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FINAL REPORT

STREAM INSTABILITY COUNTERMEASURES APPLIED AT KANSAS DEPARTMENT OF TRANSPORTATION HIGHWAY STRUCTURES

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Lawrence, Kansas

November 2008

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16 Abstract

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A Report on Research Sponsored By

THE KANSAS DEPARTMENT OF TRANSPORTATION
TOPEKA, KANSAS

November 2008

PREFACE

The Kansas Department of Transportation's (KDOT) Kansas Transportation Research and New-Developments (K-TRAN) Research Program funded this research project. It is an ongoing, cooperative and comprehensive research program addressing transportation needs of the state of Kansas utilizing academic and research resources from KDOT, Kansas State University and the University of Kansas. Transportation professionals in KDOT and the universities jointly develop the projects included in the research program.

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ABSTRACT

This project considered stream instability countermeasures used by the Kansas Department of Transportation (KDOT) to protect the highway infrastructure at stream crossings from changes due to the dynamic nature of streams. Site visits were made to 13 locations in Kansas where stream instability countermeasures were constructed. The visits were documented with photographs taken on site. Plans and pre-project photographs were reviewed and included in the report. The function and design of the scour countermeasures used by KDOT at these sites are presented along with photographs of the KDOT projects. The countermeasures discussed are bendway weirs, jetties (or spurs), drop structures, hard points, gabion baskets and bank protection.

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CHAPTER 1 - INTRODUCTION

1.1 Overview

Alluvial streams are dynamic in nature and can seldom be considered static. This is supported by the following statement from HDS-6, section 1.2.1 (1).

> "In summary, archaeological, botanical, geological, and geomorphic evidence supports the conclusion that most rivers are subject to constant change as a normal part of their morphologic evolution."

Consequently, it is essential that we continually monitor and protect bridges and highways near stream crossings. This will ensure public safety and minimize costly highway repair and bridge replacements caused by bridge scour and by instability of alluvial streams. Bridge scour is usually considered local scour and includes contraction, pier and abutment scour. Stream instability includes aggradation/degradation, head-cuts and bank erosion. This study will consider countermeasures for stream instability in alluvial streams.

The topic of stream stability has received considerable attention during the last decade. Stability is maintained when a stream system is able to transport its sediment load without aggrading or degrading. *This does not mean, however, that a stable stream is a static stream with unchanging geometry.* Rosgen (6) states "When the stream laterally migrates, but maintains its bankfull width and width/depth ratio, stability is achieved even though the river is considered to be an "active" and dynamic" system." Therefore, the lateral migration of a stream does not necessarily classify the stream is unstable – it only confirms that it is a dynamic stream. The location of the meanders, pools and riffles for a stable channel may change over time even though the general geometric characteristics of the stream will remain constant.

Lateral migration of a stream can pose a serious threat to a bridge or roadway. The highway engineer has no choice but to take measures necessary to protect the infrastructure at stream crossings. Not all stream changes requiring countermeasures are due to changes in unstable streams. Consequently, in this report the term *stream instability countermeasures* will refer to countermeasures taken to protect bridges and roadways from dynamic stream changes for both stable and unstable streams. Significant aggradation/degradation are signs of an unstable stream.

Stream instability can be due to natural environmental changes and/or human activities. The following are a few of the myriad of human activities that can cause stream instability.

- Loss of riparian vegetation due to overgrazing, development or farm practices.
- Channel degradation downstream from man-made reservoirs.
- Change in sediment load due to development and farm practices.
- Increase or decrease of stream runoff due to development or farm practices.

While these activities can contribute to stream instability, they are often beneficial to other aspects of the economy and general well-being. For example, reservoirs can enhance water supply, recreation and flood control even though the reduction of sediment load downstream from the dam may cause undesirable channel degradation. Similar analogies can be made for all of the other items listed above.

1.2 Project Objectives

This project will discuss selected stream instability countermeasures used by KDOT to protect the highway infrastructure at stream crossings. Photographs of selected sites where KDOT stream instability countermeasures were employed are presented. Full design procedures for the countermeasures will not be presented here since they are fully explained in the following documents.

HDS 6 River Engineering for Highway Encroachments
(http://isddc.dot.gov/OLPFiles/FHWA/010589.pdf)

HEC-11 Design of Riprap Revetment
(http://isddc.dot.gov/OLPFiles/FHWA/009881.pdf)

HEC-18 Evaluating Scour at Bridges
(http://isddc.dot.gov/OLPFiles/FHWA/010590.pdf)

HEC-20 Stream Stability at Highway Structures
(http://isddc.dot.gov/OLPFiles/FHWA/010591.pdf)

HEC-23 Bridge Scour and Stream Instability Countermeasures
(http://isddc.dot.gov/OLPFiles/FHWA/010592.pdf)

All of these publications are available on-line as PDF downloads at the websites shown.

The stream instability problems noted in Table 1 are stream meander, vertical degradation or local scour near culvert or bridge openings. Solutions for each of the problems were achieved using one or more of the following countermeasures.

- Bendway weirs.
- Jetties (spurs).
- Sheetpile sills.
- Drop structures.
- Bank protection.

Bendway weirs and jetties are employed to arrest unwanted lateral migration of the main channel and/or the banks of a stream. Jetties can also used to establish or maintain a distinct stream channel. These countermeasures will be discussed in the following sections. Sheetpile sills and drop structures are used to control degradation and, in the extreme case, headcutting. Bank protection is often a component in the countermeasure plan of either lateral or vertical stream instability problems. These countermeasures will be discussed in the following chapters.

Site visits were made to 13 locations in Kansas where stream instability countermeasures were constructed. The visits were documented with photographs taken on site. The photographs are presented along with maps in the APPENDIX. Figure 1 shows the location of the sites and Table 1 lists the stream instability problems and solution for each of the sites. The co-ordinates of the sites are given in Table 2. These can be useful for locating the sites using Terraserver or Google Earth or in a GIS format. There are a total of 17 sites although Sites 7, 8, 9 and 10 were not visited.

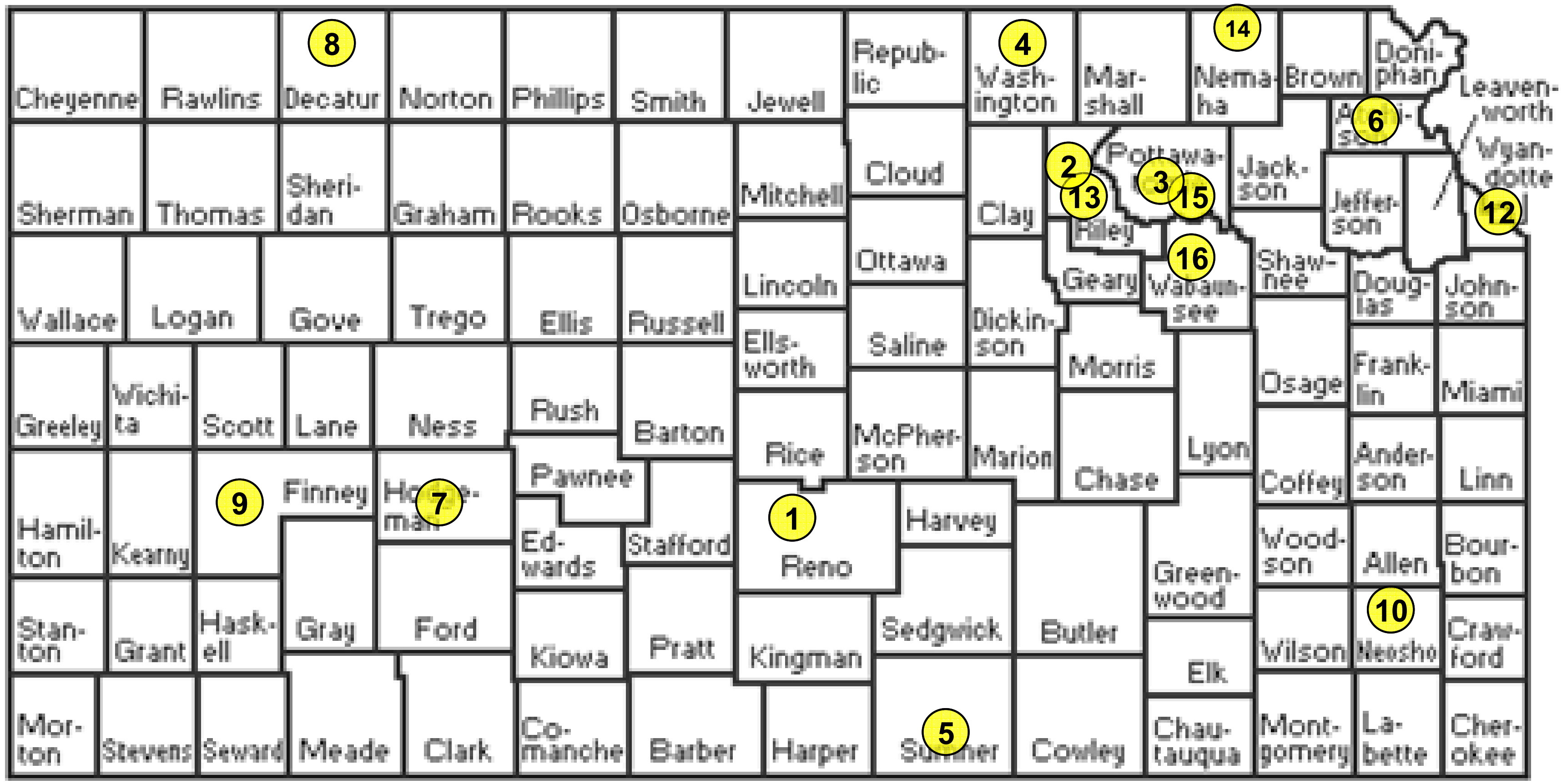


Figure 1.1: KDOT Stream Instability Countermeasure Sites

Table 1.1: KDOT Stream Instability Countermeasure Sites

Number	Date of Site Visit	Kansas County Name	Nearby City Name	Kansas Bridge Serial #	Problem (*Meander = Horizontal Instability*)	Solution
1	Jul-06	Reno	Arlington	82	River encroachment-Meander	Steel Sheetpile Jetties, Rock Bank Protection.
2	Mar-06	Riley	Manhattan	-	River encroachment	Bendway Weirs
3	Mar-06	Pottowatomie	Wamego	8	River encroachment-Meander	Guide Bank (East Abut. Berm) + Rock Jetties
4	Mar-06	Washington	Hanover	50	River encroachment-Meander	Rock Jetties
5	Jul-06	Sumner	Riverdale	132	River encroachment-Meander	Steel Sheetpile Jetties
6	Mar-06	Atchison	Arrington	46	Channel Erosion-Meander	Rock Hard Points
7	-	Hodgeman	Jetmore	10	Vertical Degrading	Steel Sheetpile Basin-Drop Structure
8	-	Decatur	Oberlin	9	Vertical Degrading	Steel Sheetpile Basin-Drop Structure
9	-	Finney	Garden City	15	River encroachment-Meander	Sec-14 COE-Buried Rock Trench + Riprap
10	-	Neosho	Porterville	57	Stream encroachment-Meander	Rock Slope Protection at Abutment
11	Mar-06	Atchison	Atchison	54	Stream encroachment-Vert. & Horiz.	Gabion protection at abutment berm
12	Mar-06	Wyandotte	Bonner Springs	84 & 85	Stream encroachment- Horiz.	Gabion protection at abutment berm
13	Mar-06	Riley	Manhattan	33	RCB Wing Erosion	Gabion protection at RCB wing
14	Mar-06	Nemaha	Goff	31	Vertical Degrading	Sheetpile Sill
15	Mar-06	Pottowatomie	St. George	6	Vertical headcut	Drop structure
16	Nov-07	Wabaunsee	Alma	-	Lateral migration	Bendway Weirs
17	Jul-06	Kingman	Kingman	-	Lateral migration	Bendway Weirs (constructed of "Sand Socks")

Table 1.2: Co-ordinate of KDOT Sites

No.	County	Nearby City	Longitude	Latitude	UTM Coordinates	UTM-x	UTM-y	Lat-Long
1	Reno	Arlington	-98.17872	37.90439	14 S 572200 4195525	572200	4195525	N37.90439 W98.17872
2	Riley	Manhattan	-96.13205	39.23407	14 S 747541 4346672	747541	4346672	N39.23407 W96.13205
3	Pottowatomie	Wamego	-96.2354	39.21317	14 S 738690 4344075	738690	4344075	N39.21317 W96.23540
4	Washington	Hanover	-96.88706	39.84089	14 S 680785 4412234	680785	4412234	N39.84089 W96.88706
5	Sumner	Riverdale	-97.33857	37.39168	14 S 647071 4139619	647071	4139619	N37.39168 W97.33857
6	Atchison	Arrington	-95.54215	39.46159	**15 S 281294 4371087**	**281294**	**4371087**	N39.46159 W95.54215
7	Hodgeman	Jetmore	-99.82009	38.09137	14 S 428087 4216270	428087	4216270	N38.09137 W99.82009
8	Decatur	Oberlin	-100.53448	39.77706	14 S 368589 4404139	368589	4404139	N39.77706 W100.53448
9	Finney	Garden City	-100.84336	37.94983	14 S 338041 4201851	338041	4201851	N37.94983 W100.84336
10	Neosho	Porterville	-95.12271	37.71964	**15 S 312914 4176830**	**312914**	**4176830**	N37.71964 W95.12271
11	Atchison	Atchison	-95.15109	39.55495	**15 S 315189 4380573**	**315189**	**4380573**	N39.55495 W95.15109
12	Wyandotte	Bonner Springs	-94.83287	39.0635	**15 S 341425 4325422**	**341425**	**4325422**	N39.06350 W94.83287
13	Riley	Manhattan	-96.54552	39.17351	14 S 712031 4338901	712031	4338901	N39.17351 W96.54552
14	Nemaha	Goff	-95.93497	39.66412	**15 S 248228 4394597**	**762931**	**4394970**	N39.66412 W95.93497
15	Pottowatomie	St. George	-96.42395	39.20607	14 S 722431 4342807	722431	4342807	N39.20607 W96.42395
16	Wabaunsee	Alma	-96.28361	39.00145	14 S 735231 4320448	735231	4320448	N39.00145 W96.28361
17	Kingman	Kingman	-98.20892	37.62591	14 S 569807 4164604	569807	4164604	N37.62591 W98.20892

Bold UTM coordinates are UTM 1983 Zone 15, others are UTM 1983 Zone 14

CHAPTER 2 - BENDWAY WEIRS

2.1 Overview

Lateral stream migration problems at river bends and highway crossings can be controlled using low elevation sills extending into the river. These are called bendway weirs and are typically constructed of stones and angled from about 5 to 25 degrees upstream. Ideally, the flow will be redirected by utilizing weir hydraulics over the structure. Thus, bendway weirs function differently than jetties (or spurs) for which the flow is designed to go around rather than over the structure.

Water passes over the bendway weir in a direction perpendicular to the weir axis. Flow, or velocity, concentration on the outer bank is reduced, and a better alignment of flow through the bend and downstream crossing will result. Moreover, deposition of soil will occur and the areas between the weirs will be filled over time. Figure 2.1 illustrates how the flow is redirected as it passes over the weir.

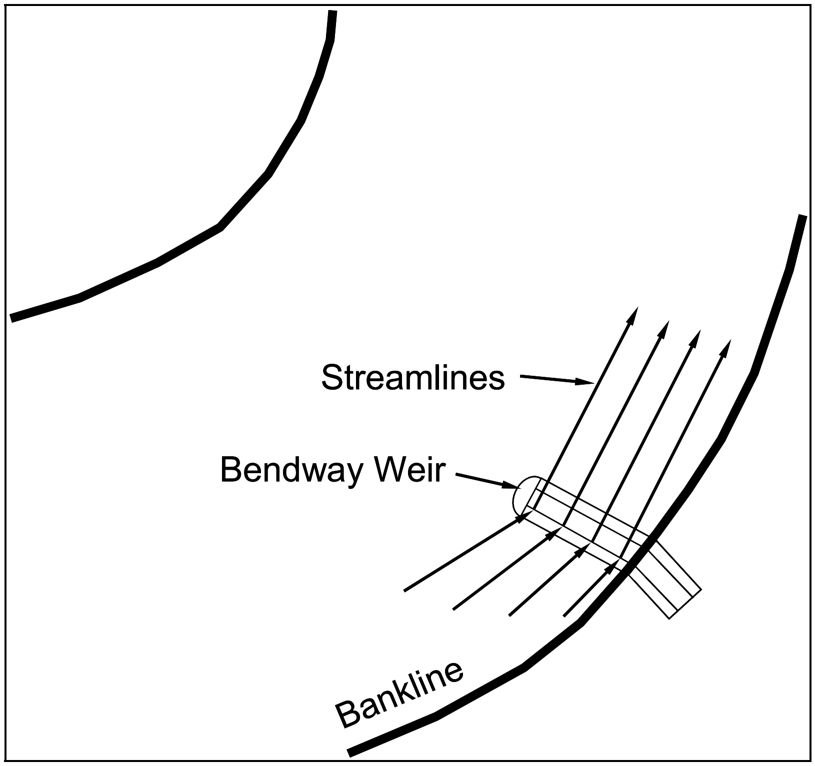


Figure 2.1: Flow Deflection at a Bendway Weir

This method is most often used for streambank protection on streams and smaller rivers, but can also be used on larger, navigable rivers. The weir is oriented such that incoming flow will perpendicularly intersect the weir's axis, and then be redirected toward the channel centerline. This is illustrated in Figure 2.2 for a series of bendway weirs.

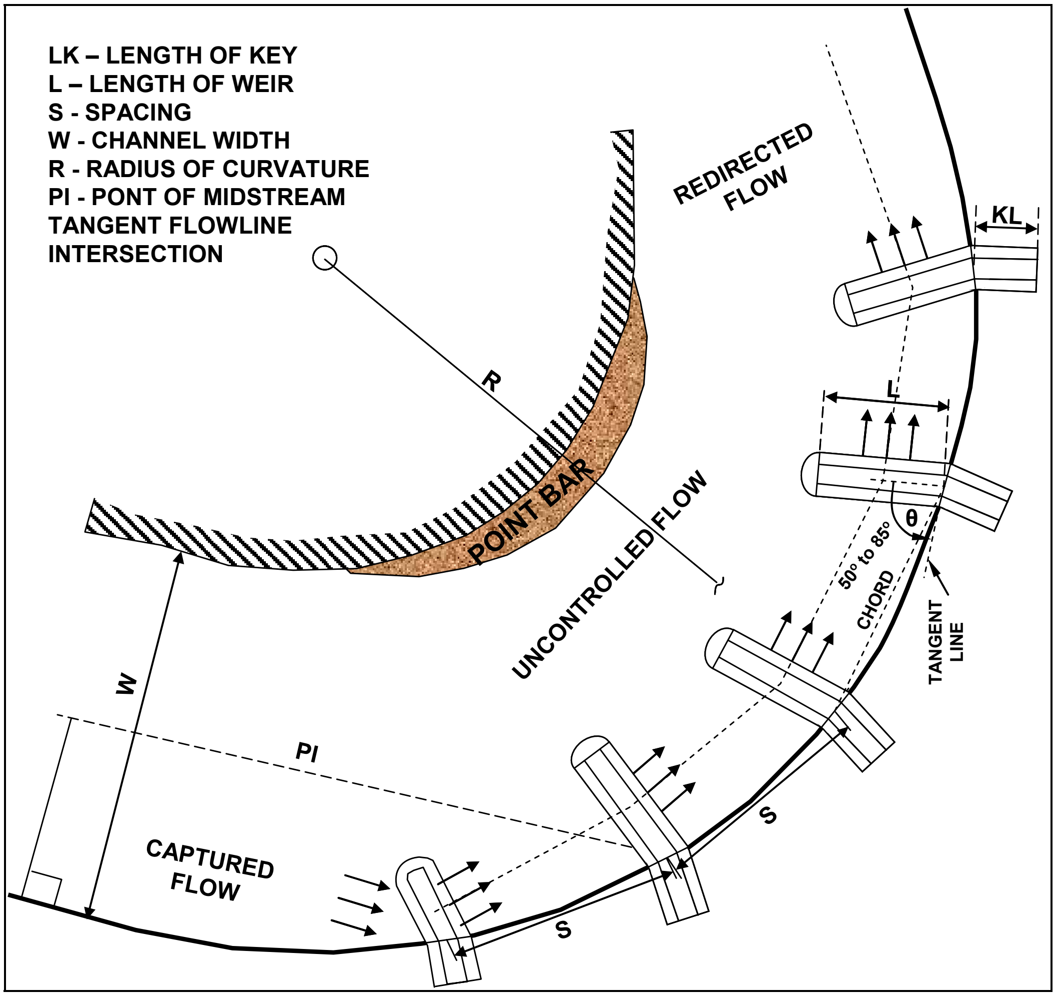


Figure 2.2: Bendway Weir Typical Cross-section (Fig. 1.2 in HEC 23 redrawn)

2.2 Design

Figure 2.3 shows a typical cross section for a bendway weir. HEC 23 gives a complete presentation of the design of bendway weirs (pp DG1.-17) and should be the principal reference used in design. This report only presents highlights of the design. The height of the weir is determined by the flow depth at the site. It should be between 30 and 50 percent of the depth at the mean annual high water level. Generally, the height should be below the normal seasonal mean water level and should not be lower than the mean low water level; the weir should be high enough to obstruct an adequate amount of flow to produce the desired results.

