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Monitoring the Effects of Knickpoint Erosion on Bridge Pier and Abutment Structural Damage Due to Scour

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MID-AMERICA TRANSPORTATION CENTER

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Monitoring the Effects of Knickpoint Erosion on Bridge Pier and Abutment Structural Damage Due to Scour

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2012

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MATC

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16. Abstract
The goal of this study was to conduct a field-oriented evaluation, coupled with advanced laboratory techniques, of channel degradation in a stream of the Deep Loess Region of western Iowa, namely Mud Creek. The Midwestern United States is an ideal place for such a study considering that ~$1 Billion of infrastructure and farmland has been lost recently to channel degradation. A common form of channel degradation in this region is associated with the formation of knickpoints, which naturally manifest as short waterfalls within the channel that migrate upstream. As flow plunges over a knickpoint face, scouring of the downstream bed creates a plunge pool. This downcutting increases bank height, facilitating bank failure, stream widening, and damage to critical bridge infrastructure. We conducted a state-of-the-art geotechnical analysis of the sediments from the knickpoint face, plunge pool, and adjacent stream banks to determine the areas of the streambed near the bridge infrastructure that favor knickpoint propagation. Soil characterization using particle size distributions and Gamma Spectroscopy identified a stratigraphic discontinuity at the elevation where the knickpoint forms. An automated surveillance camera was established to monitor the location of the knickpoint face relative to a fixed datum and provide a first-order approximation of its migration rate, which was approximately 0.9 m over a 248-day study period. Surveys conducted of the stream reach also facilitated information about knickpoint migration. Flow measurements using Large-scale Particle Image Velocimetry were conducted during the study to understand the hydrodynamic conditions at the site. The results of this research will assist local and federal transportation agencies in better understanding the following: (1) principal geotechnical and hydrodynamic factors that control knickpoint propagation, (2) identify necessary data for extraction and analysis to predict knickpoint formation, (3) provide mitigation measures such as grade control structures (e.g., sheet-pile weirs, bank stabilization measures) near bridge crossings to control the propagation of knickpoints and prevent further damage to downstream infrastructure.

17. Key Words Knickpoint, Scour, Bridge Infrastructure Safety	18. Distribution Statement

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List of Abbreviations

American Society of Testing and Materials (ASTM)
Hungry Canyons Alliance (HCA)
Iowa Department of Transportation (IDOT)
Large-scale Particle Image Velocimetry (LPIV)
Mid-America Transportation Center (MATC)
Minimum Quadratic Difference (MQD)

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About IIHR—Hydroscience & Engineering

IIHR—Hydroscience & Engineering is a unit of the College of Engineering at the University of Iowa. It is one of the nation's oldest and premier environmental fluids research and engineering laboratories. IIHR seeks to educate students on conducting research in the broad fields of river hydraulics, sediment transport, and watershed processes. IIHR has 44 faculty members and research engineers at the Ph.D. level, 8 postdoctoral scholars, and about 113 M.S. and Ph.D. graduate students. IIHR's 30 staff members include administrative assistants (including grant accounting and reporting support), IT support, and machine/electrical shop engineers.

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Executive Summary

The goal of this study was to conduct a field-oriented evaluation, coupled with advanced laboratory techniques, of channel degradation in a stream of the Deep Loess Region of western Iowa, namely, Mud Creek. The Midwestern United States is an ideal place for such a study, considering that approximately $1 billion of infrastructure and farmland has been lost recently to channel degradation. A common form of channel degradation in this region is associated with the formation of knickpoints, which naturally manifest as short waterfalls within the channel that migrate upstream. As flow plunges over a knickpoint face, scouring of the downstream bed creates a plunge pool. This downcutting increases bank height, facilitating bank failure, stream widening, and damage to critical bridge infrastructure. We conducted a state-of-the-art geotechnical analysis of the sediments from the knickpoint face, plunge pool, and adjacent stream banks to determine the areas of the streambed near the bridge infrastructure that favor knickpoint propagation. Soil characterization using particle size distributions and Gamma Spectroscopy identified a stratigraphic discontinuity at the elevation where the knickpoint forms. An automated surveillance camera was established to monitor the location of the knickpoint face relative to a fixed datum, and to provide a first-order approximation of its migration rate, which was approximately 0.9 m over a 248-day study period. Surveys conducted of the stream reach also facilitated information about knickpoint migration. Flow measurements using Large-scale Particle Image Velocimetry were conducted during the study to understand the hydrodynamic conditions at the site. The results of this research will assist local and federal transportation agencies in better understanding the following: (1) principal geotechnical and hydrodynamic factors that control knickpoint propagation, (2) identification of necessary data for extraction and analysis to predict knickpoint formation, (3) provision of mitigating measures, such as grade

control structures (e.g., sheet-pile weirs, bank stabilization measures), near bridge crossings to control the propagation of knickpoints and prevent further damage to downstream infrastructure.

Chapter 1 Introduction

1.1 Problem Statement

Over the last century, the severity of stream channel erosion in the Deep Loess Region of western Iowa and eastern Nebraska has increased due to straightening of the stream corridor (fig. 1.1a), coupled with intensive agriculture and highly erodible loess soils. As a result, canyon-like systems (fig. 1.1b) have formed from persistent down-cutting and widening of the channels. These "hungry canyons," as termed by local residents, consume an estimated 450 million metric tons of eroded sediment annually from channel reaches in the Midwestern United States (Baumel 1994).

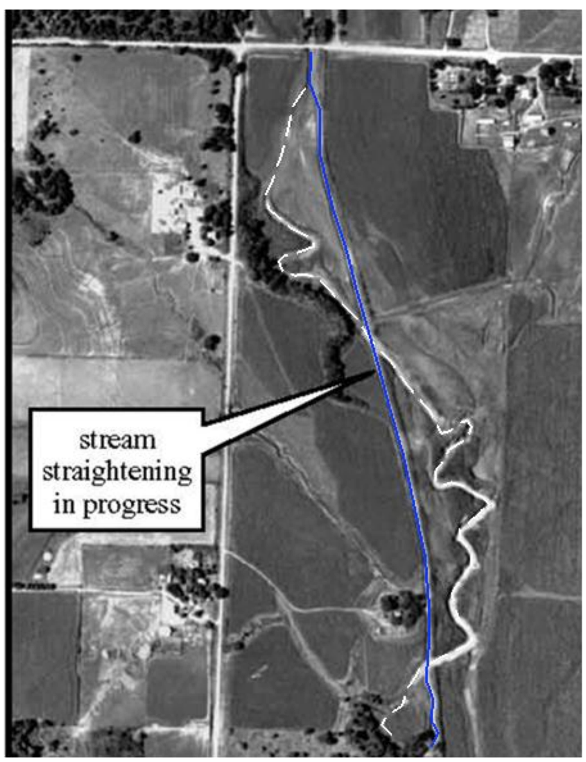


Figure 1.1 (a) Channel straightening of Mud Creek, IA in the 1950s. The white line is the original channel. The blue line is the creek after straightening.

Figure 1.1 (b) Channel incision at Mud Creek

Streams in the region are now deep, straight ditches, having once been merely wetlands or shallow meandering creeks. One example is West Tarkio Creek in western Iowa, where channel degradation has yielded an estimated loss of 147,000 metric tons/year resulting in a 6 m increase of channel depth (Simon 1992).

Channel erosion in Midwestern streams has damaged highway- and county-road infrastructure on a scale of $1.1 billion from scour around bridge piers, pipelines, and fiber-optic lines, as well as the loss of farmland adjacent to the channels due to stream bank collapses (Baumel 1994). Governmental agencies, such as the Hungry Canyons Alliance (HCA) and Iowa Department of Transportation (IDOT), have constructed hundreds of sheet-pile weirs, flumes, and other grade control structures in the region to stabilize the stream channels and prevent further damage to the local infrastructure. Despite these remedial actions, the problem still continues, due mostly to the lack of alluvial sediment delivery and freeze/thaw mechanisms (Simon and Rinaldi 2000).

Current efforts by city and county engineers, as well as state DOTs, include routine monitoring of threatened bridges using established procedures and checklists, which have been reasonably effective (Nixon 1982). However, the lack of field-oriented research related to channel degradation processes hinders the development of a truly successful remediation protocol (May 1989).

To date, laboratory studies have been used almost exclusively. Although these laboratory studies have provided valuable insight into the mechanisms driving channel degradation, they cannot capture the complex morphology of degrading channels.

Our goal in this study was to conduct a field-oriented evaluation of channel degradation, coupled with advanced laboratory methods, in a stream of the Deep Loess Region of western Iowa, namely, Mud Creek. This system contains multiple knickpoints, a common form of channel degradation in this region, that move upstream and threaten local and county bridges. We performed state-of-the-art geotechnical analyses of sediment cores from the knickpoint and adjacent stream banks to determine if there were specific layers of weakness along which the streambed would fail. Additionally, continuous monitoring of the knickpoint propagation and scour was conducted. This continuous monitoring contributed missing, but key, data regarding the exact timing of knickpoint propagation and its associated scour depth, as well as the conditions under which they occurred. This information will assist governmental agencies in better understanding the principal geotechnical and hydrodynamic factors that cause knickpoint propagation, and help to estimate the response time required to control the propagation of a knickpoint after one has been identified. This study will lead to developing predictive tools for knickpoint migration and help engineers in monitoring, maintaining, and protecting bridge waterways so as to mitigate or manage scour occurring at the bridge structures.

1.2 Definitions

Streambed degradation occurs in the loess soils of western Iowa and eastern Nebraska by the formation and headward migration of knickpoints (fig. 1.2). Ongoing research suggests that knickpoints can account for more than 60% of the erosion in the streams where they form (Alonso et al. 2002). In addition, preliminary observations suggest that knickpoints greatly influence the flow thalweg (i.e., line of deepest flow) in small rivers, which is a primary factor contributing to bank erosion and scour.

Figure 1.2 Knickpoint formation. The circled area is a knickpoint in Mud Creek, IA.

A knickpoint is a discontinuity in the channel bed elevation along the longitudinal stream profile (May 1989). Knickpoints naturally manifest as short waterfalls, often occurring in series. Flow plunges over the knickpoint and scours the bed, leading to knickpoint face collapse and plunge pool development (fig. 1.3) that over-steepen the stream banks, causing further failure. There are generally four mechanisms of mass failure observed at knickpoints (May 1989): (1) Undercutting that leads to cantilever toppling; (2) Undercutting that leads to tensile failure and toppling; (3) Undercutting that leads to shear failure; and (4) Rafting of material from water entering fractures. Fluid boundary shear, secondary flow currents, seepage, and pore pressure can also contribute to the formation and evolution of knickpoints (Clemence 1987).

