Title

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DESIGN AND CONSTRUCTION OF AQUATIC ORGANISM PASSAGE AT ROAD-STREAM CROSSINGS

SITE ASSESSMENT AND GEOMORPHIC CONSIDERATIONS IN STREAM SIMULATION CULVERT DESIGN

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Abstract: Jackson (2003, current volume) describes the types of damage to aquatic populations and metapopulations caused by barriers to aquatic species movement along stream corridors. Road-stream crossing culverts designed in the traditional way---sized for some rare flood flow---also have predictable detrimental effects on stream channels themselves. These occur not only during floods, when culverts may plug or be overtopped, but also over time if the culvert impedes downstream movement of woody debris and sediment.

This paper describes common stream responses to culverts, such as chronic aggradation and degradation; long-term changes in stream stability due to interruption of woody debris transport; and sedimentation sustained when culverts plug and fail, etc. It also describes the range of approaches to crossing design, from a culvert sized only to pass a certain flood to valley-spanning bridges and viaducts. Stream simulation is placed in the context of other design approaches that provide more or less biological and geomorphic connectivity. Biological and geomorphic priorities and risks must be weighed against site constraints and costs to select the appropriate level of continuity for each site.

Site assessment procedures for stream simulation design are then described. These include surveying and describing the longitudinal profile and valley cross-sections, bed material assessment, and reference reach selection. Channel stability interpretations needed for design are also discussed.

Introduction

Streams are transport corridors for water, sediment, debris, and nutrients moving downstream and laterally across the floodplain, as well as for fish and other animals moving upstream. When a rigid culvert is placed in a highly dynamic stream environment, perhaps the greatest challenge involves ensuring passage continuity over time, as the stream adjusts to variable flows and other environmental changes. Observing the effects of large storms on mountain roads over the past several decades, it has become clear that traditional methods of culvert design, which size culverts to convey only floodwaters, have resulted in substantial damage to channels, roads, and aquatic and riparian habitats (Furniss et al. 1998). Such culverts typically are much smaller than the stream channel itself, and even in the absence of large floods the backwatering and scour they cause is often detrimental to aquatic habitat and to channel stability. During large floods they frequently plug with debris and may overtop the road or flow down the road ditch, adding tremendous quantities of sediment and debris to downstream reaches. A portion of the cost of this damage can be seen in ERFO (Emergency Relief Federally Owned) flood damage reports, although those reports usually do not consider the costs to aquatic species nor their habitats.

Stream simulation is a culvert design method in which the diversity and complexity of the natural streambed are created inside a culvert in such a way that the streambed maintains itself across a broad range of flows. The premise is that if streambed morphology is similar to that in the natural channel, water velocities and depths will also be similar, and the crossing should be invisible to aquatic species. The design process begins by gaining a thorough understanding of the form and process of the stream to be crossed: its hydrology, stability, adjustment potential, and history. Careful scrutiny of channel history and current form permit an understanding of the processes that maintain the channel, and of the potential changes that must be accommodated or compensated for to ensure long-term structural integrity and passage success.

Dynamic Streams -- Rigid Culverts

Except for streams that flow over non-erodible materials like bedrock or colluvium, channels are “self-formed.” Wherever bed and banks are erodible, a stream adjusts its width, depth and slope to transport just the amount of water and sediment supplied by the watershed. Over the decade-to-century time scales road managers are interested in, what we normally think of as “stable” streams are actually in *quasi equilibrium* (Leopold and Maddock 1953). This refers to the fact that, although streams adjust as water and sediment inputs fluctuate, channels tend to maintain approximate equilibrium dimensions. Most crossing structures alter flow dimensions and slope, thereby changing water velocity and sediment transport capacity. Channel segments up- and down-stream often respond dramatically, with sediment depositing above and the channel bed eroding below. This can result in large elevation differences between the culvert inlet and outlet, and it can create a passage barrier at each end of the crossing. In sensitive (flat and/or erodible) channels, crossings can generate such disequilibrium that these adjustments can sometimes propagate long distances up and downstream.

Fig. 1. Channel degradation downstream (left) and fig. 2 aggradation upstream (right) of a road crossing a wide floodplain on the Superior National Forest, Minnesota.

Crossing structures also lock the stream in place in meandering streams that naturally move across the floodplain over time. As the stream continues to shift laterally, it enters the inlet at a greater and greater angle enhancing the tendency for sediment deposition and debris plugging.

During floods, narrow or poorly aligned crossings interrupt the flow of water, sediment and debris. Especially if a culvert plugs, the roadfill may fail, sometimes causing substantial damage to aquatic habitat. Cascading roadfill failures turning into debris torrents have been observed in the Pacific Northwest (Furniss et al. 1998). A plugged culvert can cause a stream to be diverted down the road ditch, and even more damage may occur as it spills over a hillside or increases flood flow in the adjoining drainage.

Fig. 3. Woody debris plugging culvert inlet.

