6 Stream-Simulation Design

6.1 Project Alignment and Profile

6.2 Design of the Stream-Simulation Channel Bed

6.3 Crossing Structure Dimensions and Elevation

6.4 Bed-Mobility and Stability Analysis

6.5 Managing Risk Factors

6.6 Design Documentation

Steps and Considerations in the Stream-simulation Design

Determine project alignment and profile
- Crossing alignment relative to road and channel.
- Lateral channel adjustment potential.
- Vertical adjustment potential.
- Upstream and downstream project profile control points.

Verify reference reach and stream simulation feasibility
- Reference reach slope similar to project profile.
- Reference reach length similar to crossing structure.
- Reference reach bed characteristics, and water and sediment inputs similar to crossing site.

Design bed material size and arrangement
- Bed mix particle size gradation.
- Bank rock size and placement.
- Key feature rock sizes and placement (clusters, bars, steps, etc.).

Select structure size and elevation
- Channel bankfull width including margins.
- Range of possible streambed profiles (vertical adjustment potential)
- Flood and woody debris capacity.
- Largest rock sizes in bed.
- Results of bed mobility analysis.

Verify stability of simulated streambed inside structure
- Bed mobility similar to reference reach and upstream reach.
- Key features stable during high bed design flow.

Document design decisions and assumptions

RESULTS

Sketches or descriptions of project elements
- Simulated streambed longitudinal profile, cross section dimensions.

Grade controls, bank stabilization measures, etc. in upstream and downstream channel segments

Stream-simulation bed material gradation

Bed material placement including banks, edges, overbank flow surface

Flood-plain drainage structures

Crossing structure dimensions and invert elevation

Figure 6.1—Steps and considerations in the stream-simulation design.

In this phase of the project, the team integrates the information from the watershed and site assessments and designs the streambed through the crossing—the stream-simulation channel. The crossing structure is then designed to fit around the stream-simulation channel. The design process is not linear: as design decisions are made, previous steps may have to be repeated to include or compensate for changes that affect their results. Whoever takes the lead in this phase should ensure that all team members continue to be involved as needed. Issues relevant to all fields (biology, hydrology, geomorphology, engineering, construction) may arise in this phase of the project.

Match the level of care in design to the risks at the site. If the site is prone to channel change or if the consequences of failure would be severe, recheck assumptions, use multiple methods to estimate stability, be more careful with stabilization outside the crossing structure, get help from experienced designers, etc.

6.1 PROJECT ALIGNMENT AND PROFILE

The first step in stream-simulation design—as with any crossing design project—is to establish the project layout in three dimensions, including:

- The two-dimensional plan view that connects the upstream and downstream channels through the crossing.
- The streambed longitudinal profile that connects stable points upstream and downstream of the crossing.

The longitudinal profile and the plan view must be considered together because they are interdependent. When a culvert straightens the natural channel, as most culverts do, it also shortens and steepens the channel, increasing the velocity and energy of flow through the culvert. Figure 6.2 shows how straightening a channel reduces its length and increases its gradient.

The first step in designing the project layout is to understand the natural channel location and pattern through the crossing area. There may be various types of evidence: sometimes the natural pattern is obvious from a plan map; sometimes the site survey produces clues about a previous channel location, such as an **abandoned channel** segment. A relocated or realigned channel may have eroded one bank near the existing culvert inlet as it tried to reestablish its natural pattern, or it may have incised in response to straightening. Understanding the natural **channel pattern** helps explain how the existing culvert affected both stream length and slope. Try to formulate different layout options that approximate the natural pattern so that the replacement culvert conforms better to the natural channel.

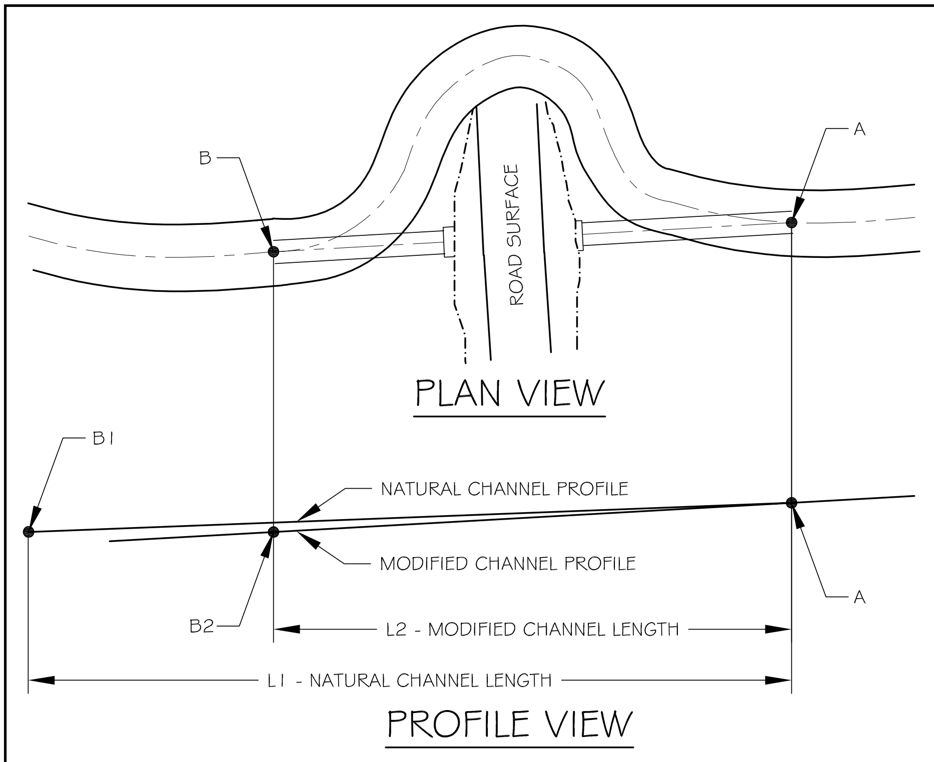

Figure 6.2—Cutting off a bend results in channel length and slope changes.

Ideally, the project layout approximates the natural channel pattern and slope at the site. The simplest situations occur where the crossing is a new installation and/or the road crosses perpendicular to a stable, uniform stream channel. In such cases, the existing channel defines the project layout and profile. For more complex sites, evaluate the tradeoffs associated with the issues discussed in sections 6.1.1 and 6.1.2. It may be worthwhile to compare the pros and cons of a number of different profiles and alignments to find the best combination.

6.1.1. Alignment

`Culvert alignment is the orientation of the culvert structure relative to both the road and the stream channel. If the road crosses a straight uniform channel at right angles, the upstream and downstream channel reaches can be easily connected through a straight crossing. Alignments, however, are often not this simple.

> A crossing that best maintains ecological connectivity over the long term has a channel cross-section area, slope, and streambed similar to that of the upstream channel, and does not disrupt the natural channel pattern.

Poor structure alignment with respect to the stream (skew) is a perennial source of problems. Over 90 percent of culvert failures studied after the 1995–96 floods in the Pacific Northwest resulted from debris plugging and sediment accumulations attributable in part to poor alignment (Furniss et al. 1998). Pieces of wood may rotate as they approach a skewed culvert, increasing their likelihood of lodging at the inlet. Energy losses due to the channel bend at a skewed inlet mean that backwatering and sediment deposition frequently occur upstream (even if the inlet is not plugged). Local bed scour inside the culvert inlet is a common problem caused by the inlet contraction or because flow is focused to one side. A skewed inlet or outlet can also cause severe bank erosion outside the culvert by directing the flow at erodible banks. Because all of these risks are associated with high flows, visualize the flow patterns at high flows when considering alignment.

The relationship between the **radius of curvature** (R_c) of the upstream bend and **bankfull** width is an indicator of the level of risk posed by a skewed alignment (refer to figure 6.6). When R_c is greater than 5 times bankfull width, sediment and debris transport are essentially the same as on a straight channel. As R_c decreases, the risk of affecting sediment and debris transport increases and when R_c is less than twice bankfull width, the risk of impeding sediment and debris transport is substantial. More flow is forced to the outside of the bend, and large eddies form on the inside of the bend, impeding flow and reducing the effective width of the channel (Bagnold 1960; Leopold et al. 1964). Figure 6.6 shows a skewed culvert where the radius of curvature is well within the danger zone.

Aligning a properly sized structure parallel to the upstream channel minimizes the risk of backwatering, sediment deposition, debris blockage, and capacity exceedence for that structure. However, aligning the crossing structure with the channel often results in a skewed alignment relative to the road, which can require a longer structure and/or the installation of headwalls.

6.1.1.1. Risks of longer culverts

Longer culverts are less forgiving of erroneous design assumptions or construction inadequacies. The longer the structure, the higher the risk that hydraulic energy is not adequately dissipated within the culvert. The length of the crossing structure should not be longer than the **reference reach** (section 5.5). When a culvert would exceed the length of the reference reach, consider alternative structures, such as bridges.

One hazard of longer culverts in meandering streams is that they are more likely to cutoff channel bends and steepen the channel (figure 6.2), increasing the risk of streambed instability inside the culvert.

In steep channels, which are usually straighter than flatter ones, channel straightening is less of a risk. However, steep channels often have jutting banks, debris jams, large exposed rootwads, and abrupt bends, all of which add **roughness** and dissipate energy. Take care, when designing long culverts on steep streams, to ensure that energy is adequately dissipated. Otherwise, the streambed may wash out of the culvert.

Always consider minimizing structure length to manage risk. In some locations, shifting the road location to avoid a bend can be a solution. You can also shorten structures by:

- Adding retaining walls and/or wingwalls: in some cases, this adds cost to the project.
- Lowering the road elevation to reduce the width of the roadfill.
- Steepening the embankment: on high volume roads, required additional safety measures may increase cost.

Increasing structure width can partially mitigate the risks associated with long culverts. A wider culvert permits more lateral variability in the channel and provides space for **overbank flows** inside the structure. Space will also be available inside the wider culvert for replicating reference channel roughness by placing large rocks as roughness elements.

There is no universal rule about which is better: a longer culvert with a good alignment relative to the stream, or a shorter crossing with a poor alignment. Do not reduce culvert length by realigning the channel to be normal to the road without first evaluating the tradeoffs associated with the poorer alignment relative to the stream. One of the tradeoffs is a higher risk of debris-plugging; however, stream simulation culverts are less subject to debris-plugging because they are as wide as the natural stream channel. If a site has easy access for maintenance, the benefit of a shorter skewed culvert may outweigh that of the better-aligned but longer one. These decisions are highly site specific.

6.1.1.2. Channels skewed to the road

One common alignment challenge is shown in figure 6.3, where the road is aligned at an acute angle to the stream. Three alignment options for this situation are:

(a) Matching culvert alignment to stream alignment.

(b) Realigning the stream to minimize culvert length.

(c) Widening and/or shortening the culvert.

A project can combine elements of all three options. Other possible approaches include relocating the road to a better stream alignment or building a bridge with a wider span.

Of the options above, (b) entails the greatest risk. The risks listed in table 6.1 should be evaluated and compared for projects where the road crosses the stream on a strongly skewed alignment. Minor skews are not likely to have important effects on the stream. The effects and impacts listed in table 6.1 are general, and may not apply to all situations.

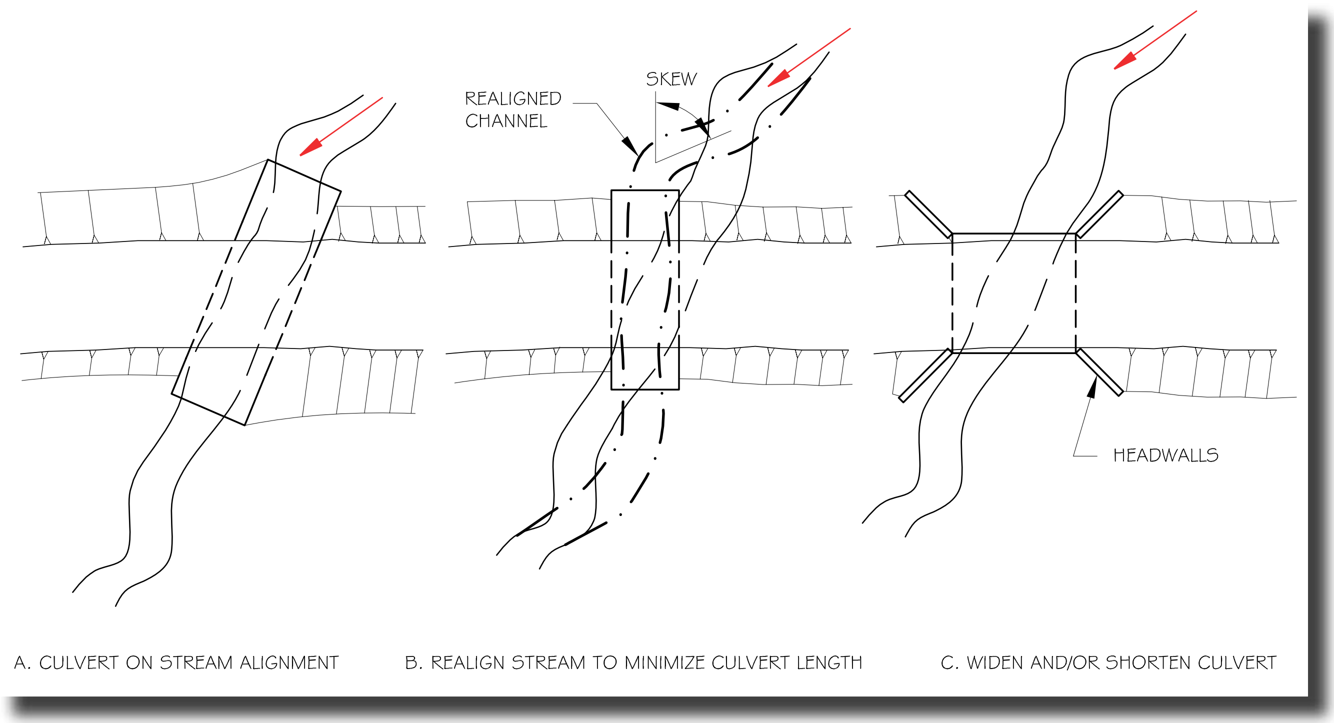

Figure 6.3—Three alignment options for a culvert where the road crosses the stream at an acute angle (high road-to-channel skew).

Table 6.1—Comparison of alignment options, attributes, and associated effects for road crossings acutely skewed relative to the stream channel

Alignment Option	Attributes	Associated Effects and Comparison of Options
a. Crossing on stream alignment	Inlet and outlet match channel alignment.	• Risk of debris and/or sediment blockage is low.
	Culvert is long.	• Permanent direct loss of aquatic habitat is highest. • Risk of bedform failure in the simulated channel and loss of aquatic organism passage is higher than in shorter culverts
	Culvert is skewed to road.	• Special design and construction methods may be required.
b. Realign channel	Inlet is skewed to channel.	• Probability of blockage by debris and sediment is greatest. • Passage of aquatic organisms may be blocked at times. • Risk of culvert failure is greatest.
	Channel, riparian area and banks are disturbed.	• Riparian area is removed, and habitat impacted. • Newly constructed and/or oversteepened banks are less stable and risks of bank failure or erosion are higher. • Realignment may extend beyond right-of-way.
	Channel grade is flattened due to added length.	• Risk of upstream aggradation is increased. • Need for maintenance to remove sediment is increased.
	Outlet may be skewed to channel.	• Risk of bank erosion downstream is greatest.
c. Widen and/or shorten culvert	Inlet and outlet match channel alignment.	• Risk of debris and/or sediment blockage or plugging is low.
	Open area is large.	• Culvert capacity is greatest; lowest risk of culvert failure. • Risk of failure due to debris blockage or plugging is lowest. • Opportunities for passage of aquatic and terrestrial organisms are greatest.
	Construction duration may be long.	• Risk of construction activity detrimentally affecting wildlife is greatest. • Road closure is required for longer time. • Project may be most expensive.
	Channel area covered by project is small.	• Permanent direct habitat loss is least.

6.1.1.3. Culvert on a bend

Another common alignment problem arises where the crossing is located at a bend in the channel (figure 6.4). Where road relocation is not feasible, the same three options pertain: matching channel alignment, realigning the stream, and widening and/or shortening the culvert.

None of these options necessarily stands alone. The best solution might be optimizing a combination of skew, culvert length, and culvert width changes. Table 6.2 lists attributes and effects of each channel-bend option.

Consider how far the channel is likely to migrate laterally during the life of the project (sections 4.4 and 5.3.2). Options for accommodating expected changes include the following:

- Widen the culvert and offset it in the direction of meander movement.
- Control meander shift at the inlet with appropriate bank stabilization measures or training structures, such as rock weirs or J-hook vanes.

If banklines are constructed within the culvert, the rocks on the outside bank (the bank in the direction of channel shift) will be exposed to higher shear stresses and might therefore need to be bigger than bank rocks in other locations (see section 6.4.2).

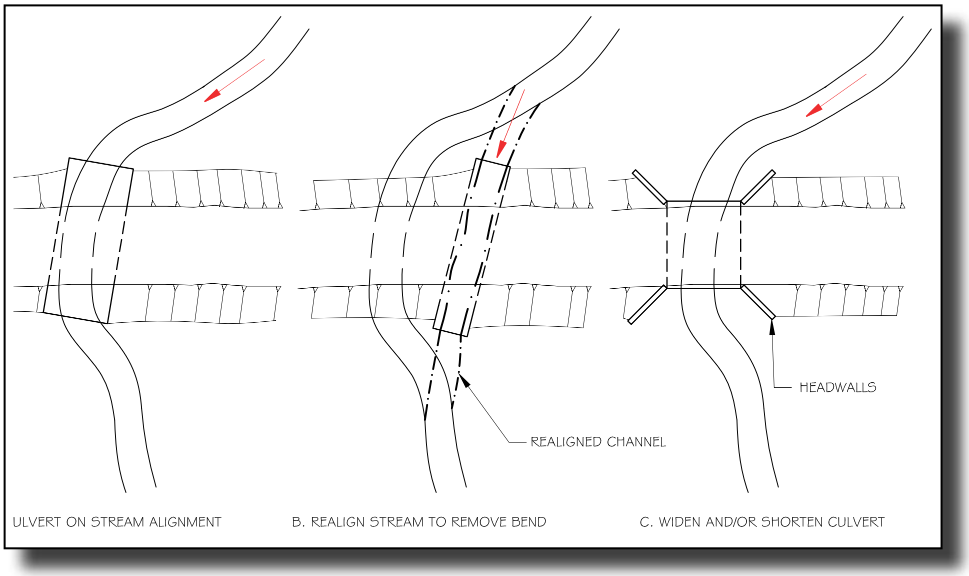

Figure 6.4—Three alignment options for a culvert on a channel bend.

Table 6. 2—Comparison of alignment options, attributes, and associated effects for a road crossing on a channel bend

Alignment Option	Attribute	Associated Effects and Comparison of Options
a. Crossing on stream alignment	Bend location results in skewed outlet.	• Risk of bank erosion downstream is higher.
	Bend location results in skewed inlet.	• Risk of upstream sediment deposition and debris blockage increased over straight alignment. • Likelihood of bank erosion upstream increased.
	Channel bends in culvert.	• Natural bend characteristics (increased shear on outside of bend, pool, point bar) may not be feasible in a culvert.
b. Realign channel	Disturbance to channel, banks, and riparian area.	• Riparian area is removed and habitat impacted. • Channel realignment is excavated through high ground leaving bank slopes vulnerable to erosion or failure.
	Inlet and outlet match channel alignment.	• Risk of debris and/or sediment blockage is low.
	Channel is shortened and steepened.	• Risk of bedform failure in the structure is higher. • Risk of upstream headcutting is higher than other options. • Realignment may extend project beyond right-of-way.
c. Widen and/or shorten culvert	Culvert length is short, open area is large.	• Hydraulic capacity is greatest. • Risk of culvert failure is least. • Risk of passage obstruction and culvert failure due to debris blockage or plugging is least. • Opportunities for passage of aquatic and terrestrial organisms are greatest.
	Construction duration may be long.	• Risk of detrimental effects due to construction is greatest. • Road closure is required for longer time. • Project may be most expensive.
	Channel area covered by project is low.	• Permanent direct habitat loss is least.

For long pipes on bends, a curved pipe offers an alternative solution. A curved pipe is a series of culvert sections formed into a bend that preserves the inlet and outlet channel alignments, as well as channel length and slope (figure 6.5). Curved pipes might be useful, for example, in incised channels where alignment cannot be changed, or where property boundaries limit alignment options. They require special culvert design, special product, and careful construction. The simulated streambed should have the characteristics associated with a bend of similar radius of curvature. For example, the design might anticipate the formation of a pool at the apex of the bend and include a higher bank there.

Figure 6.5—Curved concrete pipe installation at Arrington Development, Durham, North Carolina, June 2001. (Pipe is 142 feet long, with a 24-foot span and a 7-foot rise.)Courtesy of CON/SPAN Bridge Systems.

Many projects require comparing the relative merits of a longer versus a steeper culvert, or a poor channel-to-culvert alignment versus a channel realignment. See section 6.1.4 for an example from the Tongass National Forest where all these alternatives were considered.

6.1.1.4. Transitions

Transitions into and out of the culvert are important, especially if the alignment is not ideal. A good transition can smooth an abrupt change of flow direction. It can also eliminate poor inlet conditions caused by a previous pipe; for example, the wedge of sediment deposited upstream of an undersized culvert might be removed, and the widened channel might be restored to its normal width. Design the transition by contouring the banklines smoothly, beginning at the natural streambank upstream, continuing through the section to be modified by the project, and into the crossing (figure 6.6).

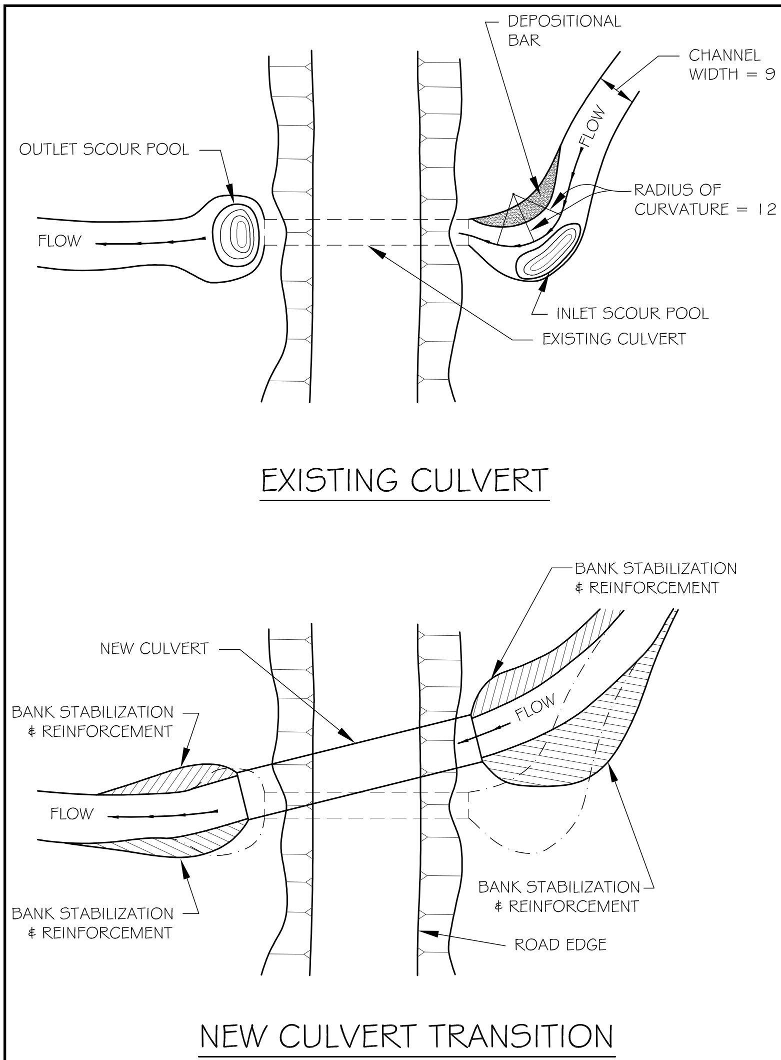

Figure 6.6—Channel bend upstream of existing culvert has a radius of curvature less than two times bankfull width ($R_{c/w}$ = 1.3), with serious potential to obstruct sediment and woody debris. *New culvert is realigned, and banklines are excavated and reinforced to create smooth transitions at inlet and outlet.*

If the stream must make a turn into the inlet, the bend should be no sharper than bends in the natural channel, so that debris that moves in the channel will also move through the structure. Visualize the bend during high flow when most debris will be moving.

A poor transition will exacerbate all of the alignment risks that the previous section described. For example, where a channel widens immediately upstream of the culvert inlet (as in basins excavated during road maintenance), the wider basin causes pieces of floating wood to swing perpendicular to the channel and plug the culvert inlet. The wider cross section also reduces the shear stress exerted by flow, thereby reducing sediment-transport capacity per unit of channel width. As a consequence, both woody debris and sediment tend to accumulate (Furniss et al. 1998).

