A review of techniques available for riverbank protection: a sustainable approach to managing bank erosion

Draft Report

Prepared for:

Korea Institute of Construction Technology,

Republic of Korea

By:

Shukran Sahaar

Dr. Pierre Y. Julien

Colorado State University

Engineering Research Center

Department of Civil and Environmental Engineering

Fort Collins, Colorado 80523

October, 2013

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1. Introduction

In the last century, world has faced a rapid increase in population, urban development, and industrial growth. This caused serious changes in river flow during floods and droughts, as well as an increased awareness about climate change, environmental impact and water quality. South Korea is expected to suffer a 0.8 billion m^3 water shortage in 2011 and 1 billion m^3 of water shortages in 2016. The yearly amount of flood damage increased from 17 billion (KRW) in 1970s to 270 billion (KRW) in 2002-2006. The drought in 2001 caused limited water supply to 86 cities and counties. The pollution level of (COD) and (TP) causing eutrophication has also increased. Therefore, the South Korean Government prepared fundamental countermeasures against flooding, droughts, and water quality under the “Four Major Rivers Restoration Project.” The five key objectives of this project were: (1) securing abundant water resources to combat water scarcity; (2) implementing comprehensive flood control measures; (3) improving water quality and restoring river ecosystems; (4) creating multipurpose spaces for local residents; and (5) regional development centered on the rivers. This project covers restoration of nearly 700 km of the main river channels as well as fortifying of the levees along the main streams.

A river restoration project often requires extensive use of bank protection techniques. When fortifying the levees, deferent types of revetments are needed to achieve the structural stability. Therefore this report focuses on the protection methods to prevent bank erosion and lateral migration of the rivers. The main objectives of this report are as follow:

- Review of bank erosion processes
- Classification of bank protection techniques
- Design guideline and case studies of bank protection structures

2. Riverbank Protection

Bank protection works may be undertaken to protect the riverbank against fluvial erosion and/or geotechnical failures (Hey, 1994; Brookes, 1988; Escarameia, 1998; McCullah and Gray, 2005).

Riverbank protection works can be classified according to two different approaches: (1) strengthening the banks and (2) reducing the hydrodynamic forces. The type of bank protection work has to be in accordance with the conditions of the specific site. A method suitable for one location of a river may not be so for another location of the same river or at another river. For a proper appreciation of the techniques of bank stabilization, one has to have awareness about fluvial geomorphology and channel processes. In a watershed where numerous alterations (dams, levees, channelization, land use changes, etc.) have occurred, the channel morphology will reflect the integration of all these factors. Unfortunately, it is extremely difficult to sort out the precise contributions of each of these components to the system instability. The interaction of these individual factors coupled with the potential for complex response makes assessing the channel stability and recommending channel improvement features, such as bank protection, extremely difficult. There are numerous qualitative and quantitative procedures that are available to prevent bank erosion in the rivers. Regardless of the procedure used, the designer should always recognize the limitations of the procedure, and the inherent uncertainties with respect to predicting the behavior of complex river systems. It must also be recognized that the solution to a particular problem may generate problems elsewhere in the river system.

3. Bank-erosion Processes

Processes of bank erosion are directly linked to the later migration of alluvial channels .Bank erosion is the result of flowing water that applies active forces met by the passive forces of the bank material to resist motion. As shown in [Figure 1(a)], the hydrodynamic forces in the river bends induce secondary flow where the free-surface streamlines are deflected toward the outer bank and the near-bed stream line are deflected toward the inner bank. Along a cross section [Figure 1(b)], the streamlines are deflected downward near the outer bank and deflected upward on the point bar. The resulting effect is to decrease the stability of sediment particles and cause degradation near the outer bank. On the other hand, the particle stability increases and aggradation is expected near the point bar. The score at the toe of the outer bank shifts the thalweg to the outside of the river bend and causes steepening of the outer bank. Increased steepening of the outer-bank material causes bank failure.

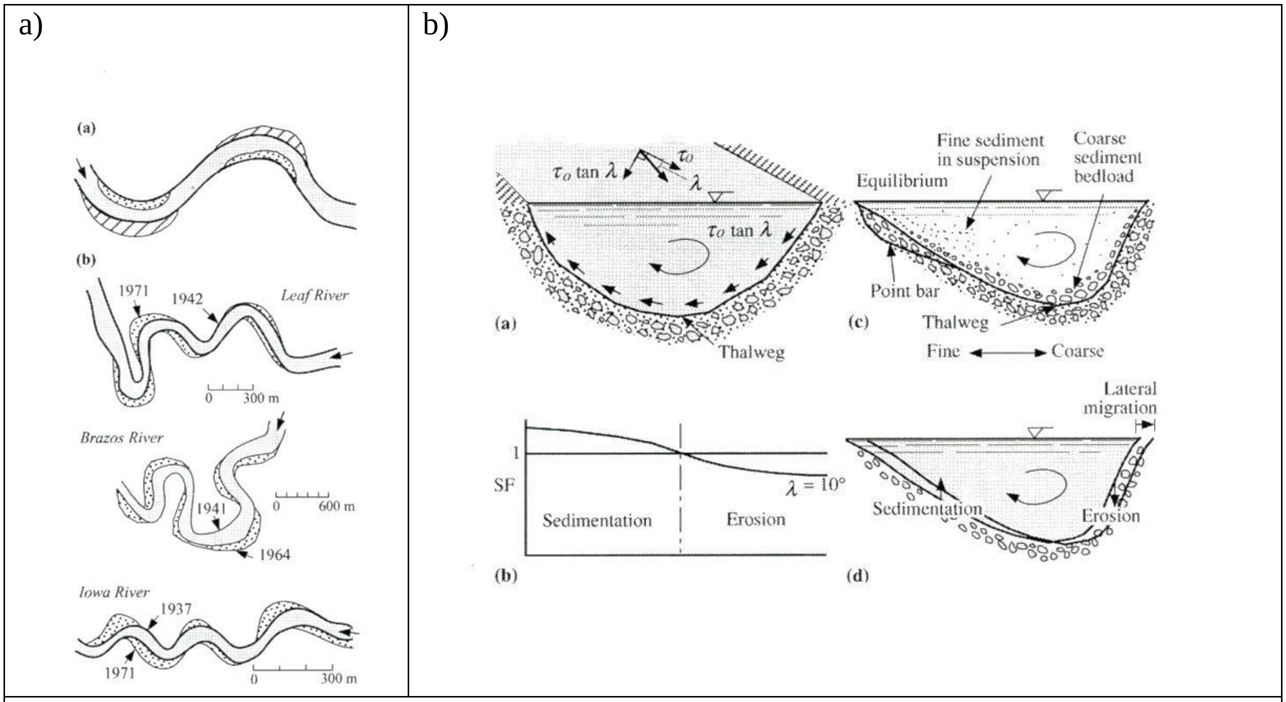


Figure 1- a) Example of lateral migration b) Stability and equilibrium in river bends (Julien, 2002)

4. Causes of Bank Failures

Tree modes of failure are typical of alluvial rivers as sketched in Figure 2.

