STREAMBANK EROSION CAUSES, AND LARGE WOODY MATERAL (LWM) SOLUTIONS FOR STREAMBANK EROSION AND SEDIMENT REDUCTION

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ABSTRACT

Watershed and reach level changes can impact streambank erosion. Most of the focus of streambank erosion at the reach level is the bank instability caused by cantilever failure, planer failure, rotational failure, or preferential flow failure. These mechanisms are modified by high pore press; liquefaction; high bank height exceeding a critical bank height; stratigraphy; Rc/Wbkf < 2.5; flow condition (flow duration, helicoidal flow, cavitation, pre-wetting); boundary shear stress along eroding bank; root density and depth; waves; ice condition; desiccation, and animal burrows. For the gravel bed rivers of the western states the predominant cause of bank failure is catilever failure. The cantilever is created because the fines and sands are washed out of the gravel and cobble stratigraphy to create the cantilever overhang. Local sedimentation, especially from debris flows, can cause streams to erode their streambanks, because it is easier to erode the streambanks than it is to erode the coarse material of the debris flow. Large woody debris jams in stream channels can cause stream to change course and to create stream avulsions. The avulsions cause extensive streambank erosion by downcutting and widening. Tight curve meanders with a Rc/Wbkf < 2.5 tend to fail unless they have extensive deep toe protection. For environmental reasons, bank protection in recent years has tended to use large woody materials. This could be the placement of logs, stumps, rootwads, whole trees with branches, along with spacer logs, deflectors logs, and vertical wood post for stability. The trend in recent years is to install rootwad and boulder buttressed structures, log vanes, and engineering log jams. Critical to the success of these structures is how well the toe protection works. Most large woody material structures, tend to have associated streambank Soil Bioengineering treatment with fascines, brush mattresses, and stake and pole planting. It is essential that this type of Soil Bioengineering material be applied above the bankfull stage of the river, otherwise failure is likely.

INTRODUCTION

Streambank erosion is a natural phenomenon but can become accelerated because of changes at the watershed and/or reach scale. There was little need to do streambank protection prior to the 1920, as roads and the locations of bridges avoided the most hazardous situations (CDPW,

1960) Eventually the expansion of the use of automobiles and trucks placed more roads in more hazardous situations and floods were causing more damage in built infrastructure. For many years the causes of streambank erosion were only minimally evaluated, and agencies favored the use of riprap structures. Over the years researchers figured out causes of failure but solutions tended to be tied to altered straightened streams, so the causes of failure were not considered in the evaluation. The straightening made solutions even more difficult as straightened rivers tended to downcut and widen as a response to the straightening.

DESCRIPTION OF STREAMBANK EROSION CAUSES

To evaluate streambanks background conditions are established using old photographs and maps rates compared over time, in the context of floods, and watershed and reach scale changes. These are combined with recognizing reach level changes in stage of channel evolution, scour patterns, sediment deposits, side slopes, slumping, and cultural features. Changes at the watershed scale might be caused by logging, mining, road and railroad construction. Reach scale alterations might be riparian area modifications due to vegetation change or loss, animal use, stream channel straightening, or channel excavation and/or removal of material (stream bed mining), avulsion (abrupt change in stream course such as a meander cut-off), or climate change.

One investigates whether bank instability is caused by mass failure such as cantilever failure (Figures 1 and 2), planer failure, rotational failure (Reckendorf, 2009a), preferential flow failure (Figure 3) including piping (Hagerty, 1991); high pore pressure, liquefaction and seepage forces especially during the falling stage of floods; popout failure; or because bank height exceeds some critical bank height (Schumm et al. 1984, Reckendorf and Tice, 2003, and 2001). Investigate if failure mechanisms are accelerated or modified by a stratigraphy caused cantilever (Reckendorf, 2010, 2009a, 2009b, 2008b, 2001, 1996, 1989). Is failure mechanism accelerated by Rc/W_{bkf} geometry as discussed in, Bagnold (1960), Thorne et al. (1997) Welch and Wright (2005), Southerland and Reckendorf (2008); flow condition (peak, duration, angle of attack parallel to perpendicular to location of failure); helicoidal flow, Wolman, 1959, Hooke, 1979, Thorne et al. 1997, Welch and Wright, 2005); pre-wetting (Knighton, 1995, and Thorne et al. (1997, Wolman, 1959); boundary shear stress; depth of bed scour along eroding bank; local sedimentation (Reckendorf, 2008b), and Rosgen 2006b); root density and depth (Reckendorf, 2001, and Rosgen 2006b); waves (Reckendorf, 1989); ice condition (freeze thaw, Knighton, 1995), and gouging); desiccation (Thorne et al. 1997), animal burrows (Reckendorf, 2008b); large woody debris jams or other mechanisms causing stream avulsion (Reckendorf 2010).