On the other hand, a replacement culvert that is much wider than the existing one may direct water against streambanks that have encroached into the stream channel below the previous narrow culvert. Consider the possible effects of bank erosion, and transition the culvert bed and/or banks into the natural streambanks to minimize erosion risk. Banklines built within a stream-simulation culvert should be continuous with the upstream- and downstream-channel banklines. Rebuilding eroded banks around an outlet scour pool, such as in figure 6.6, usually requires filling the pool.

A good way to evaluate transitions is to compare the cross section of the **simulated channel** with the natural channel upstream and downstream from the crossing. The geometry and dimensions of the adjacent cross sections should be similar to one another.

6.1.2. Designing the Project Longitudinal Profile

The project profile represents the surface of the streambed that will be constructed through the project reach to connect the upstream and downstream channel profiles. It corresponds to the slope segments discussed in section 5.2.2, which connect the **grade controls** in the natural channel. At new culvert installations where the road alignment is perpendicular to the stream, the existing channel longitudinal profile *is* the project profile. The project-profile analysis is one of the most critical elements in a stream-simulation design, whether the project is a new crossing, a replacement, or a crossing removal. A good project-profile analysis ensures that the new structure will accommodate expected future vertical streambed adjustment.

The scale of any channel adjustment problem caused by the previous culvert determines the scale of the solution. The project profile can be short if no large scale vertical adjustment is anticipated, such as where nearby stable steps or bedrock outcrops anchor the ends of the profile. The project profile will be longer where upstream aggradation and downstream incision at an undersized culvert create a large elevation drop. The profile will be longer still if large-scale downstream channel incision has occurred. In this case, connecting the upstream and downstream channels requires dealing with potential upstream headcutting (and/or downstream channel rehabilitation) over a longer stream reach.

Designing the project profile involves the following steps.

1. Identify stable endpoints for the project profile.

   Select stable grade control features upstream and downstream of the crossing that will anchor each end of the project profile. They should be stable enough that they will not be affected by removal of the existing crossing structure. Profile endpoints might be bedrock outcrops or highly stable steps, riffle crests, debris accumulations (e.g., large, well-embedded logs), etc. Several features may be good candidates for stable endpoints, and you might evaluate various project profiles using different combinations of endpoints. In this context, 'stable' means the bedform will last as long as the structure lifetime. It does not necessarily have to be permanently immobile. The cobbles on a high-stability riffle crest (table 5.3), for example, may mobilize in the 10- or 25-year flood, but the riffle crest itself will remain at or very near its current location and elevation if the channel is stable.

   If the downstream channel is incised, the lower VAP line (section 5.2.2.2) indicates the length and depth of potential channel incision upstream. Most alluvial bedforms higher than the lower VAP line would not be expected to constitute stable endpoints in this case. If you decide to allow a headcut to progress through the crossing, the upstream project profile endpoint would need to be upstream of the projected extent of incision. Alternatively, if you decide to maintain the crossing as a grade control, you may need to construct permanent grade control structures as the project profile endpoints (see section 6.1.3).

2. Delineate possible project profiles.

   Draw one or more tentative project profiles between sets of control points to connect the upstream and downstream segments across the crossing. The project profile should extend at least as far upstream and downstream as the new culvert installation could directly affect the channel. The profile does not show bed topography, only the elevation and slope of the streambed that will be constructed (see figure 6.7 for an example). Calculate slope and length of the profile options.

The best project profile is a uniform one beginning and ending on stable bedforms. However, some project profiles may have two segments with different grades. Sites with convex or concave profiles, for example, might have more than one segment. In these cases, we recommend the slope break be outside the culvert. The incised channel solution in figure 6.10 (c) is an example of a project profile in two segments. The same type of segmented project profile, with the steeper section constructed outside the culvert, could be used at any site where the elevation change exceeds the slope of available reference reaches and where the adjacent natural channel is stable enough to sustain the transition.

3. Verify the reference reach.

After identifying one or more good project-profile options, recheck the reference reach tentatively identified during the site assessment (section 5.5). Determine whether it adequately represents the preferred slope. The reference reach should be straight, and as long as the crossing structure. Ideally the reference reach should also be as long as the project profile, but this is not always feasible on meandering streams or where wood is a frequent bed feature. If the tentative reference reach does not match the desired project profile, evaluate other slope segments in the site survey (section 5.2.2) as a possible reference reach.

If the site assessment survey did not include a reach as long as the project profile and within 25 percent of its slope, revisit the site to see if the natural channel includes reaches closer to your needs. If not, consider controlling the project profile to more closely fit an available reference reach (section 6.1.2.5). This need commonly arises when (1) there has been a large amount of aggradation upstream and deep local scour downstream of an undersized crossing or, (2) the downstream channel has incised and the existing culvert is acting as a grade control to prevent upstream headcut migration, or (3) the natural channel profile is concave, convex, or complex.

If profile modification will not work, the remaining options for crossing design are to:

- Use a hydraulic or hybrid design method to achieve partial passage (see appendix B) or,
- Locate a reference reach on a different channel that has similar landscape characteristics: valley type, streambed materials, watershed size, hydrologic regime, etc. This option has strong limitations (see section 5.5).

4. Adjust VAP lines if necessary.

   Where the project profile will be controlled by permanent grade control structures, the VAP lines may require adjustment to correspond with the project profile and reference reach. Examples are shown in figures 6.10b and 6.10c, which show an incised-channel site where the project profile will be controlled to avoid headcutting upstream of the replacement culvert. The lower VAP line in and upstream of the culvert is adjusted upward since the constructed grade controls will stop the progress of incision.

5. Locate key bed features.

   Based on the reference reach, determine the spacing, height, and location of any bedforms that need to be constructed. Bedforms are generally spaced based on average spacing in the reference reach. Tying them into the endpoint bedforms, however, sometimes requires varying bedform spacing. Meander bends, which control pool locations, must also be considered when locating the bedforms in the project reach. The average spacing may need to be varied to locate the pool appropriately in relation to the bend. Limit the variability in spacing to the range found in the reference reach.

The following sections describe project profile delineation on various channel profile types.

6.1.2.1 Uniform channels with local scour and fill around an under sized culvert

In uncomplicated channels with uniform profiles (not incised), the project profile simply connects profile control points in the upstream and downstream channels at the same slope as the channel profile. The design slope is the same as the upstream and downstream channels. In figure 5-16a, for example, the project profile is the existing channel profile extended through the crossing. The replacement project entails nothing more than installing an appropriately sized and embedded culvert and filling the scour pool. Since the volume of sediment accumulated above the culvert inlet is not large, the sediment can be allowed to regrade naturally if desired. The project footprint will be quite limited.

In some cases, the amount and extent of aggraded sediment upstream of an undersized culvert are so large that allowing the sediment to flush through the system all at once would be undesirable. In such cases, the team may elect to place control structures in the aggraded reach to meter sediment movement more gradually. This will extend the project's footprint.

6.1.2.2 Steep channels with large key features

On streams controlled by large **key features** (bedrock outcrops, large woody debris, stable debris jams, boulder steps, manmade structures), the project profile reflects the team's assessment of the probability that key features might move. In the Fire Cove Road example (site sketch and VAP analysis shown in section 5.2.3), several project profiles were evaluated under different assumptions about potential movement of the upstream and downstream key features.

Recall that the Fire Cove Road crosses a wood-forced step-pool Rosgen A channel, where a 2.5-foot-diameter log about 50 feet downstream of the culvert (figure 5.14c) controls channel slope across the crossing. A debris-and-boulder cascade over 20 percent slope is about 30 feet upstream of the culvert. The existing culvert slope is 5-percent, flatter than the adjacent channel, where slopes range between 6 and 22 percent. In spite of the complex profile shape, this steep transport channel has had no problems with aggradation at the culvert inlet.

Figure 6.7 displays possible project profiles at the Fire Cove Road crossing. The steepest profile assumes that the downstream log control moves or will be removed, and that a boulder step in the middle of the cascade also may move. For solid anchor points, this profile uses the highly stable boulder-log structure at the top of the cascade upstream of the crossing, and a log-boulder complex further downstream of the crossing. The intermediate slope profile also assumes the downstream control moves. Both of these steeper profiles would entail constructing a very steep simulated streambed with a design gradient of over 6 percent. These options would not only avoid any potential aggradation problems but also would result in a channel where stability does not depend on the downstream log.

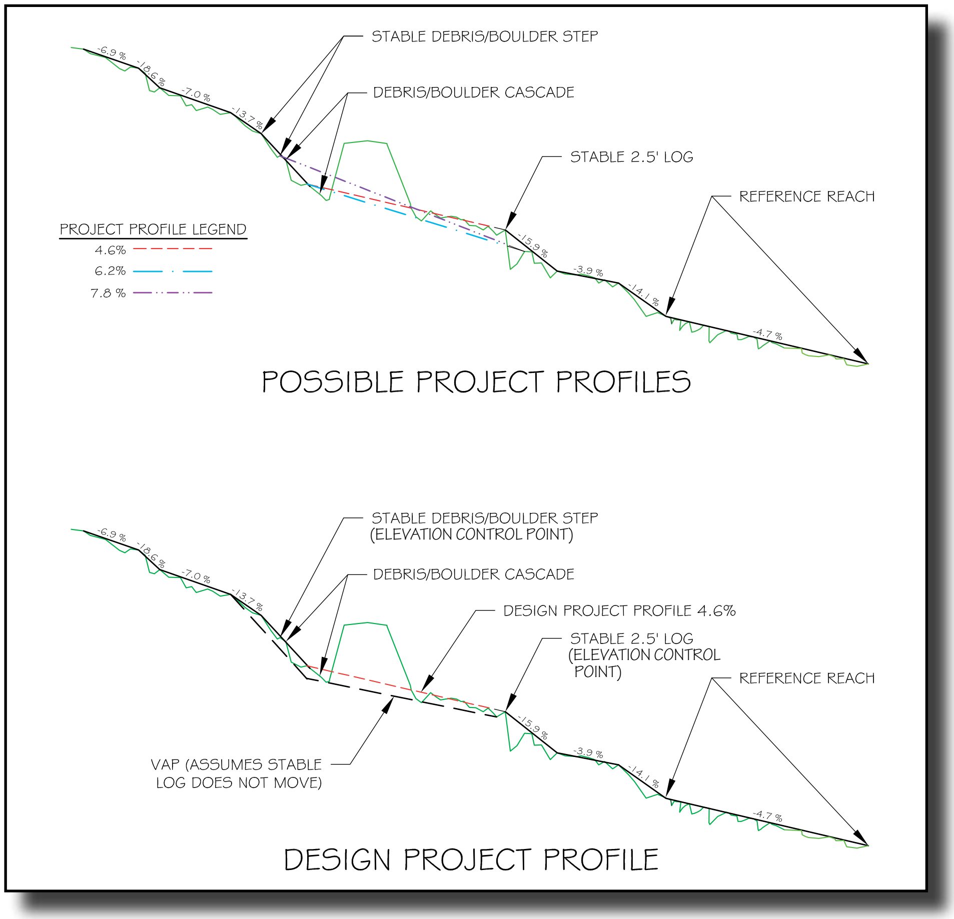

Figure 6.7—Project-profile options on a channel with large key features, and the selected project profile: Fire Cove Road, Tongass National Forest, Alaska.

The flattest profile in figure 6.7 has a 4.6-percent slope, and assumes that no existing grade controls move. This design project profile was used because the probability is very low that either of the nearest grade controls will move over the lifetime of the new culvert. The existing culvert, at a 5-percent grade, had no problems with aggradation. This option preserves the valuable pool habitat in the vicinity of the culvert, and requires the least channel regrading. A reference reach with a similar slope exists downstream of the crossing.

6.1.2.3 Concave slope transitions

The concave transition (see section 5.2.1.4) is common, because many roads are located at the outer edge of valleys, where the steeper sideslope meets the valley floor. Shear stress decreases abruptly with the change in channel slope, and these areas are natural sediment depositional zones. A crossing that constricts the stream will exacerbate the natural tendency toward sediment deposition. Even where no constriction exists, natural aggradation can reduce a structure's hydraulic capacity.

If a culvert has to remain at or near a concave grade break where it could be affected by aggradation, the project profile should include the grade break. Figure 6-8a shows an undersized culvert at a concave-channel transition, along with the upper and lower VAP lines. No regional channel incision is anticipated here, so the lower VAP line is drawn below the typical depth of pools in each segment. The upper VAP line here is at the top of the streambank. The channel has downcut through a sloping bench (an old depositional surface) where the hillside meets the valley bottom. Upstream of the crossing on the hillside is an entrenched step-pool channel; downstream is a less well-entrenched pool-riffle channel.

Replacement option 1 would be the desirable project profile if a reference reach can be found at an intermediate grade. Such a reference reach might be a steep, riffle-dominated reach with transverse bars, like the project profile shown in figure 6.8b. This alternative reduces risk by moving the probable locus of aggradation away from the culvert, where maintenance can access the channel if necessary.   Note that the lower VAP line has been adjusted upward in this scenario, because the project profile is raised and its elevation is controlled by constructed riffle crests. Option 2 (figure 6.8c) involves oversizing the structure so as to accommodate any aggradation that may occur. The project profile is a smooth transition between the profiles of both adjacent channel segments. This alternative is less than ideal because of the difficulty of predicting future aggradation (see section 4.5, Brewster Creek example).

Table 6.3 lists and compares common options for design solutions at concave transitions. Note that the vertical curve of the roadway influences design options, because it controls how much the road surface can be raised to allow more room for sediment deposition in the crossing structure.

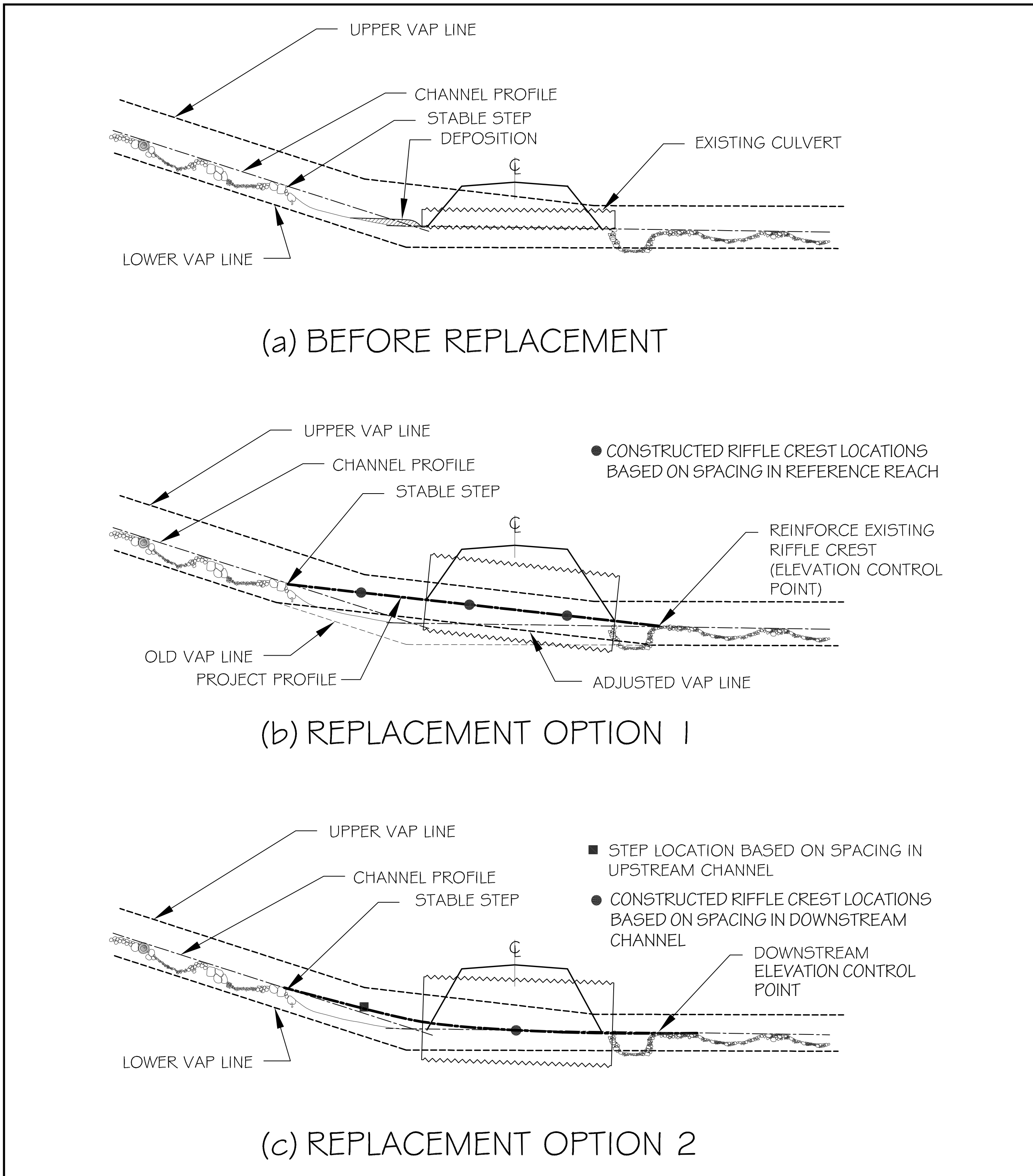

Figure 6.8—Hypothetical determination of VAP lines and project profile at a concave transition: (a) undersized culvert before replacement showing upper and lower VAP lines; (b and c) two options for possible project profiles inside replacement culverts (see text). Steps or constructed riffle crests could be designed for these installations, based on bedform spacings in the respective reference reaches (see sections 6.2.2.4 and 6.2.2.2).

Table 6.3—Design options for concave transitions

Profile Option	Attributes	Associated Effects and Comparison of Options
Relocate crossing away from grade break.	Places crossing upstream or downstream of the depositional zone.	• Most reliable solution. • Reduces maintenance requirements. • Depending on road alignment, can have undesired trade-offs, e.g., changes in sight distance, safe driving speeds, etc.
Adjust channel profile to ensure sediment is transported through the crossing.	Steepens profile inside pipe and moves grade transition away from culvert.	• Only possible when downstream channel is steeper than ~1% and somewhat entrenched (so flow does not spread out and deposit sediment immediately downstream of culvert). • Carries risk that downstream deposition may progress upstream toward crossing (important on low gradient alluvial fans). • Depositional area may be moved to channel reach not adjusted to it, or on another property. • Road grade may be raised to accommodate steeper culvert; diversion potential can increase.
Oversize culvert to accommodate sediment accumulation (to upper VAP line).	Allows aggradation without sacrificing structure performance.	• Road grade may need to be raised to accommodate larger culvert. • Only desirable where geometric road requirements can be met without causing a potential for stream diversion (i.e., road approaches should slope down to crossing).
	High potential profile is estimated based on site history, sediment sources, amount of debris moving in system, etc.	• Estimate of high potential profile (and therefore culvert size) is subject to considerable uncertainty.
Design for long term maintenance.	Alternatives include: • Embedded concrete boxes with removable lids. • Bridge. • Excavated sediment pond accessible to maintenance equipment upstream of crossing.	• Useful where roadway constraints or rapid sedimentation rates make other options infeasible. • Requires a maintenance commitment. • Upstream excavation carries a risk of destabilizing the steeper channel upstream and possibly causing a headccut and/or loss of aquatic habitat.

6.1.2.4 Convex slope transitions

Where the channel gradient steepens downstream of a crossing, there is an inherent risk of headcutting unless permanent grade controls exist or are constructed. Traditional culverts at these locations control streambed elevations, but stream-simulation culverts do not function that way. Local headcutting might occur due to disturbance during construction or movement of local grade controls (steps, short cascades) during floods. The risk depends on the stability of the grade controls. Unless grade controls are highly stable, protecting the simulated streambed in the replacement culvert may require constructing additional grade control structures.

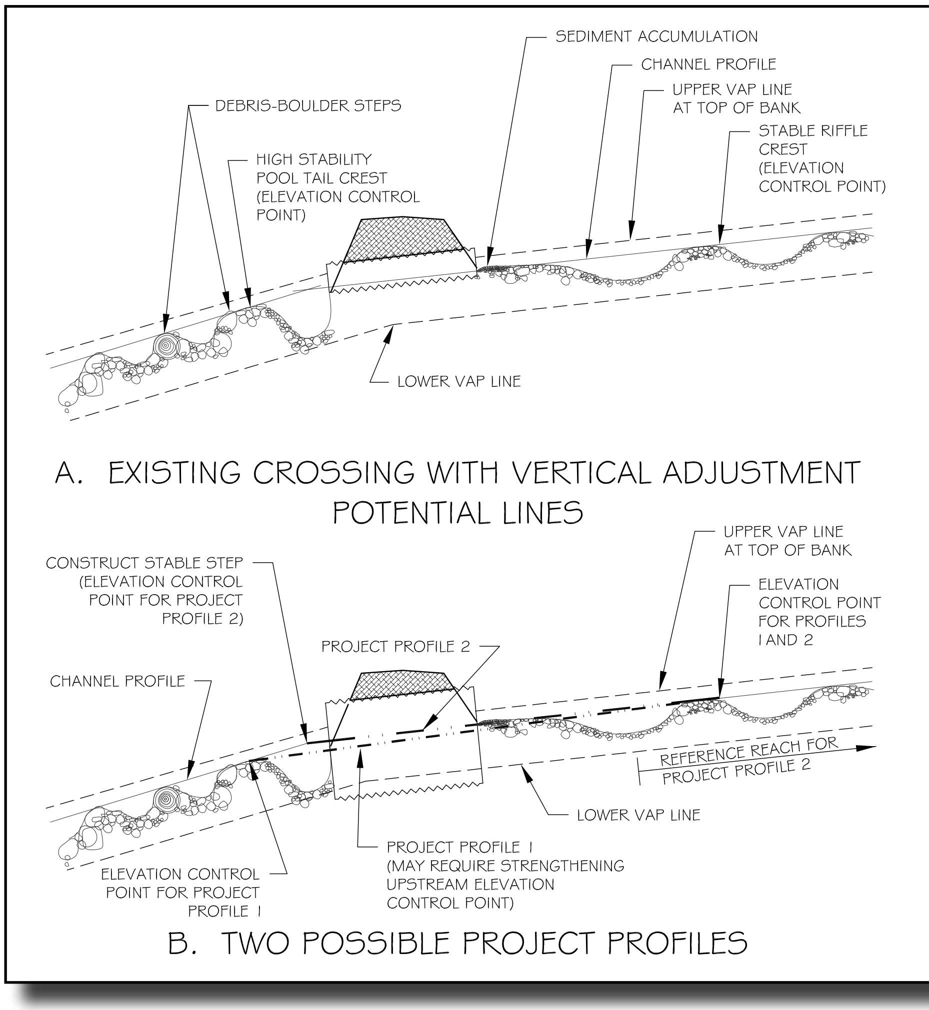

Figure 6.9—Road crossing near convex slope transition. (a) Existing crossing with bed topography, channel profile, and VAP lines. (b) Two possible project profiles.

Figure 6.9a shows a crossing near a convex slope transition, where a pool-riffle channel breaks to a steeper step-pool channel. If one or more of the downstream steps is destabilized by construction or a flood, the downstream channel could incise to approximately the height of the grade controls. In this example, we are not anticipating regional channel incision such as might occur with a base level change somewhere downstream. We are only designing for local bed elevation changes that could occur if one or two log or boulder grade controls move during a flood. If regional channel incision were anticipated, the lower VAP line in figure 6.9a would need to be lowered to account for that, or permanent steps would need to be constructed downstream.

Two possible project profiles are delineated in figure 6.9(b). Both start at the same upstream elevation control point—a stable riffle crest. Profile 1 has a slope intermediate between the two adjacent channel segments. It could be selected if a reference reach with a similar slope exists nearby, and if the elevation control points are stable enough to sustain the steeper slope. Both the outlet pool-tail crest (the downstream profile control point) and the upstream riffle would need to be highly stable structures to make this a viable option. Profile 2 extends the channel profile of the upstream reach through the new crossing, and would require constructing an immobile grade-control structure downstream of the new culvert to maintain the slope. The reference reach for profile 2 would be the reach immediately upstream of the culvert.

6.1.2.5 Incised channels

Where a culvert is protecting the upstream channel from incision, but the amount of prospective incision is acceptable, you may decide to simply lower the culvert and allow the upstream channel to regrade naturally. Once again, see section 5.3.3 for a checklist of things to consider when deciding whether to allow incision to progress. Either ensure incision downstream of the crossing is not ongoing, limit it by constructing permanent grade controls, or provide adequate depth to accommodate it.

One way of mitigating some of the effects of expected **channel incision** is to limit the rate of upstream headcut migration using temporary grade-control structures, such as scattered, buried, or other rock structures, which are expected to fail over time. Although you can place woody debris for the same purpose, be aware of the potential impact on the culvert, should that debris move.