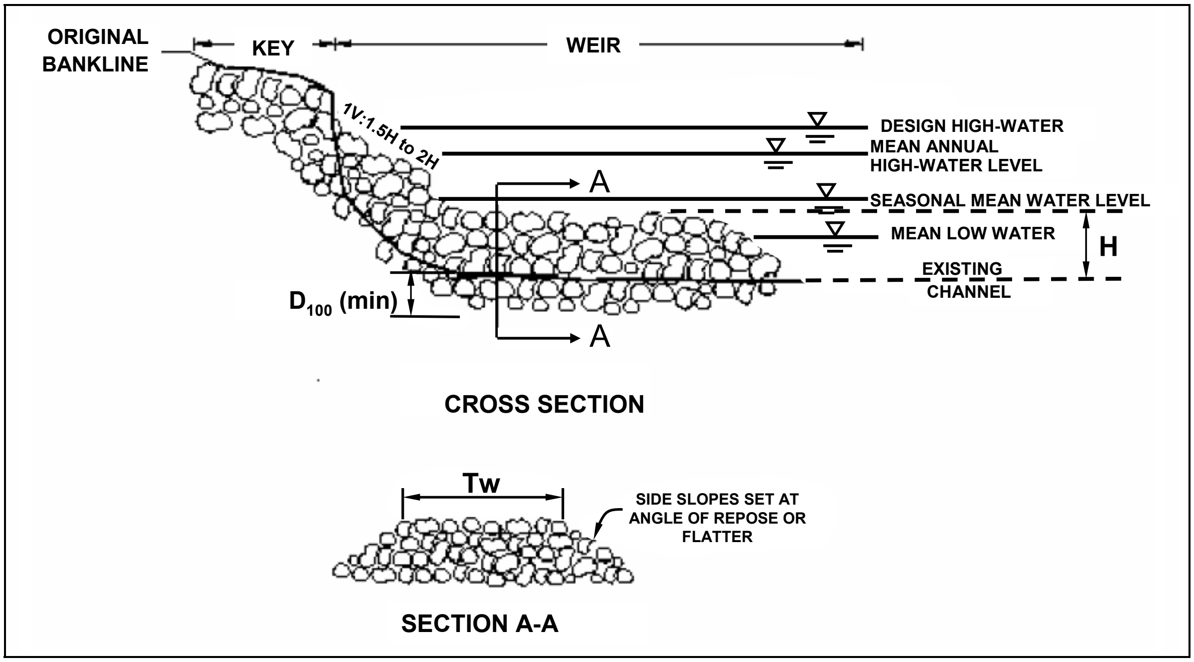


Figure 2.3: Bendway weir typical cross-section (Fig. 1.2 in HEC 23 redrawn)

The angle of projection is typically 50 to 85 degrees, and should be measured from a chord drawn from the points of intersection of the weirs and the streambank. (See Figure 2.2.) This angle is determined by the location of the weir in the bend and the angle at which flow lines approach the structure. The angle of projection should be such that the perpendicular line from the midpoint of an upstream weir points to the midpoint of the following downstream weir. For the first several weirs, the angle of projection should result in streamline angles of attack of less than 30 degrees to the normal of the weir centerline at high flow and greater than 15 degrees at low flow. In general, the projection angles increase with increasing radii of curvature of the bend.

The slope along the centerline of the top of the weir should be flat, or no greater than 1V:5H. (See Figure 2.3.) The flat weir section should transition into the bank with a slope of 1V:1.5-2H. At the bank line, the height of the weir should be equal to the height of the maximum design high water level. This prevents the flow from flanking the structure. The weir also needs to be keyed into the streambed at a minimum depth of the D_{100} grain size.

The bendway weir should extend to the stream thalweg (the line along the stream following the lowest point in the channel). At channel bends the thalweg will be closer to the outer bend. Satisfactory bendway weir applications have been made with weir lengths, L, for 1.5 to 2 times the distance from the outer bank to the thalweg. L typically ranges from $W/10$ to $W/4$. Undesirable erosion problems can occur on the inside bank if L exceeds W/3. This is due to significant changes in the stream flow patterns. It is important to note that weir length will affect weir spacing.

A short weir should be placed a distance S, defined by Equation 2.1, upstream from the location where the midstream tangent flowline, located at the beginning of the curve, intersects the streambank, PI. Site conditions affect the placement of additional weirs, usually set at a distance S apart. (See Figure 2.2.)

Weir spacing, S, is determined by the direction of the streamflow leaving the weir and its intersection with the downstream structure or bank. S can be calculated as given by

$$S = 1.5L\left(\frac{R}{W}\right)^{0.8}\left(\frac{L}{W}\right)^{0.3} \qquad \text{Equation 2.1 (Eq. 1.2, HEC 23)}$$

where

L is the weir length

R is the channel radius of curvature

W is the channel width. Generally

S is between 4 and 5 times the weir length.

S_{max} is based on the intersection of the tangent flow line with the streambank on simple curves, but is not recommended for implementation. S_{max} is given by

$$S_{max} = R\left[1-\left(1-\frac{L}{R}\right)^2\right]^{0.5} \qquad \text{Equation 2.2 (Eq. 1.4, HEC 23)}$$

Spacing and resulting flowlines should be investigated and drawn in planform to ensure the desired results are being achieved.

Weirs should be keyed into the streambank a minimum length, LK, of either about half the length of the short weirs, or about 1/5 the length of the long weirs. (See Figure 2.4.) LK can be extended in critical locations, and should always be greater than 1.5 times the total bank height. When R is greater than $5W$ and S is greater than L/tan(20°), LK can be calculated by

$$LK = S\tan(20^o) - L \qquad \text{Equation 2.3 (Eq. 1.5, HEC 23)}$$

When R is less than $5W$ and S is less than L/tan(20°), LK can be calculated by

$$LK = \frac{L}{2}\left(\frac{W}{L}\right)^{0.3}\left(\frac{S}{R}\right)^{0.5} \qquad \text{Equation 2.4 (Eq. 1.6, HEC 23)}$$

Where LK should not be less than 1.5 times the total bank height.

Refer to HEC-11 (1989) for determining whether a filter between the weir key and the bank material is necessary.

The top width of the weir should be 3-12 feet, and no less than 2 to 3 times D_{100}.

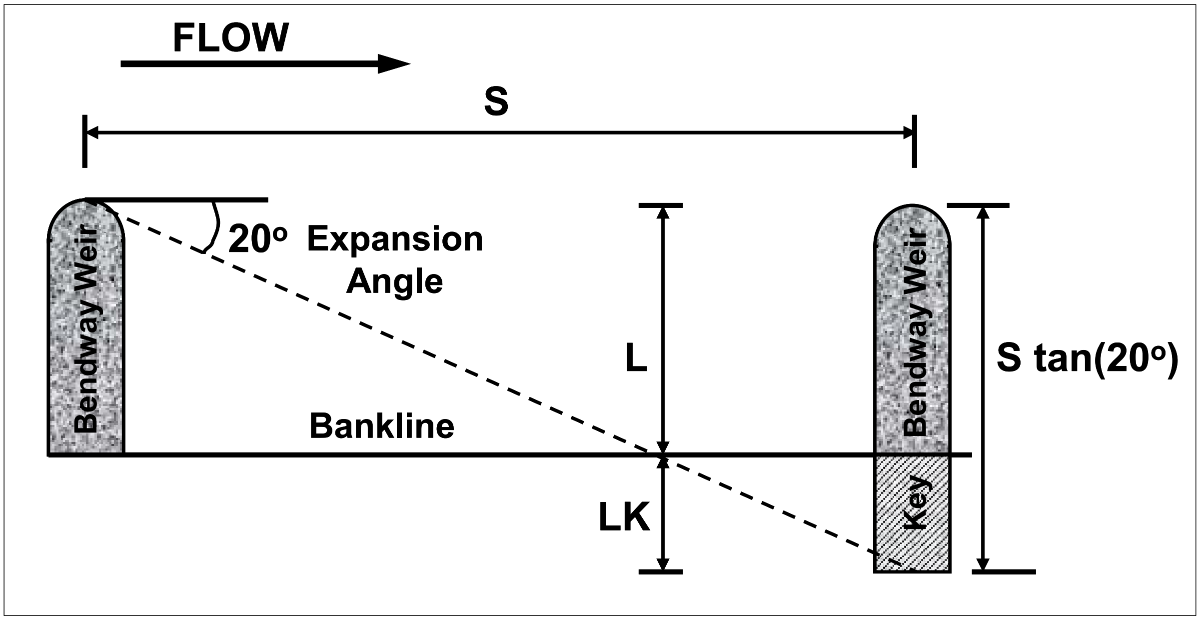


Figure 2.4: Length of key for mild bends (Fig. 1.3 in HEC23 redrawn)

2.3 KDOT Applications

Projects 2, 16 and 17 from Table 1 used bendway weirs to provide a reactive stream erosion countermeasure.

2.3.1 Site 2

The channel was widening at Site 2 and the left bank of the river was threatening the bridge abutment. The ban was fairly steep. The water was just overtopping the weirs on the day of the field survey but they looked to be in good condition. Figure 2.5-7 show Site 2.

2.3.2 Site 16

Lateral channel migration on the left side of the main channel posed a potential problem to the roadway and bridge for Site 16. Figures 2.9-11 show the benway weirs from different locations. Overall, the condition of weirs was excellent and the migration of the main channel appeared to have been arrested.

2.3.3 Site 17

Figure 2.12 is an aerial view showing the region where sand tube bendway weirs were installed. Figure 2.13 shows the location of the main channel banks in 1938, 1964, 1972, 1983, 1997 and 2000. It is apparent that the right bank of the channel is migrating toward the road. Thus the roadway and the right bridge abutment are threatened. Figure 2.14 is a drawing showing the channel location for all the years displayed in Figure 2.13 but also for 2002. Note that there was significant channel migration between 2000 and 2002. Figure 2.15 through 2.18 show the preparation and installation of a sand tube. Figures 2.19 -2.21 show the sand tubes in operation. Note that they are oriented upstream and the flow passes over them perpendicular to the longitudinal axis of the sand tube, which is directed away from the bank on the downstream side of the sand tube. The soil in the overbanks was non-cohesive and highly erodible. The sand tubes appeared to be functioning very well in halting the channel migration.

Figure 2.5: Site 2, Aerial, Rock Bendway Weirs, Manhattan, KS, Riley County

Figure 2.6: Site 2, Rock Bendway Weirs, Manhattan, KS, Riley County (Looking Upstream)

Figure 2.7: Site 2, Rock Bendway Weirs, Manhattan, KS, Riley County

Figure 2.8: Site 16, Aerial, Alma, KS, Wabaunsee County

Figure 2.9: Site 16, Rock Bendway Weirs, Alma, KS, Wabaunsee County (Looking Upstream)

Figure 2.10: Site 16, Rock Bendway Weirs, Alma, KS, Wabaunsee County (Looking Upstream)

Figure 2.11: Site 16, Rock Bendway Weirs, Alma, KS, Wabaunsee County (Looking Downstream)

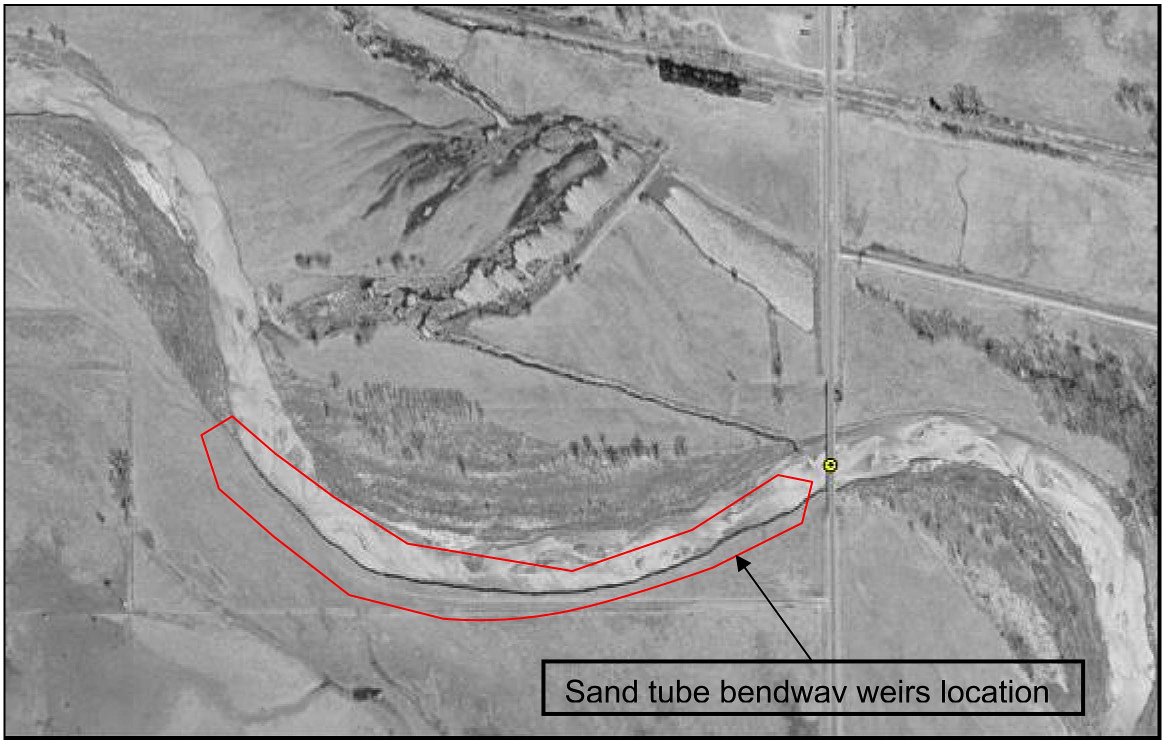


Figure 2.12: Site 17, Aerial, Kingman, KS, Kingman County

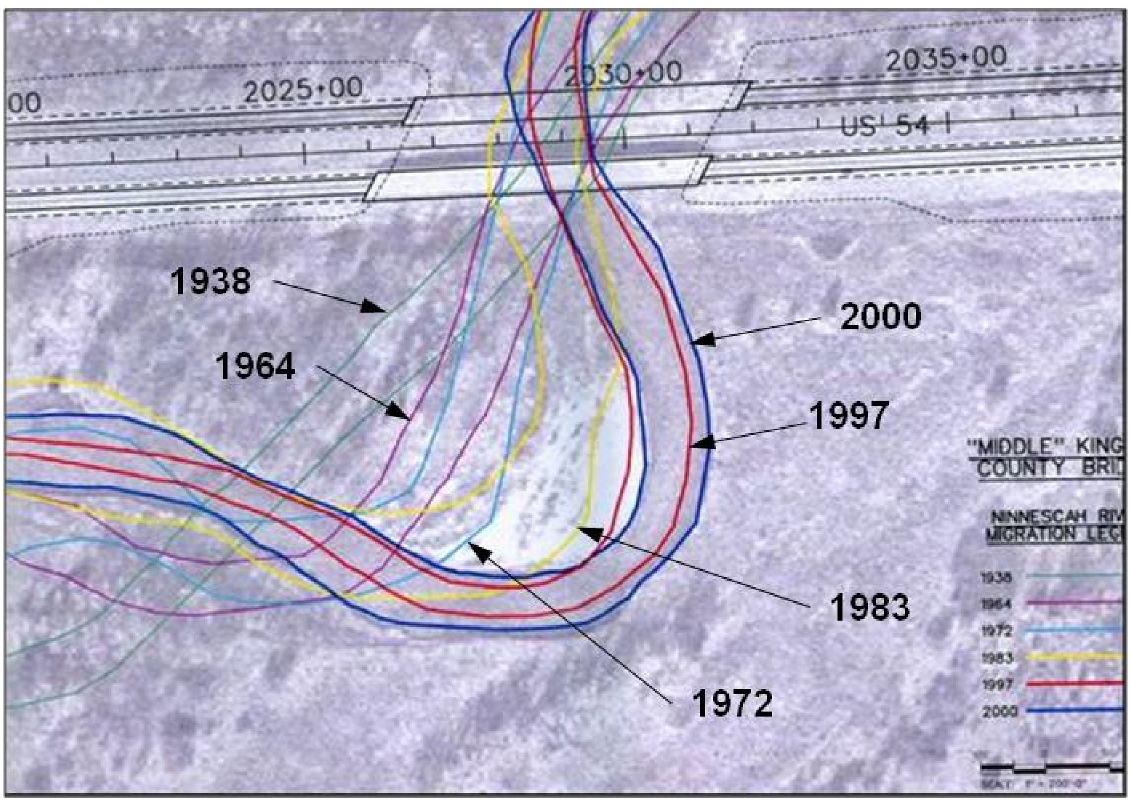


Figure 2.13: Site 17, Aerial with Channel Migration, Kingman, KS, Kingman County

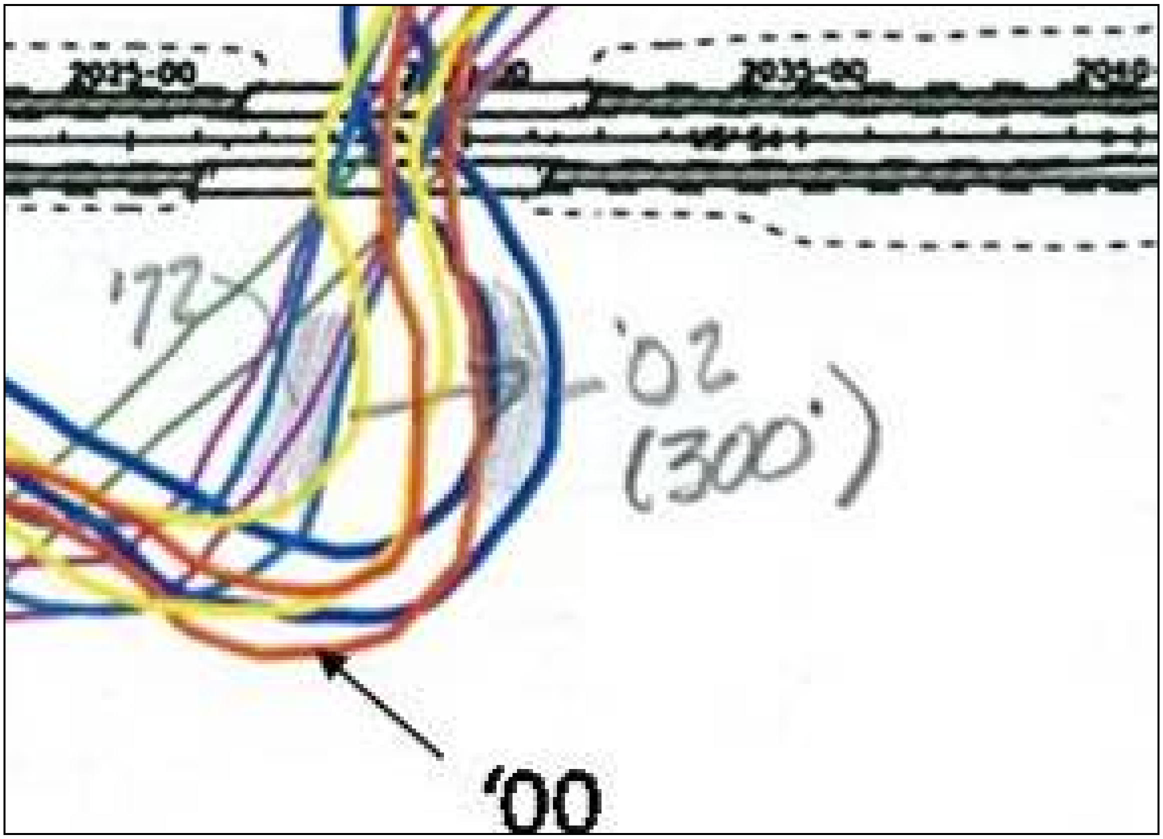


Figure 2.14: Site 17, Channel Migration, Kingman, KS, Kingman County

Figure 2.15: Site 17, Sand Tube Bendway Weirs, Kingman, KS, Kingman County (Installation)