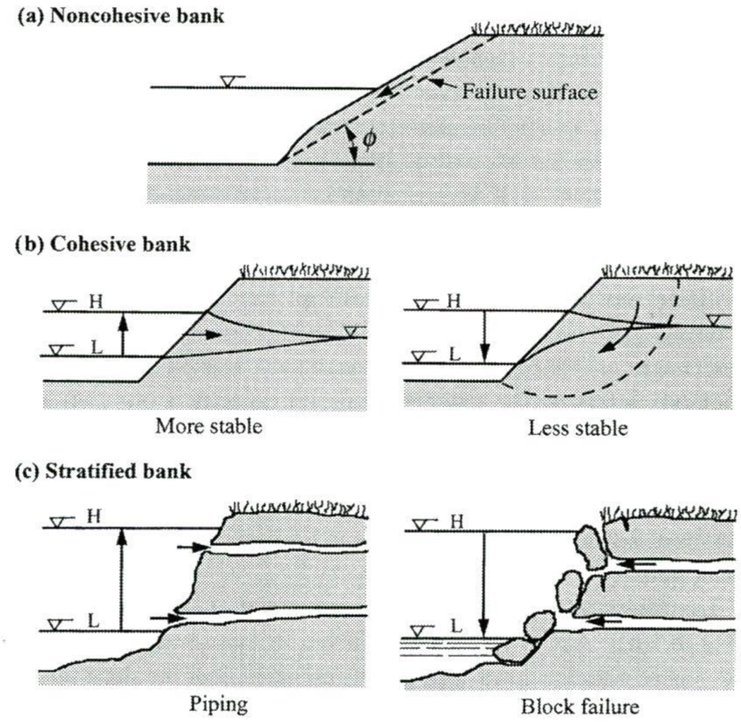


Figure 2 – Bank erosion types

4.1 Bed and Bank Material Failure

Resistance of river bank to erosion is closely related to several characteristics of the bank material. Bank material deposited in the river can be broadly classified as cohesive, noncohesive and composite. With noncohesive granular material, grain removal at the toe of the outer-bank induces sliding of the granular material as soon as the bank angle exceeds the angle of repose of the material [Figure 2 (a)]. In the case of cohesive bank material, rotation failure is typical and the presence of tension cracks may accelerate the bank-erosion process [Figure 2 (b)]. In alluvial streams flowing in stratified deposits, the underlying noncohesive material is mobilized, thus leaving the overlying cohesive material unsupported and subject to tension cracks and cantilever failure [Figure 2 (c)]. In general, the most erosive banks are sandy and silty, whereas the least erosive are clayey and gravelly.

4.2 Mass Wasting

Mass wasting is an alternative form of bank erosion. If the bank becomes saturated and possibly undercut by flowing water, blocks of bank may slump or slide into the channel. Mass wasting may be further aggravated by construction of homes on riverbanks, operation of equipment on the flood plain adjacent to the banks, added gravitational force resulting from tree weight, saturation of banks, and increased infiltration into the floodplain.

Landslides refer to the downslope movement of earth and organic materials [Figure 2 (b)]. Active forces are involved in mass wasting. These forces are associated with the downslope gravity component of the slope mass. Resisting these downslope forces are the shear strength of the Earth's materials and any additional contributions from vegetation by means of root strength or human slope-reinforced activities. When a slope is acted on by a stream or river an additional set of forces is added. These forces are associated with removal of material from the toe of the slope, fluctuations in groundwater levels, and vibration of the slope. A slope may fail if stable material is removed from the toe. When the toe is removed, the slope loses more resistance by buttressing than it does by downslope gravitational forces. The slope materials may then tend to move downslope into the void in order to establish a new balance of forces or equilibrium.

4.3 Piping

Piping is caused by groundwater seeping out of the bank face. With stratified banks flow is induced in more permeable layers by changes in river bank stage and by wind- and boat generated waves. If the flow through the permeable lenses is capable of dislodging and transporting fine particles form the permeable lenses, the material is slowly removed, undermining portions of the bank. Without this foundation material to support the overlaying layers, a block of bank material drops down and results in the developing tension cracks, as sketched in Figure 2 (c) .These crack allow surface flows to enter, further reducing the stability of the affected block of bank material.

5. Techniques for bank protection

There could be two broad ways of stabilizing banks – firstly the direct methods of protecting the slope, and secondly the indirect way by providing structures that extend into the stream channels and redirect the flow so that hydraulic forces at the channel boundary are reduced to a non - erosive level. Amongst the direct methods available for bank stabilization, the following broad categories are as follows:

- Riverbank riprap revetments
- Vegetation protection
- Windrows and trenches
- Sacks and blocks, Gabions and Mattresses
- Articulated mattresses, soil cementing and retaining walls

The advantages of this type protection are that armoring the surface of the bank is a proven approach which can be precisely designed for a given situation, and which provides immediate and effective protection against erosion. Also, existing or potential problems from erosion by over bank drainage can be effectively addressed integrally with the design of the streambank armor work. Disadvantages for these types of bank protection include preparation of the bank slope is usually required, either for geotechnical stability or to provide a smooth surface for proper placement of the armor. This may result in high cost, environmental damage, and disturbance to adjacent structures. The extent of earthwork associated with an armor revetment will be especially significant if the existing channel alignment is to be modified either by excavation or by placing fill material in the channel.

As for the indirect methods for bank stabilization, these may be classified into the following categories:

- Bendway weirs
- Spurs or groynes, guide banks, retards
- Jetties, fences, vanes, and hard points.

The advantages of this type of protection are that little or no bank preparation is involved. This reduces costs of local environmental impacts, and simplifies land acquisition. However, the main disadvantage is that these are not very effective where geotechnical bank instability or erosion from overbank drainage is the main causes of bank erosion. Further, the construction of these structures induce significant changes in flow alignment, channel geometry, roughness and other hydraulic factors, which have to be carefully checked to find out any adverse implication of the river’s geomorphology.

Some types of indirect protection may also pose safety hazard if the stream is used for recreation or navigation. Lastly, since indirect methods require structures to be constructed deep into the stream channel, their construction may become practically difficult, especially during high flows.

Details about these indirect methods of bank protection are not presented in this lesson, but may be obtained from references such as "The WES Stream Investigation and Streambank Stabilization Hand book", published by the U.S. Army Engineer Waterways Experiment Station (WES) in 1997 (Biedenharn, 1997). A few design guidelines were presented in the following sections.

5.1 Riprap

Riprap is defined as a layer or blanket of rock or broken concrete dumped or placed to protect a structure or embankment from erosion (Richardson et al., 2001). When rock riprap is available in sufficient size and quantity, it is usually the most economical and widely used material for bank protection. Construction of riprap is not complicated so for many cases special equipment and construction practices is not necessary. Local damages or loss is easily repaired by the placement of more rock. A riprap blanket is usually durable, and flexible to slight movement of the bank resulting from settlement or other minor adjustment. The important factors to be considered in designing rock riprap bank protection are:

- The velocity (both magnitude and direction) of the flow or shear stress in the vicinity of the rock
- The side slope of the bankline being protected
- The density of the rock
- The angle of repose for the rock, which depends on stone shape and angularity

- The durability of the rock
- The riprap blanket thickness
- The filter needed between the bank and the blanket to allow seepage but to prevent erosion of bank soil through the blankets
- The blanket must be tied at the toe of the bank
- The blanket must be tied into the bank at its upstream and downstream ends

To determine rock size of the riprap, two methods can be identified for stream bank stabilization. The first one is the shear stress method and the second one is the flow-velocity method.