Understanding historic channel changes will consistently help us understand streambank erosion The Channel Evolution Model (CEM) of Schumm et al. (1984), and Simon (1989) provide an excellent perspective. The CEM has been used to field identity the CEM stages and streambank erosion on dozens of streams in dozens of states (Reckendorf and Steffan, 2006). The Schumm et al, (1984) CEM Stage II stage of downcutting is often a result of channel straightening (Reckendorf and Tice, 2003). This creates a very high bank relative to a critical bank height where the streambank fails, and a headcut that migrates upstream. The distance downstream of the headcut represents the passage of time. Stage III in the CEM, reflects widening so one ends up with U shaped channels or F stream types (Rosgen 1996). Streambank protection work, drop structures, soil bioengineering, or stream restoration work should not proceed without identifying the stage of channel evolution, with the associated headcut migration.

Accelerated streambank erosion at the reach level is often modified by local sedimentation patterns that redirect flow, to the extent that avulsions occur where not expected. Landslides and debris flow often provide such a large quantity of coarse material to streams that the lateral shear accelerates streambank erosion, instead of transporting the coarse material (Reckendorf, 2006, 2008b). Debris flows tend to migrate downstream in pulses (Benda and Dunne, 1997a, 1997b) and Reckendorf (2006, 2008), reworking the course material during high flow. Often streams don't have the competence to transport the commonly available largest sediment particles resulting in lag deposits that accumulates. This coarse accumulation exacerbate the bank erosion, as the river flanks the coarse deposit.

Watershed level changes, like logging, can cause increased sedimentation downstream that completely bury the natural channel and adjacent flood plain. This results in a whole new cycle of streambank erosion (Trimble, 1982). The author has evaluated some streams in the Driftless area of Southwest Wisconsin, that took over 100 years of stream downcutting and widening through the post cultural sediment, to downcut back to the former streambed, buried because of watershed logging and associated erosion an sedimentation.

There are hundreds of miles of streambank, where the author has concluded that stratigraphy (especially washing fines and sand matrix out of gravel strata) is the principal cause of cantilever failure, along gravel bed river streambanks. For example in just one county (Clackamas County in Oregon) five rivers (Sandy, Salmon, Zigzag, Clackamas, Molalla), representing hundreds miles of river streambank have primarily cantilever failure that was caused by high water removal of sands and fines matrix material. In one study by the author on over 150 miles of streambanks in the Walla Walla and Columbia Counties in WA (Reckendorf and Tice, 2001, 2003), the majority of the streambank failures were from downcutting (Stage II, CEM) and widening (Stage III, CEM) associated with cantilever failure because of the removal of fines and sand matrix material from the gravel strata.

In a post project appraisal study of the failure of engineering log jams in Washington (Southerland and Reckendorf, 2008) those streams with a radius of curvature divided by bankfull width (Rc/W_{Bkf}) of less than 2.5 were found to be the most prone to failure along meandering streams. These type of tight meander curves are thought to have deep thalweg (deepest part of channel) along the outside curves and high helicoidal flow contributing to streambank failure (Welch and Wright 2005).