In valleys with wide floodplains, floodwater, sediment and debris may all flow down the floodplain, too, and roadfills built up to cross the stream effectively dam the overbank flows. The channel and floodplain downstream of such a road receive less sediment and debris, and water and energy are distributed differently. The section downstream may be less able to create and maintain diverse habitats in channel and floodplain.

Progressively or catastrophically, these geomorphic effects not only put the road at risk; they also create passage barriers and damage to aquatic habitat.

What geomorphic principles can be used to fit a rigid structure into a dynamic stream/valley system? The key is to permit water, sediment and debris transport through the crossing by maintaining natural channel dimensions and slope through the structure, and considering flow through the entire riparian area.

- Locate crossings to avoid unstable landforms and those where river channel change is expected, such as wide flat valley floors.
- Maintain channel dimensions and slope through the crossing structure in order to maintain sediment and debris transport capacity during frequent high flows. Otherwise, channel adjustments will occur that can (1) require maintenance or replacement, and/or (2) cause severe damage to stream and/or floodplain habitats.

- The adjacent valley floor must be considered in design of both the crossing structure and its approaches. Overbank and down-valley flows of water, sediment and debris over the floodplain need to be maintained to allow the valley to continue to (1) form diverse habitats and (2) regulate water quantity and quality in channel.
- Design all crossings for failure, acknowledging the possibility that any design peak flow may be exceeded and that road washouts can add significant quantities of sediment to the aquatic system. All crossings should be designed either to sustain overtopping flows or to fail in a predictable way that minimizes channel damage.

There may be conflicts between accommodating fluvial processes through the crossing vs. traffic on the road. The necessary compromises should be made with a clear understanding of risks to both systems, and the cost/benefit trade-offs, including effects on aquatic habitats and populations.

Setting Specific Objectives for Crossing Replacements

Design objectives for a site control what structure type and design approach are selected. They involve biological, geomorphic, traffic access, and financial considerations. Establishing them requires balancing the costs, benefits and risks in all those areas. It is truly an interdisciplinary exercise.

There is a continuum of design approaches to achieving biological and geomorphic continuity at stream crossings, depending on the degree of continuity the interdisciplinary team desires at a site (figure 4).

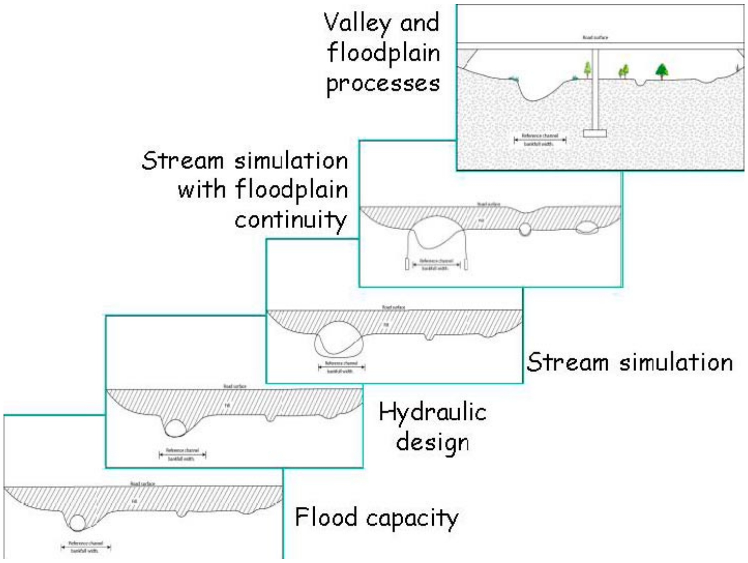

Fig. 4. Various road-stream crossing design approaches.

In valleys with very active floodplains, and especially where the valley flat may be a migration corridor for large mammals or where the full range of riparian habitat diversity must be maintained to provide critical habitat, a bridge and/or viaduct that spans the entire meander belt (or more) may be selected. On very low volume roads where traffic interruptions are acceptable, there may be other less expensive ways to maintain a high level of valley and channel connectivity, such as by the use of fords and dips.

A lesser degree of floodplain connectivity can be maintained using a stream simulation culvert or bridge with floodplain culverts or dips. In this case, floodplain pipes are placed to connect side channels, overflow channels, or swales, among other locations. This is particularly important when floodplains are wide and convey large amounts of water and debris, and/or where floodplain habitats are critical to some species or lifestages. Channel transport of debris and sediment is assured with this approach, and the streambed inside the culvert is less at risk from large flood flows than if all the flow detained by the roadfill were forced through the main channel pipe. Even so, the main pipe will probably be designed wider than bankfull width, and banks might be constructed inside. This would not only offset the higher erosive forces expected as more water is concentrated through that opening, but would also permit passage of animals preferring dry riparian passage. Side channel culverts should also be designed as stream simulation structures where aquatic species use them for refuge, rearing, etc.