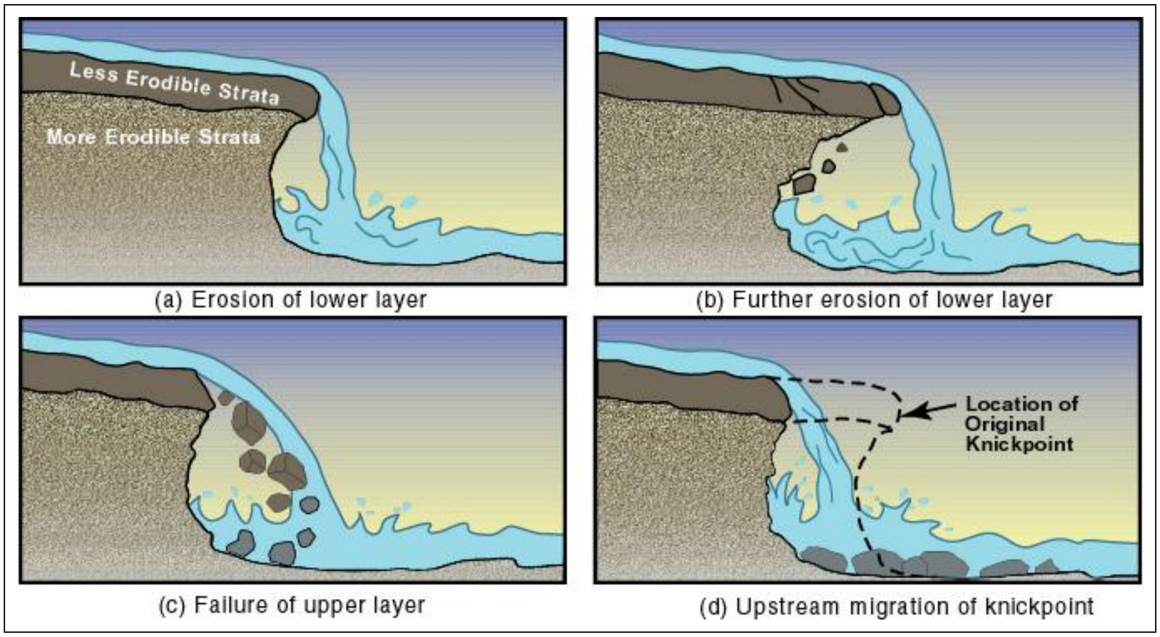


Figure 1.3 Knickpoint processes. A sketch of the steps involved in knickpoint migration.

As the downstream portion of the channel bed erodes, the knickpoint moves upstream (fig. 1.3). Once a knickpoint has formed, it will continue to advance upstream, erode the channel bed, lower the base level for tributary streams, and, if unchecked, eventually affect the entire watershed. The knickpoint can cease its upstream advance once it reaches a more resistant bed layer, when it has advanced so far upstream that the drainage area does not provide enough runoff to continue the erosional cycle, or if tailwater conditions change downstream.

Several factors that can affect the upstream migration of knickpoints (e.g., Schumm 1973; Grissinger and Bowie 1984; Clemence 1987; May 1989) include geotechnical characteristics (e.g., bed/bank sediment cohesion, erodibility, density, and homogeneity). Additionally, hydrodynamic variables (e.g., water discharge, shear stress, angle of impinging flow into the scour hole, conditions under the nappe, negative pore-water pressures, tailwater depth, the presence of upward directed seepage forces on the falling limb of hydrographs) can affect a knickpoint's upstream advance.

The geotechnical controls of knickpoint migration stem from either structural discontinuities, which are products of natural compressive or tensile forces, or stratigraphic discontinuities, which are represented by unconformities, different bedding planes, or changes in sediment structures/ textures (May 1989). Knickpoints in the loess regions of Mississippi, for example, are products of stratigraphic discontinuities between the highly erodible loess and more resistant, underlying paleosol (Whitten and Patrick 1981).

The hydrodynamic controls of knickpoint migration predominantly influence the angle of the impinging flow, which scours and undercuts the sediments below the knickpoint. Both low and high flows can influence knickpoint erosion. For lower flows, the impinging jet is closer to the knickpoint causing more scour (May 1989). During a runoff event, the relative amount of scour changes as the discharge changes. The impinging jet moves further from the knickpoint face, thereby decreasing scour, as flow increases. Thus scour most likely occurs at the beginning and end of the runoff events.

1.3 Previous Research

In the loess regions of the Midwest, most knickpoints form in unlithified, cohesive sediments. Previous studies of knickpoints in these environments have been either theoretical or conducted under simplified, scaled-down laboratory conditions focused on controlling hydrodynamic forces.

An extensive literature search provided only a few examples of field studies regarding knickpoint migration through unlithified, cohesive sediments. One study conducted in the loess alluvium deposits of Willow Creek, IA (Daniels 1960) described a knickpoint that migrated upstream 2,819 m over a five-year period. The highest recorded migration during a single runoff event was a 183 m advance over four days. Further studies (Daniels and Jordan 1966) in Thompson Creek, IA, observed that freezing and thawing, in conjunction with runoff, exacerbated annual migration rates.

Extensive observations over five years of 11 major knickpoints in the Yalobusha River, MS watershed documented migration rates between 0.4 and 16 m/yr, depending on the parent material (Simon et al. 2000; Thomas et al. 2001; Simon and Thomas 2002; Simon et al. 2002). Measurements of the critical shear stress and erodibility for the different bed materials demonstrated a discrepancy between observed knickpoint retreat rates and available hydrodynamic shear stress, which suggested other mechanisms influenced knickpoint retreat (Simon and Thomas 2002; Simon et al. 2002), namely: (1) weathering and crack formation during low-flow periods, exacerbated by desiccation and fluvial erosion; (2) detachment of aggregates during the falling limb of hydrographs from upward-directed seepage due to a pressure imbalance at the bed surface and the inability of the streambed to dissipate excess pore-water pressure (Simon and Collison 2001); (3) static liquefaction in areas with little jointing from upward-directed seepage; and (4) more rapid erosion and migration from a cyclical mass failure mechanism.

The relative dominance of the four above mechanisms was a function of the hydrodynamic forces and geotechnical resistance of the cohesive material, as well as the nappe structure, tailwater depth, and flow stage. For example, during periods of low tailwater, a steep hydrodynamic gradient formed within a knickpoint scour hole, which exacerbated seepage and undercutting. During periods of high tailwater, knickpoint erosion by mass failure was less likely because of the confining pressure afforded to the knickpoint face meaning erosion was probably dominated by particle-by-particle shear erosion enhanced by upward-directed seepage forces.

Chapter 2 Objectives and Tasks

Several factors (e.g., May 1989) affect the upstream migration of knickpoints, including both geotechnical characteristics (e.g., the presence of joints or cracks, stratigraphic discontinuities, and bed sediment characteristics) and hydrodynamic variables (e.g., water discharge, shear stress, angle of impinging flow into the scour hole). To better understand the driving forces behind knickpoint propagation in the Deep Loess Region of the U.S. Midwest, detailed studies of both the knickpoint's internal, geotechnical properties, as well as external hydrodynamic forces are necessary.

The goal of the current project was to conduct field-oriented research, coupled with advanced laboratory methods, on the headward migration of a knickpoint in western Iowa, (i.e., Mud Creek). In order to accomplish this goal, we performed two encompassing tasks: we performed a state-of-the-art geotechnical analysis of the stream bank and knickpoint sediments in the laboratory; in addition, we conducted continuous monitoring of the knickpoint propagation and scour through time-lapse photos of the knickpoint face relative to a fixed datum; flow measurements using Large-scale Particle Image Velocimetry (LPIV) were periodically conducted during the study to understand the hydrodynamic conditions at the site.

Chapter 3 Methodology

3.1 Study Site

This study focused on a knickpoint (fig. 3.1) located in northeast Mills County, IA (N41^{O}05’51’’; W95^{O}31’00’’) along Mud Creek (HUC-12: 102400020505), a tributary of the West Nishnabotna River. The Mud Creek watershed covers approximately 97.5 km^2 in Pottawattamie and Mills Counties of the Deep Loess Region in western Iowa. The creek flows south 25.75 km through an agricultural landscape. The knickpoint is approximately 4.44 km above the confluence with the West Nishnabotna River, and located about 30 m downstream of a sheet pile weir with a grouted limestone riprap cascade, or, 70 m downstream of the Elderberry Road county bridge. Mud Creek was straightened in the early 1950’s (fig. 1.1). The stream channel is approximately 19 m wide, and the channel banks are 4 to 5 m high. At baseflow, the channel at the knickpoint face is 4.8 m wide, with average depths of ~24 cm upstream of the knickpoint face and ~10 cm over the knickpoint.

The soils and geology of the study site are functions of the multiple glaciation periods during the Pleistocene. The upland soils in the watershed are loess-derived and well-drained. They are characterized as silty clay loams with 2 to 4% organic matter (Nixon 1982). The soils in the bottomlands and floodplains are silt loams to silty clay loams with high organic matter content (3 to 7%), and are primarily derived from alluvium (Nixon 1982). Multiple layers of highly erodible loess deposits, which have eroded from the uplands and deposited in the valley bottoms, overlay the base paleosol, a glacial till (Bettis 1990). Mud Creek cuts through these different loess layers, which are unstratified and unconsolidated silt-sized particles. Conversely, the paleosol is less erodible than the loess (Ruhe 1969). At present, there is a stratigraphic discontinuity near the elevation of the top of the knickpoint, and more geotechnical analysis is needed to identify accurately the layers at this critical boundary.

3.2 Core Extraction

Sediment cores were collected from both the channel banks and stream bed along the reach of Mud Creek, IA containing the knickpoint seen in figure 3.1 (below).

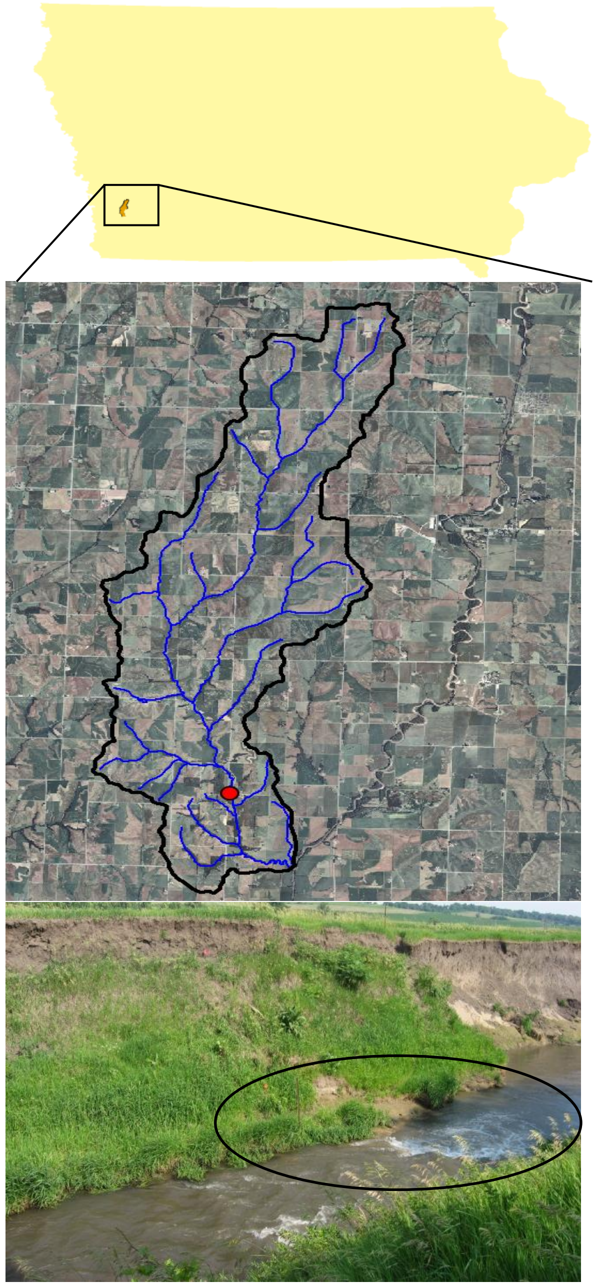


Figure 3.1 Mud Creek, IA. The red dot on the aerial photo is the monitored knickpoint. The circle in the site photo highlights the knickpoint.