Where the projected VAP is *not* tolerable, several options exist for adjusting and controlling the project profile. Most of these situations are where the downstream channel has incised, and the depth or extent of possible upstream incision is unacceptable. Again, the first step in dealing with these situations is to identify stable grade controls (or control points that can be stabilized) upstream and downstream of the crossing, and connect those points to delineate a tentative project profile. Determine the slope of the profile and verify that a reference reach exists at that slope. If the project profile exceeds the slope of potential reference reaches, adjusting the profile may be possible using one or more of the following strategies.

- Reconstruct the incised channel to pre-incision conditions.
- Steepen the culvert.
- Lower the culvert and steepen the adjacent reach(es); control grade with key features like boulder weirs or logs, or constructed grade-control structures.

Figure 6.10 illustrates these options and table 6.4 describes and compares them. Many projects include a combination of two or all of these options.

Projects dealing with large-scale channel incision are often much longer than those dealing only with local scour because they require restoring or controlling streambed elevations on the adjacent channel segments. The objective is to smooth the transition between the unincised channel upstream and the incised channel downstream so as to avoid impeding aquatic organism passage. Right-of-way limits, property boundaries, and other infrastructure can sometimes constrain the length of the project. However, do not automatically assume that they do. Instead, consider options that cross or move these features if those options have advantages.

Reconstruct the channel

Channel reconstruction [figure 6.10(a)] should be considered as an option in any project associated with an incised channel. Channel reconstruction is the reestablishment of equilibrium channel dimensions, structure, and grade, with the goal of achieving a self-sustaining channel that can remain in **dynamic equilibrium** over the long term. It is a more elegant, durable way of correcting a large elevation drop resulting from channel incision, as opposed to forcing the culvert into an artificially oversteepened profile. Reconstruction might involve realigning a straightened channel to restore meander pattern and length at its original elevation. Oversteepened banks could be laid back and the excess material used to build the incised bed back up to an elevation that provides access to the culvert.

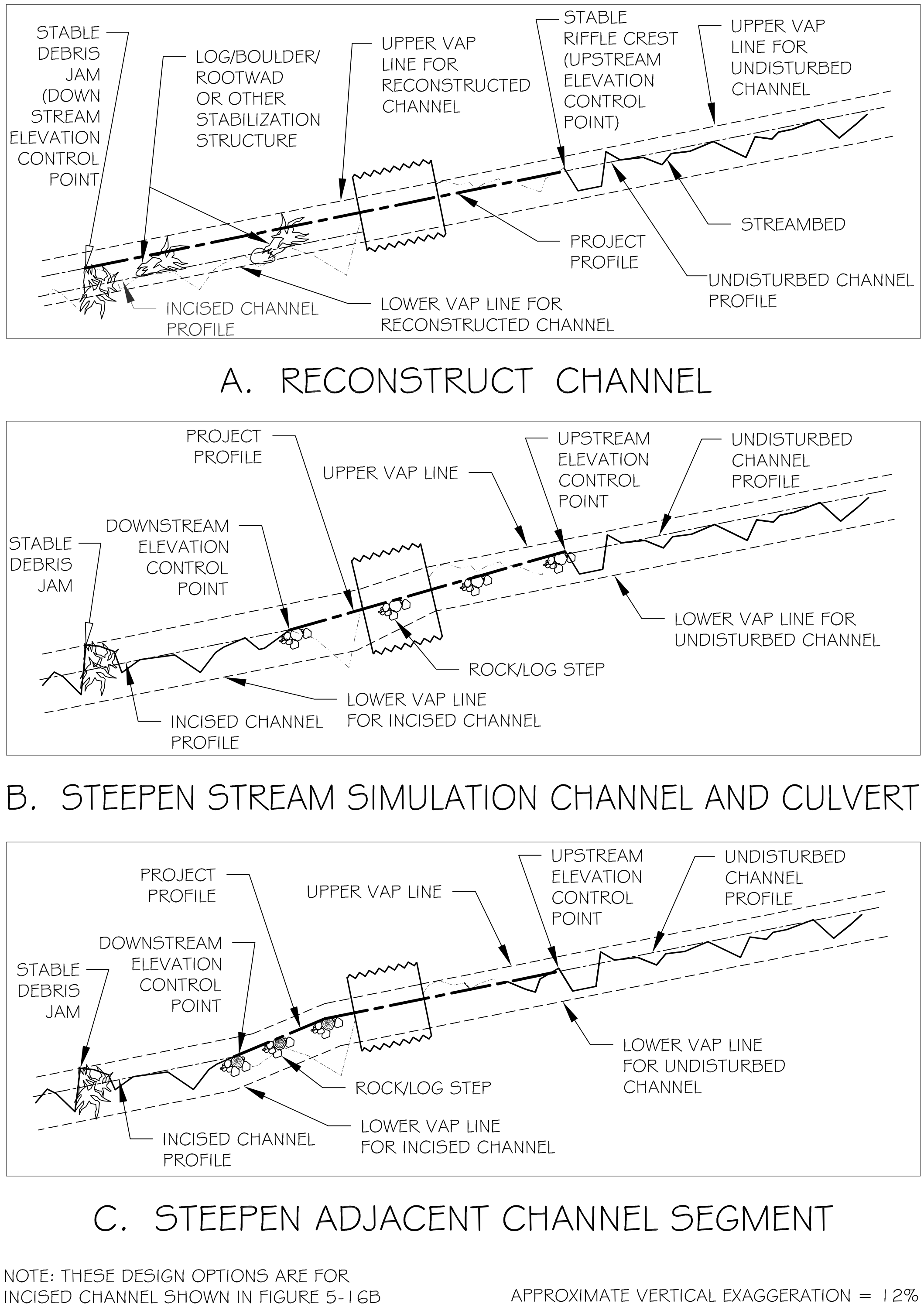

Figure 6.10—Several project-profile options for an incised channel (reference figure 5.16b).(a) Reconstruct channel; (b) steepen stream-simulation channel; (c) steepen adjacent channel segments The lower VAP lines represent the lowest channel elevations expected over the life of the replacement structure given the profile controls constructed in each case. Incision is judged to have ended.

Table 6.4—Comparison of project-profile design options for incised channels

Profile Option	Attributes	Potential Effects and Comparison of Options
a. Reconstruct channel.	May restore downstream channel to natural length and grade.	• Greatest habitat gain of the three options. • Most self-sustaining of the three options. • Risk that downstream channel may continue to incise if the cause of instability is not resolved.
	Project scope includes longer reach than other options.	• Initial disturbance may be more extensive and construction cost may be higher. Potential issues with property boundaries or rights-of-way, short-term wildlife habitat impacts.
	Usually includes habitat improvements.	• Creates or enhances in-channel, flood plain and/or riparian habitats.
	Often improves channel flood-plain connectivity.	• Improves flood-plain water storage and other flood-plain functions.
	Avoids abrupt slope changes along profile.	• Stream-simulation crossing is more sustainable and less vulnerable to headcutting or sediment deposition.
b. Steepen culvert.	Higher streampower and coarser rock in simulation than in adjacent reach.	• Risk that simulation will be unsustainable if upstream reach does not resupply the same caliber of sediment eroded from culvert. • More likely an impediment to aquatic species passage than other options (minimize this risk by staying within 25% of reference reach slope for stream simulation).
c. Lower culvert and steepen upstream and/or downstream reaches.	Slope transitions at upstream and/or downstream ends of culvert.	• Risk of headcutting upstream and sediment deposition downstream. • Grade controls may be required upstream and/or downstream.
	Natural banklines and roughness elements (especially wood) in open channel dissipate energy and help stabilize the steepened reaches	• Less risk of simulated channel instability compared to (b). • Less risk of impeding passage compared to (b) because the variety of pathways is greater.
d. Lower culvert and allow upstream headcutting.	Maintains channel connectivity through crossing but permits free channel incision.	• Potential effects of allowing upstream headcutting are outlined in section 5.3.3.

Before deciding to reconstruct a channel, it is critical to understand the cause of channel incision. Channel incision can sometimes result from long-term watershed changes (for example, in land use and the amount, timing, and distribution of runoff). In that case restoring the channel to historic, predisturbance conditions may not be possible and the channel should be designed for current and future **flow regimes**. Understanding the stage of incision is also crucial. If incision is still on-going, it could destabilize the reconstructed channel. Channel reconstruction may not be feasible for many reasons, and you should evaluate feasibility before deciding to implement this option. See the Federal Interagency Stream Restoration Working Group (1998) for an introduction to the channel-reconstruction planning process.

The reconstructed channel must tie into a stable downstream base-level control so that incision does not recur. The downstream control in figure 6.10(a)—a stable debris jam—would probably not be considered an adequate elevation control point in real life. Most channel-reconstruction projects would involve reconstruction of a longer reach, with either a more solid downstream control, such as bedrock, or a more gradual tie into the incised channel. The downstream channel might be reconstructed at a slightly steeper gradient to tie gradually back into the natural channel. Designing the steeper reconstructed channel would require finding a reference reach at that steeper gradient.

A project that includes reconstruction of an incised channel can extend a considerable distance downstream. It may have habitat-restoration values that go far beyond passage of aquatic organisms. For example, such a project can restore in-stream, riparian, and flood-plain habitats and channel **flood-plain** interactions; reconnect **side channels** previously blocked by the roadfill; and stabilize eroding banks. Channel reconstruction may be the most expensive option, but such a project is likely to be more self-sustaining and lower in maintenance costs than others.

Steepen the stream-simulation channel

A more local solution to the incised-channel problem is to steepen the simulated channel [figure 6.10(b)]. Look at the site longitudinal profile and consider the variability of reach slopes. You may find short punctuated steps that are steeper than the average gradient; these could serve as a reference reach if they are long enough. If necessary, go back and investigate beyond the surveyed longitudinal profile.

How much steeper than the reference reach can the stream-simulation channel be? The increase should not be great, because at some point, the bed material in the simulated channel must be so much larger than in the upstream reach that the upstream reach cannot replenish it if it erodes. In other words, the simulation will not be self-sustainable. Keep in mind that the premise of stream simulation is that the simulated channel is close enough to the natural one that organisms will move through it equally easily. If the difference between the slopes is great—especially if the steeper slope requires a different channel shape or bed material for stability—aquatic organisms may not be able to move through at the same flows as in the natural channel. Stream simulation may not be feasible in that case.

Bates et al. (2003) suggest a slope increase of no more than 25 percent of the natural or reference reach. The suggestion is a conservative guideline, as we have no data thus far to support a specific criterion. We use a maximum *percent* change of slope, because a flatter channel is much more sensitive to a given absolute change than a steeper one. For example, increasing a 1-percent slope channel by 1, to create a 2-percent channel, is a substantial change, whereas increasing a 10-percent slope channel by the same amount, to create an 11-percent channel, is reasonable. We recommend doing a bed-mobility analysis (section 6.4) for any slope greater than the reference reach, even if the slope of the simulation channel is within the 125-percent guideline.

Steepen adjacent reaches

The reaches upstream and/or downstream of the culvert can be steepened, either as an alternative to or in addition to the steepened crossing [figure 6.10(c)]. Steepening channels outside of a culvert is less risky for the following reasons:

- If necessary, the channel can be widened.
- The culvert wall does not constrict high flows.
- Natural banklines and channel margins provide the added benefit of vegetation for roughness and root strength.
- It is easier to repair grade-control structures outside culverts.

Reference-reach features are the basis for designing the dimensions and spacing of grade controls such as those shown in figures 6.10(b) and 6.10(c) (see sections 6.2.2.2 and 6.2.2.4). Such structures should not be placed near the culvert inlet to avoid exposing them to unusual flow patterns near the inlet at flows higher than bankfull.

Appendix F briefly describes some common grade-control structures used to steepen reaches upstream and downstream of crossings. Where channel incision has occurred and control structures are the sole means of maintaining elevation and grade downstream of a culvert, these structures should be long-lasting and stable enough to maintain the designed elevation. The designer must assess the possibility that further incision downstream of the project could create a passage **barrier** at the lowest bed control and/or jeopardize the controls and the project.

6.1.3 Project Alignment and Profile Design: Two Examples

Newbury Creek Crossing Project Profile and Reference Reach

In chapter 5, we used the Newbury Creek crossing on the Olympic National Forest to demonstrate the site-assessment process, including analysis of the longitudinal profile and VAP. Here we examine how the alignment and project-profile issues were handled at the Newbury Creek site, which channel segment was selected as the reference reach and how bedforms were spaced in the design channel. Newbury Creek illustrates a case where the VAP was acceptable, and the project profile did not require modification to control vertical adjustment.

Figure 6.11 shows that the original culvert straightened a slight bend on Newbury Creek, which explains the need for riprap on the east bank just above the inlet. The degree of straightening is slight, and the replacement culvert requires no alignment adjustments.

Figure 6.12 shows the longitudinal profile with two possible project profiles drawn between stable grade-control features upstream and downstream of the crossing. The downstream elevation control point for both profiles is the riprap rock weir at the outlet pool tail crest (photo in figure 5.11). The flatter profile uses bedrock as the upstream elevation control point, assuming that the sediment wedge above the existing culvert will erode. Erosion of the sediment wedge is expected to destabilize the log weirs and other grade controls in the steeper reach above the crossing, allowing for some channel downcutting there. Slope of this profile is 2.26 percent, less than 3 percent steeper than combined segments F/G, which are downstream of the crossing and can function as a reference reach.

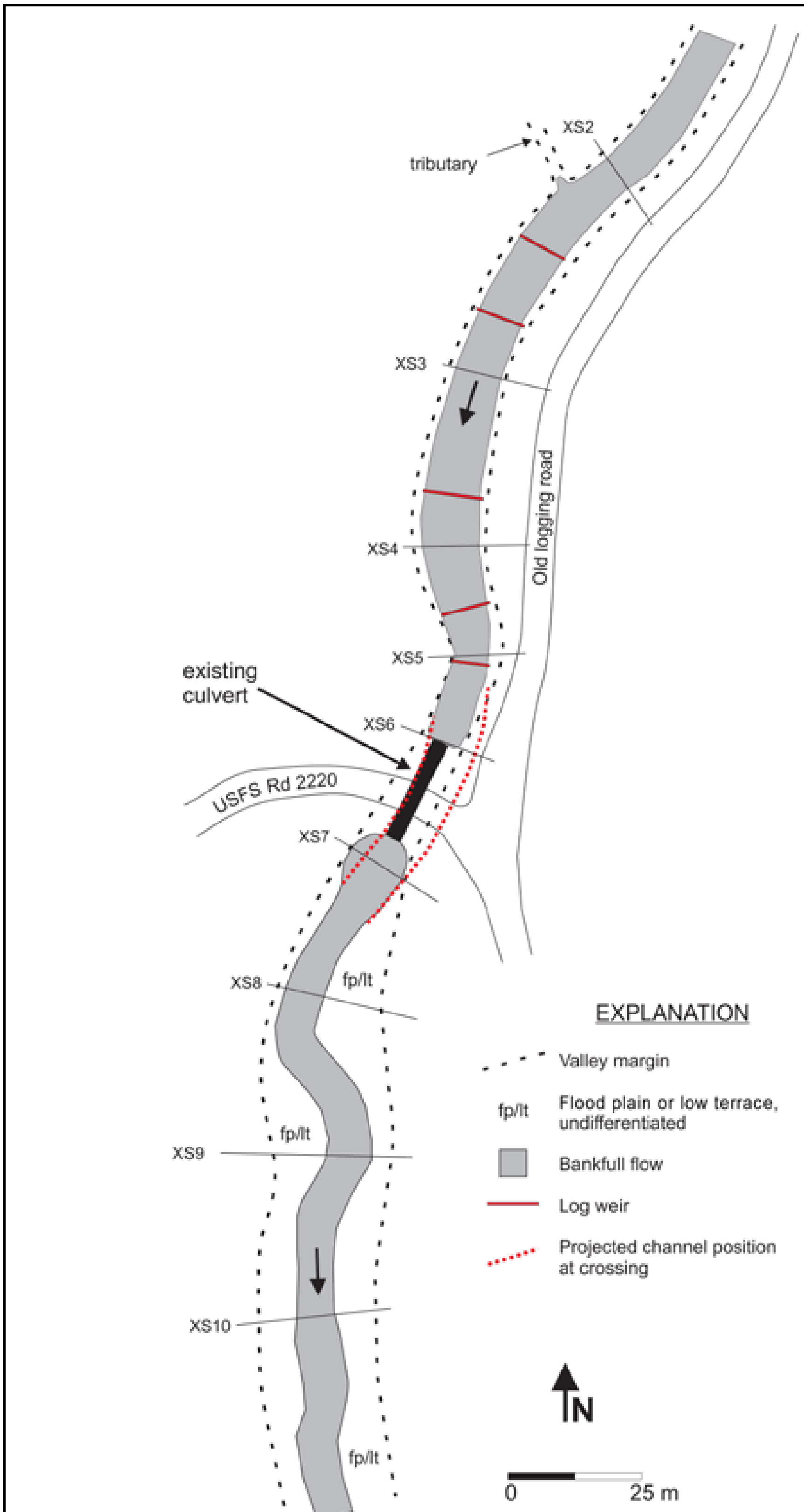

Figure 6.11—Newbury Creek site plan map showing interpretation of natural channel alignment.

segment	elevation change (ft)	segment length (ft)	gradient	% gradient difference between successive segments	maximum residual pool depth (ft)	number of grade controls	distance between grade controls (ft)
A	0.94	53.17	0.0178	n/a	1.54	2	53.2
B	0.41	81.53	0.0050	-71.9	0.34	2	81.7
C	2.68	185.21	0.0145	190.4	1.07	4	62.0, 101.7, 21.6
D	1.78	92.69	0.0193	32.9	2.29	3	57.7, 34.8
E	0.73	11.01	0.0665	245.2	0.99	2	11.2
culvert	0.27	72.09	0.0037	-94.4	4.38	2	72.2
F	5.70	234.28	0.0243	551.5	0.82	3	145.7, 88.6
G	1.27	66.25	0.0192	-21.0	1.70	2	66.3
F,G	6.97	300.53	0.0232	-4.6[a]	1.70	4	145.7, 88.6, 66.3
H	4.69	151.32	0.0309	60.8[b,c]	0.68	3	92.2, 59.1

a. Percent gradient difference when compared to slope segment F.

b. Percent gradient difference when compared to slope segment G.

c. When compared to combined slope segments of F and G, the percent gradient difference is 33.3%

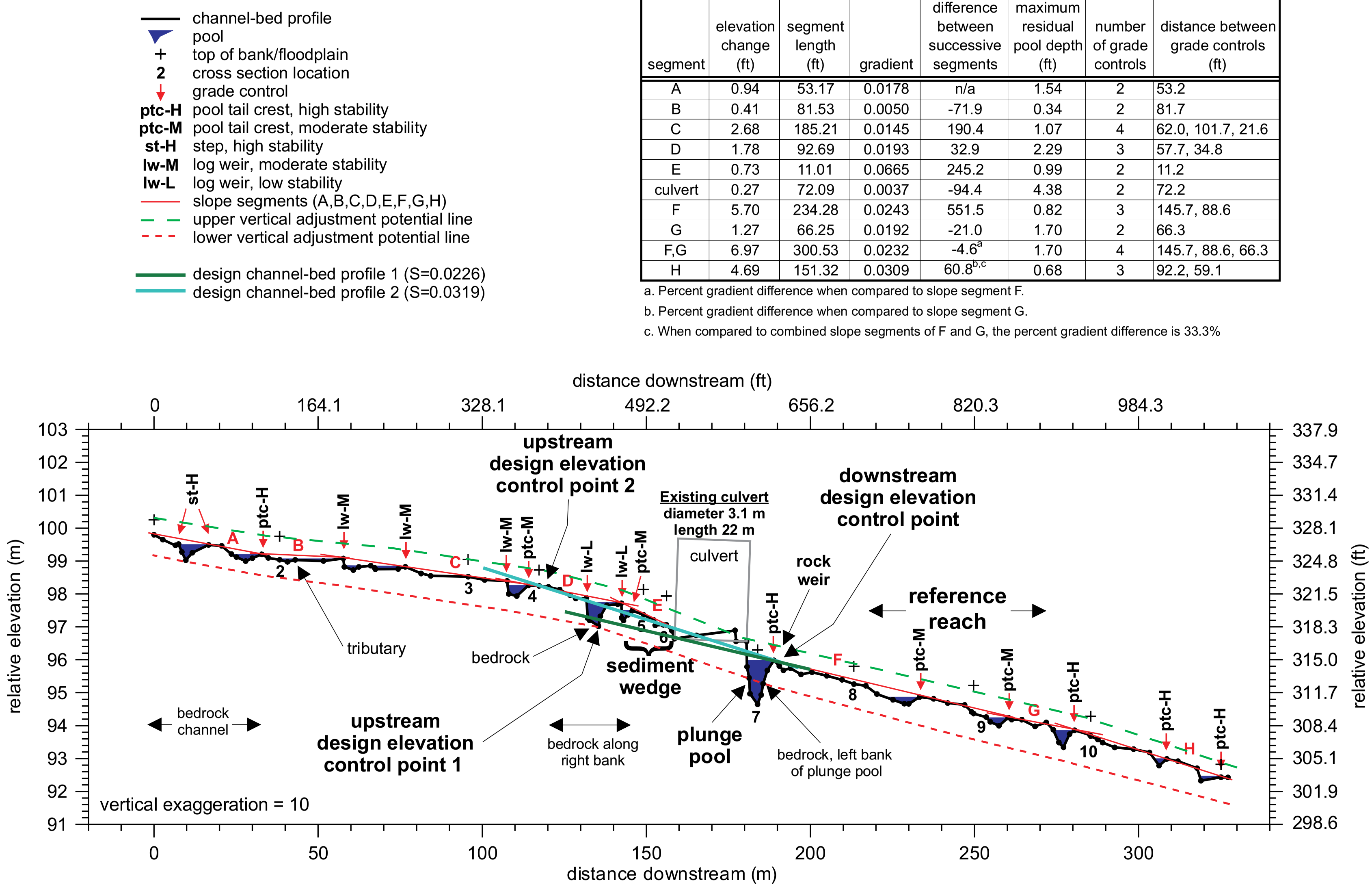

Figure 6.12—Newbury Creek: two possible project profiles.

segment	elevation change (ft)	segment length (ft)	gradient	% gradient difference between successive segments	maximum residual pool depth (ft)	number of grade controls	distance between grade controls (ft)
A	0.94	53.17	0.0178	n/a	1.54	2	53.2
B	0.41	81.53	0.0050	-71.9	0.34	2	81.7
C	2.68	185.21	0.0145	190.4	1.07	4	62.0, 101.7, 21.6
D	1.78	92.69	0.0193	32.9	2.29	3	57.7, 34.8
E	0.73	11.01	0.0665	245.2	0.99	2	11.2
culvert	0.27	72.09	0.0037	-94.4	4.38	2	72.2
F	5.70	234.28	0.0243	551.5	0.82	3	145.7, 88.6
G	1.27	66.25	0.0192	-21.0	1.70	2	66.3
F,G	6.97	300.53	0.0232	-4.6[a]	1.70	4	145.7, 88.6, 66.3
H	4.69	151.32	0.0309	60.8[b,c]	0.68	3	92.2, 59.1

a. Percent gradient difference when compared to slope segment F.
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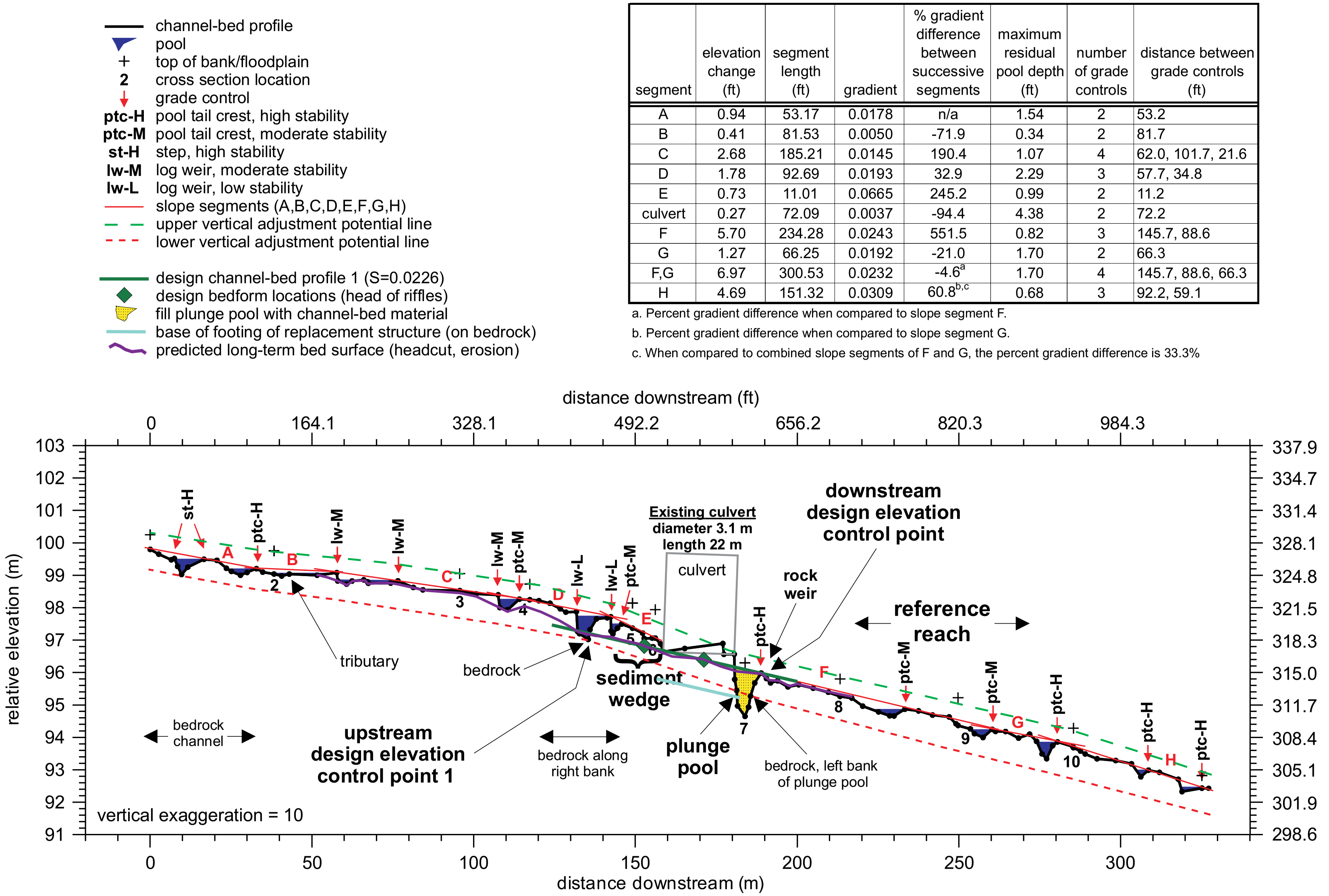

Figure 6.13—Newbury Creek channel profile anticipated after channel response to culvert replacement.