Stream simulation culverts are used where passage is desired for all aquatic organisms present in the channel. These culverts have streambeds of at least bankfull width with bed longitudinal profiles and structure similar to the natural channel. Flow hydraulics at least up to bankfull must be similar to the natural channel in order to freely transport sediment and debris, and to maintain a streambed structure that offers a similar diversity of water velocities, depths, cover and bed material. The degree of match in gradient, streambed material size, distribution, and structure between channel and culvert depends again on river and site conditions. For example where an aggraded area upstream (caused by the previous structure) is desired as valuable wetland habitat and the downstream reach has downcut, a large elevation drop may need to be maintained across the structure. While some grade control work could be done on the downstream section to bring it up to original grade, the structure will still be steeper than the natural channel. In such a case, a tradeoff may be made by, for example, increasing the bed material size inside the pipe to sustain the higher shear stresses of a steeper gradient. In a different situation, such as where a narrow floodplain is present, it may be wise to expand culvert width beyond bankfull and/or slightly increase particle sizes to avoid the potential for concentrated overbank flows to erode the bed material inside the pipe.

The least inclusive approach to aquatic organism passage is hydraulic design. The objective here is passage of a target fish. Hydraulic design aims to hold velocities over a specified flow range below those believed negotiable by most individuals of a target species and lifestage. The goal is achieved by balancing culvert width, slope and roughness to produce no more than the specified velocity. It can be done with baffles and weirs, by "oversizing" the culvert (compared to those designed to pass water only), or by embedding the culvert and adding oversized roughness elements (usually rocks) to the streambed. For fish with 'known' swimming capabilities, hydraulic design may result in culverts that can pass many individuals, but weaker individuals may not pass. Weaker-swimming species or crawling species that may provide 'ecosystem services' needed to sustain the target fish over the long term may not be able to pass either.

Except for some hydraulic designs like baffled culverts, all these approaches provide larger structures that pose less of a risk to the road itself (from plugging or capacity exceedance) than culverts designed in the traditional way for flood capacity. In many environments, these structures probably have lower maintenance requirements for the same reason.

Understanding the Watershed Context

Watershed-Scale Considerations and How They Influence Structure Type Selection and Design

Culverts are non-adjustable structures in the most dynamic part of the landscape—the stream. Designers must anticipate future channel changes and design for them; if not, they risk losing the structure or its ability to pass aquatic organisms, or both. Predicting channel change requires assessment at both the watershed and project site scales. Watershed-scale assessments should occur first, to set the context for project-scale assessment.

The large-scale assessment should answer key questions about watershed and channel history, stability and sensitivity:

- Is the channel highly responsive to climatic events or watershed changes? Both may alter runoff amount and distribution and/or sediment load.
- What events and processes led to the current channel form? Is the channel "stable" or is it still responding to past events?
- What channel changes are possible during the service life of the structure? What changes are likely during the design event? Larger events?

Is the Channel Responsive?

It is useful to classify stream segments based on their sensitivity to climatic events or watershed changes. The following classes were developed by Montgomery and Buffington (1993). In mountainous areas of the Pacific Northwest, channel classes at this general level usually correspond to watershed location.

> *Source reaches* are colluvial channels at the tips of drainage networks, where sediment from the hillslopes is stored until scour occurs during large flow events or debris flows. Such channels are unresponsive until a threshold for erosion of the accumulated material is reached. These areas of the watershed are introduced here only because it is important to recognize the potentially massive effects on downstream channels when infrequent transport events—such as debris avalanches—do occur.

[Note: Strictly speaking, the term *colluvium* means materials transported to the valley floor by gravity (AGI 1962). In this article, we use it to include large rock transported to its current position by processes other than fluvial transport by the current river (e.g., debris flows, landslides, glaciofluvial transport). As used here, colluvial particles in the streambed are those that are too large for the current river to move, and that therefore act as key structural elements in a streambed.]

Transport reaches are higher gradient streams, typically with step-pool or cascade type morphology. They have persistent bed and bank structures dominated by large rock or embedded wood, and therefore tend to resist erosion. These streams are usually steep enough to transmit all the sediment supplied by the watershed to lower gradient reaches without large changes in channel size, shape or slope. They are usually (but not always) the smaller tributary streams located in the upper parts of watersheds. Floodplains are usually narrow if they exist.

Response reaches are generally found lower in the drainage network. They are lower gradient reaches with pool-riffle, plane bed or regime type morphology, and often have associated floodplains. Sediment transport capacity is low relative to supply, so when watershed or climatic changes alter sediment supply or flow regime, they often respond by making large adjustments in size, shape, slope or pattern. Because of this sensitivity, understanding off-site conditions that may affect response channels is critical for stream simulation design.

What Geologic Hazards are Present?