Two cores were collected having a 7.6 cm diameter and being approximately 10 m in length from the stream banks along Mud Creek, near the location of the knickpoint face. One core was collected from the east bank, and the other was collected from the west bank. These cores were collected using a Shelby-tube system (fig. 3.2), in conjunction with the U.S. Department of Agriculture – Natural Resources Conservation Service. In addition, eight 2.5 cm diameter cores, approximately 3 m in length each, were collected from the stream bed of the reach containing the knickpoint.

Figure 3.2 Core collection. Cores from the stream banks near the knickpoint face were collected using a Giddings probe and Shelby tube system (cont'd. next page).

Figure 3.2 (cont'd.) Core collection. Cores from the stream banks near the knickpoint face were collected using a Giddings probe and Shelby tube system

3.3 Core Parameterization

The collected sediment cores were transferred to IIHR in the core tubes for geotechnical analysis. The cores were characterized for any stratigraphic discontinuities that could facilitate knickpoint migration.

One of the 10 m stream bank cores was classified using a standard stratigraphic interpretation of the Natural Resources Conservation Service (NRCS). The examined soil characteristics during this stratigraphic interpretation included matrix color, soil texture, soil structure, and organic matter (fig. 3.3).

Figure 3.3 Stratigraphic interpretation. A close-up of the surface section for the stream bank core used in the stratigraphy analysis. The ruler in the image is in inches.

Following the classification, the core was sub-sectioned into 10 cm intervals, and geotechnical analyses of each core sub-section were conducted. The geotechnical analyses included measurements of the particle size distribution, Atterberg limits, porosity, and bulk density.

Established methods (e.g., ASTM method D422-63; American Society of Testing and Materials 2004) were used to determine quantitatively the particle size distribution of each sub-section of the core. For particle sizes larger than 75 micrometers, a nest of sieves was used to separate the coarser soil size fractions. For particle sizes smaller than 75 micrometers, the distribution of the fine sediments was determined through sedimentation using a hydrometer.

The Atterberg limits were determined for select core sub-sections using ASTM method D4318-10 (American Society of Testing and Materials 2004) to provide further classification of the fine-grained soil fractions. The Atterberg limits include the liquid limit, plastic limit, and plasticity index of soils, which are used to characterize other soil properties, such as compressibility, hydraulic conductivity, shrink-swell, and shear strength.

The fall-cone test was used to evaluate the Atterberg limits of the select sub-samples (Skempton and Bishop 1950). The fall cone was held over a sample and allowed to penetrate based on gravity. The depth of penetration of the fall cone into the sample was related to the water content.

The second, 10 m stream bank core was kept intact for analysis of the soil pore structure and bulk density using a non-destructive means, namely, an automated gamma radiation scanning system (fig. 3.4; Papanicolaou and Maxwell 2006).

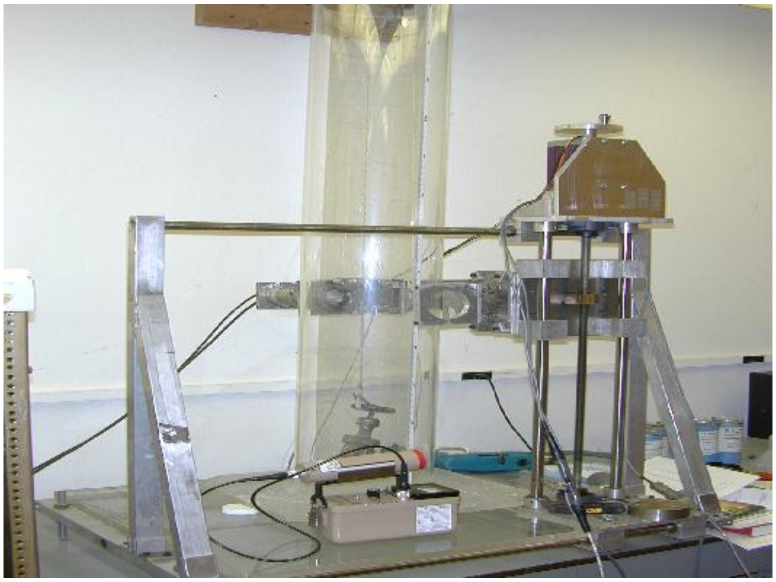


Figure 3.4 Gamma scanner. The gamma scanner system at IIHR. Typical results of a core's density.

The gamma scanner, housed at IIHR, consisted of a 550-mCi, sealed Americium-241 (^{241}Am) source, which produced gamma energy at a wavelength of 60 keV, and a Harshaw

6S2/2-X NaI(Tl) detector with an integrated photo-multiplier for detection of the gamma radiation. The signal from the detector was amplified and passed through a single-channel analyzer, operated in windowed mode to filter out noise. Collimation was provided by a 9.5-mm thick lead plate with a 6.35-mm circular hole for the source beam and a 0.889-mm x 36.8-mm slit for the detector, machined in a 31.8mm deep block of lead. Vertical motion of the source and detector was provided by a QuickBASIC - controlled step motor, and measurements were taken at discrete points. By examining profiles and comparing with visual observation, the spatial accuracy of the system was ~1mm at a 5mm scan interval. The system was calibrated before the analysis using a core with a known density and recording the gamma count rate. Errors of 3–5% for the volume fraction of solids were typical and highest at very low volume fractions, due to the statistical nature of radiation interactions.

Figure 3.5 Measuring core bulk density. A section of the stream bank core was placed in a vertical frame. A ^{241}Am sealed source was moved up and down the core length in conjunction with a gamma energy detector on the other side of the core. The attenuation of the received radioactivity was indication of the core density.

3.4 Knickpoint Propagation Using a Time-Lapse Camera

A time lapse camera was installed at the study site to continually monitor knickpoint progression and changes in bank topography. The camera was installed on the west descending bank of the channel, and was programmed to take a picture of the knickpoint every 30 minutes. Because images captured after nightfall were too dark to allow the observation of change, only daylight-captured images were useful. It was determined that the 30-minute temporal resolution was unnecessary, and that one image per day was sufficient for analysis. Of the images that were collected, 248 daily images were reviewed between July 14, 2011 and March 21, 2012. The camera continues to be in operation, collecting images for future analysis.

Two issues associated with the time-lapse images required correction: (1) small changes in the camera position and (2) obliqueness of the images:

First, the angle of the camera changed slightly from day to day because of thermal expansion of the camera mount, and possibly due to slight changes in the soil moisture content and temperature of the channel bank supporting the camera mount; furthermore, when images were downloaded from the camera, the design of the camera made it difficult to return it exactly to its original position. However, image magnification and camera distance remained the same; only camera angle changed slightly over the course of the study. To correct for camera rotation, approximately six base points near the water surface of the stream were identified in the time-lapse images. The base points were easily identifiable points that were stationary from image to image (e.g., rocks that were known to have not changed position, strategically placed stakes, etc.). To apply the correction, a guide image (one of the initial time-lapse camera images) was loaded. The base points were identified in the guide image. A misaligned image was then loaded, and the same base points were identified in the second image. A program then applied equation

3.1 to determine the required coefficients to properly align the second image with the guide image. This was repeated for all of the time-lapse images prior to correcting them for obliqueness. Changes to the rotation angles of the images were relatively small, but were necessary in order that the same oblique correction could later be applied to all of the time-lapse images.

Second, the images were collected at an angle not directly above the target, i.e., they were oblique. In order to properly determine distance in the time-lapse images, the images had to be rectified so that they appeared undistorted and as they would from directly above. To correct for obliqueness, seven to nine control points (different than previously identified base points) were chosen that were evenly distributed in the imaged area of the knickpoint and located at the intersection of the water surface and the stream bank during low flow. The control points were identified with markers for easy identification in the time lapse images. The control points were then surveyed so that each control point had a set of coordinates in the image plane (image coordinates), as well as in the object plane (surveyed coordinates). The images were then rectified using the oblique correction equations (after Fujita et al. 1997, 1998).

$$X = \frac{b_1 x + b_2 y + b_3}{b_4 x + b_5 y + 1} \qquad Y = \frac{b_6 x + b_7 y + b_8}{b_4 x + b_5 y + 1} \tag{3.1}$$

In equation 3.1, x and y are the control point coordinates in the image, and X and Y are the surveyed object coordinates of the control point. The coefficients b_1 through b_8 were determined using a least squares optimization that minimizes the sums of the squares of the differences between predicted and surveyed values of all control point object coordinates.

Lastly, the rotational correction described in the first step was imperfect, and the images from the second step were also horizontally and vertically adjusted (by translation only) until stationary parts of the banks in sequential images were aligned. The overall accuracy of the alignment and rectification process in the region of interest is estimated to be 5 to 10 pixels (2.5 to 5 cm). As an example, figure 3.6 shows the oblique, unaligned images from the time lapse camera for the dates of September 15, 2011, December 3, 2011, and February 12, 2012. The corrected images are shown in figure 3.7.

(a) (b) (c)

Figure 3.6 Time-lapse images collected on (a) September 15, 2011, (b) December 3, 2011, and (c) February 12, 2012

(a) (b) (c)

Figure 3.7 Corrected time-lapse images from (a) September 15, 2011, (b) December 3, 2011, and (c) February 12, 2012

Note that the banks are three dimensional, while the water is only slightly three dimensional. Equation 3.1 is based on the assumption that the control points and everything in the image fall within the same object plane. Because this is not completely true, objects outside of the plane of the control points (e.g., the banks) appear physically distorted when rectified. However, the water surface itself is not significantly distorted since care was taken to survey only control points that were at the water surface, and the water surface elevation did not change significantly within the knickpoint region.

After aligning and rectifying the images, the knickpoint face was identified in each image, and was highlighted. The exact location of the knickpoint was not always known accurately because during higher flows the position of the knickpoint was sometimes hidden by the flow. However, for a significant part of the year, the stream had relatively low flows and the position of the knickpoint could be observed most of the time.

3.5 Knickpoint Propagation Using Survey Data

Surveys of the banks and stream bed were collected during all site visits. These surveys were used to provide control points for rectifying the time-lapse images and LPIV videos, as well as yield stage information for the channel. In addition, two extensive surveys of the bed and banks were conducted on September 27, 2011 and March 21, 2012. These extensive surveys contained detailed information about changes in the knickpoint bathymetry that provided insight into the mechanisms associated with knickpoint migration at the Mud Creek site.

