4 ROAD AND STREAM CROSSING DESIGN

A. INTRODUCTION

1. BASIC DESIGN CONSIDERATIONS

Road design is often a combined result of economic and environmental factors that influence construction, operating and maintenance costs. Unfortunately, because construction costs are felt immediately, economics was once the most important consideration employed in choosing a road's final design. However, excessive hauling expenses and difficulty of travel on a road, high road maintenance costs, as well as high environmental costs may have a far greater effect on the long-term economics of forest or ranch operations, or rural development, than the savings in initial construction of a low standard, poorly located or inadequately designed road.

Roads are designed for the expected type and frequency of use. Most forest, ranch and rural roads are designed as "low volume roads" that carry an average of less than 400 vehicles per day (Keller and Sherar, 2003), and have an appropriate design geometry for that level of use. Over-design can be a costly mistake. For example, construction costs for a 14-foot wide road on a steep sideslope may be as much as 30% higher than for a 12-foot wide road in the same location, simply because of the extra 2 feet of excavation width. Long-term maintenance costs are also likely to be higher for the wider road. For this reason, it is important to determine the main types of vehicles and the expected volume and speed of traffic so that the required, minimum road standards can be established well before actual construction begins.

Both road length and road width should be designed to minimum standards for the anticipated uses of the road. Narrow roads without inside ditches dramatically reduce excavation and sidecast volumes, thereby reducing cutbank height and decreasing the likelihood of slope failures (Table 15). For example, building a 12-foot wide insloped road with a 3-foot wide inside ditch requires moving almost 60 percent more material during construction than if the road were outsloped with no ditch (Table 15).

TABLE 15. Excavated soil volume for full bench roads with various road widths and hillslope gradients

Hillslope gradient (%)	Excavated volume to construct a full bench road assuming ½:1 cutbanks (yd^3 excavated per ft of road)			
	Road width 12 ft	Road width 14 ft	Road width 16 ft	Road width 18 ft
30	0.94	1.28	1.62	2.17
35	1.13	1.54	2.01	2.55
40	1.33	1.82	2.37	3.00
45	1.55	2.10	2.75	3.48
50	1.78	2.42	3.16	4.00
55	2.02	2.81	3.60	4.55
60	2.28	3.11	4.06	5.14
65	2.57	3.50	4.57	5.78
70	2.87	3.91	5.11	6.46
75	3.20	4.36	5.69	7.20

Road design begins with planning for the road's location. Selection of the final route will constrain many future design decisions. Two important design questions that need to be answered early in the planning process are 1) road prism design and 2) road surface design. Routing the alignment through or around various obstacles and hazards may dictate the use of certain road prism designs. In addition to these, there are special situations that often arise and require special road design considerations.

When considering road prism design, it is impossible to over-emphasize the importance of drainage in maintaining stable roads and protecting water quality. Roads should be designed and constructed to cause minimal disruption of natural drainage patterns. Provisions for two components of road drainage should be included in every road project: 1) road surface drainage (including drainage which originates from the cutbank, road surface and fill slope) and 2) hillslope drainage (including drainage from large springs, gullies and streams which cross the road alignment).

Finally, because hillslope morphology and hydrology varies greatly across the landscape, rarely can a single type of road prism and road surface drainage design be uniformly applied to a new or reconstructed road. One size does not fit all circumstances, and both road prism and road surface design is best varied to meet local conditions!

2. DESIGNING ROADS TO MINIMIZE HYDROLOGIC CONNECTIVITY AND PROTECT WATER QUALITY

Roads can adversely impact streams, water quality and aquatic habitat in several ways, including erosion and sediment delivery, altering hillslope and stream hydrology, and discharging chemical spills to streams and water bodies. Sediment is delivered to streams as a result of both episodic (usually storm related) and chronic (every runoff event) erosion processes. The most common storm-triggered erosion includes stream crossing washouts (gullying), stream diversions (and resultant hillslope gullying and slope failures), culvert outlet

erosion, hillslope gullying, bank erosion, and road and landing (turnout) fill slope failures.