Figure 2.16: Site 17, Sand Tube Bendway Weirs, Kingman, KS, Kingman County (Installation)

Figure 2.17: Site 17, Sand Tube Bendway Weirs, Kingman, KS, Kingman County (Installation)

Figure 2.18: Site 17, Sand Tube Bendway Weirs, Kingman, KS, Kingman County (Fabrication)

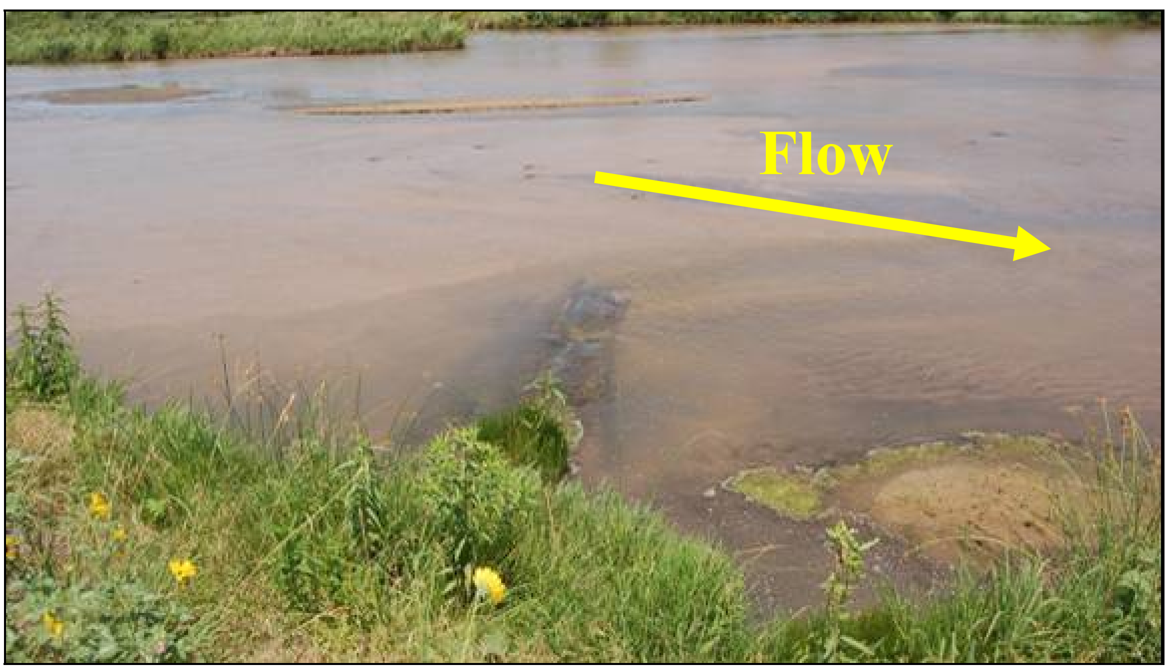


Figure 2.19: Site 17, Sand Tube Bendway Weirs, Kingman, KS, Kingman County (Flow Patterns)

Figure 2.20: Site 17, Sand Tube Bendway Weirs, Kingman, KS, Kingman County (Flow Patterns, Looking Downstream)

Figure 2.21: Site 17, Sand Tube Bendway Weirs, Kingman, KS, Kingman County (Flow Patterns, Looking Downstream)

CHAPTER 3 - JETTIES (OR SPURS)

3.1 Overview

Jetties (or spurs) are arranged as a series of angled, low-elevation stone (or steel) sills used as scour countermeasures for controlling meander. Jetties control meander migration by redirecting currents and velocities through a bend and promoting deposition in the bank regions between the jetties. The stability of these deposition regions become more stable as vegetation develops. Jetties are designed to be above the water level thus flow is diverted around the structures. This is unlike bendway weirs which function in the submerged condition for normal and design flows.

Jetties control erosion by reducing flow velocities near the outer bank and producing better current alignment through the bend and the downstream reach. Jetties also serve to break up the stream's strong secondary currents that play an important role in promoting bank erosion. They function well with other bank protection methods and work best under high-flow, high-energy conditions. On the occasions where water does flow over a jetty, the overtopping water is redirected at an angle perpendicular to the axis of the jetty.

Jetties are also used as scour countermeasures in areas where distinct stream channels do not exist naturally or where the natural stream alignment poses potential scour problems. In these areas the jetties function in the river training mode to define a channel and/or its alignment to minimize scour at or near stream crossings. Such an example would be a braided stream. By restricting the flow to a narrower region, a shorter, less expensive structure can be used at road crossings.

Jetties are classified as retarder, retarder/deflector and deflector jetties depending on the degree of permeability or the structure. Steel jetties are clearly impermeable and function solely in a flow deflection role. Rock jetties can vary significantly in permeability thus the relative role in retarding and deflecting the flow can also vary significantly.

3.2 Design

It is strongly recommended to carefully assess the existing bend condition, geometry, planform, stages and discharges, sediment transport capacity, and stream features. The flow field entering the area of the proposed jetty field should be carefully analyzed. Either field investigation or a two-dimensional flow model could serve to analyze the flow.

Figure 3.1 gives guidance on the recommended longitudinal extent of the spur field. The shaded region represents the spur field. Problems sometimes arise when the spur field does not extend far enough downstream from the bend.

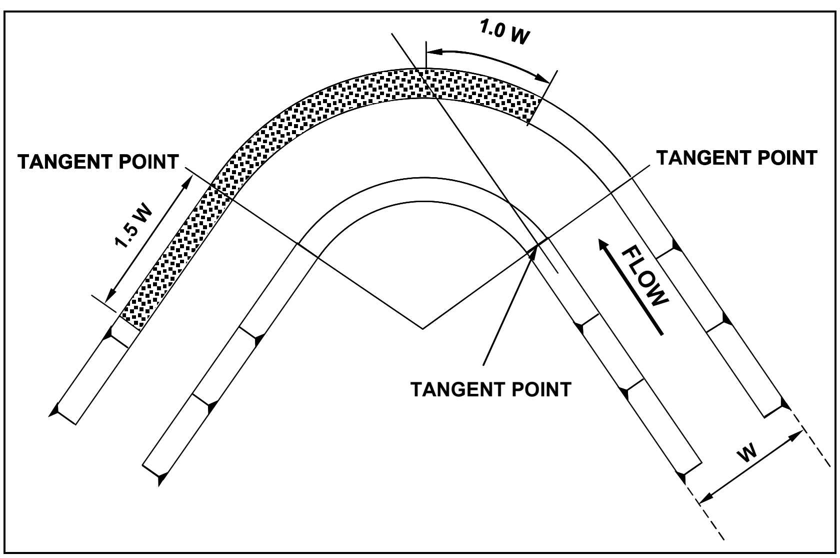


Figure 3.1: Extent of Protection Required at a Channel Bend (Fig. 9.1 in HEC 23, redrawn)

The spur length is the length of the spur projected in the direction of the main flow. This is shown in Figure 3.2. Usually spur lengths for impermeable spurs do not exceed 0.2 W. The spur orientation, or the spur angle, is also shown in Figure 3.2.

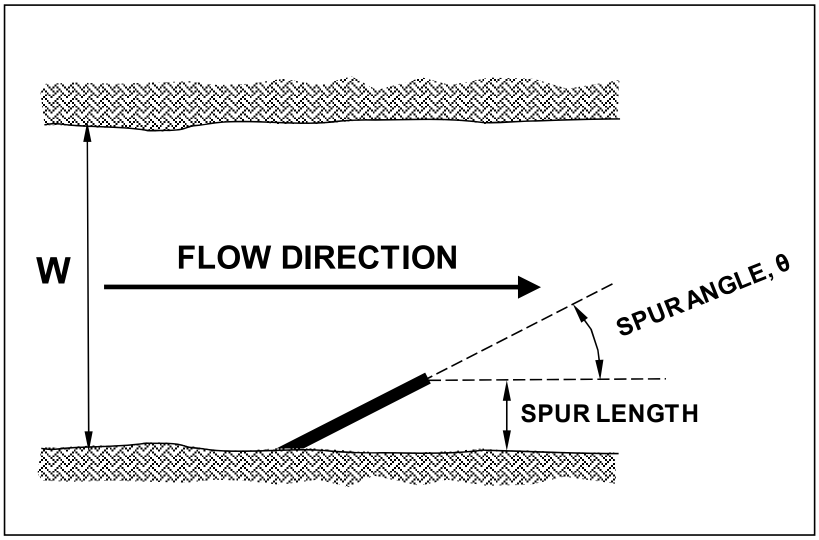


Figure 3.2: Definition Sketch for Spur Length and Orientation Angle, θ (Fig. 9.2 in HEC 23, redrawn)

It is interesting to note that the orientation of spurs can be either angled in the downstream direction ($\theta < 90^o$) as shown in Figure 3.2 or in the upstream direction ($\theta > 90^o$) like bendway weirs. HEC 23 notes that there is no consensus on the correct orientation, however, the upstream oriented spurs do create greater scour depths near the toe of the spur. This is shown in Figure 3.3 where the ratio of scour depth to that at a spur normal to the bank is plotted versus the spur angle in degrees. It is recommended, however, that the most upstream spur be oriented downstream ($\theta < 90^o$) in order to create smooth flow transition and to minimize scour at the leading spur.

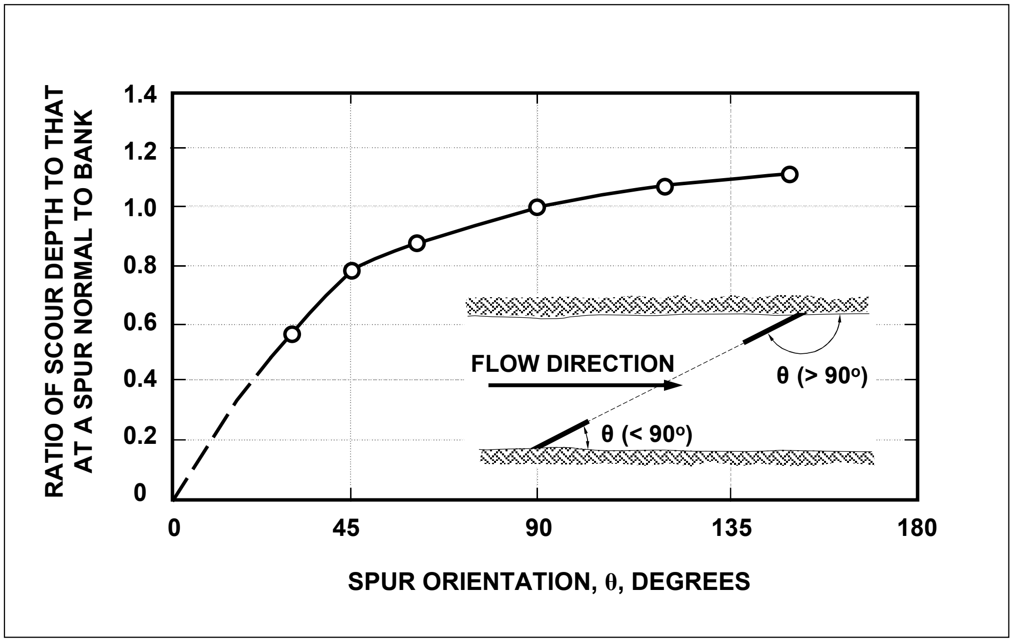


Figure 3.3: Scour Adjustment for Spur Orientation (Modified from HDS 6) (Fig. 9.3 in HEC 23, redrawn)

The flow past a jetty can be visualized as shown in Figure 3.4 below. The flow expands at an angle θ towards the bank as it passes the end of the obstruction. This is known as the expansion angle. *Note that HEC 23 refers to both the vane orientation angle and the expansion angle by the same symbol, θ.* The areas between the effective flow lines and the stream banks are ineffective flow regions. There is no net flow in the ineffective flow areas and the flow field is characterize by eddies. Consequently, suspended sediment particles are deposited in these areas. It is apparent from the figure that the spacing of the spurs depends on the expansion angle and the length of the spurs. Figure 3.4 shows a series of jetties (a) as initially constructed and (b) after equilibrium conditions are reached. The spur length L is the projected length of the spur after equilibrium has been reached

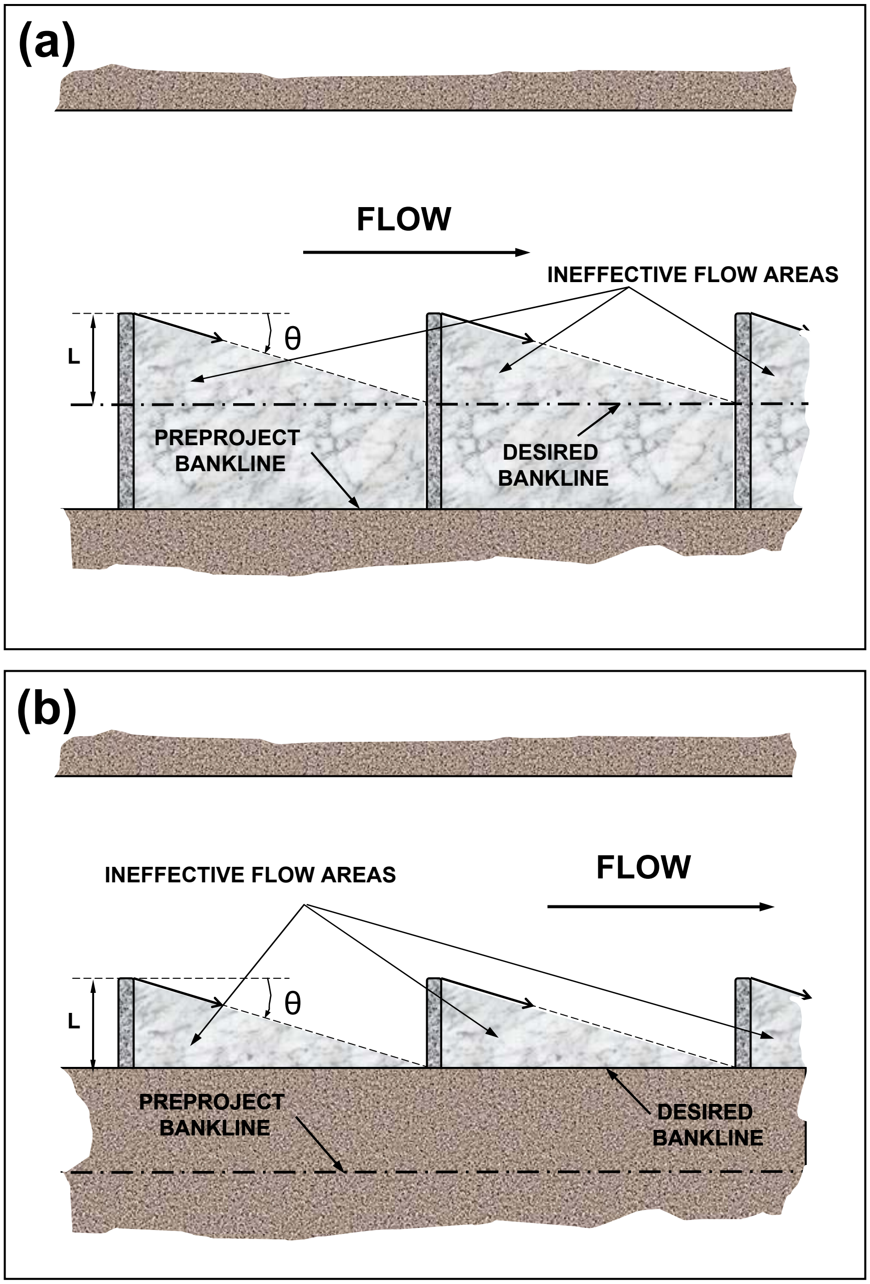


Figure 3.4: Definition Sketch for Flow Expansion Angle θ and Ineffective Flow Areas Initial Installation (b) Equilibrium Conditions

The expansion angles for jetties (spurs) depend on their permeability. Figure 3.5 shows the expansion angle as a function of spur permeability and spur orientation angles of 30, 60 and 90 degrees. This data was based on experimental studies with the projected spur lengths equal to 20 percent of the channel width.

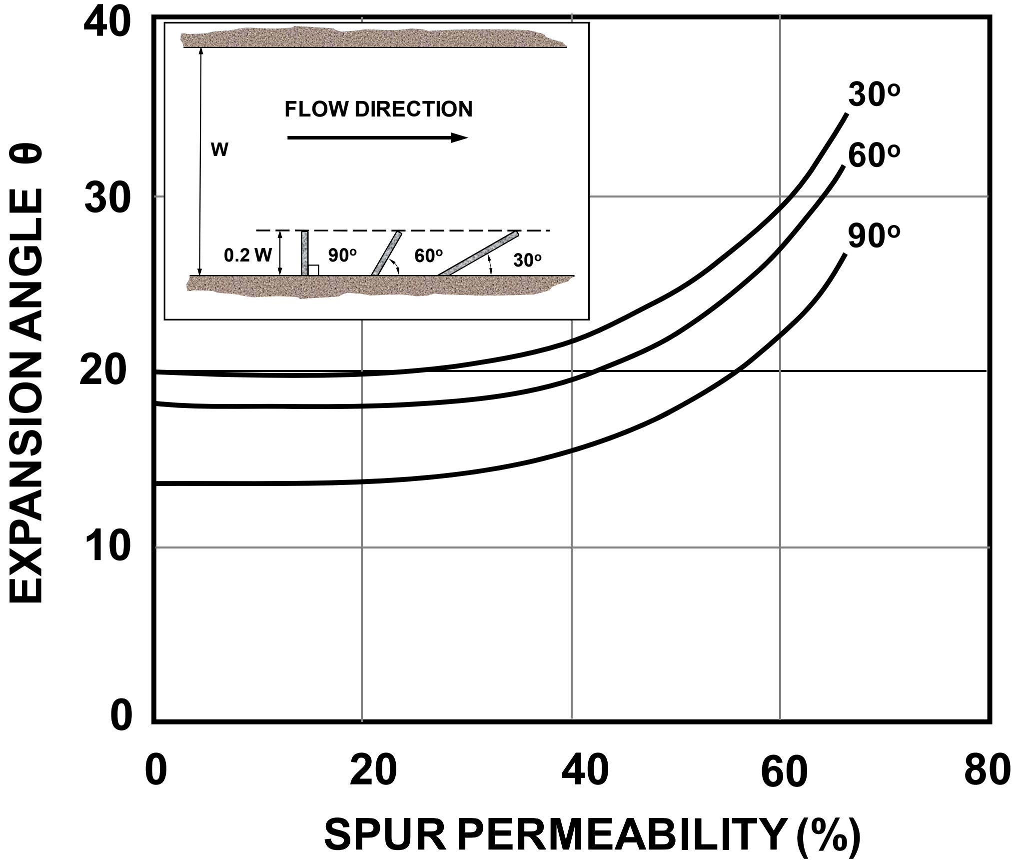


Figure 3.5: Flow Permeability and Spur Orientation vs. Expansion Angle (Fig. 9.5 from HEC 23, redrawn)

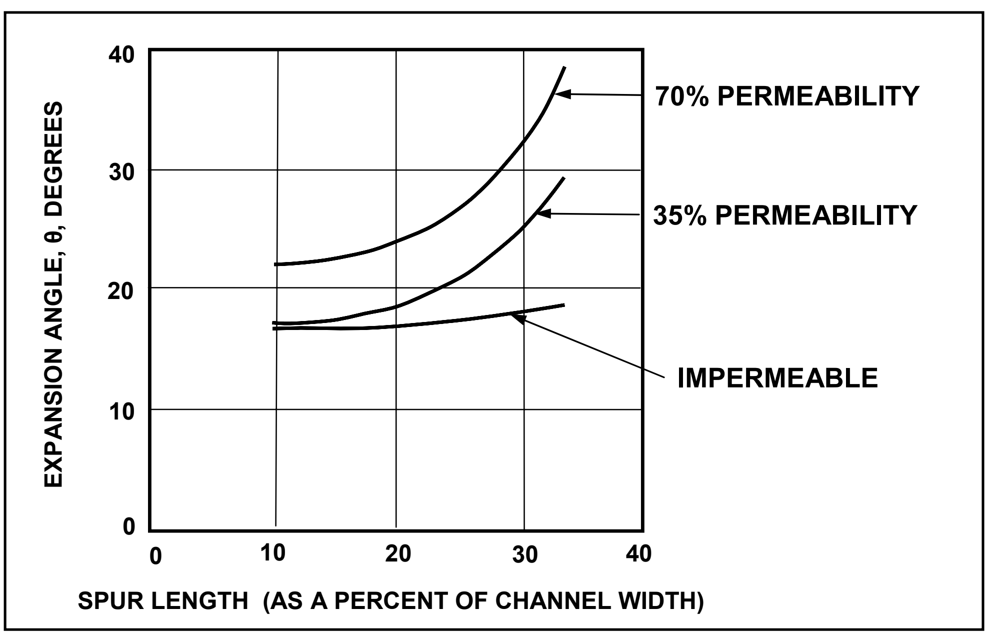


Figure 3.6 Relationship between Spur Length and Expansion Angle for Several Spur Permeabilities (Fig. 9.10 from HEC 23, redrawn)

$$S = L \cot \theta$$ Equation 3.1 (Eq. 9.1 HEC 23)

where:

S = spacing between spurs at the nose, m (ft)

L = effective length of spur, or the distance between arcs describing the toe of spurs and the desired bank line, m (ft)

θ = expansion angle downstream of spur nose, degrees

At less than bankfull flow rates, flow may approach the concave bank at angles greater than those estimated from Figure 3.7. Therefore, spurs should be well-anchored into the existing bank to prevent outflanking, especially the spur at the upstream end of the installation, Outflanking occurs when the design flow extends beyond the inner edge of the jetty.