In terms of the shear stress method, riprap stability on a side slope is a function of the magnitude and the direction of the flow velocity or shear stress in the vicinity of the streambank, the side slope angle, and the properties of the rock including size, density, and angularity. The effective rock size d_m required for stabilizing a riverbank under applied shear stress τ_0 is estimated from Lane's relationship as

$$d_m = \frac{\tau_0}{\tau_{*c}\gamma(G-1)\left[\sqrt{1-\frac{sin^2\theta_1}{sin^2\phi}}\right]}$$

Where, τ_0 : applied shear stress

τ_{*c}: critical value of the Shields number

γ : specific weight for water

G: specific gravity for the rock

θ_1: side slope angle

ϕ: angle of repose of the rock riprap

In terms of the velocity method, the stone size needed to protect a streambank from erosion by a current that is moving parallel to the embankment can also be determined as a function of flow velocity. The rock size of the riprap using the critical mean flow velocity $V_C$is shown in Figure 3.

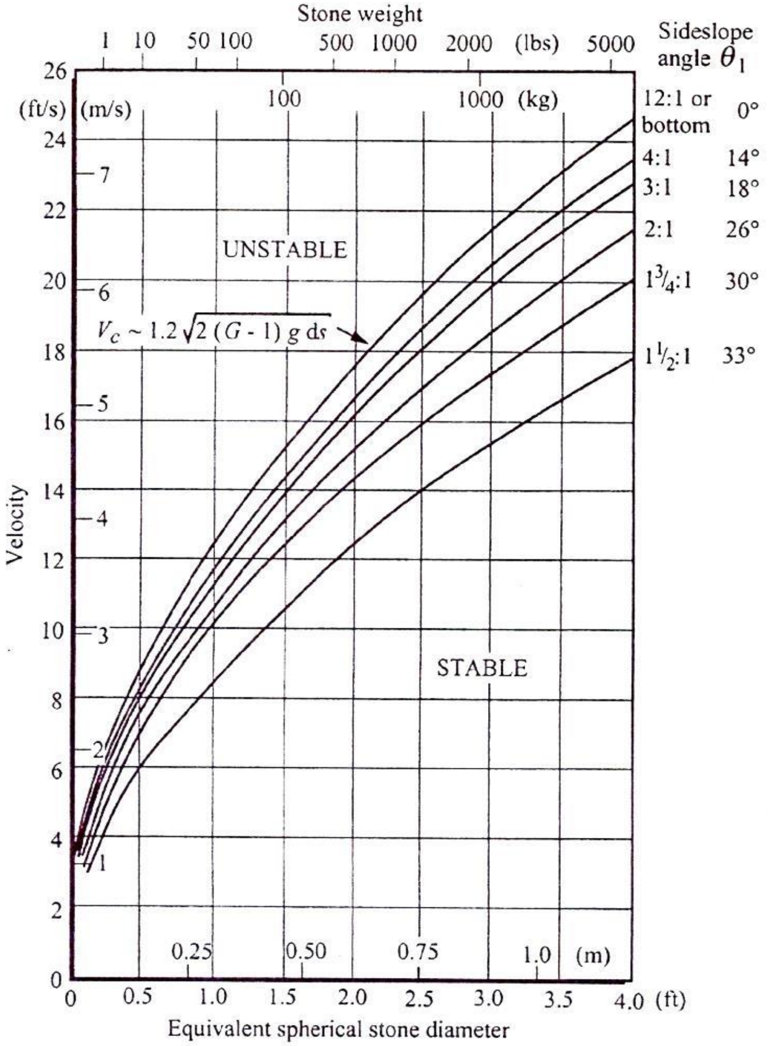
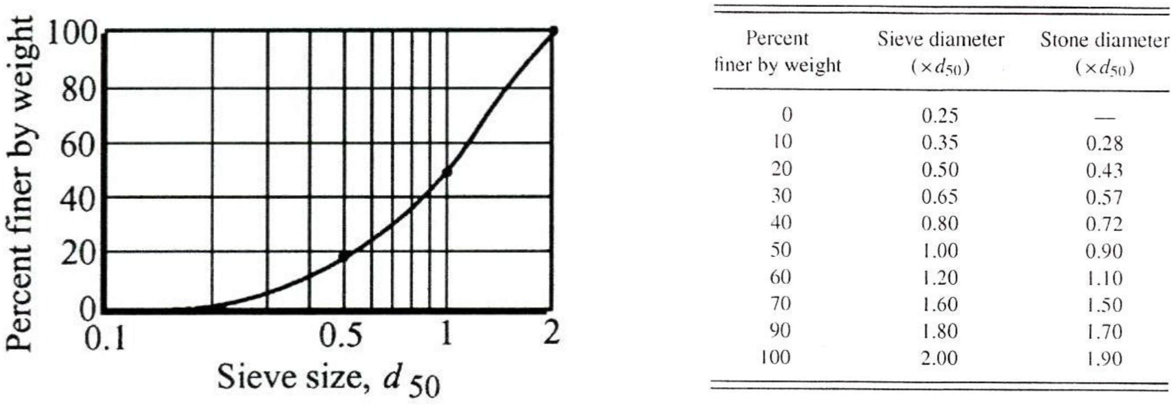


Figure 3 - Rock riprap size selection using velocity method (Julien, 2002)

This graph should be used when the relative submergence $\left(h/_{d_s}\right)$ is smaller than 10, at larger flow depths where$\left(h/_{d_s} > 10\right)$, the shear stress method is preferable.

Size gradation is an important criterion in placing ripraps. A uniformly graded riprap with a median size d_{50} scours to a greater depth than a well-graded mixture with the same median size. It should be noted that riprap consisting of angular stones is more suitable than that consisting of rounded stones. The suggested riprap size gradation is shown in Figure 4.



Percent finer by weight	Sieve diameter ($\times d_{50}$)	Stone diameter ($\times d_{50}$)
0	0.25	—
10	0.35	0.28
20	0.50	0.43
30	0.65	0.57
40	0.80	0.72
50	1.00	0.90
60	1.20	1.10
70	1.60	1.50
90	1.80	1.70
100	2.00	1.90

Figure 4 – suggested riprap a) gradation curve b) size gradation (Julien, 2002)

It is necessary to use filters under riprap revetments to allow water to drain easily form the bank without carrying out soil particles. Filters are required when the d_{15} of riprap gradation exceeds five times the d_{85} of the bank material. The design example of filter is shown in Julien (2002) as outlined in Figure 5.

