PAP-641

MUDDY CREEK DEMONSTRATION PROJECT
(Review of proposed plan for limited channel reclamation)

January 21, 1994

by

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January 21, 1994

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RE: Muddy Creek Demonstration Project

Dear Rod:

In accordance with your request and subsequent to our meeting of January 18, 1994, we have reviewed your proposed plan for limited channel reclamation, which was based on a survey by the USDA, SCS for the Muddy Creek Demonstration Project. As a result of our review and discussions of the project, we have several comments, recommendations, and/or suggestions for your consideration. Please note that these recommendations are based only upon a review of the plan and profile drawings. Our comments follow:

1. The scope of the project is limited by the budgetary constraints pertaining to construction materials (i.e., riprap and filter material). We recommend that priority be in constructing stable drop structures/sills and that the barbs (dikes) be considered a second priority. Should a drop structure(s) fail, the stabilization effort in the entire reach will be in jeopardy. However, should a dike fail, the negative impact will most likely be local.

2. It is apparent that a systems approach to stabilizing the stream was not implemented. The adjacent upstream and downstream reaches will remain unstable after construction of the proposed demonstration project. Therefore, the results of the stabilization may be relatively short term.

3. Proper construction staging may be a key component to maximizing the Muddy Creek study reach reclamation plan. The recommended staging sequence is:

   a) Construct the cutoff bends first. Then, learn to construct the drop structures beginning with a one (1) ft structure (i.e., structure 1E). Complete construction of the two (2) ft structures located in the upper end of the reach before conclusion of the first construction season. Dike placement should follow the construction of the first stage structures unless a second construction crew is available.

b) Construct the lower reach, one (1) ft structures (i.e., 1A, 1B, 1C, and 1D) after stabilizing the upper reach. Then, complete dike placement throughout the reach.

4. It is recommended that drop structure 1E be moved approximately 450 ft downstream from the proposed location in cut 2 to Station 95. The structure stability will increase in the straight reach. The chances of flow by-passing the structure will be reduced.

5. It is recommended that dikes be keyed into the bank and be placed either perpendicular to the bank or be directed in the upstream direction. Furthermore, all dikes do not need to be the same length. Dike length should increase as flow migrates through the dike field. Gradual lengthening of the dikes will enhance the training of the flow.

6. It is recommended that an additional dike be considered for placement upstream of Station 96. The proposed dike placement does not lend to training the flow entering the bend.

7. It is recommended that a dike be considered for placement at or near Station 77.

8. It is suggested that a riprap apron be constructed along the downstream edge of the drop structure. The current design may enhance local scour downstream of the drop structures thereby placing the structure stability at risk. The apron will protect the structure from local scour and headcutting.

9. Consider placing a longitudinal toe dike along each bank downstream of each drop structure. The dike should tie into the drop structure. The dike should be constructed with 1.5 to 2 tons/ft of riprap per foot of bank.

10. A filter cloth or bedding material is recommended beneath each structure. However, filter/bedding is not recommended beneath each dike.

11. The proposed Muddy Creek Demonstration Project should assist in stabilizing the study reach. However, once the sediment yield is reduced through the reach, degradation may resume.

12. It is recommended that a monitoring program be initiated to record/document the performance of the proposed demonstration project. The monitoring program should include the following components:

    a) Repeat surveys of comparative cross-sections;

    b) Monitoring of the discharge and water surface slope;

    c) Photographic documentation of pre-construction, construction, and semi-annual post-construction conditions of all excavation and stabilization structures;

    d) Monitor the sediment size distribution of the bed in the upper reach, mid reach, and lower reach;

    e) Conduct an annual inspection of the drop structures and the dikes.

Cross-sections should be monumented on both banks using rebar placed a distance back from the top bank to minimize loss. Each section should be generally perpendicular to the channel flow direction. Both monuments should be labeled. Our experience using aluminum tags made for gardening purposes has been good. The detail of the survey should be sufficient to document all breaks in bed and bank slope, and the deepest point in the cross-section. Surveys should be made annually. Spacing of the cross-sections should not exceed 500 feet, and all surveys should be on a common datum.

A continuous record of the channel discharge is very valuable. Hopefully, a gauging station exists upstream or downstream of the study reach. To obtain water surface slope, we suggest that three staff gauges be installed along four reaches, each approximately 1000 feet in length, for a total of 12 staff gauges. The reaches should be evenly spaced along the reclamation reach. Each series of three gauges should be read at about the same time, say within 30-60 minutes, and all 12 gauges should be read without a change in discharge. With a known distance between gauges and a common datum, a record of water surface slope can be developed. Perhaps someone living near the site can be given a field data sheet for recording these data. As an alternative or in addition, crest gauges could be installed at the same locations to record the maximum flows.

Photographic documentation of the proposed construction sites prior to construction, during construction, immediately following construction, and semi-annually thereafter should be made. The survey party for the cross-sections should follow the same procedure, and all slides should be cataloged and stored in a common location. Video tape may also be considered.

Sediment samples of the bed should be taken before construction, immediately after construction, and annually thereafter in at least three (3) locations in the study reach. The grain size distributions should be monitored to track changes in the sediment yield of the reach and the sediment characteristics.

The drop structures and barbs should be inspected annually. Since the riprap tends to move/adjust to a multitude of flow conditions, monitoring the structure will provide feed-back for repairing structures, determining the life of the structures, and providing input for altering structure design criteria. Since this is a demonstration project, design criteria for these structures must be compiled and refined for application to other stream systems.

Based upon our experience in monitoring other sites (i.e., Mississippi streams, Rapid Creek, SD, etc.), it is advantageous to have continuity in the persons performing the monitoring. A constant change in personnel performing the work results in inefficiencies in data collection and even the quality of data recorded.

Thank you for the opportunity to provide these comments, suggestions, and recommendations pertaining to the Muddy Creek Demonstration Project. We will be pleased to provide further explanation of these comments if desired. Do not hesitate to contact us if you have questions relating to any of our recommendations.

Respectfully submitted,

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LITERATURE REVIEW

General - A number of erosion control structures and techniques are available to the engineer for controlling the bank erosion that naturally occurs along alluvial rivers. The Sacramento District has proposed that bank erosion at RM 192.4 on the Sacramento River be controlled with a permeable fence/fabric net dike system. The following sections present a literature review of bank protection measures in general, with specific emphasis on design guidelines for construction of permeable dikes.

Stream Bank Erosion Control Techniques - Two general techniques are available for the protection of stream banks from erosion. One group of stream bank erosion control practices involves the placement of structures or materials that resist the erosive force of flowing water directly on the bank. A second group involves a more indirect method in which structures are built to divert the erosive flow from the bank or to reduce the velocity of flow immediately adjacent to the eroding stream bank. The use of one type of erosion control method over another is dictated by a number of factors including size of river, cost, related navigation projects, bank materials, other site specific characteristics and ecological considerations.

Traditional methods of bank protection that involve placement of erosion resistant material include riprap, concrete paving, articulated concrete mattress asphalt mix, vegetation, gabions, erosion control matting and bulkheads (Thackston and Sneed, 1982). Newer forms of erosion include tire matting: membrane/soil cement systems; chemical stabilization, honeycomb matrices filled with cement, sand or soil; filter fabric; and waste or surplus products (such as portion of temporary bridges, etc.). For the above materials and techniques to provide successful erosion control, the eroding bank must be graded to a stable angle and smoothed in preparation for placement of the material. Considerable disruption of the existing bank and overbank areas often result from placement of this type of erosion control system (King, 1986). However, riprap can be utilized with or without bank shaping and is one of the most successful and common stream bank protection methods.

Flow is diverted from eroding banks by placement of dikes or extension of dikes outward from the bank generally perpendicular to the flow (Winkley, 1971). Revetments are placed parallel to the flow along eroding stream banks; these structures also keep the flow from contacting the bank (Figure 1).

Methods that reduce the flow velocity adjacent to the stream bank include placement of jacks, jack fields, permeable fences or flexible netting and pile dikes. All these structures reduce flow by increasing flow resistance. Pile dikes, once used at numerous locations on the lower Mississippi River, have almost all been reinforced with stone dumped around the base of the piles (Winkley, 1971). Jacks, jack fields and other permeable dikes have been utilized on numerous rivers with varying degrees of success. They can be placed with less cost and minimal disruption of the existing bank (Richardson et al., 1987).