In chronic erosion, sediment is delivered to streams every time there is a rainfall and runoff event sufficient to cause erosion of bare soil areas, concentrated runoff on compacted road surfaces and ditches, and sediment transport to nearby streams. The most common road-related bare soil areas include unpaved road surfaces, as well as unvegetated fill slopes, cutbanks, ditches and landslide surfaces. **If the runoff path from one of these bare soil areas delivers surface runoff and eroded sediment (even turbid water) to a stream it is termed "hydrologically connected" to the stream system. Hydrologic connectivity refers to the length or proportion of a road or road network that drains runoff directly to streams or other water bodies.**

A hydrologically connected road or road segment has been defined as: "Any road segment that has a continuous surface flow path to a natural stream channel during a 'design' runoff event" (Fumiss et al., 2000). A suitable "design" runoff event for many purposes has been suggested to be the 1-year, 6-hour storm, with antecedent moisture conditions corresponding to the wettest month of the year. This is the type of frequent rainfall and runoff event that is likely to generate surface runoff from most or all compacted and bare soil surfaces. **During runoff events, a hydrologically-connected road becomes an extended part of the natural stream network. Inboard ditches that drain to stream crossings and roadside ditches draining to gullies below ditch relief culverts are the most common road segments that are hydrologically connected to streams** (Figure 21). Other road drainage structures (e.g., rolling dips and waterbars) may also discharge runoff and sediment to nearby waterbodies. Wherever a hydrologic connection exists, concentrated runoff, eroded sediments and road-associated chemicals have a direct route to the natural channel network and surface waters.

Compared to unroaded hillslopes, roads always increase hydrologic connectivity. Hydrologic connectivity is affected by natural processes and human intervention. It will increase with increasing intensity and duration of precipitation or snowmelt. **In contrast, connectivity will be reduced where there are sediment obstructions and natural depositional areas, soils are deep and permeable, hillslopes are gentle and ungullied, streams are far away, and cross-drains are spaced closely together on the road.** All these road and hillslope factors are important in predicting sediment travel distances below cross-drains,

FIGURE 21. *Road approaches to bridges are often hydrologically connected. This through cut approach to a temporary bridge drains directly into the stream.*

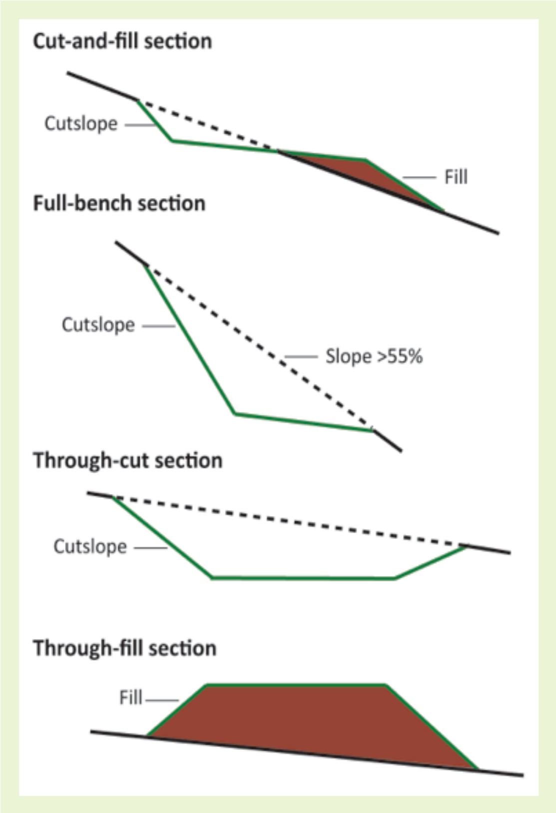


FIGURE 22.
Idealized diagrams depicting (a) a partial bench or cut-and-fill road (with both cut and sidecast); (b) full bench road (all material endhauled—no sidecasting); (c) a through cut section (all cut, with spoil material endhauled); and (d) a full (through) fill road (no cut—all fill placed and compacted in shallow layers). Road surface shapes can be outsloped, outsloped with a ditch, crowned with a ditch, or insloped with a ditch, depending on local conditions (Modified from: Kramer, 2001).

and in planning and designing for reduced connectivity and sediment pollution.