For the steeper alternative profile, the upstream elevation control point is a medium-stability pool tail crest composed of gravel and small cobbles. Slope of this project profile is 3.19 percent, and if it were selected the steepest section of this complex profile would extend through the culvert. Because the grade is about 38-percent steeper than segments F/G, some downstream aggradation might be expected with this alternative; however, as seen earlier, the probability of aggradation is low in this stream. Segment H is steep enough to constitute a viable reference reach for this alternative. Both potential profiles are well within the VAP lines.

The lower gradient project profile was chosen because of the lower risk associated with the lower gradient, and the lack of confidence that the medium-stability pool tail crest (elevation control point 2) would remain stable at the steeper grade. The steeper alternative might have required construction of more grade controls, extending the project's footprint further upstream than the selected alternative.

Figure 6.13 shows the expected final channel profile after culvert replacement, in-channel construction, and projected future channel adjustments. The riffle crests ("head of riffles") are similar in spacing to the pool tail crests in the reference reach. Minor local downcutting may occur upstream of elevation control point 1 as the log weirs deteriorate and fail. Shallow bedrock will limit downcutting, and trees falling into the channel may offset it. The projected final profile in figure 6.13 is an estimate based on all those considerations.

Tongass National Forest, Mitkof Island, Road 6245

The 6245 road crossing is a situation where culvert replacement could have caused unacceptable channel incision. Avoiding incision in this case required modifying the crossing alignment. The example does not showcase an ideal solution; however, it does demonstrate the trade-offs between channel alignment and slope that are sometimes needed. At this site, no ideal solution existed and the final alignment required substantial engineering control.

Existing condition

The unnamed stream at this crossing is a 6- to 10-foot-wide step-pool channel (Rosgen A3) with steps formed of cobbles, boulders, and wood. Average channel slope is 6.4 percent, with short steep segments up to 20 percent. The gravel layer on the streambed is thin, and bedrock outcrops frequently. The existing 36-inch pipe has a slope of 3.5 percent, and was probably constructed with a perch. Currently, the outlet **invert** is perched 2.7 feet above the outlet tail crest of the outlet plunge pool (figure 6.14).

Natural grade controls upstream and downstream of the road indicate that the segment now covered by the crossing was at least 7 percent. Flatter segments where log jams control grade (one is just downstream of the crossing) provide good spawning gravels, which are in short supply in this watershed.

Figure 6.14—Looking upstream at outlet of existing pipe, road 6245. Photo: Chinook Engineering.

The log jam controlling the flat reach immediately downstream of the crossing is only moderately stable, and is likely to readjust or fail over the life of the replacement. The lower VAP line in figure 6.15 (longitudinal profile) accounts for the probability that the log jam may move, and that incision could progress upstream, as sequential steps readjust to the steeper local slope. There is little or no risk of larger-scale (regional) channel incision here.

The existing culvert approximates the natural channel alignment, and it lines up well with the upstream reach. The sharp bend downstream of the outlet is a natural bend, but erosion caused by the crossing has made the bend more acute. The pipe is skewed relative to both the road and the downstream channel (figure 6.15 planview). Issues with both alignment and vertical adjustment potential complicate stream-simulation design at this site.

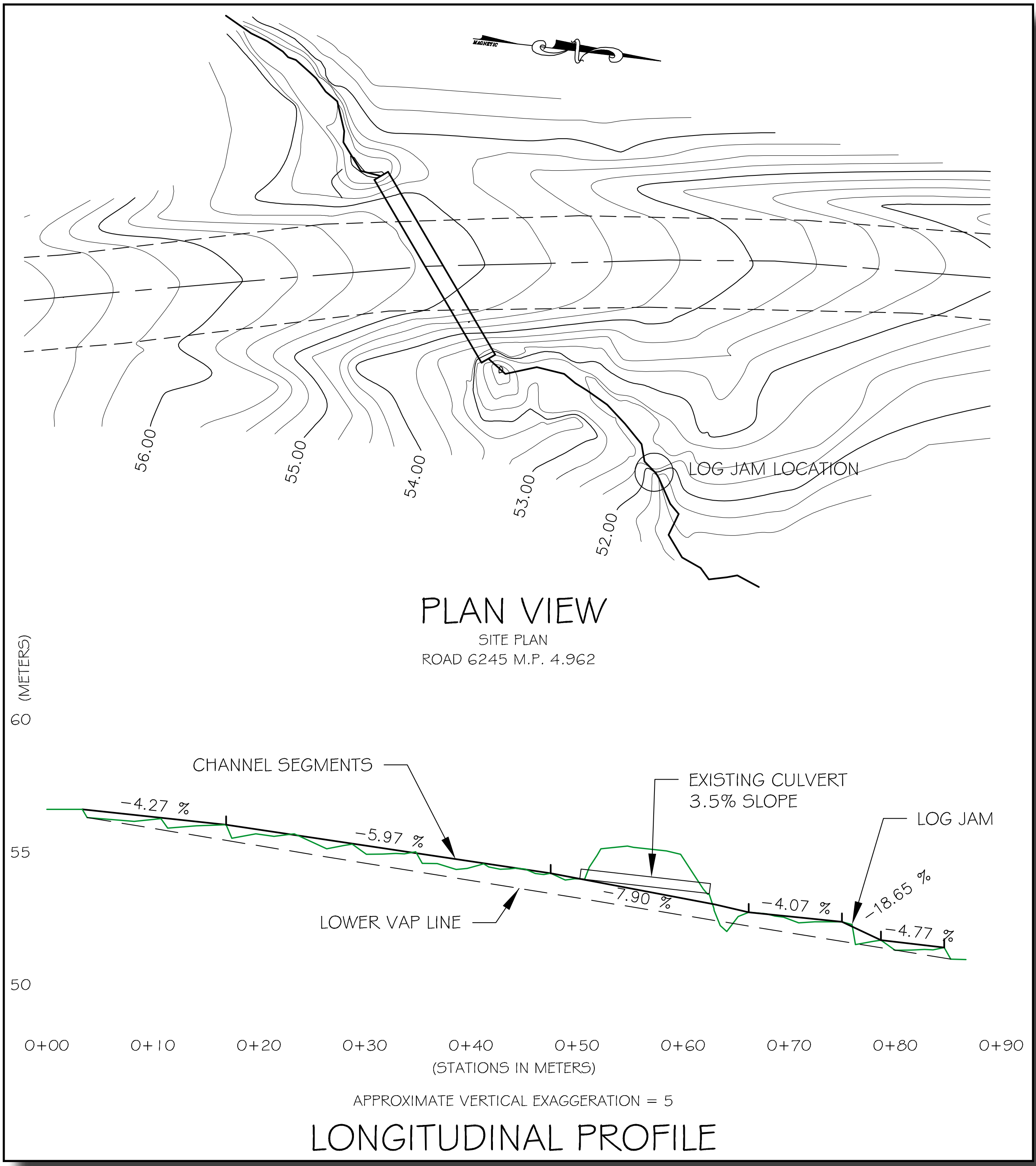

Figure 6.15—Existing condition: planview and longitudinal profile.

Options for stream-simulation replacement

Option 1

Aligning culvert with channel. To improve the culvert's hydraulic alignment, option 1 would increase skew relative to the road and lengthen the pipe (figure 6.16). Both inlet and outlet would be aligned with the stream, but the simulation would be steep—8.5 percent (figure 6.17). This slope is within the range of variability in the natural channel, but segments this steep are shorter than the culvert, and could not function as reference reaches. This alternative is also steeper than the upstream channel segment, and the streambed material for the simulation would need to be larger to achieve stability. In addition, the log jam, which is the downstream grade control, is only 30 feet downstream of the outlet pool in this option. When the log jam moves, incision through the simulation will be a real possibility unless additional grade controls are constructed.

Option 2

Using the existing culvert alignment. This option has similar drawbacks to option 1: it is steep (7.9 percent) and only slightly further upstream from the questionably stable debris jam (figure 6.16). In addition, the bend at the outlet would require bank-stabilization measures.

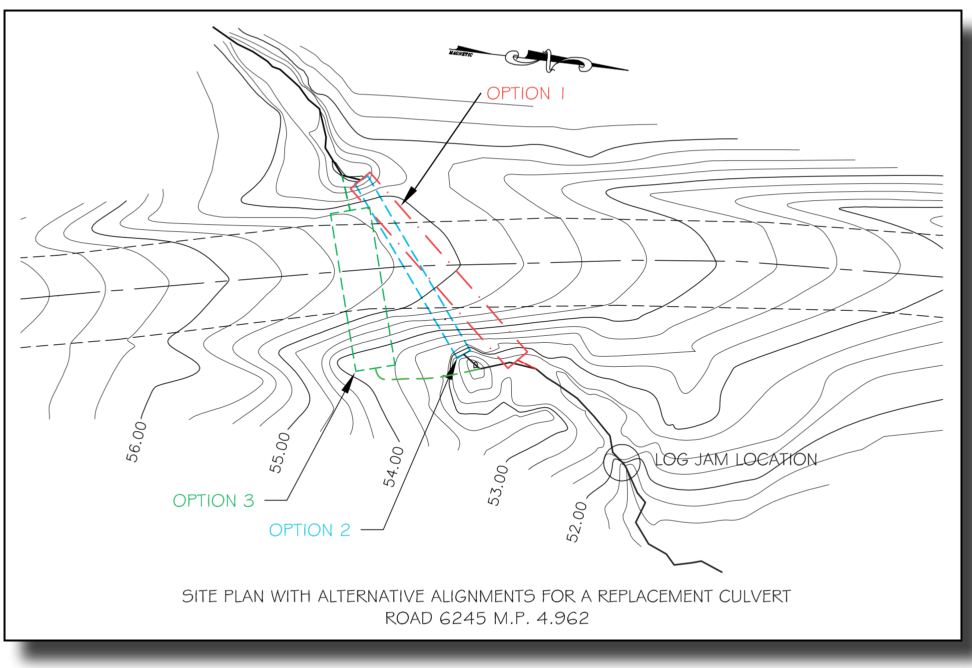

Figure 6.16—Alternative alignmentsfor replacement culvert.

Option 3

Realigning the channel and shortening the culvert. Option 3 accepts a poorer culvert-to-channel alignment at the outlet for the sake of a shorter and flatter pipe, and better control of VAP. The channel downstream of the crossing would be lengthened to meet the outlet of the pipe, which here is placed perpendicular to the road. The added channel length raises the outlet elevation so that culvert slope is only 6.25 percent, near the average channel slope for the entire reach, and only slightly steeper than the upstream reach.

Selected design option

Option 3 was selected largely because no valid reference reach exists in the surveyed longitudinal profile (figure 6.15) for either option 1 or 2. In addition, the steeper culverts in options 1 and 2 would require larger streambed material for stability, creating a risk of loss of surface low flows due to infiltration into the streambed. The simulated channel would also be less self-maintaining because the flatter upstream reach may not resupply the larger bed material as it moves out of the culvert during floods.

In option 3, the simulated channel slope is similar to the slope of the upstream channel, and the simulated streambed is more likely to be self-maintaining; that is, sediment washed out of the simulation will be replaced by incoming sediment of similar size from the upstream reach. The upstream reach will serve as a reference reach. Option 3 constructs 21 feet of new channel at a moderate grade between the culvert outlet and the log jam [figure 6.18(a)]. When the jam does break up and the channel downcuts locally, two rock weirs constructed in the new channel segment will mitigate any risk to the stream-simulation channel in the culvert. A secondary benefit of the new channel segment is that it adds spawning habitat to the reach.

Because of the abrupt bend at the outlet, the culvert-channel transition is very important in this design, to avoid bank erosion and excessive sediment deposition. The design overwidens the bend at the outlet to leave space for a gravel bar that is expected to form at the inside of the bend [figure 6.18(a) and (c)]. Riprap is placed on the outer bank. The two rock weirs below the bend not only stabilize grade, but also bring the **thalweg** to the center of the channel. They are designed to be immobile during the 100-year flood.

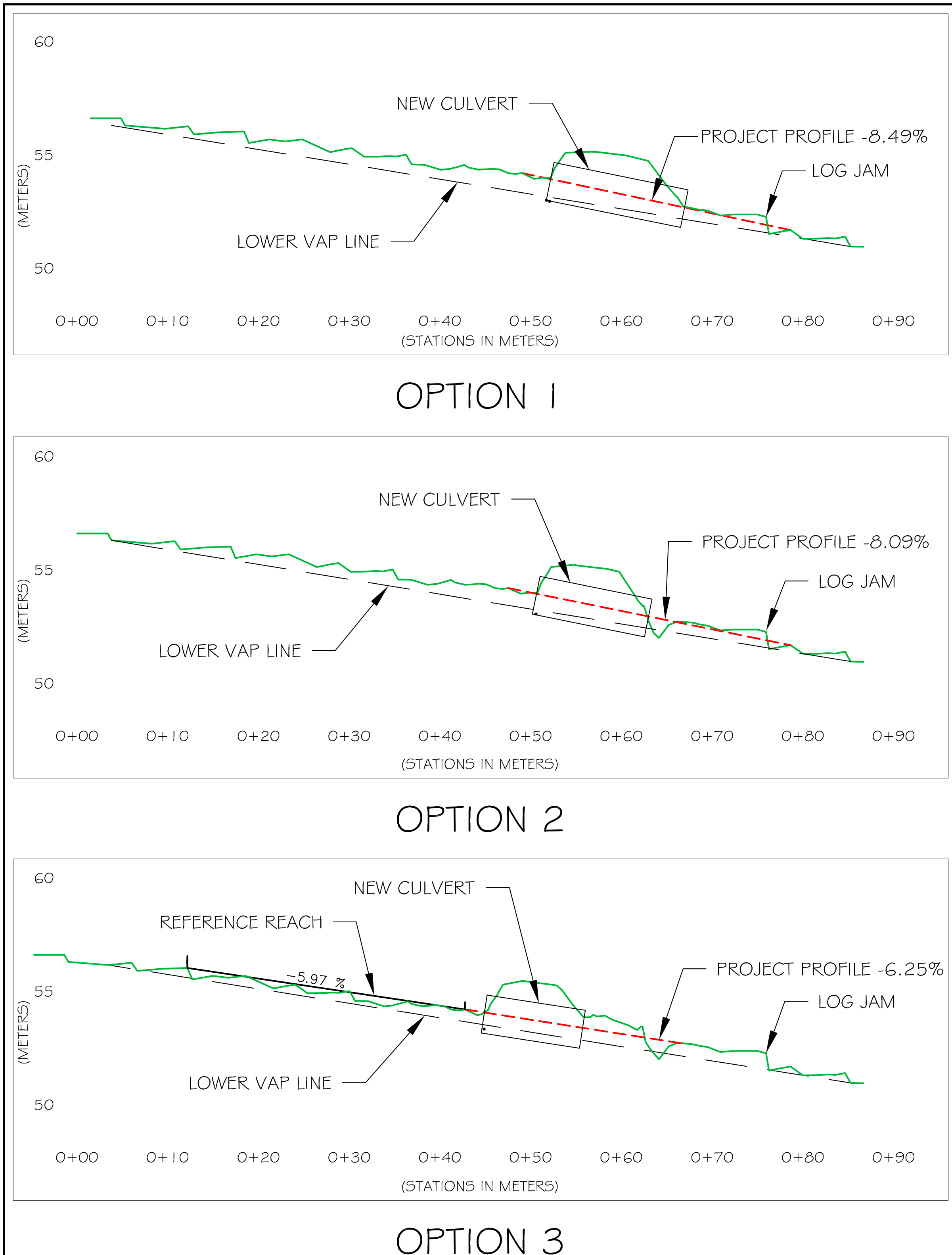

Figure 6.17—Channel and existing ground profiles associated with the alignment options. Project profiles are drawn between stable grade controls.

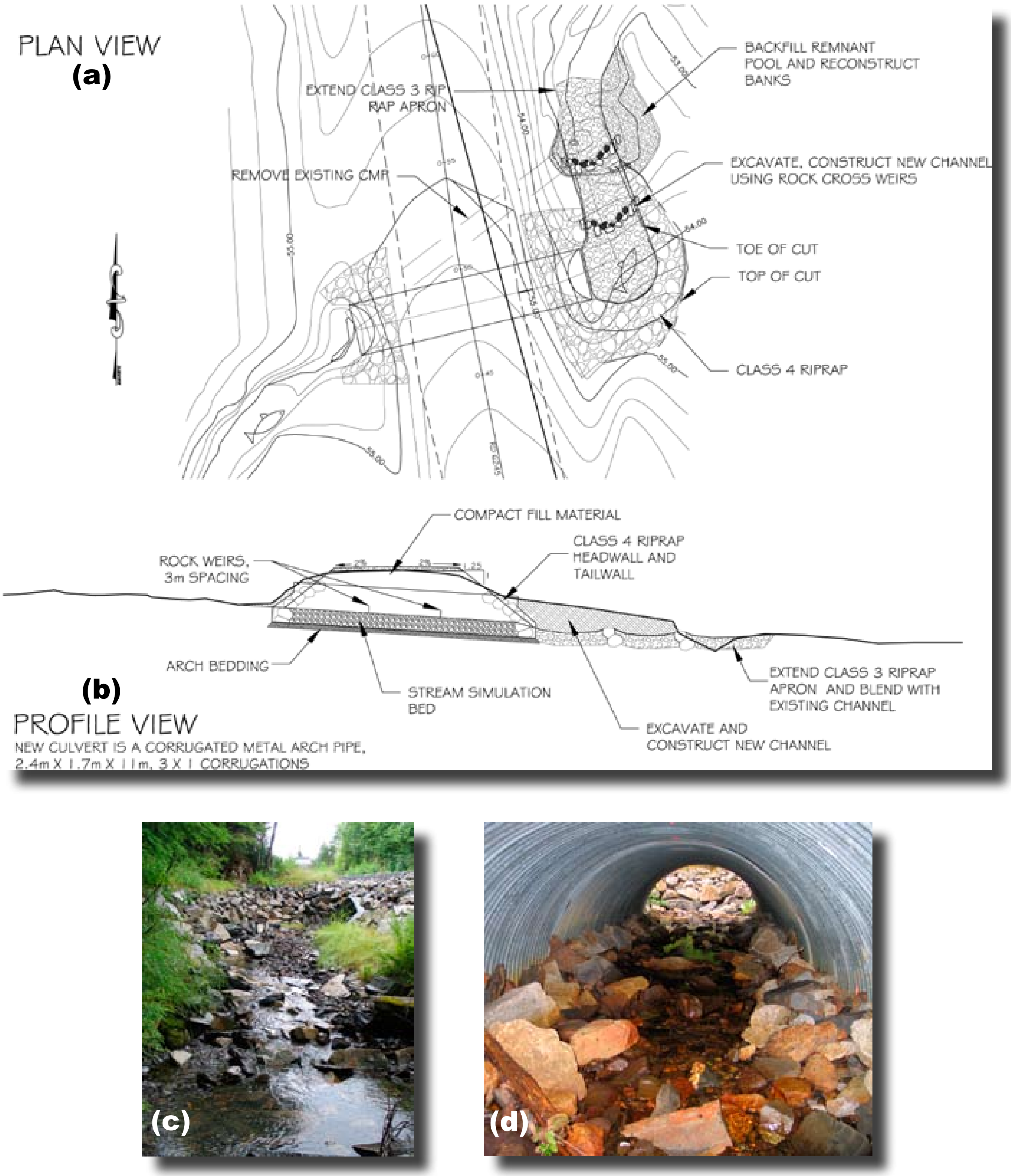

Figure 6.18—(a) Design site plan.(b) Design longitudinal profile. (c) Realigned channel at outlet. (d) Looking downstream through the finished stream simulation culvert. (Design by Robert Gubernick, Tongass National Forest, and Chinook Engineering.)

6.2 DESIGN OF THE STREAM-SIMULATION CHANNEL BED

After determining the best site layout (i.e., horizontal alignment and vertical slope profile), design the stream-simulation channel using the characteristics and dimensions of the reference reach.

This section describes design of the following streambed elements:

- Particle-size distribution of the bed material.
- Channel width and cross-section shape.
- Banklines, margins, and key features.
- Bedforms: pool-riffle, step-pool, or other sequences.

These elements control channel gradient and provide enough **flow resistance** (roughness) to maintain the diverse range of water depths and velocities needed for fish and other aquatic species passage. The reference reach is the template for all these elements. Flood conveyance considerations and other project objectives, such as terrestrial animal movement, will determine the amount of bank space allowed inside the structure.

One of the keys to stream-simulation design is creating roughness conditions that are similar to the reference reach. Total roughness depends on a number of features (see appendix A), including:

- Bed material particle-size distribution.
- Channel shape.
- Bedforms (fixed or mobile).
- Key features that constrict the channel and are major roughness elements.
- Vegetation.
- Bank irregularities.
- Channel bends.

Not all these features can be replicated inside the crossing structure, but the design still needs to approximate total reference-reach roughness. The following sections describe how to simulate those elements that can be simulated. Clearly, since channel bends cannot be simulated (except in very unusual circumstances—see section 6.1.1.3), a straight, uniform reference reach is ideal.

Section 6.2.1 describes basic procedures for designing a simulated stream bed using reference reach characteristics. Section 6.2.2 covers special considerations for specific channel types. The key is to mimic those features in the reference reach that influence channel gradient, energy dissipation, bed stability, and physical and hydraulic diversity.

6.2.1. General Procedures for Simulated Streambed Design

6.2.1.1. Bed material size and gradation in armored channels

Stream-simulation bed material is designed based on the reference reach particle-size distribution (see section 5.1.6.1). It should be well graded (consisting of a wide range of particle sizes), and it must include enough sand, silt, and clay (particles less than 2 millimeters in diameter) to fill voids between larger particles and reduce infiltration into the channel bed. The procedure described here produces a particle size distribution curve that approximates the reference reach. Later in the design process, particle sizes may need to be modified to deal with various risk factors; for example, you might increase particle sizes somewhat if the simulation needs to be slightly steeper than the reference reach (see section 6.5.1). Section 7.4.3 shows how to work the particle-size distribution curve into a contract specification.

If particle size results from a depth-integrated bulk sample of the reference reach are available, the simulation can have the same grain-size distribution as the bulk sample. However, bulk sampling is unusual in coarse-bedded streams because representative samples must be very large(section 5.1.6.1). Usually, stream-simulation bed-material gradation is based on the reference reach pebble count, which represents only the bed surface. In unarmored or weakly armored channels, the surface pebble count characterizes the entire streambed, and the simulation bed mix will have the same gradation as the pebble count. In armored channels, however, the surface pebble count underrepresents the smaller sizes in the subsurface, and therefore the smaller **particle size classes** must be either estimated or calculated. The D_{95}, D_{84}, and D_{50} percentile particle sizes of the reference reach bed become the corresponding grain sizes of the stream-simulation gradation in both armored and unarmored channels.

The smaller grain sizes in the streambed are extremely important for **bed permeability** and stability. A porous bed can allow substantial infiltration and loss of surface flow. The simulation bed mix must therefore have enough fine materials (2 millimeters and finer) to fill the voids between the larger particles. Do not assume that the stream will transport sufficient fines to seal an open-graded bed surface, because a natural filling-in of the voids could take years. Cases exist where the entire summer streamflow infiltrated into the subsurface and flowed through the porous culvert bed for at least a decade after construction. The problem of loss of surface flow is especially critical in steep channels, where bed particles and voids between them are larger, and the steeper hydraulic slope can drive the flow into the subsurface.