<u>Dikes</u> - Dikes fall under the category of an erosion control or flow diversion structure extending roughly perpendicular from a stream bank that either diverts flow from the bank or reduces flow velocity adjacent to the bank. Dikes can be distinguished as either permeable or

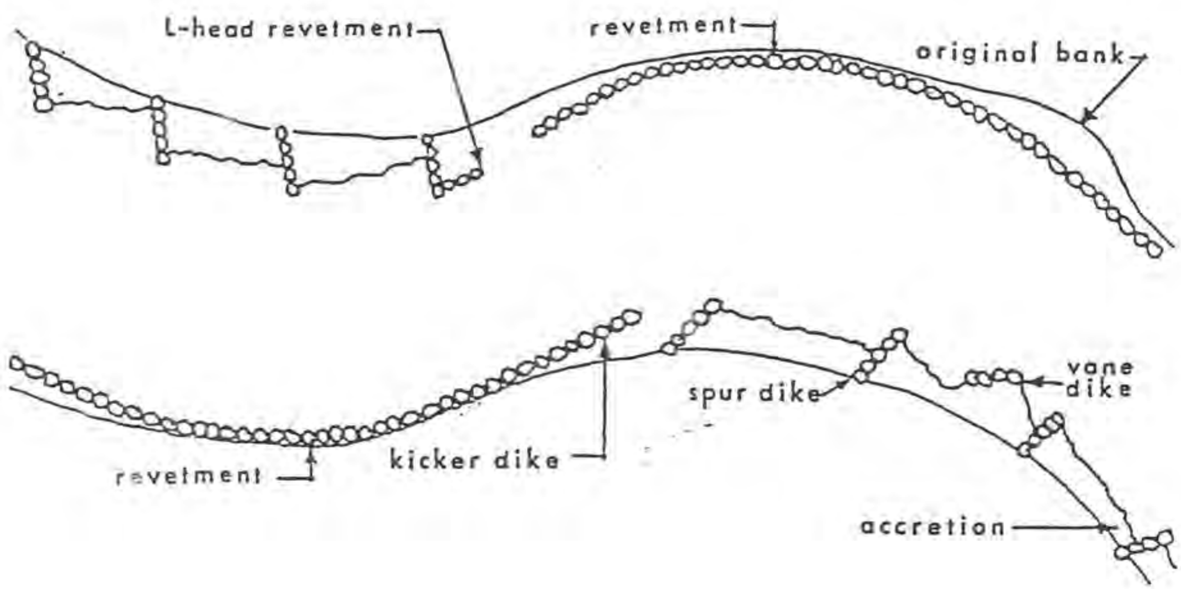


Figure 1 Typical arrangement of different dike types common to the Missouri River (from Thackston and Sneed, 1982).

impermeable (Winkley, 1971; Brown, 1985). A permeable dike is also known as a retardance structure because its main function is to reduce flow velocity (Fenwick, 1969). Impermeable dikes are known as diverter structures because their main function is to redirect flow. Brown (1985) presents criteria for selection of appropriate dike systems (Table 1).

Permeable Dikes - Jacks, jack fields, board fences and flexible netting systems fall into the specific category of permeable dikes. The permeability of each dike system varies and is important in selecting the system for a specific application (Richardson et al., 1987).

Jacks typically are constructed of steel or concrete in one of two forms known as Kellner and tetrahedron jacks (Figure 2). Individual jacks are reinforced with wire, then tied together with cable to form a jack field. Success of this highly permeable jack field depends upon trapping debris and sediment. Therefore, jack fields function optimally in systems with high sediment transport.

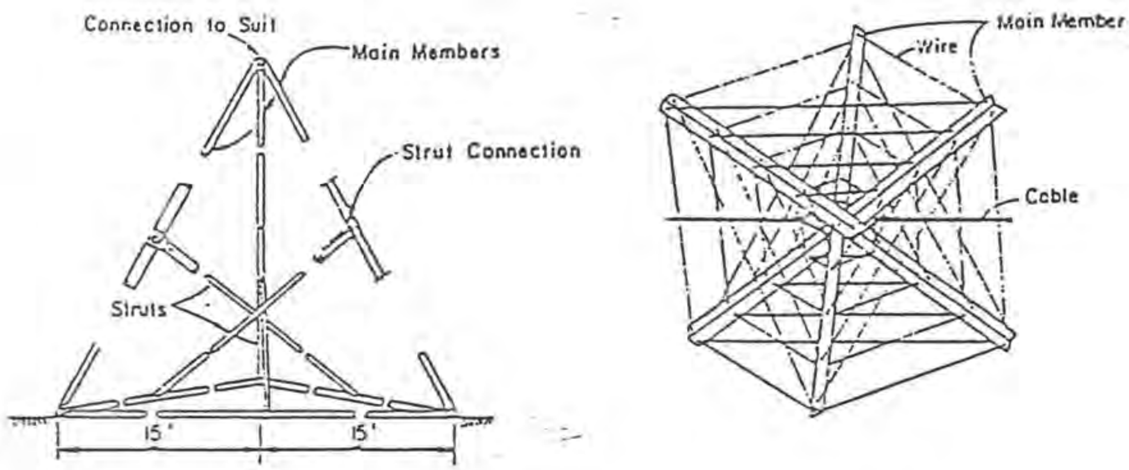
Fencing and netting are low cost, relatively non-disruptive methods of stream bank erosion control for small- to medium-sized streams (Richardson et al., 1987). A number of special consideration must be made to ensure success of these structures (Richardson et al., 1987): 1) fence structures must be designed to withstand floating debris such as ice and/or trees; 2) these structures must promote sediment deposition and vegetation establishment; 3) erosion protection should be provided at the toe of dikes to prevent failure due to scour and at the bank end of dikes to prevent flanking of the fence. Two examples of permeable dikes marketed under

Table 1 Spur Type Selection Table (from Brown, 1985).

SPUR TYPE	FUNCTION			EROSION MECHANISM				SEDIMENT ENVIRONMENT			FLOW ENVIRONMENT						BEND RADIUS			ICE/DEBRIS ENVIRONMENT		
											VELOCITY			STAGE								
RETARDANCE																						
Fence Type	3	2	2	3	3*	1	1	4	3	2	3	3	2	3	2	1	3	2	1	3	3	2
Jack/Tetrahedron	3	3	1	3	3	1	1	4	3	1	3	2	1	3	2	1	3	2	1	2	4	1
RETARDANCE/DEFLECTOR																						
Light Fence	3	3	3	3	3	2	2	3	3	2	3	3	2	3	3	2	3	3	2	3	4	2
Heavy Diverter	3	4	4	3	3	4	3	2	3	3	3	3	2	3	4	4	3	3	2	3	4	3
DEFLECTOR																						
Hardpoint	3	4	4	3	3	3	4	2	3	4	3	3	4	3	3	2	3	4	4	3	3	5
Transverse Dike	3	4	4	3	3	3	4	2	3	4	3	3	4	3	3	2	3	4	3	3	3	5

* Henson spur jetties are rated a 4 for this condition

1. Definite disadvantage to the use of this type structure.
2. Some disadvantage to the use of this type structure.
3. Adequate for condition.
4. Some advantage to the use of this type structure.
5. Significant advantage to the use of this type structure.



(a) Typical Tetrahedron (b) Kellner Jack

Figure 2 Types of steel jack systems (from Richardson et al., 1987).

specific trade names are the Henson Dike Jetties (Brice et al., 1987) and the Ercon Palisades (King, 1986).

Environmental Effects of Dike Systems - Placement of dikes along the banks of a river system can have both positive and negative impacts on the aquatic biota within the river. Impacts due to construction of dikes are considered minimal (Shields and Palermo, 1982). An initial, short-term effect of dikes is the creation of spawning and nursery habitat for fish; however, long-term effects may include the reduction in backswamp, oxbow lake and other overbank habitat (Sandheinrich and Atchison, 1986).

The purpose of dikes is to reduce flow velocities adjacent to the stream bank, thus creating areas of backwater, eddy current, or protected areas conducive to various types of aquatic biota. Therefore, the initial placement of dikes or a dike filed will create new aquatic habitat (Sandheinrich and Atchison, 1986).