Simple road location, design, construction and maintenance measures can be employed to reduce hydrologic connectivity. Connectivity can be reduced by good road location, such as upper hillslope locations far from streams. Hydrologic connectivity is also increased with increasing stream crossing frequency; so roads should be located where there will be fewer crossings. Hydrologic connectivity on existing roads can be greatly reduced by designs that remove ditches and convert road shapes from insloped to outsloped, as well as by constructing frequent road surface and ditch drainage structures to disperse road runoff so it cannot reach a stream. **Reducing the length of road that is hydrologically connected to streams will directly and immediately improve water quality and protect downstream aquatic habitat.**

B. ROAD PRISM AND ROAD SURFACE DESIGN

1. ROAD PRISM DESIGN

Road prisms may be designed to be **full bench**, **partial bench** (part cut and part fill, also called balanced cut and fill) or **full fill** (Figure 22). Roads which are constructed without endhauling are **partial bench** roads where spoil generated during initial grading is used to widen the roadbed and fill depressions and stream channels crossed by the road. This has been the most commonly used construction practice for rural forest and ranch roads. The fill is placed and compacted, or (more commonly) sidecast loosely into the desired location. However, there are many circumstances where sidecasting is no longer acceptable and alternative designs and methods are needed and required to reduce environmental impacts and to provide a stable roadbed. The fourth design type is a **through cut** road where the alignment is cut through a ridge and for a short section the road has a cutbank on both sides. Through cut road sections, if needed, should be short because they are not easily drained.

Roads may need to be **full bench** on steep slopes (those over about 55%), especially where the road is close to or approaches a watercourse, or where water quality could be impacted by road work (Figure 23)[1]. Full bench construction requires that all the spoil generated by cutting into the hillside must be either used in filling local stream crossings and low spots in the new road, or endhauled to a stable storage site where spoil materials have no risk of entering a watercourse.

Outside of stream crossings, which are always full fill, road segments constructed with **full fill** techniques are less common, but may be employed on lowlands, wet valley bottoms,

1 See Appendix C for California Forest Practice Rules requirement for full bench slopes.

FIGURE 23. *Full bench road. The height of the cutbank, the slope of the natural hillside and the small amount of sidecast indicates that this road is full bench and cut entirely into native hillslope materials. Note that the road has no inboard ditch.*

extended wet areas, or wherever the road needs to be elevated to provide proper subsurface drainage, or where it is inadvisable to cut into the hillside. Roads using this technique are usually confined to short reaches where slopes are potentially unstable and cuts into the slope could trigger soil movement. Full fill sections of road are often supported by structurally engineered fills with steep fill faces.

Cut-and-fill design: For most forest, ranch and rural landowners, use of cut-and-fill road construction has been preferred because it minimizes the amount and cost of earth moving. In other words, less soil moved generally means less expense (Figure 24). Most older roads on the landscape have probably been built with this construction technique, using only a bulldozer for road building.

However, the indiscriminate use of sidecast road construction (the simplest method of cut-and-fill construction) has probably caused more problems for landowners than any other type of road building. Sidecasting construction techniques should not be used on slopes over 55 to 60 percent because this results in fill slopes of about 67 percent, the average angle of repose (stability) for most loose soil materials (Figure 25). For this reason, **sidecast construction should be limited to gently sloping areas where streams are far from the road prism.**

Cut-and-fill construction techniques can be used on slightly steeper slopes when excavated keyways and subgrade benching are employed to develop stable, well compacted road fills. In general, cuts should equal the needed fill volume, plus about 20 percent to allow for expansion and settling of loose fill. That is, the loosened, excavated soil will take up about 20% more space than when it was "in-place" (before it was excavated). During the process of cutting and filling, it is critical to avoid letting sidecast or waste material enter streams or watercourses, or placing it on unstable or steep slopes where it might erode and be delivered to a nearby water body.

