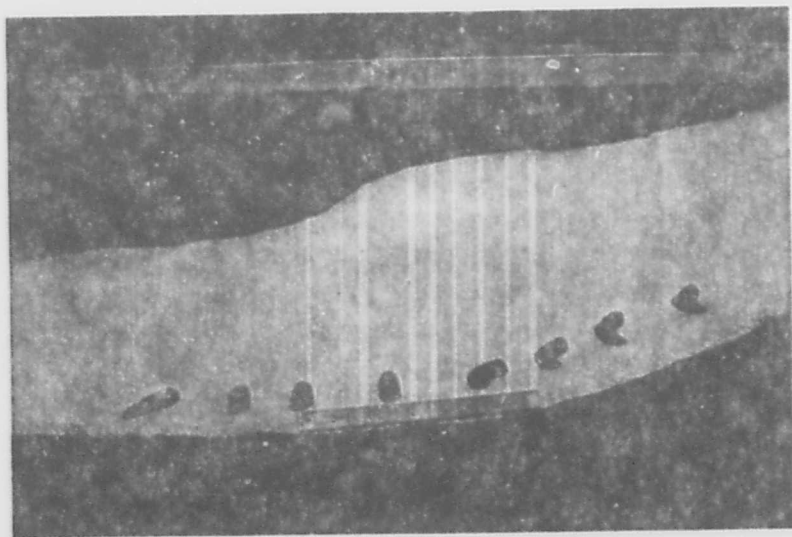
The model tests were conducted in a sand-filled steel tank 7 feet long, 4 feet wide and 1.7 feet high. A Willamette River reach having a new spur dike field was molded in the sand. The Froude number (ratio of inertial to gravitational forces) formed the basis for open channel modeling and for scaling various parameters between the prototype and model. A horizontal scaling ratio of 600:1 was selected, based upon the space available. A vertical scaling ratio of 200:1 was used. This vertical distortion allowed prototype turbulence to be simulated in the model. The molded sand was covered with a layer of cement approximately 1/4" thick and sprinkled with a fine layer of plaster of Paris. Spur dike models were formed from modeling clay using the same scaling ratios as for the river model. Water was supplied from a recirculating pump and was passed through an entrance box and a baffle to distribute the flow uniformly over the width of the model river bed. The model is shown in Figure 7.

### Experimental Procedures

To conduct each experimental test, spur dikes were first placed in the model in the desired arrangement and at the desired locations. Dry sand was



A. Looking Downstream



B. Looking Across the Channel (flow from left to right)

Figure 7. Scale Model of Willamette River Reach  
With Prototype Spur Dike Arrangement

then sprinkled over the model bed and banks using a sieve with a mesh spacing equal to 0.59 mm (i.e., sand finer than 0.59 mm was used) until a uniform depth of approximately 1/8" was obtained. This sand was used to detect scour patterns due to the flow. Water was then allowed to flow in the channel for about five minutes. This was sufficient time for bank erosion and scour to occur and scour patterns around the spur dikes to become relatively stable. A discharge of about 0.03 cfs was used for each test, equivalent to a prototype discharge of 50,000 cfs. At the end of each experimental run, the scour and bank erosion patterns were recorded. During several runs, red dye was introduced at the entrance box so that eddy currents around the spur dikes could be recorded.

Experimental runs 1 through 12 were conducted in the straight section of the river reach upstream from the prototype spur dike field. The tests were done to determine the relative ability of single dikes of varying length and orientation angle to deflect the main river current away from the bank and protect it from erosion. After each run, the distances downstream from the spur dike to the points where the main current returned to the bank and where bank erosion began to occur were measured and recorded.

Experimental runs 13 through 33 were conducted in the concave section of the river reach. Various combinations of spur dike shapes, lengths, orientation angles and arrangements were tested. The resulting scour and bank erosion patterns were recorded.

Experimental runs 34 through 37 were conducted using the entire river reach. The prototype spur dike field arrangement was tested in run 34 in order to obtain scour patterns for comparison with those obtained from the field study. Several modifications of the prototype arrangement were also tested. Run 37 was a control run conducted with no dikes.

## Experimental Results

Table 4 summarizes the test conditions used for each experimental run. The effective dike length is used. This is the component of total dike length measured perpendicular to the bank from the base to the tip of the dike and is equal to the true dike length along its axis times the sine of the dike orientation angle between the downstream bank line and the axis of the dike. For L-head, J-head, and T-head dikes, the length of the main body of the dike, from base to point of dike axis alignment change, is used in this calculation.

Figure 8 shows the scour patterns obtained during the test of the prototype arrangement in run 34. Scour patterns and bank protection patterns were recorded for each of the runs. Results are presented in Figures 9-15.

Figure 9 presents model test results from runs 1-12 showing the distance downstream that the main current is deflected by a dike before again impinging against the bank, based on various dike lengths and orientation angles. This distance is  $X_2$  when measured from the dike base and is  $X_4$  when measured from the dike tip. For dikes with 90-degree orientation angles,  $X_2 = X_4$ . Figure 9 also shows the distance downstream that the bank is protected from erosion, being  $X_1$  as measured from the dike base and  $X_3$  as measured from the dike tip. (For 90-degree dikes,  $X_1 = X_3$ .) The effective dike length  $L$  (perpendicular distance from bank to dike tip) is shown as a fraction of the uncontracted channel width  $W$ .

Figure 10 presents model test results from runs 13-21 showing the scour patterns associated with single dikes at various  $L/W$  ratios and orientation angles. The dimensions of the scour area are shown lengthwise and crosswise at prototype scale and the scour area is given in units of square inches as measured in the model. To convert scour area to square feet, the model

Table 4. Summary of Model Test Conditions

A. Experiments Using Straight Section of River Reach:

Run	L/W	$\theta$	Run	L/W	$\theta$	Run	L/W	$\theta$
1	1/6	90	5	1/6	45	9	1/6	135
2	1/4	90	6	1/4	45	10	1/4	135
3	1/3	90	7	1/3	45	11	1/3	135
4	1/2	90	8	1/2	45	12	1/2	135

B. Experiments Using Concave Section of River Reach:

Run	L/W	$\theta$	Number of Dikes	Dike Spacing	Dike Shape
13	1/2	90	1		Straight
14	1/2	120	1		Straight
15	1/2	60	1		Straight
16	1/4	30	1		Straight
17	1/4	60	1		Straight
18	1/4	90	1		Straight
19	1/4	120	1		Straight
20	1/4	150	1		Straight
21	1/6	90	1		Straight
22	1/4	90	2	L	Straight
23	1/4	90	2	2L	Straight
24	1/4	90	3	2L	Straight
25	1/4	90	1		L-head
26	1/4	90	1		J-head
27	1/4	90	1		T-head
28	1/2	90	1		L-head
29	1/2	90	1		J-head
30	1/4	90	2	2L	L-head
31	1/4	90	1		Straight (submerged)
32	1/4	90	1		Straight (sloping)
33	1/3	$\theta_1 = 45$ $\theta_2 = 90$	2	2L	Straight

C. Experiments Using Entire River Reach:

Run	Description
34	Prototype arrangement (8 dikes)
35	Prototype arrangement with dikes 2, 3, & 6 removed (5 dikes remaining)
36	Prototype arrangement with dikes 2, 3, 4, 6, 7 removed (3 dikes remaining)
37	Control test - no dikes

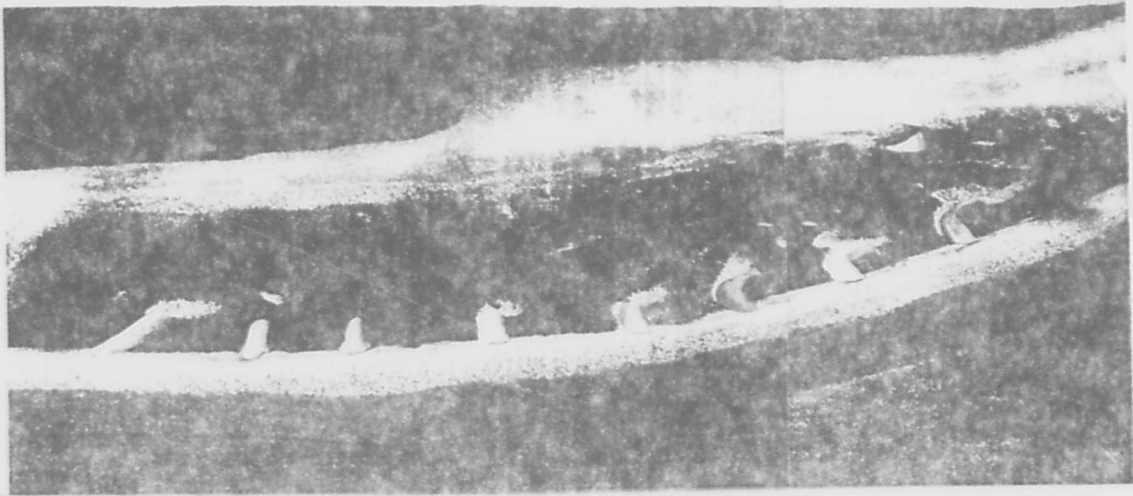
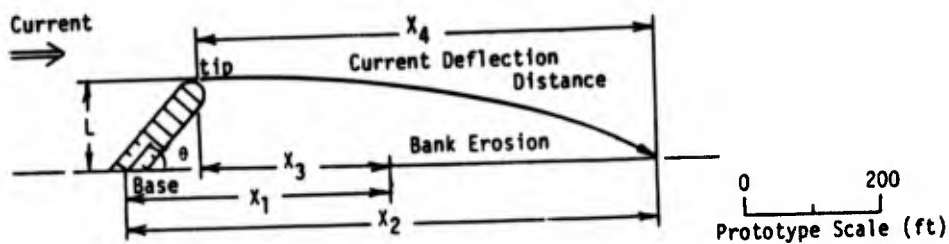
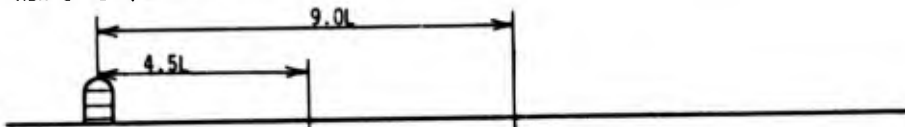


Figure 8. Example of Scour Patterns Around Prototype Spur Dikes in Scale Model Tests (Experimental Run 34)

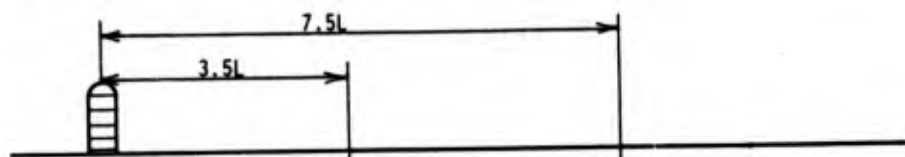
Definition Sketch for Runs 1-12



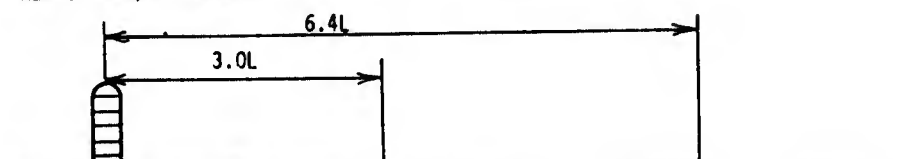
Run 1  $L=W/6$   $\theta=90^\circ$



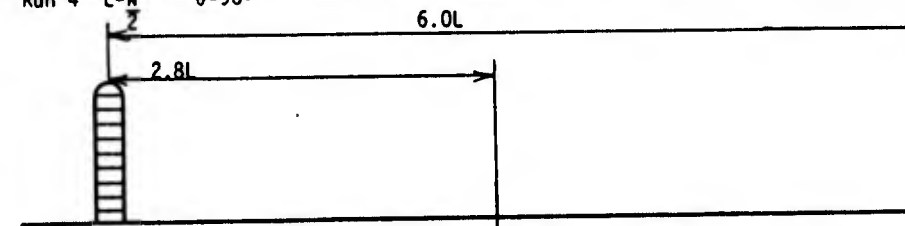
Run 2  $L=W/4$   $\theta=90^\circ$



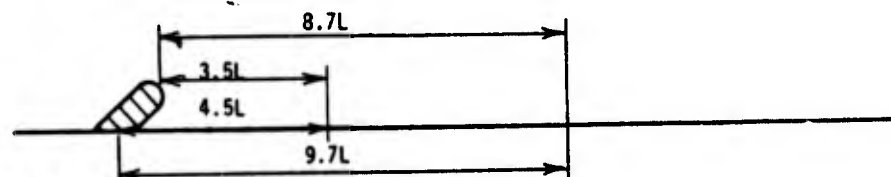
Run 3  $L=W/3$   $\theta=90^\circ$



Run 4  $L=W$   $\theta=90^\circ$



Run 5  $L=W/6$   $\theta=45^\circ$



Run 6  $L=W/4$   $\theta=45^\circ$

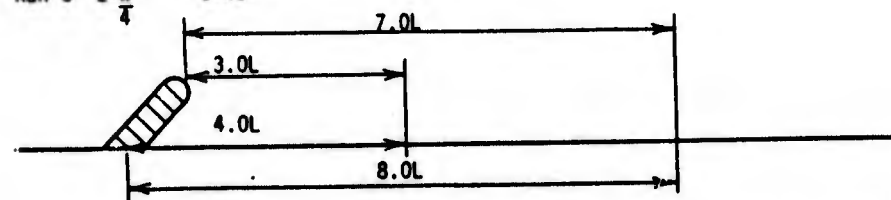


Figure 9. Model Test Results Showing Current Deflection and Bank Protection Distances (Runs 1-12)