Understanding the geomorphic history of a stream helps in our understanding of the nature of stratigraphy. Meandering streams traditionally develop gravel deposits on their point bars because of helicoidal flow. These become overlain by vertical accretion flood pain deposits during floods. The traditional view may have distorted our perceptions of the materials in the gravel stratigraphic deposits. On occasions studies such as Karlstrom (1964), on Kenai River, AK have shown that the gravel stratigraphy was formed by a braided paleo-channel and paleo-hydrology, and that the existing stream is underfit. The Kenai River, AK, paleo-channel formed a coarse cobble gravel strata now apparent in flood plain and low terrace streambanks, that are extensively undercut by cantilever failure. High flows and wave impacts now remove sand and fines matrix material from the cobble strata (Reckendorf and Seale,1991, and Reckendorf, 1989). The condition is that the coarse cobble gravel stratigraphy in the streambanks formed by braided streams with a early Holocene or Pleistocene paleo-hydrology, which was later overlain by vertical accretion deposits. Over time, with a reduced runoff in the Holocene (and reduced base level), streams down-cut through the prior deposits and formed single or multiple thread meandering streams, with the vulnerable coarse gravel stratigraphy in the streambanks. A mixed stratigraphy in streambanks may also have developed because of avulsion history. Neck and chute cut-off avulsions tend to leave a bio-modal distribution of coarse sediment over finer sediment, where the avulsion reconnects with the main channel. This coarser over finer bi-modal distribution is often reversed on the main stem from which the avulsion occurred (Reckendorf, 2010). Once the avulsion occurred on the main stem part of the flow is diverted down the avulsion channel that is eroding. This results in lower flow on the main stem and this loss of stream capacity tends to cause deposition along the main stem. In this case the sediment load that had been carried by the main stem now deposits on a coarse bar that represents the capacity of the channel when the main stem had all the flow. In other words the bi-modal deposition is reversed comparing below the avulsion outlet sediment dump to the downstream reach immediately below the avulsion.

USE OF WOOD IN STRAMBANK EROSION CONTROL

Early use of woody material in stream stabilization is documented in patents issued for spur dikes of trees (1878), tree jetties (1883), pile A-frame jetties (1885), boom of trees (1902), cribs filled with brush (1915), mesh crib (1923), and pile fence and trees (1936) (CDPW, 1960). Early work was done in combination with fascines and brush mattresses Soil Bioengineering. The Civilian Conservation Corps (CCC) developed many parks along riparian areas in1930's, and used large and small wood in bank stabilization such as along Means Creek in Tongas State Park in Florida (Ray, 2003). Other early work in the 1930's, is described in Edminster et al, (1949). At some unknown time people started using the terms Large Woody Material (LWM) or Large Woody Debris (LWD). The use of those terms has varied from the placement of logs, stumps, and rootwads to whole trees with rootwads and limbs attached (Hopkins, 1999), to portions of trees with or without rootwads (CDEP,2003). For this paper the LWM definition, will include trees, branches, rootwads, and other large wood , essential for stabilizing the LWM structure. That may include logs for spacers, or deflectors, and or vertical wood post. For those wood structures that only involve logs and or vertical post without rootwads this paper will use the term large wood (LW). Installations (LWM) are intended to provide habitat as well as bank stabilization. Large woody debris deposition occurs naturally and is installed with the intent of collecting more LWD and LW. It may be appropriate to use LWD to refer to natural wood accumulation and LWM to refer to installed woody material. A research and demonstration study in the 1970's done by the Corps of Engineers (1981), and reported on by NRCS (2007), included several field trials using LWM for streambank protection. The California Department of Fish and Game (Flosi, and Reynolds, 1994) improved on the use of LW and LWM as bank armor by providing a toe trench with a partially buried log, and then securing all LW with re-bar, metal fence post, and culvert stakes, and cabling back to a deadman or boulder. The United States Forest Service installed many LWM structures in the 1970' and 1980"s and was a leader in developing the technology for attaching wood to boulders using epoxy's and using various types of pins and rods, as well as the rootwad and boulder technology. In the middle 1980's Dave Rosgen (1989), started doing extensive work throughout the US installing rootwads, and logs with boulder buttress. A spacer rootwad or log was installed in a trench, and at about a right angle one or more rootwads were installed in a trench that was oriented upstream. The spacer log or rootwad was boulder buttressed, and than the bankfull bench trenches were backfilled. Rosgen referred to these installations as native material bank revetment (Rosgen, 1989, 1993). Rosgen (1993) introduced the concepts of log-vane (LV) for re-direction of streamflow for bank protection, using logs or rootwads. The log-vane is pointed upstream at about a 20 to 30 degree angle to the streambank. The log or rootwad vane, redirects streamflow as the flow crosses the log perpendicularly across the wood structure, and away from the streambank. The log-vane or rootwad vane are secured with boulders. Later versions of log-vanes and rootwad vanes, used reverse rootwads in bankfull bench trenches that are boulder buttressed. The log or rootwad vanes are ballasted at the tip and back adjacent to a bankfull bench. Reckendorf (2007) modified this concept by using an eco-block, chained below the rootwad, near the bankfull bench and below a rock boulder placed on the upstream side of the rootwad. This modification was necessary to offset buoyancy because the LV's installed in the Pack River and Delta Project, (Reckendorf, 2008a) were inundated up to five feet deep in Lake Pend Oreille, after they served their purpose to re-direct flow during spring runoff. Log and rootwad vanes have the effect to create backwater on their upstream side, such that sedimentation can occur adjacent to the streambank, where erosion had formally occurred. Rosgen started building LW cross-vanes in about 1997, which redirect flow away from both streambanks, and keeps the channel thalweg in the center of the river. These are illustrated in Rosgen (2006a). Engineering log jams (ELJ's) for streambank stabilization were first introduced in the early 1990's by Tim Abbe. The application of ELJ's have been discussed by Abbe, and Montgomery, (1996), and Abbe, Montgomery and Petroff (1997). Engineering Log Jams (ELJ's) are patterned after natural log jams, and are usually formed by using several key member rootwads that stabilize and anchor other debris. A toe trench is desirable, although not always provided (Southerland and Reckendorf, 2008). Large woody material are stacked on key members for ballast. Rootwads are held in place by pilings or poles that are usually wood, but steel piles have been used. The piles added for stability, are to be driven below scour depth. The whole structure is backfilled with excavated sediment to provide additional ballast. ELJ's are built with passive (weight and shape of structure are the anchor) or active anchoring (Saldi-Caromile et al, 2004). Active anchors can be flexible or ridge. Rigid anchors are ballast, pilings, cabling or chaining, pinning, deadman anchors, anchoring to rocks, and combinations of above (Saldi-Caromile et al, 2004). Reckendorf (2008a) developed conceptual designs for ELJ's chained to eco-blocks for toe protection and buttress. These have been done in combination with rootwad roughness structures on and adjacent flood plains for backwater effects and sedimentation. Most river restoration stabilization work involves some combination of the techniques mentioned, and most LW and or LWM installations is done in conjunction with soil-bioengineering for treatment in areas above the toe position. Millions of dollars of LW and LWM work has been done in the past 25 years. Federal and State environmental laws and regulations have forced the installations using LW and LWM in combination with soil-bioengineering, to provide a habitat component along rivers that was lost when only rip-rap, barbs, gabions, or concrete walls were installed. Soil-bioengineering on streambank side slopes is generally not recommended, unless toe protection is provided, and is very dependent on stream type and stage of channel evolution (Reckendorf and Steffan (2006).