The angle or steepness of both cut and fill slopes is very important in building stable

FIGURE 24. *In contrast to the road in Figure 23, this partial bench road was built by extensive side-casting. At least half the roadbed is built on fill materials.*

roads. There is a tradeoff in determining the optimum cut slope angle to construct (Table 16). **Cutbank slopes** should be designed to achieve maximum stability as well as a minimum exposure of bare soils.

Cut and fill slopes are usually expressed as horizontal-to-vertical ratios, such as ½:1, 1:1, or 1½:1 (Table 1). Road banks can be cut as steep as the stability of the material will permit, ranging from ¼:1 for very stable rock materials to 3:1 for erodible or unstable soils (Table 17). The stability of cut slopes is also highly dependent on soil types, groundwater conditions and local climate. Observations of cut slopes in settings similar to your proposed road project will provide useful information on in-the-field performance of cuts of various heights and angles. Use this field information to help you design the best cuts possible. A general guide for the maximum steepness of road cuts in various rock and soil materials is

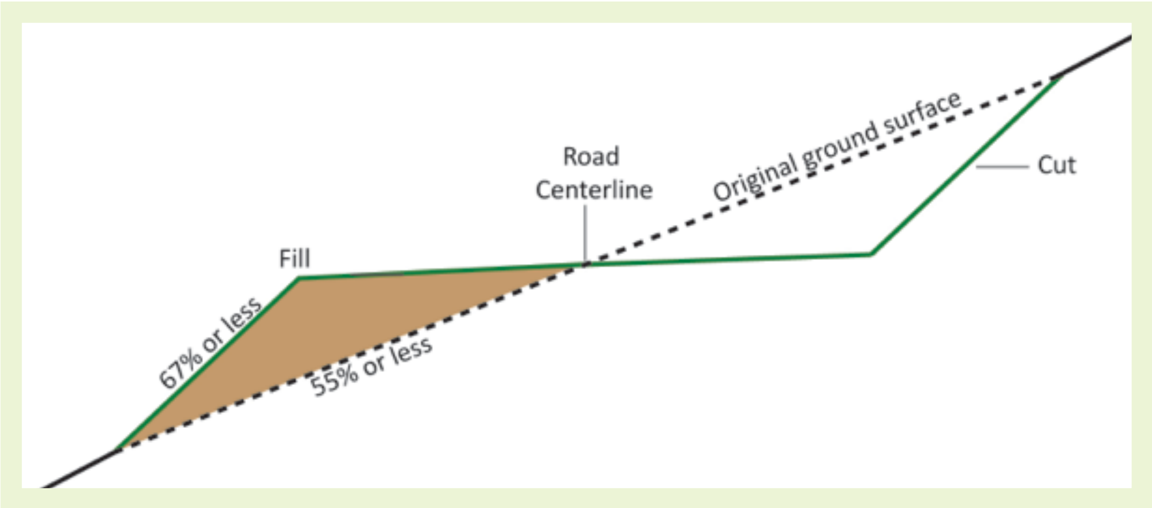


FIGURE 25. *For most earth materials, sidecasting on natural slopes over about 55% in steepness will result in steep, loose, unstable sidecast slopes that are easily eroded or prone to sliding. The face of an uncompacted sidecast slope should not exceed about 67% with most materials (less with granular or non-cohesive soils). This is the maximum angle of stability for most uncompacted, sidecast soil material.*

TABLE 16. Advantages and disadvantages of steep cut slopes[1]

Advantages of steep cut slopes	Disadvantages of steep cut slopes
1. Less right-of-way	1. Difficult to revegetate
2. Less excavated material	2. Prone to raveling
3. Less sidecast material	3. Prone to tension cracks and failure
4. Shorter slope exposed to surface erosion	4. Slightly greater risk of a rotational failure

[1]BCMF (1991)

shown below (Table 17). Note that wet slopes, unstable or erodible soils, and highly fractured or bedded rocks may require gentler slope cuts.