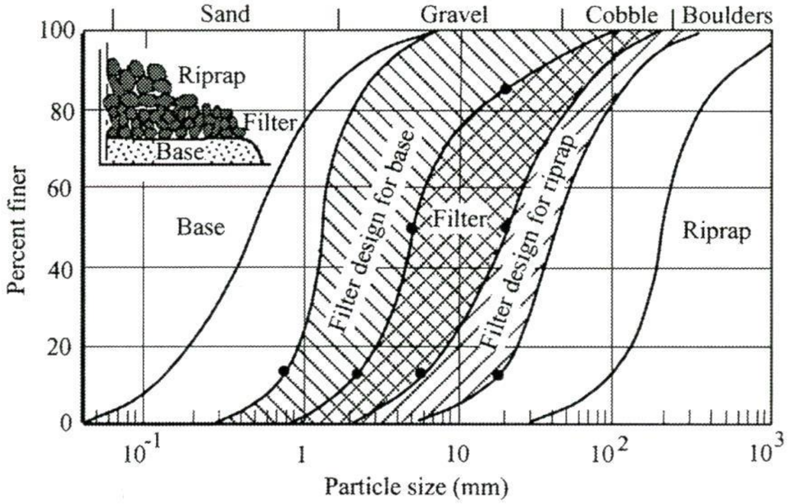


Figure 5 – Example of filter design (Julien, 2002)

Riprap revetment should be toed down below the toe of the bank slope to a depth at least as great as the depth of anticipated long-term bed degradation plus toe scour. Installations in the vicinity of bridges must also consider the potential for contraction scour. If toe down cannot be placed below the anticipated contraction scour and degradation depth (Figure 6), a mounded toe approach (Figure 7) is suggested.

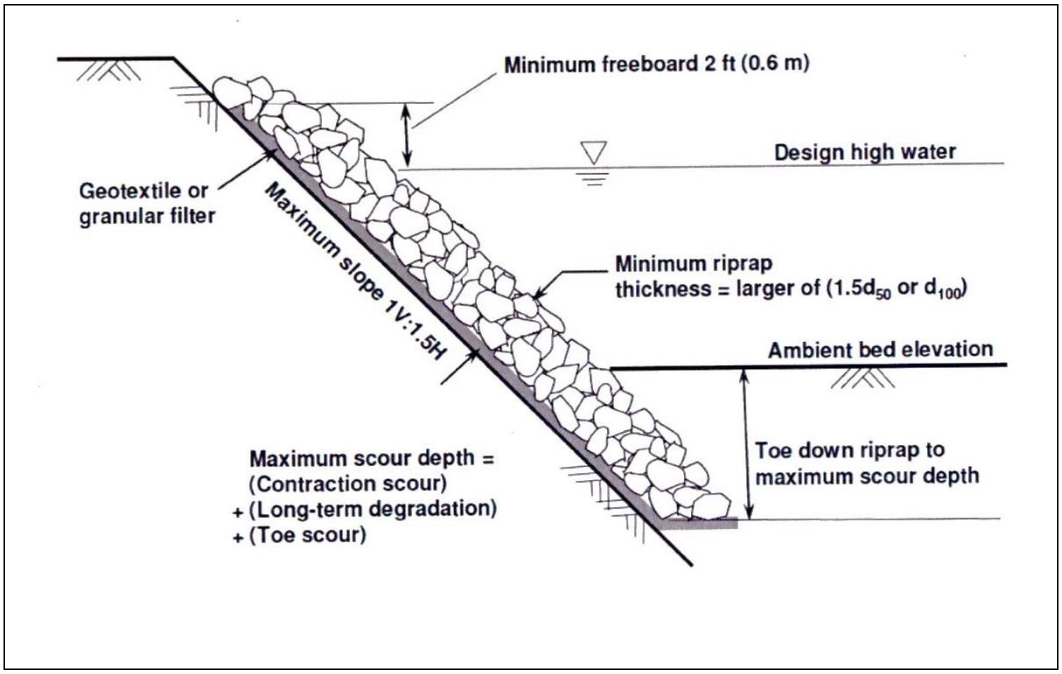


Figure 6 - Riprap revetment with buried toe (Lagasse et al., 2009)

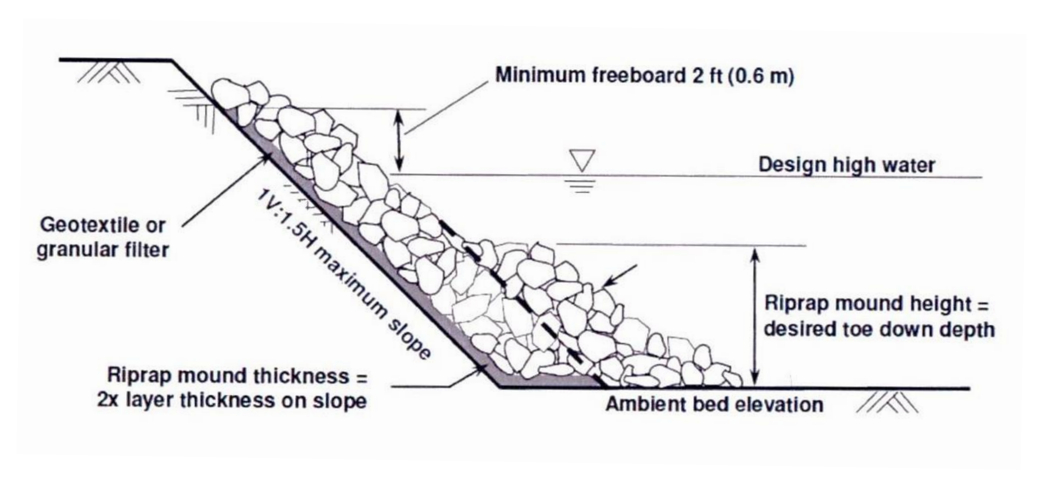


Figure 7 - Riprap revetment with mounded toe (Lagasse et al., 2009)

5.2 Vegetation

Vegetation is the most natural method for protecting streambanks. It is less expensive than most structural methods and it improves environmental conditions for wildlife. The presence of vegetation below the water surface can effectively protect a bank in two ways. First, the root system helps to hold the soil together and increases overall bank stability by forming a binding network. Second, the exposed stalks, stems, branches, and foliage provide resistance to the stream flow, causing the flow to lose energy by deforming the plants rather than by removing soil particles. Vegetation is generally divided into two broad categories: grasses and woody plants (trees and shrubs). The grasses are less costly to plant on an eroding bank and require a shorter time to become established. Woody plants offer greater protection against erosion because of their more extensive root system.

On very high banks, tree roots do not always penetrate to the toe of the bank especially. If the toe becomes eroded, the weight of the trees and its root mass may cause a bank failure. Using the planted vegetation for streambank erosion control also has its limitations. They may include the following: (1) their failure to grow; (2) they are subjected to undermining; (3) they may not withstand alternate periods of wetting and drying for varied durations; (4) they may be uprooted by freezing and thawing of ice; and (5) they may suffer wildlife or livestock damage.

Native plants should normally be used because they have adapted to climate, soils, and other ecological characteristics of the area. Chosen plants for vegetation purposes should have some tolerance to flooding. A mixture of grasses, herbs, shrubs, and trees should be used to prove diversity of wildlife habitat.

Figure 8 defines the fundamental riparian zones where the toe and bank zones form the streambank.