Since pebble counts of armored bed surfaces underrepresent the finer material in the subsurface, grain sizes smaller than D_{50} must be determined another way. One method is the equation developed by Fuller and Thompson (1907), which defines dense sediment mixtures commonly used by the aggregate industry. This equation has not yet been widely field-tested for this application, so apply good professional judgment when using it.

The Fuller-Thompson equation is:

Equation 6.1

$$P/100 = \left[\frac{d}{D_{max}} \right]^n$$

where d is any particle size of interest, P is the percentage of the mixture smaller than d, D_{max} is the largest size material in the mix, and n is a parameter that determines how fine or coarse the resulting mix will be. An n value of 0.5 produces a maximum density mix when particles are round.

The Fuller-Thompson equation can be rearranged to base the particle size determination on D_{50} rather than D_{max}. Basing the calculation on D_{50} avoids a discontinuity in the particle size distribution curve, which otherwise occurs when the actual D_{50} is different from the value calculated from D_{max}. The equations for D_{30}, D_{10} and D_5 are:

Equation 6.2 $D_{30} = 0.6^{1/n}\ D_{50}$

Equation 6.3 $D_{10} = 0.2^{1/n}\ D_{50}$

Equation 6.4 $D_5 = 0.1^{1/n}\ D_{50}$

To develop the particle-size distribution curve for the for the finer portion of the simulation bed mix, use n values between 0.45 and 0.70, a standard range for high-density mixes. The goal is a dense, well-graded bed mix with a percentage and type of fine material (sand, silt, clay) similar to the percentage and type in the reference reach subsurface. The fines are essential to limit infiltration into the bed and to help lock the larger pieces together. Type and percentage of fines vary with geology and stream slope, but generally the bed mix should contain at least 5-percent fines. If the D_5 resulting from the Fuller-Thompson equation is larger than 2 millimeters (for n = 0.45, this occurs when D_{50} is larger than 330 millimeters or 13 inches), adjust the mixture so that fines comprise at least 5 percent. If your field estimates of fines (section 5.1.6.1) differ substantially from this, adjust the mixture to approximate the field composition.

Figure 6.19 shows how the results of the Fuller-Thompson method compared to field data for the South Fork Cache la Poudre River (figure 5.6). Field data for the surface armor are from a pebble count. The subsurface particle size distribution curve is from a sieved bulk sample.

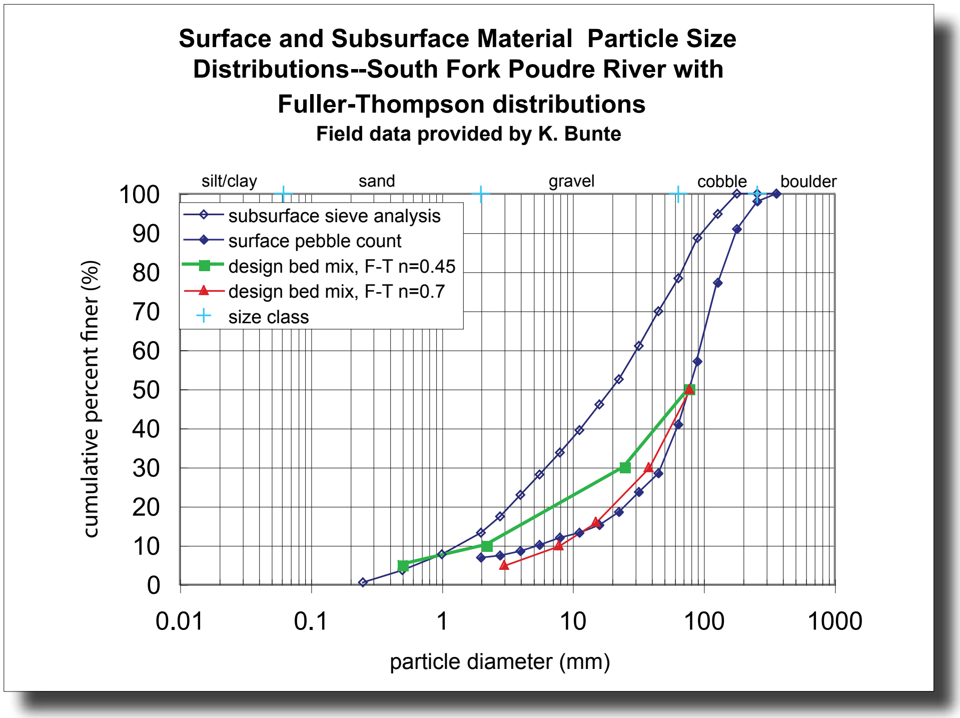

Figure 6.19—Bed material particle size distribution designed using the Fuller-Thompson method, compared to field data for the South Fork Cache la Poudre River. Field data provided by K. Bunte, 2004.

The surface ("pebble count") curve in figure 6.19 was used directly to define the larger particles of the design gradation. The lower half of the particle-size distribution curve can be anywhere between the two Fuller-Thompson distributions (labeled "F–T") with n values of 0.45 and 0.70. In this case, selecting an n value of 0.45 produces a gradation with approximately 10-percent finer than 2 millimeters, a percentage close to the actual fines content in the subsurface.

Using the Fuller-Thompson method does not reproduce the natural subsurface particle size distribution in the reference reach subsurface, but it does result in a dense, well-graded distribution. Similar results may be obtained by smoothly redrawing the lower half of the particle size distribution curve by hand, such that the tail has an appropriate percentage of fines smaller than 2 millimeters.

Note that these design procedures result in a bed mix that is coarser overall than the reference reach subsurface gradation. This constitutes a safety factor for the simulated bed; if the bed scours, there will be additional armor material below the surface, and the resulting bed surface will become coarser and rougher.

The method of deriving a design gradation from the pebble count is not critical. What is critical is that the design gradation have the following key characteristics:

- Large particles (D_{95}, D_{84}, and D_{50}) that provide **bed structure** and buttress finer material should be accurately sized based on the reference reach. In channels where wood controls or influences the channel form, structures composed of angular rock can substitute for wood to simulate channel features in the crossing structure (see section 6.2.1.5).
- The entire bed mix should be **well graded** (poorly sorted). A dense, stable bed requires all particle sizes, so no gap in sizes should exist between any classes of material in the design bed mix. Ideally, each class of bed material that makes up the mix will be well graded, so that all sizes within the category are represented. This representation is especially important for the smaller-size fractions in a mixture that includes large particle sizes.
- The percentage of sand, silt, and clay should approximate the reference reach channel bed subsurface (visually estimated, see table 5.5), and should be adequate to limit bed permeability by filling voids between the larger particles. Including sand, silt, and clay in the simulation bed material commonly arouses concerns about

water quality and habitat impacts, because some fine sediment in a freshly constructed bed will move during low flows, and could affect downstream fish habitats. Any such effects can be limited during construction by using water to wash the fine material down into voids between the larger particles in the bed (sections 7.5.2.3 and 8.2.11.2).

- Bed material rock should be durable, and it should be at least as angular as in the reference channel. If it is less angular, it may be significantly more mobile than intended. It makes sense to try to find local material, as it will more likely resemble the natural bed material.

6.2.1.2 Channel cross section

The width of the simulated channel is typically the bankfull width of the reference reach or greater. This is not necessarily equal to the culvert width (see section 6.3 for selecting culvert dimensions). Bank features and/or overbank flow surfaces may require additional culvert width.

In channels with **mobile beds** (dune-ripple, fine-grained pool-riffle), complex channel shapes like those that develop over time in a natural channel need not be constructed. However, some bank features should be constructed to set the stage for channel margins to develop (figure 6.20). Without constructed features, the bed initially tends to flatten into an unnatural flat surface. Then, the main thread of flow often migrates to the culvert wall and progressively erodes a trench along the wall.

In mobile channels, in addition to banks and any other key features, a roughly V-shaped low-flow channel can be constructed to help keep flow from hugging the culvert wall until a natural bed structure develops. The V-shape is not intended to persist; when high flows occur, they will redistribute the bed material and construct a diverse channel with a natural thalweg. The precise shape of the V-shaped initial low-flow channel is not critical; the channel in figure 6.20 has a 5h:1v lateral slope which is a reasonable starting point.

Stream simulations in less mobile channels are often constructed with some initial bed structure such as steps. Specifics for each channel type are described in section 6.2.2.

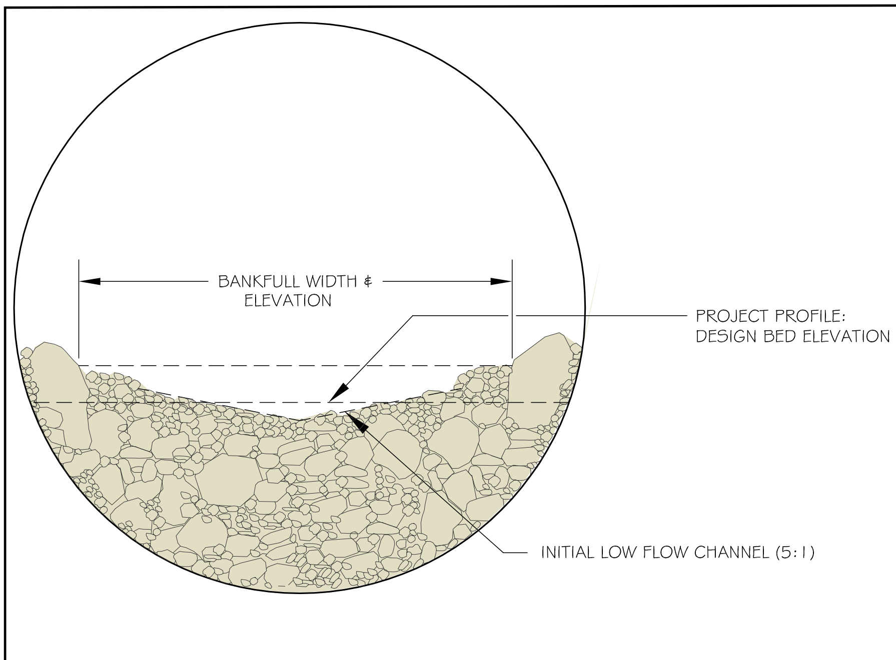

Figure 6.20—Channel cross-section shape in a stream-simulation channel with rock banks.

6.2.1.3 Bank and channel margin features

In natural channels, the diversity, roughness, and shape of channel margins and banklines are critical for movement of some species. For example, terrestrial animals may need dry passage; weak swimmers and crawling species may need margins of slow, shallow water with eddies in which they can rest. At flows between low-flow and bankfull, channel-edge diversity is necessary for accommodating the different movement capabilities of all aquatic species. Banks must continue through the inlet and outlet transitions.

Bars may form in a crossing structure—perhaps on just one side or through part of its length—and they may provide some of the benefits of a bankline. However, without root structure, cohesive soils, or the ability to scour into parent bed material, true banklines will not form naturally inside the structure. Therefore, specific channel-margin features should be designed into the project when they are needed for hydraulic roughness, habitat diversity, or for preventing channel trenching along culvert walls and protecting footings from scour. In designing the bankline/margin, use the reference reach bank height and bankline diversity (including frequency and size of wood or rock protrusions) as a guide. Where wood is an important feature on the channel banks, use permanent rock to simulate its functions.

Because the intent is to create permanent bankline features, use material large enough to be stable during the **high bed design flow**. In the absence of vegetation, bank stability inside the structure will depend primarily on rock size, packing, clustering, and embedment. Base an initial estimate of rock size on the reference channel. As a starting point, bank material might be up to twice the size of D_{95} in the reference reach. If D_{95} is 3 inches or less, you can use 6-inch-minus quarry spalls or other rock. The size of rocks that appear to be immobile in the reference reach may also be a clue to sizing bankline rocks. Later in the design process (section 6.4.2), a stability analysis will verify that the bank rock and other key pieces are large enough to be immobile.

The simplest **bankline** is an irregular line of large rock placed along each wall (figure 6.20). Most natural banks are rougher and more diverse than that, and a discontinuous line of rocks or rock clusters may better simulate the reference reach (see figure 6.21). Clusters of rock obstruct any tendency to scour along the culvert wall, and help create the bed diversity that exists in natural channels where water deflects off bankline irregularities like woody debris or root-wads. Fill the spaces between individual bank rocks and between the rocks and the culvert wall with 'filler' material (section 7.5.3), so that the finer material helps to stabilize the larger rocks.

Overbank flow surfaces, or flood-plain benches, are sometimes constructed inside culverts (see 6.5.1.1). Construct them the same way as bank clusters or banklines, with the entire surface being stable rock infilled with filler material. The flood-plain bench should start at bankfull elevation on the margin of the bankfull channel, and slope up and out at about 10h:1v (figure 6.22).

One way of simulating a bankline in an open-bottom arch might be to roughen the concrete stem wall using embedded rocks or shaped concrete elements built into the wall. To our knowledge, no one has tested this method.

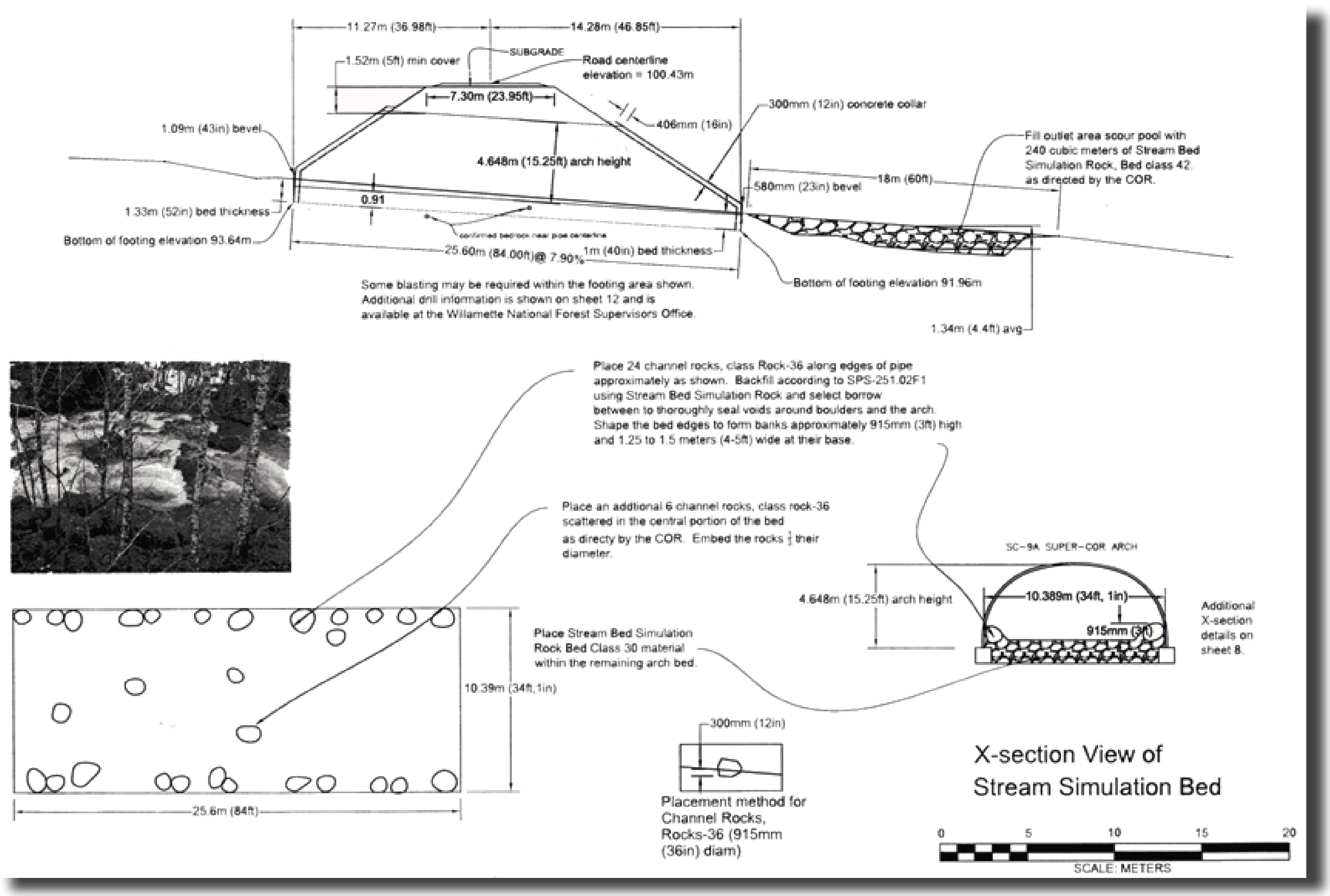

Figure 6.21—Open-bottom arch stream-simulation design showing bankline diversity. Design by Kim Johansen, Ore Creek, Siuslaw National Forest.

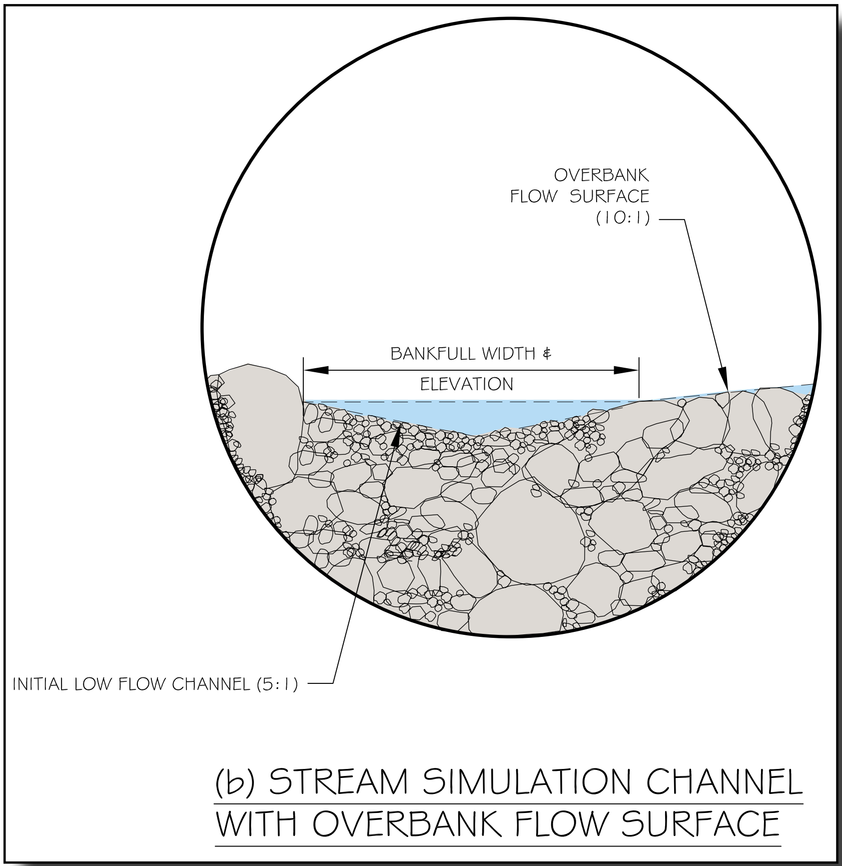

Figure 6.22—Stream-simulation channel with overbank flow surface.

6.2.1.4. Key features

Many forest streams have highly stable features, such as large wood, embedded or jammed wood, and large boulders, which may have fallen or slid into the stream or are remnants of glacial action. Other woody debris in the reference reach might take the form of small jams, buried wood that buttresses the bed and/or forms steps, or wood protruding from a bank. These 'key features,' often partially buried in the bed, may block part of the channel cross section and are long-lasting grade control and/or energy dissipation structures in the channel. Key features also include stable steps and **imbricated** or well-packed riffle crests that move only in infrequent high flows.

Functions of these key features that need to be replaced in the simulated channel include buttressing the bed material and controlling grade, providing diverse hydraulic conditions that aquatic species can use for cover and resting areas, and providing hydraulic roughness.

Streambed mobility is discussed in sections 5.1.6.1 and 5.1.6.2

In current practice, key-feature roughness is simulated directly by imitating the size and distribution of individual elements using rock. Intermediate-mobility riffle crests and steps are constructed using rock sized like the rock forming those features in the reference reach (section 6.2.2.2). In the site assessment, separate measurements of 10 to 25 rocks from key features like riffle crests and steps were taken (section 5.1.6.1) as the basis for specifying rock sizes for these features. Slightly larger rock sizes, or more angular rock, may be needed to simulate the stabilizing effects of imbrication and particle packing in the natural channel that cannot be replicated in the simulation. Later in the design process (section 6.4), a bed mobility analysis will be conducted to check that these rocks are sized properly and will be as stable in the simulated channel as in the reference reach. In chapters 7 and 8—dealing with construction and contracting—these key-feature rocks are referred to as "**channel rocks**." Various size classes of channel rock may be specified to simulate different channel-bed features.

Key features, such as embedded logs, often span the entire channel, and you should simulate them that way, constructing them like a step (see section 6.2.2.4), and simulating the height of the features in the reference reach. A cluster of rocks jutting out from the culvert wall can simulate a bank log in a natural stream, providing some edge diversity and helping prevent a low-flow trench next to the culvert wall. If space permits, simulate the roughness and functions of scattered or clustered boulders in the reference channel by placing the same general size and pattern of rocks in the stream simulation.

An alternative method of simulating roughness created by individual roughness elements in the reference reach would be to measure the total frontal area of all roughness elements in the reference channel and use boulders to reproduce it in the simulation. Ferro (1999) describes a method of quantifying the roughness created by various arrangements and concentrations of boulders placed on a gravel streambed. To our knowledge, this method has not yet been applied to stream-simulation design.

For immobile key features, mimic the size of immobile rocks in the reference channel, and/or do a stability analysis (section 6.4). Rocks locked together in clusters are more stable than individual rocks and can be somewhat smaller. Angular rock is more stable than round rock. For these permanent key features, you can over-design rock sizes to reduce the risk of failure.

To protect the culvert floor, place large rocks carefully by embedding them into the bed mix rather than allowing them to drop directly on the culvert floor. Careful construction is essential, especially in steeper (greater than 6 percent) channels where less experience with stream-simulation construction exists. Energy dissipation by key features is critical for the stability of steep channel designs; if possible, consult with experienced stream-simulation practitioners about steep simulated-channel designs.

6.2.2. Bed Design Considerations for Specific Channel Types

This discussion uses the channel classification system developed by Montgomery and Buffington (1997).

The general procedures described in section 6.2.1 apply to all channel types. This section describes additional bed design considerations that apply to specific channel types. Table 6.5 summarizes important channel bed characteristics and channel design strategies for each type.

6.2.2.1. Dune-ripple channels

Although dune-ripple channels are usually sand-bed streams (table 6.5), for design purposes we include channels with fine- and medium-gravel beds (D_{max} is medium gravel, 16 millimeters or smaller). Creating custom bed material gradations (section 6.2.1.1) with these materials is impractical because D_{95}, D_{84}, D_{50}, etc., are close in absolute size. In addition, custom bed material designs usually are unnecessary for these fine materials. The bed typically mobilizes during moderate flows, and bed material turnover occurs frequently. Bank features may need to be constructed to avoid culvert wall trenching by providing edge diversity and the roughness present in the reference reach.