Cut height and cut angle also affect the stability of the final cut slope. Cuts which are stable at ½:1 at a 6-foot height may not be stable when the cut height is twice as high at 12 feet. Higher cuts lead to increased gravitational force and reduced stability at the face of the slope. Tall (deep) cuts are also more likely to intercept emerging soil water that can weaken the cut slope and cause failures that block the road or result in persistent ditch and roadbed maintenance problems.

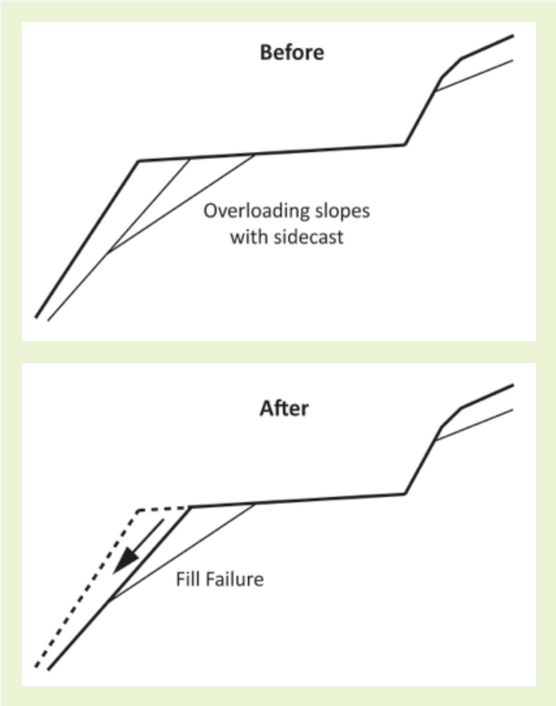
Fill slopes can be built to a variety of angles depending on the properties of the material used, the amount of properly applied compaction, soil moisture and the type and density of vegetation that is established on the surface. In contrast to cut slopes, a typical fill slope angle of 1½:1 or 2:1 will be stable under normal soil and site conditions. The greater the rock fragment content in the soil, the steeper the fill slope can be and still remain stable. A slope angle of 2:1 is most easily vegetated and provides the best long term stability to most fills. In general, thick accumulations of loose, dry, side-casted soil that is not compacted will not usually hold a slope over about 60 percent, whereas many fill materials that are placed and properly compacted in thin, less than 1-foot horizontal layers (lifts) may be stable at slopes up to or slightly greater than 1½ to 1 (67%), or steeper. While a thin veneer of angular sidecast materials may hold on a slope steeper than 65%, a thick wedge of loose sidecast may not be stable even at a 50% slope (Figure 26).

TABLE 17. Common soil/rock types and stable slope ratios[1]

Soil/Rock type	Slope Ratio (horizontal:vertical)
Most rock	¼:1 to ½:1
Most in-place rocks	¾:1 to 2:1
Very fractured rock	1:1 to 1 ½:1
Loose coarse granular soils	1 ½:1 to 3:1
Heavy clay soils	2:1 to 3:1
Soft clay-rich zones or wet seepage areas	2:1 to 3:1
Fill of most soils	1 ½:1 to 3:1
Fill of hard angular rock	1 1/3:1 or flatter
Low cuts and fills (<6–10 feet high)	2:1 or flatter (for revegetation)

[1]From Keller and Sherar, 2003. Note that slope stability is also very particular to the soil type and slope angle, and somewhat to rainfall, soil moisture, and other factors.

FIGURE 26. *Overloading steep slopes with uncompacted sidecast material can result in landsliding that damages streams hundreds of feet downslope (Modified from: BCMF, 1991).*



Stable road fills can be built on moderate and steep slopes by using benching, keyways and layered compaction methods. Here, a bench is excavated at the base of the proposed fill, and layers of moist, compacted soil are built up on this stable bench. The stability of the fill can be further increased by starting with an insloped bench that helps anchor the base of the fill into the native hillslope. A keyway is sometimes used to "lock" the fill into the denser or more stable underlying native soils or bedrock materials. Fill can then be compacted in lifts on top of this bench and steeper fill slope angles are possible. A keyed and benched fill depends on the fill being as strong as, or stronger than, the soil removed in the excavation. This bench and keyway locks the fill in place on the slope and prevents the fill from developing a failure plane where it is placed on the natural ground surface (Figure 26).