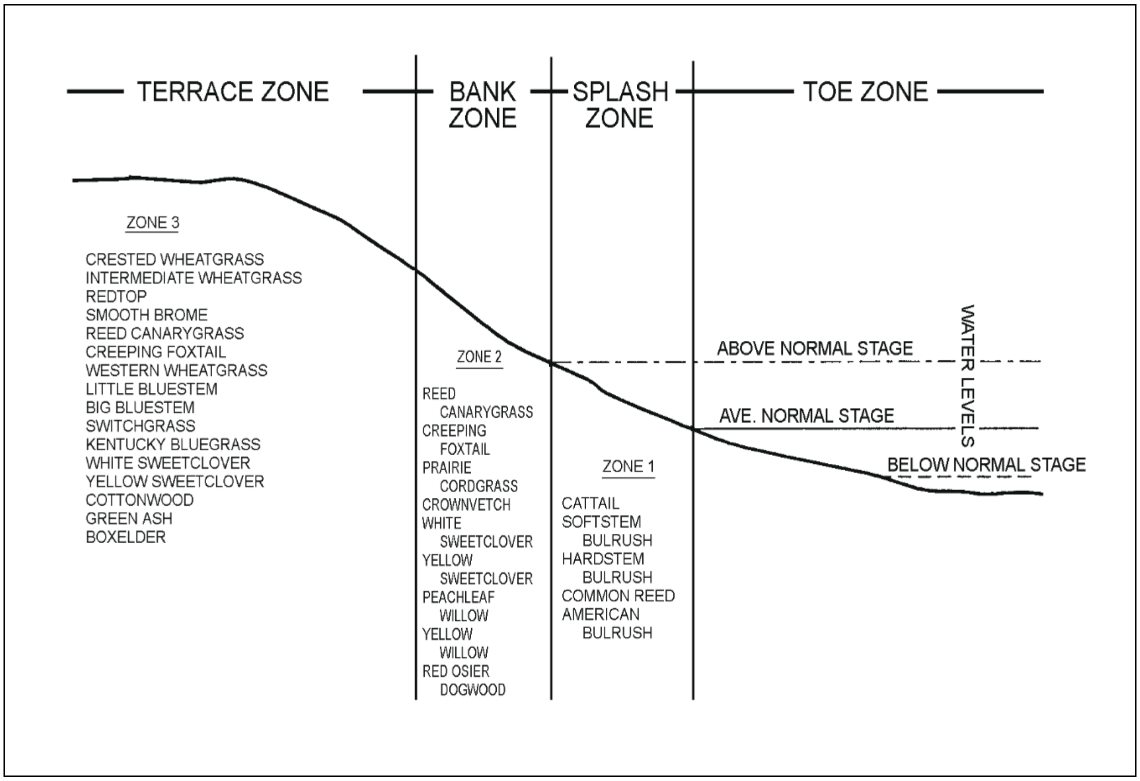


Figure 8 – Streambank zones and possible species to plant by zone (Biedenharn, 1997)

Streambank zones depend on the ability of certain plants to tolerate various durations of flooding and their attributes of dissipating wave and current energies. The splash zone located between normal high water and normal low water is the zone of highest stress. The splash zone is exposed frequently to wave wash, erosive river currents, ice and debris movement, wet-dry cycles, and freezing-thawing cycles. This section of the bank would be inundated throughout most of the year (at least 6 months/yr.).

The bank zone lies above the normal high-water level; yet this site is exposed periodically to wave wash, erosive river currents, ice and debris movement, and traffic by animals or humans. The site is inundated for at least a 60-day duration one every 2-3 year. The water table in this zone frequently is close to the soil surface because of its closeness to the normal river level. The terrace zone is usually not subjected to erosive action of the river except during occasional flooding.

For the splash zone, only herbaceous semiaquatic plants, such as reeds, rushes, and sedges, are suggested for planting. These types of plants can tolerate considerable flooding and are more likely to live in this zone. In the bank zone, both herbaceous and woody plants are used. These should still be quite flooding tolerant and able to withstand partial to complete submergence for up to several weeks. Various willows can be used in this zone. The terrace zone is less significant for bank protection because it is less often flooded, and thus less easily eroded. The terrace zone contains native grasses, herbs, shrubs, and trees that are slightly less flood tolerant than those in the bank zone. A combination of trees, shrubs and grasses in this zone will not only serve as an integrated plant community for erosion control, but will improve wildlife habitat diversity and aesthetic appeal. The banks of some rivers have not been eroded for durations of 100-200 years because heavy tree roots bind the alluvium of floodplains.

Bank protection with vegetation is not suitable where flow velocities exceed the strength of the bank material or where pore water pressure causes failure in the lower bank. In contrast, vegetation technique may be suitable where some sort of engineered structure solution is required because the risk associated with using just vegetation is considered too high. Combining riprap with deep vegetative planting (e.g., brush layering and pole planting) is also appropriate for banks with geotechnical problems, because additional tensile strength is often contributed by roots, stems, and branches. Figure 9 presents the use of rock riprap as a toe stabilizer for streambank vegetation.

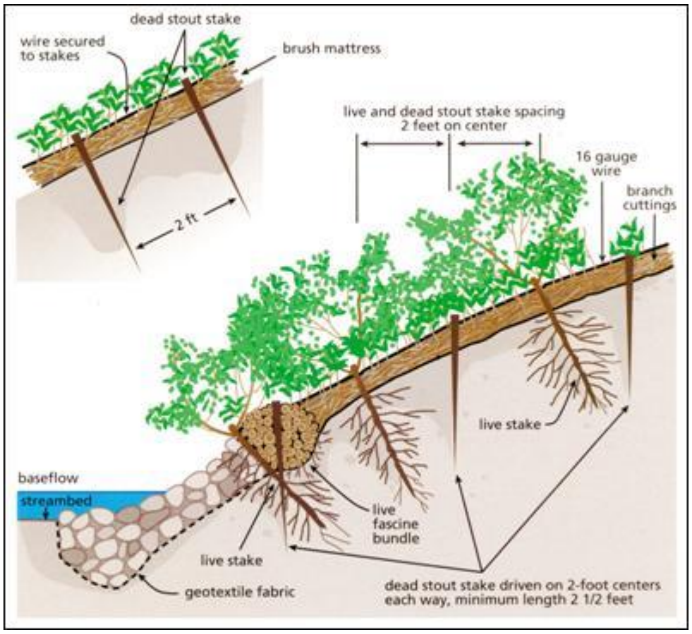
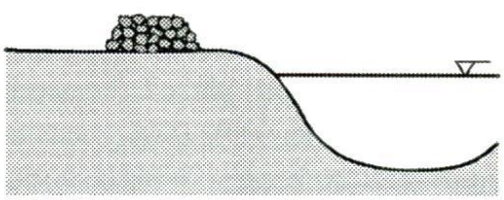


Figure 9 - Details of brush mattress technique with stone toe protection (FISRWG 1998).

5.3 Windrows and trenches

A windrow revetment consists of pilling a sufficient supply of erosin-resistant material on the existing land surface along the bank. Trenches are similar exept that the material is burried as sketched in Figure 10.

(a) Windrow



(b) Trench

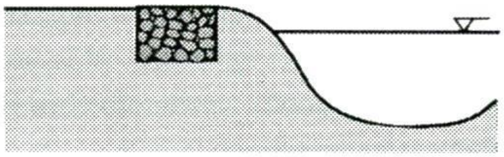


Figure 10 - windrows and trenchs

Windrows and trenches permit the area between the natural riverbank and the windrow to erode through natural processes until the erosion reaches and undercuts the supply of riprap. As the rock supply is undercut, it falls into the eroding area, thus giving protection against further undercutting and eventually halting further landward movement. Most powerful use of windrows and trenches are in the following circumstances:

- Where a smooth alignment of the stabilized channel is required (usually to meet navigation criteria); and
- Where rapid erosion rates, high velocities, large depths of flow, or rapid fluctuations in river stages make construction within the stream channel very difficult.