Each site should be evaluated for its proximity to currently or potentially unstable landforms. Look for features like

- slope stability problems such as mass wasting, debris flows, or earthflows
- inherently unstable landforms such as alluvial fans, deltas, tidal flats
- downcut channel downstream, migrating headcut
- glaciers, avalanche tracks

In general, sites like these are unsuitable for any type of culvert because of risks of plugging, channel relocation, or downcutting. For example, channels on active alluvial fans frequently change location as sediment accumulates on the fan. If an unstable site cannot be avoided, the preferable crossing structure might be a bridge rather than a culvert, to accommodate the foreseeable changes as much as possible.

Even where no “geologic hazard” is present, it is important to recognize channels that transport large volumes of woody debris and/or bed material load since this might determine whether a culvert or bridge is more practical at a site. Locations prone to deposition are especially critical to recognize, since both debris and bedload deposition can affect structure capacity and even change the local streambed slope through the crossing.

Watershed History/ Event Chronology

Knowing the history of significant episodic events (such as mass wasting, floods, dredging), as well as chronic influences--such as bankfull flows, upstream logging, road construction and mining, sedimentation, drought, and so on--contributes valuable insights about current conditions and the direction of potential future changes in the stream. Understanding how these events have altered stream plan-form and base level in the past will assist in determining structure type, site layout and structural responses to anticipated channel adjustments.

For example, in Therriault Cr in Montana, anecdotal and field evidence was used to unravel a classic story of channel degradation and plan an appropriate solution (Watershed Consulting LLC 2002). A highly sinuous, relatively stable stream channel that meandered across a wide alluvial flat had been straightened in the 1940s to increase hay production. Severe channel downcutting resulted. The headcut progressed upstream, but was stopped by a culvert, which protected the upstream channel from degradation, but prevented fish passage at the culvert. Understanding the channel degradation as a human-caused disturbance that would damage upstream reaches if allowed to progress led to a decision to maintain the elevation control at the culvert. To solve the fish passage problem, a floodplain side channel with a separate culvert was built.

Is the Channel Stable?

Taken together, these watershed-scale investigations will go a long way toward building an understanding of how much the channel may change over the life of the structure, and how sensitive the channel will be to flow changes caused by the structure. Once past responses to watershed changes are understood, responses to potential future climatic or land use changes can be predicted.

It is particularly important to identify system-wide instability, such as the downcutting described on Therriault Cr, since the design will have to account for predicted changes in the channel to achieve the goal of long-term structure stability. If a headcut is migrating upstream toward the culvert, for example, grade control structures may need to be installed downstream to avoid developing a perch and losing streambed continuity in the pipe. Distinguishing large-scale channel change from the noise of 'natural' variability in channel width, depth and slope can be difficult because variability can be large even in channels in quasi-equilibrium. This is usually accomplished using a series of historical aerial photos and any other historical accounts of the stream and watershed. System-wide instability usually can be seen on aerial photos as noticeable changes in channel width, rapid growth and movement of depositional bars, alluvial fans at tributary mouths, and so on (Grant 1988). These signals are frequently associated with observable land use changes such as mining, agriculture, subdivision and road development, or forest harvest.

Assessing the Project Stream Reach: Is Stream Simulation Appropriate?

In addition to ecological connectivity objectives, channel stability is the most important factor determining whether a stream simulation culvert is a wise choice for a site. In most cases, the same considerations apply to siting any culvert, although the larger pipes used in stream simulation may reduce the failure risks associated with smaller culverts. Some of the most common inherently unstable channel types and landforms that are best avoided are listed below.

> *Active alluvial fans* are usually located where a confined channel emerges into a wider valley, spreads out, and deposits sediment. During high debris-laden flows so much sediment may be deposited that the major channel is blocked, and flow jumps to a new location and carves a new channel. Several channels may be active at once. Crossing structures placed on fans can be isolated when the channel changes location. They can also increase the likelihood of channel shift if they frequently plug.
>
> *Very steep channels prone to debris-torrents* are another example of a landform where large sediment and debris transport events can be expected to cause significant channel changes. Even stable channel reaches, if they are immediately downstream of a slope prone to mass wasting or severe bank erosion, can be expected to undergo flow events where sediment loads are high enough to cause plugging and overtopping failure. In steep terrain, where there are many crossings on a single channel, the domino effect of a single crossing failure can cascade downstream and may actually cause a debris flow.
>
> *Braided stream valleys* where high flows can simultaneously occupy several channels are another example. These streams often have little deep-rooted, stabilizing vegetation, so streambanks erode and permit channels to shift location frequently. Crossings are frequently constructed only on the major channel with upstream levees acting as funnels to route water under the road. Downstream effects of this kind of flow concentration can include severe channel downcutting (degradation).
>
> *Unconfined meandering streams on wide floodplains* migrate across the floodplain, as banks on the outsides of meander bends erode while deposition occurs on bars on the insides of bends. Such streams are still considered stable so long as they maintain equilibrium channel dimensions and slope. Nonetheless, land development and management frequently accelerate this natural process of channel migration, and one should bear this in mind before investing in a crossing structure. A shifting channel can move such that it no longer approaches the crossing perpendicularly, and an oblique angle of approach tends to increase sediment deposition above the inlet by forcing the water to turn. Likewise it increases the potential for debris blockage and therefore overtopping failure. An additional effect of crossings on such channels is that their approaches often are built up to cross seasonally wet or inundated floodplains. Damming the floodplain obstructs the erosional and depositional processes that construct floodplains and their diverse habitats. It may obstruct side channels that are essential habitats for fish. Forcing the overbank flows to concentrate in the constricted crossing also causes bed and bank scour around the crossing.