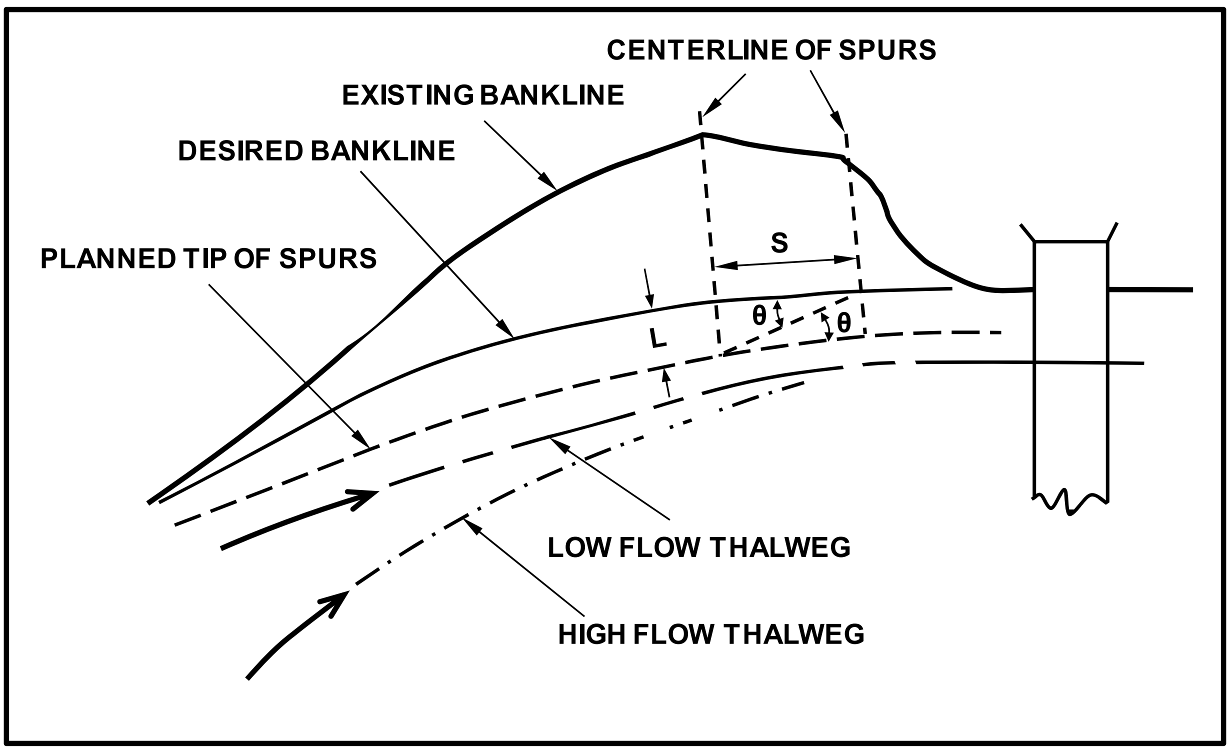


Figure 3.7: Flow Permeability and Spur Orientation vs. Expansion Angle (Fig. 9.11 from HEC 23, redrawn)

HEC 23 discusses the design example of a jetty (spur) installation depicted in Figure 3.8 below. Jetty 1 is positioned to allow the expanding flow to meet the bank line just downstream from the abutment. The effect of the additional potential scour of the jetty on pier and abutment scour should be considered. The potential scour due to the jetty can be estimated using methods presented in Chapter 4 of HEC 23. Superposition of the jetty scour depth on the pier and/or abutment scour depths is recommended for assessment. The dimension and location of the other upstream jetties are determined using Eq. 3.1.

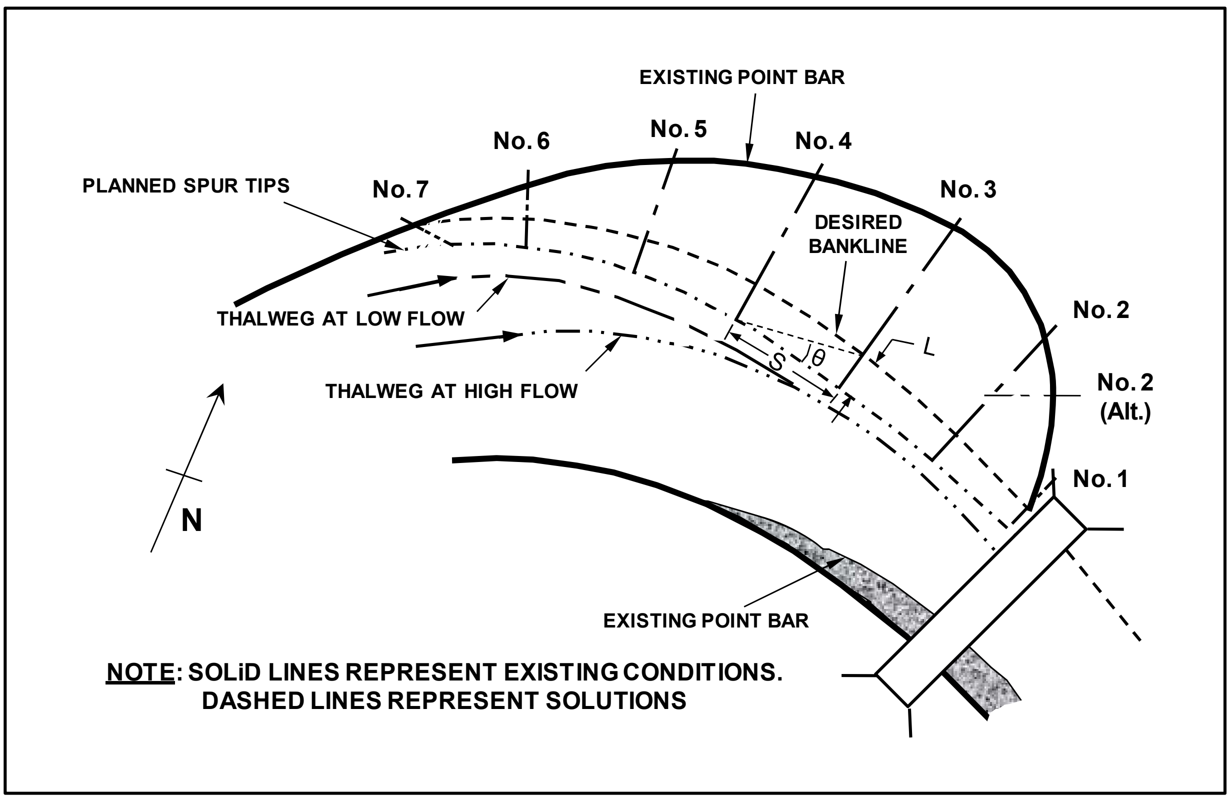


Figure 3.8: Example of Spur Design (Fig. 9.14 in HEC 23, redrawn)

HEC 23 presents a thorough discussion of jetty design and includes most of the figures presented above as well as others. It should, therefore, be used in the design of a jetty system. This chapter was intended to clarify some of the discussion in Chapter Design Guideline 9 in HEC 23.

3.3 KDOT Application

Sites 3 and 4 had rock jetties and Sites 1 and 5 had steel sheetpile jetties. All four of these sites were designed to halt bend migration to protect roadways and structures. The design reports for the Sites indicated that several alternative countermeasures were considered.

3.3.1 Site 3

Figure 3.8 indicates the rock jetty installation. The left bank of the channel was threatening the roadway and the bridge. These jetties were massive. The degree to which the region between the jetties had filled in and revegetated was impressive. Figures 3.9 and 3.10 are photographs of the jetties.

3.3.2 Site 4

Figure 3.11 shows aerial photos from 1941 and from approximately 2002. These pictures dramatically show the significant changes that can occur to a stream over several decades. The 1941 stream centerline is shown on the 2002 aerial for comparison. The 2002 picture clearly shows the jetties. Figure 3.12 is a portion of the plans for the 5 jetties. Figures 3.13 and 3.14 show the jetties in 2001 and 2006, respectively. The area between the jetties had filled in and vegetation was evident throughout the jetty series.

3.3.3 Site 1

Figure 2.15 is an aerial view that shows where a series of steel sheet pile jetties were installed. Note in Figure 3.16 that the channel bend made a dramatic migration between 1986 and 1998 and came very close to the highway. Apparently this was due in large part to a major storm that occurred in 1995. The construction layout of the levees is shown in Figure 3.17. Note that all but the most upstream jetty, No. 9, are oriented upstream with the angle of orientation greater than 90 degrees. Figures 3.18 to 3.22 are pictures of the jetty system in July 2006. This site is characterized by a flat floodplain left overbank.

3.3.4 Site 5

Aerial photos of the site are shown in Figures 3.23-25. The left bank of the river is extremely close to US-81 in the area encircled in Figure 3.23. Figure 3.26 shows the layout for the final 12 jetty configuration adopted. The details of selected jetties are shown in Figure 3.27. The left bank of the river was steep in the region of the 90-degree jetties. The vegetation was well established and significant deposition had occurred between the jetties. Figures 3.28-31 show pictures of the jetties taken July 2006.

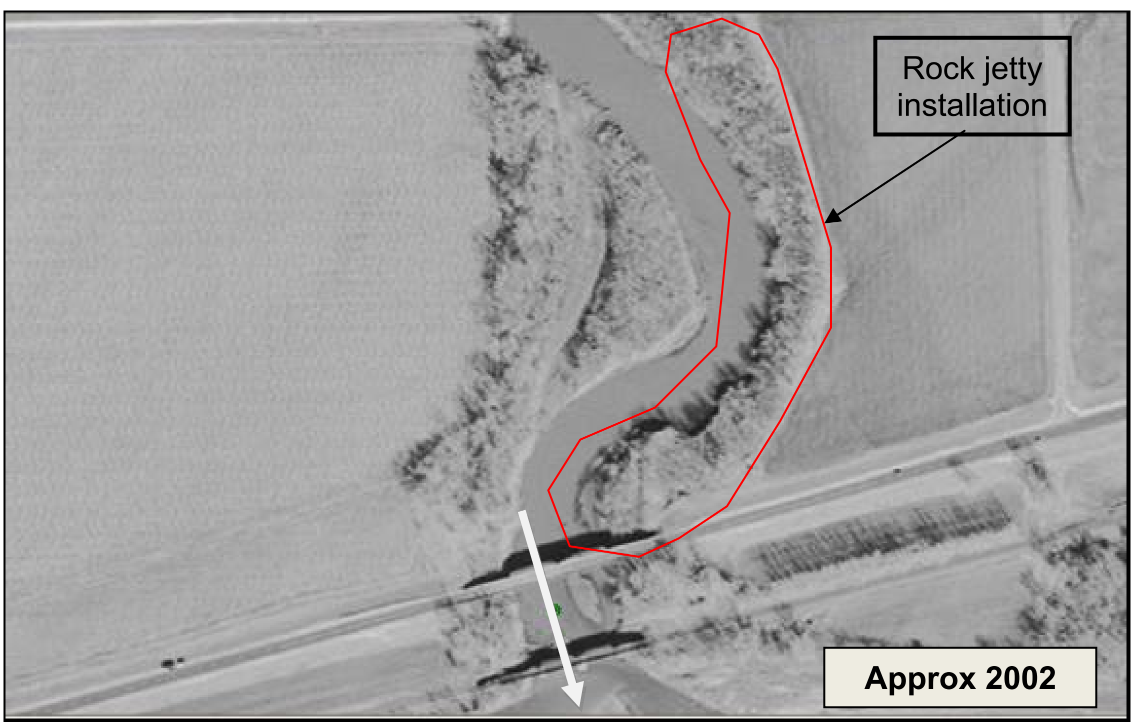
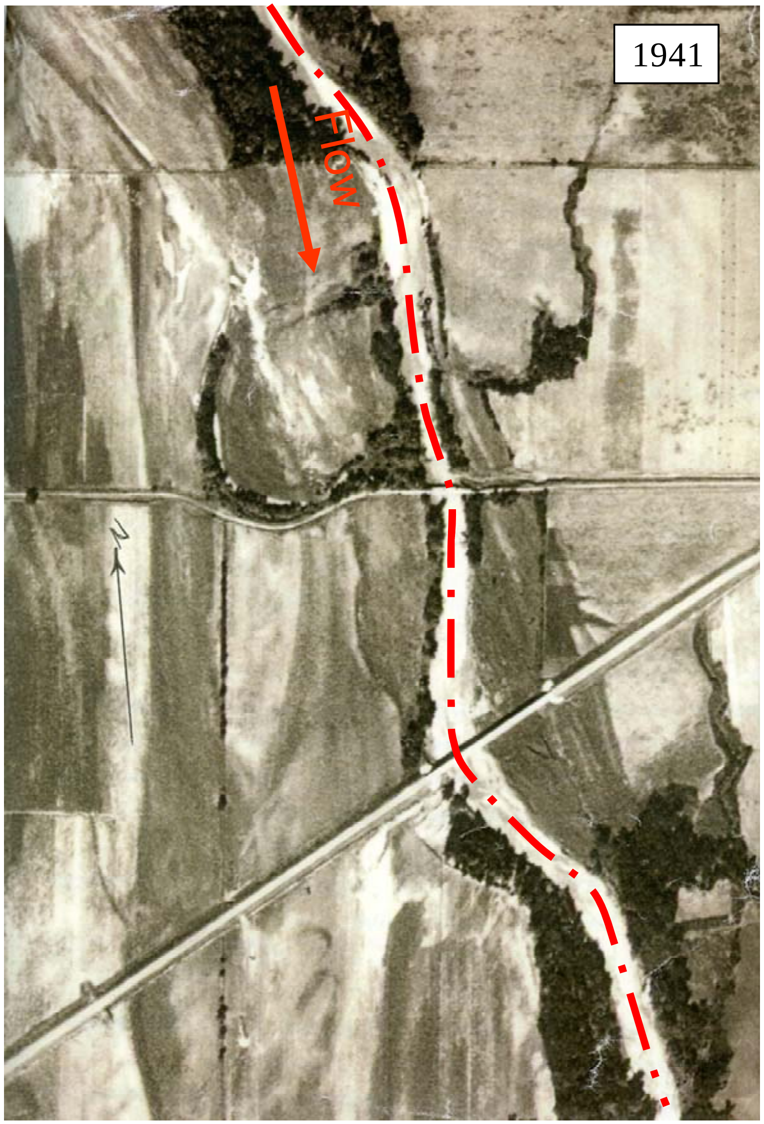


Figure 3.9: Site 3, Aerial, Wamego, KS, Pottawatomie County

Figure 3.10: Site 3, Rock Jetties, Wamego, KS, Pottawatomie County

Figure 3.11: Site 3, Rock Jetties, Wamego, KS, Pottawatomie County



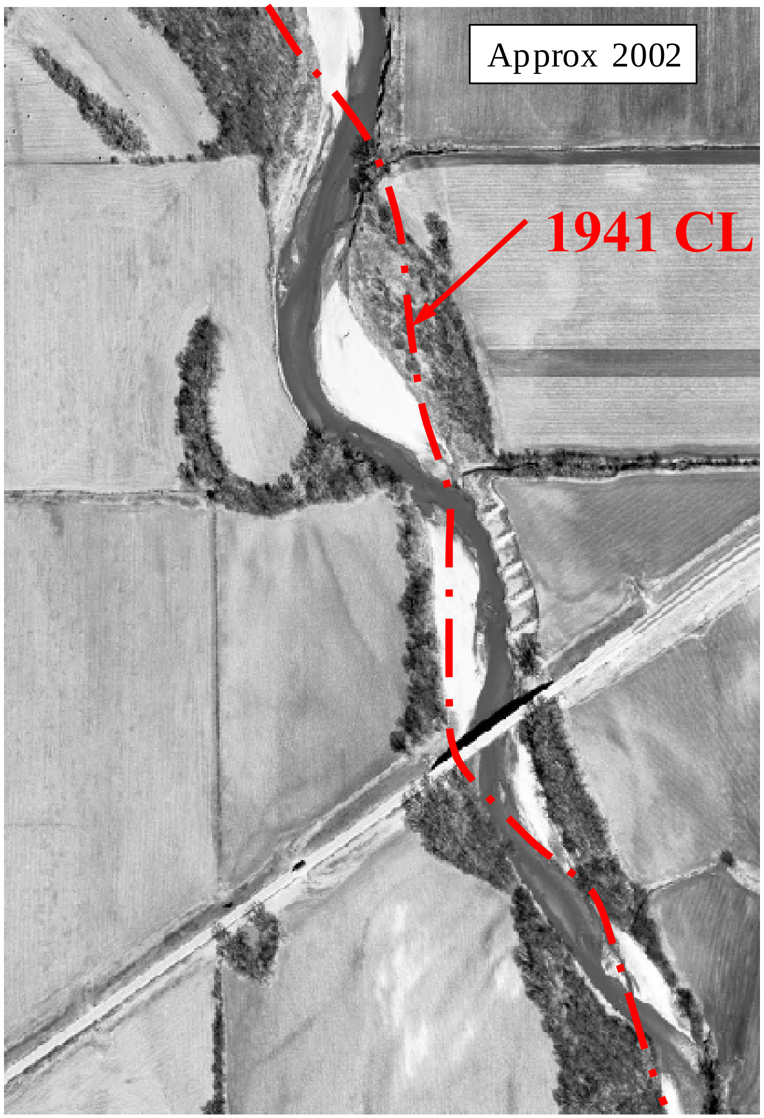


Figure 3.12: Site 4, Rock Jetties, Hanover, KS, Washington County1941 and recent Aerial Photos (Scale is not exactly the same)

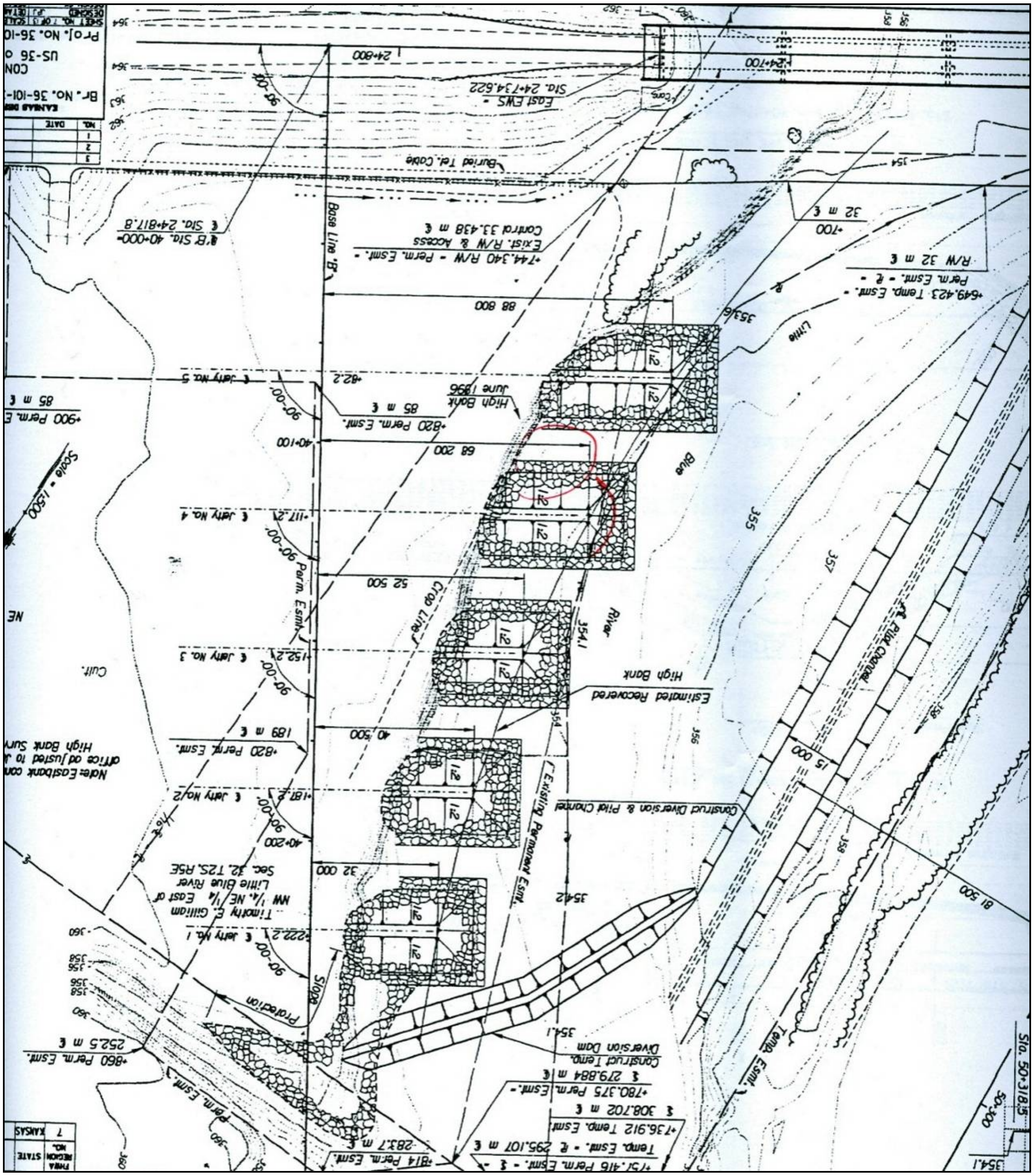


Figure 3.13: Site 4, Rock Jetties, Construction Plans, Hanover, KS, Washington County