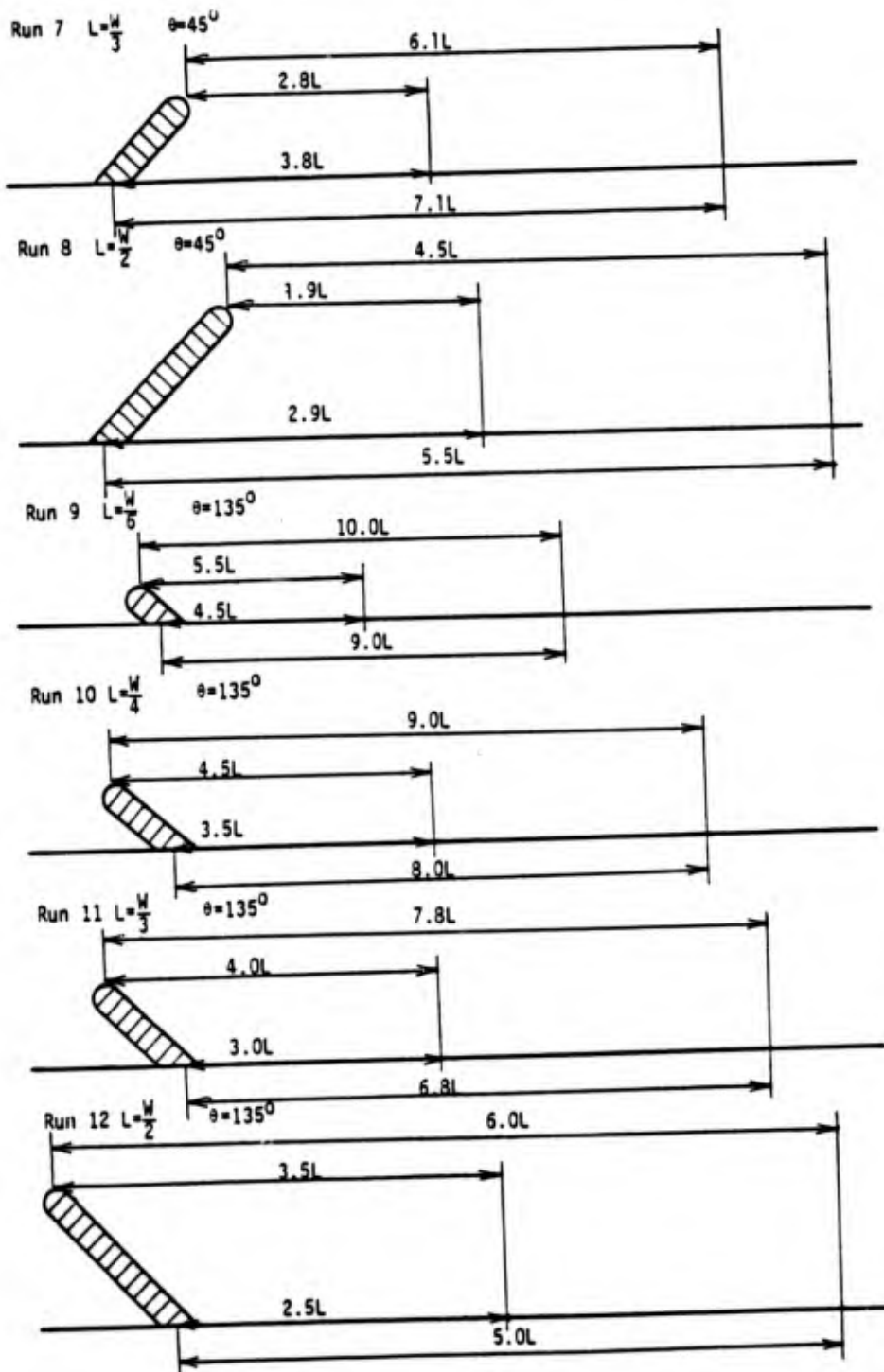


Figure 9. Continued

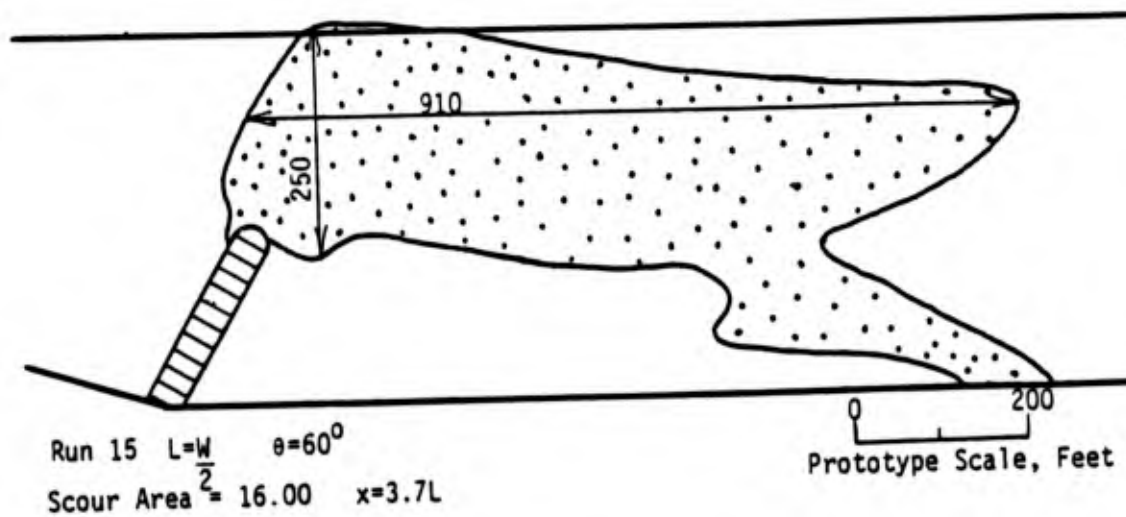
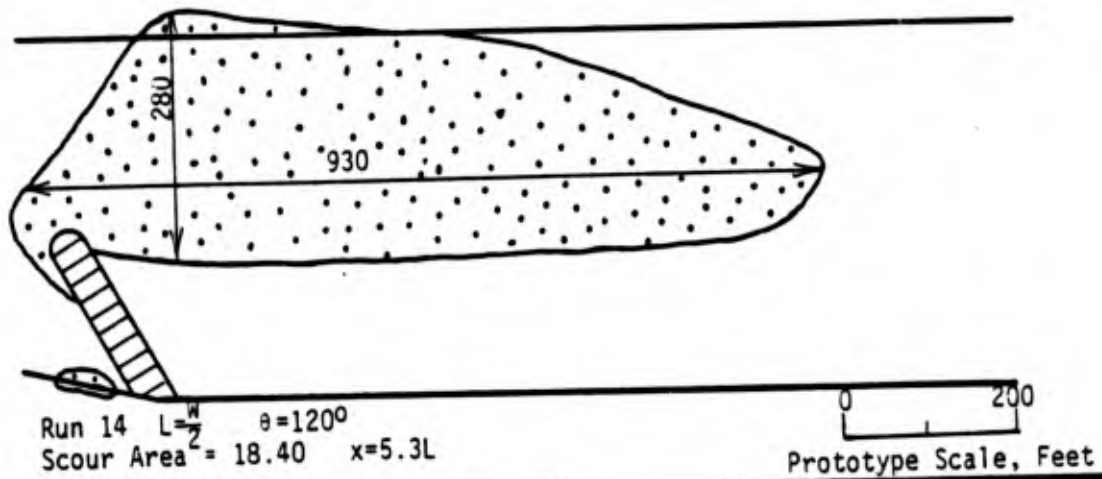
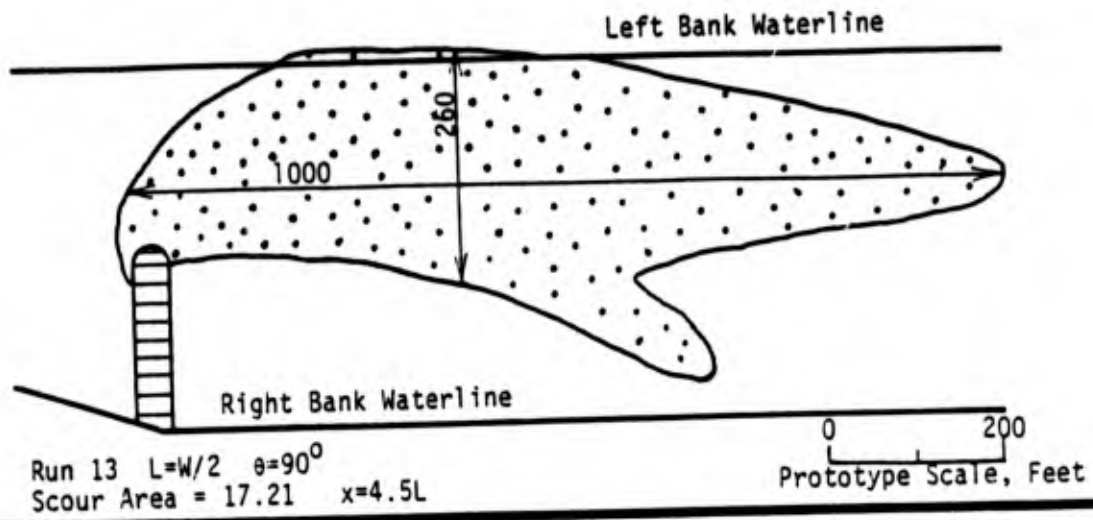


Figure 10. Model Test Results Showing Scour Patterns Associated with Single Dikes (Runs 13-21)

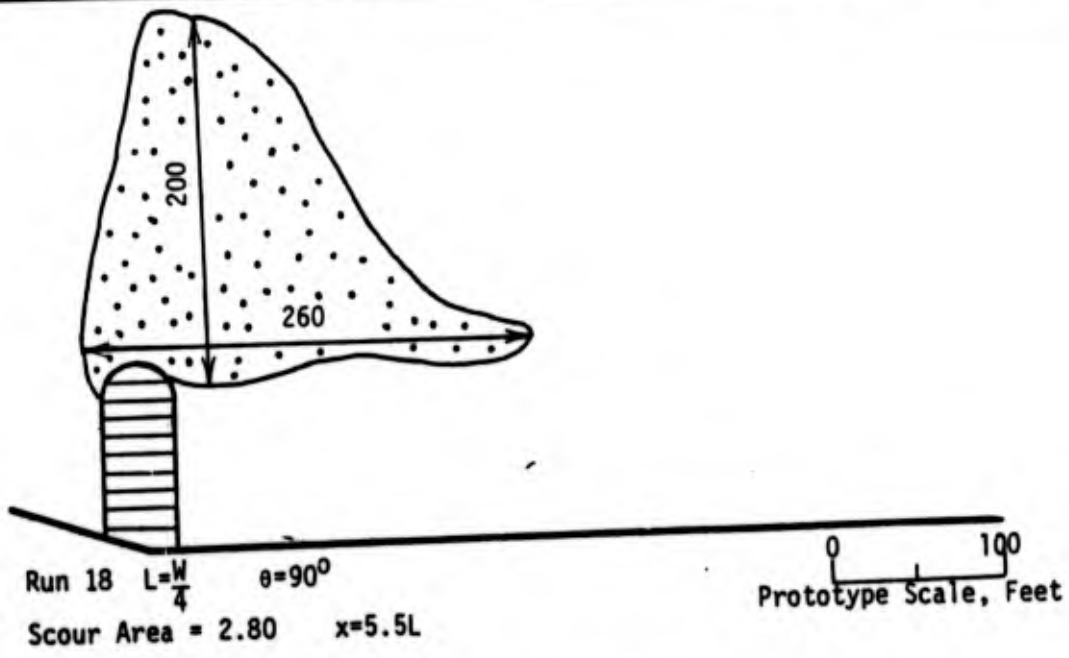
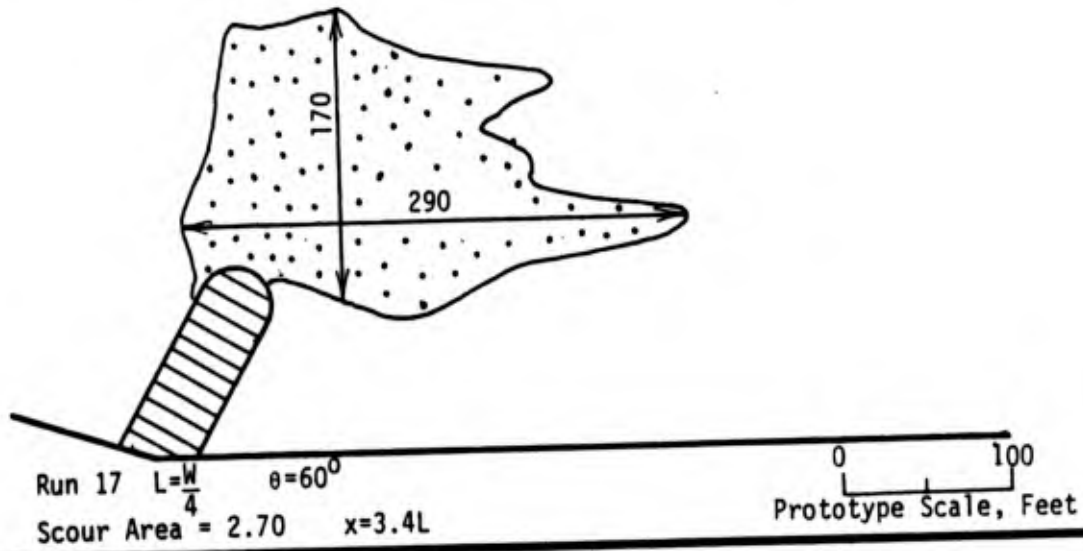
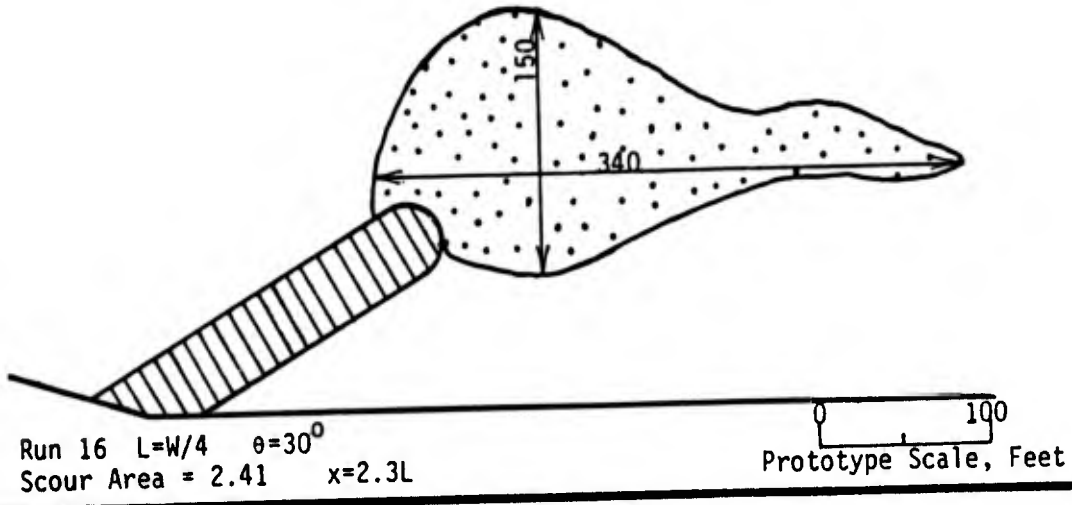


Figure 10. Continued

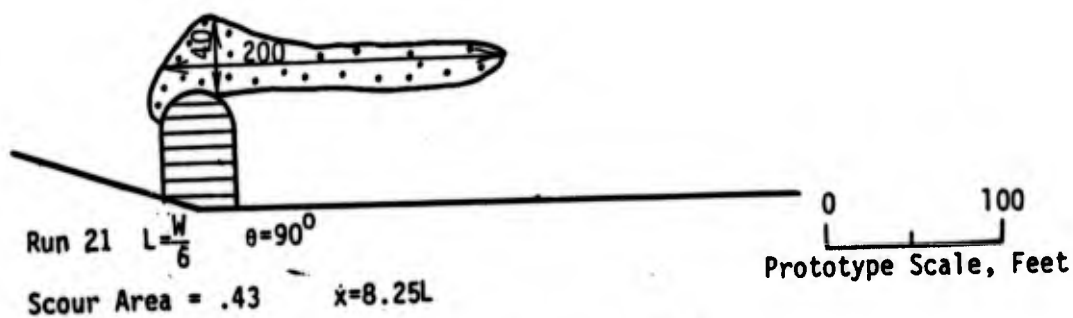
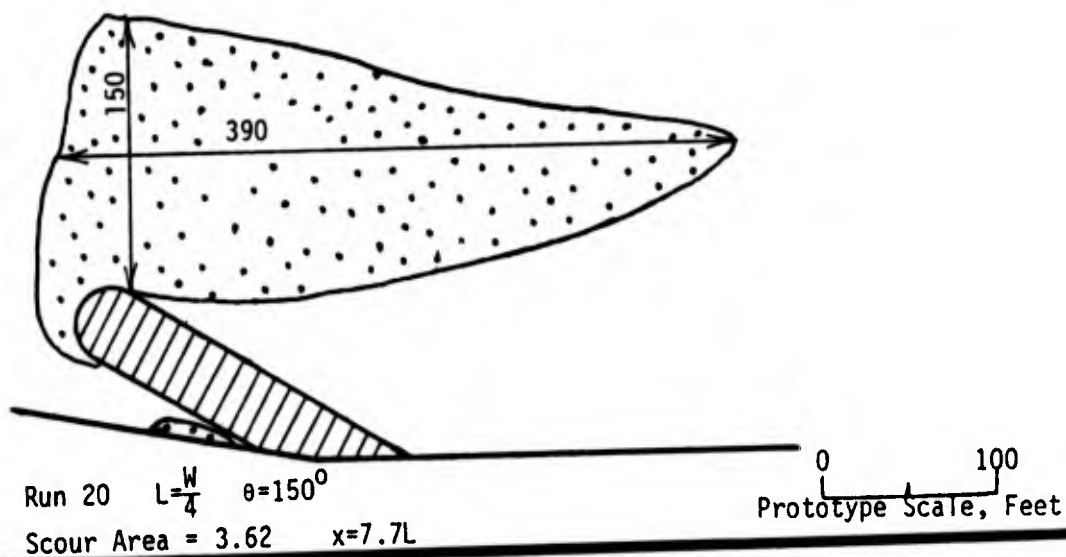
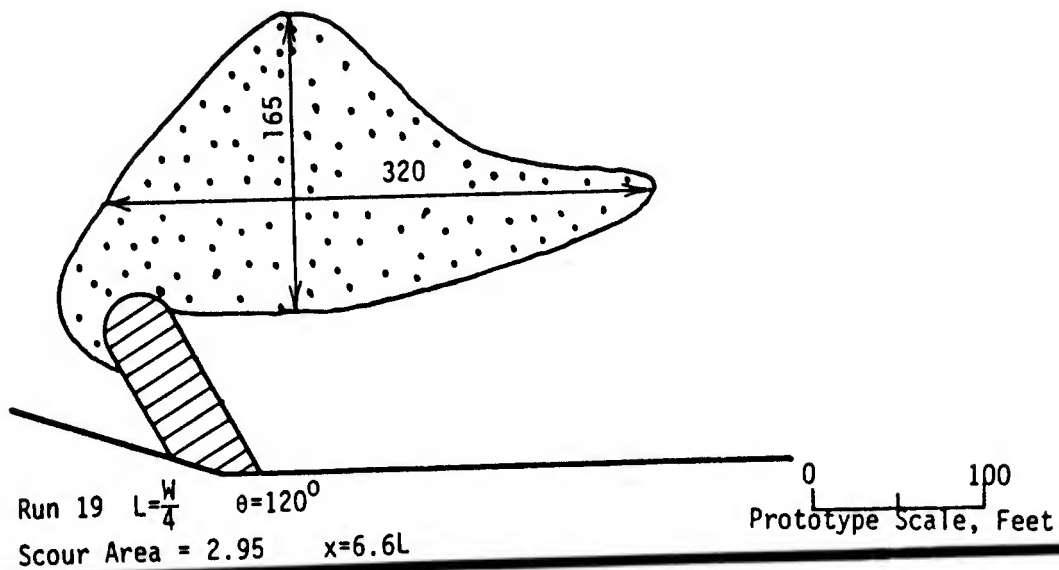