3.6 Flow Velocity Distributions Using LPIV

Water surface velocity distributions were determined for the knickpoint stream reach using LPIV. During each site visit, a series of videos was collected that captured sequences of the flow. The lowest flow was seeded with cereal (slightly buoyant and biodegradable), but higher flows were sometimes unseeded for practicality and safety reasons. To date, three flows have been captured at the site. These flows consist primarily of low flow conditions, since high flows were rare during the period of study and it was unsafe to collect velocity data during high flows using the method presented herein. The lowest flow was captured on September 27, 2011. Two higher flows were captured on June 27, 2011 and March 21, 2012. Due to an equipment error, survey data for the June 27 flow was faulty and the data could not be fully analyzed; some of this information may be recoverable in the future. The flows from September 27, 2011 and March 21, 2012 have been analyzed, and the results can be seen in chapter 4. All of the videos were converted into sequences of bitmaps with a known separation time of $1/30^{th}$ of a second. Using surveyed control points, the LPIV images were corrected for obliqueness. Corrections were applied in the same way as for the time-lapse images, where surveyed control points were identified in the LPIV images and then used in conjunction with equation 3.1 to correct the images. Figure 3.8 shows an example of a captured and rectified image. Note that for the LPIV images there was no need to align the images, since the camera was stationary during the tests and the tests were short enough (typically five to ten minutes) that long-term changes in camera position were not an issue.

(a) (b)

Figure 3.8 LPIV image samples: (a) original image sampled from LPIV video and (b) rectified LPIV image.

The rectified images were loaded into an LPIV program where they were analyzed for surface velocities as follows:

(1) Since LPIV analysis is based on image intensity, color images were converted to gray scale intensities prior to interrogation.

(2) Velocities were calculated at cross-sections where detailed bathymetry of the stream was known from surveys. The cross sections were 0.74 m downstream of the knickpoint, and 0.48, 2.00, 3.53, 5.05, 6.58, and 8.10 m upstream of the knickpoint.

(3) For each cross section, interrogation points were selected at 20 cm intervals from bank to bank.

(4) The velocity was calculated at each interrogation point using a multi-file minimum quadratic difference (MQD) algorithm. The algorithm summed MQD objective functions from 40 pairs of images to determine the mean surface velocity at each point.

Applying a multifile approach offered two distinct advantages over the traditional approach of analyzing one pair of images at a time. First, the number of tracers in the present arrangement was low for many of the flows, and analyzing the combined objective function from multiple files vastly improved the signal-to-noise-ratio of the interrogation procedure. Second, the improvement in signal-to-noise-ratio allowed us to apply a much smaller interrogation area, resulting in much better spatial resolution. Of course, the disadvantage of combining objective functions from multiple pairs of images is that temporal resolution is lost, but if the goal is to determine average velocities, loss of temporal resolution is a minor issue.

Using the surface velocity distributions, discharges at the site were also determined for each cross section. To accomplish this, it was assumed that the velocity distribution obeyed the power law. While this assumption was not rigorous, it was likely sufficient in locations where the channel was shallow and wide. Assuming the power law was valid, the mean velocity for each interrogation point would be approximately $7/8^{th}$ of the surface velocity. The mean velocity for each interrogation point was then calculated, multiplied by the flow area of the point to obtain the discharge flux associated with the point (see fig. 3.9), and then summed with the fluxes from all of the subareas in the cross section to obtain the discharge in the channel.

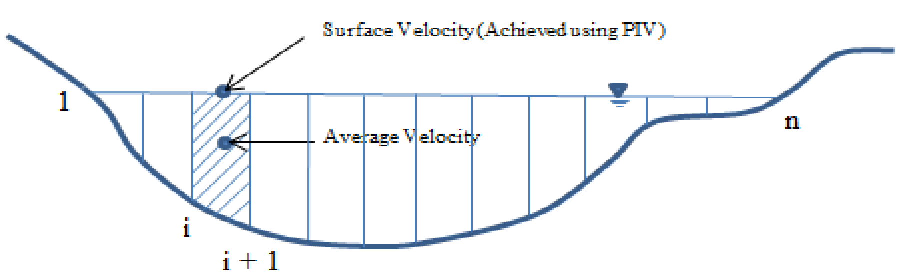


Figure 3.9 Depiction of subareas associated with interrogation points used for discharge calculations

To apply this method for calculating the discharge, the depth variation in the channel cross section must be known. For the analysis in this report, contour plots from surveyed data were used to obtain cross section depths for each of the cross sections. This method worked reasonably well, although there were a few locations where rapid streamwise changes in the depth led to erroneous results.

Chapter 4 Results

4.1 Geotechnical Analysis

A visual analysis of the stratigraphy of the bank soil profile at the knickpoint site in Mud Creek identified a discontinuity that can be seen in figure 4.1. The image distinctly shows two different layers, as well as what appears to be a “fault” between the two layers. This stratigraphic discontinuity is at the same level (i.e., elevation) as the top of the knickpoint face.

Figure 4.1 Stratigraphic discontinuity. There appears to be a stratigraphic discontinuity close to the knickpoint with a darker sediment (in the black circle) overlaying a lighter-colored sediment (in the red circle).

A detailed geotechnical analysis of the bank soil profile was conducted to confirm the site stratigraphy and accurately identify the layers at this critical boundary. Herein, the top layer will be called the bank soil and the lower layer will be called the bed sediment.

A classification of one of the 10 m cores from the adjacent stream bank was conducted using the established Natural Resources Conservation Service Field Book for Describing and

Sampling Soils (Whitten and Patrick 1981). The classification identified two distinct layers: (a) the Roberts Creek Member, which overlaid (b) the Gunder Member.

The Roberts Creek Member is characterized as dark, clayey, silty, and loamy late-Holocene alluvium that has been observed throughout the region along the modern floodplain and parallel to the modern channel (Bettis 1990). The age range for the Roberts Creek Member is approximately 4,000 to 500 B.P.

The Gunder Member is characterized as oxidized brown to yellowish-brown to grayish-brown silt loam, silty clay loam, or loam grading, to sand and gravel at depth (Bettis 1990). These soils are from mid-early Holocene alluvium (~10,500 to 3000 B.P.), and are found at low terrace positions merging with side slopes.

The Roberts Creek Member is usually darker in color than the older, underlying Gunder Member. The two members are often separated by a fluvial erosion surface or an unconformity (Bettis 1990).

More detailed characterization of the 10 cm sub-sections for this core was conducted to confirm any differences between the two layers. Determination of the particle size distribution for each sub-section was part of this characterization. Figure 4.2 shows the depth profiles for key particle diameters (i.e., d16, d50, and d84; the number represents the percentage of sediment mass that is finer the associated particle size diameter).

In this core, the stratigraphic discontinuity was found at a depth between 600 and 650 cm below the surface. The red circle in figure 4.2 highlights the location of this discontinuity. The bank soils above the discontinuity and the bed sediments below the discontinuity had slightly different particle size distributions (fig. 4.2). Visually, a shift was observed where the particle sizes of the key diameters increased at the discontinuity, signifying a coarsening of the sediment.

Further analysis of the particle sizes for the different sub-sections showed that the bank soil had higher clay percentages and lower sand percentages than the bed sediment (fig. 4.3). Again, the red circle highlights the location of this discontinuity. Quantitatively, the differences in size classes are seen in table 4.1, which contains the average values for each size class. Using a Student's t-test, the average clay percentage for the bank soil was significantly higher ($p <<< 0.001$) and the bank soil sand percentage was significantly lower ($p << 0.001$) than the corresponding values of the bed sediments.

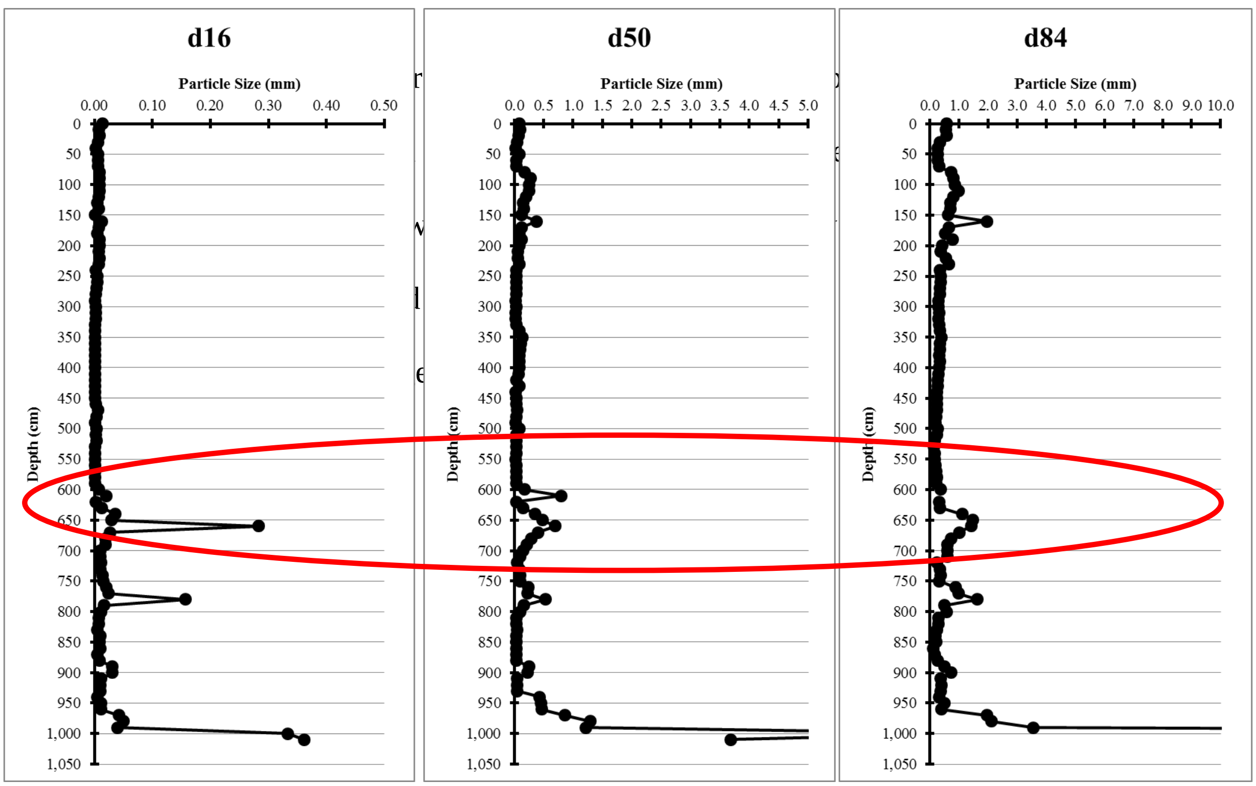


Figure 4.2 Particle size distribution. These graphs show key particle size diameters of the sampled depth intervals in a stream bank core from the study site. The d16, d50, and d84 for each interval are plotted relative to depth. The red circle highlighting the 600-650 cm depth interval corresponds to a coarsening of the overall particle size distribution, as there are increases in the d50 and d84. This elevation corresponds to the top elevation of the knickpoint face.