You might choose to allow the culvert to fill naturally with bed material if **sediment loads** are high and/or the culvert is backwatered by the downstream channel. This technique, however, has the potential to create a headcut in the upstream channel. Native bed material approximating

Table 6.5—Bed material design considerations for various channel types

REFERENCE CHANNEL TYPE	TYPICAL CONDITIONS[1]			STREAM-SIMULATION DESIGN STRATEGIES
	Bed material	Dominant roughness and structural elements[2]	Streambed mobility	
Dune-ripple	Sand to medium gravel	Sinuosity, bedforms, banks. Small debris may provide structure.	Termed "live bed"; significant sediment transport at most flows.	• Simulated bed can be native bed material or imported dense mix based on reference reach. • Rock clusters (key features) added to simulate diversity from wood and bank shape. • Key features and banks designed to be immobile.
Pool-riffle (mobile)	Fine to coarse gravel	Bars, pools, grains, sinuosity, banks	Bed is often armored; usually mobilizes near bankfull.	• D_{95}, D_{84}, D_{50} based on reference reach. • Material smaller than D_{50} is dense mix based on D_{50}. (section 6.2.1.1) • Key features (rocks or rock clusters in bed and/or banks) added for diversity. • Key features and banklines designed to be immobile.
Pool-riffle (intermediate mobility)	Coarse gravel to cobble	Bars, pools, grains, sinuosity, banks	Finer sediment moves over immobile armor layer at flows near bankfull. Armor layer mobilizes at higher flows.	• D_{95}, D_{84}, D_{50} based on reference reach. • Material smaller than D_{50} is dense mix based on D_{50}. • Riffle crests constructed with material sized based on riffle crests in reference reach. • Key features, banklines designed to be immobile.
Plane-bed	*Gravel to cobble, usually armored*	*Grains, banks*	*May be either 'mobile' or 'intermediate mobility' (see pool-riffle).*	• *D_{95}, D_{84}, D_{50} based on reference reach.* • *Material smaller than D_{50} is dense mix based on D_{50}.* • *Key features, banklines designed to be immobile.*
Step-pool	*Cobble to boulder*	*Steps, pools, banks. Debris may add significant structure.*	*Fine material moves over larger grains at frequent flows. Bed-forming rocks move at higher flows depending on size; often >Q_{30}*	• *Steps are spaced similar to reference reach* • *Step-forming rocks are sized to be immobile.* • *Smaller material size distribution is dense mix based on D_{50} of material other than steps in reference reach* • *Banklines designed to be immobile.*

[1] *Based on Montgomery and Buffington (1997) with some modifications.*

[2] *Woody debris can be an important structural feature in any channel type.*

Table 6.5—Bed material design for various channel types (continued)

REFERENCE CHANNEL TYPE	**TYPICAL CONDITIONS**[1]			**STREAM-SIMULATION DESIGN STRATEGIES**
	Bed material	**Dominant roughness and structural elements**[2]	**Streambed mobility**	
Cascade	Boulder	Grains, banks	Smaller bed material moves at moderate frequencies (floods higher than bankfull). Larger rocks are immobile in flows smaller than ~Q_{50}.	• D_{95}, D_{84}, D_{50} based on reference reach. • Smaller material size distribution is dense mix based on D_{50}. • Key features, banklines designed to be immobile.
Bedrock	*Rock with sediment of various sizes in transport over rock surface*	*Bed and banks.*	*Bedload moves over bedrock at various flows depending on its size. May be thin layer of alluvium over bedrock. Wood can strongly affect sediment mobility.*	• *Stream simulation bed is bedrock.* • *Banklines and roughness elements are important but difficult to design as stable.* • *Condition, extent, and shape of bedrock are important.* • *Bottomless structure reduces rock removal compared to full pipe and can be anchored and shaped to rock.*
Channels in cohesive materials	*Silt to clay*	*Sinuosity, banks, bed irregularities*	*Fine sediment moves over immobile bed at moderate flows depending on its size. May be thin layer of alluvium over immobile bed.*	• *Stable cohesive bed and banks cannot be constructed in culvert.* • *Culvert walls may simulate smooth natural clay banks.* • *Bottomless structure might leave clay bed undisturbed.*

[1] Based on Montgomery and Buffington (1997) with some modifications.

[2] Woody debris can be an important structural feature in any channel type.

the reference reach size distribution may be available from the crossing excavation. If so, use it to fill the culvert. Since dune-ripple channels are not armored, mixing and replacing excavated bed material carries no great risk. Either use the bed material by itself, or supplement with imported material to make up the required channel-fill volume.

To achieve more or less the same initial mobility, use material that is similar to (and not larger than) the reference reach bed material. Rounded river rock is not always available as fill material, and quarried angular rock can be substituted. However, recognize that sediment mobility for angular rock may initially be somewhat lower than in the adjacent reaches. Including fines for sealing the bed is not necessary in these mobile channels.

Bed structures form readily in fine-grained channels, so building structure into the simulated channel generally is unnecessary. Nonetheless, consider the roughness characteristics of the reference reach. Small pieces of debris scattered and partially buried in the bed stabilize some fine-grained channels at slopes steeper than they would otherwise be. Although the small wood will be transported into the simulated channel over time, you may need to place it during construction if it is critical for maintaining initial slope. Again, bank features also may be needed to simulate the reference reach.

Dune-ripple streams are usually—though not always—unentrenched, and overbank flood-plain flows may occur frequently. The design issues associated with the road fill obstructing flood-plain flows (see section 6.5.1.1) can be very important. To accommodate some flood-plain flow and to avoid excessive bed and outlet scour at the culvert during floods, banklines and a flood-plain surface may be important components of a dune-ripple channel simulation. Off-channel flood-plain drainage structures also may be important.

6.2.2.2 Pool-riffle channels

The basic design process described in section 6.2.1.1 applies directly to mobile pool-riffle channels. For pool-riffle channels of *intermediate* mobility, riffle crests may need to be constructed as key features (6.2.1.4). Place constructed riffle crests or bars at locations on the project longitudinal profile where a riffle crest would naturally fit. Locate the riffle crests based on average riffle crest spacing in the reference reach unless the crossing site includes a channel bend where a pool is expected to form.

In that case, locate the riffle crests where they would naturally fit upstream and downstream of the pool. Then, place any other constructed riffle crests at spacings within the range found in the reference reach (see riffle spacing, figure 5.19).

A constructed riffle crest is a structure that spans the channel as illustrated in figure 6.23. Rocks of similar size to reference reach riffle crest particles compose the structure (see section 5.1.6.1 for assessment procedure), and it is constructed with a low point in the center of the channel to help form the low-water channel. The objective is to establish grade control and energy dissipation structures with spacing and mobility similar to the reference reach.

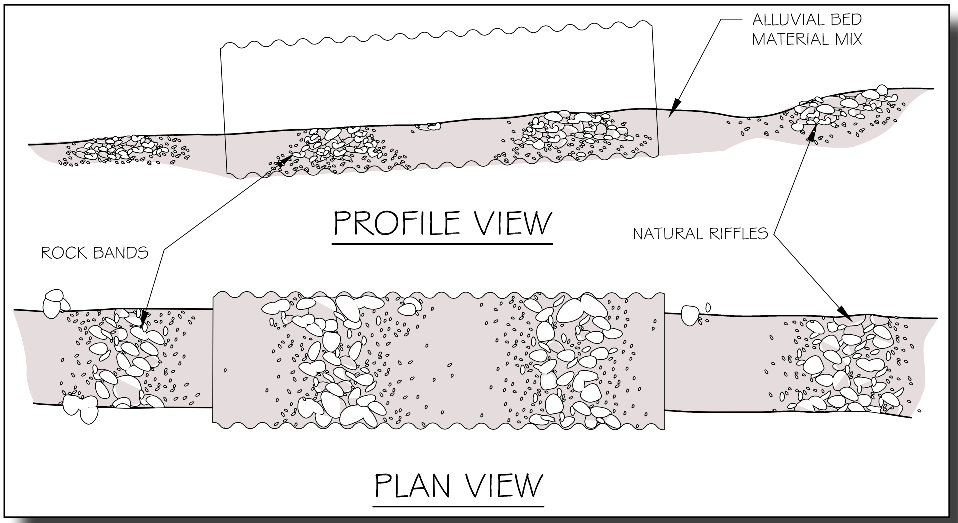

Figure 6.23—Placement of constructed riffle crests to simulate natural riffle crests of intermediate mobility.

Refer to the Newbury Creek site assessment text boxes throughout chapter 5. They begin in section 5.1.1.

Where imbrication, **embeddedness**, or any mode of particle packing increases the stability of riffle crests in the reference reach, constructed riffle crests will not achieve the same stability unless they are carefully constructed to replicate the particle packing. Figure 6.24 shows an example design, done by the Olympic National Forest project team for the simulated channel at Newbury Creek, which required constructing riffle crests by embedding rocks in an imbricated pattern. Recall that this is a cobble-bed pool-riffle channel, where riffle-crest materials are not mobilized until flows substantially exceed bankfull. Because the team did not expect bed structures to form rapidly, it decided to construct them. The **transverse bars** in figure 6.24 are analogous to riffle-crests in the reference reach. Rock spurs jutting out from the culvert wall mimic the indented and debris-strewn bankline in the reference reach. (see photo, figure 5.10).

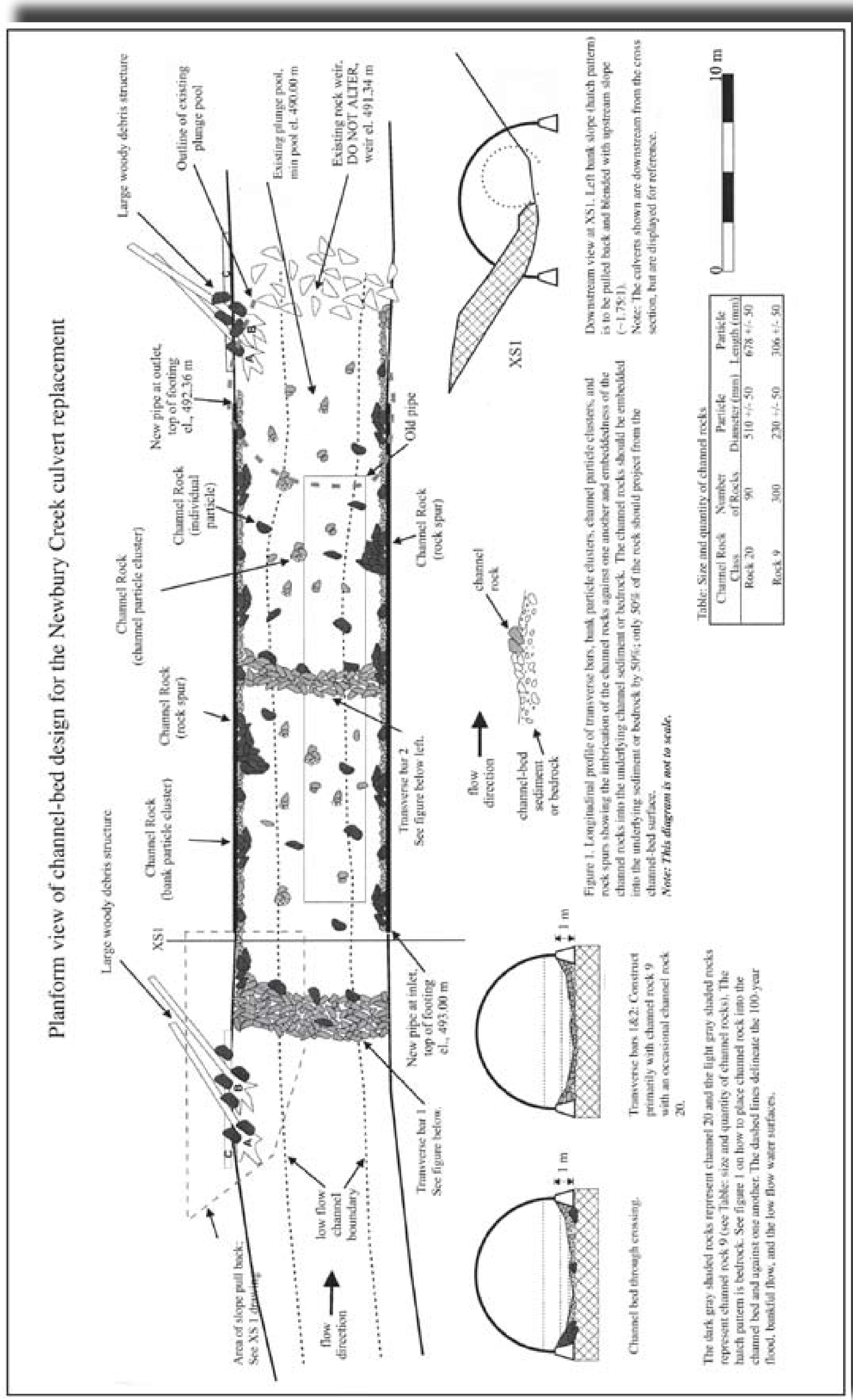

Figure 6.24—Newbury Creek stream-simulation design, Olympic National Forest. See chapter 5 for site assessment information.

6.2.2.3 Plane-bed channels

Plane-bed channels do not have regularly spaced bedforms. In these channels, although the bed is relatively featureless, large rocks protrude from the water surface at most times of the year. The basic design process (6.2.1.1) applies to plane-bed channels. Rock clusters along the culvert walls are recommended for helping to keep the thalweg from trenching along the wall and for fostering sediment deposition on channel margins. Bank features are important, because the bed itself has less hydraulic diversity than most channel types.

6.2.2.4 Step-pool channels

In this channel type, both steps and pools are important for energy dissipation and channel stability. Steps form when the largest particles in the bed congregate and support each other, creating a bedform that is more resistant to movement than the individual pieces. Usually boulders or logs form the step framework, which supports smaller cobbles and gravels. In nature, steps can take several decades to form (Madej 2001), depending on when channel-organizing flows occur and what key features are present. Bed-organizing flows are generally higher than bankfull; depending on the size and embedment of the step-forming materials, steps may not form at flows less than the 30-year flow or higher (Grant et al. 1990). Because steps are critical for energy dissipation and channel stability but are unlikely to form naturally in a short period of time, they should be constructed and monitored carefully after high flows.

Base step height and length on the reference reach, and keep step spacing within the range of variability observed in the reference reach (see figure 5.19). This ensures that step spacing is similar to the reference reach, while still allowing enough flexibility to tie the step-pool sequence into the stable profile endpoints. It also permits you to accommodate a channel bend that forces a pool in a specific location on the project plan and profile. Spacing is important because pools large enough for adequate energy dissipation must have room to develop, and each step affects the stability of the adjacent one. Steps in natural channels are typically spaced one- to four-channel widths apart and are closer in steeper channels.

To construct the steps, use rocks at least as large as the step-forming rocks in the reference reach. The rocks should have similar roundness or angularity. Embed or layer the rocks to below the expected depth of pool scour in such a way that the lower rocks support those above them. Construct steps with the expectation that individual rocks will adjust their position during high flows and lock together. Until the larger particles adjust and support each other, they are vulnerable to being scoured out of the culvert. Therefore, a conservative objective—designing the steps to be immobile for the life of the project—is a wise approach (section 6.4).

In a step-pool channel, even with a bankfull-width culvert, bed-organizing flows may be more confined than in the natural open channel, and shear stress in the culvert may be higher. Steps may not reform inside the culvert if the constructed ones wash out. For this reason and because of the potentially long time before new boulders might be recruited during subsequent high flows, designing steps for immobility is common practice. You can increase rock angularity and/or size (as compared to the reference reach) to increase stability.

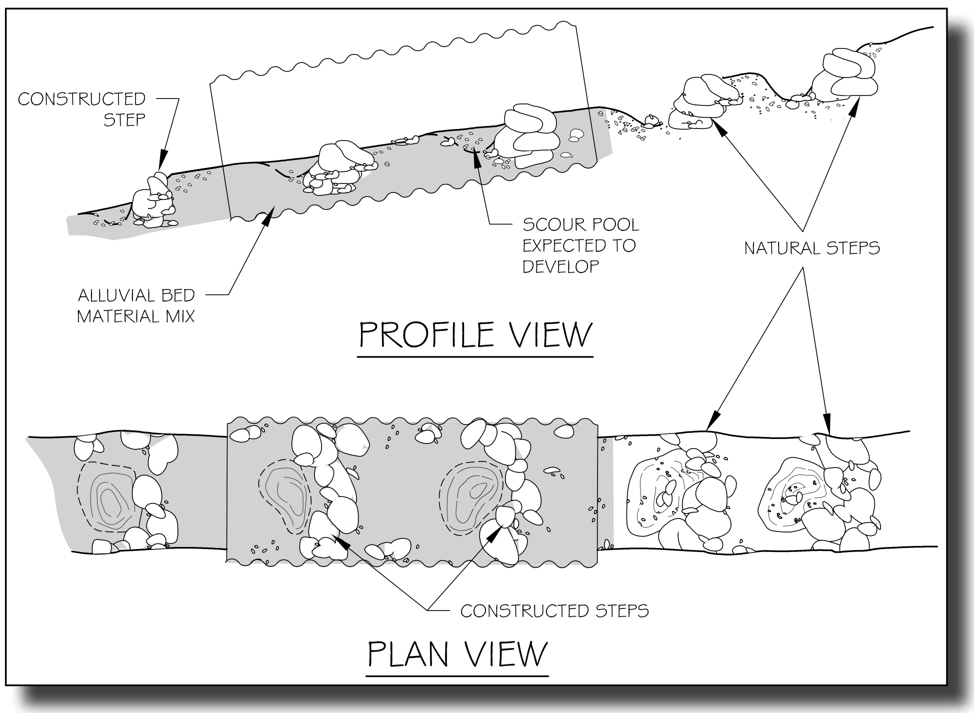

Figure 6.25—Schematic of step-pool stream-simulation design.

Aside from the steps themselves, design the step-pool bed mix based on the reference channel pebble count (see basic design process, section 6.2.1.1). Frequent high flows scour and replenish the finer material between steps as bedload moves through the system.

Once the steps are in place, pools will form naturally during moderate flows and generally do not need to be constructed. Pools are typically wider than steps, and the simulated channel should be as wide as maximum pool width in the reference reach. This will allow pools to form that are large enough to achieve the same degree of energy dissipation as in the reference reach.

As a safety factor in steep (greater than 6 percent) simulations, bed retention sills are sometimes used for buttressing the steps and preventing material from sliding or washing out of the culvert. These sills may consist of metal, wood, or logs fastened in place. Unlike baffles, bed retention sills are not intended to control water velocity, and they do not extend above the surface of the streambed. Neither are they intended for placement in a bare pipe to trap bedload in transport. Place the tops of the sills below the lowest potential bed profile (lower VAP line), so that they will not be exposed above the streambed surface over the project lifetime (figure 6.26).

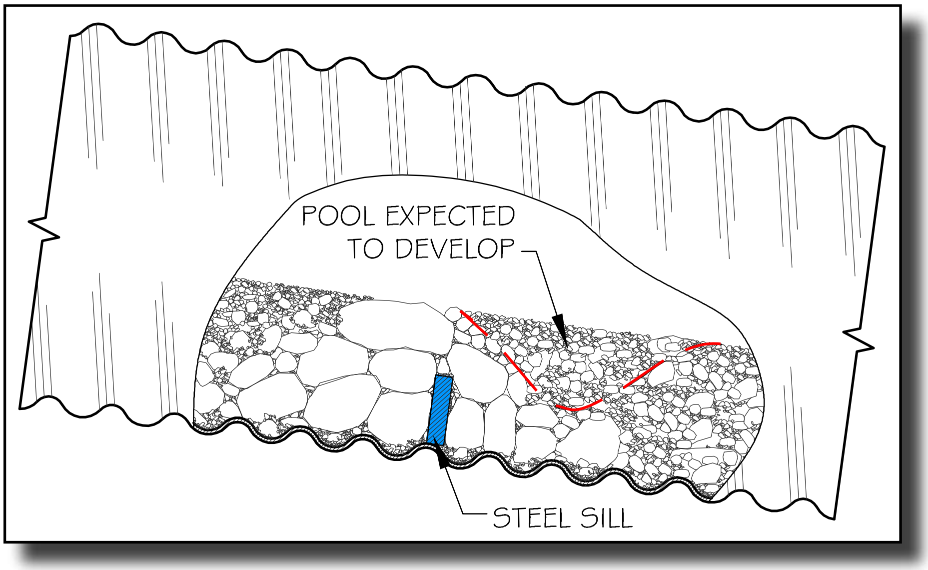

Figure 6.26—Profile view of steel bed-retention sill stabilizing a boulder step (cutaway view).

6.2.2.5 Cascade channels

Cascade channels are steep (greater than 8 percent), and their largest bed particles are large relative to normal flow depths (Montgomery and Buffington 1993). Energy is dissipated by water flowing over or around individual rocks. Smaller sediments move over or around the larger rocks at flows somewhat larger than bankfull. Rocks that are key to bed structure and stability, however, are immobile up to very high flows (greater than 50-year). Again, at these flows, shear stresses inside a pipe may be higher than in an open channel. Bed stability is critical in a simulation because, if the bed fails, the bare culvert is unlikely to recover naturally. On a simulation this steep, after sizing the bed material based on the reference reach, conduct a hydraulic stability analysis (section 6.4) to ensure that the largest bed-forming particles (e.g., D_{84} and D_{95}) are stable in the design flood. Also consider using bed-retention sills as in step-pool channels.

6.2.2.6 Bedrock channels

If a culvert is being replaced and the adjacent channel is primarily bedrock, investigate the channel and likely footing locations to determine bedrock location, elevation, and suitability for a foundation. If the road is located on a concave transition, be aware that the steeper channel upstream may be bedrock while the flatter culvert site is on erodible **fluvial** material.

If the bed at the site of a new crossing is sound bedrock continuous throughout the site, stream simulation may consist merely of placing an open-bottom arch culvert over the bedrock. Depending on the shape of the rock surface, you might anchor the entire footing to it, with a stem wall extending up to the bottom of the prefabricated culvert. The height of the footing and stem wall accommodate any variation in the bedrock surface. Where exposed bedrock is tilted, a deep, smooth channel may form along one wall of the culvert at low flow. In such situations, consider adding boulders for roughness and to deflect flow toward the center of the structure. You may need to use special construction procedures, such as embedding, anchoring, or clustering, to keep large boulders from rolling or sliding out of a bedrock channel.

Frequently, bedrock is exposed in the channel bottom while the streambanks are composed of alluvial or colluvial material. The banks may have large roughness elements, such as wood and single or clustered boulders. These may be important key features for retaining sediment and debris that provide diverse habitats and migration pathways in bedrock channels (McBain and Trush 2004). Channel margins and/or banklines therefore may be important to the objective of the project.

Bedrock channels sometimes exist where a bed of alluvial material has scoured, leaving the bedrock exposed. This exposure often occurs where woody debris has been removed or where a debris flow has scoured the channel to bedrock. Bedrock that does not show typical erosional features, such as fluting, longitudinal grooves, or potholes, could indicate that an alluvial veneer has recently washed away. In these cases, consider placing debris and/or immobile key feature rocks to help develop a natural alluvial bed and/or to stabilize a constructed bed. Exposed bedrock with no evidence of fluvial erosion also may result from channel incision caused by channel realignment and straightening during placement of the previous culvert. This can be a signal to seriously consider correcting the alignment during the replacement project.

6.2.2.7 Channels with cohesive bed material

A channel with cohesive bed or banks cannot be constructed inside a pipe. For new installations in cohesive bed channels, avoid disturbing the bed. The best stream-simulation alternative is probably to span such a channel completely, using a bridge or arch. Cohesive-bed channels often pose foundation challenges, and require a good geotechnical investigation.

6.3 CROSSING STRUCTURE DIMENSIONS AND ELEVATION

Now, for the first time in the design process, we consider the crossing structure itself. Up to this point, we have used geomorphic design methods to define both the probable range of stream profiles at the site and the size, shape, materials, and arrangement of the stream-simulation channel bed. Now we size the structure by fitting it around the designed channel. This discussion is primarily about culvert design, but similar width and height considerations also apply to bridges.

Culvert elevation and dimensions are determined at this point because they affect the bed mobility calculations in the next design step. It may take several iterations to select the final dimensions, because the bed mobility calculations (section 6.4) may indicate the need to change culvert dimensions. Only the dimensions and elevation of the culvert are determined in this step; many other considerations enter into the final choice of structure type and materials. Section 7.2 discusses them at length.

One of the goals in stream simulation is that the simulated channel be self-sustaining. That means it must simulate the hydraulics of the natural channel at sediment-transporting flows, especially the flows that create and rearrange major bed structures. To achieve these objectives, the simulated channel must be free to adjust to changes in incoming flow and sediment loads, and the culvert must be large and embedded deeply enough to accommodate both vertical and lateral adjustments.

Several factors go into determining culvert size and elevation. These include:

- The bankfull width of the channel.
- The width of any banklines and overbank surfaces.
- The range of possible bed profiles (VAP).
- The maximum sizes of alluvial and immobile rocks.
- The results from the bed stability and flow capacity analyses (6.4 and 6.5.2.1).

The structure must satisfy all these conditions at the same time.

6.3.1 Culvert Width

A variety of factors determine the structure width needed to achieve project objectives and to accommodate site conditions (see table 6.6).

Table 6.6—Considerations affecting choice of stream-simulation culvert width

Based on project objectives:
• Width of bankfull channel.
• Stability of the simulated streambed.
• Hydraulic capacity of the culvert.
• Risk of blockage by floating debris or beaver activity.
• Construction, repair, and maintenance needs.
• Passage of nonaquatic species.
• Meandering channel pattern.
• Protection of flood-plain habitats.
Based on site characteristics:
• High flood-plain conveyance and potential to concentrate overbank flows in culvert.
• Channel migrating laterally.
• Wider channel expected in future.
• Channel skewed to road crossing or crossing on channel bend.
• Ice plugging in cold climates.
• Large bed material relative to culvert width.

Extra structure width is necessary for creating a stable bankline without constricting the bankfull channel. In entrenched and moderately **entrenched channels**, the first estimate of culvert width is simply the width needed to span the simulated bankfull channel plus the size of the rocks used to construct the banks (figure 6.27). This initial estimate, of course, is subject to change depending on the results of the stability analysis of the bankline rocks. As noted in section 6.2.1.3, where the reference reach has a rough, irregular bankline, the simulated banks may be laterally deeper and may require more structure width.