Figure 10. Continued

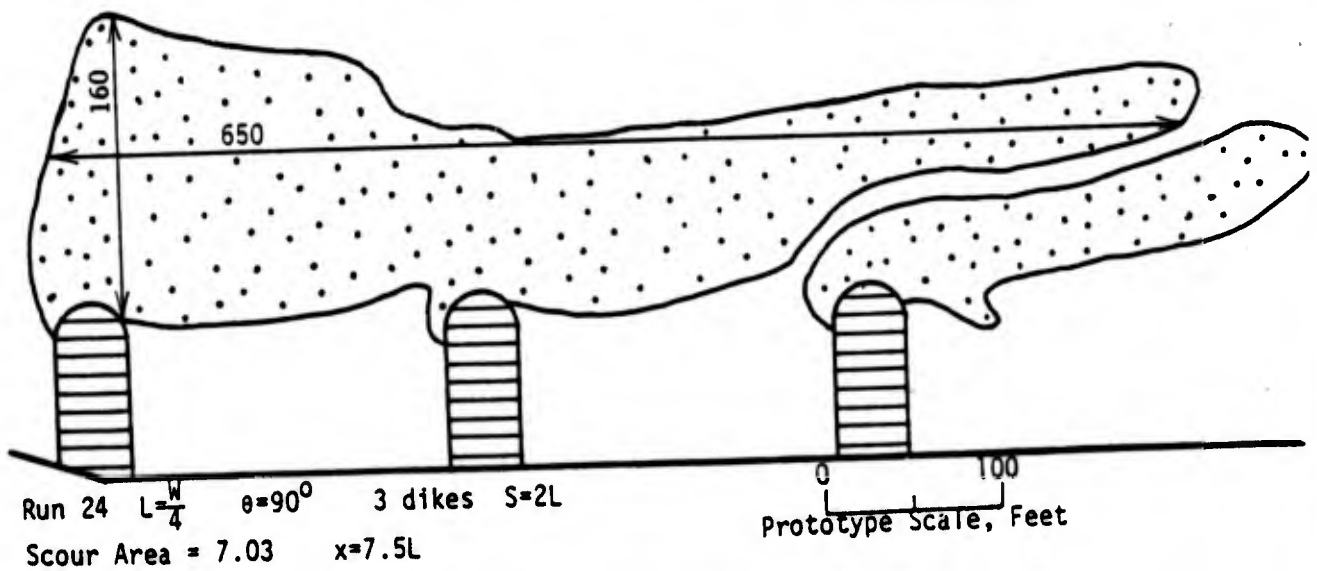
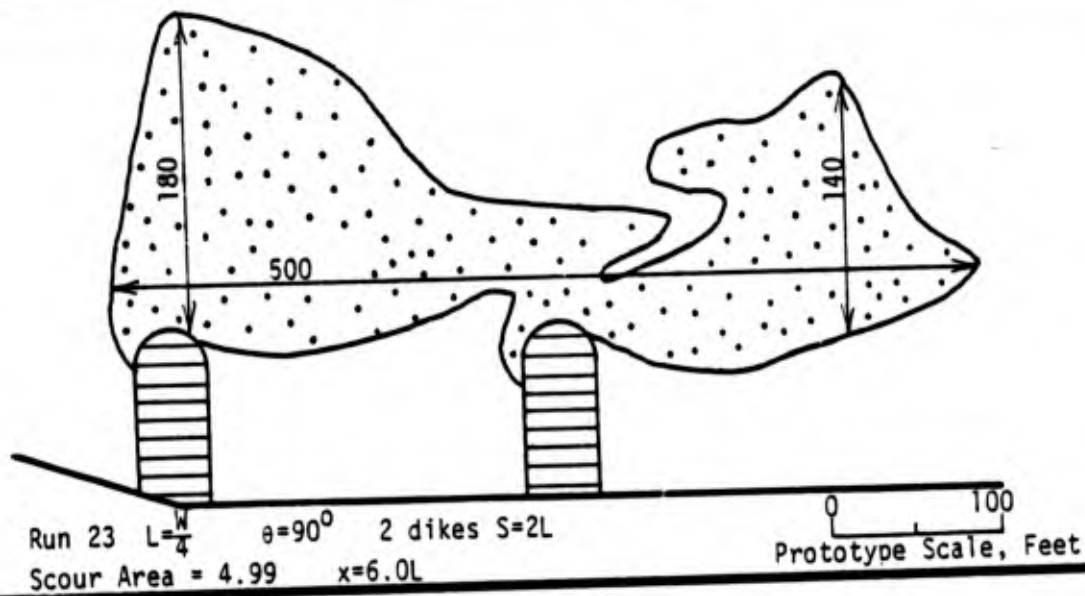
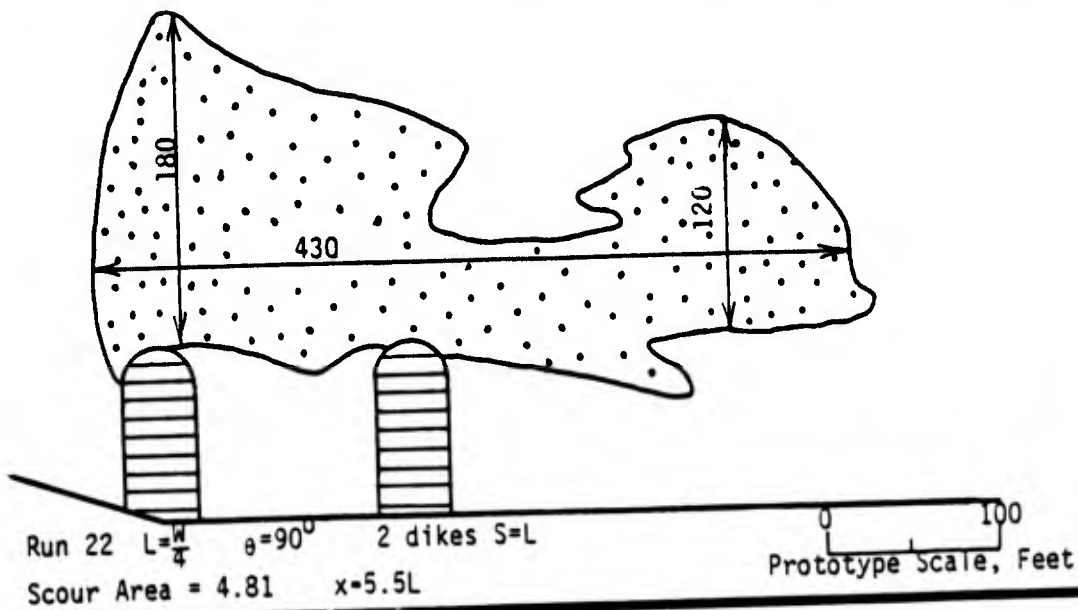


Figure 11. Model Test Results Showing Scour Patterns Associated with Multiple Dikes (Runs 22-24, 33)

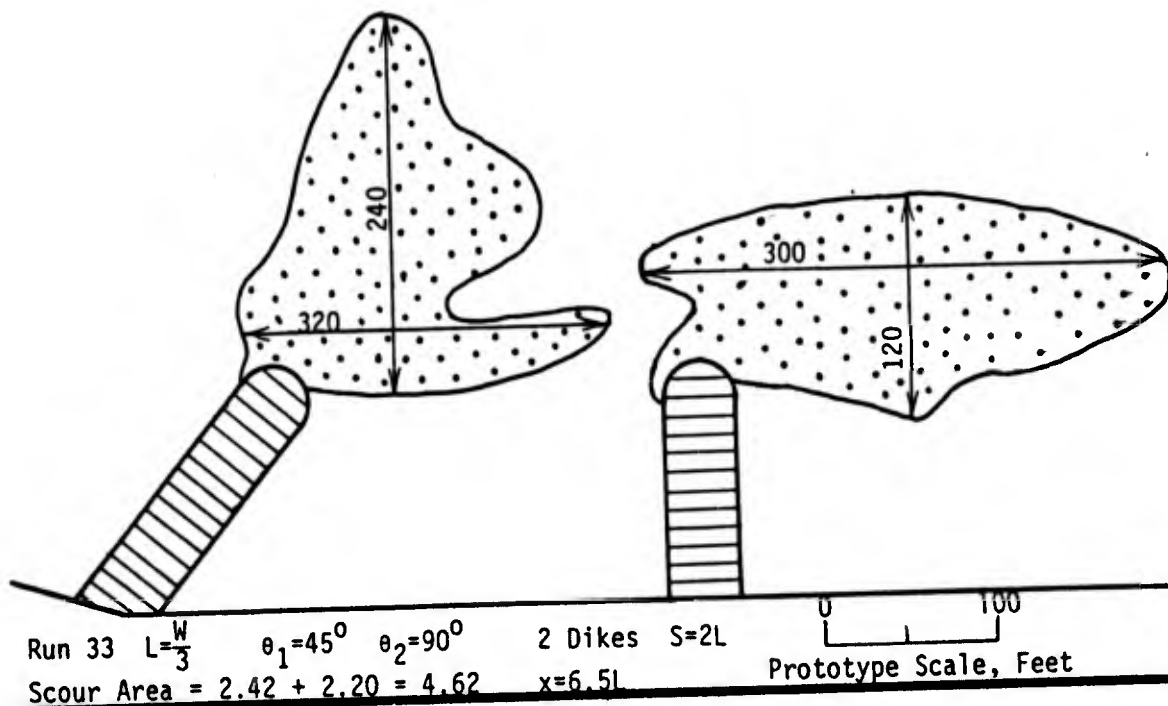


Figure 11. Continued

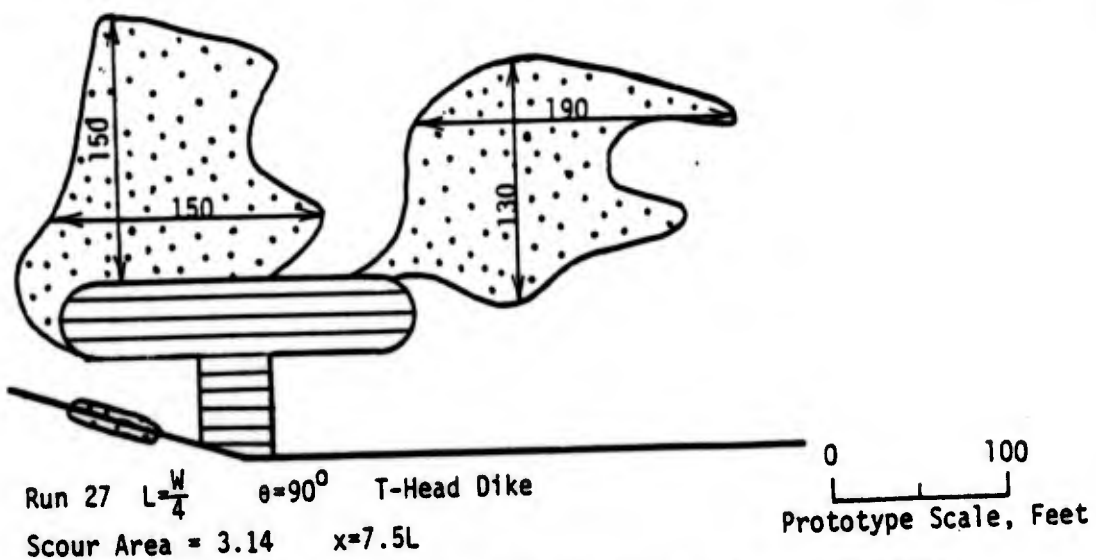
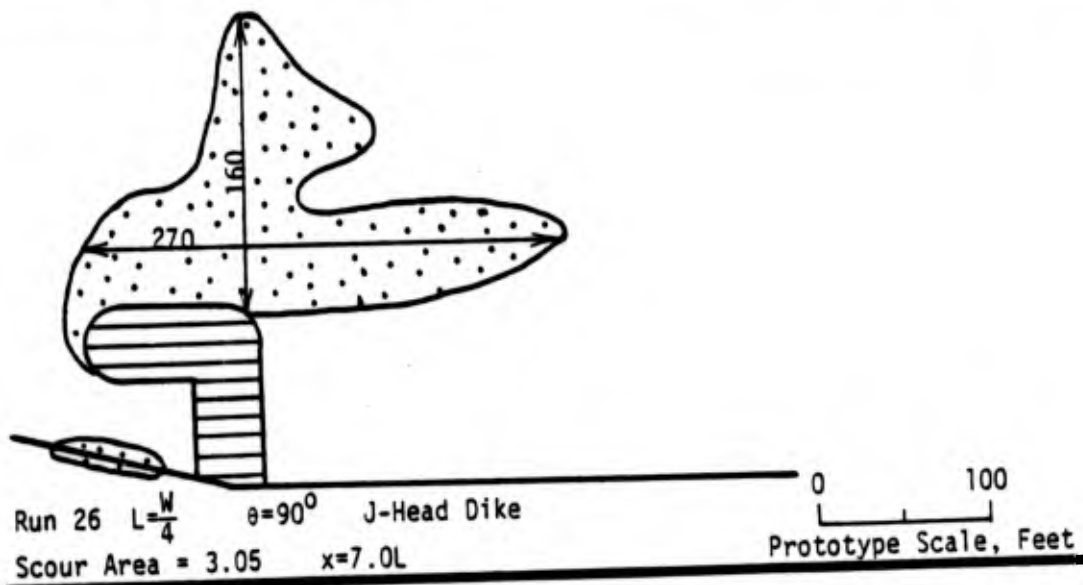
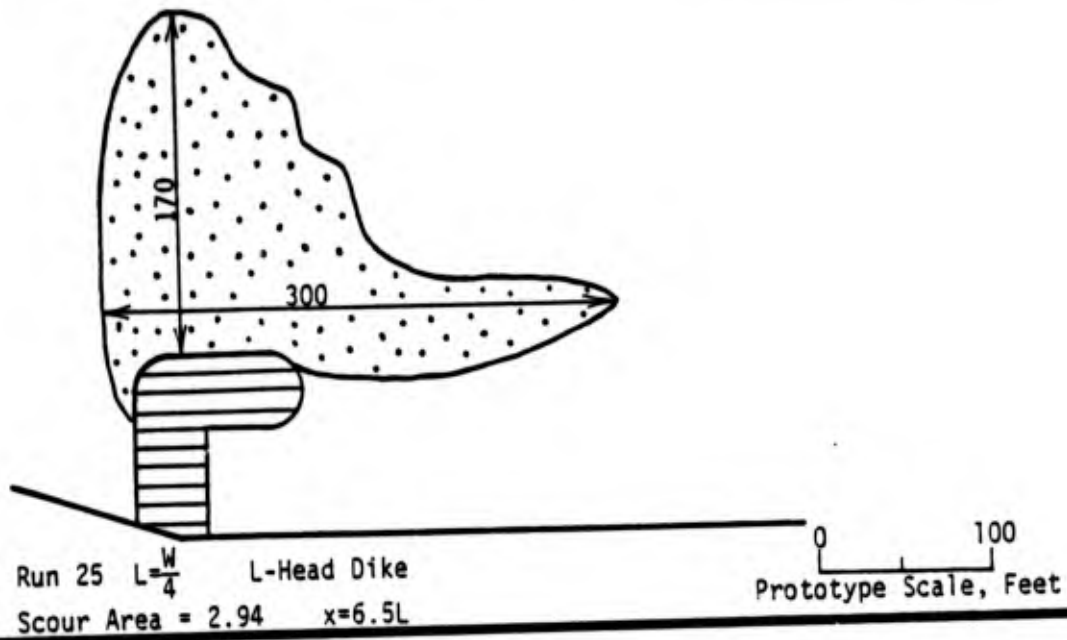
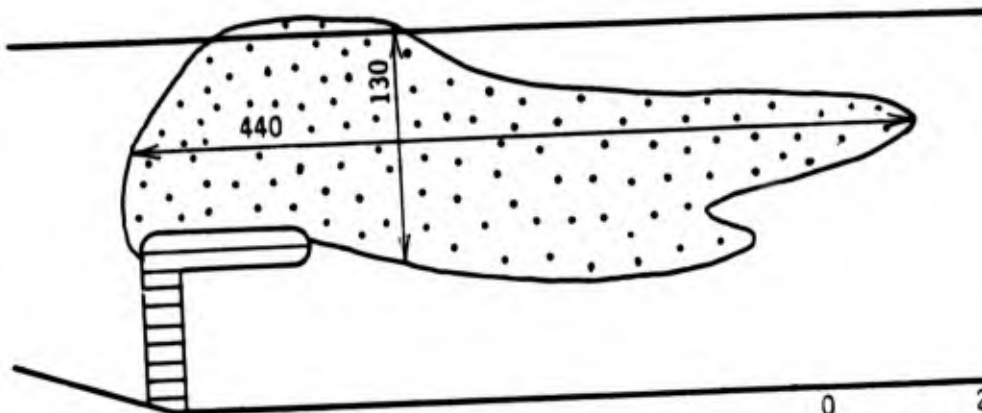
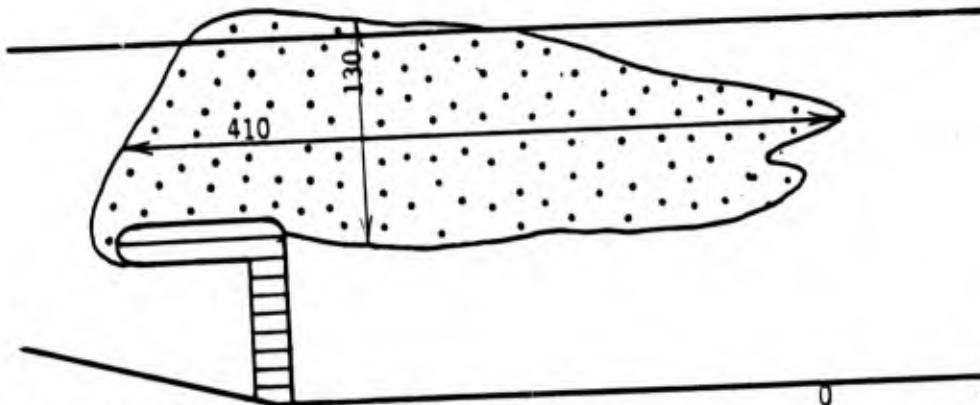