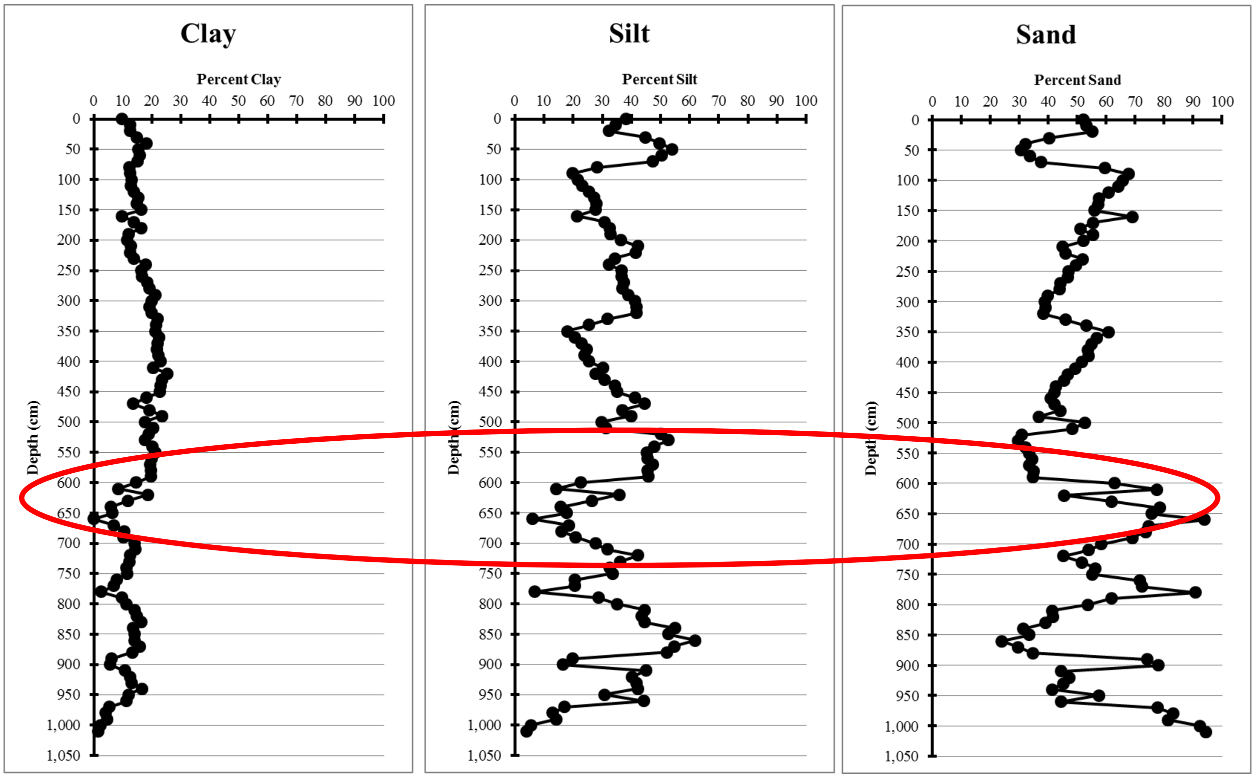


Figure 4.3 Soil texture. The percentages of clay, silt, and sand for each depth interval of a stream bank core from the study site. The red circle highlighting the 600-650 cm depth interval corresponds to a discontinuity in bank stratigraphy. This discontinuity corresponds to the top elevation of the knickpoint face.

Table 4.1 Average percentages of sediment size fractions

	Sand	Silt	Clay
Bank	47 ± 10%	35 ± 9%	18 ± 4%
Bed	60 ± 19%	30 ± 15%	10 ± 5%

Thus, the particle size distribution and soil texture data support the division between the two stratigraphic layers at the study site. The Roberts Creek Member was found in the bank soils, while the Gunder Member was found in the bed sediments. The higher clay content of the Roberts Creek Member caused (at least partially) the darker soil color relative to the Gunder Member of the bed sediment (fig. 4.1). The Gunder Member also trended from loam to sandy texture (Bettis 1990), as seen in the ternary diagram of figure 4.4. The higher percentage of sand particles could have resulted in cementing the bed sediment, making it more resistant to erosion. The discontinuity that formed between the two members can be a key component in the development of knickpoints. These findings appear to be similar to those in the loess region of Mississippi (Whitten and Patrick 1981) where a stratigraphic discontinuity was a primary control of the knickpoints.

Additional geotechnical tests conducted in this study included the determination of the Atterberg limits for select fine-grained samples of the bank soils and bed sediments (fig. 4.5). Again the samples were divided into bank and bed samples as designated by the discontinuity between 600 and 650 cm below the ground surface.

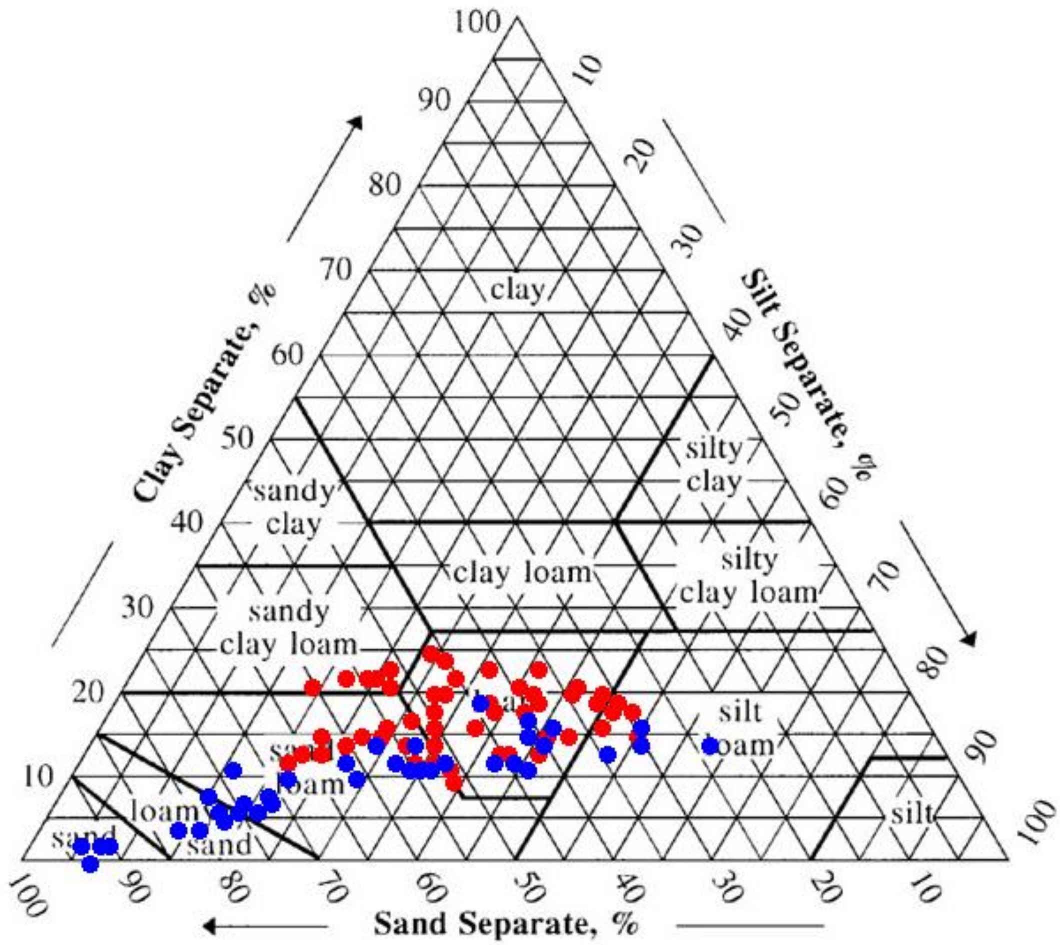


Figure 4.4 Soil ternary diagram. The soil texture of depth intervals in a stream bank core based on USDA soil classifications and particle size measurements. Red circles represent samples above 600 cm, and blue circles represent samples below 600 cm. The 600-650 cm elevation corresponds to the top elevation of the knickpoint face. There is a coarsening of sediment below this elevation, as seen through a shift in the texture as the material becomes sandier.

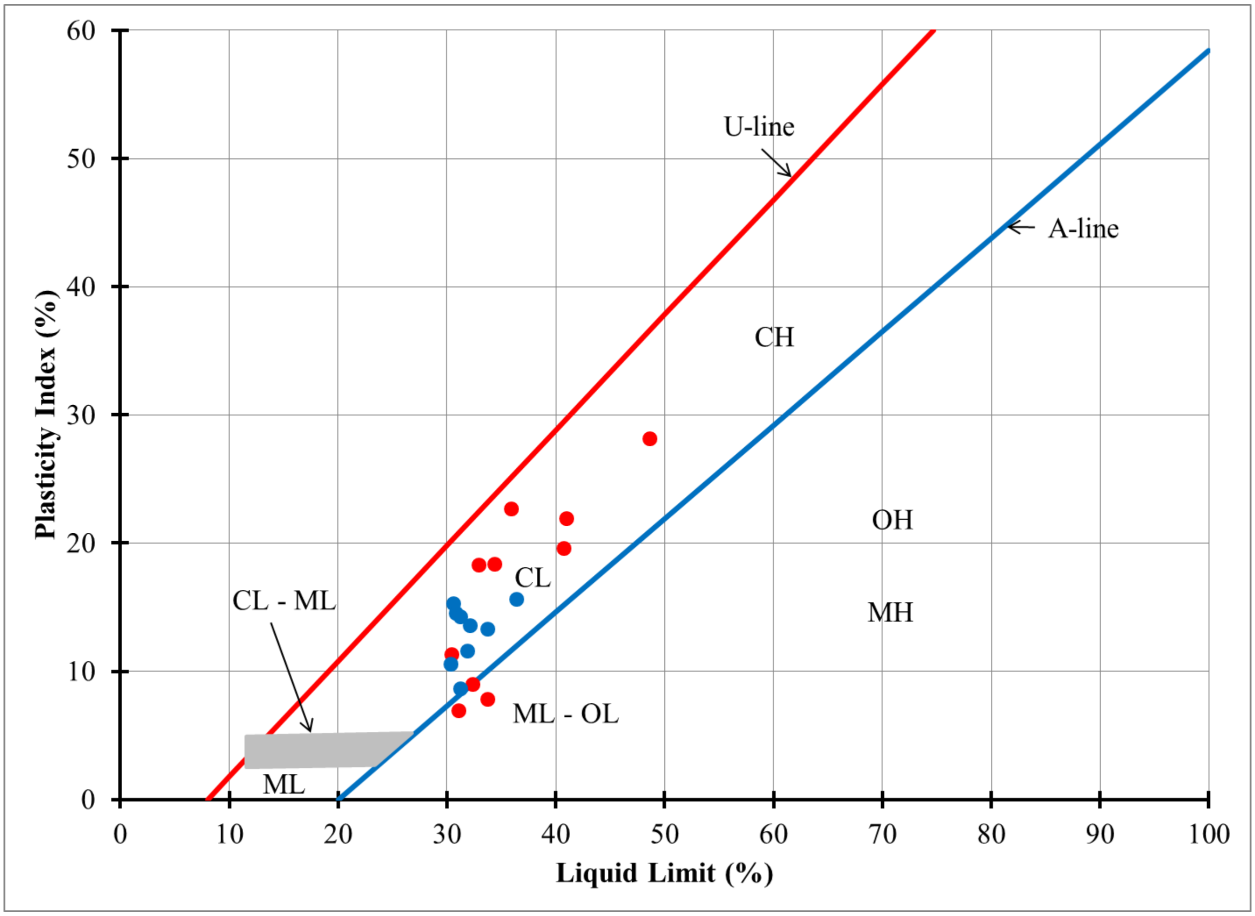


Figure 4.5 Atterberg limits. The Atterberg limits of select depth intervals were measured using a fall cone. The samples were chosen because they had a majority of fine particle sizes. Red circles represent samples above 600 cm, and blue circles represent samples below 600 cm. The 600-650 cm elevation corresponds to the top elevation of the knickpoint face. The samples are mostly characterized as clay with low plasticity.

