CHAPTER 3

MODES AND CAUSES OF BANK FAILURES

To effectively control bank erosion, river bank management must be compatible with the nature of the river system and the composition of its banks. Before restorative methods are applied to eroding banks, it is essential to understand the mechanism of erosion. Otherwise, large investments of time and money may potentially be wasted in projects that fail or require frequent maintenance. This chapter discusses various forms and causes of bank failure.

3.1 STREAMBANK ZONES

Streambanks can be divided into three general zones: toe, bank, and overbank zones. Although the boundaries between these zones are imprecise because river levels vary seasonally, they are useful in subsequent discussions. These zones are shown in Figure 3.1, and can be described as follows (adapted from Logan 1979):

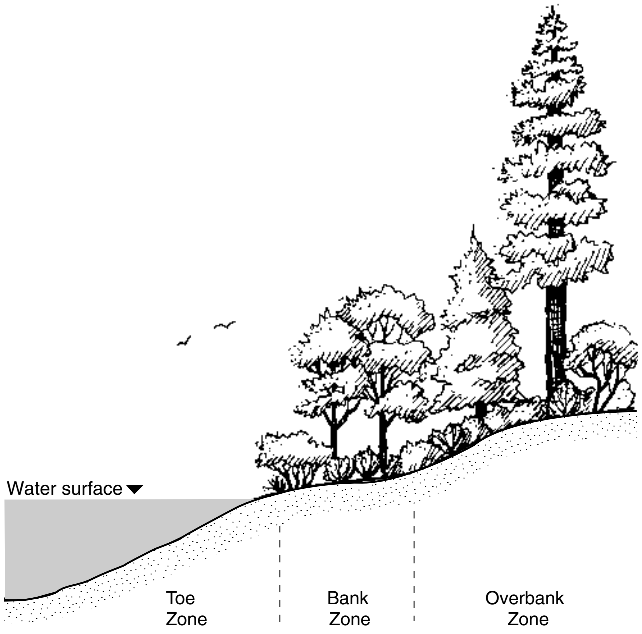
Toe Zone. The toe zone is that portion of the bank between the ordinary high water (OHW) and low water levels. This is the zone most susceptible to erosion as it is exposed to strong currents, debris movements, and wet-dry cycles. This zone is normally inundated throughout much of the year. In areas where stabilization is necessary, non-vegetative structural protection is normally required in this zone because few woody plants can tolerate year-round inundation.

Bank Zone. The bank zone is that portion of the bank above the OHW mark (OHWM) that is inundated during periods of moderate flows (i.e., up to bankfull flow). Although above OHWM, these sites are still exposed to periodic erosive currents, debris movement, and traffic by animals and humans. The water table in this zone is frequently close to the soil surface because of its proximity to the river.

Overbank Areas. The overbank area is that portion of the bank from the bank zone inland that is subjected to inundation or erosive action only during occasional periods of high water (i.e., greater than bankfull flows). This zone is generally subjected to periodic dry periods in which the soil moisture is primarily dependent on characteristic rainfall of the area. When relatively flat and generally underlain by alluvial deposits, this area is also called a floodplain. When it rises steeply and directly from the streambank, this area is called a bluff.

In some situations, toe protection with riprap or other structural means may be the only streambank protection required. Usually, structural protection below OHWM will be combined with vegetative designs above OHWM. Combined systems of this sort provide maximum protection against failure and yield greater benefits for aquatic and terrestrial ecosystems. The design of bank protection measures is discussed in Chapter 7.

Figure 3.1 Section of streambank zones in natural channels.



3.2 CHARACTERISTICS OF BED AND BANK MATERIAL

The resistance of natural river banks to erosion is closely related to the characteristics of the bank material. While these materials are highly variable, they can be broadly classified as follows (Henderson and Shields 1984; Simons, Li and Associates 1982):

Bedrock. Bedrock outcrops normally are quite stable and subject only to quite gradual erosion and intermittent mass failure. Bedrock outcrops in a bank or bed can prompt erosion of the opposite bank.

Cohesionless Banks. Streambanks composed of cohesionless soils normally are highly stratified heterogeneous deposits. Cohesionless soils consist of mixtures of silts, sands, and gravels. These soils have no electrical or chemical bonding between particles and are eroded grain by grain. Erosion of cohesionless soils is controlled by gravitational forces and particle characteristics such as size, grain shape, gradation, moisture content, and relative density. Other factors include the direction and magnitude of flow velocities next to the bank, fluctuations in water turbulence, the magnitude and fluctuations in the shear stress exerted on the banks, seepage force, and piping and wave forces.