Figure 3.14: Site 4, Rock Jetties, Hanover, KS, Washington County, 2001 (Looking Upstream)

Figure 3.15: Site 4, Rock Jetties, Hanover, KS, Washington County, 2006 (Looking Upstream)

Figure 3.16: Site 1, Aerial, Arlington, KS, Reno County

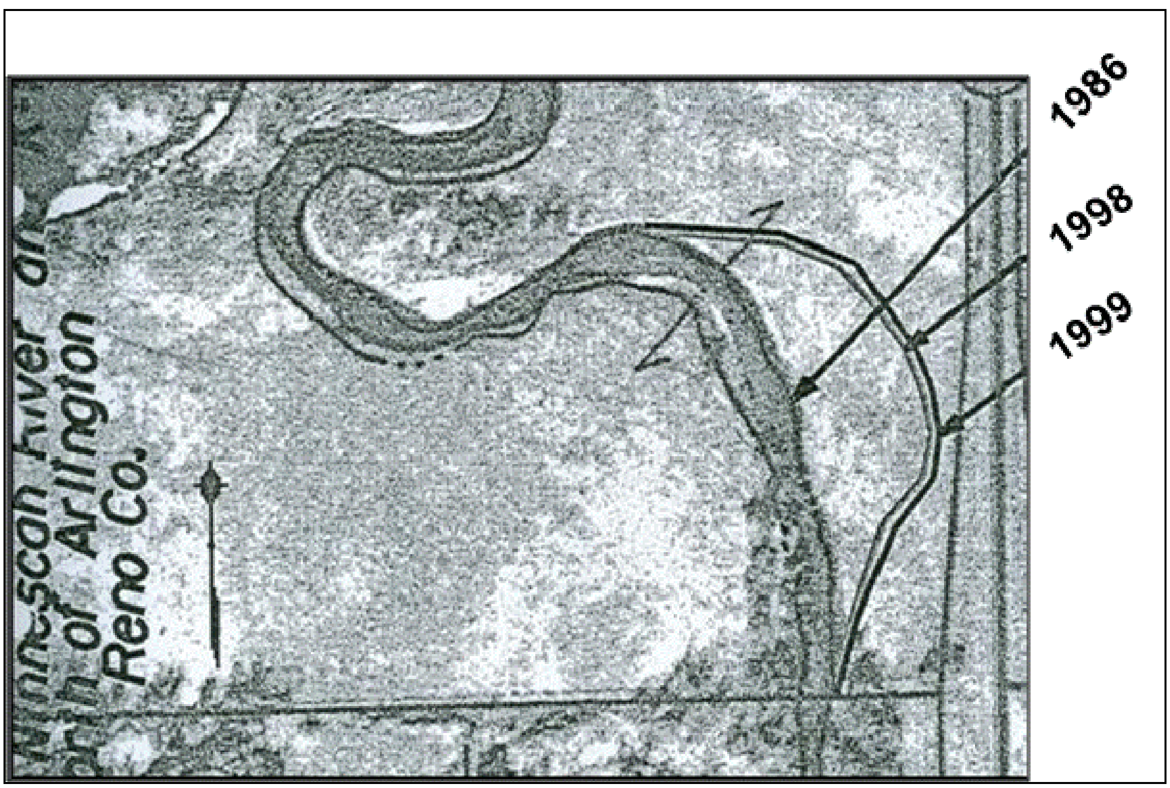


Figure 3.17: Site 1, Channel Migration, Arlington, KS, Reno County

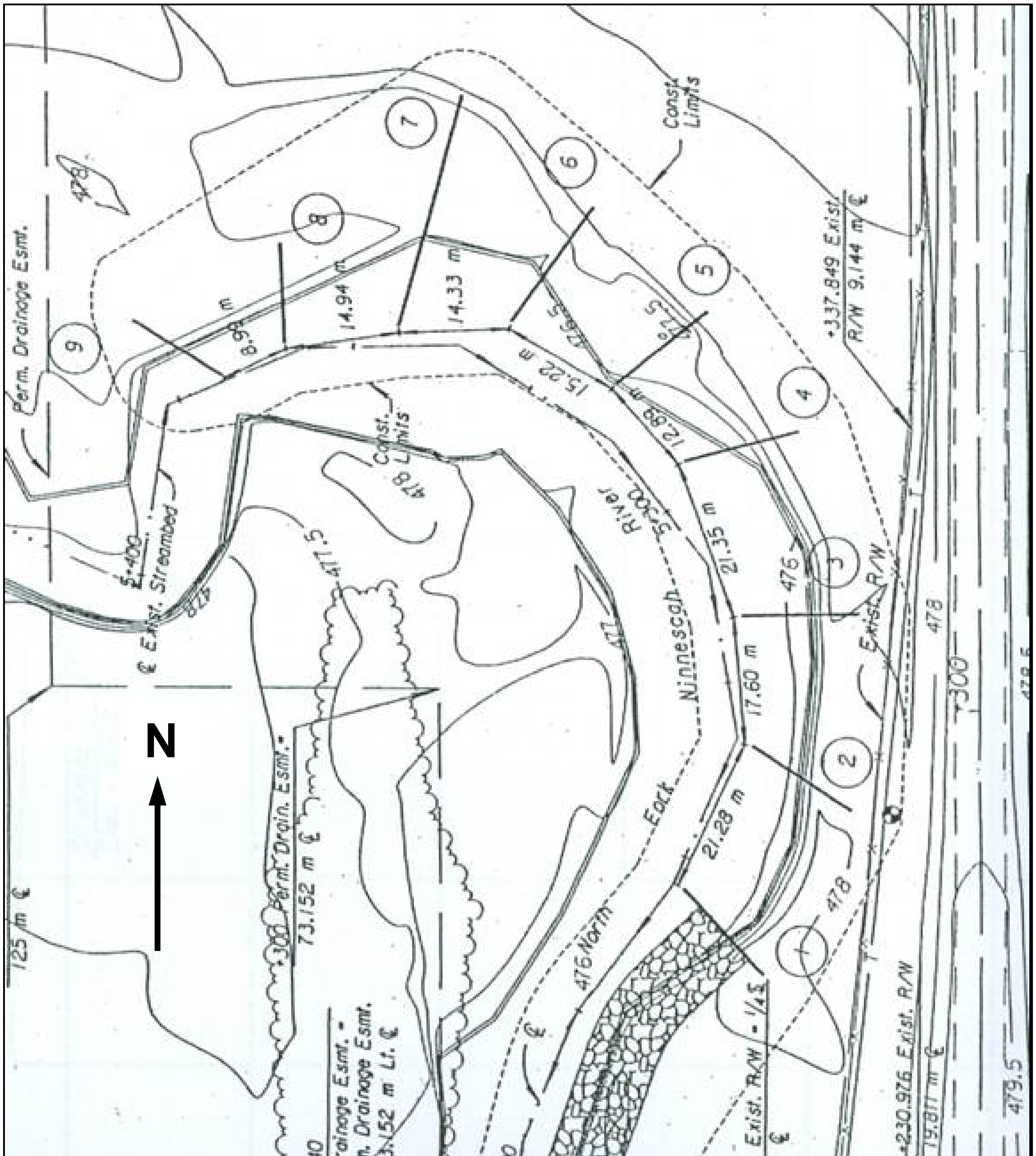


Figure 3.18: Site 1, Construction Plans, Sheet Pile Jetties, Arlington, KS, Reno County

Figure 3.19: Site 1, Sheet Pile Jetties, Arlington, KS, Reno County

Figure 3.20: Site 1, Sheet Pile Jetties, Arlington, KS, Reno County

Figure 3.21: Site 1, Sheet Pile Jetties, Arlington, KS, Reno County

Figure 3.22: Site 1, Sheet Pile Jetties, Arlington, KS, Reno County

Figure 3.23: Site 1, Sheet Pile Jetties, Arlington, KS, Reno County

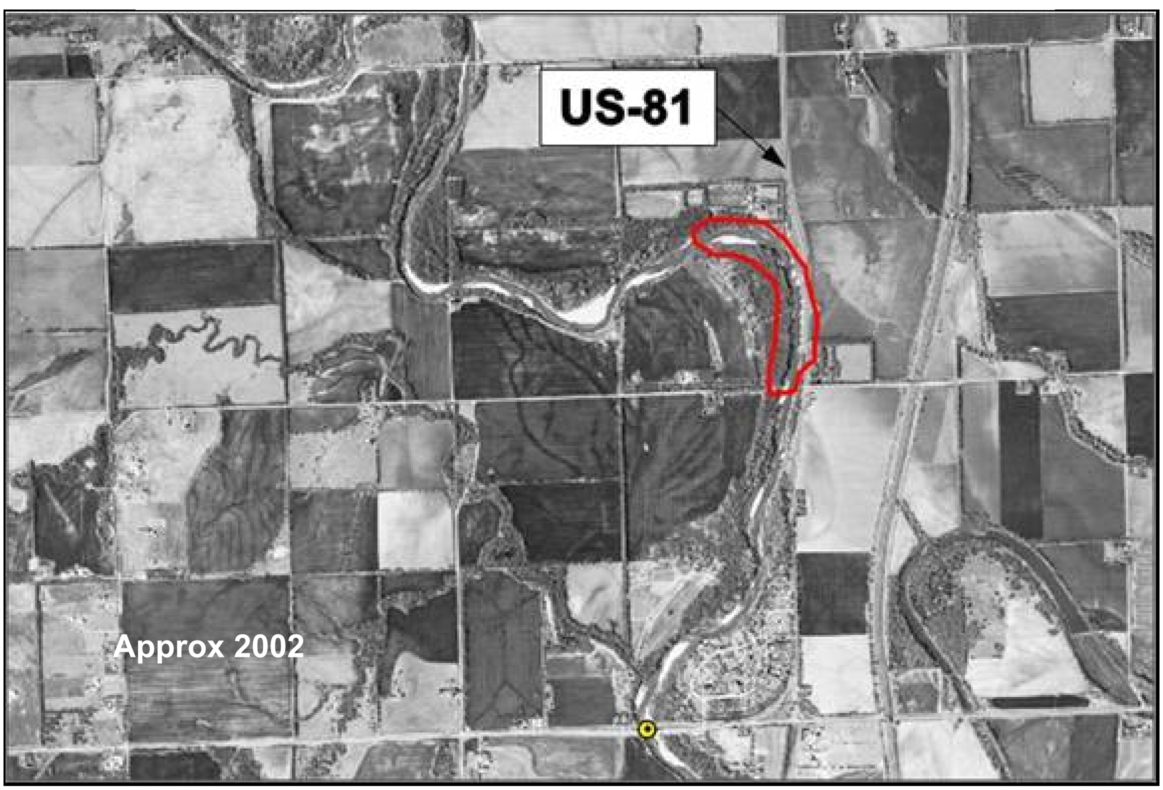


Figure 3.24: Site 5, Aerial, Riverdale, KS, Sumner County

Figure 3.25: Site 5, Aerial, Sheet Pile Jetties, Riverdale, KS, Sumner County

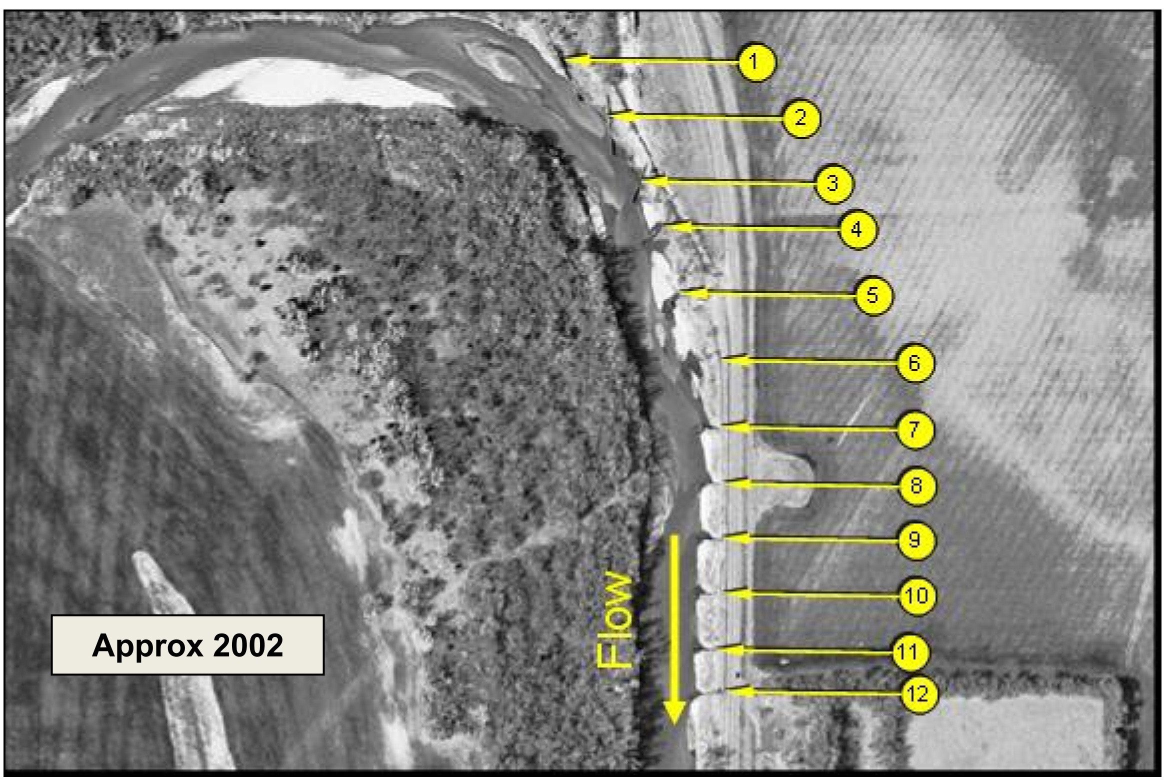


Figure 3.26: Site 5, Aerial, Sheet Pile Jetties, Riverdale, KS, Sumner County

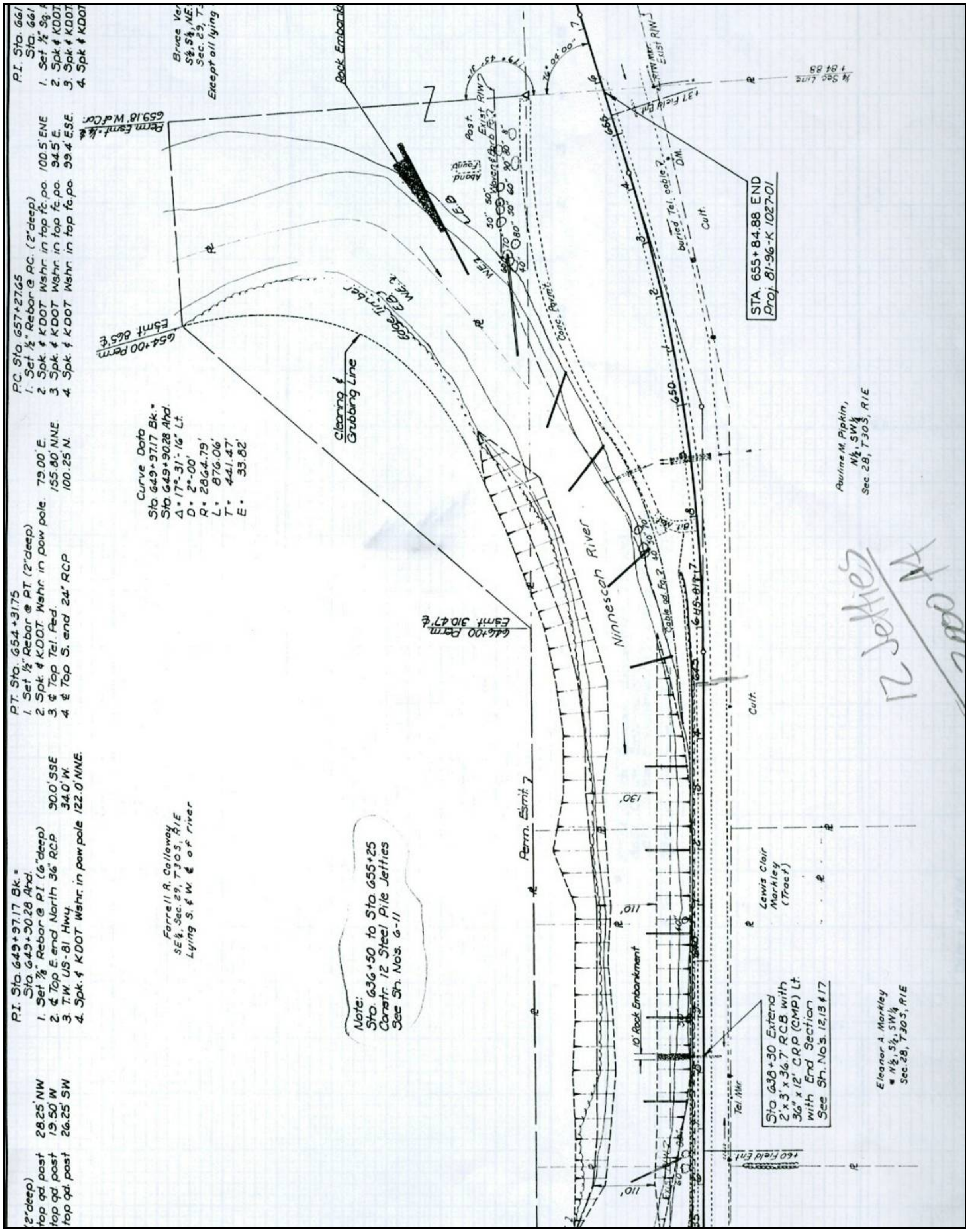


Figure 3.27: Site 5, Sheet Pile Jetties, Riverdale, KS, Sumner County Jetty Layout Plans