CONCLUSIONS

There are many causes of streambank that work in combination to cause a variety of streambank failures. In hundreds of gravel bed rivers in the western states streambank cantilever failure is the primary mechanism of failure. The reason for the cantilever tends to be the washing of sands and fines out of gravel and cobble stratigraphy. The sloughed material creates the cantilever. The mixed stratigraphy of fines over gravel and cobble beds is a combination of lateral accretion over vertical accretion deposits, and braided stream gravel and cobble stratigraphy that is later overlain by vertical accretion deposits from flooding. Flood peak and duration are important contributions to bank failure with most bank failure occurring during the falling stage of flood events. During flood events two other modifications of bank failure are of particular importance. One is seepage forces because during the falling stage a head differential exists between water tapped in old channels on the flood plain and seepage goes subsurface to set up seepage forces and liquefaction along the streambank. Bank protection for years has been done primarily by installing rock in riprap, barbs, groins, and jetties, and in some streams placing concrete walls. Both the rock work and concrete walls have not been environmentally enhancing, so emphasis in recent years has gone towards use of large woody materials, that can be built with a habitat component. Various types of crib walls, spur dikes, and rootwad and boulder structures have been installed, with some degree of success. In recent years emphasis has been placed on re-direction of flow using log vanes, or use of extensive wood structures like Engineering Log Jams. The Engineering Log Jam structures have had a mixed success, because many have been installed with limited if any toe protection, and or placed on river bends with Rc/Wbkf ratios of less than 2.5.