Cohesive Banks. Erosion of cohesive streambanks is more complex to analyze than cohesionless banks because of the characteristics of soil particle bonding. Cohesive soils contain large quantities of fine clay particles composed of chemically active minerals that create strong chemical and electrochemical bonds between particles. Other soil characteristics affecting cohesive soil erosion are the type and amount of cations in pore water and the eroding fluid, and composition of the soil including the type and amount of clay minerals. Cohesive material is generally more resistant to surface erosion because its low permeability reduces the effects of seepage, piping, frost heaving, and subsurface flow on the stability of the banks. Because of the low permeability, this material is more susceptible to failure during rapid lowering of water levels. When undercut and/or saturated, these banks are more likely to fail due to mass wasting processes such as sliding.

Stratified or Interbedded Banks. Stratified banks are the most common bank type in natural fluvial systems. The soils in stratified banks consist of layers of materials of various sizes, permeability, and cohesion. When cohesionless layers are interbedded with cohesive soils, erosion potential is decided by the erodibility of the component layers and the thickness and position of the cohesionless strata. Where cohesionless soil is not at the toe of the bank, the layers of cohesionless soil are protected by adjacent layers of cohesive soils (the cohesionless soils are still subject to surface erosion). This type of bank is vulnerable to erosion and sliding because of subsurface flows and piping. Where the cohesionless soil occurs at the toe of the bank, it will generally control the retreat rate of an overlaying cohesive unit (Thorne and Lewin 1979).

3.3 STREAMBANK FAILURES

All stream banks erode to some degree. Because is a natural ongoing process, it is unrealistic to believe that bank erosion can be or should be totally eliminated. Major floods can always make significant changes in bank lines despite steps taken to prevent it. Thus, it is important to understand that the concern is not that erosion occurs, but rather the location and rate at which it occurs.

While bank erosion is occurring naturally over time, it is a process that may be accelerated or decelerated by human activities. Henderson and Shields (1984) define natural erosion as the processes that occur without significant human activities in the drainage basin or catastrophic natural events such as volcanic eruptions or forest fires. They define accelerated erosion as erosion that is atypically high in magnitude and is different in nature than the erosion experienced at the site or reach in question in the recent past. Both natural events (e.g., high flows) and human activities (e.g., changes in land use) can cause accelerated erosion. In western Washington, for example, major changes in water quantity, flow direction, or debris loads often accelerate bank erosion. These types of changes are often caused by human activities such as urbanization, logging or overgrazing. These activities usually result in increased runoff and sediment yield compared with a basin in a natural condition.

Bank stabilization projects should not degrade the river environment or create a need for continued, costly maintenance. To prevent this, it is essential to understand both the channel responses to changes in flows and debris loads, and the processes of river bank erosion. Simons, Li and Associates (1982) provide a thorough discussion of the variables affecting river channels and the forces causing failure and erosion of river banks.

3.4 MODES OF FAILURE

Bank failures in riverine systems occur through one of three modes (Fischenich 1989): 1) hydraulic forces that remove erodible bed or bank material; 2) geotechnical instabilities; or 3) a combination of hydraulic and geotechnical factors. Fischenich explains each as follows:

> When bed or bank erosion occurs because water flowing in the channel exerts a stress that exceeds the critical shear stress for soil erosion, the mode of failure is hydraulic. Critical shear stress is dependent upon the type and size of the material. It can be exceeded by tangential shear stress caused by the drag of water or by direct impingement of water against a bank. Bed degradation is an example of the first, while local scour induced by debris is an example of the second. Hydraulic failure is usually characterized by a lack of vegetation, high boundary velocities, and no mass soil wasting at the toe of the bank.

The hydraulic mode of bank failure generally occurs on rivers with noncohesive gravelly banks, such as the Tolt River in King County (Shannon and Wilson 1993a). Rivers with fine-grained bank sediments, such as the lower Green River, generally experience the geotechnical mode of failure discussed below (Fischenich 1989). A geotechnical failure occurs when gravitational forces acting on the bank material exceed the strength of the resisting forces, causing downward displacment of the soil mass.

> Geotechnical failures that are unrelated to hydraulic erosion are nearly always caused by excess bank moisture problems. Moisture can affect both the stresses and the ability of the bank material to withstand stresses. Failure usually results when the shear strength of the bank material is exceeded. Mass wasting of soil at the toe of the bank is one indication that a geotechnical failure has occurred. The appearance of the failed bank can vary with the material type and the precise cause of the failure.
>
> Bank failures from a combination of hydraulic and geotechnical forces are more common than either force alone. Literally hundreds of scenarios can be developed under which a combination of these forces result in bank failures. Examples include: bed degradation that leads to oversteeping the banks and subsequent geotechnical failure; or, when successive slip plane failures occur on a geotechnically unstable bank and hydraulic forces erode mass wasted material at the toe that is resisting further slips.