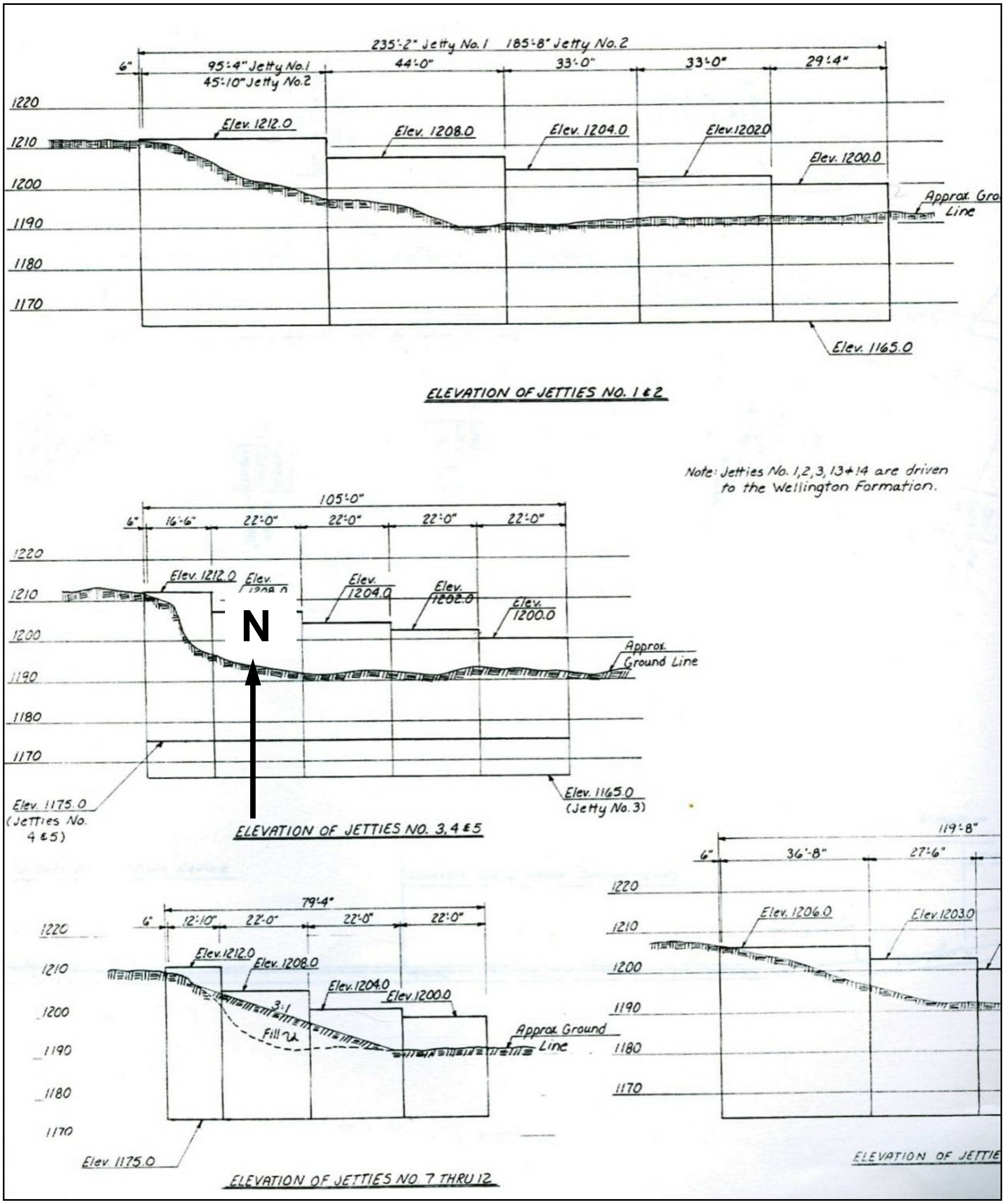


Figure 3.28: Site 5, Sheet Pile Jetties, Riverdale, KS, Sumner County Details of Selected Jetties

Figure 3.29: Site 5, Sheet Pile Jetties, Riverdale, KS, Sumner County

Figure 3.30: Site 5, Sheet Pile Jetties, Riverdale, KS, Sumner County

Figure 3.31: Site 5, Sheet Pile Jetties, Riverdale, KS, Sumner County

Figure 3.32: Site 5, Sheet Pile Jetties, Riverdale, KS, Sumner County

CHAPTER 4 - DROP STRUCTURES

4.1 Overview

Drop structures are used to arrest headcutting. Headcutting is erosion of a stream bed that proceeds in the upstream direction. It is characterized by an abrupt vertical drop in the stream bed at the upstream end of the head cut as shown in Figure 4.1. Note that the location of the headcut moves upstream with time. At low flows, the abrupt bed drop behaves like a waterfall with the flow at the headcut behaving like a plunging pool. Eddies and significant scour occur for both high and low flow events. This leads to degradation and undercutting of the streambanks as well as the headcut . Both bank and bed erosion will continue until equilibrium is reached, causing major problems throughout the stream. This can include disruption of the flood regime, which changes the critical river-floodplain interactions, thereby degrading adjacent floodplain ecosystems.

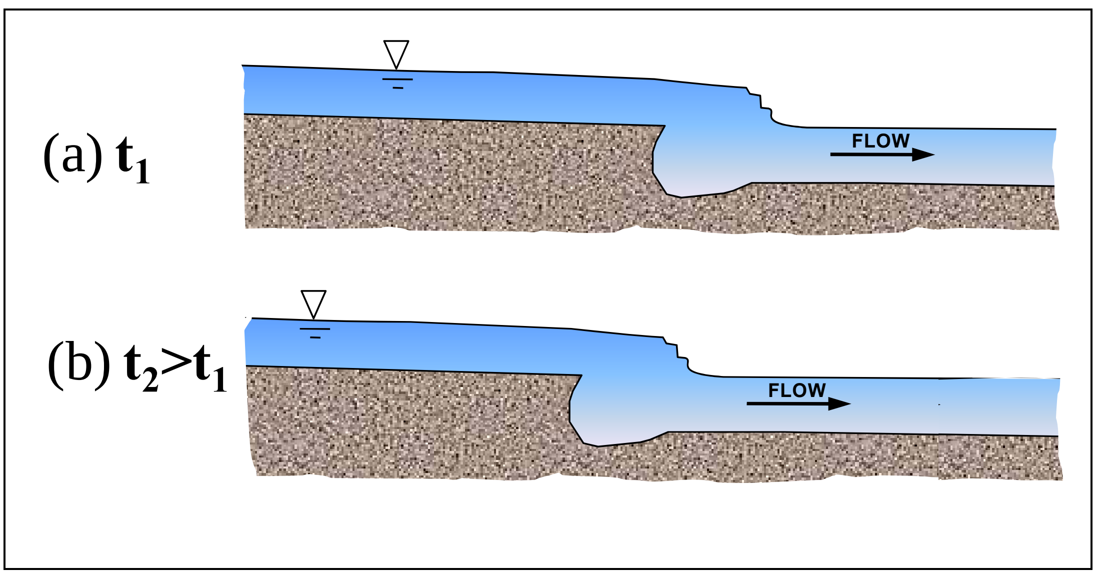


Figure 4.1: Head Cut Moving Upstream

Many natural or human modifications to stream channels, stream networks or watersheds can cause headcutting. Some of the modifications are discussed below.

- *Channel straightening* The channel slope is increased when a channel is straightened. This, in turn, increases velocities and induces channel degradation. To compensate for the increased slope, the channel upstream from the straightened portion will degrade, lowering the bed elevation. Often this degradation takes the form of a head cut.
- *Increased Discharge* Development that increases the discharge will cause the channel velocity to increase and the stream to degrade. This degradation may create a head cut that can move to reaches upstream from the portion of the stream experiencing increased discharge.
- *Drop of Water Surface at a Tributary Confluence* Tributaries are affected when the primary channels they flow into experience lowered water surface elevations. The lowering of the water surface could be due to degradation of the primary streambed or a decrease in the discharge of the primary channel. The lowered tributary tailwater elevation at the confluence with the primary stream increases the energy grade line in the tributary. This, in turn, increases the tributary velocity and promotes degradation.
- *Gravel mining*: One major cause of headcutting is “in-stream” sand and gravel mining. Increased channel erosion and downstream sedimentation resulting from the material eroded from upstream of the excavation site are principal causes of headcutting. This phenomenon usually occurs when the placement of fill was not properly performed, or by heavy equipment travel.

Problems especially occur when mining extends below the water level. Materials pushed into the bank vegetation will eventually cause vegetation to die and expose the banks to erosion if not corrected.

- *Channelization*: Another cause of headcutting is channelization, which was widespread in the early 1900's and ended about a half century later. (Herein, channelization refers to long reaches of straightened channels. This is opposed to fairly short reaches where a channel is straightened to accommodate a road crossing.) Channelization was undertaken to reduce flooding and to drain wetlands for farming. The result of this is currently evidenced by erosion and degradation of stream stability. As rivers are straightened, velocity increases significantly. This causes sediment to be carried away in much greater measures, eroding riverbeds and riverbanks. This can be especially devastating when highly erodible soils are present. As the bottom of the river becomes deeper, the banks widen quickly, causing trees and vegetation to fall into the river, eventually blocking up the river and making flood control worse.
- *Loss of Riparian Buffer Zone* The vegetation along the banks of a stream can be lost or dramatically decreased by development, farm practices or livestock. The result of this is to make the banks as well as the stream unstable. Rosgen's description of the process of stream evolution in response to a disturbance such as loss of bank stability due to overgrazing progresses for an originally stable E4 stream to C4 to D4 to G4 to F4 and finally back to E4. The final E4 stream is stable provided the riparian buffer

is reestablished. It is, however, at a lower base level than the original E4 stream. Headcutting definitely plays a role in this process of stream transition. Overgrazing affects the stream banks both by consumption of vegetation and by the physical tearing-down of the bank by trampling.

Significant degradation of a stream reach due to natural or human perturbations can have widespread effects on other portions of the stream network not “directly” affected. Lowering the bed of a stream reach extends upstream as discussed above to the tributaries and to the upper portion of the stream. Downstream from a degrading reach, the sediment load is increased thus deposition occurs. This has the potential to change the stream classification in the downstream reach as well as its tributaries.

Headcutting can pose serious threats to roads, culverts and bridges. Since headcutting is prevalent in Kansas, a major effort has been made to address protecting our highway system from the damage it could cause by the use of check dams or drop structures.

4.2 Design

Drop structures are used to arrest head cutting downstream from bridges and culverts. Essentially a drop structure is made of steel sheet piles and/or concrete and bank protections of rock riprap. Figure 4.2 shows a typical drop structure and the parameters needed to estimate the depth of scour downstream from a vertical drop. The design equations and procedure for the drop structures are presented in detail in HEC 23 and only a brief discussion will be given here. HEC 23 also gives an example design problem.

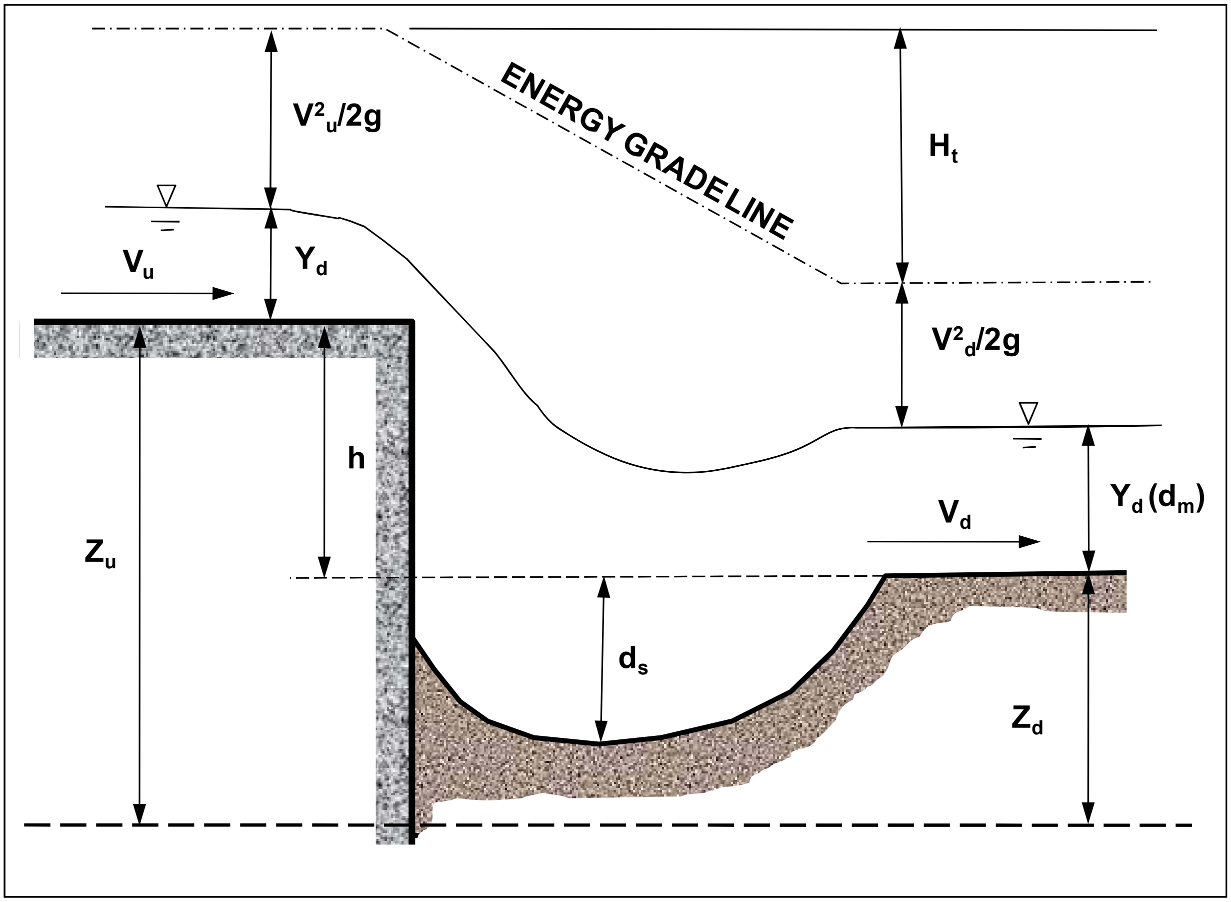


Figure 4.2: Schematic of a Vertical Drop Caused by a Check Dam (redrawn from HEC 23)

The recommended equation proposed by the Bureau of Reclamation (4) for the scour depth, d_s, is:

$$d_s = K_u H_t^{0.225} q^{0.54} - d_m \qquad \text{Equation 4.1 (Eq. 11.1, HEC 23)}$$

Where:

d_s = local scour depth for a free overfall, measured from the streambed downstream of the drop, m (ft)

H_t = total drop in head, measured from the upstream to the downstream energy grade line, m (ft) d_m, Y_d = tailwater depth, m (ft) K_u = 1.90 (SI)

K_u = 1.32 (English)

The total energy loss, Ht, is given by:

$$H_t = \left(Y_u + \frac{V_u^2}{2g} + Z_u\right) - \left(Y_d + \frac{V_d^2}{2g} + Z_d\right) \qquad \text{Equation 4.2 (Eq. 11.2, HEC 23)}$$

Where:

Y = depth, m (ft)

V = velocity, m/s (ft/s)

Z = bed elevation referenced to a common datum, m (ft)

g = acceleration due to gravity, 9.81 m/s^2 (32.2 ft/ s^2)

Eq. 4.1 is the ultimate equilibrium scour depth and it is independent of bed material. If the bed were composed of small unconsolidated sand, the equilibrium scour depth would be reached quickly. Alternatively, if the bed were rock it might take many centuries for the equilibrium scour depth to be reached.

It is paramount to design the structure to dissipate the tremendous energy that is generated at the plunge pool before the water exists into the natural channel. Riprap and/or revetments may be needed to provide protection of the stream banks and bed from both vertical and lateral scour due to the scour hole. Large car-size stones are sometimes used to protect the channel. It is also important to install sufficient armoring in the overbank areas to prevent damage due to flow outflanking the project during major floods.

4.3 KDOT Applications

Sites 14 and 15 used drop structures to control headcutting.

4.3.1 Site 14

The location of Site 14 is shown in Figure 4.3. A sheet pile drop structure was used at this location. It is a fairly small stream with a drainage area of 4.75 square miles so the extent of the scour hole was limited. Figure 4.4 shows the sketch of the scour hole prior to installation of the drop structure. It is apparent that the scour hole was a serious threat to the bridge prior to the installation of the drop structure. Figures 4.5-7 are photographs of the sheet pile drop structure, the post-installation scour hole and the downstream channel.

4.3.2 Site 15

Figure 4.8 shows the location of Site 15. A large head cut was located downstream from the bridge on HW US-24. Figure 4.9 shows the location of the sheetpile wall. Figures 4.10-13 are photographs of the drop structure and upstream and downstream channels.

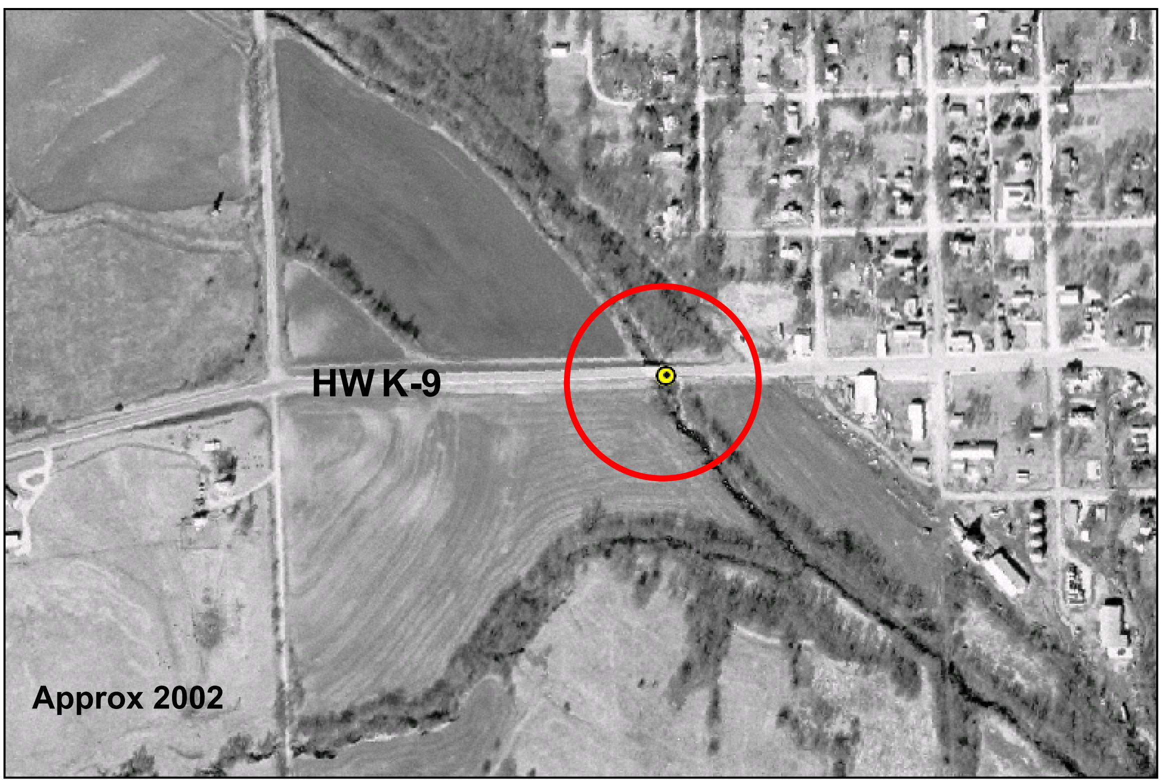


Figure 4.3: Site 14, Aerial, Sheet Pile Sill, Goff, KS, Nemaha County

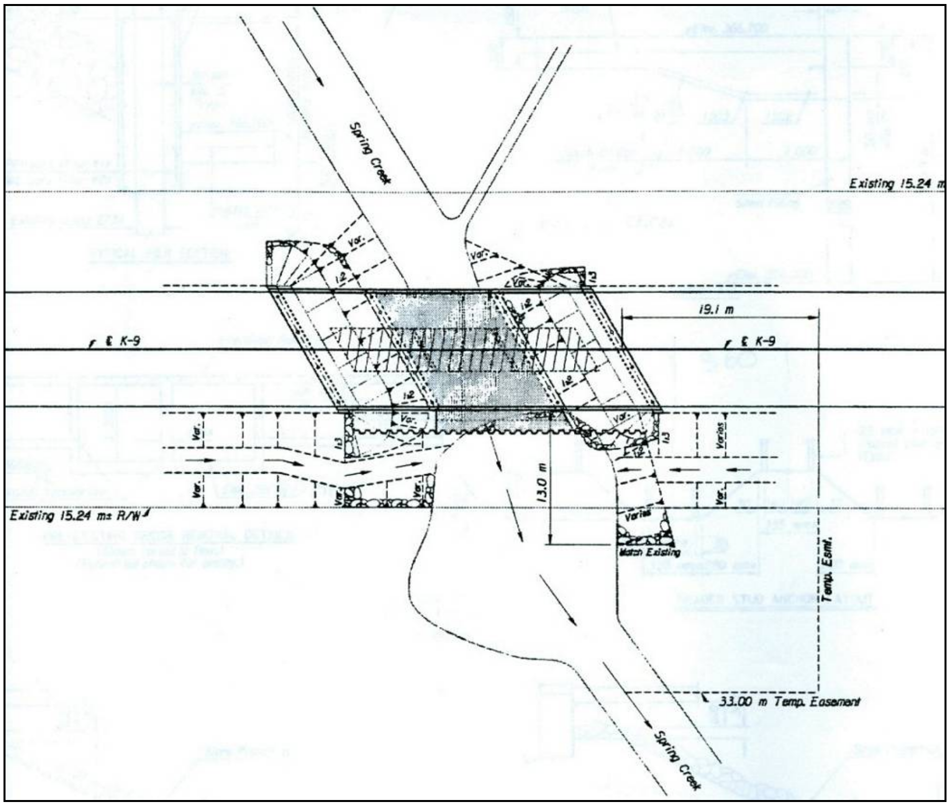


Figure 4.4: Site 14, Sheet Pile Sill, Goff, KS, Nemaha County

Figure 4.5: Site 14, Sheet Pile Sill, Goff, KS, Nemaha County

Figure 4.6: Site 14, Sheet Pile Sill, Goff, KS, Nemaha County

Figure 4.7: Site 14, Sheet Pile Sill, Goff, KS, Nemaha County (Downstream Channel)