The velocity and the stream characteristics dictate the size of stone forming a windrow revetment. The size of stone must be large enough to resist being transported by the stream. The ratio of the relative thickness of the final revetment to the stone diameter is an important design parameter. Large stone sizes will require more material than smaller size to produce the same relative thickness. A well graded stone is important to ensure that the revetment does not fail from leaching of the underlying bank material. The stream velocity was found to have a strong influence on the ultimate sideslope of the revetment. In general, the greater the velocity, the steeper the sideslope of the final revetment. A schematic cross section of a trenchfill revetment is shown in Figure 11.

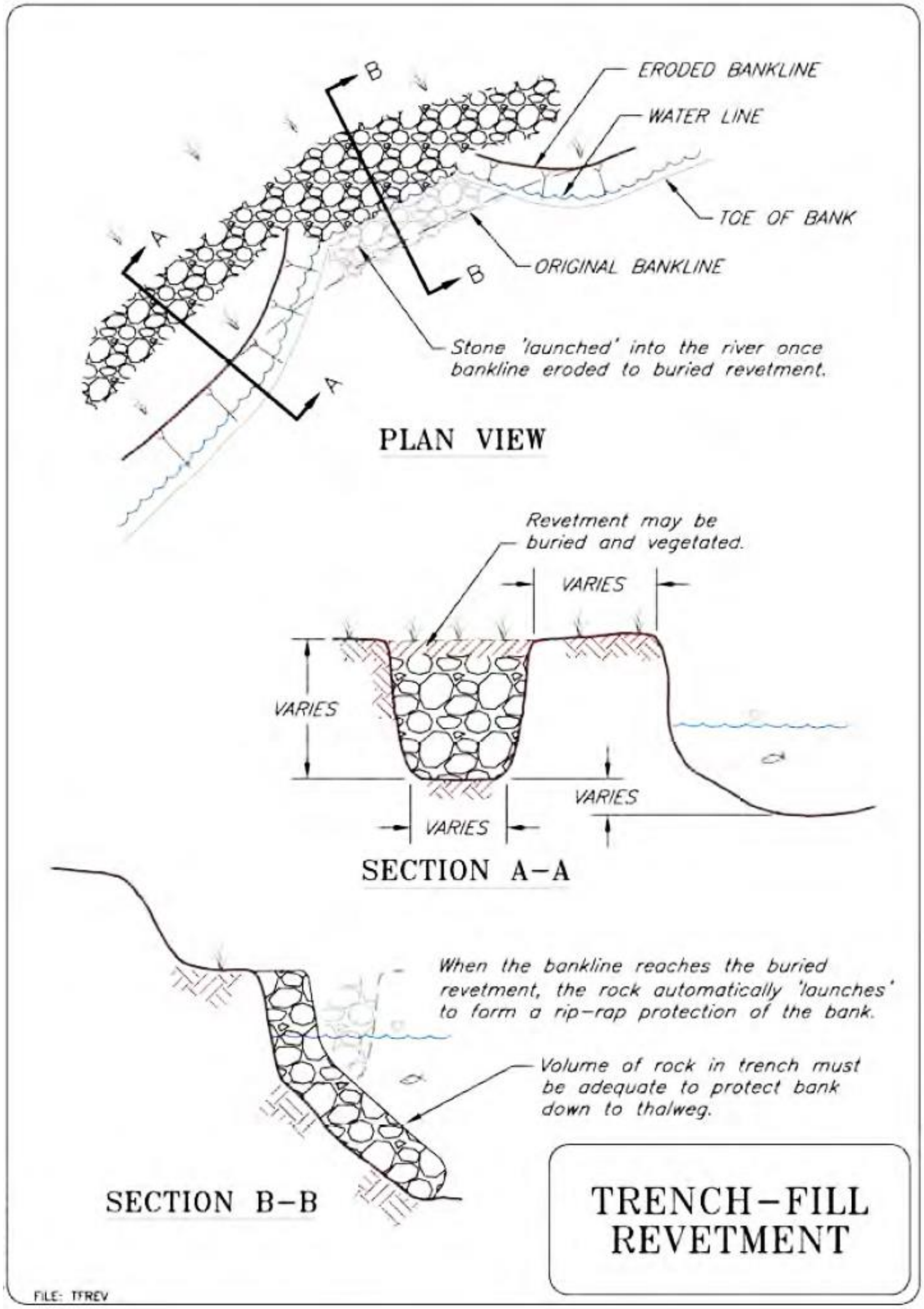


Figure 11 - Schematic drawing of trenchfill revetment (Boyd, 2010)

6. Case studies

A few case studies are presented here. The first section presents a case study on lateral migration of the river caused by the bank erosion. The second section will focus on case studies where implementation of bank protection methods prevented further erosion in the riverbanks.

6.1 Alluvial changes of the Jamuna River in Bangladesh

Jamuna River is the lowest reach of the Brahmaputra River in Bangladesh. It is one of the largest braided rivers in the world. Figure 12 shows the location of Jamuna River.

Figure 12 – Location map of the Jamuna River in Bangladesh

Jamuna River drains an area of 550,000 Km^2, and the mean annual discharge is 20,000 m^3/s. The total width of the braided channel varies between 5 and 17 km. Klaasen et al. (1993) report that the Jamuna River is quite active, with frequent channel shifts and lateral migration rate frequently exceeding 500 m/yr. The shifting rate of the first-order channel is 75 to 150 m. Bank-erosion rate of second-order channels of 250 to 300 m are common. Lateral migration rates exceeding the channel width in one year have also been seen. Jamuna River is a good example of showing lateral shift in the river caused by an extreme bank erosion.

Significant changes in cross-section geometry of Jamuna River are shown in Figure 13.