Other large scale features that can affect river systems, such as landslides, debris torrents, or mass failures will not be discussed in this document.

3.5 CAUSES OF FAILURE

The actual causes of bank erosion related to hydraulic and geotechnical modes of failure are complex and varied. They involve streamflow characteristics, streambank properties including groundwater conditions, and the effect of human activities. Successful bank stabilization projects begin by identifying the cause of failure.

Fischenich (1989) describes the causes of erosion as follows:

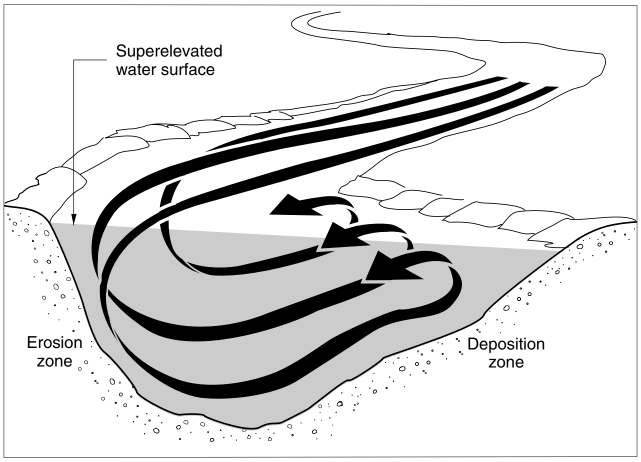
> Erosion from hydraulic forces is generally restricted to circumstances that either affect the velocity or direction of flow. Frequently, human actions are responsible. Examples of actions that can increase mean [and local] velocities include increased flows with land use changes, steeper channel slope from channelization, or constriction of the channel for bridge crossings. Changes in flow direction are usually the result of debris in the channel, formation of new islands or bars, or the improper placement of flow deflection structures. Destruction of bank vegetation from land clearing, logging, live-

> stock grazing, or other riparian use can also promote erosion by hydraulic forces."

An example of bank failure caused by hydraulic action is toe erosion. Toe erosion typically occurs when flow is directed toward a bank at a bend (Figure 3.2). In channel bends, the highest velocity is close to the outer edge of the channel and near the center of water depth. Forces act on the bank in both the downstream and the vertical direction toward the base of the bank. Centrifugal force causes the water surface elevation to be highest at the outside of the bend (superelevation). As gravity pulls the additional mass of water downward, a rolling, helical spiral is created, with high downward velocities against the bank material. This downward erosive force, coupled with the stream velocity, can undercut the toe of the bank. The downward erosive force on the bank will be greatest in tight bends as opposed to gradual curves. The most severe toe erosion will occur immediately downstream from the point of maximum curvature. At these locations, an increased level of protection will be required. Levees and revetments can become undercut, resulting in slumps, modified slumps and translational slides. These are discussed in detail in Section 3.6.

The process of undercutting is presented in a sequence of illustrations in Figure 3.3a, b, c, and d. In the initial position (a), the bank has composite layers consisting of an upper layer of cohesive silt material (commonly reinforce by plant roots) underlain with noncohesive gravels. As water flows along the bend, secondary currents remove the noncohesive material at the toe creating a cantilever overhang of cohesive material (b). At the toe of the bank, where shear stress exceeds critical shear stress, particles are detached from the bank by the flowing water. This oversteepens the bank, causing noncohesive particles higher up on the bank to fall off in thin, vertical slices. When the cohesive silt layer is undercut, the cantilever overhang collapses into the eroded pocket (c). This loose, fallen material is then washed downstream, resulting in a repositioned bank line or bank retreat (Thorne and Lewin 1979).

Figure 3.2 **Erosion and deposition caused by spiral secondary flow. (Adapted from Kunzig 1989.)**