Figure 12. Model Test Results Showing Scour Patterns Associated with Various Dike Shapes (Runs 25-30)



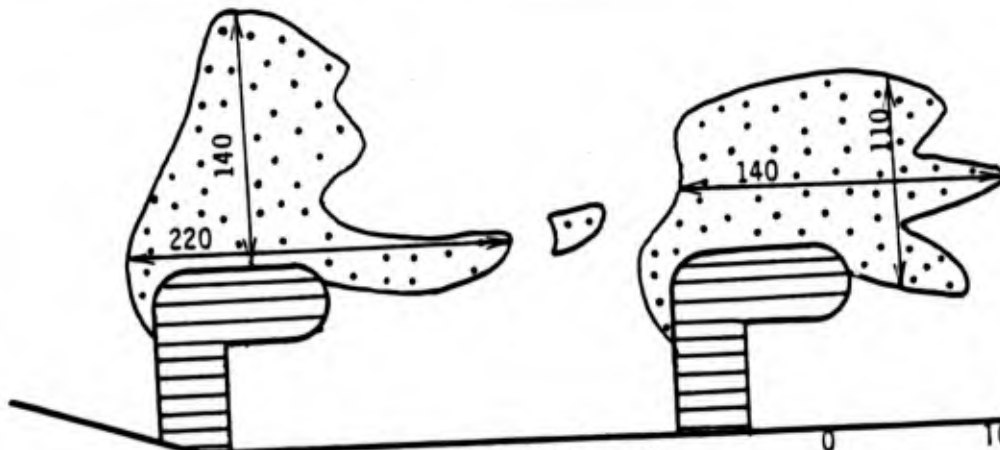
Run 28  $L = \frac{W}{2}$   $\theta = 90^\circ$  L-Head Dike  
 Scour Area = 15.24  $x = 4.0L$

0 200  
 Prototype Scale, Feet



Run 29  $L = \frac{W}{2}$   $\theta = 90^\circ$  J-Head Dike  
 Scour Area = 14.92  $x = 4.25L$

0 200  
 Prototype Scale, Feet



Run 30  $L = \frac{W}{4}$   $\theta = 90^\circ$  2 L-Head Dikes  $S = 2L$   
 Scour Area = 1.68 + .05 + 1.44 = 3.17  $x = 7.0L$

0 100  
 Prototype Scale, Feet

Figure 12. Continued

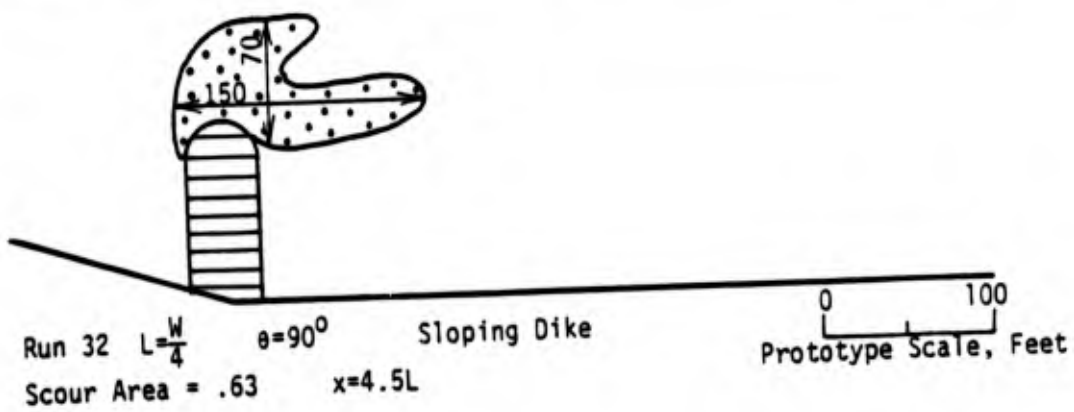
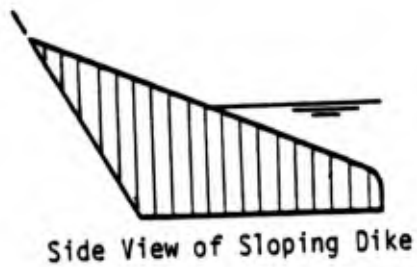
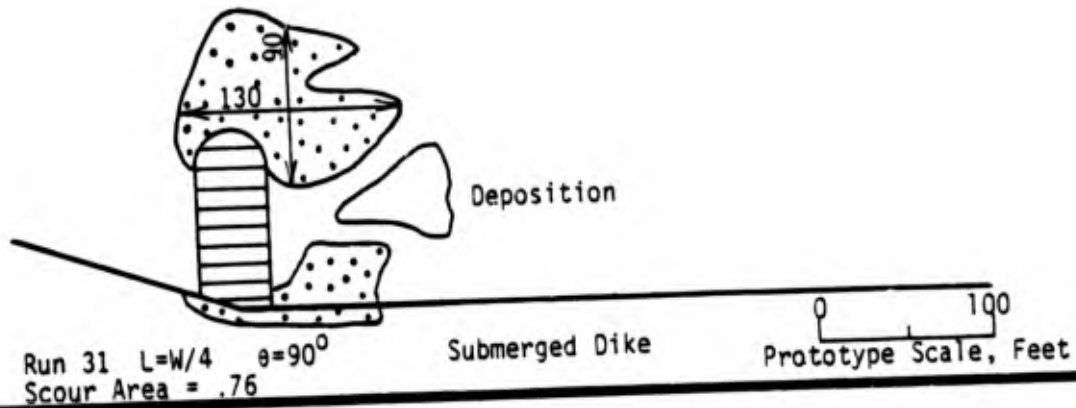
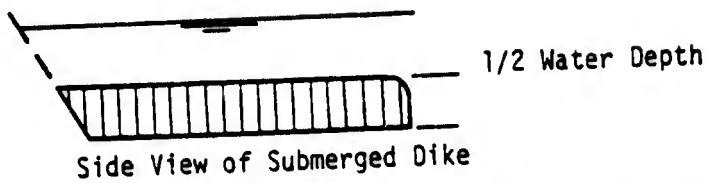
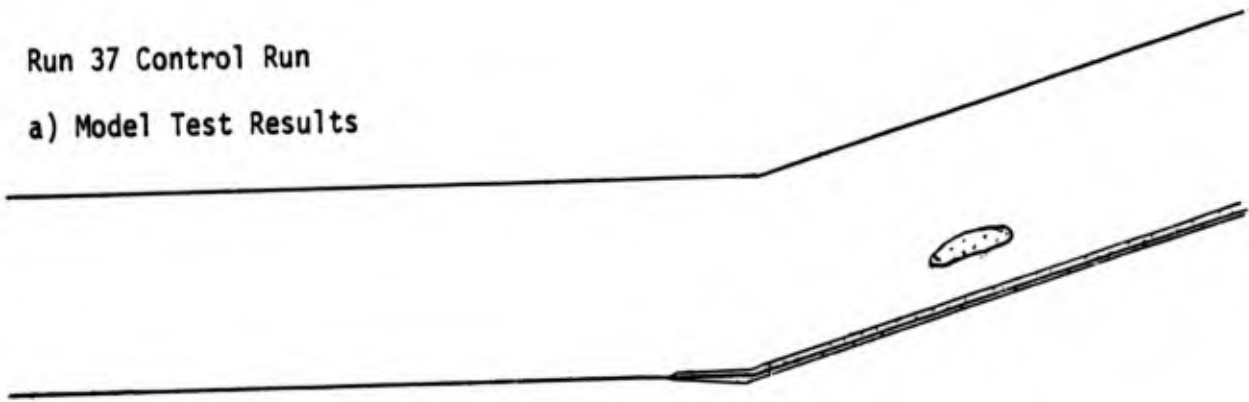


Figure 13. Model Test Results for Partly and Totally Submerged Dikes (Runs 31-32)

Run 37 Control Run

a) Model Test Results



b) Dikes Superimposed on Test Results  
for Location Reference

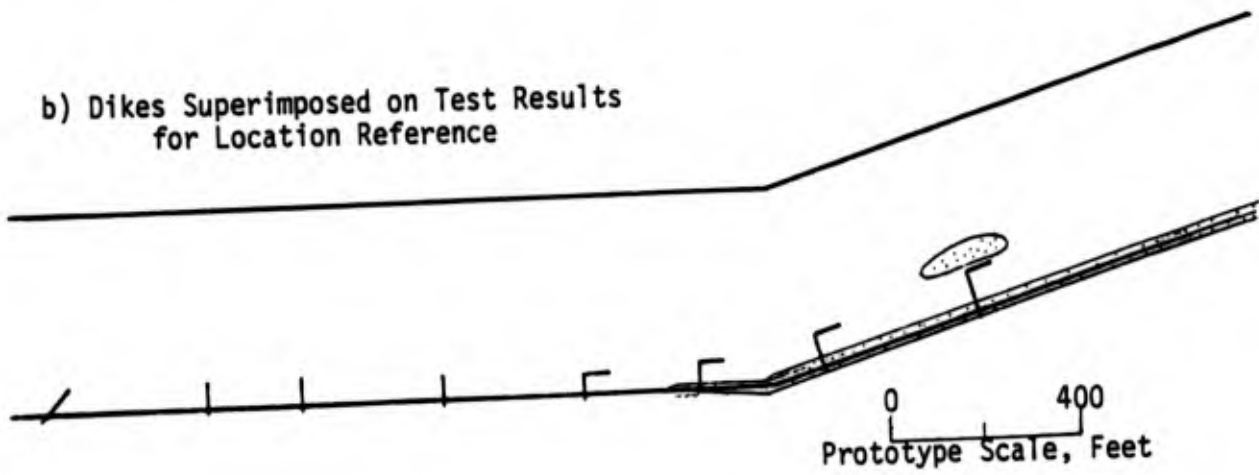


Figure 14. Model Test Results for Prototype River Reach With No Dikes Installed.