All samples, bed and bank, fell in the range of the clays with low plasticity (designated as the "CL" region in fig. 4.5). The soils in this classification are defined as inorganic clays with low to medium plasticity, and can be sandy in nature. These soils are practically impervious, having fair shearing strength and medium compressibility when compacted or saturated. Using a Student's t-test to differentiate the bank and bed sub-samples showed that Liquid Limits and Plasticity Indices for the two groups were not significantly different ($p > 0.05$), thus, no further analysis using Atterberg limits was performed to describe the samples.

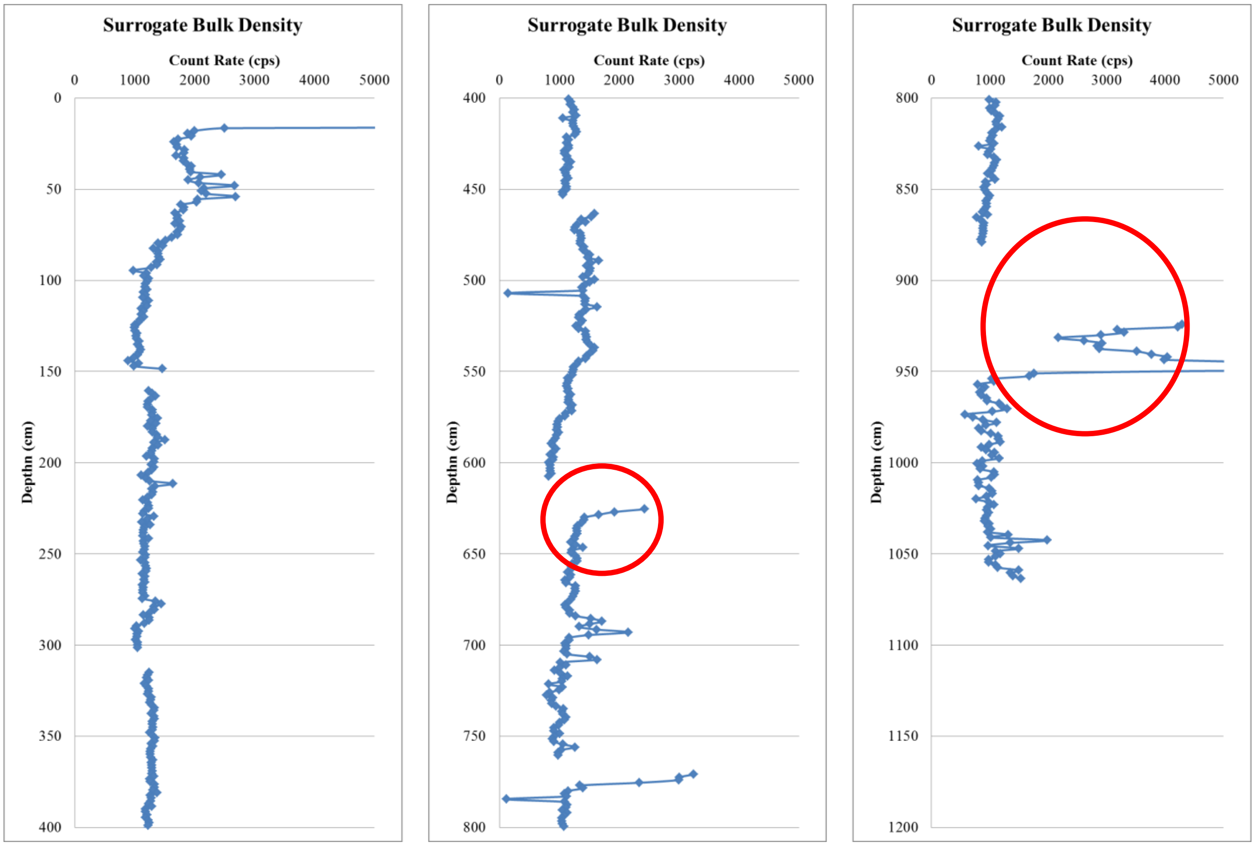


Figure 4.6 Surrogate bulk density. The density of a stream bank core was measured using the attenuation of a gamma radiation source. These graphs show the depth profile of attenuation count rates for a stream bank core. A high count rate translates to high transmission of the gamma source through the core, so that depth interval will have a lower bulk density. The red circles highlight shifts in the depth profile.

The second, intact, 10 m core from the stream bank was used in the next set of analyses. A radioactive ^{241}Am sealed source and NaI detector were used to determine the porosity/density of this second core. Figure 4.6 shows the depth profile of the attenuation count rates determined as a result of this analysis.

As the gamma energy emanated from the sealed source, it traveled through the core. The energy was attenuated as it passed through the core, based on the pore structure of the core. If the core density was low, then more of the gamma energy passed through the higher area of pore spaces. Thus, a high count rate translated to high transmission of the gamma energy through the core, so that sub-section had a lower bulk density. The average count rate for samples above the discontinuity (i.e., the bank soils) was 1304 ± 289 counts/second, while the average count rate for samples below the discontinuity (i.e., the bed sediments) was 1079 ± 219 counts/second. These sets of samples were significantly different using a Student's t-test ($p <<< 0.001$).

This is in agreement with the previous results. Since the bank soils contained more clay than the bed sediments, they were expected to have a higher porosity than the coarser bed sediments. The porosity for clays is around 40-70% of sand, while the porosity for sand is lower—around 25-50% (Freeze and Cherry 1979).

Finally, additional cores were collected from a longitudinal transect in the stream channel from the current location of the knickpoint and moving downstream. A quick analysis of the percentage of sand-sized particles in these cores was conducted to identify any change as the knickpoint migrated upstream. Figure 4.7 shows four cores collected in the transect. There was no significant change (either fining or coarsening) in the cores moving upstream from the location of the knickpoint in 2009 (Old KP) to the Chute, then Sensors, then current knickpoint locations. However, there was a coarsening at depth, approximately 4-5 ft (122-152 cm) below the top of the knickpoint. This was the approximate location of the scour hole floor immediately downstream of the knickpoint face, based on visual observations and prior geodetic surveys.

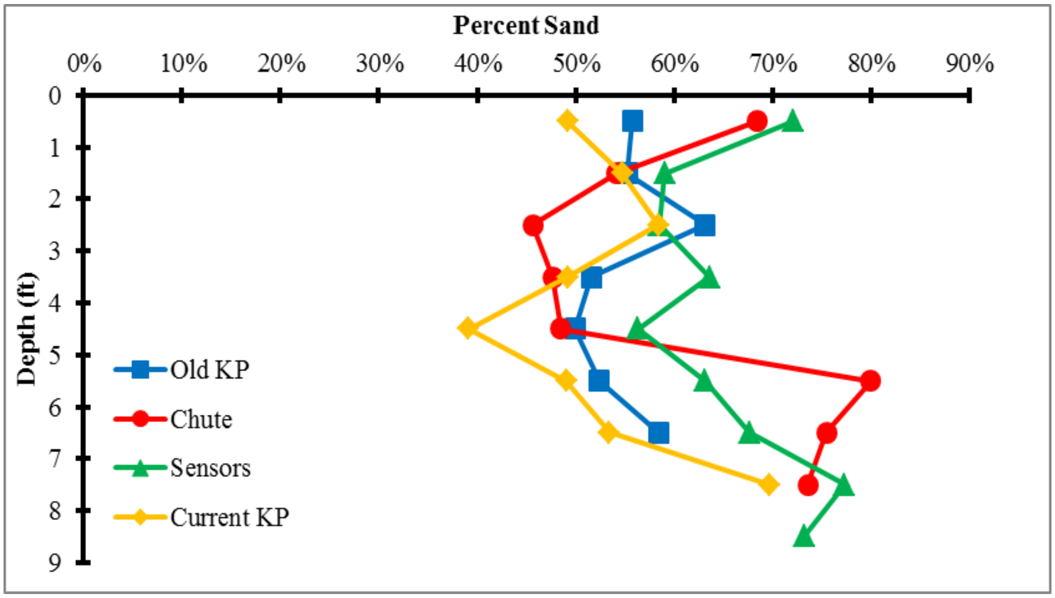


Figure 4.7 Stream bed cores. The depth profile of the percent sand of cores collected along a transect of the stream bed reach near the knickpoint. The zero level represents the top of the knickpoint face. Old KP represents the core furthest downstream where the knickpoint was in 2009. The transect moves upstream as follows: Chute -> Sensors -> Current KP. There appears to be no difference in the depth profiles; however, there is a coarsening four feet below the surface.

4.2 Knickpoint Propagation

Between July, 14 2011 and March, 21 2012, the position of the knickpoint face was observed using the collected time-lapse images. Five of these observations are shown in figure 4.8, a rectified bitmap of the knickpoint, which offers a two dimensional representation of the knickpoint retreat over time. Identification of the knickpoint positions in figure 4.8 was not perfect; the face did not have sharp edges in all locations, and because the original images were oblique, the depth of water above the knickpoint and the position of the hydraulic jump below the knickpoint had an impact on the identified position of the knickpoint. Nevertheless, it was apparent that migration of the face itself was relatively slow most of the time, with pieces of the knickpoint breaking off periodically. During the study period, upstream migration of the knickpoint slowed during the fall and winter months, as the base level of the streambed was low and temperatures were mild most of the winter. In fact, there were few periods that the water surface of the stream had any ice, and it is generally agreed that freezing has a significant impact on erosion (Daniels and Jordan 1966; Simon and Rinaldi 2000). According to analysis of the time lapse photos, the knickpoint face moved upstream approximately 0.9 m over the study period, mostly near the beginning of the study. There are too many time-lapse images to publish in this report, but the images are available from the authors upon request.