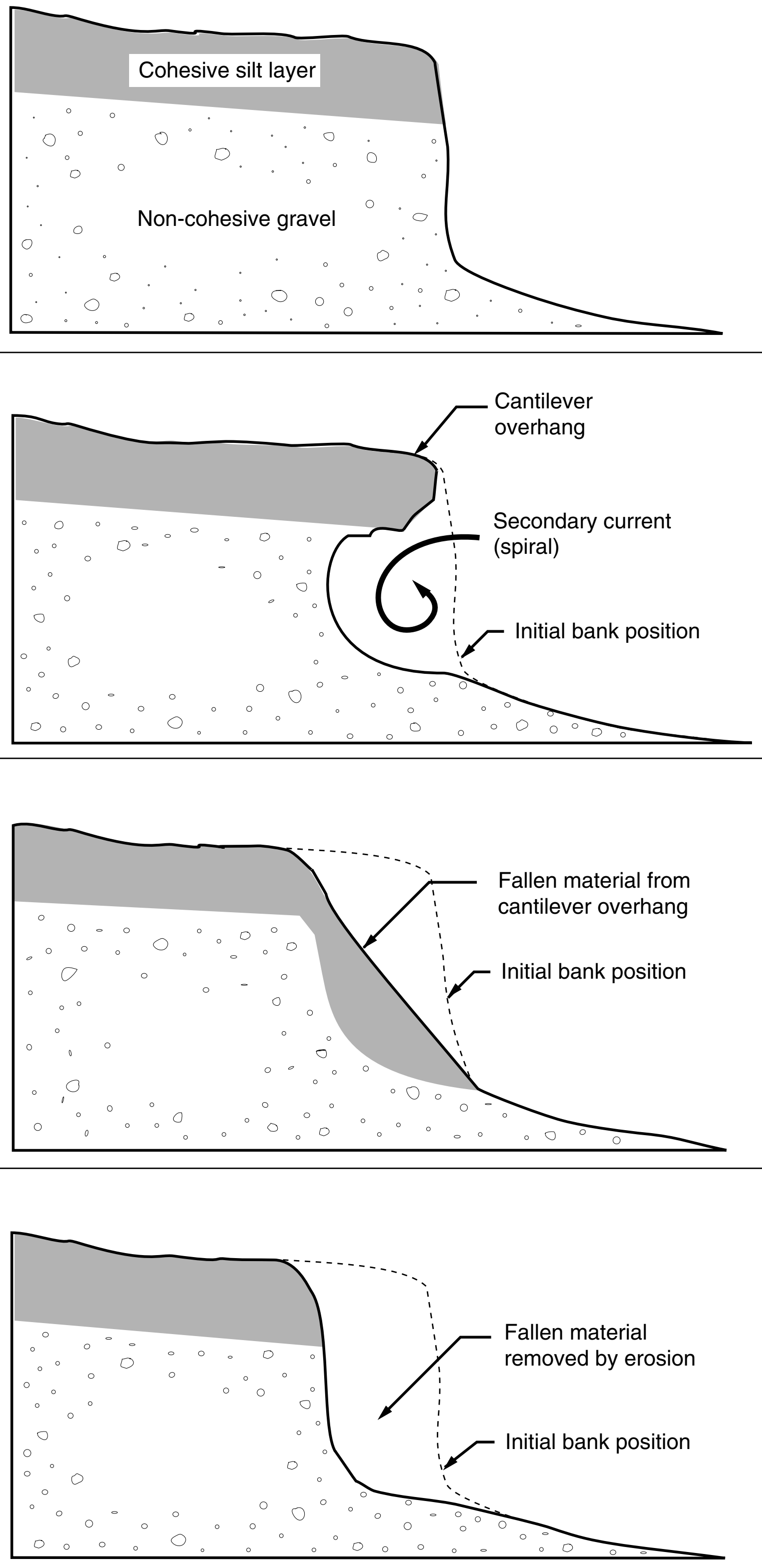


Toe erosion or streambed degradation may also lead to geotechnical bank failures by increasing the height of the bank to the point where the sliding forces exceed the resisting forces (shear strength) of the bank materials. Bank failures from only geotechnical forces are normally related to moisture conditions within the bank. As previously mentioned, moisture can affect both the stresses within the bank and the bank material's ability to withstand those forces. Geotechnical failures commonly occur after the flood peak has passed, when banks are saturated and have been oversteepened by undercutting. Common examples of situations that may lead to this type of failure are as follows (USACOE 1981 and Richards 1982):

- Failures induced by rapid drawdown occur when the river stage falls following a flood, leaving the banks saturated. The pore water pressure in the bank reduces frictional shear strength of the soil and increases sliding forces by adding weight to the soil mass. This type of failure tends to occur in fine-grained soils that do not drain rapidly.

- Banks are destabilized by the piping of soil particles from lenses (thin layers) of cohesionless sands. The piping undermines the overlying bank materials which then collapse.

Figure 3.3 Undercutting of a composite bank. (Adapted from Thorne and Lewin 1974.)



a) Initial bank position.

b) Toe erosion.

c) Failure of cantilever overhang.

d) Repositioned bank line.

- Expansion and contraction of soils during wet/dry or freeze/thaw cycles cause tension cracks that lead to bank failure by collapsing or toppling of blocks of soil.

- Subsurface moisture changes weaken the internal shear strength of the soil mass at the interface of different soil types.

- Capillary action temporarily decreases the angle of repose of the bank material to less than the existing bank slope. The oversteepened slope subsequently fails when the soil dries and capillary forces are no longer present.

3.6 CLASSIFICATION OF RIPRAP FAILURES

As vital as it is to understand the failure of natural river and stream banks, it is also important to understand the failure of riprapped structures such as rock revetments and levees. This information is particularly necessary in the design of repairs in that the inherent problem must be understood before it can be effectively corrected.