Run 34  
Prototype Arrangement  
SA = Scour Area

0 100  
Prototype Scale, Feet

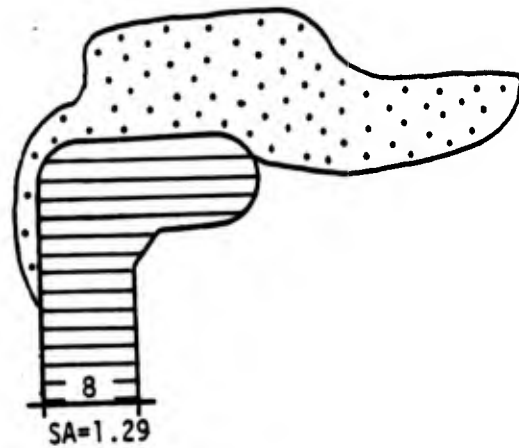
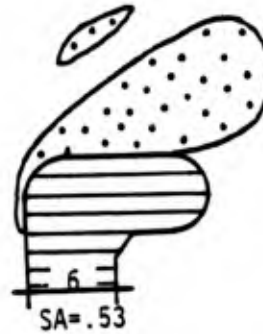
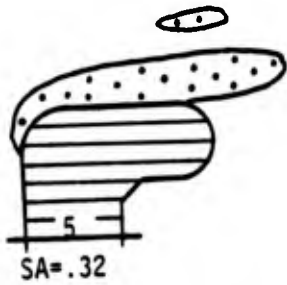
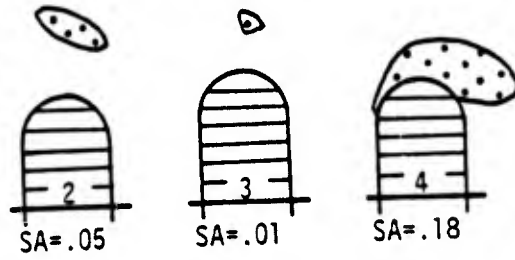
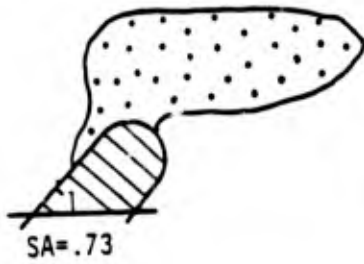


Figure 15. Model Test Results Showing Scour Patterns Associated with the Prototype Dike Field and With Modifications of the Dike Field (Runs 34-36)

Run 35  
Dikes 2, 3, 6 Removed

0 100  
Prototype Scale, Feet

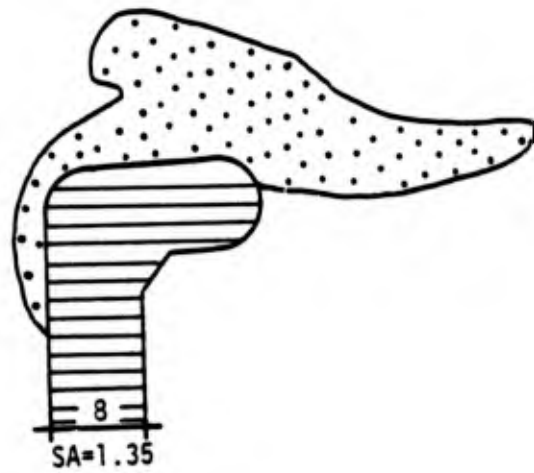
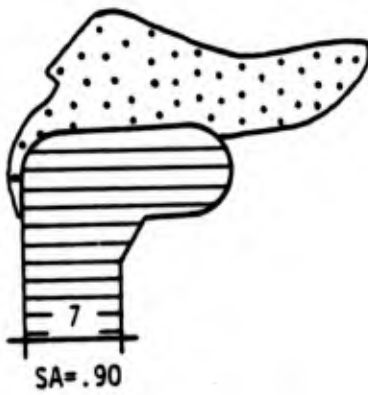
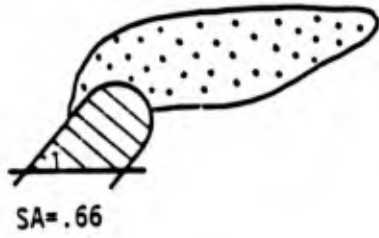


Figure 15. Continued

Run 36

Dikes 2, 3, 4, 6, 7 Removed

0 100  
Prototype Scale, Feet

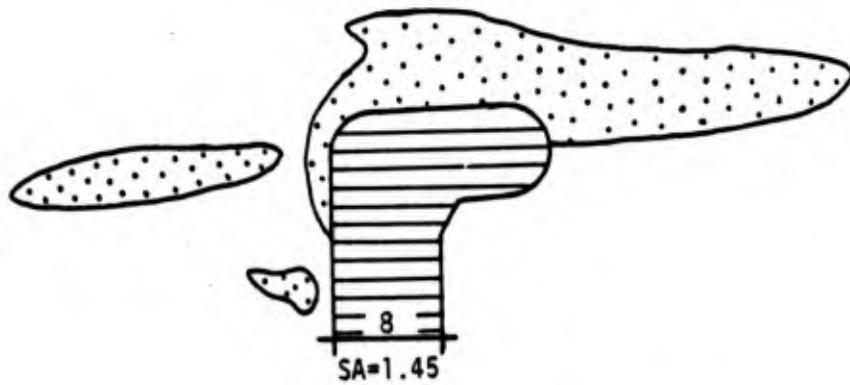
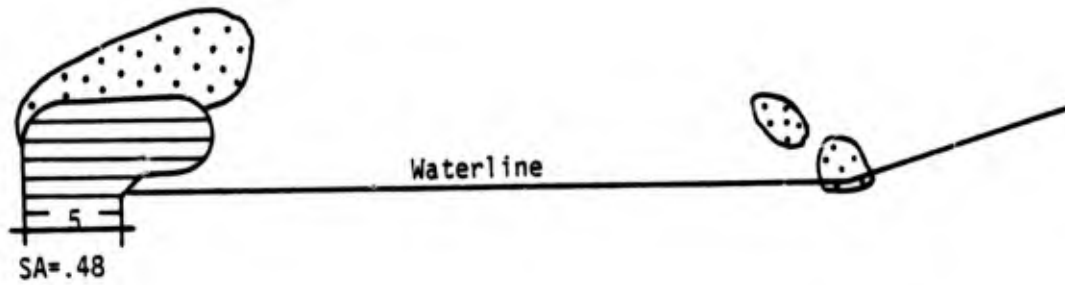
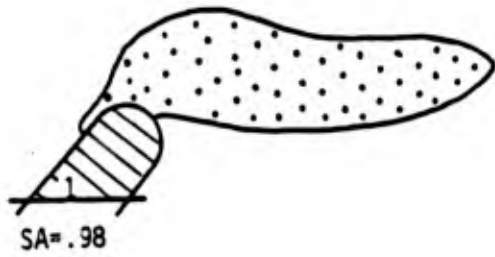


Figure 15. Continued

measurements should be multiplied by 2500. The distance X, shown as a multiple of L, represents the  $X_4$  distance defined above.

Figure 11 presents model test results showing scour patterns associated with two or three dikes in a dike field, based on runs 22-24 and 33. Dike spacing and orientation angle are varied.

Figure 12 presents test results from runs 25-30 showing the scour patterns associated with various dike shapes, including L-head, J-head and T-head. Results for a pair of L-head dikes are also shown.

Figure 13 shows the scour pattern results of model tests with a fully submerged dike (run 31) and a sloping, partly submerged dike (run 32).

Figure 14a shows the bank and bed scour that occurred in the model of the prototype reach with no structures present to give bank protection. In Figure 14b the dike field is superimposed over the Figure 14a scour results to give a reference for the locations at which dikes were installed. It should be pointed out that the model scour closely identified the actual prototype scour zone observed in the field prior to construction of the dike field.

Figure 15 presents model test results from runs 34-36 showing the scour patterns at the prototype dikes. In run 34, all eight dikes were used. For run 35 the three dikes thought to be least essential were removed. For run 36, two additional dikes were removed.

#### Effect of Spur Dike Length on Bank Protection and Flow Deflection

Figure 9 and Table 5 show the effect of spur dike length on bank protection and current deflection distances. The degree of bank protection increases as the effective length of the spur dike increases. However, it does not increase in a linear manner. For example, a dike with a 90-degree orientation angle and an effective length of 1/6 the uncontracted channel

Table 5. Effect of Spur Dike Length and Orientation Angle on Bank Protection and Current Deflection Distances (From Runs 1-12).

L/W	X <sub>1</sub> /L			X <sub>2</sub> /L			X <sub>3</sub> /L			X <sub>4</sub> /L		
	45	90	135	45	90	135	45	90	135	45	90	135
1/6	4.5	4.5	4.5	9.7	9.0	9.0	3.5	4.5	5.5	8.7	9.0	10.0
1/4	4.0	3.5	3.5	8.0	7.5	8.0	3.0	3.5	4.5	7.0	7.5	9.0
1/3	3.8	3.0	3.0	7.1	6.4	6.8	2.8	3.0	4.0	6.1	6.4	7.8
1/2	2.9	2.8	2.5	5.5	6.0	5.0	1.9	2.8	3.5	4.5	6.0	6.0

L/W	X <sub>1</sub> /W			X <sub>2</sub> /W			X <sub>3</sub> /W			X <sub>4</sub> /W		
	45	90	135	45	90	135	45	90	135	45	90	135
1/6	0.75	0.75	0.75	1.62	1.50	1.50	0.58	0.75	0.92	1.45	1.50	1.67
1/4	1.00	0.88	0.88	2.00	1.88	2.00	0.75	0.88	1.13	1.75	1.88	2.25
1/3	1.27	1.00	1.00	2.37	2.13	2.27	0.93	1.00	1.33	2.03	2.13	2.60
1/2	1.45	1.40	1.25	2.75	3.00	2.50	0.95	1.40	1.75	2.25	3.00	3.00

Table 6. Effect of Spur Dike Length and Orientation Angle on Scour Area and Current Deflection Distance (Runs 13-21)

L/W	Scour Area*					X / L				
	30°	60°	90°	120°	150°	30°	60°	90°	120°	150°
1/4	2.41	2.70	2.80	2.95	3.62	2.3	3.4	5.5	6.6	7.7
1/2	--	16.0	17.21	18.4	--	--	3.7	4.5	5.3	--
1/6	--	--	0.43	--	--	--	--	8.25	--	--

\*Scour area measured in square inches in the model. For prototype scour area in square feet, multiply by 2500.

width, will protect a bank 4.5 times its own length. Using the prototype width  $W = 400$  feet and an effective dike length  $L = 400/6 = 67$  feet, the distance downstream from the dike which will be protected would be  $4.5 \times (400/6) = 300$  ft. A dike three times longer (i.e.,  $L = W/2$ ) will protect the bank only  $2.8 \times (400/2) = 560$  ft. The distance that the main current is deflected behaves in a similar non-linear manner. For a dike with a length of  $W/6$ , the deflection distance is  $9 \times (400/6) = 600$  ft.; for a dike three times larger ( $L = W/2$ ), the deflection distance is  $6 \times (400/2) = 1,200$  ft. This diminishing increase of distance with increasing dike length occurs for all constant orientation angles. Figure 16 summarizes these relationships. Although there is some scatter of data points, the relationships of relative change are nearly linear and parallel to each other.

#### Effect of Orientation Angle on Bank Protection and Flow Deflection

Figure 9 and Table 5 also show the effect of orientation angle on bank protection and flow deflection distances. If the distance  $X_1$  from the spur dike base to the point of bank erosion is used, the effect of orientation angle on this distance is not entirely clear. However, if the distance  $X_3$  from the spur dike tip to the point of bank erosion is used, it is apparent that increasing the orientation angle increases the degree of bank protection. Figure 16 summarizes these relations.

The upstream-oriented dike is more effective in deflecting the current away from the bank than the downstream-oriented dike. The river current is deflected at nearly a 90-degree angle to the major spur dike axis and is directed toward the opposite bank. A longer distance downstream is therefore required before the deflected current is reunited with the trajectory of the main river current as unaffected by the dike. For downstream-oriented dikes, the deflected current may be somewhat attracted towards the bank, resulting

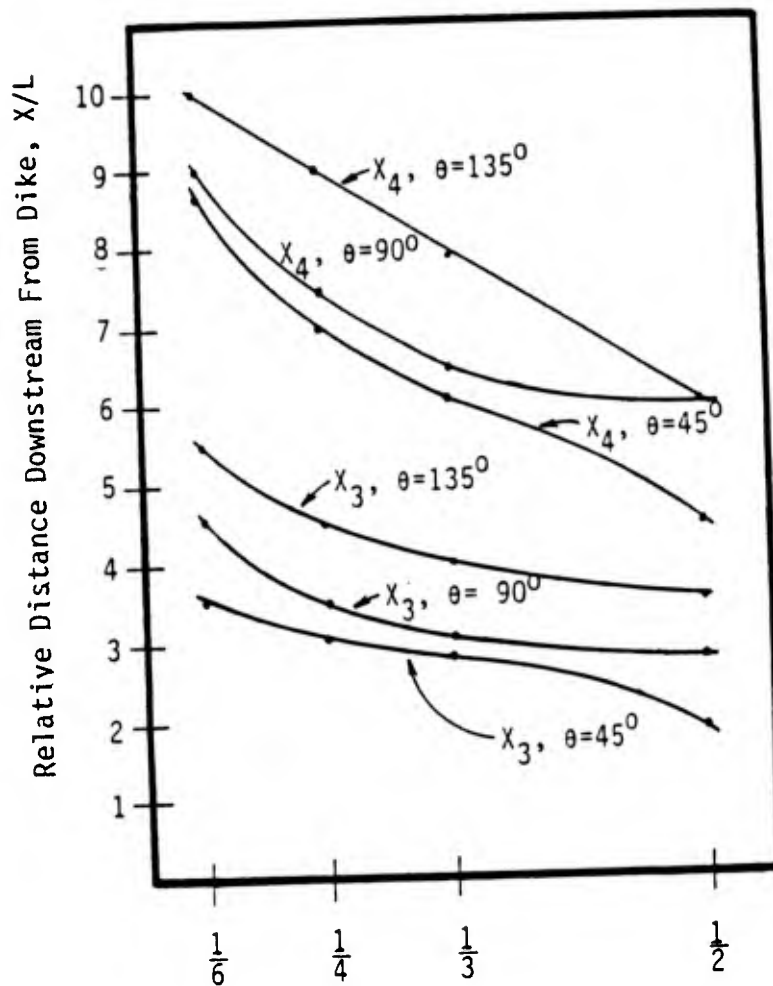


Figure 16. Effect of Spur Dike Length and Orientation Angle on Bank Protection and Current Deflection Distances.

In bank erosion at a shorter distance than the upstream oriented dike. From Table 5 and Figure 16 it is seen that a dike with a length of  $W/6$  and a dike orientation of 45 degrees will protect a bank 3.5 times its length but if the dike is oriented at 135 degrees it will protect a bank 5.5 times its length; for a length of  $W/2$ , the ratios are 1.9 and 3.5, respectively.

For upstream-oriented dikes, bank erosion may occur upstream of the dike (see Figure 10, runs 14 and 20) as part of the flow moves along the upstream side of the dike towards the bank. For long dikes (runs 13-15), an upstream orientation may cause more erosion at the opposite bank than would a downstream orientation.

#### Effect of Spur Dike Length and Orientation Angle on Scour

The length and orientation of the spur dike apparently have two effects on the scour pattern and size (see Figure 10). First, as the dike length increases the flow section contracts and general bed erosion occurs in the contracted section. Second, varying vortices develop, depending on the angle and length of the spur dike, and cause local scour around the spur dike.

Table 6 shows the effect of dike length and orientation angle on scour area and flow deflection distance. As the spur dike length increases, the scour area increases exponentially. This is shown in Figure 17. With  $\theta = 90$  degrees and a length of  $W/6$ , the scour area is  $0.43 \text{ in}^2$ ; for a length of  $W/4$ , the scour area is  $2.80 \text{ in}^2$ ; and for a length of  $W/2$ , the area is  $17.21 \text{ in}^2$ .