Over the years researchers figured out causes of failure but solutions that are environmentally friendly to deal with the causes, might not accepted by regulatory agencies. For example for very high banks with bank heights above critical bank height, and for banks with Rc/Wbkf of less than 2.5, the correct solution is to build a bankfull bench along a new channel alignment, with a bank protection of log vanes or J's. Regulatory agencies tend to reject these geometry reconstruction solutions because they are outside of their area of fluvial geomorphology understanding and expertise. In addition regulatory agencies oversimplify the solutions, by restricting the excavation of toe protection whether it be rock or wood. They due this because of questionable assumptions of the effects of sediment from toe excavation on endangered species perceived to be impacted by the sediment. The failure of structures being installed without toe protection causes tremendous amounts of sediment in rivers that far exceeds the sediment that would have gone into the river if proper toe protection is provided.

REFERENCES

Abbe, T., and Montgomery, D. 1996. :Large woody debris jams, channel hydraulics, and habitat formation in large rivers. Regulated Rivers Research and Management 12 pages, 201-212.

Abbe, T., Montgomery, D., and Petroff, C. 1997. Design of stable in-channel wood debris structures for bank protection and habitat restoration. In
S.Y. Wang, . Langendoen and F. D. Shields Jrs. (eds). Management of Landscapes Disturbed by Channel Incision, Stabilization, Rehabilitation, and Restoration, Center for Computational Hydroscience and Engineering, University of Mississippi, 809-815.

Bagnold, R. 1960. Some aspectcs of the shape of river meanders. USGS Professional Paper 282-A.

Benda, L. and Dunne, L. 1997a. Stochastic forcing of sediment supply to the channel network from landsliding and debris flows. Water Resources research 33: 2849-2836.

Benda, L. and Dunne, L. 1997b, Stochastic forcing of sediment storage routing and storage. Water Resources Research 33: 1865-2880.

California Department of Public Works (CDPW). 1960. Bank and Shore Protection in California Highway Practice. Sacramento, California. 423p.

Connecticut Department of Environmental Protection. 2003. Large woody debris fact sheet. Connecticut Department of Environmental Protection, 6p.

Edminster, F. , Alkinson, W., and McIntyre, A. 1949. Streambank erosion control on the Winooski River, Vermont. Report No. 837, USDA, Soil Conservation Service, Washington D.C.

Flosi, G. and Reynolds, F. 1994. California Salmonid Stream Habitat Restoration Manual, second edition. California Department of Fish and Game. Sacramento, CA. 271p.

Hagerty, D. 1991. Piping/sapping erosion. basic considerations, Proceedings of the American Society of Civil Engineers, Journal of Hydraulics Engineering, 117: 991-1008.

Hooke, J. 1979. An Analysis of the processes of riverbank erosion. Journal of Hydrology, 42: 39-62.

Karlstrom, T.N.V. 1964. Quaternary geology of the Kenai River lowland and glacial history of the Cook Inlet Regions. USGS Professional Paper 443.

Knighton, D. 1995. Fluvial Processes and Forms. Edward Arnold, New York 218p.

Natural Resources Conservation Service. 2007. Part 654, Stream Restoration Design Handbook, Technical Supplement 14J. The Use of Large Woody Materials for Habitat and Bank Protection. TS14J1 – TS14J13. Washington D.C.

Ray, D. 2003. Means Creek below Aspalaga Landing, south of I-10. EcoSummary. Florida Department of Environmental Protection. Tallahassee, FL. 3pp.

Reckendorf, F. 2010. East Fork Lewis River, Including West Daybreak Park Project Reach, Fluvial Geomorphology and Erosion and Sediment Evaluation. Reckendorf and Associates, Salem, OR 42p.

Reckendorf, Frank. 2009a. Causes of streambank erosion. Key Concepts in in Geomorphology Vignette Workshop Portland State University, October, 17, 2009. In Press.

Reckendorf, Frank. 2009b. Causes of streambank erosion. Abstract 159236, Geological Society of America Annual Meeting, From Volcanoes to Vinards, Living with Dynamic Landscapes. October 18 -21, 2009. Portland, OR.

Reckendorf, Frank. 2008a. Pack River Delta, Erosion and Sedimentation. Lake Pend Oreille, Bonner County, Idaho. Report Prepared for Ducks Unlimited. Reckendorf and Associates 78p.