Blodgett and McConaughy (1986) identify four basic types of riprap failure along streambanks: 1) particle erosion, 2) translational slide, 3) modified slump, and 4) slump. The cause and correction of each type of failure is different. Blodgett and McConaughy describe each failure as follows:

3.6.1 PARTICLE EROSION

Particle erosion is the transport of riprap to the channel bed near the installation or to a point downstream. Particle erosion is considered the most common type of failure. Figure 3.4 shows an advanced stage of failure caused by particle erosion. Displaced riprap usually comes to rest on the bed near the eroded areas and at some distance downstream. A mound of displaced riprap on the channel bed suggests that the transport capability of the stream is insufficient to move all of the eroded riprap from the site. A detrimental effect of the mound is its tendency to confine high velocity flows between the mound and the toe of the embankment, causing additional bank and bed erosion.

The probable causes of particle erosion are:

- The median size stone (D_{50}) was not large enough to resist the shear stress of the stream.

- Abrasion or removal by impact of individual stones. For this and the previous situation, individual stones are lost, and in time, the cumulative effect results in riprap failure.

- The side slope of the bank is so steep that the displacing forces readily exceed the resisting forces of the riprap, causing instability of the individual stones.

- The gradation of riprap may be too uniform (all stones near the median size). Without sufficient smaller diameter stones to fill the voids and provide lateral support for larger material, failure may occur even if the median size is adequate and the bank side slope is not too steep.

3.6.2 TRANSLATIONAL SLIDE

A translational slide is caused by the downslope movement of a mass of stones, usually along a horizontal fault line (Figure 3.5). The riprap is undisturbed except at the fault line and a bulge at the toe. If the moving mass is not greatly deformed, it may be called a block slide. The initial phases of a translational slide are indicated by crack parallel to the channel in the upper part of the riprap bank. The movement of translational slides is controlled by: 1) variations in shear strength along the interface between the riprap and the base material, and 2) stability of the riprap at the junction point with the channel bed. A translational slide is initiated when the support of the upslope material is reduced by channel bed scour and undermining of the toe of the riprap, or by particle erosion of the toe material. In either case, the shear

Figure 3.4 Advanced stage of failure caused by particle erosion. (Adapted from Blodgett and McConaughy 1986.)