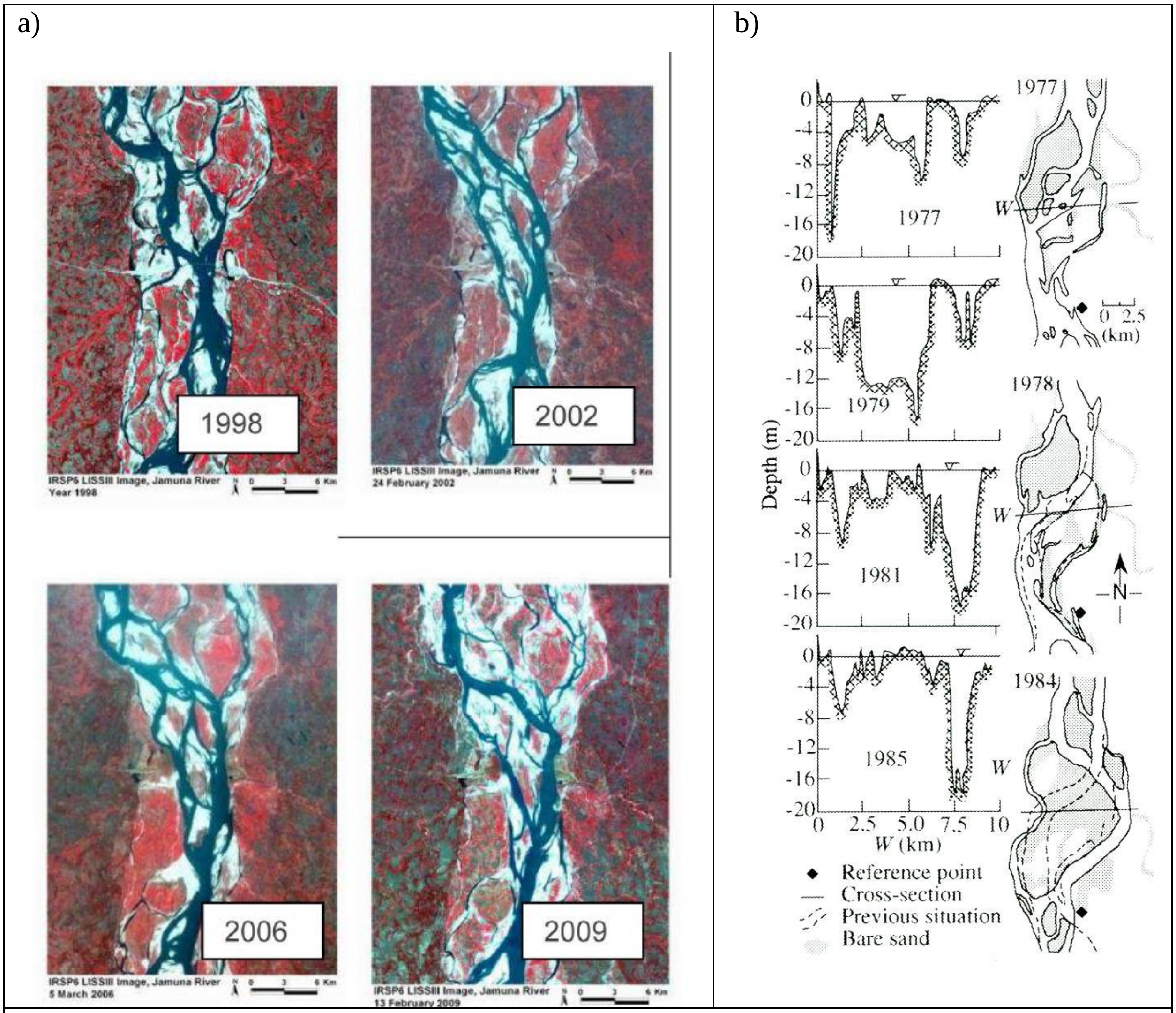


Figure 13 – Jamuna River a) Satellite images (Klaassen, 2009), b) lateral migration of the river (Julien, 2002)

6.2 Heart K Ranch, Montana, United States

Based on Boyd (2010) report, one of the trenchfill projects in Montana that has received substantial attention is located on the Yellowstone River downstream of Livingston. At this site, the river is multi-thread, and flow paths have shifted in past decades such that dominant channels have changed through time. In 1973, for example, the project site was located on a secondary channel (Figure 14). By 1999, that channel had become the primary, more erosive thread. A comparison of air photos shows approximately 200 feet of right bank migration between 2005 and 2009 (Figure 15). In order to address the rapid erosion observed in 2005, the project was constructed as trenchfill rock in 2006. The project consists of approximately 1500 feet of trenchfill rock that was installed approximately 30 feet landward from the eroding bank. Within one runoff season, virtually the entire structure was exposed to the river (Figure 16). The project was designed by a professional firm, and constructed by the landowner.

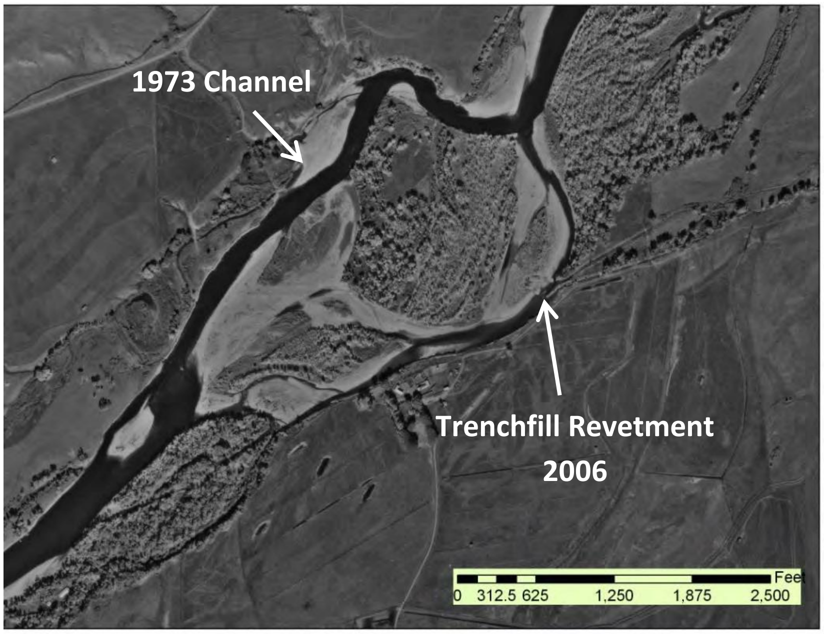


Figure 14 - 1973 aerial image of trenchfill revetment site showing dominance of north channel (Boyd, 2010)