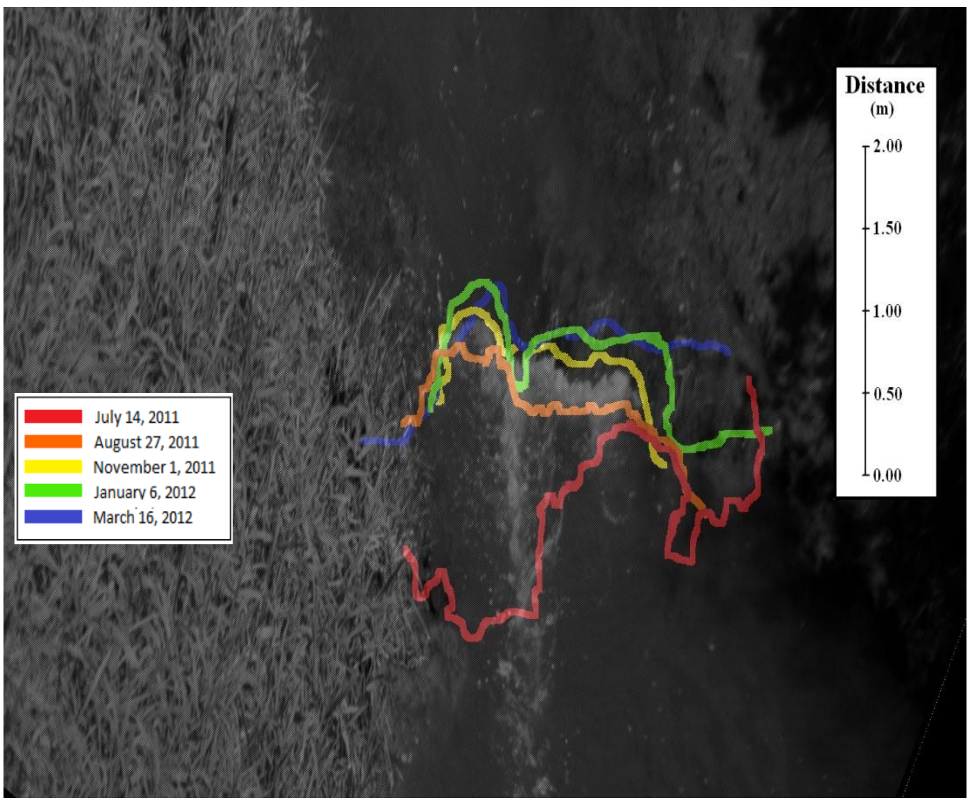
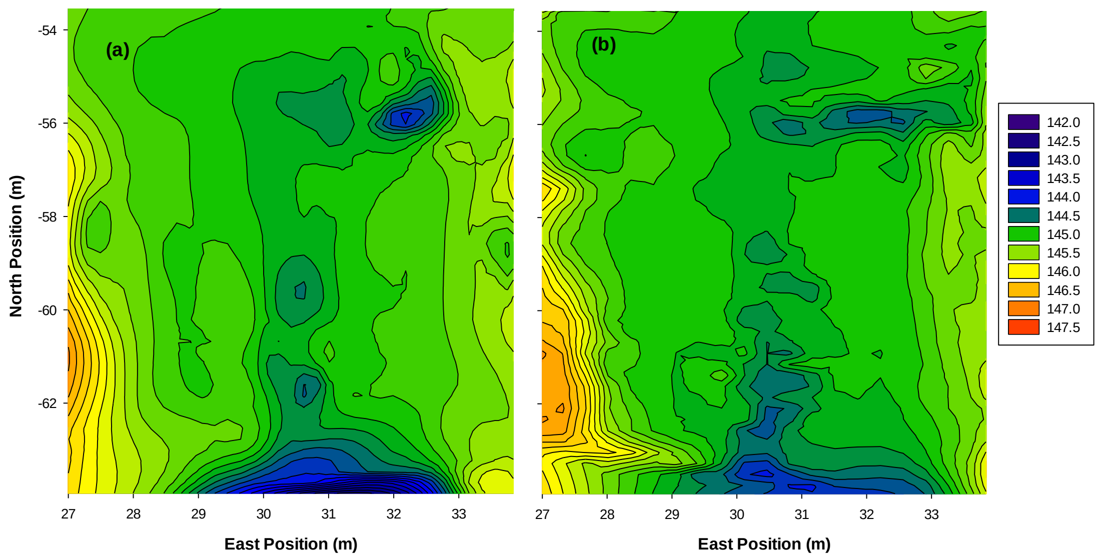


Figure 4.8 Knickpoint migration between July 14, 2011 and March 16, 2012

Extensive survey data sets collected on September 27, 2011 and March 21, 2012 were transformed into the contour plots shown in figure 4.9. The east and north positions given on the x and y axes of figure 4.9 are relative to an arbitrary benchmark located on the southwest corner of the upstream bridge. The elevations given in the contour plot are also relative to an arbitrary benchmark elevation of 500 ft. Although the position and elevation of the benchmark are arbitrary, the same benchmark was used for both datasets so that elevations in the two plots could be directly compared. The second dataset had a higher resolution of surveyed measurements, particularly along the banks and downstream of the knickpoint, so the detail of the banks and downstream of the knickpoint is more accurate in figure 4.9(b). However, the channel bed and knickpoint locations are well-defined for both datasets.

As noted in figure 4.8, figure 4.9 confirms that between September and March there was not much movement of the knickpoint face. However, the contour plots do show that, though the non-vegetated bed of the channel is about 4 m wide, there is also a deeper, narrow region in the center of the channel that is only about 1 m wide. Though the water surface covers most of the non-vegetated surface of the channel for much of the year, the bulk of the flow travels through the narrow region in the middle of the stream during non-storm events. It is only during large events that the flow is more evenly distributed over the entire face of the knickpoint, and these events have been rare and of short duration during the study period.

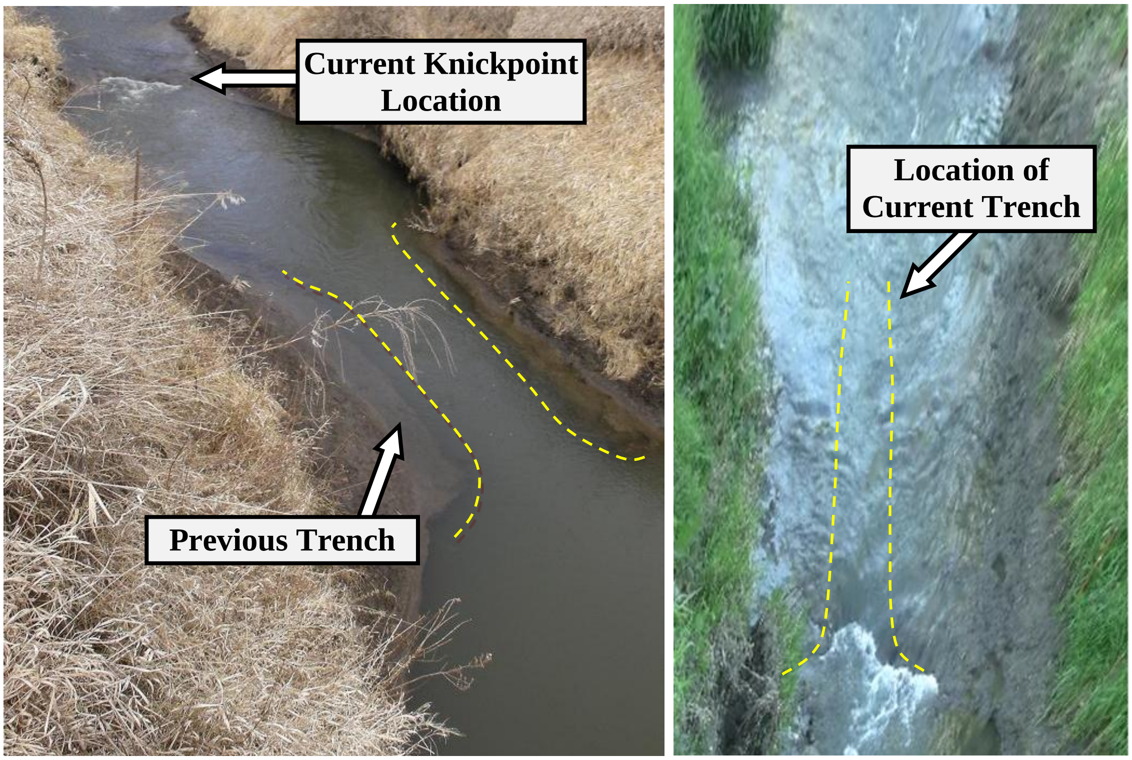
The result is that the low flows had a significant impact on the morphology of the channel in this reach; this impact was seen in the development of the narrow trench in the middle of the channel in figure 4.9. Comparing figure 4.9(a) to figure 4.9(b), the low flows slowly deepened, widened, and lengthened the trench as the knickpoint worked its way upstream primarily within the trench. The trench will continue to erode until the knickpoint has cut down to where the bed material coarsens. The knickpoint will then quickly erode upstream through the trench until it reaches a position where the base of the trench is more stable.



(a) (b)

Figure 4.9 50 cm contours for surveyed data for (a) September 27, 2011, and (b) March 21, 2012

Once the knickpoint has moved upstream, the banks of the channel immediately downstream of the knickpoint face are more susceptible to collapse, causing the channel downstream of the knickpoint to rapidly deepen and widen. When the study began at the site in 2011, the existence of a previous trench was evident (fig. 4.10a). Since the beginning of the study, evidence of the previous trench has eroded away.



(a) (b)

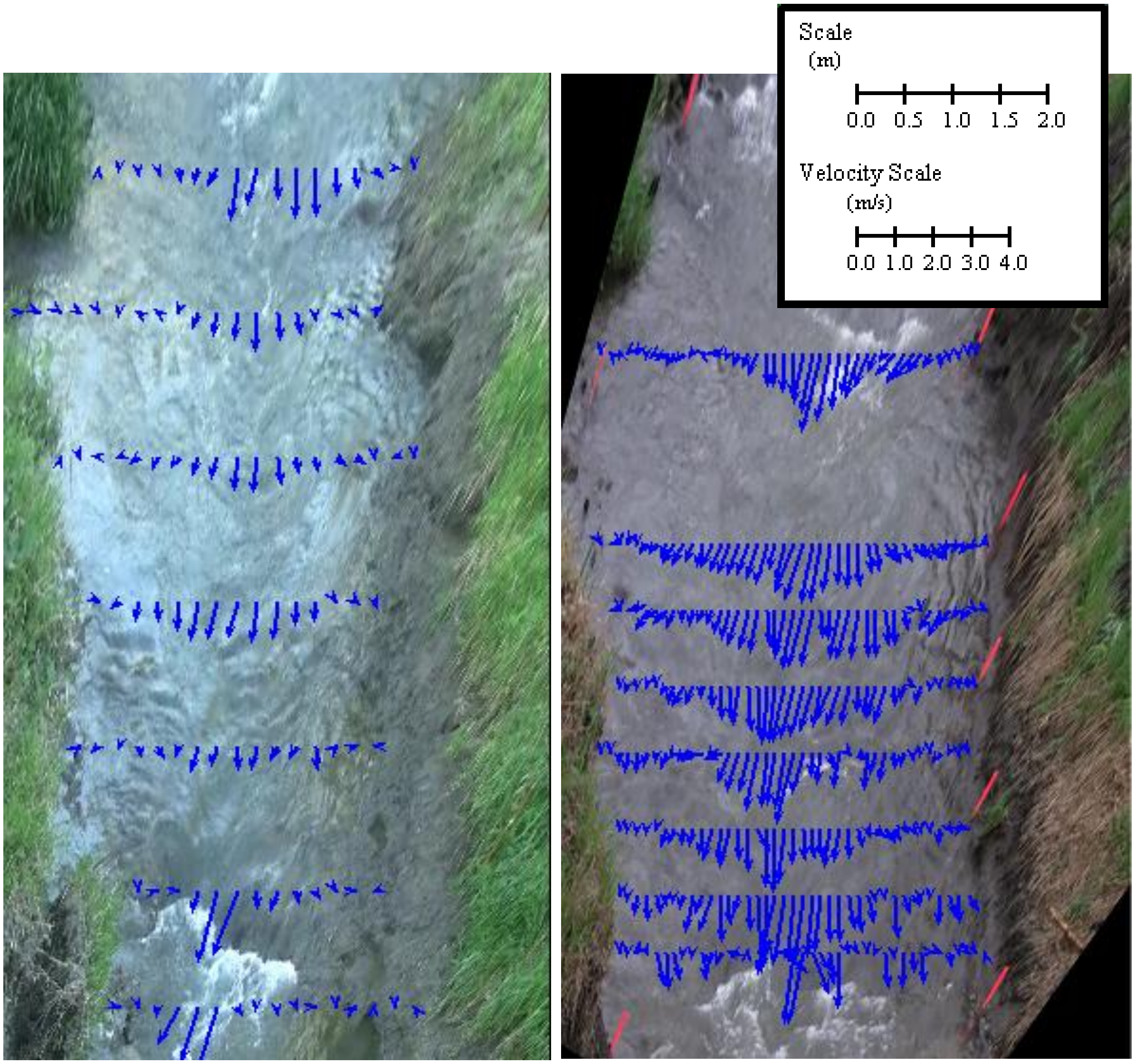
Figure 4.10 (a) Image of the knickpoint on March 18, 2011, prior to installation of knickpoint monitoring equipment. Note the previous trench in the foreground and the previous and new scour holes. (b) Plan view of the current knickpoint location depicting the approximate location of the current trench.