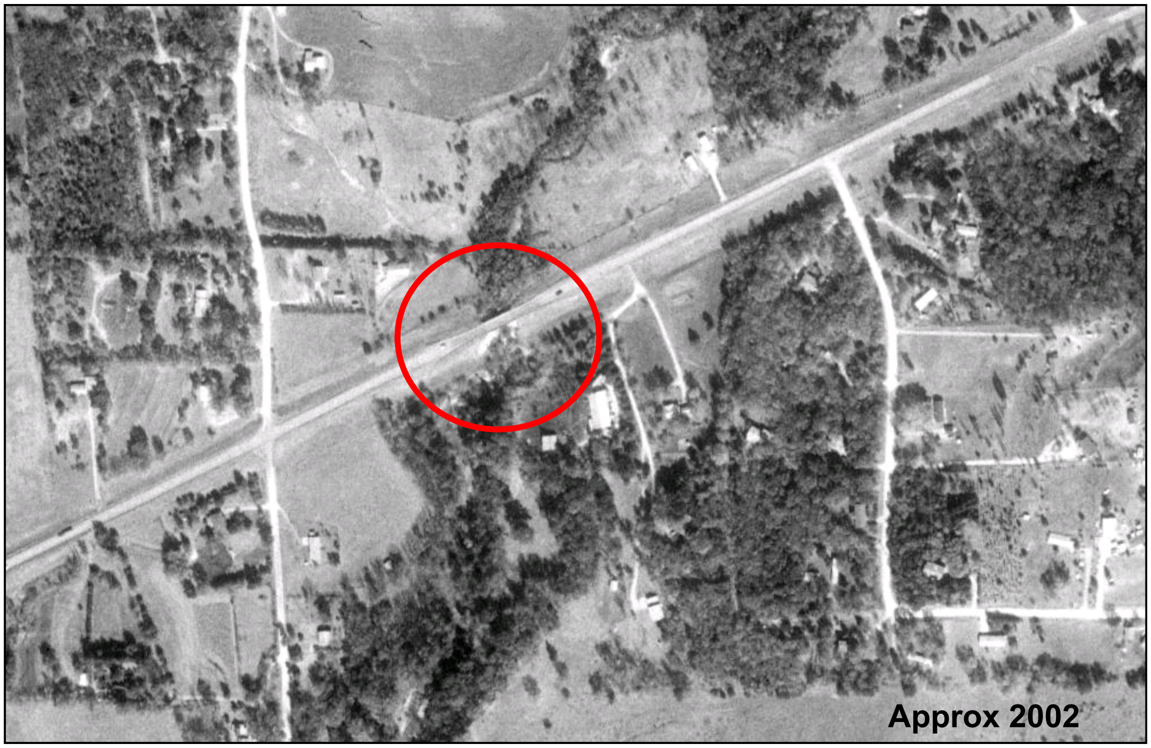


Figure 4.8: Site 15, Aerial, Concrete Drop Structure, St. George KS, Pottowatomie County

Figure 4.9: Site 15, Concrete Drop Structure, St. George KS, Pottowatomie County

Figure 4.10: Site 15, Concrete Drop Structure, St. George KS, Pottowatomie County

Figure 4.11: Site 15, Concrete Drop Structure, St. George KS, Pottowatomie County

Figure 4.12: Site 15, Concrete Drop Structure, St. George KS, Pottowatomie County

Figure 4.13: Site 15, Concrete Drop Structure, St. George KS, Pottowatomie County (Concrete Channel Upstream from Drop Structure)

Figure 4.14: Site 15, Concrete Drop Structure, St. George KS, Pottowatomie County (Downstream Channel)

CHAPTER 5 - HARD POINTS

5.1 Overview

Hard points as shown in Figure 5.1 are locations on an erodible stream bank that are resistant to erosion. They can be either man made or can occur naturally. The definition of a hard point from HEC 23 is:

> A streambank protection structure whereby "soft", or erodible, materials are removed from a bank and replaced by stone orcompacted clay. Some hard points protrude a short distance intothe channel to direct erosive currents away from the bank. Hardpoints also occur naturally along streambanks as passing currents remove erodible materials leaving nonerodible materials exposed.

Hard points can be considered very short spurs. Unlike jetties (or spurs) whose function is to both relocate a bank line then protect it, hard points are used to protect an existing bank line from further migration or degradation. Like spurs they should be well-anchored to the bank to prevent outflanking. Hard points are used effectively in relatively straight reaches with flow predominantly parallel to the bank. The elevation is at the normal water surface elevation at the toe sloping toward the bank at about a 1:10 slope (vert:hor). (USACE) Hard points are also used as the first jetty (or spur) in a jetty field.

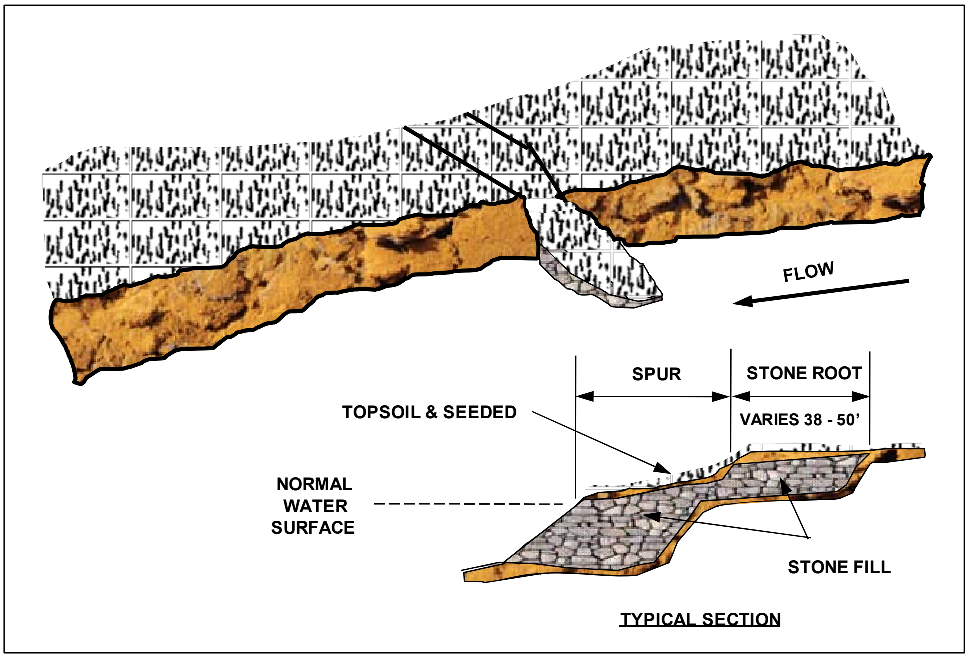


Figure 5.1: Perspective View of Hardpoint Installation with Section Detail (Fig. 6.1 HEC 23 redrawn)

5.2 Design

The design principles of jetties and bendway weirs should apply to the spacing of the hard points.

5.3 KDOT Application

5.3.1 Site 6

Site 6 is a location where the channel banks were eroding in a relatively straight reach of the Deleware River upstream and downstream from Bridge 3(046) on Highway K-116. Figure 5.2 shows an aerial photo of the site. Figure 5.3 and 5.4 show the location of hard points downstream from the bridge. Note in Figure 5.3 the location of the old channel bed to the east of the current channel. Six hard points are located on the left bank at and downstream from the point where the new and old channels meet. The photos of Figures 5.5 and 5.6 are taken looking upstream and downstream of the bridge, respectively. The hard points were barely visible downstream from the bridge as supported by Figure 5.5. The channel appeared to be in good shape relative to bank erosion. Consequently, the hard points appeared to be working as intended. This side included additional bank protection measures upstream from the bridge.

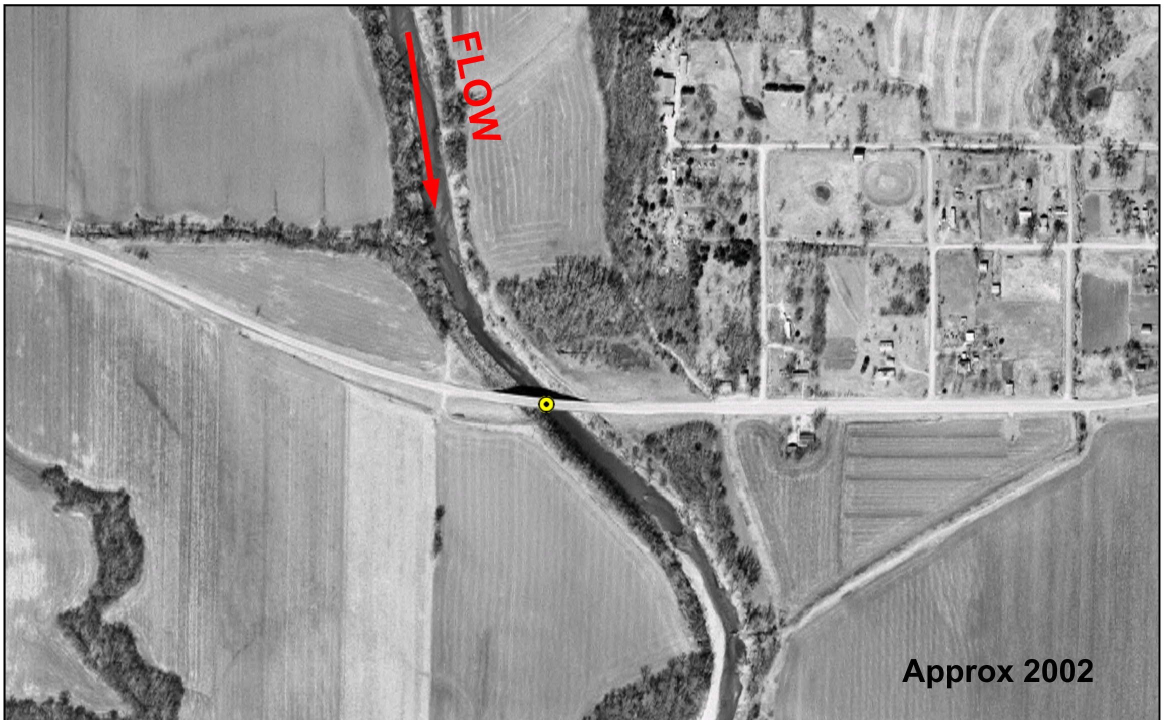


Figure 5.2: Aerial Photo of Site 6, Arrington KS, Atchison County

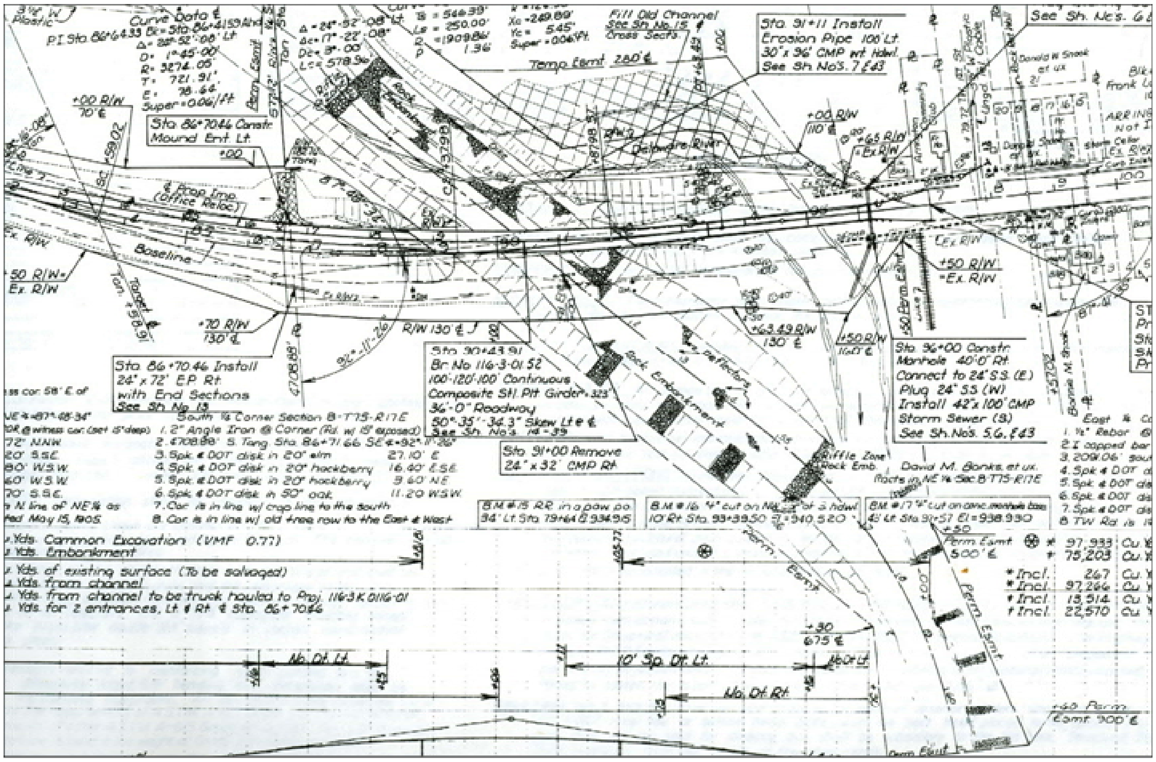


Figure 5.3: Site 6, Construction Plan View, Arrington KS, Atchison County

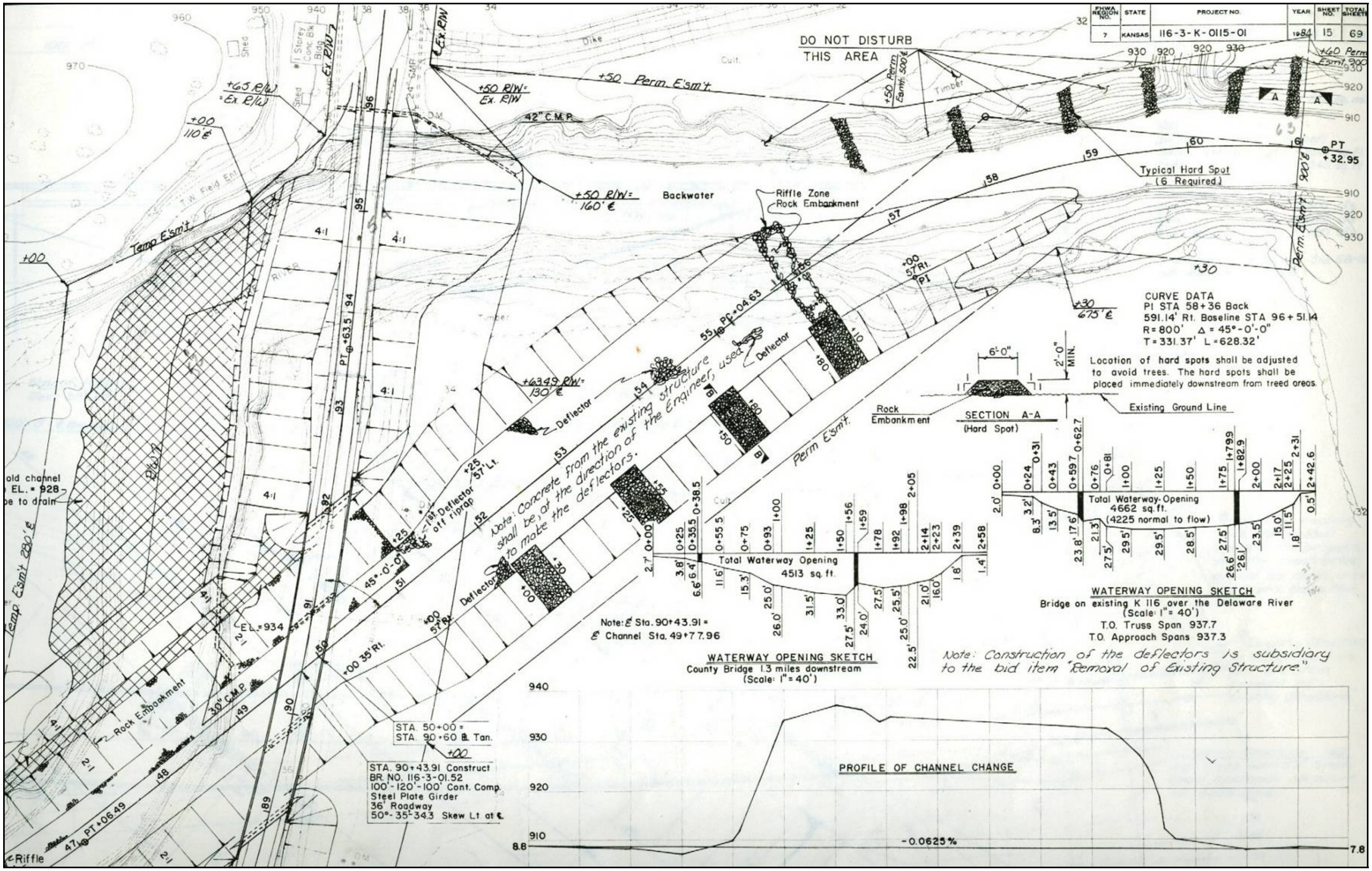


Figure 5.4: Hard Point Plan View of Site 6, Arrington KS, Atchison County

Figure 5.5: Hard Point Detail of Site 6, Arrington KS, Atchison County (Looking Upstream)

Figure 5.6: Hard Point Detail of Site 6, Arrington KS, Atchison County (Looking Downstream)

CHAPTER 6 - GABION BASKETS

6.1 Overview

Gabion baskets are rectangular-shaped wire mesh baskets filled with cobbles or rocks. They are effective in controlling erosion in streams. Figure 6.1 shows the versatility of gabion baskets due to their flexibility and weight when used as a jetty (or spur). The figure depicts the situation where scour occurs near the tip of the jetty during high flow (b). The baskets near the tip of the jetty are undermined and slide down the bankward face of the scour hole. Their flexibility allows them to bend to the shape of the scour hole. Also, their weight acts to prevent them from sliding down the face of the scour hole and detaching from the rest of the jetty except for very dynamic streams. After the high flow event subsides, the relocated baskets stay in their new position and the jetty is still intact, though altered.

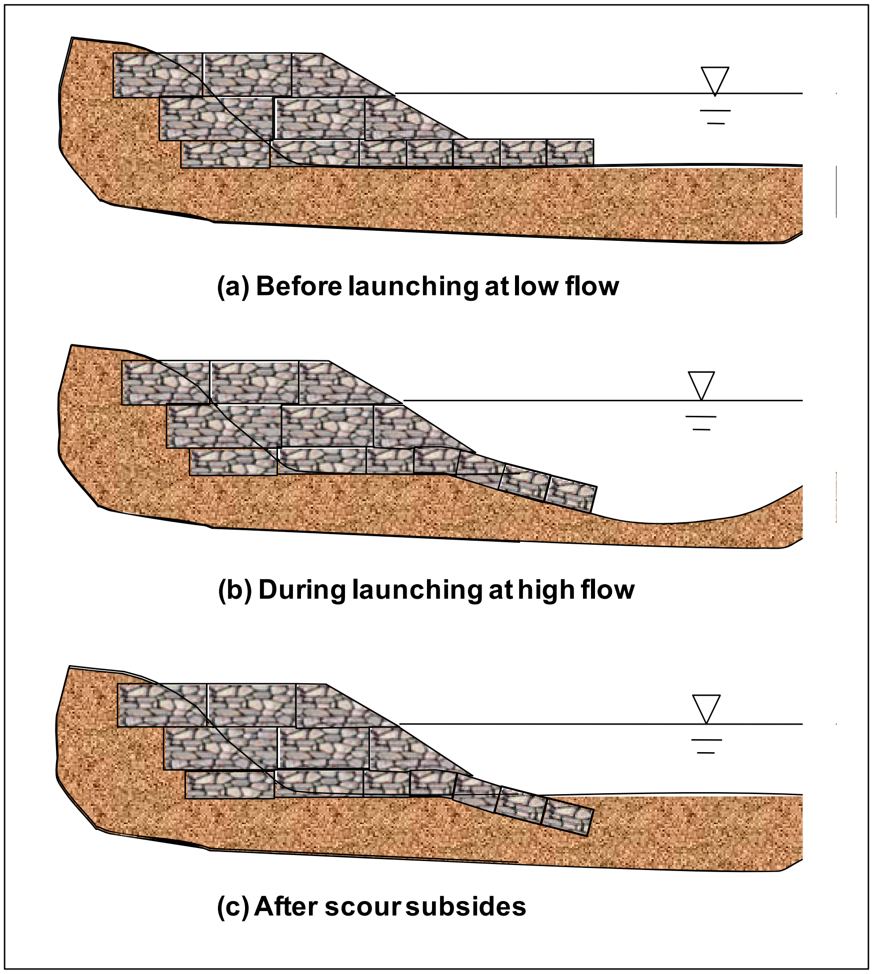


Figure 6.1: Gabion Spur Illustrating Flexible Mat Tip Protection.
(Figure 9.7 HEC 23 redrawn)

6.2 Design

The design procedures for constructing mattresses or stacked block revetments from gabion baskets is presented in detail in HEC-11. HEC-11 should be followed when designing scour countermeasures using gabion baskets.