Sampling of aquatic biota near a variety of bank protection measures on the Missouri River revealed that the most diverse fish community of all sampled sites was located in dike fields (Burress et al., 1982). However, community composition is less stable in dike fields because habitat conditions depend upon stage and velocity, which can change throughout a wide range. The long-term effects of dikes on aquatic habitat can be harmful for several reasons. First, and most often observed, is that sediment accumulates downstream from dikes (Figure 3), eventually converting the downstream area to a terrigenous habitat (Sandheinrich and Atchison,

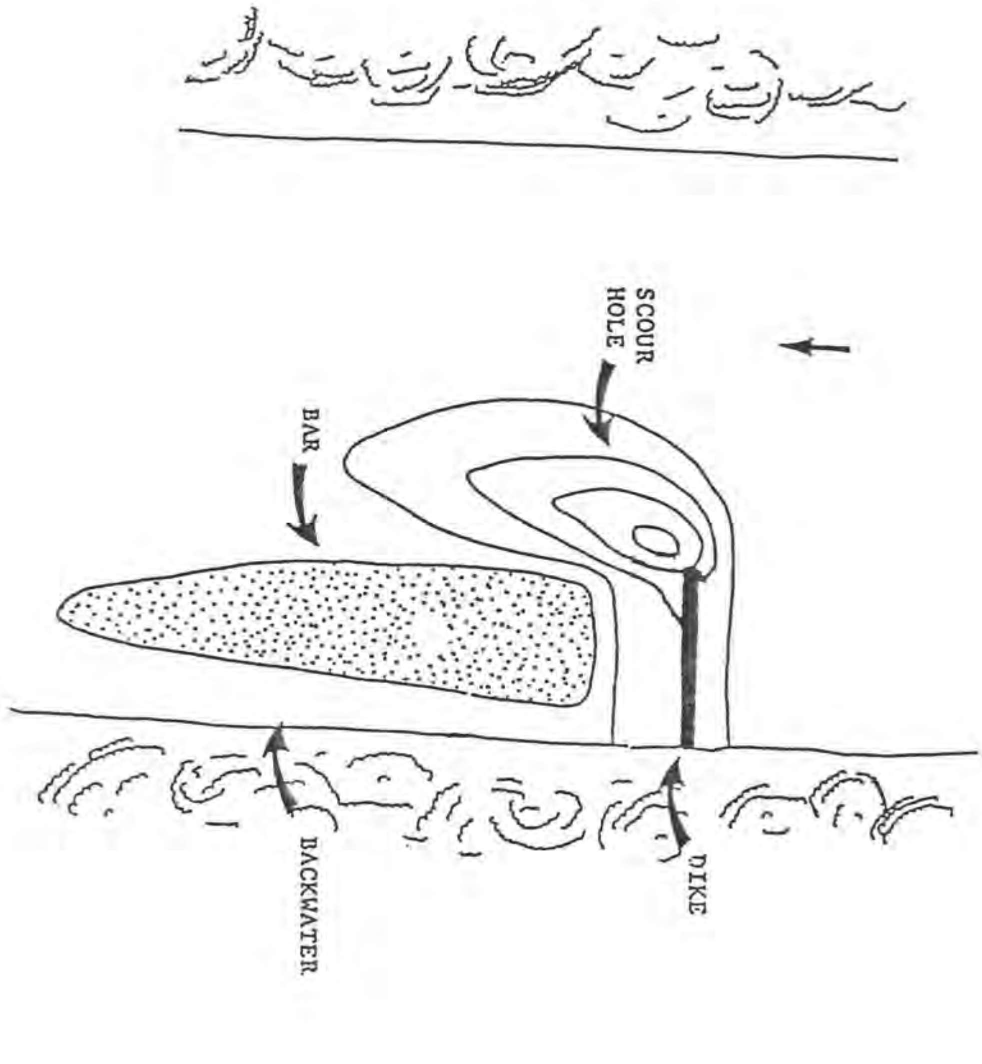


Figure 3 Typical morphological effects of an isolated dike. A local scour hole forms at the channel end of the dike. The scoured sediments are deposited in a bar immediately downstream from the dike. A backwater area is formed between the bar and the bank behind the dike (from Burch et al., 1984).

1986). Notches have been placed in several impermeable (rock) dikes, thus successfully preventing the build-up of sediment that destroys the aquatic habitat (Shields and Palermo, 1982). Other reasons for loss of habitat stem from dike systems' inherent design that constricts flow in the main channel. This includes degradation, lowering of water-surface profiles and drainage of backwater areas. In addition, the stabilization of stream banks restricts alluvial river migration.

Burch et al. (1984) summarize the effects of dike fields on aquatic habitat (Table 2) and present guidelines for the environmental design of impermeable dike systems. The primary means of reducing sedimentation downstream of dikes is with placement of notches in the crest of individual dikes (Figure 4) to enhance flow through backwater areas behind the dikes. Myers (1986) points out that notches are also used to preserve or renew shallow water areas within dike fields in order to maintain or increase total water-surface area and thus conveyance.

In virtually all cases, the study of environmental impacts of dikes is restricted to impermeable rock dikes; however, Michny (1988) summarized the results of monitoring at a permeable dike installation on the Sacramento near Woodson Bridge. Sites utilized in developing data were the permeable dike site at Woodson Bridge State Recreation Area, three natural banks utilized as controls, and one riprapped site. Fish abundance studies were conducted at each site, changes in nearshore aquatic habitat noted, and a photographic record of wildlife habitat continued.

Table 2 Summary of effects of environmental features on dike field habitat.

ENVIRONMENTAL FEATURE	SCOUR	SEDIMENT DEPOSITION	LOCAL CURRENT VELOCITY	WATER DEPTH
ACTUAL				
1) NOTCHES				
Dike Notches	Scour hole forms immediately downstream of notch	Sandbars form downstream of unnotched portion of spur dikes and closure dikes	Flow accelerates through notch. Flow patterns in vicinity of notch exhibit a wide range of velocity magnitudes and directions	Wide range of depth and diversity of flow conditions
Culverts		Culverts tend to fill in with sediment	Velocity slightly increases culverts	
2) LOW-ELEVATION DIKES	Scour hole forms immediately downstream of the dike	Submerged bar develops downstream of scour hole, sediment accretion sometimes occurs level with the crest elevation of the dike	Local velocities increase as flow passes over slightly submerged dikes. Flow acceleration is insignificant when submergence is more than 5-6'	Depending on location and structure dike field depths may either be maintained or decreased
3) ROOTLESS DIKES Rootless Spur Dikes Rootless Vane Dikes	Scour hole downstream of each end of dike, may cause bank scour	Shallow bar develops immediately downstream of the dike, typically also develops multiple secondary channels and other sandbars	Velocities increase around both ends of the dike, often forming eddies	Local depth change according to pattern of scour and sediment deposition
4) MINIMUM MAINTENANCE				
All Dikes	Variable	Variable	Local velocity increases as flow overtops the dikes	Variable
POTENTIAL				
5) DREDGING TO REMOVE SEDIMENT*		Sediment will deposit in dredged area if it is an area of natural deposition		Increase depths where dredged
6) DISPOSAL OF DREDGED MATERIAL*	Dredged material may be scoured	Placement of dredged material may encourage additional sediment deposition		Decrease depths where dredged material is placed
7) RELOCATE NOTCHES*	Create new scour holes downstream of notches	Create new sandbars or shaft existing sandbars to fit new flow patterns	Local velocity increases through notch	Diversity of depths
8) PLACING ADDITION ROCK*	May create scour holes downstream of rock piles or single boulders	May cause sediment deposition upstream of rock piles	Local increase in velocity as flow passes over or around rock obstacles	
9) ARTIFICIAL REEFS*			Slight velocity decrease as current passes through reef	
10) GATES IN CLOSURE DIKES*	Reduced scour by reduced entry of erosive flows dependent on gate operation	Sediment deposition may increase, dependent on gate operation	Velocity will decrease, dependent on gate operation	Goal would be to maintain depths while excluding some sediment-laden flows