As the orientation angle increases, the size of the scour hole also increases. Figure 17 shows that for a length of  $W/2$ , the scour area increases linearly as the angle increases from 60 to 120 degrees. For a length of  $W/4$ , the scour area increases linearly from 30 to 120 degrees but more rapidly from 120 to 150 degrees. The scour dimension perpendicular to the bank is greatest for a dike oriented at 90 degrees and the scour

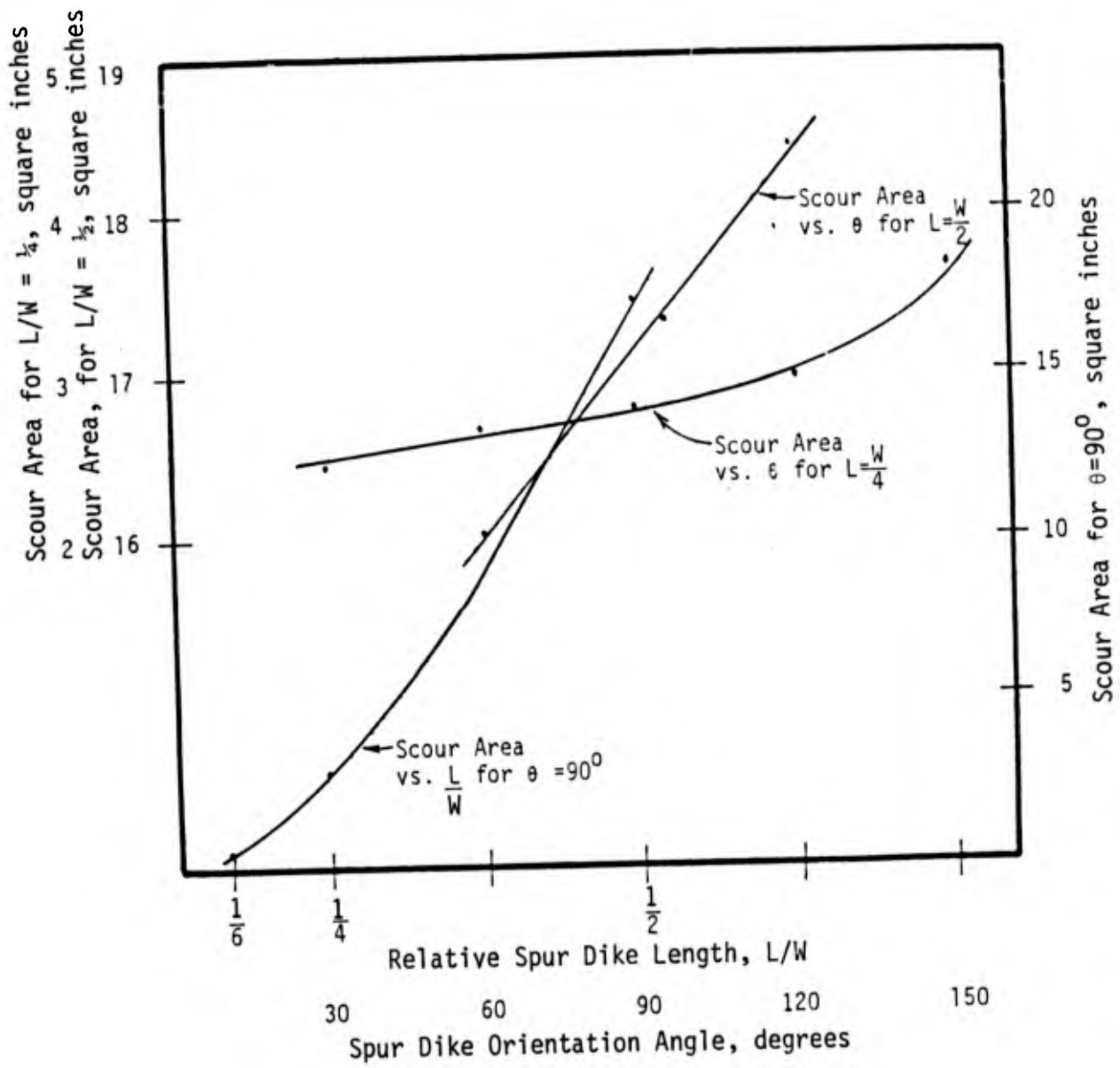


Figure 17. Effect of Spur Dike Length and Orientation Angle on Scour Area.

dimension parallel to the bank is greatest for a dike oriented at 30 degrees or 150 degrees (runs 16-20 in Figure 10).

Scour also increases upstream of the spur dike tip as the spur dike becomes more upstream-oriented.

#### Effect of Multiple Dikes on Scour Area and Bank Protection

Figures 11 and 15 and the scour areas given in Table 8 show that as the number of dikes in a dike field is reduced, the total scour area for the dike field decreases but the scour area at the individual dikes increases. Multiple spur dikes appear to afford some mutual protection from scour-producing currents.

Comparing run 18 in Figure 10 and runs 23 and 24 in Figure 11 shows that as the number of dikes increases (from one to three dikes) the total scour area increases less rapidly. The current deflection distance beyond the downstream dike also increases (from  $5.5L$  to  $7.5L$ ).

#### Effect of Spur Dike Shape on Scour Area and Bank Protection

Table 7 shows the effect of spur dike shape on scour area and current deflection. Figure 12 and Table 7 show that the T-head dike caused a slightly larger scour area than the other shapes for a particular  $L/W$  ratio. The J-head was the most effective in deflecting the current. The L-head dike produced the smallest scour area but was also the least effective in deflecting the current. The J-head and T-head dikes caused bank erosion to occur upstream of the dike. The T-head also caused scour areas to develop both upstream and downstream.

#### Effect of Spur Dike Submergence

Figure 13 shows that a totally submerged spur dike experienced bank erosion near its root. Some of this eroded bank material was deposited just downstream of the dike.

Table 7. Effect of Spur Dike Shape on Scour Area and Current Deflection Distance (Runs 25-29).

Shape	Scour Area*	$\times 4/L$
<u>L/W = 1/4</u>		
L-Head	2.94	6.5
J-Head	3.05	7.0
T-Head	3.14	7.5
<u>L/W = 1/2</u>		
L-Head	15.24	4.0
J-Head	14.92	4.25

\*Scour area measured in square inches in the model. For prototype scour area in square feet, multiply by 2500.

Table 8. Scour Areas for Prototype Dike Arrangement and Effect of Removing Various Dikes (Runs 34-36).

Dike and Scour Area*								
1	2	3	4	5	6	7	8	Total
.73	.05	.01	.18	.32	.53	.87	1.29	3.98
.66	--	--	.24	.37	--	.90	1.35	3.52
.98	--	--	--	.48	--	--	1.45	2.91

\*Scour area measured in square inches in the model. For prototype scour area in square feet, multiply by 2500.

For a sloping dike, the scour area and current deflection distance were similar to those expected from an unsubmerged dike with a length equal to the exposed portion of the sloping dike.

#### Prototype Dike Arrangement and Comparison With Field Study

Figure 15 and Table 8 show the scour areas for the prototype dike arrangement. The effects of removing some dikes on local scour at each remaining dike and on total scour at the dike field are also shown.

The scour patterns developed from the model test of the Willamette River Reach without dikes (Figure 14, run 37) and with the prototype arrangement of dikes (Figure 15, run 34) compare reasonably with the actual patterns observed before dike construction and obtained from the field investigation after dike construction. The amount of scour measured near dikes 2, 3 and 4 in run 34 was very small. During run 36 in which dikes 2, 3, 4, 6, and 7 were removed, bank erosion occurred between dikes 5 and 8 but little bank erosion was observed between dikes 1 and 5. Dikes 2, 3, and 4 apparently contributed little protection to the bank in that part of the reach. During the field investigation it was observed that dike 1 deflected the river current sufficiently that dikes 2, 3, and 4 provided little additional benefit. Based on the model study, at least one of those dikes could have been omitted from the dike field with little effect on bank protection. The field investigation also revealed that bank erosion was occurring downstream of dike 8 and that perhaps an additional dike was required there. The model test also showed that bank erosion occurred downstream of dike 8.

As already noted, the total scour area diminished when dikes were removed from the dike field but scour at the individual remaining dikes increased (Figure 15 and Table 8). However, more than three dikes appear to be required to adequately protect the riverbank.

## VI. FIELD INVESTIGATION OF SPUR DIKES

### Background

During the summer of 1983, a spur dike field (called a groin field by the designers) was constructed by the U.S. Army Corps of Engineers along 1800 feet of bankline of the Willamette River near River Mile 136 approximately two miles southeast of Corvallis, Oregon. Streambank protection was mandated because erosion at the location, estimated at 10 to 30 feet per year, was affecting cultivated farmland and because of the potential formation of a new channel away from the city's principal water intake. Figure 18 shows an aerial view of the dikes, copied from an infrared color photograph taken on October 1, 1983. The river discharge is approximately 7,700 cfs.

The U.S. Army Corps of Engineers chose a spur dike system instead of a conventional revetment. This was done for environmental reasons, in order to diversify fish habitat through the creation of a series of large pools and slackwater areas between the dikes.

A model study was conducted by the Corps of Engineers for design purposes at the U.S. Army Engineer Waterways Experiment Station in Vicksburg, Mississippi. The design solution consists of eight spur dikes spaced 250 to 350 feet apart, extending 50 to 115 feet into the river (at crest elevation) and consisting of rockfill and riprap. Dike 1, the extreme upstream dike, is oriented 40 degrees from the bank in a downstream direction. Dikes 2-4 are oriented normal to the bank. The four downstream dikes (dikes 5-8) are L-shaped with extensions approximately 60 feet long and parallel to the bank. A 3-foot layer of class V riprap was placed on the upstream side of the dikes and a 2-foot layer of class III riprap was placed on the downstream side to protect the dikes from scour and debris.

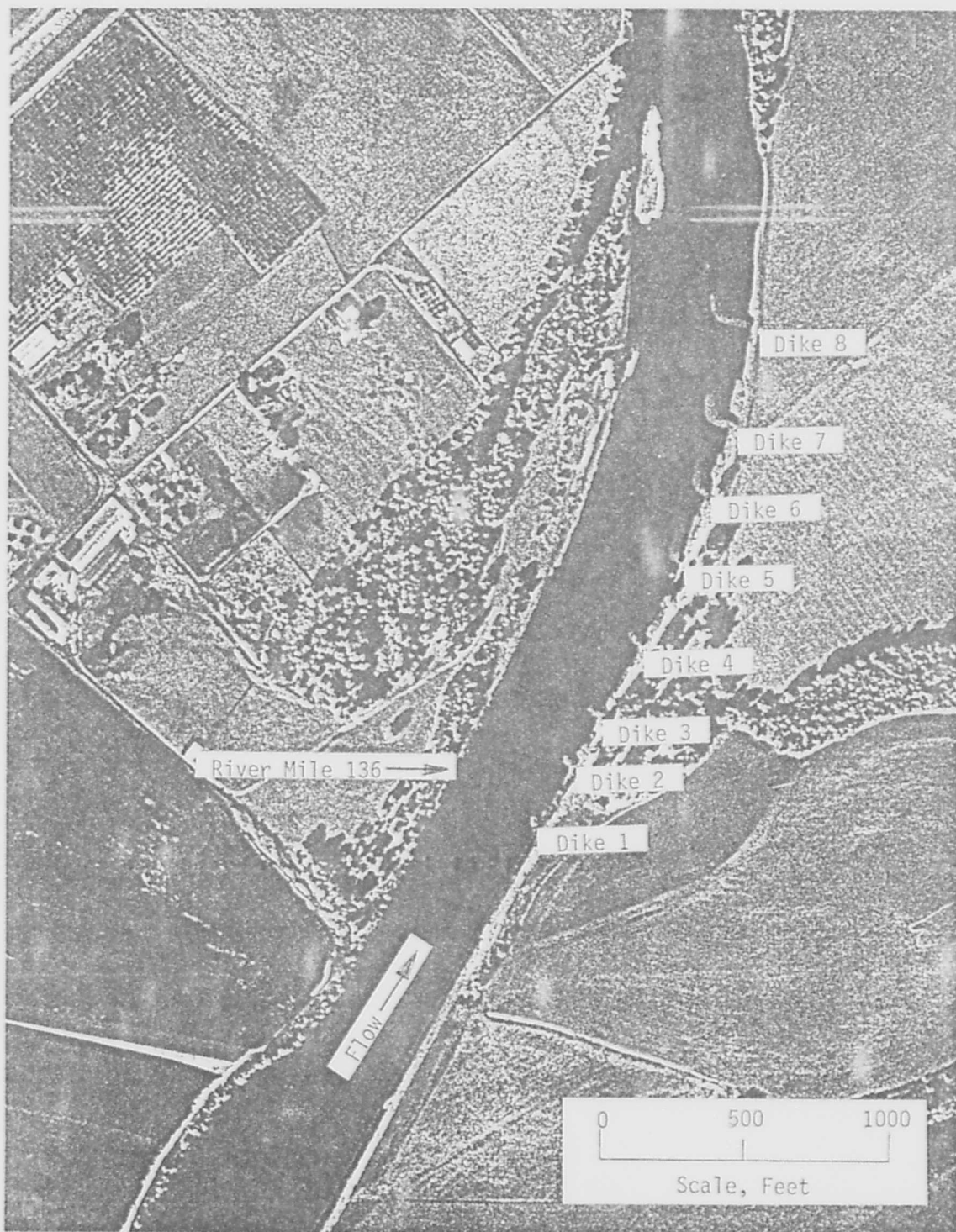


Figure 18. Willamette River Spur Dike Field Upstream of Corvallis

Table 9 summarizes the spur dike dimensions and Figure 19 shows typical cross-sections of the spur dikes. Figure 20 shows the placing of class V riprap on dike 7 during construction of the spur dikes. Figure 21 shows two views of the completed spur dikes.

#### Research Procedures, Equipment and Data

The purpose of the field investigation was to gather the necessary data in order to determine the hydraulic effects of the spur dikes on the river flow and bed topography.

In mid-September 1983, approximately one week after construction was completed, a detailed site survey was conducted which included obtaining current velocity measurements and river cross-sections. To determine the evolution of scour patterns around the spur dikes, subsequent site surveys will be conducted in mid-winter 1983-84, after a few months of high water have allowed scour to rearrange the river bed and flow patterns, and in late spring 1984, to observe the effects of a full season of high-water conditions.

On September 14, 1983, current velocities were measured with a Price current meter. Velocity measurements were taken at depths equal to 20 and 80 percent of the total depth to get the depth-averaged velocity. The depth-averaged velocities are shown in Figure 22.

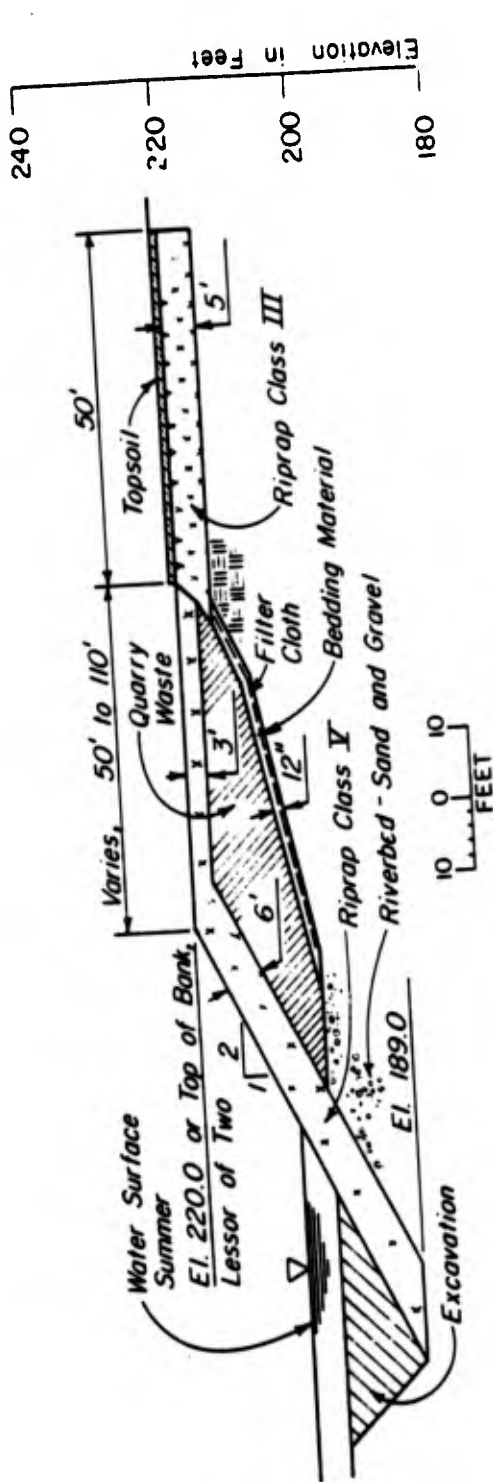
Surface current patterns around the spur dikes were sketched at the time of velocity measurements. These are shown in Figure 23. Figure 24 is a photograph of eddy currents being shed off dike 6, as seen from dike 7 looking upstream.