Channels that are actively changing---aggrading, degrading, widening, etc.---whether the reason is management-related or natural, may be difficult or impossible to simulate in a culvert with any long-term success. Channels can go through a series of complex responses to environmental change, and the rate and magnitude of adjustment may not be predictable (Schumm 1977). Such channels should be spanned if they cannot be avoided, not only to preserve the crossing structure, but also to allow the channel to freely adjust toward a new equilibrium form.

Some channel types are more easily simulated inside a culvert than others (Gubernick and Bates this volume). Since the streambed inside a pipe will not have the stabilizing effects of bank vegetation, channels that are highly dependent on vegetation for stability will require its function to be simulated by some other mechanism.

The same is true of streams where woody debris plays an important role in bed stability and sediment retention. This does not mean these channels cannot be simulated, but other materials, such as rock, must replace the stabilizing functions. On very steep streams, large bed structures are hard to maintain inside a confined pipe because of extremely high stream power during larger than bankfull flows. Bedforms in such streams may be mobilized and reconstructed naturally during rare floods (Wohl 2000). Hydraulic conditions during such high flows cannot be simulated inside a confined pipe because flow cannot widen with increasing depth. Where these conditions are critical, a bridge with adequate width may be a more suitable choice than a culvert. On very low traffic or seasonal use-only roads, some types of fords may function adequately for traffic, and create only minor obstructions to channel processes and aquatic species passage.

Site Assessment for Stream Simulation Design

A stream simulation culvert must fit into the reach both laterally and longitudinally. Ideally, the streambed inside the pipe should be able to retain sediment and adjust its elevation (sustain local aggradation and scour) in the same way as the upstream and downstream reache. It must also be able to convey flood flows, including overbank floodplain flows, or the floodplain itself must be connected through the road approaches by dips or additional pipes.

The site reach assessment has two basic objectives.

- Develop a thorough understanding of reach stability and adjustment potential during flows that mobilize the streambed.

  The assessment helps the practitioner estimate how much change is likely over the life of the structure, and how sensitive the channel will be to the structure's effects. It helps the design team decide whether additional channel structures are necessary to maintain grade control downstream of the structure, and how floodplain connectivity should be provided for.

- Develop a template for bed design inside the pipe, including longitudinal profile, bedforms and cross section.

  The assessment is the source of information needed to determine channel dimensions as well as the size, slope and arrangement of streambed material inside the pipe.

The streambed design template is taken from the reference reach, which is a reach similar to the crossing reach that is judged to be in quasi-equilibrium with prevailing flows and sediment loads. Generally the reference reach can be located upstream of the crossing, out of the existing crossing influence zone if any. If so, it is included in the longitudinal profile of the site reach. Where this is not possible, such as where land use changes dramatically upstream of the crossing, or where road-induced aggradation extends long distances above it, the reference reach might be a reach morphologically similar to the crossing site, but located at some distance up- or downstream. In unusual cases, the reference reach might be a similar channel in the near vicinity. Channel types (Rosgen 1996 level II size; Montgomery and Buffington 1993) can help in judging similarity, but they should be interpreted with great care, since even nearby watersheds may have different land use and flood histories (Juracek and Fitzpatrick 2003). All the extrinsic influences on channel morphology—including drainage area, geologic context, and land use/vegetation—should be similar for a reference reach.

The site and reference reach surveys include longitudinal profile and cross section surveys, and observations of bed material and bed structure. During the surveys, we "read" the stream for clues about the magnitude of channel-forming flows, frequency and type of sediment transport events, and other channel processes like woody debris transport, beaver influences, bank erosion, and streambed aggradation and degradation potential.

The Longitudinal Profile

For the longitudinal profile, the thalweg (a line connecting the deepest parts of the channel) is surveyed with a surveyors' level in enough detail to capture all slope breaks along the channel length. The profile is usually the single most valuable tool during the design process. It shows not only the average reach gradient and major slope breaks at the site, but also any aggradation and/or degradation around existing culverts. These conditions determine elevation change required through the crossing, which can affect selection of a reference reach. In cases where the elevation difference is large, it is sometimes necessary to set the culvert at a slope steeper than the adjoining segments. For a simulation design template, one would then look for a stable reach elsewhere with the desired slope, and similar geomorphic context and materials. If one can be found, it would be used as the template assuming there is no dramatic discontinuity with the adjoining reaches.