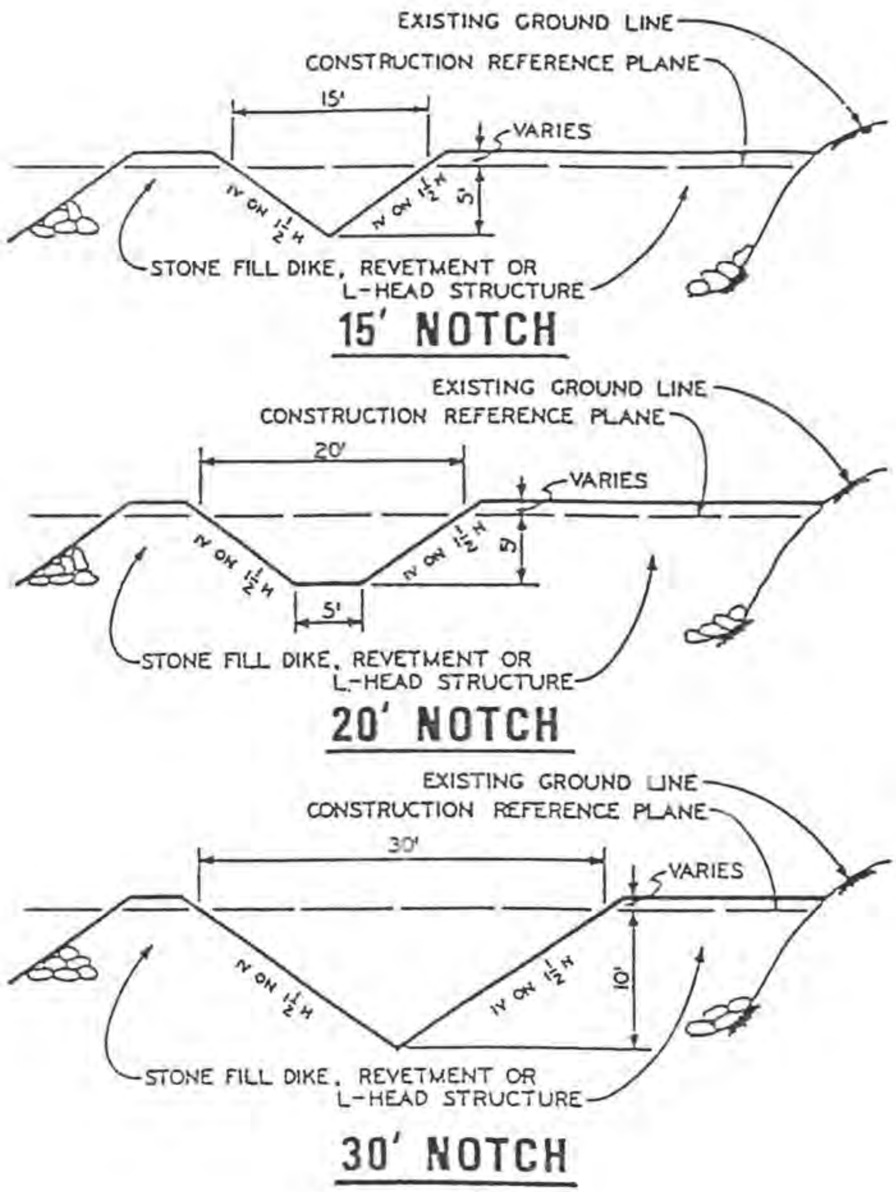


Figure 4 Notch design; as-built dimensions varied considerably from these designs (from Omaha District, 1982).

Juvenile salmon, the primary aquatic study species, were found to utilize all sites (Table 3). The fewest juvenile salmon were observed at the riprapped site. The relative abundance of juvenile salmon at the dike site increased following construction. Based upon the two years of available post-project data, the permeable dike was found to be comparable to natural banks in terms of juvenile salmon, rearing habitat values, and clearly superior to rock revetment. The primary area used by salmon at the palisades was near the waterward panels. Data on abundance of other fish species encountered are provided in Table 4. Table 4 indicates that the riprap site yielded the largest number of fish in 1988 (45.5 fish per minute) and had the greatest average diversity for the three sampling periods. Table 5 shows that the diversity includes four species not found at the natural sites.

Salmon spawning activity was noted prior to construction in the fall of 1986 at the permeable dike site. Following construction, no salmon spawning occurred. However, Michny (1988) reports that this change may have resulted from natural erosion changes prior to dike construction. Michny (1988) noted that, in most cases, wildlife values are directly related to the vegetative cover present. The entire project area with the exception of the steep eroding banks can be considered high value habitat for those species normally associated with riparian ecosystems. While not generally considered good wildlife habitat, the steep eroding banks provide the proper conditions for hole-nesting birds such as bank swallows, rough-winged swallows and kingfishers. The bank swallow, a species of special concern in California, is being considered for listing as a State Threatened Species. A large company of about 3,400 burrows of these colonial nesting swallows was present prior to palisade construction. The 3,400

Table 3 Normalized catch per minute of juvenile salmon during spring-summer sampling periods (from Michny, 1988).

	1986	1987	1988
Permeable Dike Site	.43*	.74	.55
Natural Sites	.99	.94	.53
Difference Palisade relative to natural sites)	-.56	-.20	+.02

* Prior to permeable dike construction.

Table 4 Total number of species collected and catch per minute of electroshocking electofishing station, 1986, 1987 and 1988 spring study periods (from Michny, 1988).

	A Natural	B Riprap	C Palisade		D Natural	E Natural
Total number of species						
1986	9	11	14	(1)	6	11
1987	8	9	8		6	10
1988	9	10	11	(2)	4	8
Avg.	8.7	10.0	9.5		5.3	9.7
Actual fish per minute of electroshocking						
1986	11.2	13.0	6.5	(1)	8.7	21.3
1987	27.5	19.6	28.5		11.6	38.2
1988	25.2	45.5	28.8	(2)	9.0	36.0
Avg.	21.3	26.0	28.7		9.8	31.8

(1) Permeable Dike site prior to construction.
(2) Average diversity following construction.

Table 5 List of species collected, occurrence at electrofishing transects 1987-1988 study period (from Michny, 1988).

		A Natural	B Riprap	C Permeable Dike	D Natural	E Natural
American shad	**Alosa sapidissma**	X		X		
Chinook salmon	**Oncorhynchus tshawytscha**	X	X	X	X	X
Rainbow trout	**Salmo gairdneri**	X	X	X		X
Steelhead trout	**Salmo gairdneri gairdneri**	X				
Hardhead	**Mylopharodon conocephalus**	X	X	X		X
Sacramento squawfish	**Ptychocheilus grandis**	X	X	X	X	X
Sacramento sucker	**Catastomus occidentalis**	X	X	X	X	X
Bullhead	**Ictalurus sp.**		X			
Threespine stickleback	**Gasterosteus accleatus**		X	X		
Bluegill	**Lepomis macrochirus**		X			
Green sunfish	**Lepomis cyonellus**		X			
Smallmouth bass	**Micropterus dolomieui**	X	X	X		
Tule perch	**Hysterocarpus traski**	X	X	X		X
Pricky sculpin	**Cottus asper**	X	X	X	X	X

burrows were roughly evenly distributed within two areas along the downstream third of the proposed palisade site. This was one of the two largest of 60 colonies known along the Sacramento River.

In the spring-summer of 1987, the colony was smaller, numbering about 1,000 burrows, and utilized only one of the previous year's two areas. In 1988, the colony was considerably smaller, numbering about 200 burrows. While bank swallow colonies do change naturally over time, the exact cause of this reduction in nesting population is unknown. It is surmised to be related to the presence of the palisades. Biological data gathered to date indicate that bank swallows prefer an unobstructed flight path into and away from burrow sites. The presence of the palisade structure clearly interferes with this behavior (Michny, 1988).

Design Guidelines for Dike Construction - At present, there are no specific criteria for the design and construction of dikes, revetments and other river training and stabilization measures. Winkley (1971) describes river engineering as a rule of thumb art; Burch et al. (1984) note that dike field design is a mixture of engineering and art. The general consensus is that design of dike systems depends heavily on previous experience and engineering judgement (Fenwick, 1969; Thackston and Sneed, 1982).