Reckendorf, F. 2008b. Bar Scalping of Donaldson, Barker, Dill, Gomes, and Waldron Gravel Bars in Tillamook County, Report prepared for Coast Wide Readymix, Tillamook, OR. Reckendorf and Associates, Salem, OR 77p.

Reckendorf, F. 2006. Environmentally sensitive gravel bar scalpking. Federal Interagency Sedimentation Conference, April 2-6, 2006. Session 4B-3. CD pdf.

Reckendorf, F. and Steffan, L. 2006. Regional application of stream classification systems in planning and design of stream stabilization projects. ASCE, World Environmental and Water Resources Congress, Omaha, NB. pdf.

Reckendorf, F. and Tice, B. 2003. Basin wide stream degradation limits spawning and rearing habitat for salmonids. GSA Conference Horizons, Seattle 2003. Abstract 8-16, p25.

Reckendorf, F. and Tice, B.. 2001. Rapid assessment procedure for aquatic habitat, riparian and streambank (RAPFAHRS), Proceedings of the Seventh Federal Interagency Sedimentation conference, March 25-29, 2001, Reno Nevada. 7p.

Reckendorf, F. 1996. Stream system evaluations with interpretations for habitat rehabilitation, restoration, and land use planning. Conference Dinner Presentation, Sixth Federal Interagency Sedimentation conference, Sahara Hotel, Las Vegas, Nevada, March 12, 1996. Reckendorf and Associates, Salem OR. 23p.

Reckendorf, F. and Saele, L. 1991. Kenai River, Bank Inventory Report. USDA, Soil Conservation Service. West Technical Service, July,1991. 92p.

Reckendorf, F. 1989. Kenai River Streambank Erosion Special Report. USDA, Soil Conservation Service, West National Technical Center, Portland, Oregon, December 1989. 55p.

Rosgen, D. 2006a. Cross-Vane, W-weir, and J-hook. Description, design and application of stream stabilization and river restoration. Wildland Hydrology, Fort Collins, CO. pdf.

Rosgen, D. 2006b. Watershed Assessment of River Stability and Sediment Supply (WARSSS). Wildland Hydrology, Lakewood, CO. 533p.

Rosgen, D. 1996. Applied River Morphology. Wildland Hydrology, Pagosa Springs, Colorado. 386p.

Rosgen, D. 1993. Applied Fluvial Geomorphology, training manual. River Short Course. Wildland Hydrology. Pagosa Springs, CO 450p.

Rosgen, D. 1989. Short Course on River Restoration, Principles and Applications, Sacramento, CA, January 10-11, 1989. Wildland Hydrology, Fort Collins, CO. 138p.

Saldi-Carolmile, K. Bates, K., Skidmore, P,., Barenti, J., and Pineo, D. 2004. Stream Handbook Restoration Guidelines. Prepared for Washington State Aquatic Habitat Guidelines Program. Olympia, WA.

Schumm, S. Harvey, M. , and Watson, C. 1984. Incised Channel, Morphology, Dynamics, and Control. Water Resources Publications, Littleton, CO. 199p.

Simon, A. 1989. A model of channel response in distributed alluvial channels. Earth Processes and Landforms 14(1)11-26.

Southerland, B. and Reckendorf, F. 2008. Performance of ELJ,s in Washington State-post project appraisal. River Restoration Northwest Symposium, February 4-7, 2008, Skamania, WA pdf.

Thorne, C., Hey, R., Newson, M. 1997. Applied Fluvial Geomorphology in River Engineering and Management. John Wiley and Sons, New York. 376p.

Trimble, S. and Lund, S. 1982. Soil Conservation and Reduction of Erosion and Sedimentation in the Coon Creek, Basin. Wisconsin. USGS Professional Paper 1234.

Welch, S. and Wright, S. 2005. Design of Stream Barbs. USDA Natural Resources Conservation Service, Technical Note 23. 23p.

Wollman, G.. 1959. Factors influencing erosion of a cohesive river bank. American Journal of Science, 257: 204-216.