A Raytheon fathometer was used to record water depths. Cross-sections were taken at stations upstream of the spur dike field, at and between each dike, and downstream of the dike field. Cross-sections were also taken parallel to the current flow along the river center line, 20 feet from the

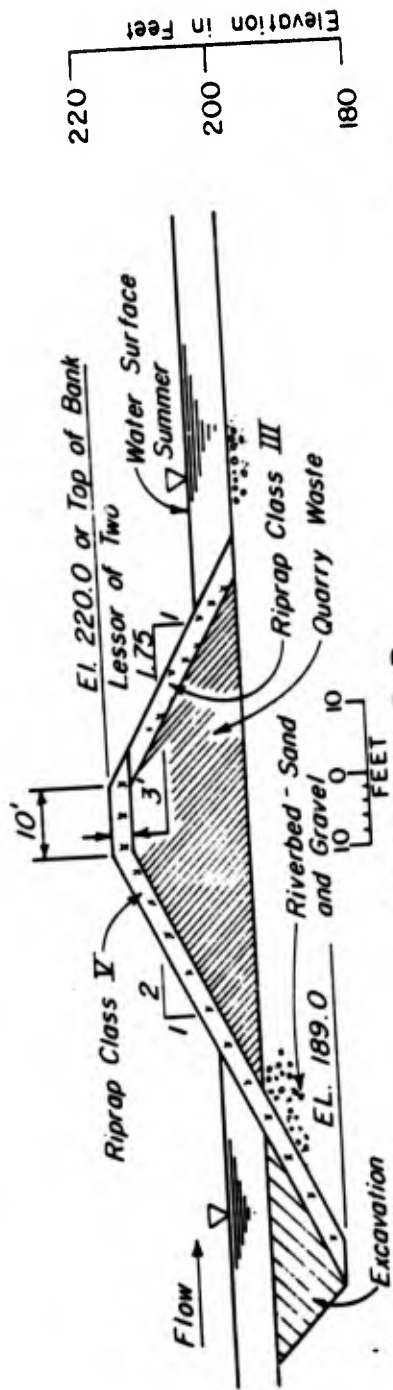
Table 9. Reference Dimensions for Prototype Spur Dike Field

Description	Groin Referencing Dimension							
	Groin 1	Groin 2	Groin 3	Groin 4	Groin 5	Groin 6	Groin 7	Groin 8
Distance from Bank Line (Jan. 1983 Survey) to end of quarry spalls at 3' below crest elevation, feet	43	37	47	52	32	42	82	82
L-Head Dimension, feet	---	---	---	---	65	65	75	80
Angle Between "B" Line and Groin $Q_1$ , degrees	40	87	87	89°30'	91	91	86°35'	90
Angle Between L-Head and Groin $Q_1$ , degrees	---	---	---	---	95	100	98	113
Crest Elevation, ft msl	216.0	220.0	220.0	217.0	216.5	217.0	220.0	218.0
Toe Elevation at End, ft msl	189.0	189.0	189.0	189.0	189.0	189.0	184.0	184.0
Distance from Bank Line to Tip of Class V Riprap, feet	44	52	52	46	45	46	62	58

Note: "B" line is survey line approximately parallel to the bank.



SECTION A-A



SECTION B-B

FIGURE 2

BASS LOCATION, PHASE II

WILLAMETTE RIVER

Figure 19. Cross Sections of Prototype Spur Dikes



Figure 20. Construction of Spur Dikes Along Willamette River  
Upstream of Corvallis (Dike No. 7 Shown)

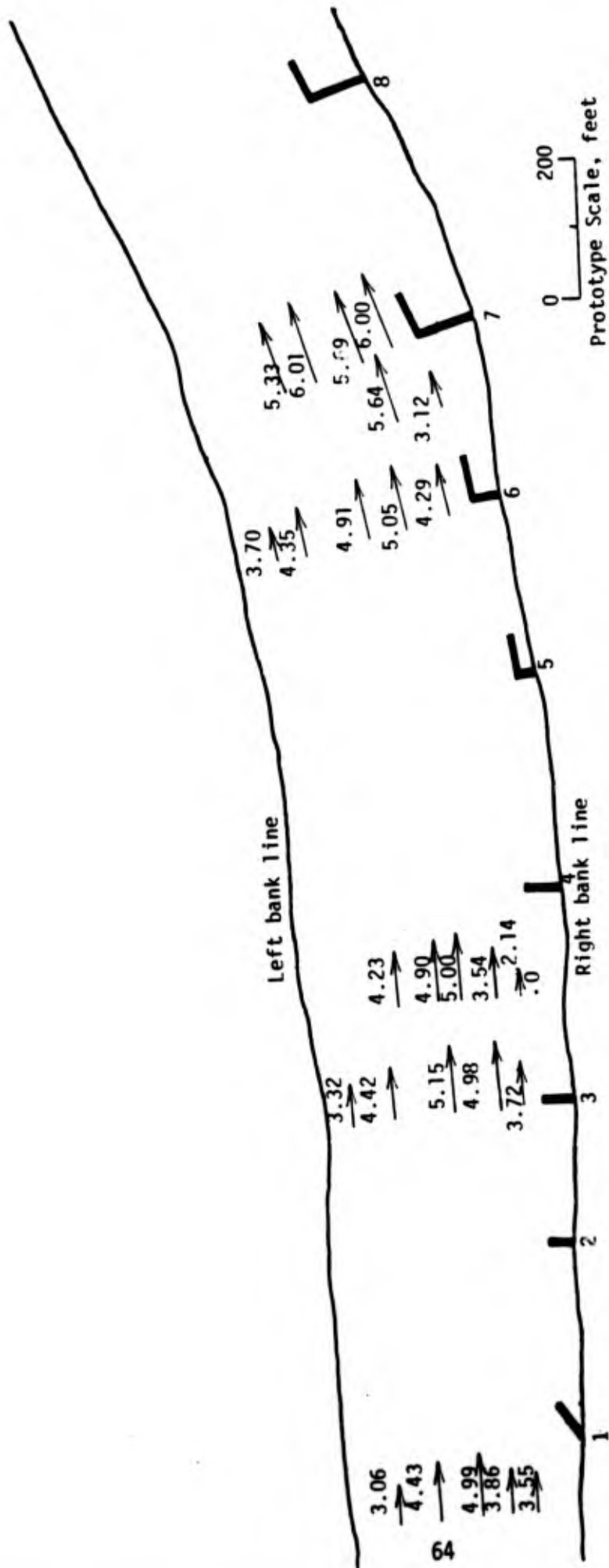


A. Looking Downstream From Dike 5



B. Looking Upstream From Dike 6

Figure 21. Completed Spur Dikes Along Willamette River Upstream of Corvallis



Velocities shown are in feet per second and represent average values for vertical water column at each point

Figure 22. Average Current Velocities at Spur Dike Field, 14 September 1983.

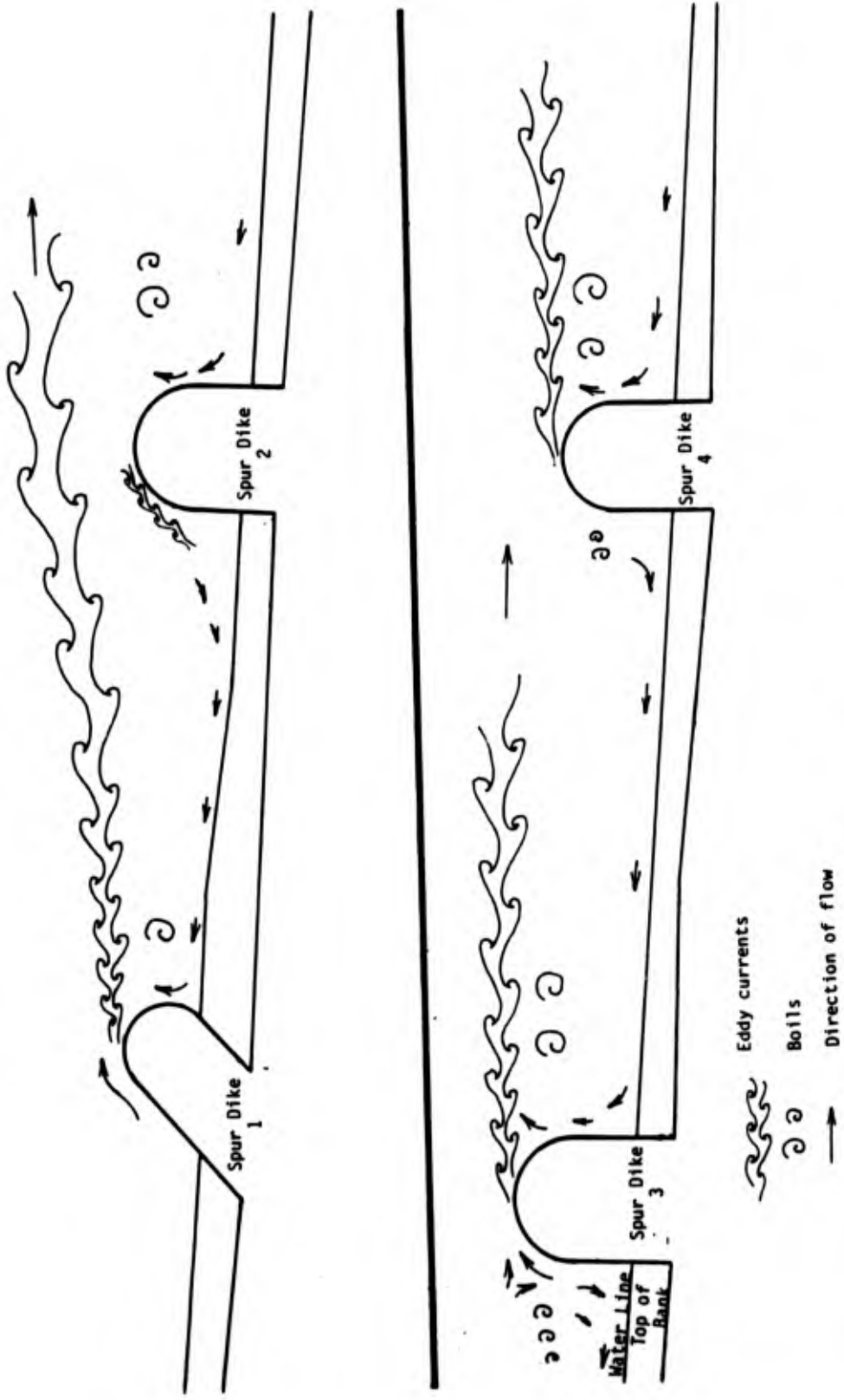


Figure 23. Surface Current Patterns at Spur Dike Field, 14 September 1983

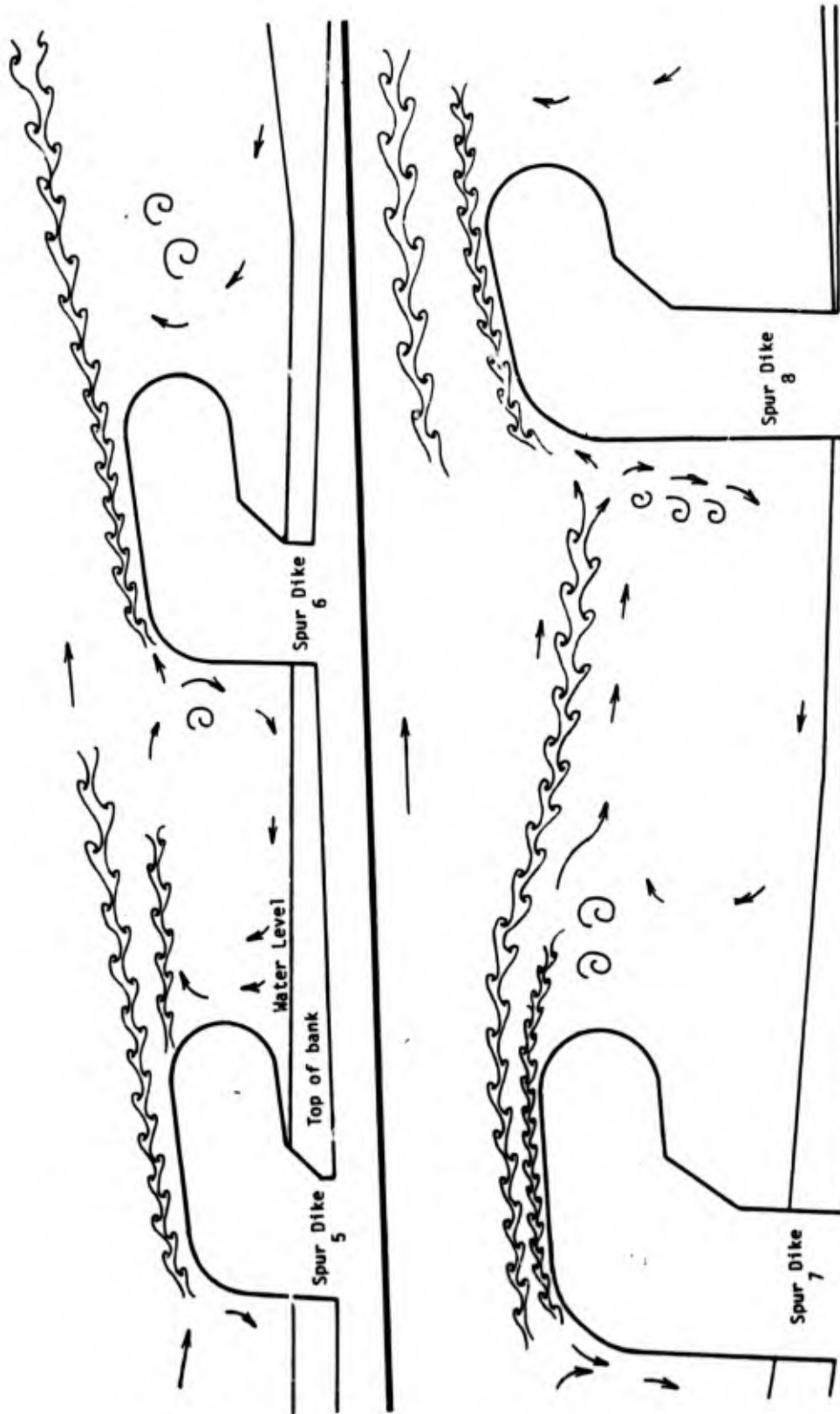


Figure 23. Continued



Figure 24. Eddy Currents Being Shed From Spur Dike 6,  
14 September 1983

dike tips, 10 feet from the dike tips, and 20 feet from the bank line in between the dikes. For dikes 1, 3 and 7, cross-sections were also taken radially around the dikes approximately 10 feet and 20 feet from the dike edge. A contour map of the river bed was constructed using the data obtained from the fathometer recordings. This is shown in Figure 25.

#### Discussion of Field Investigation

The field investigation was conducted during late-summer low-flow conditions. The river discharge was approximately 7,000 cfs. High-flow winter conditions are much greater, with a two-year flood hydrograph discharge of about 50,000 cfs. At the time of the field investigation, local scour around the spur dikes and general streambed erosion had not yet had an opportunity to adjust to initial high water discharge. The scour was therefore expected to increase during the following winter season.

Table 10 contains the prototype spur dike lengths in terms of the river width, spacing ratios in terms of both the spur dike length and river width, and initial scour hole depths.

The prototype spacing ratios in Table 10 are greater than the typically recommended values of  $2L$  to  $4L$  given in Table 3. However, there was no observed bank erosion between the dikes. The current velocities are greatly accelerated in the vicinity of the spur dikes (see Figure 22) as separate dike currents are formed around the dikes and converge with the main channel flow. At dike 7, the dike current velocity was recorded to be approximately equal to the main channel current velocity. In the compartments between the dikes, the velocities were reduced to zero and an upstream current formed due to eddy effects.