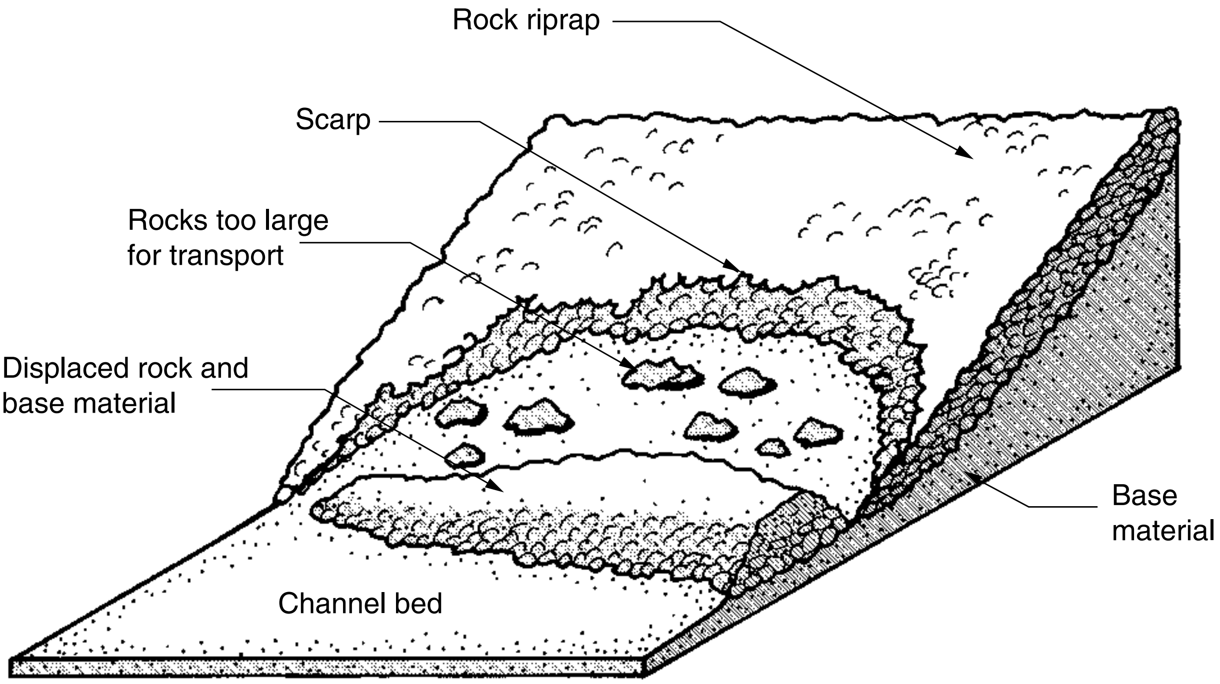
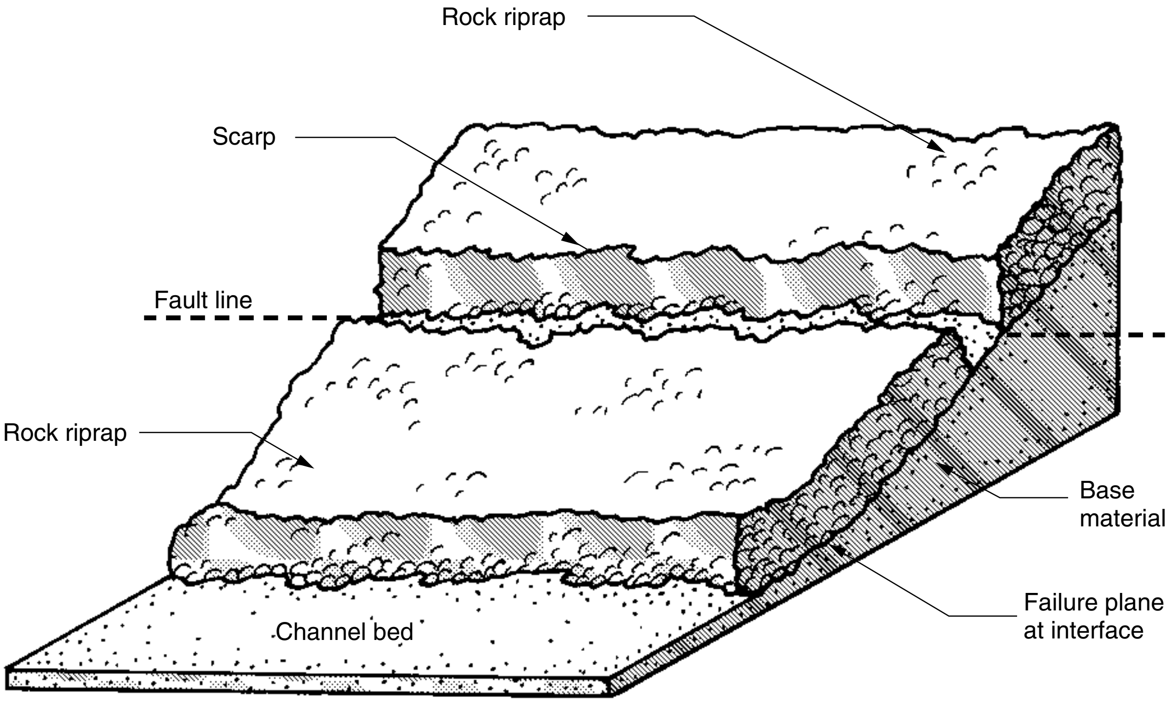


Figure 3.5 Failure caused by translational slide. (Adapted from Blodgett and McConaughy 1986.)



resistance of the interface between the bed material and riprap may be insufficient to resist translational movement.

The translational slide may progress downslope indefinitely if erosion of riprap at the toe continues. Continued downslope creep of the riprap may also occur if the base material underlying the riprap is saturated with water and the shear resistance along the interface is less than the sliding force.

A translational slide with the fault line located high on the embankment suggests that extensive channel bed scour or particle erosion undermined the toe of the embankment material. In this situation, the slide would occur only when the mass of riprap was sufficiently large for the downslope forces to exceed the shear strength at the interface. Translational slides also occur when excess hydrostatic (pore) pressure in the base material causes reduced frictional resistance in riprap at the interface between the two layers. Excess pore pressure may develop during periods of high precipitation, flooding, or rapid fluctuation of water levels. A filter blanket on the base material probably would not prevent this type of failure and may provide a potential failure plane.

The probable causes of translational slide failure are:

- The bank side slope is too steep.
- The loss of foundation support at the toe of the riprap because of channel bed scour or degradation, or by particle erosion of the lower part of the riprap.
- Excess hydrostatic (pore) pressure reduces the frictional resistance along the interface between the riprap and base material.