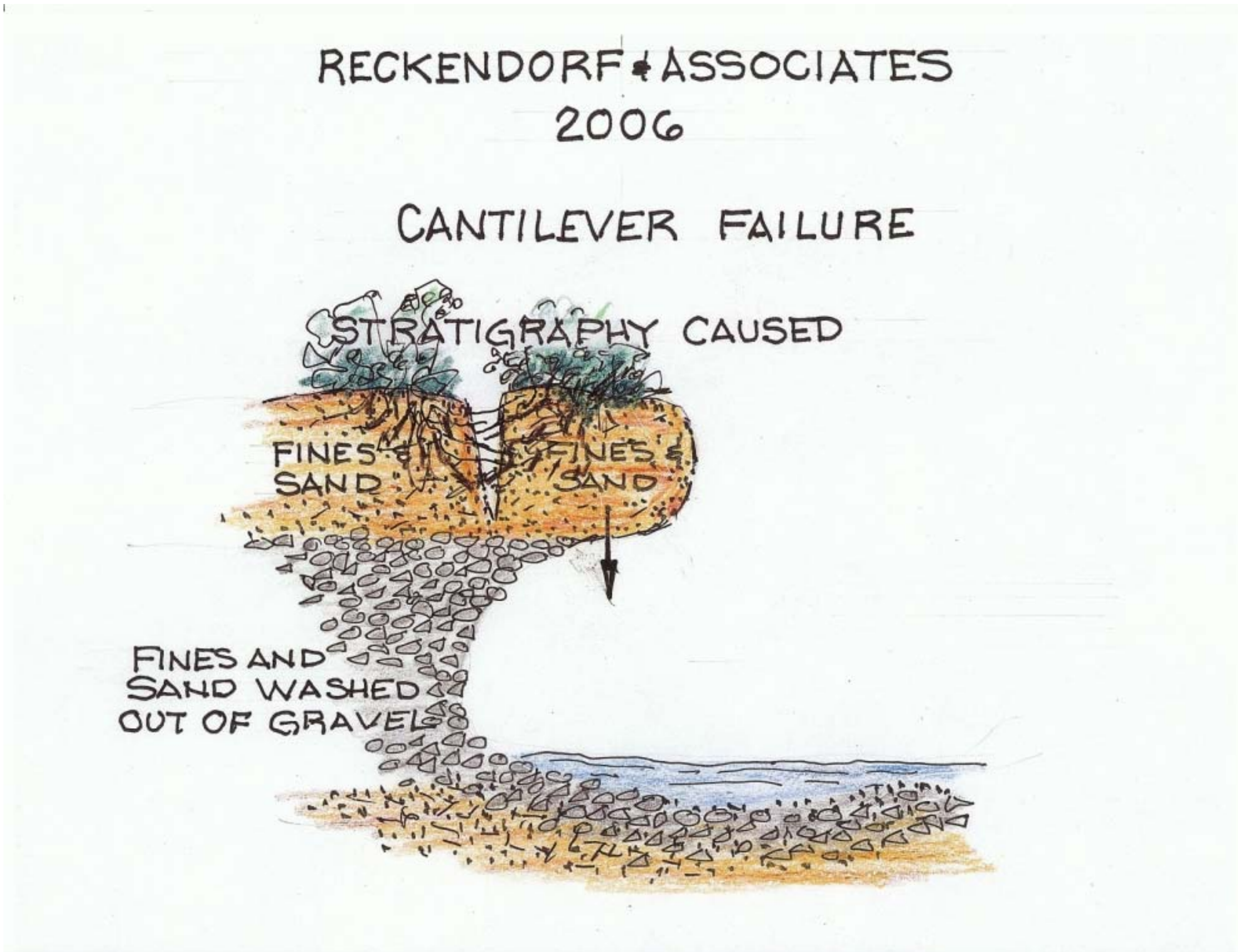

Figure 1. Stratigraphy caused failure because sands and fines are washed out of gravel matrix, which causes gravel to sluff, and creating a cantilever that Falls.


Figure 2. Upper slope cantilever of streambank along Molalla River, Clackamas, Co. OR. Small gravel, sands and fines are washed out of gravel matrix at bankfull flows causing gravel to sluff, and settle at the angle of repose of the slope.