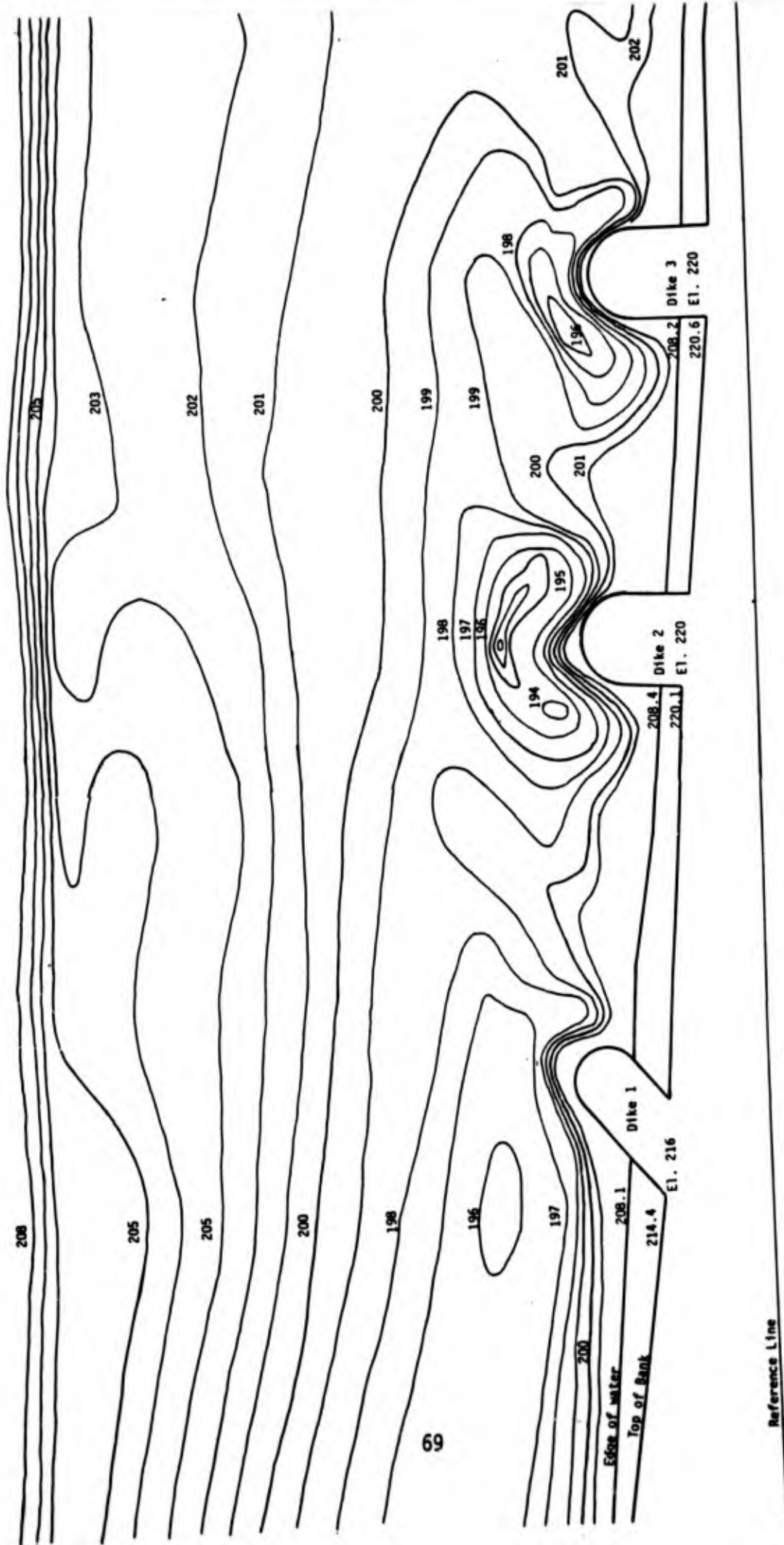


Figure 25. Contour Map of River Bed at Spur Dike Field, 14 September 1983

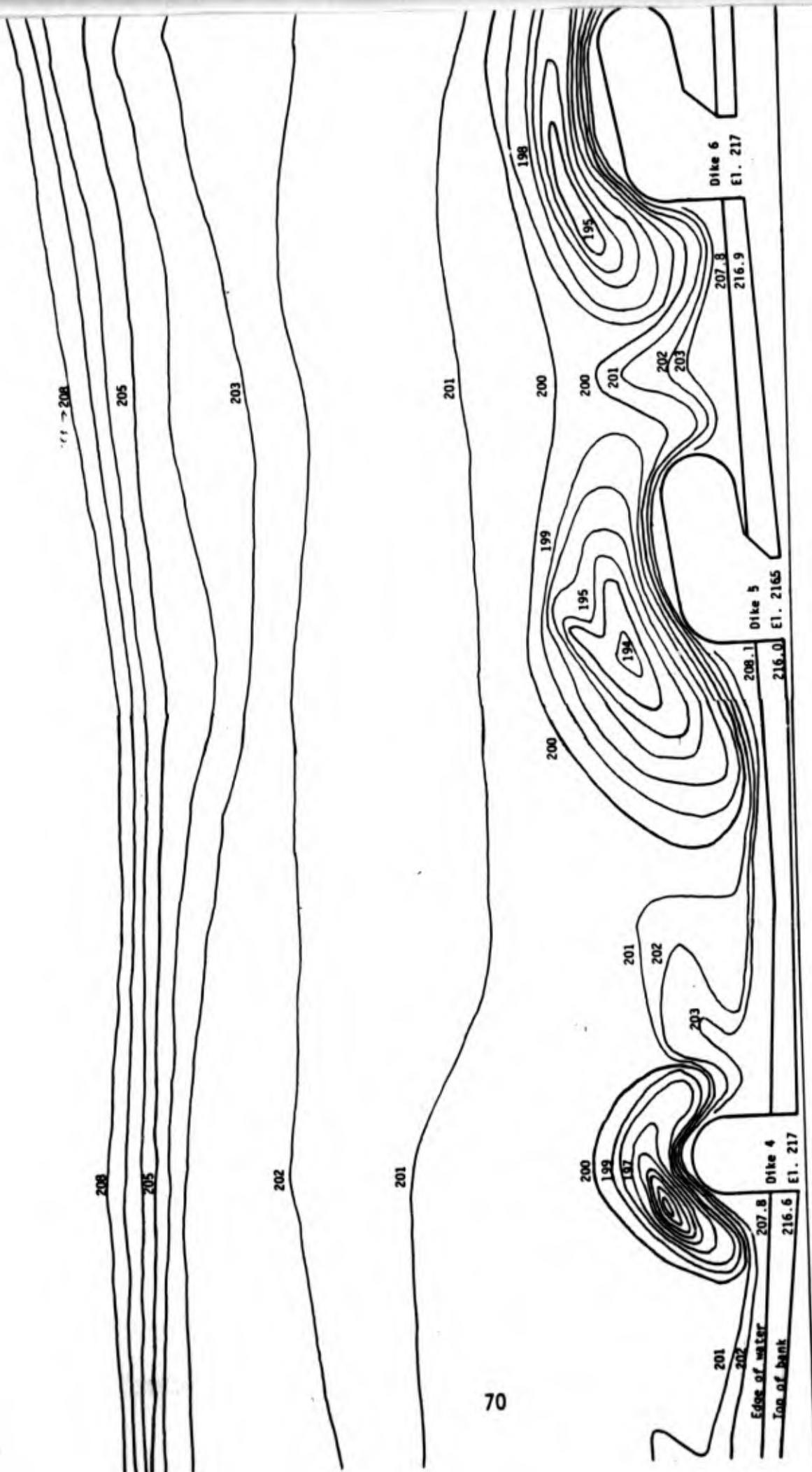


Figure 25. Continued

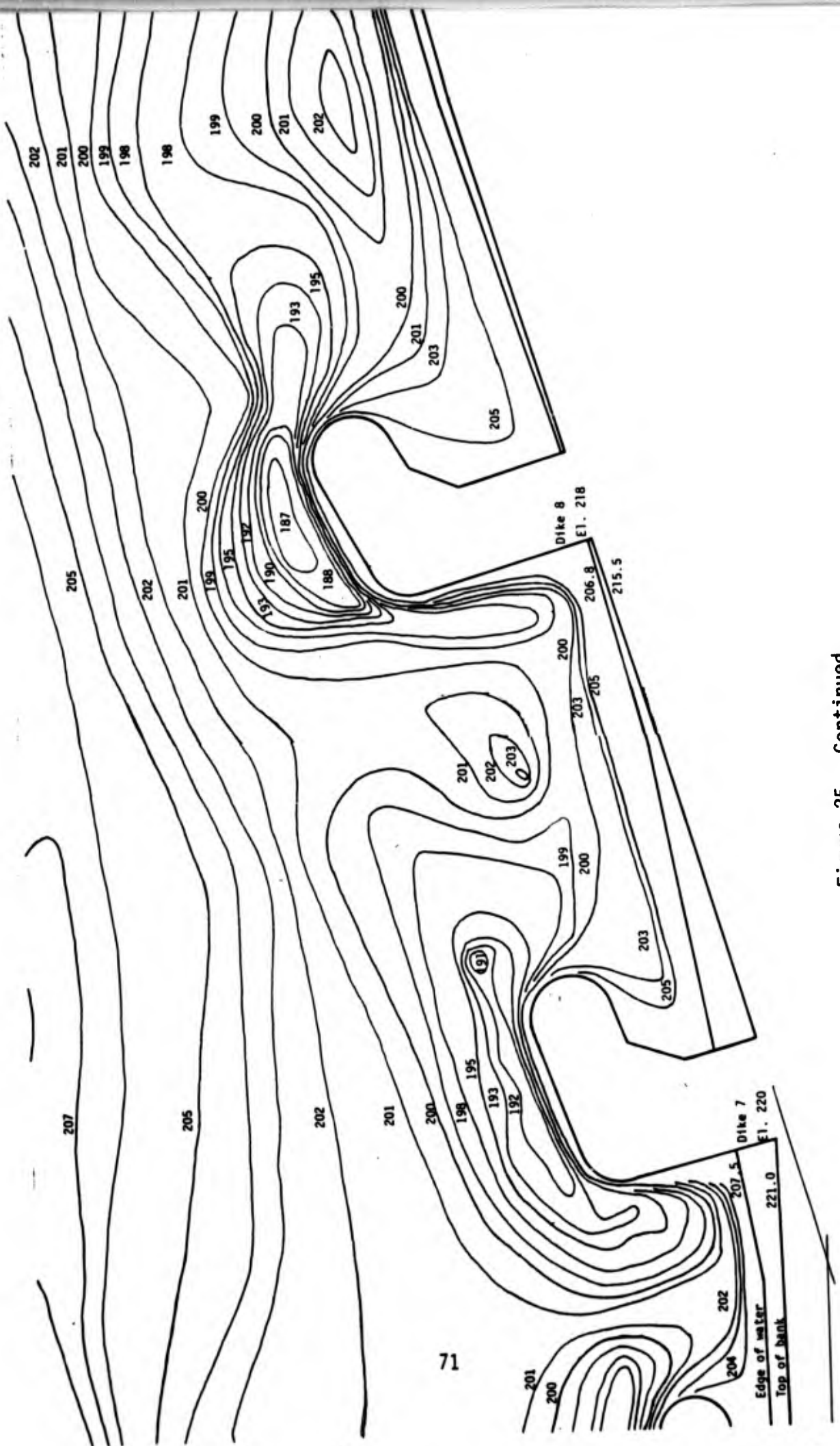


Figure 25. Continued

Table 10. Spur Dike Lengths, Spacing Ratios and Initial Scour Hole Depths in Prototype Spur Dike Field

Spur Dike Number	Length/Width (In terms of W)	Spacing/Length (In terms of L)	Spacing/Width (In terms of W)	Initial Scour Hole Depth (ft)
1	9.1	6.0	0.65	4
2	9.1	4.4	0.52	5
3	7.7	5.6	0.72	4
4	7.7	8.0	0.81	8
5	12.0	6.3	0.64	6
6	7.7	3.7	0.60	5
7	4.7	4.0	0.88	10
8	4.3			13

## VII. SUMMARY AND CONCLUSIONS

Local scour around spur dikes and the degree of bank protection provided by spur dikes are affected by a multitude of factors, including characteristics of the spur dikes themselves and the flow kinematics of the stream.

While the general qualitative effects of many factors have been researched and documented, few quantitative relationships exist to be of use as design aids. Recommended spur dike orientation angles and spacing ratios vary greatly, depending on the researcher and source. Equations for predicting scour hole depths around spur dikes are questionable, as the results deviate greatly. Model testing may be the most important and effective means to predict results and aid in the design process.

In this report, various spur dike shapes, orientation angles and arrangements have been investigated both experimentally and with a prototype field study. Under the limitations imposed by the model, the following major conclusions can be made:

- (1) The degree of bank protection provided by spur dikes is a function of the spur dike length, orientation angle and spacing.
- (2) As the length of the spur dike increases, the protected distance downstream of the dike to where bank erosion begins to occur increases, but not proportionately with the increasing spur dike length. In the model tests, a spur dike could protect a bank from 2.5 to 4.5 times its own length, depending upon the spur dike length.

- (3) Upstream-oriented spur dikes are more efficient in deflecting the river current away from the bank. Downstream-oriented dikes seem to attract the current towards the bank. Upstream-oriented spur dikes thus provide bank protection farther downstream from the dike tip than downstream-oriented spur dikes.
- (4) Upstream-oriented spur dikes cause greater scour holes in terms of area than do downstream-oriented spur dikes. This is because of the increased flow turbulence resulting from the upstream orientation. If it may be inferred that the scour hole depth also increases as the area increases, than upstream-oriented dikes also cause deeper scour holes.

These conclusions are consistent with past studies and literature cited in Chapter IV of this report.

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## APPENDIX 2. LIST OF SYMBOLS

B = average width of approach channel

b = average width of contracted channel

B<sub>1</sub> = original channel width

B<sub>2</sub> = constricted channel width

C = sediment concentration by weight

$$C_D = \text{drag coefficient} = 1.33 \frac{\Delta \gamma_s D_{50}}{\omega^2 \rho_w} = 1.33 \frac{(\rho_s - \rho_w) g D_{50}}{\omega^2 \rho_w}$$

d<sub>s</sub> = limiting depth of scour below original bed level

D = average depth of flow

D<sub>50</sub> = median grain size of bed sediment

F<sub>bo</sub> = Blench's "zero bed factor" = function of grain size

$$F = \text{Froude number} = \frac{V}{\sqrt{gh}}$$

F<sub>n</sub> = F

$$f = \text{Lacey silt factor} = 1.59 \sqrt{D_{50, \text{mm}}}$$

g = acceleration due to gravity

h = average depth of flow in uncontracted approach channel

h<sub>m</sub> = maximum depth of approach flow

k = function of approach conditions; k varies with investigator

K = function of C<sub>D</sub> and varies between 2.5 and 5.0

K<sub>β</sub> = factor accounting for effects of varying dike head slope on scour

L = effective length of spur dike measured normal to the bank from the dike base to the dike tip

m = contraction ratio = α

n = function of C<sub>D</sub> and varies between 0.65 and 0.9

N = dimensionless term for bed roughness = (n<sup>2</sup>g)/(h)<sup>1/3</sup>

N<sub>ns</sub> = term N applied to approach channel

N<sub>ns\*</sub> = term N applied to approach channel at beginning of scouring motion

$Q$  = total stream discharge

$q$  = stream discharge per unit width at constricted section

$r$  = assumed multiple for scour at dike compared with scour in a long contraction (taken to be 11.5 by Laursen)

$U_m$  = maximum velocity of approach flow

$V$  = average velocity in uncontracted approach channel

$W$  = width of uncontracted channel

$X_1$  = distance from dike base to downstream bank point where erosion begins

$X_2$  = distance from dike base to downstream bank point where main current impinges

$X_3$  = like  $X_1$  but measured from dike tip

$X_4$  = like  $X_2$  but measured from dike tip

$y$  = average depth in uncontracted section

$y_s$  = equilibrium scour depth measured from the water surface

$\rho_s$  = specific density of bed sediment (mass per unit volume)

$\rho_w$  = specific density of water (mass per unit volume)

$\alpha$  = contraction ratio =  $\frac{B-b}{b}$

$\beta$  = angle between the side slope of dike and vertical plane

$\theta$  = dike orientation angle between axis of dike and downstream bank (or channel thalweg)

$\mu_{gd}$  = term describing the size gradation of the bed material

$\mu$  = absolute viscosity of water

$\omega$  = settling velocity of sediment

$\Delta\gamma_s$  = difference in specific weight between sediment and water =  $(\rho_s - \rho_w)g$

$\xi$  = ratio of  $D_{85}$  to  $D_{50}$  for bed sediment

$\tau_c$  = critical bed shear stress

$\tau_{ns}$  = bed shear stress in approach channel

$\tau_{ns}^*$  = bed shear stress in approach channel at beginning of scouring motion

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