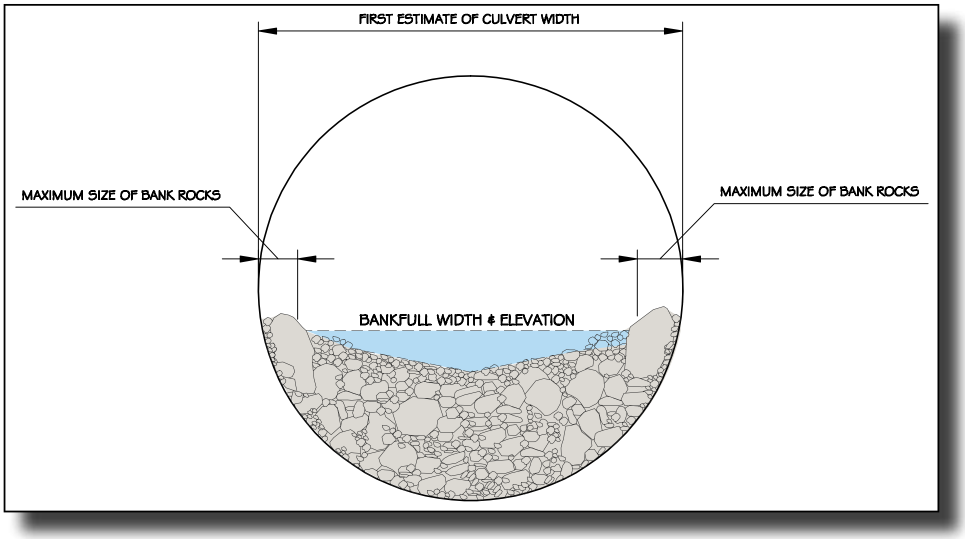

Figure 6.27—For a stream-simulation design with banks, minimum culvert width is bankfull width plus twice the maximum diameter of rocks used to construct the banks.

In an unentrenched channel with an active flood plain, the road fill could block overbank flood flows and force them through the culvert. Section 6.5.1.1 discusses at some length the risks associated with flow concentration in active flood plains and their possible solutions. Placing additional culverts or dips that permit flood-plain flow through or across the road fill may reduce the risk to acceptable levels. If not, you may also need additional culvert width to allow for an overbank-flow surface within the culvert (figure 6.22).

In choosing culvert width, also consider how the largest key-feature rocks (or rock clusters) in the simulated bed will interact with rock and wood pieces moving during high flows. A natural channel can usually scour around a large boulder or debris accumulation. In a culvert, however, a large individual boulder can create a constriction or form a bridge with other large particles, creating a culvert-wide drop structure or debris jam, and possibly limiting aquatic species passage, culvert capacity, and/or bed stability. A good guideline is that bankfull bed width inside the culvert should be at least four times the intermediate diameter of the largest immobile particles in the simulated bed.

Early in their development, incising channels may look narrow, but they will widen with time because the banks become unstable and fail in response to bed lowering (Schumm et al. 1984). Size a stream-simulation culvert to anticipate the expected widening of the natural channel near the crossing. On the other hand, if a channel is unnaturally wide from disturbance, and you expect it to narrow in the future, size the culvert for the current channel, with the expectation that recovery will occur inside the culvert as in the adjacent reaches.

As noted in section 6.1.1, you may need to increase culvert width if the culvert is skewed to the road alignment or if natural lateral migration of the channel will likely create a skewed-inlet condition.

6.3.2. Culvert Elevation and Height

Points on the stream channel bed may at some time be at any elevation within the range of potential vertical adjustment (see section 6.1.2.2). The culvert invert elevation and culvert height must allow for these vertical bed elevation adjustments over time. The stream simulation bed should be thick enough (and the invert deep enough) to avoid exposing the bare culvert floor during floods, and to allow large particles to be supported by the finer bed matrix, even at the bottom of a pool at the lowest potential bed elevation (figure 6.28).To achieve this, set the elevation of the bottom of the culvert or footing below the lower VAP line, adjusted to include the estimated depth of streambed scour during floods (2 times D_{90}, see section 5.2.2.2). For bottomless culverts, structural design of the footing and any engineering scour analysis that may be conducted may dictate a lower elevation (see section 7.3.2). Placement of bank rocks to protect footings may also affect their depth.

Once the culvert invert elevation is set, determine the culvert height needed to maintain flood and debris capacity when the bed is at its highest possible elevation. Setting the widest point of a round culvert at or above the highest potential bed elevation is an efficient design technique because it uses the full width of the culvert. Generally it also ensures headroom for floodwater and debris, although very large floating debris may not clear the inlet of the pipe during very high flows.

Recheck both culvert height and width after selecting the high bed-design flow. The bed-design flow is the highest flow that immobile particles are designed to sustain without moving. They are unlikely to remain in place if the culvert inlet becomes submerged and pressurized during a flood. For stability, we

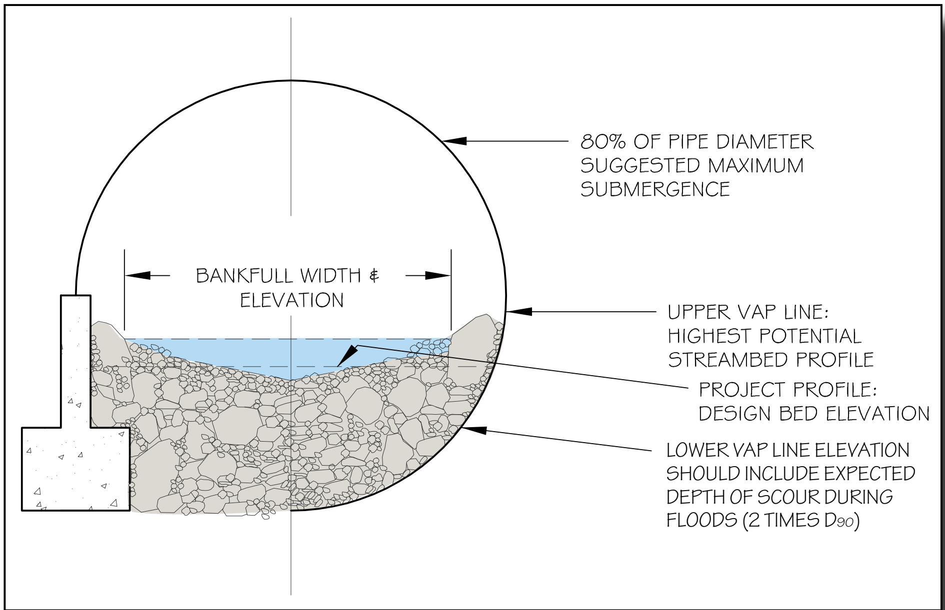

Figure 6.28—Embedment for full-pipe and bottomless culverts.

recommend that the inlet not exceed 80-percent submergence during the high bed-design flow, 67 percent where woody debris is a significant concern. Ensure that the actual free space is large enough to accommodate the size of debris moving in the channel. Naturally, this does not apply to submergence caused by backwatering when water levels are similar on both sides of the crossing.

The culvert also must be able to convey the structural-design flow. Flows that exceed the structural-design flow may destroy the crossing or cause the stream to divert down the road. Select the structural- and bed-design flows based on tolerable probabilities of exceedence (section 6.5.2.1) and the consequences of each type of failure. The two flows may be different, because the consequences of each failure type are different. For example, you may be able to accept the bed's washing away in a lower flow than one that could destroy the entire structure—because the bed material is replaceable. Where bed-load transport is high enough, sediment will be replenished, and the bed may reconstruct itself as the flood recedes. Provide a safety factor for invert depth and/or culvert height commensurate with the level of uncertainty and the risk of failure. Where the consequences of failure are large, use a larger culvert or a deeper footing.

Hypothetical small-stream culvert sizing example

Some small streams can have a relatively large range of vertical adjustment potential. A good example is a 4-foot-wide meadow stream with densely vegetated 1-foot-high banks and pools as deep as 1 foot. Bed material D_{90} and D_{95} are 2 inches and 2.5 inches, respectively. After delineating the VAP lines on the longitudinal profile, we find that at the cross section shown in figure 6.29 the upper VAP line is at the top of the banks, and the lower VAP line is 1.33 feet below the project profile. The lower VAP line here includes 1 foot for reference reach pool depth, and 0.33 foot to allow for the depth of scour during floods (2 times D_{90}).

The culvert should be wide enough to allow for placement of bank rocks, which are needed for simulating reference reach bank roughness. An initial estimate of the size of stable bank rocks is 2 times D_{95} or 0.4 foot (see section 6.2.1.4). The first estimate of culvert width is 4.8 feet: 4 feet to accommodate bankfull width, and 0.8 foot to allow for stable rocks on both banks. The culvert also should be embedded deeply enough that the channel bed never scours to bare metal. In this example, we could conveniently use a 5-foot round culvert. Then, if the invert is 0.25 foot below the lower VAP line (2.6 feet below the upper VAP line at bankfull elevation), the project profile (bed elevation to be constructed) will be at 32 percent of culvert height, and the upper VAP line will be at 52 percent.

Next, check culvert capacity for the eventuality that the streambed aggrades to the upper VAP line. Ideally, the culvert will be large enough to allow passage of the bed design flow with at least 1 foot of headroom (80-percent submergence). Assuming headroom is adequate, embedding the culvert slightly below the lower VAP line is simply a small additional safety factor; it may or may not be necessary depending on site risk factors affecting scour potential.

After you analyze bed stability (section 6.4), you may need to reevaluate culvert size.

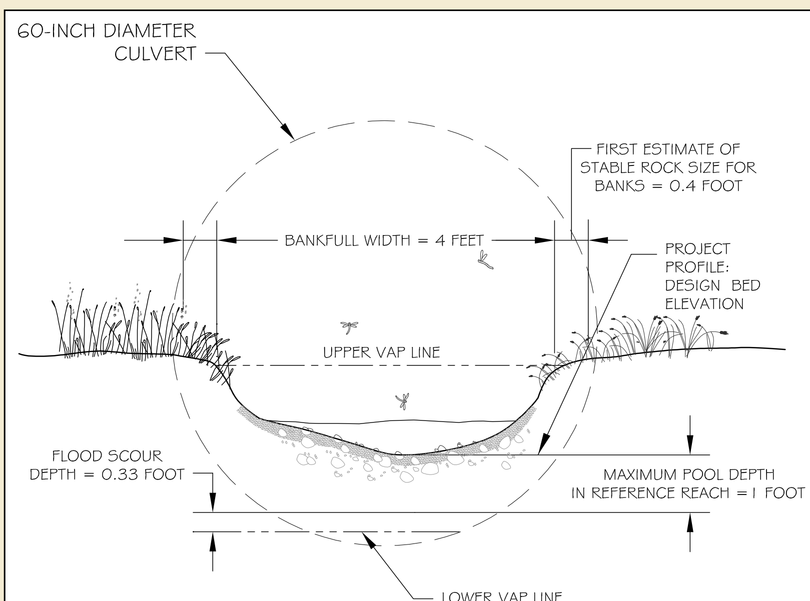

Figure 6.29—Hypothetical example of using reference reach channel size and bed material (described in text) to size a small culvert. VAP lines shown in the figure were determined from a longitudinal profile analysis. This drawing does not show the designed simulated channel bed; rather, it shows how the culvert would fit around the reference reach.

6.3.3 Culvert Shape and Material

Aside from the size, elevation, and alignment issues already discussed, most of the considerations for culvert shape and material involve site conditions, designer preference, and cost. These considerations include:

- Commercial availability.
- Structure longevity.
- Road elevation and fill height.
- Streambed and culvert constructability.
- Construction time, sequencing, and allowable ‘in-water’ work period.
- Soil-bearing capacity.
- Site access.
- Flood capacity.

Guidance for selecting culvert shape and material is in section 7.2.

6.4 BED-MOBILITY AND STABILITY ANALYSIS

The purpose of the bed-mobility and stability analyses is to answer the following questions:

Do the bed materials in the simulation move at the same flows as those in the reference reach? (mobility analysis)

Do key particles that control channel form and hydraulics stay in place during the high bed-design flow (see section 6.4.5)? (stability analysis)

The bed-mobility analysis is useful where the simulated channel design differs from the reference reach with respect to slope or entrenchment. At other sites, the analysis may or may not be needed, depending on channel type, risks associated with the site, etc.

The bed-mobility analysis compares critical flow for **entrainment** (the flow at which a particle just begins to move) in the reference reach to critical flow in the culvert for the particle size of interest. Except for the least mobile channel types (coarse step-pool and cascade channels), stream simulations should be designed such that bed particles of similar size become mobile at similar flows in the reference reach and the stream-simulation reach:

Equation 6.5 $$Qc_{\text{culvert}} \approx Qc_{\text{reference reach}}$$

where Qc is the critical **entrainment flow** (or the critical shear stress) for the particle size of interest. When this goal is achieved, the amount and size of incoming and outgoing sediment balance, maintaining the bed structure and bed forms that are necessary for aquatic organism passage. In the mobile channel types, only banklines and other large key features are routinely designed to be permanently stable.

If the simulated channel closely mimics the reference reach, bed-mobility analysis will show that similar particle sizes move at similar flows in both channels. If the simulation is steeper than the reference reach, the designer can use the analysis results to adjust the simulation design for similar bed mobility. Adjustments can be made to one or a combination of design parameters, such as bed-material size, channel width, and flood-plain capacity within the culvert. Adding flood-plain relief dips or pipes and changing the project profile are other ways to adjust the design.

To ensure that the simulation achieves its objectives, keep it within the range of natural variability in the reference reach. As a rule of thumb, increase slope, bed-material sizes, and/or active or bankfull channel width no more than about 25 percent unless you have a clear understanding of the implications of a greater change.

6.4.1 When is a Bed-mobility Analysis Necessary?

Mobility analysis usually is not conducted on low-gradient, fine-grained response channels where the bed is fully mobile during frequent high flows. After a flood, such channels reestablish preflood-channel form more quickly than coarser-grained channels. In straightforward projects (e.g., a stable, moderately entrenched, moderate-gradient, gravel pool-riffle channel where the culvert bed closely replicates the reference reach) you can assume similar bed mobility. Again, bed-mobility analysis usually is not necessary.

Intermediate-mobility channels (coarse pool-riffle, plane-bed, and perhaps some cobble step-pool channels) do require a bed-mobility analysis. They may be fully mobile at flows that are fairly frequent (5- to 10-year **recurrence interval**), yet infrequent enough that a partial bed failure may not recover to its preflood channel form within a reasonable time. In these channels, risks may justify evaluating whether the same sizes are entrained in both the structure and the reference reach over a range of flows from bankfull to the high design flow (see the example illustration of such an analysis in appendix E).

It is most important to analyze bed mobility when the slope or entrenchment of the simulated channel differs somewhat from the reference reach. Sections 6.5.1.1 and 6.5.1.2 discuss the analysis in greater detail.

6.4.2 What Particle Sizes Are Analyzed?

Generally bed-mobility analysis is done on the portion of the bed material that provides structure, stability, and roughness, that is, the larger sizes. D_{84} is the recommended grain size to analyze in most cases because when D_{84} is mobile, most of the smaller bed sediments are mobile as well. D_{95} also can be used as a more conservative indicator of 'bed mobility.' Where riffle crests or bars are designed and built, as in the Newbury Creek example (figure 6.23), the particle-size class used to construct those features would be analyzed. The aim of the mobility analysis is not to make the channel stable; the goal is to create a channel bed in the simulation reach that has similar sediment transport characteristics to the reference reach.

6.4.3 What Flows Are Analyzed?

This is a comparative analysis, which does not require working with a flow of any predetermined return interval. First, find the flow that entrains D_{84} or D_{95} in the reference reach. Then, determine whether the same flow entrains D_{84} in the simulated channel. To verify that the calculated critical flow is valid, estimate its recurrence interval and compare it to the bed mobilization flow ranges listed in table 6.5 for the channel type.

If the critical flow in the simulation is different from that in the reference reach, various design parameters can be adjusted until the same flow moves D_{84} in the simulation. See section 6.5 and appendix E for examples and more explanation.

6.4.4 Bed Mobility Analysis Equations

Bed mobility is evaluated using equations that estimate the critical flow for entrainment of specified particle sizes (the flow at which a particle just begins to move). Because these equations do not apply equally to all stream types, and because a great many variables are involved, this guide devotes appendix E to presenting and discussing them.

Briefly, the most useful equations for stream-simulation applications are:

- The critical unit discharge equation (Bathurst 1987).

  This equation estimates the critical unit discharge (flow per unit channel width) at which a particle of a certain size will begin to move in a steep, rough channel. The equation applies to steep (3.6 to 5.2 percent), gravel-cobble channels where water depth is shallow compared to the size of the bed material.

- The modified critical shear stress equation.

  This equation can be used to assess particle stability in channels with gradients less than 4 to 5 percent and D_{84} particles ranging between 10 and 250 millimeters.

Like all hydraulic and hydrologic models, these equations approximate and simplify the real world. The Bathurst and modified critical shear stress equations apply best in alluvial settings; they do not account for the stabilizing effects of key features, such as embedded debris or **colluvium**. All the equations are based on empirical field and laboratory studies with data sets of limited size and variability, and they should be applied within those limits. In some cases, where it is not evident which equation is most appropriate, use more than one and compare the results. Understanding why the results differ can be important in developing a good design. Appendix E describes in some depth the background and limitations of the equations. It also provides examples of applying the equations to stream-simulation problems.

Do not allow the equations to drive the design. Instead, use them as tools to validate the design and check the results against your understanding of how the channel will function in real life. Visualize how the channel will look and function as it adjusts over time, and use the equations to help predict bed mobility in different channel/structure configurations. The equations allow you to test the sensitivity of the bed to changes in different design parameters (e.g., slope, width, bed-material size). Test sensitivity by varying design values in the equations to see if the changes greatly affect the results. The risk of error is less when changes to the results are small.

If increasing bed-material size or channel width by 25 percent is not sufficient to match bed mobility in the simulated channel with bed mobility in the reference reach, review section 6.5 on managing risk in various situations. You may need to consider selecting a new project profile. Alternatively, you may decide that stream simulation is not feasible at the site.

6.4.5 Stability Analysis for Immobile Key Feature Rocks

The stability of key features that are intended to be permanent is crucial to a stream-simulation installation's long-term sustainability. Because of the closed boundary in a culvert, a large flood may exert higher shear stresses and cause more turbulence than an open channel. Particles of a given size may move at lower flows than in the reference reach, and large rocks may not be replaced as the flood recedes. Loss of bed structure—possibly of the whole bed—could be essentially permanent. Therefore, design these structural pieces to be immobile at the high bed design flow:

Equation 6.6. $Qc_{\text{key feature in culvert}} \geq Q_{\text{bed design}}$

where Qc is the critical entrainment flow (or critical shear stress) for the rock size of interest.

This analysis consists of verifying that the bed-design flow will not mobilize the rocks that comprise the key features. The bed-mobility equations described in 6.4.4 and appendix E can be used for this analysis. Their results should be compared to results from equations developed to size boulder clusters and riprap blankets (appendix E.4). Accurately estimating entrainment flow for rocks that are embedded in much finer material is difficult, so it is wise to compare the results of several equations. The best validation is the size of material that appears to be immobile in the reference reach.

6.5 MANAGING RISK FACTORS

This section recaps the risks associated with stream-simulation culverts as well as other culvert types, and outlines approaches to mitigating them. Section 6.5.1 focuses on risks specific to stream-simulation installations, while section 6.5.2 looks at risks that apply to all culverts.

In any situation, there are two ways to "manage" risk:

First, *reduce the probability* of failure by identifying the processes or conditions that could lead to failure, and by mitigating them in design or construction. "Failure" in this context means not only structural failure (culvert washes out, flow diverts down road, etc.), but also failure to achieve stream-simulation objectives. Simply having bed material inside a culvert does not constitute stream simulation. For the project lifetime the simulated streambed should maintain a suite of characteristics similar to those found in the natural channel near the culvert (bed material type and structure, channel dimensions, flow velocities and depths). Any of the risk factors listed in table 6.7 could lead to failure.

Second, recognize that any crossing can fail in an extreme event, and design to *reduce the consequences* of failure. Methods for reducing failure consequences include preventing diversions down the road or ditch if water overtops the road fill, armoring road fill overflow dips, and ensuring that the culvert is accessible and large enough to permit future access for maintenance and repair. Chapter 7 discusses these strategies in more detail.

6.5.1 Potential Culvert Failure Risks—Stream-simulation Culverts

An installation can have multiple failure risks; evaluate and mitigate each risk in the context of all the others. For example, a straight culvert and road fill placed over a sinuous stream in a wide active flood plain constrict the flood plain and shorten the channel. In addition to adding flood-plain relief dips or pipes and increasing culvert width to mitigate these risks, you could also increase the size of the bed material. However, increasing bed-material size to mitigate for flood-plain constriction, and then again to mitigate for channel straightening, could defeat the purpose of stream simulation. A bed-mobility analysis integrates the risk factors, and is frequently the key to determining the magnitude of the risk and finding appropriate ways to mitigate it. In table 6.7, asterisks denote design strategies that involve bed-mobility analysis.

If bed-mobility analysis indicates that the simulated streambed materials will move at lower flows than in the reference reach, revisit the site to see if you can find a more appropriate reference reach. For example, if you have selected a project profile that is steeper than the reference reach, see if a natural-channel reach exists at the higher slope—one that may be appropriate as an reference reach. Be sure the new reach meets all the requirements, such as similar length, flow regime, sediment loading, and if possible entrenchment (see section 5.4). Other design solutions may have to be considered also, such as modifying the project profile or enlarging the culvert.

Table 6.7—Potential risk conditions and design strategies

RISK FACTOR	DESIGN / CONSTRUCTION STRATEGY	OUTCOME OF DESIGN STRATEGY
Flood-plain constriction.	Widen culvert*	● Permits high flows to occupy wider 'flood plain' inside culvert.[1]
	Increase bed material size. *	● Increases bed stability.[1]
	Add flood plain relief culverts, road overflow dips. *	● Avoids flow concentration.
	Place layer of large rock under simulated bed.	● Reduces risk of complete loss of all embedment. ● Reduces risk of upstream headcutting if simulation fails. ● Requires larger culvert to allow for combined depth of rock layer and fully vertically adjustable streambed.
Rapid lateral channel migration.	Widen culvert and offset it in the direction of expected channel shift.	● Slows development of channel-to-culvert skew caused by channel shift. ● Stream-simulation channel may function normally for a longer period of time before being constrained by culvert.
	Provide best possible culvert alignment; stabilize banks; provide flow control structures such as rock weirs or J-hooks.	● Prevents channel movement. ● May move channel alignment problems to reaches further from culvert.
Steepened channel: culvert steeper than reference reach. Note: if a slope steeper than 125% of the reference reach is required, consider alternative designs or design methods (appendix B).	Minimize slope increase; modify downstream and/or upstream channel.	● Simulation is more sustainable over long term.
	Increase bed material size. *	● Increases bed stability.[1]
	Increase width of stream-simulation channel, widen culvert. *	● Reduces shear stress inside culvert.[1]
	If simulation is step-pool type, install bed retention sills.	● Reduces risk of loss of structural rocks.
Downstream channel instability.	Verify vertical adjustment potential, and ensure simulated bed is deep enough and culvert is large enough to accommodate range of potential profiles.	● Allows for natural variation in streambed elevation as long as actual degradation is within projected limits.
	Provide adequate downstream grade controls.	● Ensures simulated bed is protected from downstream headcut. ● Grade controls themselves may become passage barriers.
	Use full-bottom pipe or deepen foundation of open-bottom structure; place layer of large rock under simulated bed.	● Deeper foundation reduces probability of structural failure by undermining. ● Reduces adjustment potential of simulation. ● If simulated bed is eroded, the bed is more likely to reconstruct itself on rough rock surface than on bare metal.
Pressurized inlet. (Inlet is submerged; outlet is not submerged)	Increase culvert size to limit headwater depth during high bed design flow to 80% of culvert height above bed.	● Reduces incidence of very high water velocity in culvert. ● Roadway vertical curve can be problem with round culverts.
	Add flood-plain relief culverts and/or road overflow dips. *	● Lower water elevation upstream of crossing.
Submerged inlet.	Optimize inlet alignment and transition; bevel pipe inlet.	● Lowers inlet energy loss and increases culvert capacity.

Note: "" denotes strategies that can be designed using bed-mobility analysis. Mobility analysis may indicate a need for bed material larger than reference reach, a wider culvert, flood-plain culverts or dips, bed sills, etc.*

[1] These strategies are effective within limits. See sections 6.5.1.1 and 6.5.1.3 for their limitations.