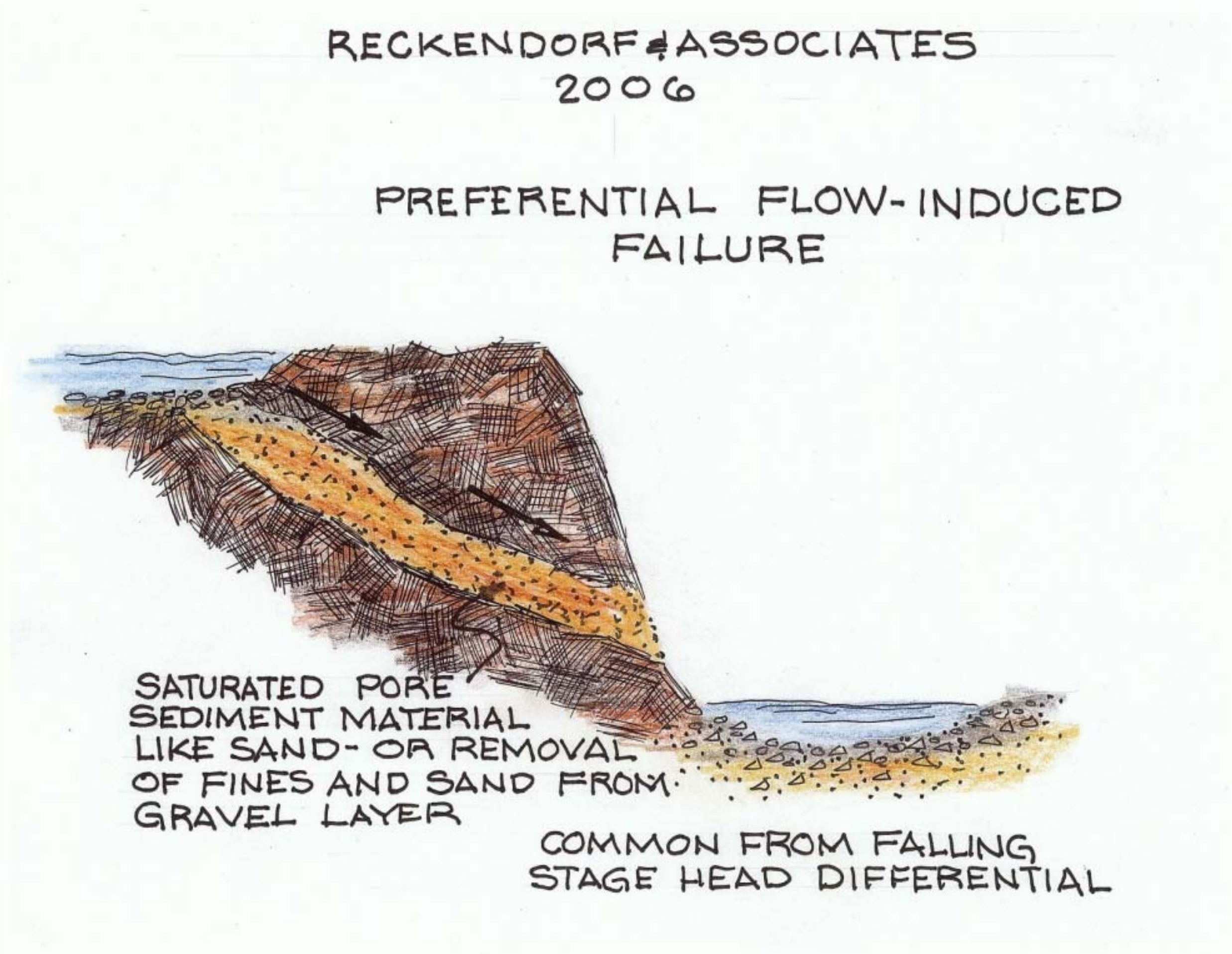

Figure 3. Preferential flow induced failure is created by side hill or overbank flow creating an elevation head differential such that there is an increase in the materials pore pressure. For flood plains this is often associated with bank failure during the falling stage of floods creating liquefaction of sands and washing sands and fines out of gravel to create cantilever conditions. Landslides can create sag pond on the landscape that fill with water, which seeps downslope along some preferential strata. This can cause increased pore pressure of material that contributes to decreased material strength and rotational and plainer failure. Flow velocity from preferential flow failure can be so high as to cause piping of the lower bank where the seepage water daylights creating a void area in which the overlying material collapses into the void.