3.6.3 MODIFIED SLUMP

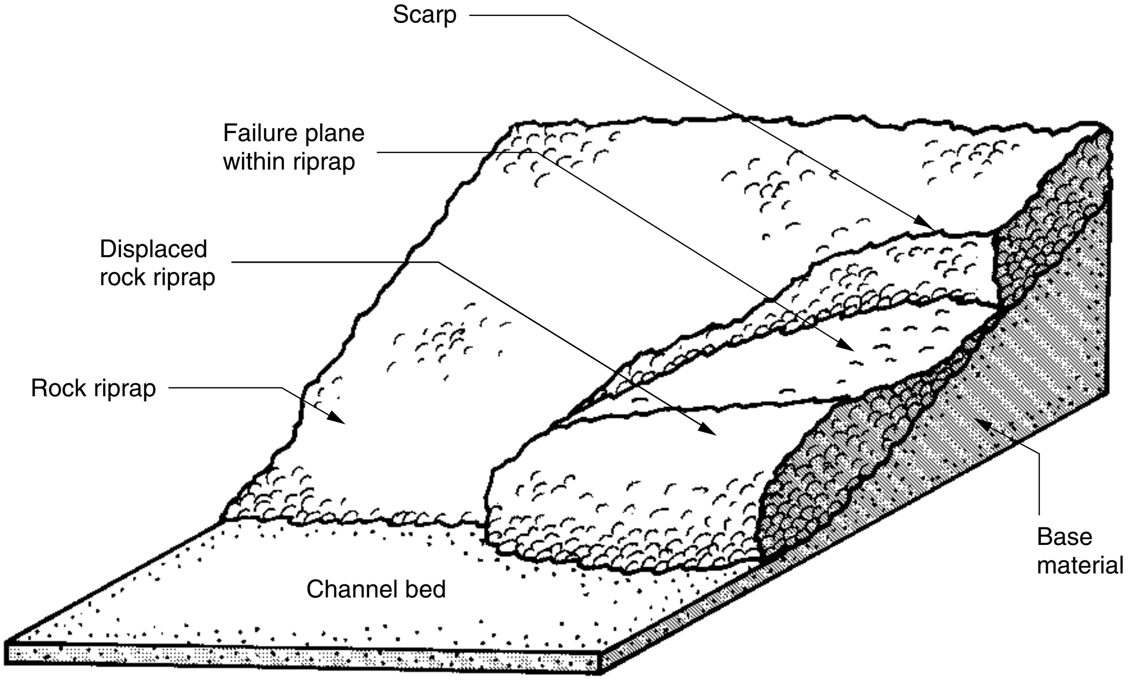
Riprap failure that occurs as a mass movement along an internal slip surface is called a modified slump. Slumps are described by Schuster and Krizek (1978) as rotational slides along a concave surface of rupture. A modified slump is different from the various slumps discussed by Schuster and Krizek in that the failure plane is located in the riprap, and the underlying material supporting the riprap does not fail (Figure 3.6). As a result, the surface of the rupture is not concave, but is a relatively flat plane.

While this failure is similar in many respects to a translational slide, the geometry of the damaged riprap is also similar in shape to the initial stages of failure caused by particle erosion. The new side slope within the modified slump area is flatter than the slope of the interface between the base material and the riprap. Material that is dislodged from the failure is similar to what occurs in a typical slump failure on hilly terrain. The displaced stones may cause increased turbulence of flow and eddy action along the bank in the area of the slump. The secondary current may then cause additional riprap failure by particle erosion of smaller materials, especially those exposed at the scarp. An interesting factor about modified slump failures is that while the median stone size (D_{50}) may be adequate for the site, movement of certain key stones (possibly due to poor gradation) leads to a localized failure of the riprap.

The probable causes of modified slump failures are:

- The bank side slope is so steep that the riprap is resting very near the angle of repose. Any imbalance or movement of individual stones creates a situation of instability for other stones in the riprap.
- Certain stones, critical in supporting upslope riprap, are dislodged by settlement of the submerged riprap, impact, abrasion, or particle erosion. The loss of support provided by the key stones results in the downslope movement within a local area near the point of the dislodged stones. This cause of failure may be reduced in frequency if the riprap material is of proper size gradation.

Figure 3.6 Failure caused by modified slump. (Adapted from Blodgett and McConaughy 1986.)