Nevertheless, there are general guidelines for designing dikes and dike fields. During the process of planning a dike field, a number of parameters (Figure 5) must be determined before a system can be constructed. The following sections describe each parameter in more

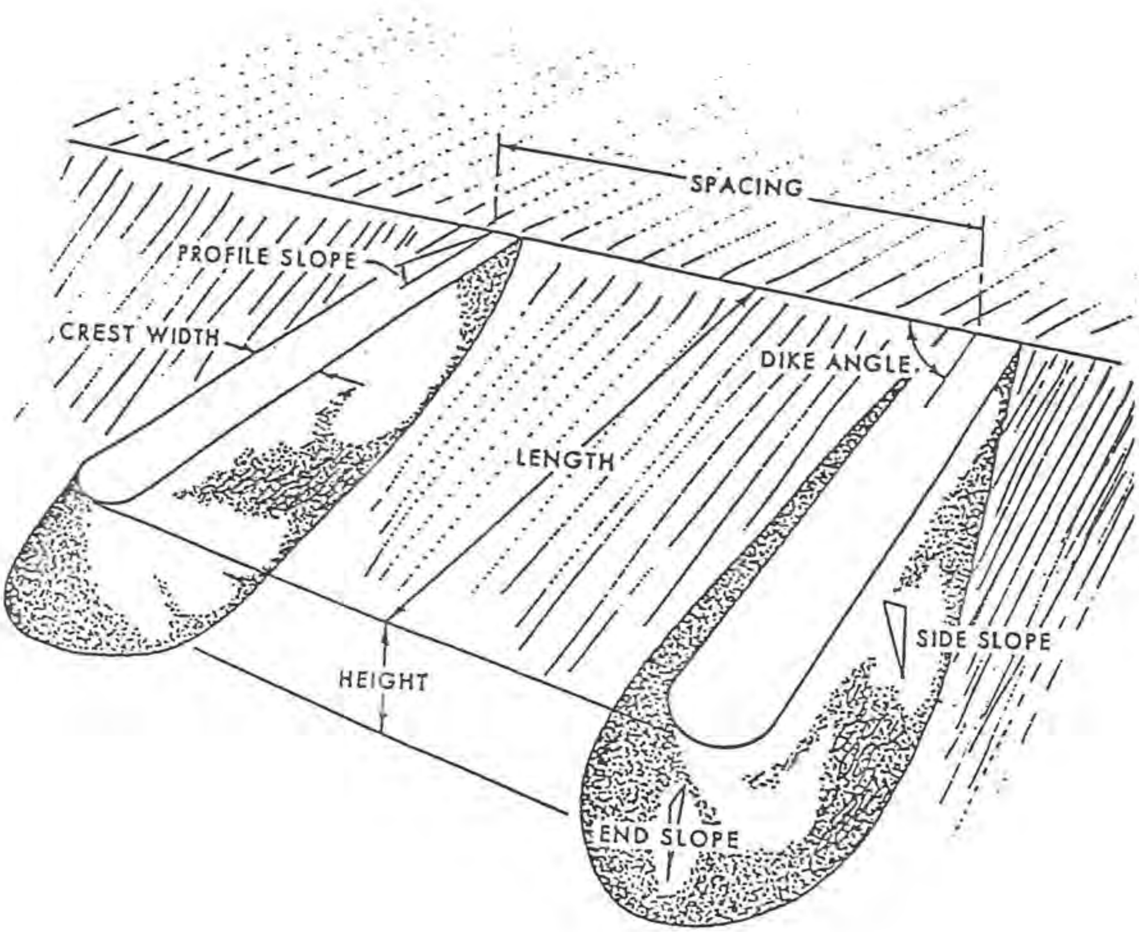


Figure 5 Basic design parameters for spur dikes (from Shields and Palermo, 1982).

detail and present guidelines that have been developed for each through previous experience or hydraulic model studies.

Extent of Channel Bank Protection - A common mistake in streambank protection is to provide protection too far upstream and not far enough downstream. Criteria for establishing the extent of channel bank protection have been developed by the U.S. Army Corps of Engineers (1981). These criteria are based on a series of model studies to define more completely the limits of bank protection as suggested by Parsons (1960). From these studies, it was concluded that the minimum distances for extension of protection are an upstream distance of 1.0 channel width and a downstream distance of 1.5 channel widths from corresponding reference lines as shown in Figure 6. A similar criterion for establishing the upstream limit of protection was found by FHWA (1983); however, a downstream limit of 1.1 ties the channel width was found. The FHWA study was not, however, as extensive in this respect as the COE study.

Erosion of the concave bank of a stream occurs because of convective acceleration in downstream flow (Henderson, 1966), and because of intensification of helical flow (Dietrich and Smith, 1984; Carson, 1986). Both are caused by flow convergence and are intensified as the radius of curvature of the bend decreases, which implies that meander geometry significantly affects bank erosion rates (Nanson and Hickin, 1983). As the radius of curvature of the bend decreases, the pool zone is constricted laterally because of vertical accretion of the point bar (Knighton, 1984; Carson, 1986). Therefore, the rate of concave bank erosion is dependent on the two-dimensional flow hydraulics and the bendway geometry, as well as the resistance to

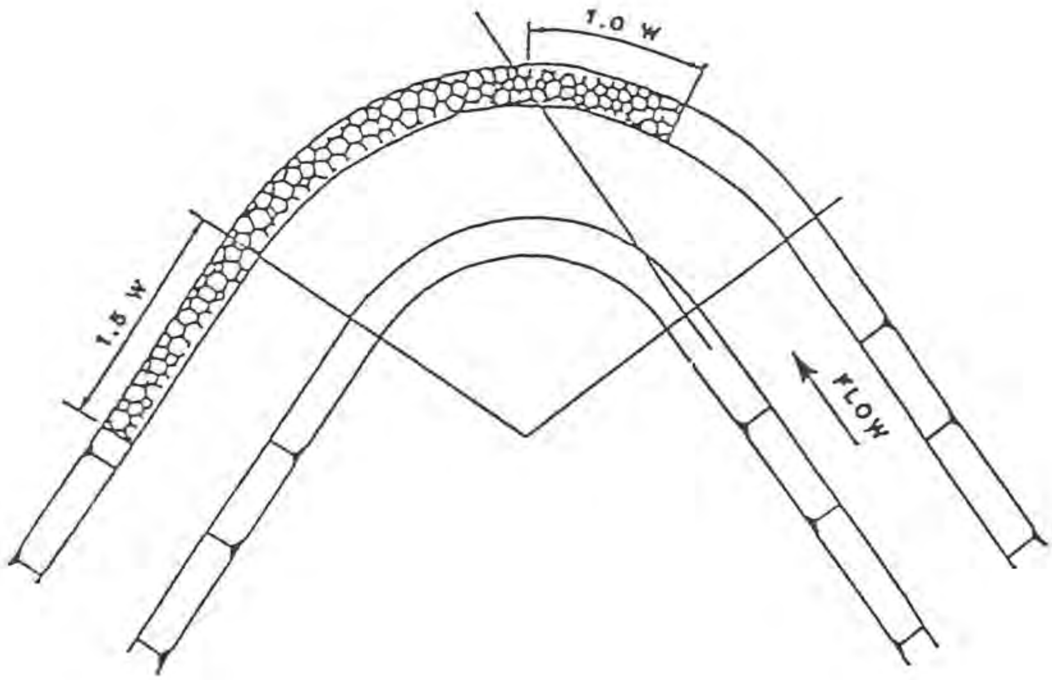


Figure 6 Extent of protection required around a channel bend (after U.S. Army Corps of Engineers, 1981).

entrainment of the concave bank materials (Nanson and Hickin, 1986), the duration and magnitude of the flows (Odgaard, 1987), and the capacity of the flows to transport bed-material sediment (Neil, 1984; Nanson and Hickin, 1986).

The location of the highest rates of bank erosion in a bend is also dependent on the radius of curvature of the bend (Bagnold, 1966; Leeder and Bridge, 1975; Nanson and Hickin, 1983, 1986). Channel migration, which involves both point bar deposition and concave bank retreat, is both a discontinuous and directional process (Nanson and Hickin, 1983). Initially, when the radius of curvature to width ratio (Rc/w) of the bend is greater than about 2.5, bend migration direction is transverse to the valley axis (extension), but when Rc/w is less that about 2.5, bend migration direction is down-valley (translation), (Bagnold, 1966; Brice, 1977; Knighton, 1984; Nanson and Hickin, 1983, 1986). Therefore, initial bank erosion rates will be highest near the apex of the bend, but eventually the highest erosion rates will occur along the downstream limb of the bend. Increased flow resistance in low radius of curvature bends can cause deposition of sediment in the upstream limb of the bend, which results in the formation of a mid-channel bar. Flow divergence around the bar can cause erosion of the concave bank in the upstream limb (Harvey, 1988).

The extent of bank protection should be evaluated using a variety of techniques, including: empirical methods, field reconnaissance, evaluation of flow traces for various flow stage conditions, and review of flow and erosion forces for various flow stage conditions. Information from these approaches should then be combined with personal judgment and a knowledge of the geomorphic processes occurring at the local site to establish the appropriate limits of protection.