The profile may be uniform, but in less ideal situations, grade may change dramatically near the crossing. Traditional road layout for low-volume forest roads tends to follow landscape contours, and roads are often located on flat ground at the edge of a steep slope, or on a natural bench. These different situations result in four types of stream profiles through crossings, with different culvert-related risks and design implications:

> *Concave profile:* steep stream grade transitioning to milder grade downstream (e.g., edge of valley flat). Sediment deposition above the crossing is expected here. This may steepen the grade locally, creating an adverse inlet condition for fish passage. If the area is an active alluvial fan, large-scale deposition might occur and the culvert might be plugged. Alternatively if the new culvert excavation cuts into the bed of the steeper reach and there is no upstream grade control, a headcut can form, destabilizing the upstream reach.
>
> *Convex profile:* mild slope transitioning to steeper grade downstream. Many times this is associated with a bedrock control at the break to the steeper slope. This type of profile could also occur, however, at the edge of a terrace in unconsolidated and erodible materials. Depending on how close the crossing outlet is to the grade break, the disturbance created by excavation for an embedded stream simulation culvert could destabilize the channel materials at this sensitive location. It is wise in this situation to move the road back from the grade break if at all possible.
>
> *Concave- convex profile:* steep stream grade transitioning to mild grade, then back to steeper grade (e.g., alluvial/colluvial bench). This situation has the same upstream problems as the concave type, and the same downstream problems as the convex type.
>
> *Uniform profile:* uniform grades with no abrupt transitions through the crossing. This is the ideal crossing situation.

Gubernick and Bates (this volume) give examples of design treatments for concave and uniform situations.

Permanent or persistent controls on streambed elevations in the vicinity of the crossing must be identified, and the ends of the surveyed long profile should be tied into them. The range of possible design project profiles (slope through the crossing) will be constrained by these hard controls if they exist. In general, persistent grade controls, such as a boulder step or a large piece of embedded wood, are usually frequent in transport reaches, and the surveyed long profile can be relatively short. In response reaches, though, they may be hard to find or nonexistent. Channel grade and elevation may be controlled by relatively mobile small woody debris or simply by valley slope and stream sinuosity. In these cases, the profile should be quite long to get a good idea of how bed elevations may vary over the long term.

In many alluvial streams, bedforms such as pools, riffles, and steps tend to be spaced regularly (Montgomery and Buffington 1993). Their functions---energy dissipation (velocity control) and sediment retention---are essential to simulate, and the culvert streambed must fit into their spacing pattern and match their dimensions as closely as is feasible. The survey catches all longitudinal slope breaks, including smaller scale differences such as the top and bottom of wood or boulder steps or, for a pool, the head, deepest point and tail crest elevation (figure 5).

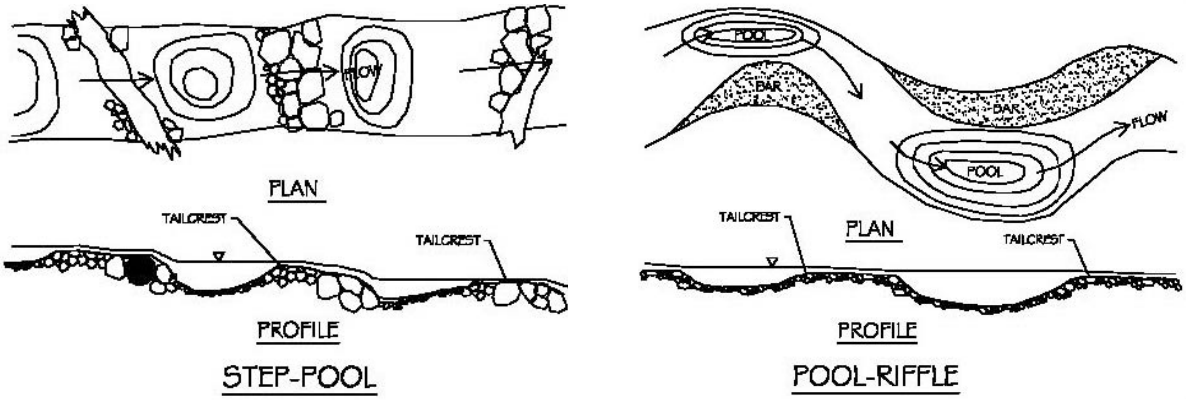

Fig. 5. Natural grade control structures and bedforms.

Streambed elevations adjust locally when grade-controlling bedforms or structures (e.g., embedded woody debris, boulder steps, etc.) shift or are washed away. The culvert streambed must be able to scour to depths similar to those in the adjoining reaches to maintain similar bed structure and water velocities. In a reach with a uniform profile, a line connecting the lowest bed elevations ---generally the bottoms of pools---represents the adjustment potential line (figure 6): the minimum elevation to which the streambed would adjust if local grade-controls move. Embedding the culvert invert below this line allows the bed material inside the structure to adjust within the range of expected changes in bed elevation. This is especially important in low-gradient response channels, which adjust their slopes more frequently than steeper channels normally do. To confidently identify the adjustment potential line, it is critical to survey pool bottom elevations, even if they are deeper than it is possible to stand.