Table 6.7—Potential risk conditions and design strategies (continued)

RISK FACTOR	DESIGN / CONSTRUCTION STRATEGY	OUTCOME OF DESIGN STRATEGY
Long culvert.	Minimize length of culvert using headwalls, lower road profile, etc.	• Allows use of shorter culvert .
	Add safety factor to stability analysis (e.g., increase bed material size or culvert width). *	• Compensates for compounding design flaws.
Initial lack of bed consolidation.	Compact bed layers during construction.	• Increases initial bed stability.
	Wash fines in between and around larger material to embed and stabilize it .	• Increases initial bed stability.
	Hand-place key bed features for stability.	• Increases initial bed stability. • Increases construction cost.
	Construct thicker streambed (to elevation higher than design project profile).	• Allows for initial streambed erosion.
Excessive infiltration into streambed.	Design and use well-graded bed material mix (section 6.2.1.1) with adequate content of sand, silt and clay.	• Smaller particles fill voids between larger particles.
	Construct densely packed streambed by compacting bed in layers and/or jetting fines into bed layers.	• Minimize large void spaces in new streambed.
Debris blockage, debris flows.	Increase culvert size: Limit headwater depth during high bed design flow to 80% culvert height above bed; ensure open area is large enough for debris being transported.	• Provides space for debris to float through culvert.
	Ensure efficient transition from upstream channel (match alignment and width); bevel pipe inlet.	• Facilitates debris and sediment passage.
	Harden fill; design for overtopping and cleanout; plan for possible streambed maintenance after overtopping.	• Structure and road survive overflow and debris blockages.
	Provide inlet riprap or other protection.	• Reduce stream bank erosion caused by backwater eddies during very large flood events.
	Provide access for maintenance.	• Allows removal of debris jam in culvert or at inlet.
Stream diversion.	Increase culvert size.	• Reduces probability of exceding culvert capacity or blocking with debris
	Provide roadway dip over culvert. Sag vertical curve to avoid diversion during floods and minimize fill height; armor fill.	• Contains overtopping flow at crossing. • Minimizes flood damage to soils and habitats.
	Provide ditch dams; redesign road ditches to direct flood and overtopping water to erosion resistant areas.	• Prevent a stream diversion into a roadside ditch downgrade from the crossing. • Reduce erosion caused by overtopping flows.

Note: "" denotes strategies that can be designed using bed-mobility analysis. Mobility analysis may indicate a need for bed material larger than reference reach, a wider culvert, flood plain culverts or dips, bed sills, etc.*

[1] These strategies are effective within limits. See sections 6.5.1.1 and 6.5.1.3 for their limitations.

6.5.1.1 Flood-plain constriction

A wide active flood plain is often considered a highly valuable hydrologic and biological resource. Overbank flows and sediment moving down a flood plain build and maintain many of the unique flood-plain habitats that can be critical for some aquatic and terrestrial species (Naiman et al. 1992). Project objectives will usually include protecting and/or restoring flood-plain processes and habitats.

The major challenge in constructing a sustainable stream-simulation culvert on a **high-conveyance flood plain** is the potential for the road fill to block overbank flood flows and force them to concentrate through the culvert. In such installations, bed scour inside the culvert occurs at lower flows than in the natural channel upstream. Material eroded out of the culvert may not be replenished, and the culvert is at risk of bed failure during floods. The inlet area is more susceptible to scour than other areas of the culvert under these conditions, because water-surface elevation drops abruptly as the water moves from the backwatered flood plain into the culvert inlet. The inlet may scour even when hydraulic conditions in the rest of the culvert are similar to the reference reach.

Depending on the site, you may want to use a combination of some or all of the following design strategies to mitigate the risk.

Minimize flow concentration

In valleys with very high flood-plain resource values, such as important aquatic and riparian habitats, consider building a viaduct or bridge that spans as much of the active flood plain as possible. For stable multichannel systems (**anastomosing** channels), consider providing for stream simulation on each channel.

Another strategy is to keep the road fill as low across the flood plain as is feasible given traffic needs. If the road can be closed during floods, designing it for overtopping can avoid the need for many flood-plain culverts. Combining some flood-plain culverts with a low road fill designed for overtopping allows smaller floods to drain under the road without forcing a road closure. Larger floods overtop the road so that the road fill does not work like a dam funneling water through the main crossing structure.

Provide flood-plain culverts and/or dips at swales, side-channels, and other locations as needed (figure 6.30). Add enough drainage structures to avoid unduly concentrating flow in any one area. Maximize the cross sectional area of dips, and armor them to sustain expected flow depths and velocities as well as the drop over the downstream edge. Providing well distributed flood-plain culverts and dips minimizes the risk that flood-plain flows concentrated in a single side channel might divert and capture the main channel. Nonetheless, side channels may carry more flow than normal because of the **backwater** caused by the road fill, and the potential for them to scour should be examined during the design process. In some cases buried rock may need to be installed just downstream of a flood plain or side-channel culvert to prevent incision. Be aware of the potential for woody debris to plug flood-plain culverts, and provide enough dips to handle flood-plain flow if needed.

Side-channels are sometimes important fish habitat requiring aquatic organism passage. Culverts at these sites should simulate the size and character of the side channel, while providing protection against scour that flow concentration may cause.

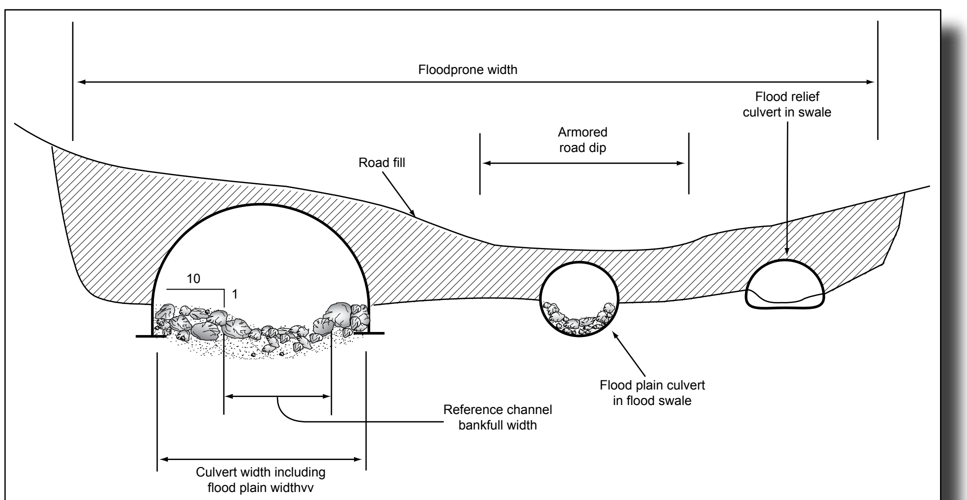

Figure 6.30—Stream simulation on an unentrenched channel may include a flood-plain surface inside the culvert and flood-plain relief culverts and dips.

Permeable roadfills can replace flood-plain culverts in some situations. Permeable fills are constructed with coarse granular fill, such as 2- to 6-inch rock, sandwiched between layers of geotextile. On the downstream side, the base of the fill has a small toe drain of geotextile and rock to let water exit the fill safely without scouring (Pekuri, personal communication). Although a permeable roadfill can allow a more natural and uniform movement of water and maintain some flood-plain function, it does not allow movement of most aquatic species or debris. For more information on permeable fills, see USDA Forest Service 1996.

Conduct a backwater and bed mobility/stability analysis

These analyses should be done at any site where significant overbank flow is expected on the flood plain. We particularly recommend it where the entrenchment ratio (flood-prone width: bankfull width) is around 6 or higher. This recommendation is based on model results for several forested flood plains in western Washington. This entrenchment ratio threshold will be lower for smoother, unforested flood plains with high conveyance.

Compare the critical unit discharge or critical shear stress in the stream-simulation channel to the reference reach during a range of flows that will be constricted by the road. The choice of which flows to analyze depends on risks at the site and on flow conveyance. A 10-year recurrence interval flood seems a reasonable minimum flow to use for this analysis in mobile channels with considerable movement of bed material. In intermediate-mobility channels, the flood that moves D_{84} in the reference reach might be a good choice for a minimum flow for this analysis.

The reference reach critical shear stress or critical unit discharge for this analysis is not the average of the entire floodway. Instead, the analysis considers only the flow within the bankfull or **active channel** width, because that is the flow condition that entrains sediment on the reference reach bed. Use a step-backwater model like HEC-RAS to predict backwatering behind the road fill, accounting for the effects of multiple flood-plain culverts and/or road dips planned for the site. Compare the reference reach shear stress or unit discharge to the stream-simulation channel, factoring in the additional flood-plain flow that will be forced through the culvert.

If you have already added flood-plain relief dips and pipes to the design, and shear stresses are still higher in the main channel culvert than in the reference channel, the following two strategies provide options for offsetting the difference. These two strategies should normally be combined.

Increase culvert width

Widen the pipe and construct a flood-plain surface inside. The width of the simulated bankfull channel should remain the same to avoid aggradation during moderate flows, and possible loss of low-flow passage. The constructed flood plain will relieve some of the excess shear stress by accommodating some of the overbank flow. All surfaces above the bankfull channel should slope toward the bankfull channel at a slope of about 10h:1v (see figures 6.22 and 6.30).

Widening the culvert is not a panacea. Channel adjustments inside the pipe are likely to change the installation over time. For example, unless the culvert flood-plain surface is wide enough that water depth and velocity in the simulated active channel are similar to the reference reach, the simulated channel may incise. After that, flood flows will not access the overbank surface as easily, water depth and velocity at flows above bankfull will increase, and the original problem will not have been solved. For this reason, widening the culvert is generally combined with increasing bed material particle sizes.

Increase bed material particle size

As mentioned previously, particle size can be changed only to a moderate degree if the simulated bed is expected to be self-sustainable. We recommend not increasing D_{84} more than 25-percent over the reference reach.

If you increase bed-material sizes, increase each size class D_{50} and higher by the same percentage, and recalculate the finer particle sizes to maintain the dense-bed mixture (review section 6.2.1.1 bed design). Consider how the new particle-size distribution will fit into the channel context and whether that distribution is likely to achieve stream-simulation objectives.

If an unacceptable risk of bed failure still exists after all the mitigation measures above have been applied, place individual large rocks in the bed to buttress the bed and provide additional roughness. Another option is to bury a layer of riprap deeply below the simulated streambed. The riprap should be deep enough that under normal conditions the simulated bed can scour and fill on top of it without being affected by it. Thus, the depth of the stream-simulation bed on top of the rock layer should be the same as if it were on top of the culvert floor (section 6.3). Base the thickness of the riprap sublayer on a riprap design protocol such as the U.S. Army Corps of Engineers method referenced in appendix E. That method requires a thickness not less than the D_{max} stone, or 1.5 times D_{50}, whichever is larger.

6.5.1.2 Rapid lateral channel migration

Where a channel is experiencing rapid lateral shift, culvert-to-channel skew will intensify over time. Section 6.1.1.1 described the problems associated with skew, and ways to mitigate them. If a channel is shifting very rapidly, the most effective solutions might be relocating the road to a more stable site, or placing a temporary structure that can be moved.

Table 6.7 lists possible solutions for channels where lateral shift is less extreme. They include widening the culvert and offsetting it in the direction of expected shift. Adjust the size of bankline rocks if needed to accommodate a deeper pool that can form as the bend becomes more acute. Bank-stabilization and flow-training structures such as rock weirs or **J-hook vanes** can be built above the crossing to slow down or minimize channel shift.

6.5.1.3 Steepened channel

Section 6.1.2.3 described conceptual design options for sites where the downstream channel is incised. As emphasized there, downstream-channel rehabilitation may be the solution with the highest probability of long-term success, as opposed to maintaining a culvert as grade control.

Steepening the simulated channel relative to the reference reach increases bed slope and shear stress (compared to the reference reach) and creates a higher potential for bed failure. Increases of up to 25 percent in particle size and/or channel width are likely to be within the range of variance of most natural channels and constitute a reasonable design limit. Nevertheless, conduct a bed mobility analysis whenever the stream-simulation channel is steeper than the reference reach.

The analysis may suggest that an increase in bed-material size or channel width is necessary to offset the increase in slope. An increase in channel width reduces the calculated average shear stress to resemble a flatter reference reach. Do not accept such a solution without thinking through how it will work in the real simulation. For example, in a natural channel, short, steep reaches are normally narrower than average rather than wider, with larger bed material and/or key pieces. If the thalweg in the steeper simulation incises so that flow width narrows, the calculated increase in stability due to increased channel width may not persist. In such a situation, burying a layer of large-size rock below the simulated streambed to prevent excess scour might be a useful added safety factor. An added benefit of the extra channel width is that it provides capacity for large floods, making failure less likely.

Where the reference reach is steeper than the channel immediately upstream, analyze the mobility of the larger particle sizes in the simulated channel compared to the same sizes in the upstream reach that will be supplying sediment. Those sizes should be mobile at similar flows in both reaches in order for the simulated channel to be self-sustaining.

Avoid steepening a channel past a geomorphic threshold (see table 6.5 and appendix A, figure A.25) that would—in nature—make the channel a different type. Staying within the 25-percent guideline will usually prevent the design from exceeding a channel-type threshold; however, if a threshold would be exceeded, first verify that a more appropriate reference reach does not exist. For example if the reference reach is a 4-percent plane-bed channel but the required crossing slope is 5 percent, investigate whether step-pool reaches exist nearby. If no more appropriate reference reaches exist, consider building the appropriate channel type as a hybrid design. In this example, the hybrid installation would be a step-pool channel. Steps would be designed for immobility during the high bed-design flow, because if the step-forming rocks wash away, they may not be replenished from upstream. If either a step-pool channel or one with other key features (such as wood) is steepened, consider decreasing the spacing of steps or key features to increase roughness. (See appendix B for more on hybrid design.)

6.5.1.4 Downstream channel instability

If the elevation of the channel bed downstream of the crossing degrades beyond the range to which the project can adjust, the simulated streambed could fail to function. If a risk of continued channel degradation downstream could jeopardize the structure, reevaluate your plans to control VAP (section 6.1.2.3). Consider restoring the downstream channel and/or adding grade control structures to support the project profile.

Design conservatively. Take extra care in projecting VAP and, if possible, ensure that the culvert can accommodate it. One safety measure is to use a full-bottom pipe with a layer of large rock placed below the simulated bed. Even if the simulated bed partially or entirely washes away, the opportunity to reconstruct it will still exist. The layer of large rock will protect the upstream reach from channel incision. In a bottomless pipe, increase the depth of footings. Consider placing a layer of immobile rock below the streambed elevation and constructing the simulated bed on top of it, giving the bed enough depth to make normal vertical adjustments (such as scour pools).

6.5.1.5 Inlet control with submerged inlet

A stream-simulation bed will likely fail if the culvert is in inlet control, especially if the inlet is submerged and a high head differential exists between inlet and outlet. These conditions produce a strong flow contraction in the pipe near the inlet. In culverts flowing in inlet control, supercritical flow—a very high velocity flow extremely rare in alluvial channels—occurs in at least part of the pipe.

Conduct a culvert analysis and verify that supercritical flow does not occur at the high bed-design flow. FishXing and HEC-RAS with the lid function are good tools to use for this because they analyze flow inside the barrel of an embedded or open-bottom pipe. Be conservative, because high-flow hydrology, effects of debris, and culvert inlet losses are all uncertain.

If supercritical flow is likely to occur, or if the inlet may be submerged, one obvious solution is to increase the pipe's size. We recommend that headwater depth at the high bed-design flow not exceed 80 percent of the culvert opening above the bed (67 percent where debris is a significant hazard). Improving the culvert's alignment with the upstream channel and/or designing an efficient culvert inlet configuration, such as a wingwall, may lower the headwater and reduce the flow contraction near the inlet. Again, if the site has an active flood plain, adding flood-plain culverts and/or road dips will reduce flow concentration through the culvert.

6.5.1.6 Long culvert

Review section 6.1.1.1 on risks associated with long culverts. We can presume that a culvert can safely be as long as a straight reference reach at the same slope. If a culvert is longer than straight segments of the reference reach, it is likely that channel bends were straightened to construct the culvert; therefore, the simulated bed is not as rough as the natural channel. The excess culvert length exacerbates the risks of any design uncertainties, invalid assumptions, flaws, or construction inadequacies. Unfortunately, there is no specific hydraulic method for quantifying the risks of bed failure due to culvert length.

As section 6.1.1.1 notes, the risk can be minimized by locating the crossing so that it avoids channel bends and minimizes culvert length. Adding headwalls and/or lowering the road fill may permit shortening the pipe. Other possible measures include adding a safety factor to the size and/or embedment of the culvert or the size of the bed material. Larger bed material or key roughness pieces will add roughness, thereby helping to dissipate energy in long culverts. However, be aware that the additional turbulence caused by the larger material may affect opportunities for aquatic species passage.

6.5.1.7 Initial lack of bed consolidation

In natural channels, hydraulic forces sort and structure bed materials so that they are in relatively stable positions and orientations. In newly constructed streambeds, the risk of bed failure during a flood is somewhat higher until moderate flows sort, structure, and consolidate the new bed. Characteristics like armoring and imbrication cannot be constructed, and must be allowed to develop naturally.

Although we cannot quantify this lower initial stability, there are several ways of managing the risk:

- Add extra material initially to allow for some bed erosion and consolidation.

Barnard (personal communication 2003) monitored steep stream-simulation channels after construction. He found that the constructed beds had lowered by about 20 percent of their depth in the first few years after construction, likely from a combination of **consolidation** and erosion of fine material. These were steep channels, and the material had not been consolidated or compacted during construction.

- For beds composed of grain sizes up to cobbles, compact the bed during installation.

Compaction can be done mechanically, by washing fines into the bed, or both. As bed material size increases, mechanical compaction becomes more difficult and more likely to damage the culvert. Bed structures such as steps and key features therefore become more important. These bed structures will support the alluvial part of the bed until it is consolidated. Ensure step and key-feature stability by specifying that individual rocks be placed so that they are in direct contact and support one another (see sections 6.2.2.4 and 7.5.2.3).

- Increase the size of the bed material slightly.
- Monitor the effects of highflows until bed structure develops, and be prepared to repair any bed failures.

6.5.1.8 Excessive infiltration into the streambed

The lack of natural **sorting** and bed consolidation also results in a potential for excessive streambed permeability and the risk of losing surface flow during low flows. A well-graded bed mix with at least 5-percent sand, silt, and clay content (section 6.2.1.1) is designed to avoid large empty spaces in the new, loose bed. Construction practices, such as ensuring the bed material is not segregated during handling, compacting the bed in layers and washing the fines into each layer help to reduce initial infiltration rates.

6.5.2 Potential Culvert Failure Risks—All Culverts

6.5.2.1 Flow exceeds culvert capacity

Like all crossings, stream-simulation designs must be checked to ensure that the culvert will convey floods up to the high structural design flow (the flow that, if exceeded, could cause culvert failure). Even when flood-capacity calculations indicate the culvert has adequate capacity, however, the potential for structural failure exists. The 50- to 100-year recurrence-interval flow is commonly used as the high structural-design flow, with the notion that this reduces the risk to an appropriate level. However, in reality the probability of a 50- to 100-year flow occurring over the lifetime of a culvert is not low. Suppose, for example, that the designer expects a culvert to last for 50 years and wants to design it so that a structural failure does not have more than a 5-percent probability of occurring. According to the following equation, the design analysis would have to be based on the 1,000-year flood!

This equation calculates the probability (P_n) that a flow with a given recurrence interval (T_r) will occur at least once during a given timespan (n):

Equation 6.7

$$P_n = 1 - \left[\frac{T_r - 1}{T_r}\right]^n$$

For n = 50-year project life, and P = .05, T_r = 1,000-year recurrence-interval flood. That is, there is a 5-percent probability that a flood with a recurrence interval of 1,000 years will occur during any 50-year span. For any 50-year period, there is a 40-percent probability that the 100-year flood will occur, and a 64-percent chance that the 50-year flood will occur.

Thus, there is a significant risk that the design flow—and even higher flows—will occur during a culvert's lifetime. Although safety factors built into the design can offset errors and uncertainty in the flow estimates and other analyses, structures should be designed to be overtopped or to fail with minimal destructive consequences.

If a likelihood of debris and/or sediment plugging exists, the culvert hydraulic analysis should also factor in partial debris blockage of the culvert inlet.

6.5.2.2 Debris or sediment blockage

In forested environments with large amounts of woody debris, hydraulic calculations may not accurately predict culvert failures. Furniss et al. (1998) state:

"The loading of sediment and woody debris is difficult to predict and subject to the stochastic nature of landsliding, streambank erosion, treefall, and other processes that contribute these materials. We might be able to anticipate which crossings are more likely to fail based on upslope/upstream geomorphology, crossing inlet configuration, and hydraulic models, but we expect that actual failures will remain difficult to predict."

Mitigate the risk of debris and sediment plugging the culvert by matching culvert width and alignment to the upstream bankfull channel. Furniss et al. (1998) suggest limiting headwater depths at the maximum design flow to 50 to 67 percent of the culvert opening, to account for sediment and debris. Correct an over-widened basin upstream of the culvert, since it allows wood to rotate perpendicularly to the culvert, exacerbating plugging potential. If an undersized culvert has widened the upstream channel, restore the channel dimensions to those of the reference reach. Avoid damaging the banks further upstream and possibly increasing their erosion potential during construction.

Consider designing the entire crossing to sustain plugging and overtopping by hardening fillslopes and approaches, and preventing stream diversion down the road or ditch. Be sure to factor maintenance into the design.

6.5.2.3 Stream diversion potential

For every culvert design, when the preliminary design is complete, ask "if the culvert plugs, where will the flow go?" If a plugged culvert backwaters flood flow so that it enters a ditch sloping away from the crossing, water will flow along the ditch until it either crosses the road (see figure 6.31) or drains into another stream channel. If diverted water outlets onto the roadfill or a slope, it can jeopardize slope stability. In some cases, entire stream channels have been diverted out of their normal alignment onto steep slopes with no capacity to carry flow, and large gullies have formed, causing slope failures. Diverted flows that enter another stream channel can cause channel erosion there.

To mitigate the risk of stream diversion at a crossing where plugging is possible, first mitigate the potential for debris or sediment blockage as described above. Then, design the road surface to keep overflow localized at the crossing. For example, you might build a sag vertical curve into the road alignment over the crossing or place a diversion dip in the road surface (section 7.7.2.1).

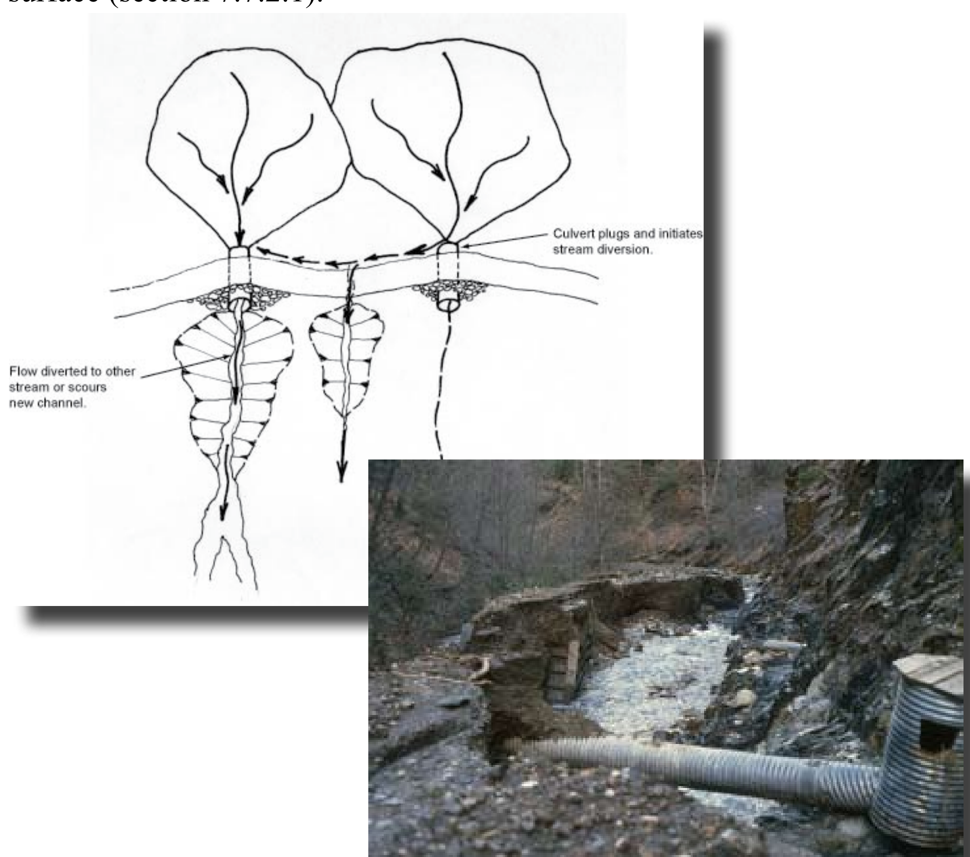

Figure 6.31—Stream diversion at plugged pipe. (photo: Stream diverted down road, Plumas National Forest 1997)

6.6 DESIGN DOCUMENTATION

Summarizing key site data, design assumptions, and decisions is important for others to understand the basis of the design. Good documentation is important for the final design phase (chapter 7) and during monitoring, when questions may arise about the intent of the stream-simulation design. Such documentation will also help reviewers and managers understand the project and design process well enough for permitting, prioritizing, and funding.

This completes the simulated-channel design. In the next step (chapter 7), the design engineer completes the design details for the installation and prepares the contract.