Dike Length - Dike length is the projected length of the dike perpendicular to the main flow direction; it has been reported as a percentage of the bankfull stage (Brown, 1985). Brown (1985) measured dike length from the desired bank line, resulting in an actual dike length longer than the reported length if the actual bank is irregular or if the bank line is to be shifted to a desired location.

Dike length is very site specific and recommendations in the literature are often directed toward fulfilling a particular condition. For example, Richardson and Simons (1974) recommend that the minimum dike length should be 50 feet and the maximum length should be less than 10 or 15% of bankfull channel width. Their minimum dike length is based on economic considerations, because shorter dikes would make riprap less costly. Limitations may exist, such as objection to full-bank riprap for ecological reasons, which negate the minimum dike length recommended by Richardson and Simons.

Laboratory testing conducted by the Federal Highway Administration (FHWA, 1983) showed that the length of both permeable and impermeable dikes impacts the local scour depth at the dike tip, the magnitude of flow concentration at the dike tip, the length of channel bank protected by the dike or dike spacing, and the apparent current deflection angle caused by the dike. Local scour increases with increased dike length or decreased permeability.

The appropriate length of dikes within a stabilization plan is highly dependent upon the particular environment; however, Brown (1985) and Richardson et al. (1987) provide these general guidelines:

- As the dike length is increased:

  the scour depth at the dike tip increases,

  the magnitude of flow concentration at the dike tip increases,

  the severity of flow deflection increases, and

  the length of channel bank protection increases.

- The projected length of impermeable dikes should be less than 15% of the channel width at bankfull stage.

- The projected length of permeable dikes should be less than 25% of the channel width. However, this criterion depends on the magnitude of the dike permeability. Dikes having permeabilities less than 35% should be limited to projected lengths not to exceed 15% of the channel flow width. Dikes having permeabilities of 80% can have projected lengths up to 25% of the channel bankfull flow width. Between these two limits, a linear relationship between the dike permeability and dike length should be used.

Dike Spacing - Spacing between dikes is a function of the dike length, angle, permeability, angle of the flow attack and radius of curvature of the bend (Copeland, 1983; and Brown, 1985). Copeland (1983) compiled Table 6 to show the variety of relationships relating dike spacing to dike length.

Table 6 Dike spacing from Copeland, 1983.

Spacing	Type of Bank	Reference		Comment
1 L 2 to 2.5 L	Concave Convex	United Nations	1953	General practice
4 to 6 L	Concave	Richardson and Simons	1973	Bank may need riprap
3 L	Concave	Grant	1948	
5.1 to 6.3 L 2.5 to 4 L	Straight Curves	Alvarez		
2 to 2.5 L		CBIP	1956	
1.5 2.0 2.5	Concave Straight Convex	Los Angeles District	1980	Levee protection with riprap
2 4		Neil	1973	If two or more dikes
3 to 5 L		Strom	1941	

Fenwick (1969) reports spacing ratio (length/spacing) values of 2 to 2.5 for flow construction applications on large rivers and a value of 3 for angled dikes used for bank protection. Richardson and Simons (1974) recommend values of 1.5 to 2.0 for retardance-type applications, and 3 to 6 for retardance-diverter and diverter applications. On straight- or large-radius bends, Richardson and Simons recommend values of 4-6; values of 3-4 are recommended on small- to moderate-radius bends. Additionally, Acheson (1968) recommends a spacing factor of 2-4, depending on the degree of bend curvature.

Laboratory investigations sponsored by FHWA (1983) provide additional information useful in establishing a criterion for dike spacing. In the FHWA study, two parameters were used to define the length of channel bank protected by individual dikes in a straight flume: the length of channel bank protected divided by the dike projected length (LBP/PL), and the flow expansion angle downstream of the dike tip. The results of the FHWA study indicate that the length of channel bank protected by individual dikes is best represented by the flow expansion angle (Brown, 1985).

The flow expansion angle is defined as the angle between a flow tangent at the dike tip and a line between the dike tip and the point on the channel bank where the flow re-expands to impact the channel bank. The definition of expansion angle is illustrated in Figure 7. The results of the expansion angle downstream of the dike tip varied only with the dike length. Figure 8 illustrates the relationships found between dike length and the expansion angle for various dike permeabilities. As indicated in Figure 7, the expansion angle for impermeable

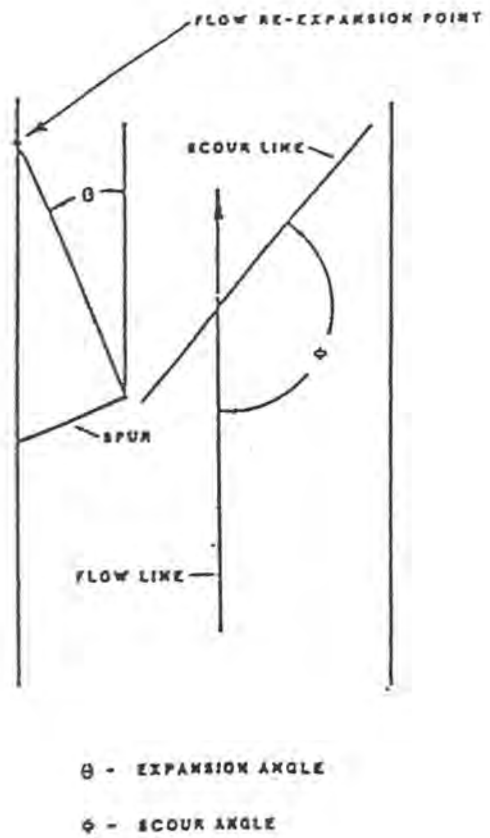


Figure 7 Definition sketch of flow expansion angle (from Brown, 1985).

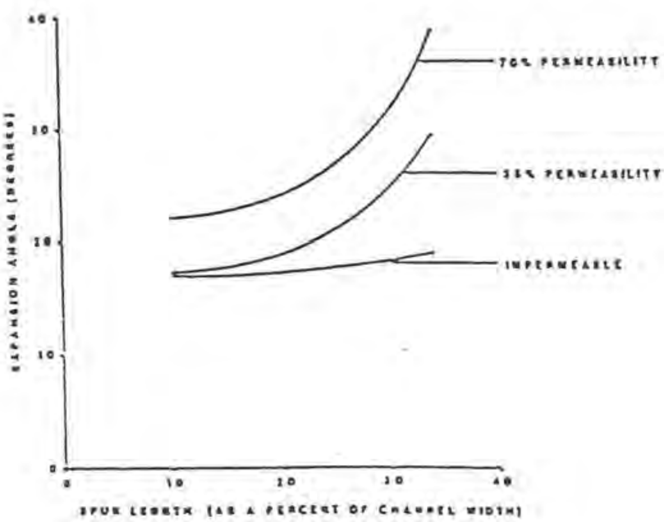


Figure 8 Relationship between dike length and expansion angle for several dike permeabilities (from Brown, 1985).

dikes is almost constant at a value of 17°. In contrast, the expansion angles for the permeable dikes were found to increase exponentially with projected dike length. Additionally, for dike lengths less than approximately 18% of the channel width, dikes having a permeability of 35% produce approximately the same expansion angles as impermeable dikes. This indicates that they protect approximately the same length of channel bank. Also, as dike permeability increases, the length of channel bank protected by the dike decreases as indicated by an increasing flow expansion angle (Brown, 1985).

The spacing criteria using the expansion angle are extremely dependent on the location of the flow thalweg through the bend. Therefore, a thorough knowledge of flow conditions in the channel bend will be required of the designer. Also, since the flow thalweg shifts with flow stage, consideration of multiple flow thalwegs is required to establish the appropriate spacing within a channel bend.