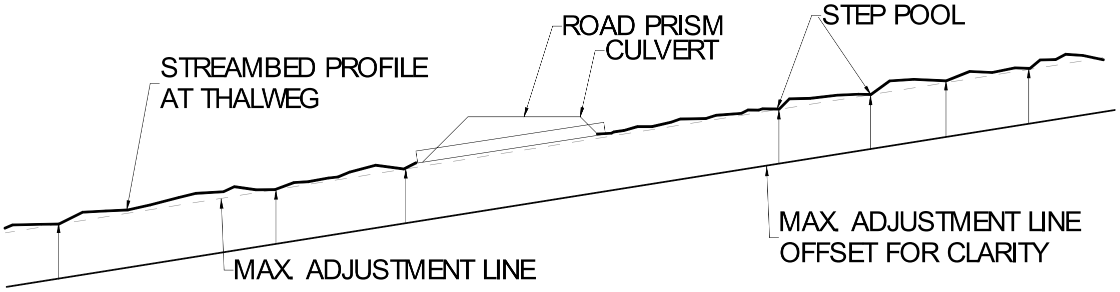

Fig. 6. Longitudinal profile and maximum adjustment line.

The designer must understand bedform stability, organization, and composition in the local channel. As the longitudinal profile is surveyed, the rod-holder makes notes on the types of bed structures and their apparent stability, as well as other significant features affecting channel stability, grade and sediment retention. As noted above, some bed structures are transitory, such as pools controlled by small decaying wood, beaver dams or steps composed of gravel. Others, like step-pools controlled by boulders or pieces of large embedded wood, can be quite stable and persistent for long periods of time (Zimmerman and Church 2001; Swanson and Lienkaemper 1978).

Stability of these bedform structures can be judged by considering the following factors:

1) Material strength
    a. Rock durability
    b. Substrate angularity
    c. Diameter and condition of wood (sound or decayed)
2) Orientation and size of particles and pieces
    a. Does the wood have roots attached? Is it embedded in bed and/or banks?
    b. Length of the wood in relation to stream width (longer is usually less mobile)
    c. How is the step formed? What are the key pieces: boulder, cobble, gravel? A combination of wood and rock? How large are they? Do the logs span the channel? Can the stream cut around the end of the log?
    d. Are particles imbricated and what is the degree of embeddedness? Are they loose on the surface and readily available for transport?
3) Relationship to other bedform structures
    a. If one structure is lost, will it undermine the next structure?
    b. Are there key structures in the reach that govern the extent of vertical and lateral adjustment?

In the Pacific Northwest, it has been helpful to identify the reference reach and project site channel type in terms of the classification offered by Montgomery and Buffington (1993). At the channel reach level, their classification of alluvial channels is directly descriptive of the bed profile and structure (cascade, step-pool, pool-riffle, plane bed, regime, and braided). These channel types are associated with qualitatively distinct frequencies of bed material mobilization, a characteristic that is essential to understand in designing a stream simulation streambed. Channel type should be identified in the site assessment notes.

Any component of an alluvial channel that is not transportable by the current river (colluvial or glaciofluvial rocks, stable embedded wood, log jams, bedrock outcrops) forces flow around or over it, and may control channel shape, stability, and local grade. Forcing features often create backwater and add roughness, so that sediment sizes in a “forced” reach may include much smaller particles than would be expected if only the overall average slope of the channel were considered. This has tremendous implications for stream simulation design, and the surveyors should note each forcing feature as it is passed, as well as its effects on sediment storage, and channel width and slope.

Roughness is an aggregate term for those channel features that create drag on the flow, slowing its velocity and increasing turbulence. It is the single most hard-to-quantify component of a flow velocity model, which the designer may use to verify culvert flow capacity. The site assessor can best assist the designer by observing in detail and photographing the components of roughness that exist in the channel. These include some already mentioned, such as forcing features, bedforms, and bedrock outcrops. Other features are overhanging bank vegetation and exposed roots, bank irregularity (undercuts, alcoves), woody debris of all sizes, and channel bends. Bed material particle size distribution is also essential information for roughness estimations.

Bed Material

The design process uses reference reach particle size distributions to specify in-pipe bed material composition. The information is usually collected by means of a standard 100-particle Wolman pebble count that samples all portions of the reference reach (pools, riffles, both key pieces and sediment stored behind steps). For step-pool channels, Bunte and Abt (2001) recommend systematically sampling at regular intervals to avoid observer bias. Where bed material size distribution is distinctly different between large-scale channel segments---say, between long riffles and pools---separate pebble counts should be done to characterize each phase. This gives the designer all the information needed to design a riffle or (less frequently) a pool section inside the pipe. In gravel bed streams, visually note whether the surface of the streambed is armored. Observations of particle hardness, color, angularity, imbrication and embedding can all help in assessing bed mobility.