6.3 KDOT Applications

Sites 11, 12 and 13 used gabion baskets at bridge abutment berms, abutments and at a steep inflow swale upstream from an RCB wingwall.

6.3.1 Site 11

Figure 6.2 shows Site 11 where gabion baskets and bank protection were used to protect a bridge abutment. The damaged left abutment is shown in Figure 6.3. Figures 6.4 and 6.5 show the left abutment in March 1994 right after construction was completed. Figure 6.6 shows the right abutment in 1994. It was also repaired using gabion baskets and riprap bank protection. Figures 6.7-9 show the site in March 2006.

6.3.2 Site 12

Figure 6.10 is an aerial view of Site 12 in Bonner Springs KS. Note that the channel makes a very sharp bend just upstream from the bridge. Also, the ditch on the upstream east side of the bridge carries flow into the channel directly upstream from the bridge. These flow characteristics may have caused the extensive should shown at the left bridge abutment in Figures 6.11-12. The scour hole allowed a significant portion of the flow to pass through the bridge on the outside of the bridge piers shown in Figure 6.12. Figures 6.13 and 6.14 are sketches from the construction plans showing the backfill and the placement of gabion baskets. Figures 6.14-18 are photographs of the repaired site.

6.3.3 Site 13

Site 13 addressed scour at the left wingwall of an RCB. Flow entered the channel just upstream from the culvert entrance at a very steep grade. Figures 6.19-21 show the gabion basket arrangement used to control the scour. The steepness of the “ditch” flow is evident from Figure 6.20.

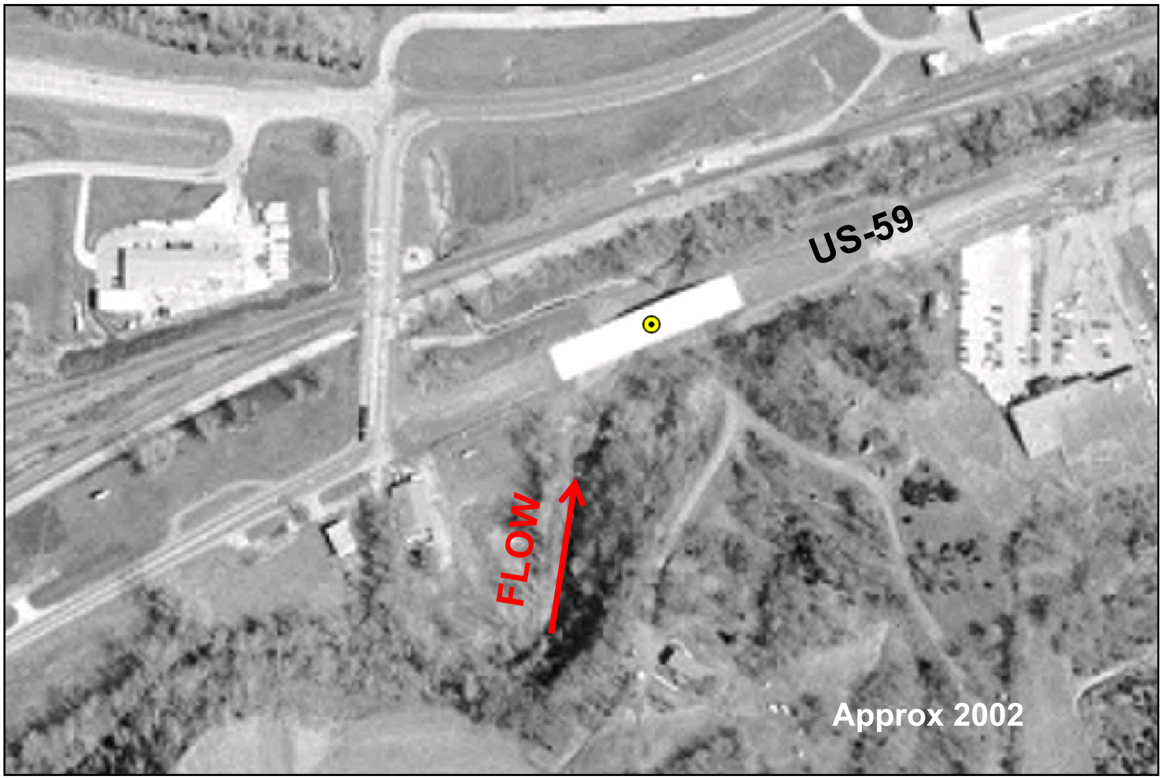


Figure 6.2: Site 11, Aerial, Atchison KS, Atchison County

Figure 6.3 Site 11, Atchison KS, Atchison County (Before Countermeasures Installed)

Figure 6.4: Site 11, Left Abutment, Atchison KS, Atchison County Gabion Baskets and Slope Protection

Figure 6.5: Site 11, Left Abutment, Atchison KS, Atchison County Gabion Baskets and Slope Protection

Figure 6.6: Site 11, Right Abutment, Atchison KS, Atchison County Gabion Baskets and Slope Protection

Figure 6.7: Site 11, Left Abutment, Atchison KS, Atchison County Gabion Baskets and Slope Protection

Figure 6.8: Site 11, Left Abutment, Atchison KS, Atchison County Gabion Baskets and Slope Protection

Figure 6.9: Site 11, Left Abutment, Atchison KS, Atchison County Gabion Baskets and Slope Protection

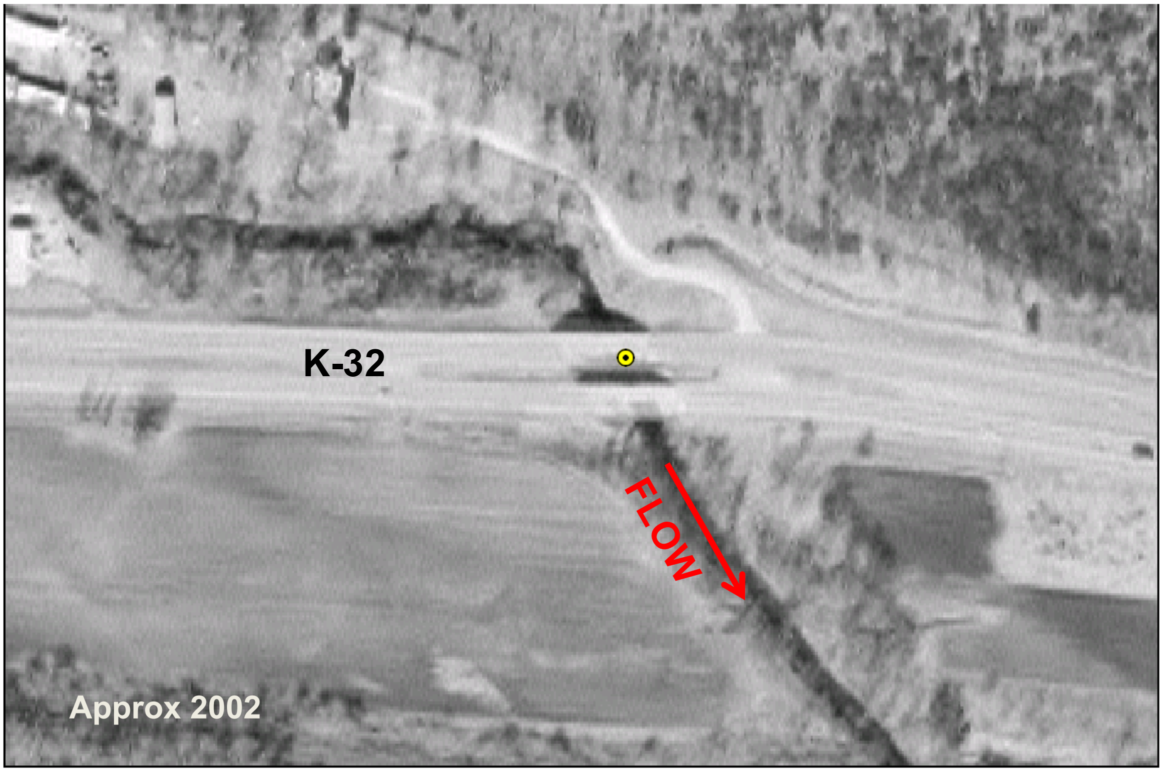


Figure 6.10:Site 12, Aerial, Bonner Springs KS, Wyandotte County Gabion Baskets and Slope Protection

Figure 6.11: Site 12, Bonner Springs KS, Wyandotte County Before Countermeasure

Figure 6.12: Site 12, Bonner Springs KS, Wyandotte County Before Countermeasure

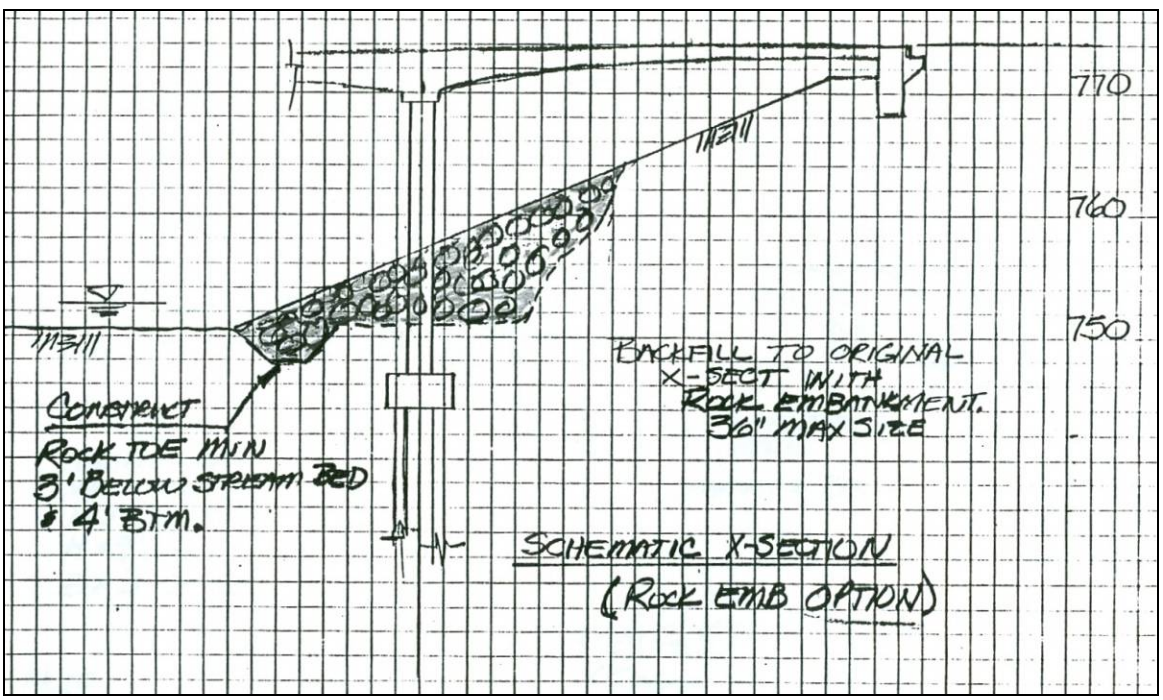


Figure 6.13: Site 12, Bonner Springs KS, Wyandotte County Gabion Baskets and Slope Protection

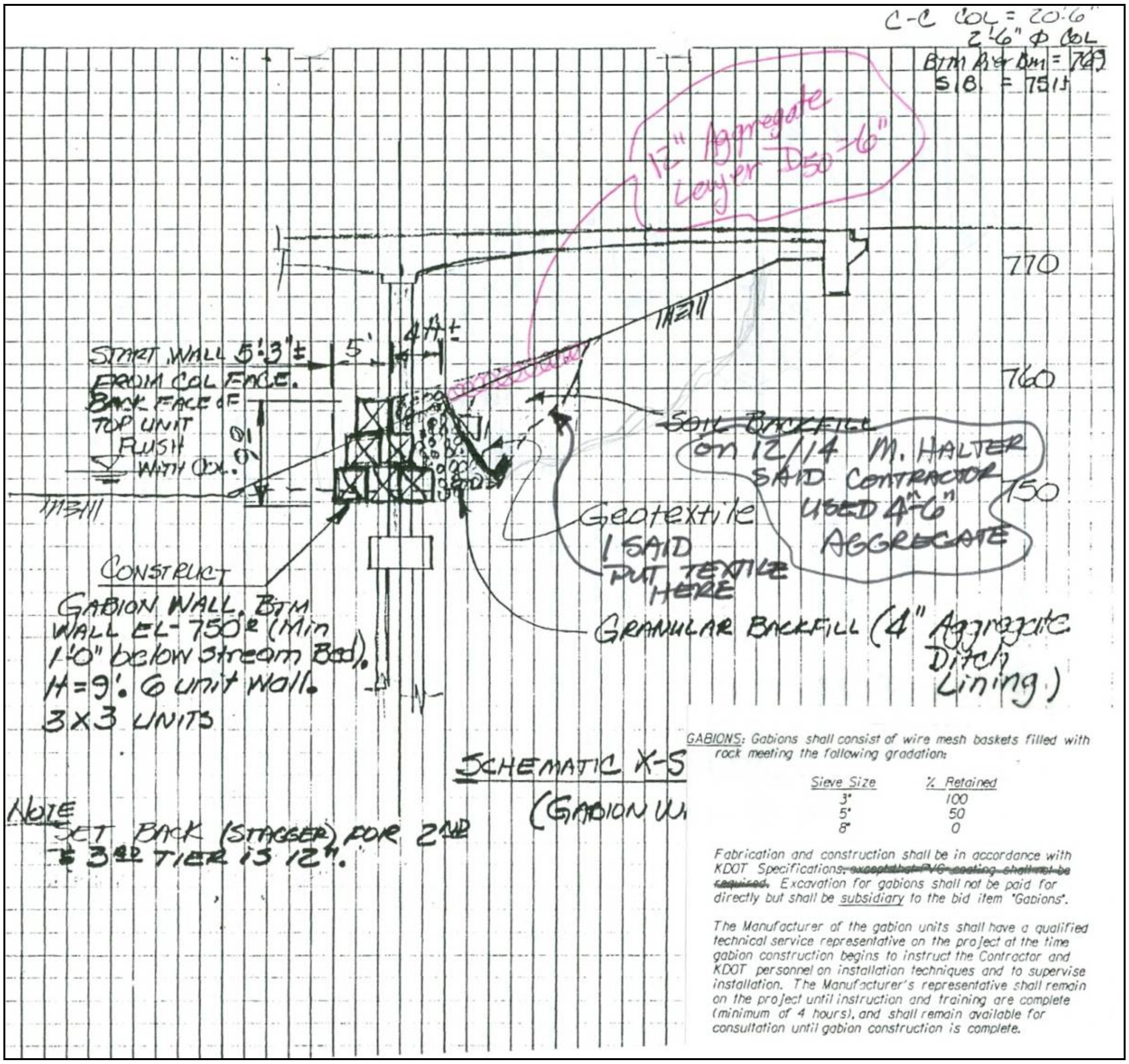


Figure 6.14: Site 12, Bonner Springs KS, Wyandotte County Gabion Baskets and Slope Protection

Figure 6.15: Site 12, Bonner Springs KS, Wyandotte County Gabion Baskets and Slope Protection

Figure 6.16: Site 12, Bonner Springs KS, Wyandotte County Gabion Baskets and Slope Protection

Figure 6.17: Site 12, Bonner Springs KS, Wyandotte County Gabion Baskets and Slope Protection

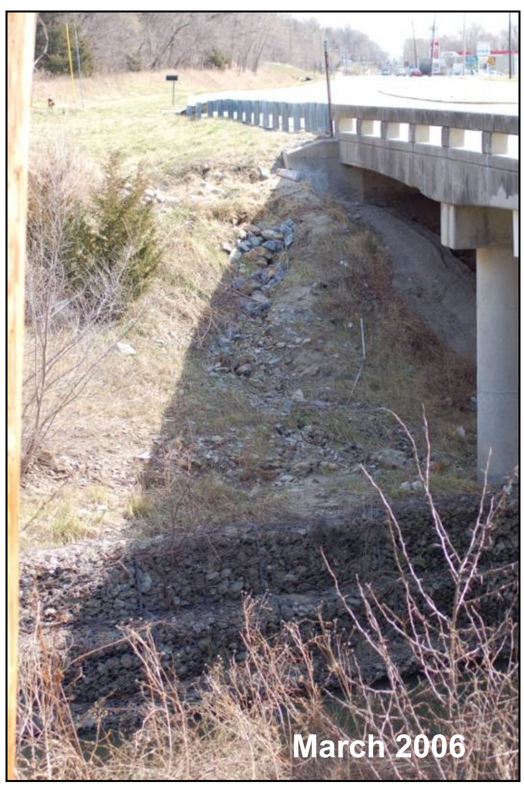


Figure 6.18: Site 12, Bonner Springs KS, Wyandotte County Gabion Baskets and Slope Protection, Upstream Side of Bridge

Figure 6.19: Site 13, Manhattan KS, Riley County Gabion Baskets RCB Wingwall Protection

Figure 6.20: Site 13, Manhattan KS, Riley County Gabion Baskets RCB Wingwall Protection

Figure 6.21: Site 13, Manhattan KS, Riley County Gabion Baskets RCB Wingwall Protection

CHAPTER 7 - SUMMARY AND CONCLUSIONS

This study considered scour countermeasures applied by KDOT to protect the highway infrastructure at stream crossings. The project included field visits to 13 sites where KDOT had installed countermeasures. The locations visited were Sites 1-6 and Sites 11-17 in Table 1 of Chapter 1. The countermeasure approaches used at these sites included bendway weirs, jetties (or spurs), drop structures, hard points, gabion baskets and bank protection. Photographs were taken at all the sites visited in order to document the effectiveness of the countermeasures. The plans and older pre-project photographs where available were also reviewed. The design of scour countermeasures is covered in detail in the Federal Highway Administration publication "Bridge Scour and Stream Instability Countermeasures" referred to as HEC-23 herein. (http://isddc.dot.gov/OLPFiles/FHWA/010592.pdf). This report presents some of the design equations and figures from HEC-23 in an effort to describe the important parameters for scour countermeasure design. Many of the HEC-23 figures presented in this report have been redrawn since some if the HEC-23 figures have become difficult to read. This is possibly due to scanning and rescanning earlier versions of the report.

The condition and effectiveness of all the locations visited appeared excellent. It was evident that the sites are monitored regularly and that modifications were made when it appeared that outflanking might threaten the countermeasure and ultimately the roadway or structure.

Rosgen states that even streams classified as stable are "dynamic" and "active" and experience lateral migration (6, p 1-3). The degree of a stream's stability and the appropriate method of determining it are still being debated. What is not being debated is that streams are dynamic whether they are stable or unstable. Typical streams and rivers are continually changing their alignments and local dimensions. If a stream is unstable its bed elevation is also changing. As a result, the role of the bridge and hydraulic engineer will continue to involve monitoring and protecting the highway infrastructure at stream crossings. Stable stream networks can be found in national parks and other areas with minimal agricultural or development activity. In Kansas, however, most of the land has been farmed or grazed and our streams are in a state of change due to loss of riparian buffer zones, changes in sediment and water runoff and channelization that occurred decades ago due to agricultural activities. Consequently, many of the streams in eastern Kansas are naturally trying to reach an equilibrium slope starting at a base elevation with the parent stream. As engineers, we will continue to be responsible for protecting our roadways and the people from the failure of our highway infrastructure due to stream instability.

This study has summarized many of the stream instability countermeasures that KDOT has implemented.

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