Brown (1985) reported that several additional comments can be made based on the results of the FHWA studies. Reducing the spacing between individual dikes to spacings closer than the maximum indicated by the criteria presented resulted in a reduction of local scour at the dike tips. Reducing the spacing between dikes in this way reduces the magnitude of the expansion/contraction between dikes and minimizes the magnitude of flow acceleration at the tip of the downstream dike in each of the two-dike sets. Also, it was found that reducing the spacing between dikes caused the stabilized thalweg to shift farther away from the concave bank towards the centerline of the channel. These findings indicate that some spacing closer than the maximum recommended by the spacing criteria indicated above should be used. Richardson et al. (1987) summaries this discussion in the following five recommendations:

- The spacing of dikes in a bank-protection scheme is a function of the dike length, angle and permeability, as well as the channel bend degree of curvature.
- The direction and orientation of the channel flow thalweg play a major role in determining an acceptable spacing between individual dikes in a bank-stabilization scheme.
- Reducing the spacing between individual dikes below the minimum required to prevent bank erosion between the dikes results in a reduction of the magnitude of flow concentration and local scour at the dike tip.
- Reducing the spacing between dikes in a bank-stabilization scheme causes the flow thalweg to stabilize farther away from the concave bank toward the center of the channel.
- A spacing criterion based on the projection of a tangent to the flow thalweg, projected off the dike tip, as present in the above discussion, should be used.

<u>Angle of Dike to Bank</u> - The orientation of a dike is defined as the angle that the dike makes with the upstream channel bank. There is considerable controversy in the literature concerning the proper orientation. Copeland (1983) provides a comprehensive review of the literature available at that time. Copeland concludes his review by referencing Lindner (1969) who stated that there has not been a sufficiently comprehensive series of tests either in the field or by model to conclude that any acute or obtuse angle for the alignment at dikes is superior or

even as good as perpendicular to flow. Richardson and Simons (1974) state that, in general, a dike orientation of 90° is recommended because it is the most economical angle for bank protection.

Dike orientation at a given site should be determined by selecting an alignment that will efficiently and economically guide the flow through the channel bend, protect the bank and minimize adverse effects. Recent work by the Federal Highway Administration provides some guidance for particular aspects of the selection of dike orientation beyond the recommendation for 90° orientation. Ahmad (1953) and FHWA (1983) provide mutually supportive findings. Those studies indicate that the length of bank protected increases with the bank angle; however, the length of channel bank protected with increasing angle is equal to the increased projected length of the dike parallel to the bank. The implication is that dike orientation does not increase length of protection; it is the greater dike length associated with the dike oriented at steeper angles that results in the additional bank protection. Thus, the decision is largely economic: whether it is cheaper to construct a smaller number of dikes at longer length or to construct a greater number of shorter dikes (Brown, 1985).

The angle of inclination of a dike also affects the magnitude of local scour at the dike head. Since channel bed scour is determined in large part by the magnitude of flow velocities, it would be expected that higher flow concentration would produce greater local scour in the vicinity of the dike tip. Ahmad (1953) showed that the area impacted by scour increases slightly as the orientation moves away from 90°. However, the more important indicator here is scour depth. His work shows that the maximum scour depth is inversely proportional in the dike angle (i.e., the smaller the dike angle, the greater the scour depth). The greatest scour depths occur for dikes angled upstream; the least local scour is associated with dikes angled downstream.

Ahmad's findings with respect to scour depth were confirmed during the recent FHWA (1983) study, where is was found that scour depth always decreases with increasing dike angle. It was also found that impermeable dikes produce the greatest change in scour elevation over a given range of dike angles, indicating the greatest variability of local scour at the dike tip. Also, this variability in scour depth with dike angle decreases with decreasing dike permeability. As dike permeability increases beyond 35%, it was observed that the rate of change of scour elevation with dike angle and dike length becomes very small, indicating that permeable dikes are not as sensitive to these parameters with regard to the magnitude of local scour as are impermeable dikes.

Another factor related to dike orientation is the effect of dike-topping flows in the channel bank behind and just downstream of the dike. During the FHWA studies, a disturbance was observed on the channel bank at the dike root and immediately downstream that was caused by the near-bank flows passing over the dike crest. The disturbance impacted only the upper portions of the channel bank; the lower portions of the channel bank remained protected by the dike. Flow patterns when the dike crest is submerged were observed by FHWA (1983). The flow component across the dike crest is of primary concern with respect to dike orientation. Flow passes over the dike crest in a direction generally perpendicular to the dike crest.

Therefore, as the dike angle is increased, the flow over the dike crest is aimed more directly toward the bank, resulting in a more severe impact on the channel bank. The magnitude of this upper-bank disturbance has appeared much more severe for impermeable dikes and dikes with permeabilities less than 35%. For dikes of greater permeability, the impact of dike-topping flows becomes less severe with increasing permeability. For dikes with permeabilities greater than 70%, very little impact on the upper channel bank was observed (Brown, 1985).

The dike root results are based on laboratory findings in a test channel with highly erodible banks. Field observations indicate that this upper-bank erosion is not a problem if upper portions of the bank are well vegetated or otherwise stabilized. In arid regions, however, with little upper-bank vegetation, these flow conditions could result in upper-bank erosion if not otherwise stabilized.

During the FHWA (1983) study, consideration of multiple dikes within a bank-stabilization scheme on meandering channel demonstrated that dike orientation had a direct effect on the position of the channel thalweg in the channel bend. Dikes having steeper orientations (about 90°) forced the thalweg more toward the center and inside portions of the channel through the channel bend. This correlates with findings of the single dike experiments, and indicates that steeply angled dikes provide a more positive, or active, flow control. Dikes oriented at greater angles to the channel flow provide a less abrupt flow control, allowing the channel thalweg to shift closer to the concave channel bank.

Brown (1985) recommends that dikes designed to provide flow diversion should provide a gradual flow training through the channel bend. This is accomplished by designing the dike system so that the dike farthest upstream is at a large angle and then reducing the dike angle for each subsequent dike. For example, the optimum scheme found in the FHWA laboratory study had the upstream-most dike oriented at approximately 150°. Subsequent dikes within the dike scheme had angles of 140, 130, 125, 120, 115, and 110°, respectively. Reducing the dike angle as one moves downstream provides stronger flow control at the downstream limit of the scheme. The following is a summary of conclusions regarding dike orientation:

- Dikes with permeability greater than 35% should be designed perpendicular to the flow direction.
- Impermeable or dikes less than 35% permeability should be designed to provide a gradual flow training around the bend. This is accomplished by maximizing the flow efficiency within the bend while minimizing any negative impacts to the channel bend.
- The greater the dike angle the smaller the magnitude of local scour at the dike tip for impermeable dikes.
- The greater the dike angle the small the magnitude of flow concentration at the dike tip.
- The greater the dike angle the smaller the angle of flow deflection.
- The smaller the dike angle the greater the magnitude of flow control as represented by a greater shift of the flow thalweg away from the concave (outside) channel bank.

- It is recommended that dikes within a dike scheme be set with the upstream-most dike set approximately 150° to the main flow current at the dike tip, and with subsequent dikes having incrementally smaller angles approaching a minimum angle of 90° at the downstream end of the scheme.

Dike Height and Profile - The height to which a structure should be built depends on the type of construction and the intended purpose. For example, for channel contraction to provide adequate low water depths for navigation, Fenwick (1969) suggests that the dike height may need to be only slightly above a low water reference plane. If bank protection is the intended purpose, then consideration should be given to the mechanism of bank failure and to the range of flows impinging on the bank.

The design flow stage should limit the height of the dike; however, if the design flow is above the bank, the most commonly advised dike height is the bank height (Brown, 1985). Pokrefke (1978) found that in constructing a dike to bank height, the dike efficiency was not affected when overtopped by as much as three feet. Impermeable dikes generally are not constructed above bank height because of flow concentration problems that may lead to erosion of the dike root (Brown, 1985).

Results of FHWA (1983) investigations indicate that the more severe conditions for scour at the tip of a dike result for flows that are below the crest of the dike, not for overtopping flows.

Fenwick (1969), Brown (1985), and Richardson et al. (1987) recommend that the crest of the impermeable dikes should slope toward the top of the dike, thus allowing a gradual contraction of the flow. Winkley (1971) reports that sedimentation in an impermeable dike field is enhanced where the elevation of each succeeding dike is lower. Permeable dikes are usually designed with level crests, although Brown (1985) reports that sloping crests have been utilized where high banks are to be protected.

Based on the above statements, the following recommendations are made for establishing the height of dike systems:

- The dike height should be sufficient to protect the regions of the channel bank impacted by the erosion process.
- If the design flow stage is lower than the channel bank height, dikes should be designed to a height no more than three feet lower than the design flow stage.
- If the design flow stage is higher than the channel bank height, dikes should be designed to bank height.
- Permeable dikes should be designed to a height that will permit the passage of heavy debris over the dike crest and not cause structural damage.
- When possible, impermeable dikes should be designed to be submerged by approximately three feet under the worst design flow condition, thus minimizing the impacts of local scour and flow concentration at the dike tip, and minimizing the magnitude of flow deflection.