Channel Cross Section Profiles

Cross sections are surveyed at intervals along the longitudinal profile and, with the profile, they provide a three-dimensional picture of the reach, including how the channel cross section changes with gradient. The number of cross sections surveyed should correspond to the complexity and risk of the site. At complex sites where the cross sections and local slopes vary greatly, or where the risk of structure failure is high, more cross sections are needed than in uniform reaches. Reference reach cross sections provide the template for the stream simulation cross sectional topography, and project site cross sections show how the pipe will relate to adjoining reaches in the cross-valley dimension.

At the reach scale, Rosgen channel types are useful in describing the relationship of the channel to adjacent hill slopes or valley flats. The entrenchment ratio is a key parameter distinguishing channel types. It is defined as the ratio of *floodprone* width (width at an elevation above the streambed of twice maximum bankfull depth) to the bankfull width, describing the degree of flow confinement (or spreading) at fairly high flows (Rosgen 1996). Streams with high entrenchment ratios---Rosgen types C, E, and F---have relatively wide floodplains, and require special design consideration to avoid concentrating overbank floodplain flows through the stream simulation pipe. Rosgen types A, B and G are in this respect easier to simulate.

The relative volume of water that is conveyed down the floodplain at high flows depends on both entrenchment ratio and the resistance to flow offered by riparian vegetation or other roughness elements on the floodplain. Again, this is important because it affects the degree to which the culvert and roadfill may block floodplain flows and concentrate flow through the crossing structure. For this reason, floodplain vegetation and other obstacles to flow should be observed as cross sections are surveyed at several points along the longitudinal profile (both reference reach and project site, if they are different). Cross sections should be long enough to show floodplain features and elevations at least out to the limit of the floodprone width. Where side channels or floodplain swales are present, these features should also be included in the survey. Side channels may require stream simulation culverts of their own in many cases.

Points to survey and document in the survey notes include:

- Top and bottom of banks
- Gravel bars
- Pool bottom
- Undercut banks
- Bankfull elevations
- High water marks
- All grade breaks along the cross section profile
- Changes in materials
- Floodplain features, vegetation type boundaries

Descriptive comments and sketches are essential aides to understanding and interpreting the profiles when they are plotted later.

Structure design must consider potential lateral channel shift at the site during the service life of the structure. Together with entrenchment ratio, bank resistance (including that of riparian vegetation) determines a reach's inherent lateral adjustment potential. Unstable banks are susceptible to erosion, which can increase the rate of lateral migration or increase the overall width of the stream. Both processes can lead to fish passage impediments due to aggradation at the culvert inlet, and must be considered in design. A bank stability assessment also helps determine what bank protection will be needed in the regraded sections adjacent to the crossing.

Bank stability indicators include:

- Bank material composition (types of materials - cohesive or non-cohesive)
- Average bank slope
- Extent of bank undercutting – infrequent, continuous
- Amount and type of existing bank failures – infrequent or continuous, deep or shallow failures, rotational failures, slab/block failures
- Amount and type of vegetation - root density, depth, and size
- Bank stratigraphy - vertical sequence of material composition, layering, unconsolidated or overconsolidated materials, ground water seepage

Bank instability can also indicate recent channel incision (Castro 2003). It is extremely important to identify and note this if it exists at a site. Other extrinsic factors, such as debris and bedload deposition potential, are also important in many streams and must be evaluated to determine actual lateral and vertical adjustment potential in the project reach.

Conclusion

To avoid the detrimental consequences to channel stability, diversity and aquatic habitat quality that traditional road crossings often cause, stream simulation culverts are sized to accommodate at least bankfull dimensions, and a streambed with similar slope and structure is constructed inside. Bed and bank transitions to the adjacent channel sections are as smooth as possible, and where necessary include grade controls or channel restoration measures to ensure the crossing streambed can maintain itself over time. If designed with due consideration of site-specific fluvial processes, stream simulation culverts can provide a degree of geomorphic process continuity over the long term, and passage for aquatic species at the times they are moving in the stream. However, passage for terrestrial species may or may not be provided. Also, active large-scale valley processes, such as meander migration and alluvial fan construction, can be constrained by any rigid structure in the dynamic valley environment. Determining site-specific design objectives, structure type and design approach is a complex task that requires balancing benefits and costs to all the resources involved. It is inherently interdisciplinary.

The success of a stream simulation design will be judged by whether aquatic species can travel through it at the times they are moving in the natural channel, and also on its stability and flexibility over the long term. The in-pipe streambed must fit into the geomorphic context of the stream and adjust with it. For that to happen, stream structure, materials and processes must be thoroughly understood and the essential functions must be simulated. The site assessment described here provides the context and the template for design. The design process is described in the following paper (Gubernick and Bates this volume).

Stream simulation practice is a developing art/science. The recommendations presented here were developed based on experience in the Pacific Northwest, and the authors anticipate that practitioners in different geographic regions will progressively add to or modify them as experience is gained elsewhere.

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