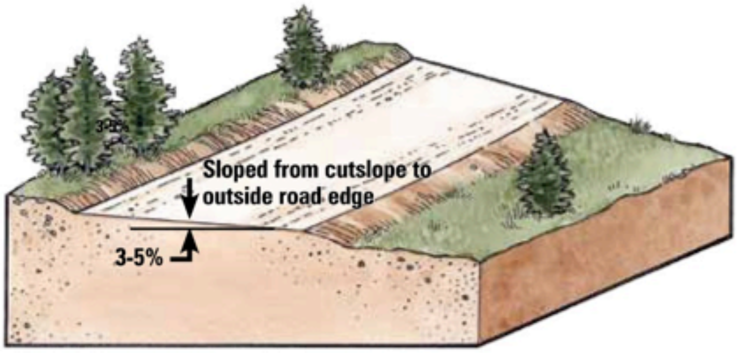
In critical areas, engineered fills that utilize reinforcing geotextiles or other internal supports can be constructed with nearly vertical faces. These are especially useful in short road sections where other fills would be unstable or erode and sediment could then enter a watercourse. In such cases, it may be necessary or prudent to employ a qualified, experienced geotechnical engineer or geologist to design a stable cut and fill road. Depending on the stability of the cut slope rock and soil materials, it may be simpler and cheaper to construct a full bench road where all the excavated material is simply endhauled off-site and deposited in a stable storage site.

2. ROAD SURFACE (SHAPE) DESIGN

Road surface design is really road surface drainage design, and should be chosen based on both maintaining safety for the intended uses, protecting the integrity of the road, and minimizing erosion and sediment pollution in streams. All three design standards should be met. Road surfaces can be designed as outsloped, crowned, or insloped (Figure 27). Often, more than one of these road surface designs is used along the road length. A road should never be graded with a flat road shape since this has no drainage. A flat road shape that does not drain to one side or the other is prone to puddling and pot holes in areas of no road grade, or to ruts and surface erosion if it is sloping up or down a hill. Flat, poorly drained roads often require a high level and frequency of maintenance.

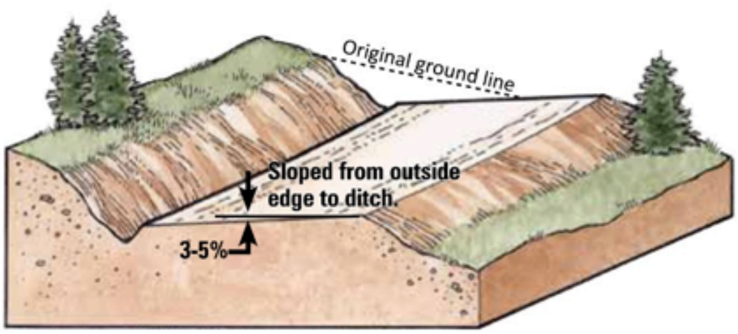
Outsloped roads are considered the best and most preferred road shape for most circumstances. Insloped and crowned roads require inside ditches, and ditches generally require regular maintenance. In addition to construction costs (ditched roads require considerably more excavation and construction costs—see Table 15), it is important to consider long term maintenance requirements and costs when deciding whether to construct an outsloped road or an insloped/crowned road.