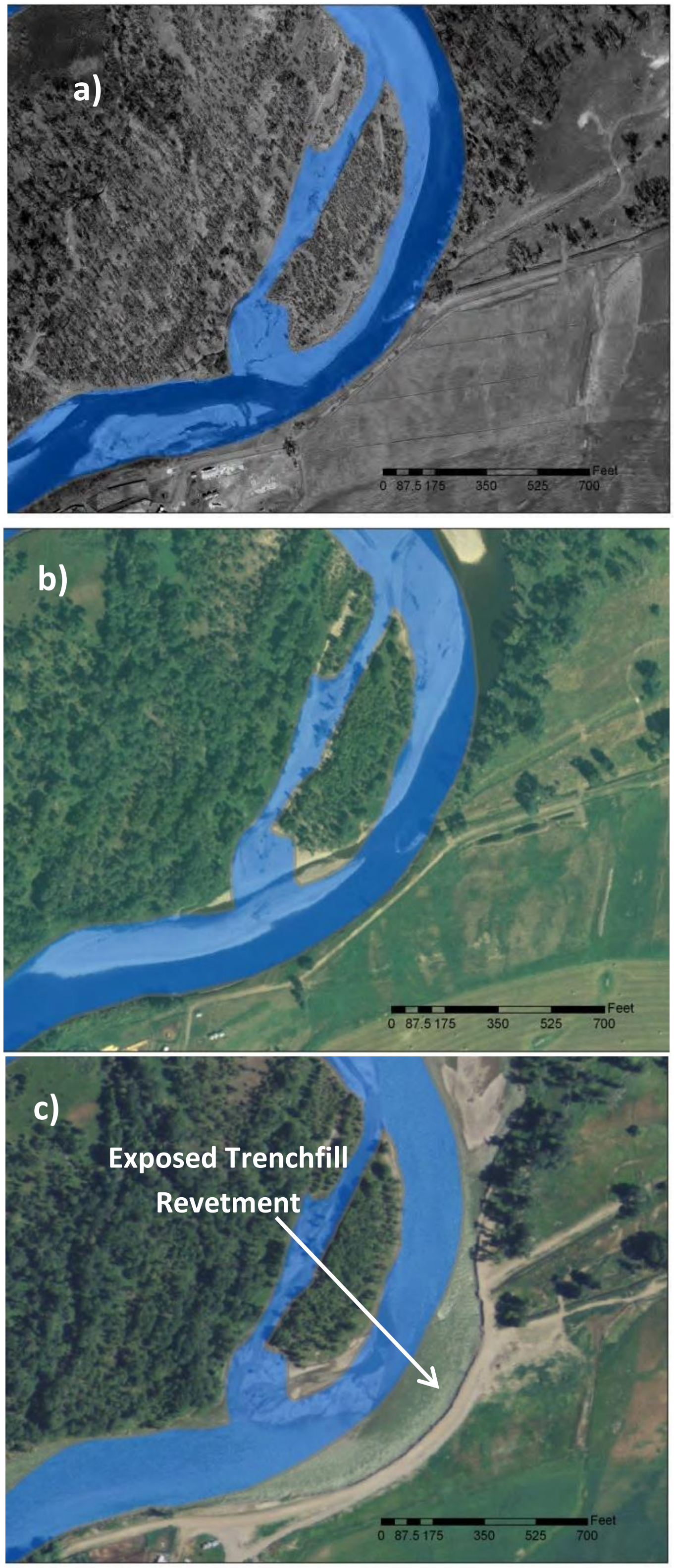


Figure 15 – banklines (blue) overlaying air photos from a) 1999, b) 2005, and c) 2009 (Boyd, 2010)

As of October 2010, the project was largely intact, although the mid-bank has been locally exposed due to excessive launching of the toe rock, which is a concern for long-term stability (Figure 17). Some rock has been launched well off of the bank, creating local hard elements in the channel bed, and flow velocities remain very high against the structure.

Figure 16 - View downstream of intercepted trenchfill revetment; local turbulence is from launched rock (Boyd, 2010)

Figure 17 - View of discontinuous rock at mid-bank level (Boyd, 2010)

6.3 Thompson Bend on the Mississippi River, United States

Thompson Bend is located on the right descending bank of the Mississippi River between river miles 30 and 45, above the confluence of the Mississippi and Ohio Rivers; see Figure 18. The river flows in a gooseneck encompassing approximately 10,000 acres (40 km^2) of valuable agricultural land. At the throat of the bend, the overland distance is approximately 2 miles. The river distance along the thalweg is approximately 14 miles (22.5 km). During large floods the river naturally tries to flow straight across Thompson Bend. The water surface drop the thalweg is 7ft (2.1 m) for a slope 0.5 ft/mile (9.5 cm/km) along the river and 3.5 ft/mile (66 cm/km) across the neck.

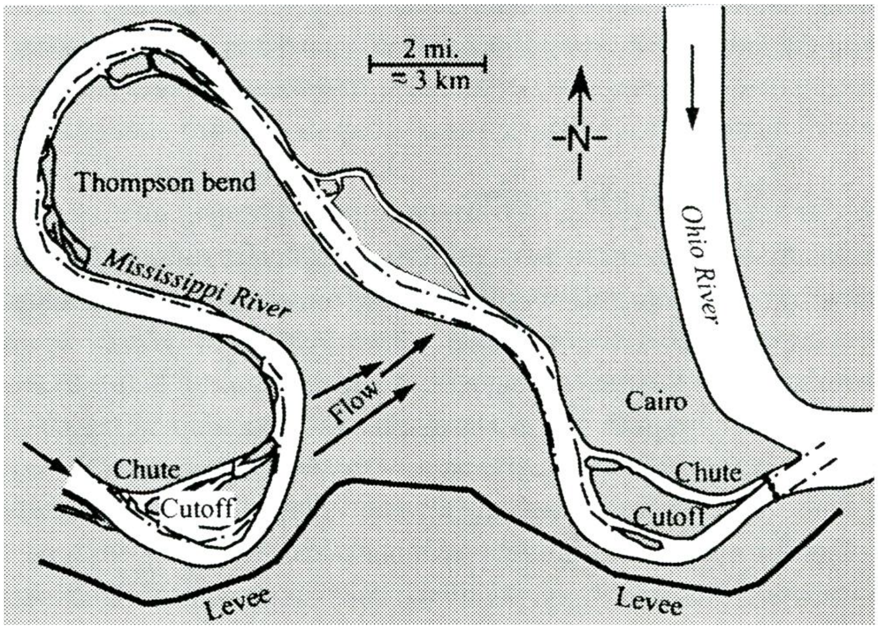


Figure 18 – Thompson Bend of Mississippi (Julien, 2002)

In the early 1980s, severe erosion of the upper bankline began along the right descending bank in the upper reaches of the bendway. In addition, localized surface erosion reached an estimated rate of 40,000 (ton/acre)/event [16,000 (tons/hectare)/event]. Continued erosion could have allowed for development of a chute cutoff across the bend. This would have impaired navigation to the steep slopes and resulting high velocities in the new channel across the bend. It would also have destroyed thousands of acres of valuable farmland and changed the river regime for miles upstream and downstream.

Thompson Bend clearly illustrates the vital importance that vegetation exerts on controlling overbank scour. The revegetation process began in 1985 and early 1986. The results were immediately evident during the fall flood of 1986. Very little erosion was observed. The area was tested again in the flood of 1990, when very little erosion occurred. The Thompson Bend also suffered very little visible damage during the Great flood of 1993, when record high stages occurred, and the duration of the overland flows reached an unprecedented 130 days. However, the flood took its toll on the vegetation. Numerous trees that were inundated for most of the 130 days died. Using the Google map tool, the current map of the Thompson Bend is shown in Figure 19.

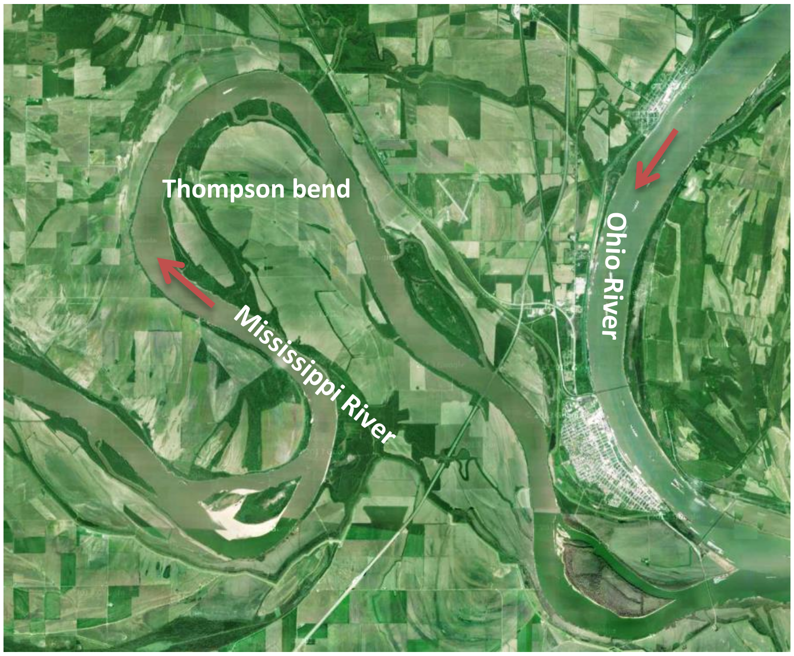


Figure 19 – Thompson Bend of Mississippi River (Google-map, 2013)

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