Downstream of the previous trench is a scour hole that developed where the knickpoint was previously located. Upstream of the trench and downstream of the new knickpoint location, a new scour hole has begun to form. Because of safety issues, it was not possible to measure the bathymetry below the knickpoint, but the scour hole downstream of the knickpoint has visibly deepened and widened extensively over the course of the study.

4.3 Flow Velocity Observations – LPIV

During the duration of the current study, three sets of LPIV data were collected. Of these sets, two have been analyzed to date. Issues with background noise required the implementation of a new algorithm capable of masking the effects of the noise; and the development of software that was able to accurately extract surface velocities from the images was time-consuming. The remaining dataset will be processed after this report has been submitted. The LPIV measurements presented herein are from video data captured on September 27, 2011 and March 21, 2012. The videos were processed into individual bitmaps that were loaded into the LPIV software. The oblique images of the knickpoint region were rectified using control points gathered at the edges of the water surface for each site visit. Then, a multi-file minimum quadratic difference algorithm was applied to the bitmaps at cross sections that were estimated from the survey data. The horizontal spacing of the interrogation points was set at 20 cm and 10 cm, respectively, for the two datasets. The calculated LPIV velocity distributions for the two datasets are shown in figures 4.11(a) and 4.11(b).

The distribution of calculated LPIV velocities is shown in Figure 4.11. Although the flow area is approximately 4 m wide, the higher flow velocities are primarily located in a 1.5 m wide region of the channel directly above the trench. Increased shear stresses associated with the concentrated flow will continue to deepen, lengthen, and widen the trench.



(a) (b)

Figure 4.11 Surface velocity distribution measured with LPIV on (a) September 27, 2011, and (b) March 21, 2012

Surface velocities measured at each cross section were converted into mean velocities, as discussed in chapter 3. The component of the mean velocity normal to the channel transect was multiplied by the subarea of the transect associated with that velocity to obtain the discharge flux through the subarea. Discharge fluxes from all of the subareas were then summed to determine the discharge of the transect. A summary of discharge calculations for each transect is given in tables 4.2 and 4.3.

The discharges provided in table 4.2 are not completely in agreement. In particular, two of the entries in table 4.2 are significantly different from the others, and are considered to be untrustworthy. The cross section located downstream of the knickpoint (cross section [a]) will not produce reliable discharge measurements, because the velocity distribution is not fully developed and is located in the vicinity of the hydraulic jump. The cross section located 5.05 m upstream of the jump (cross section [e]) is also questionable. A large hole in the bed is located in the vicinity of this transect, and the hole artificially increases the cross sectional area associated with the transect. In other words, for cross section (e), the effective flow area is significantly less than the flow area provided by the contour plot. The remaining measurements produce an average discharge of 0.265 m^3/s and have a standard deviation of 0.038 m^3/s.

Table 4.2 Summary of cross section discharge calculations, September 27, 2012

Cross-Section	**Distance Upstream of Knickpoint (m)**	**Flow Area (m^2)**	**Discharge (m^3/s)**
a	-0.74	0.410	0.386
b	0.48	0.392	0.254
d	2.00	0.647	0.290
d	3.53	0.425	0.261
e	5.05	1.393	0.527
f	6.58	1.112	0.310
g	8.10	0.425	0.211

Table 4.3 Summary of cross section discharge calculations, March 21, 2012

Cross Section	Distance Upstream of Knickpoint (m)	Flow Area (m^2)	Discharge (m^3/s)
h	0.15	-	-
i	0.75	0.413	0.448
j	1.45	0.472	0.332
k	2.25	0.578	0.412
l	2.95	0.505	0.401
m	3.75	0.485	0.336
n	4.45	0.613	0.396
o	6.45	0.871	0.539

The discharges provided in table 4.3 are also reasonable, aside from cross section (o). Cross section (o) is located in the vicinity of the scour hole that has developed along the left descending bank. For reasons previously discussed, the presence of the scour hole reduces the accuracy of discharge measurements. The remaining measurements produce an average discharge of 0.387 m^3/s, with a standard deviation of 0.045 m^3/s.

Chapter 5 Summary and Conclusions

The severity of channel erosion in the Deep Loess Region of western Iowa and eastern Nebraska is considerable, due to channelization of the stream corridor coupled with intensive agriculture and highly erodible loess soils. Knickpoints, or, discontinuities in bed elevation along the longitudinal stream profile, are common forms of channel degradation in this region. Once a knickpoint has formed, it will continue to advance upstream, eroding the channel bed, lowering the base level for tributary streams, and, if unchecked, eventually affecting downstream infrastructure. To date, information regarding knickpoint migration rates in the Deep Loess region of the Midwest is lacking. A field-oriented monitoring evaluation would assist governmental agencies in better understanding the principal geotechnical and hydrodynamic factors that cause knickpoint propagation, and help estimate the response time required to control the propagation of a knickpoint after one has been identified.

This study was developed to provide a field-oriented evaluation, coupled with advanced laboratory techniques, of a knickpoint located on Mud Creek in Mills County, IA, and to identify the key geotechnical and hydrodynamic controls of its upstream migration rate. The result of these objectives was to provide a reliable method and, ultimately, a comprehensive and practical manual that will substantially aid engineers in monitoring, maintaining, and protecting bridge waterways, so as to mitigate or manage scour occurring at bridge structures.

The geotechnical properties of the bank soils and bed sediments of the knickpoint reach supported the visual observations of a stratigraphic discontinuity located at approximately the same level (i.e., elevation) as the top of the knickpoint face. This discontinuity is most likely the separation between two district layers, namely, the Roberts Creek and Gunder Members, which are often separated by a fluvial erosion surface or an unconformity.

Monitoring methods included a state-of-the-art time-lapse camera mounted on the bank of the stream to capture the upstream migration of the knickpoint. Measurements were collected over a 248 day period from July, 2011 to March, 2012. Observations of knickpoint migration indicated a relatively slow advance of the face, totaling approximately 0.9 m during the study period, with periodic losses of sections of the face. Detailed surveys of the bed indicated that a submerged channel or trench formed upstream of the knickpoint that cut down into the knickpoint face and carried the bulk of the base flow. The submerged channel grew in size over time. It is expected that deepening of the trench will eventually lead to punctuated failure of the knickpoint.

The scour hole that developed downstream of the knickpoint appeared to cause far more erosion than the retreat of the knickpoint itself, as deepening of the bed downstream of the knickpoint led to oversteepened banks and subsequent widening of the channel through bank collapse.

Observations of the velocity distribution above the knickpoint and the associated discharge distribution in the stream confirmed that the bulk of the flow was confined to the submerged channel observed in bathymetric measurements. Measured velocities were as high as 2.0 m/s during low flows through the trench, but did not rapidly erode bed material upstream of the knickpoint. Nevertheless, erosion of the knickpoint appeared to be more closely tied to low flow conditions than to large events.

This research provided an evaluation protocol for developing predictive tools for knickpoint migration to help engineers in monitoring, maintaining, and protecting bridge waterways, in order to mitigate or manage the scour occurring at the bridge structures. The main features of this plan can be adopted by DOT personnel and county engineers for inspecting streams that have recently experienced knickpoint migration. This inspection plan is outlined on the next page in table 5.1.

Table 5.1 The main features of inspection form used by the Iowa DOT when inspecting bridges that recently have experienced a major flood flow

---

Proposed Evaluation Protocol for Knickpoints
Iowa Department of Transportation

Date inspected: ________________________
Date Received in Office: _________________
Survey Team: ____
____

Site Information
Stream name. ____________________________
County. __________________________________
Road. ____________________________________

This report contains
Comments ____ Yes ____ No
Sketches ____ Yes ____ No
Photos ____ Yes ____ No

Place an "X" by all that apply

1.____ Is there a visible knickpoint?

2. ____ Is there a documentation of the knickpoint location?

3. ____ Is there any indication of upstream movement of the knickpoint? How far is the knickpoint from the bridge crossing?

4. ____ Is there shifting of the channel alignment or erosion of the stream banks?

5. ____ How far is the knickpoint from the sheet piles

6. ____ Do scour measurements indicate: (Place an "**X**" by all that apply.)
_____A. scour developed below the bottom of the knickpoint?
_____B. scour is at equilibrium?
_____C. that the streambed has scoured five feet or more below the original streambed elevation at knickpoint?

Note:
Streambed laser data is to be documented. (sounding measurements may not be possible due to flow bubbling)

Table 5.1 The main features of inspection form used by the Iowa DOT when inspecting bridges that recently have experienced a major flood flow (cont'd.)

A streambed profile via survey should be done on the upstream side of all bridges every two years. If Item #6 is yes, then a profile on the downstream side of the knickpoint should also be done in the scoured area. If the downstream profile also indicates a problem, then laser measurements should be made at the knickpoint crest if possible.

If "No" is the answer to all of the items in the checklist, no further action will be necessary.

If "Yes" is the answer to any items on the checklist, contact the Office for further instructions.

An "*" indicates the item is not visible.

Comments: ___________________________

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Completed on ___________________________ By ____

Reviewed by ___________________________________ Date reviewed _________________________

Is a follow-up inspection recommended? _____ Yes _____ No

Comments/Recommendations:____

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