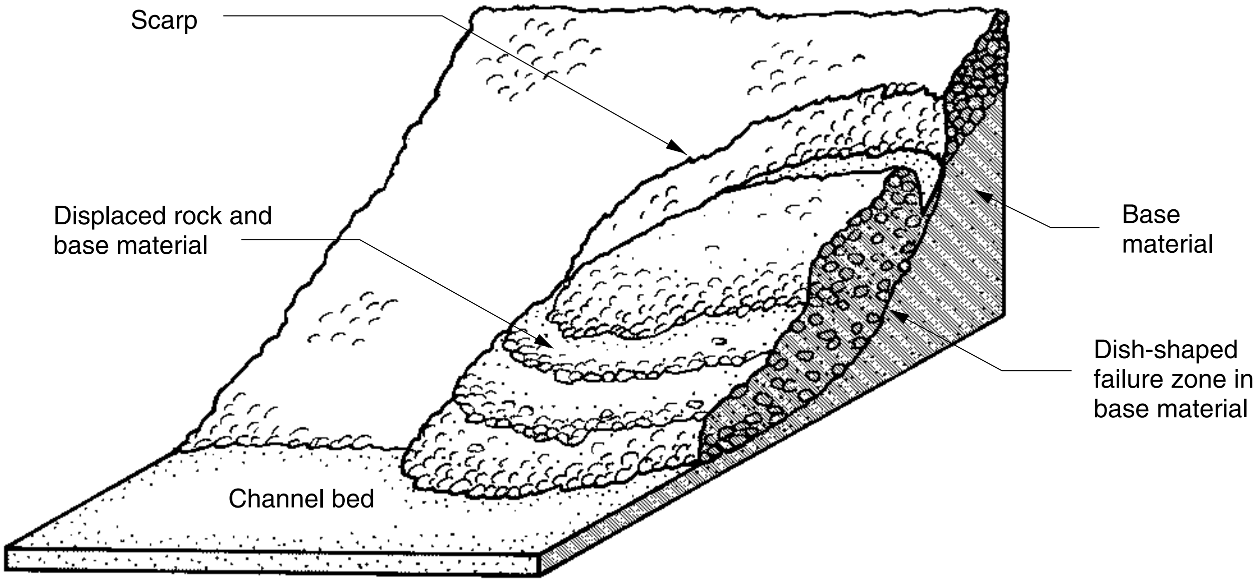
3.6.4 SLUMP

A slump is a rotational-gravitational movement of material along a concave surface of rupture. This type of failure is unlike a modified slump in that the failure zone is dish-shaped rather than a relatively flat plane (Figure 3.7). Slump failures are caused by shear failure of the underlying base material that supports the riprap. As discussed by Schuster and Krizek (1978), the rupture may not occur simultaneously over the failure area, but propagates from a local point. The displaced mass, including the riprap, moves downslope beyond the original failure area onto the surface of the riprap. A primary feature of a slump failure is the localized displacement of base material along a slip surface. This is usually caused by excess pore pressure that reduces friction along a fault line in the base material. The scarp at the head of the slump, located in both the base and riprap material, may be almost vertical. With progressive slump failures along the face of the riprap, the areas of instability may enlarge until the entire bank has failed and a new lower gradient bank slope is present. As with a modified slump, once a failure has occurred, displaced rock creates turbulence that may accelerate particle erosion.

The probable causes of slump failures are:

- The side slopes are too steep, and sliding forces exceed the inertial forces of the riprap and base material along a friction plane.
- Nonhomogeneous base material with layers of impermeable material that act as fault planes, particularly when subject to excess pore pressure.
- There is too much overburden at the top of the slope. This may be caused in part by the riprap.

Figure 3.7 Failure caused by slump. (Adapted from Blodgett and McConaughy 1986.)



3.6.5 FACTORS CONTRIBUTING TO RIPRAP FAILURES

Four types of riprap failures (particle erosion, translational slide, modified slump, and true slump) have been discussed. The specific mechanism causing failure of the riprap may be difficult to define because several factors, acting either individually or combined, may be involved. Several reasons for riprap failures are identified and grouped below:

- Toe of riprap was not keyed below depth of scour.

- Riprap particle size was too small because:
  - a. Shear stress and/or velocity were underestimated.
  - b. Inadequate allowance was made for channel curvature.
  - c. Channel geometry was not considered in the design.
  - d. Design channel capacity was too low.
  - e. Design discharge was too low.
  - f. Inadequate assessment was made of abrasive forces.
  - g. Inadequate allowance was made for effect of obstructions.
- Riprap material was improperly graded.

- Material was placed improperly.

- No filter blanket was installed or the blanket was inadequate or damaged.

- Channel changes caused:
  - a. Impinging flow.
  - b. Flow to be directed at ends of protected reach.
  - c. Decreased channel capacity or increased depth.
  - d. Scour of toe of riprap.

- Sliding forces exceeded resisting forces because:
  - a. Side slopes were too steep.

b. Excess pore pressure decreased the friction angle.
c. Rapid drawdown caused excess pore pressure in the bank.
d. Structural planes of weakness were present.
e. Resisting force components of the bank were removed by toe scour and undercutting.

RECOMMENDED SOURCES FOR ADDITIONAL INFORMATION

Blodgett, J.C. and C.E. McConaughy. 1986. Rock Riprap Design for Protection of Stream Channels Near Highway Structures. Volume 2--Evaluation of Riprap Design Procedures. U.S. Geological Survey. Water-Resources Investigation Report 86-4128. Sacramento, Calif.

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