- Permeable dikes should be designed with level crests unless bank height or other special conditions dictate the use of a sloping crest design.
- Impermeable dikes should be designed with a slight slope down toward the tip, thus, allowing amounts of flow constriction to vary with stage.
- Successive dikes within a impermeable dike field should be slightly lower to enhance sedimentation.

Channel Bed and Bank Contact - The root of the dike, that portion which ties back into the bank, must be designed to insure that erosion and eventual flanking of the dike do not occur (Fenwick, 1969). Both permeable and impermeable dike design reported by Fenwick (1969) include embedding the dike into the bank and protection using riprap. Brown (1985) reported that undermining or outflanking of dikes is the most commonly reported failure mechanism.

Impermeable rock riprap dike designs can include sufficient rock to counteract undermining. Gabion designs usually include a wire and stone mat extending outward from the structure to check undermining, which could cause structure failure. The FHWA (1983) investigation reported that extending the facing material of permeable dikes below the channel bed at the time of construction can be successful. One extension technique reported was to place a roll of the facing material at the base of the dike, the purpose being to unroll into scour as it developed. Brown (1985) reported that a system patented by Hold-That-River, Inc. allows wood-slat fencing units to slide down the supporting piles as scour develops. This system has generally been replaced by a more sophisticated system marketed by Ercon, Inc. The Ercon system uses a fabric mesh supported on a steel pipe frame affixed to collars that allow the frame to slide down the supporting pipe piles.

Careful consideration must be given to designing a dike that will maintain contact with the channel bed and channel bank so that it will not be undermined or outflanked.

Dike Head Design - Several dike head shapes have been proposed. The L-head dike has the leg extending downstream, J-head extends upstream, and the T-head extends both upstream and downstream. Fenwick (1969) recommends the L-head for bank protection with evidence that his form reduces scour at the head and protects the bank from eroding currents. He also suggests that the other head forms have little application. Richardson et al. (1987) and Brown (1985) recommend that a simple, rounded and smooth head is the most effective.

A simple straight dike head form is recommended. The dike head or tip should be as smooth and rounded as possible. Smooth, well-rounded dike tips help minimize local scour, flow concentration and flow deflection.

Local Scour - Local scour has been described as the erosion that occurs on the bed of a channel around the toe of dikes due to the scouring action of vortices that are formed as water flow around an obstruction (Galuzzi, 1977). Water builds up on the upstream face of the dike and accelerates as it flows around the nose of the dike. This flow condition creates vortices of an orientation and strength that bed material is moved from the toe of the dike, and a scour hole develops until a depth is reached at which the vortices are too weak to remove the available bed material.

Studies at WES (HL-83-1) were reported by Copeland (1983) who also observed vortices of less intensity along the upstream and downstream face of dikes. These vortices can result in attack at the root of the dike as shown in Figure 9, which emphasizes the need for adequate dike root protection.

The present status of knowledge lacks a definitive procedure for predicting scour depths at the nose of spur dikes (Copeland, 1983). Copeland lists several of the relationships for scour prediction and discusses development and application of the procedures.

$$y_s = k \left[\frac{Q}{f}\right]^{0.33}$$ Inglis (1949)

k varies between 0.8 and 1.8.

$$y_s = y + 1.1y \left[\frac{L}{y}\right]^{0.4} F_n^{0.33}$$ Liu et al. (1961)

$$y_s = 8.375y \left[\frac{D_{50}}{y}\right]^{0.25} \left[\frac{B_1}{B_2}\right]^{0.83}$$ Gill (1972)

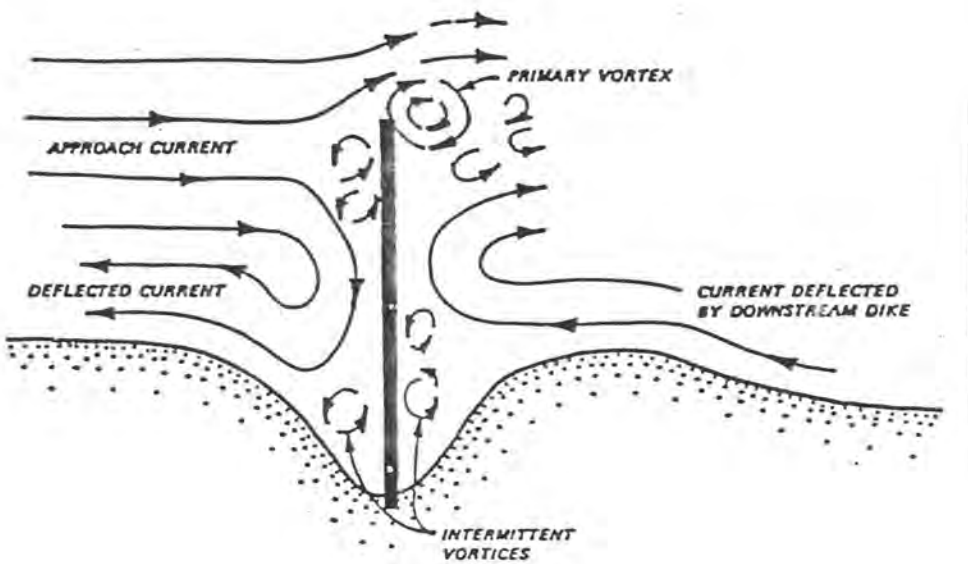


Figure 9 Flow patterns at dike.

$$\frac{L}{y} = 2.75\ \frac{y_s - y}{y}\left\{\left[\frac{1}{r}\ \frac{(y_s - y)}{y} + 1\right]^{1.70} - 1\right\} \qquad \text{Laursen (1962a)}$$

where:

B_1 = original channel width

B_2 = constricted channel width

D_{50} = median grain size

F_n = Froude number = $\frac{v}{\sqrt{gy}}$

f = Lacey silt factor = $1.59\sqrt{D_{50}}$ (D_{50} in mm)

g = acceleration due to gravity

k = function of approach conditions (varies with investigator)

L = effective length of spur dike

Q = total stream discharge

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

v = average velocity in unconstricted section

y = average depth in unconstricted section

y_s = equilibrium scour depth measured from the water surface

$\Delta\gamma_s$ = difference in specific weight between sediment and water

ρ = mass density of water

ω = settling velocity of sediment

Early investigators found that the contraction ration and velocity were the most significant parameters. Laursen (1962) maintains that when there is sediment movement upstream of the spur dike (which would be true for most alluvial streams but not necessarily true for many laboratory flumes), the scour depth is independent of the contraction ratio and velocity and is primarily a function of the upstream depth and the length of the dike. Liu et al. (1961) and Cunha (1973) also determined that the contraction ratio was not important once sediment movement was established; however, Liu et al. considered velocity to be an important parameter with or without sediment movement. Confusing the issue, studies by Garde et al. (1961) and Gil (1972), it was determined that the contraction ratio was an important parameter, with or without sediment movement. Gill concluded that velocity was not an important parameter; Garde concluded that is was. There is a division of opinion on the importance of bed material size. Inglis (1949), Blench (1969), Garde et al. (1961), and Gill (1972) found grain size to be important. Laursen (1962), Liu et al. (1961), and Ahmad (1953) determined sediment size to be insignificant. These equations are based primarily on results from laboratory testing on a single spur dike in a straight flume. Thus, the effect of current attack angle is generally neglected. Inglis, Blench, and Ahmad provided for a variable coefficient to account for severity of attack, and Laursen and Garde provided for adjustments to account for the orientation angle of the spur dike axis. None of the predictive equations presented herein has attained any widespread acceptance, and it is likely that the contestable issues will remain unsettled until sufficient prototype data are obtained (Copeland, 1983).

Galuzzi (1977) reports that a modification of the Liu et al. (1961) relationship has proven to be of value based on data developed from Mississippi River dikes, as follows:

$$\frac{y_s}{Y} = 4\ F_n^{\ 0.33}$$

Richardson et al. (1987) recommended a combination of the two relationships where the Liu et al. (1961) relationship is used for L/y values less than 30, and the Galuzzi (1977) modification used for greater L/y values.

A comparison of pertinent relationships using Sacramento River data at RM 192.4 is included in a following section.