Outsloped



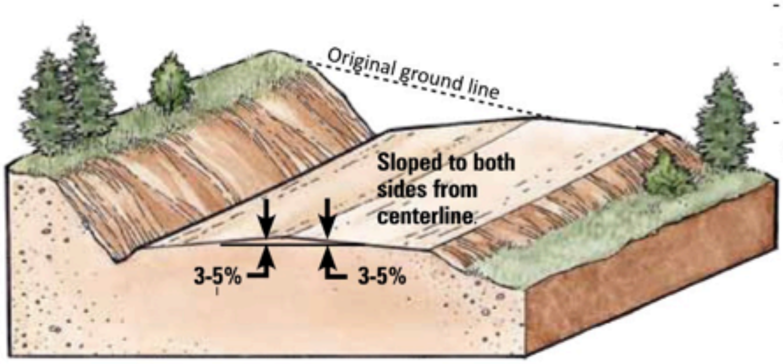
Outsloped roads are used:
- where road grades are gentle or moderate (≤8-12%)
- to minimize construction costs
- where cutslopes are dry
- with an inside ditch, where cutbanks are wet
- where road surface drainage is to be dispersed
- always in concert with rolling dips

Insloped



Insloped roads are used:
- where road grades are moderate to steep (≥8-12%)
- where road grades are moderate or steep and slippery (muddy, snowy or icy)
- where cutbanks are wet and ditches are used
- where ditches can be maintained
- where fillslopes are unstable or highly erodible

Crowned



Crowned roads are used:
- where road grades are gentle or moderate (≤8-12%)
- where ditches are maintained and can be drained frequently
- where roads are wide and two way traffic is common
  - where commercial or high traffic use is common
  - where slippery or icy conditions are common

FIGURE 27. *Road surface shapes include outsloped, insloped and crowned. The diagram depicts an outsloped road with no ditch (top), an insloped road with the inside ditch (center), and a crowned road with an inside ditch (bottom). Outsloped road shapes are generally preferred because of lower construction and maintenance costs. Where cutbanks are wet with spring flow an outsloped road shape can be combined with an inside ditch. Note that insloped and crowned roads generally require more hillslope cutting and have higher cutbanks than outsloped roads because of the extra width needed for a ditch (Modified from: Adams and Storm, 2011).*

Road shaping for proper drainage is not an all-or-nothing proposition. For example, roads which contour the landscape may alternate from outsloped to insloped as the road traverses the hillside. Roads that are outsloped for much of their length may also be locally insloped to deal with local conditions (e.g., a sharp outside curve). While some wet cutbanks may require the construction of an inside ditch (or French drain) for drainage, the roadbed itself may still be a worthy candidate for outsloping. **Ultimately, it is critical to properly design road surfaces to minimize erosion of the roadbed, ditch, cutbank and fill slope surfaces, while minimizing sediment delivery to streams.**

a. Outsloped roads, with or without an inside ditch

It is generally recommended that most forest, ranch and rural roads be constructed as single lane (minimum width), outsloped roads with minimal cut-and-fill, wherever conditions are suitable. Intervisible turnouts can be provided to allow passing. An outsloped road cross section is likely to cause the least disturbance and soil movement, create less environmental impact and have lower maintenance costs than other designs. Outsloped roads disperse and drain runoff along the entire outside edge of the road (Figure 28). They are less expensive to construct and less difficult and expensive to maintain than insloped roads, provided they are constructed in appropriate hillslope locations.

If hillslopes are dry, and cutbanks along existing roads display little or no evidence of emergent water (springs or seeps) during the wet season, there is no reason to construct or maintain an inboard ditch along a road. Analyzing cutbank and hillslope hydrologic characteristics will allow you to determine whether an inside ditch is necessary along your road.

Roads built wherever the surface can be kept dry and free draining should generally be outsloped to disperse runoff. Conditions that might limit road outsloping include: 1) steep road grades (≥20%) which may make adequate outsloping difficult; 2) winter use of

FIGURE 28. *Well built, outsloped road displaying minimum cut, smooth free draining surface, and no outside berm. The road contours the topography and its rolling grade and rolling dips disperse surface runoff.*

an unsurfaced road (snow or muddy conditions on a steep, outsloped road may be hazardous); or 3) upslope runoff or excessive spring-flow from the cutbank or roadbed (which might make an inside drainage ditch necessary).

However, many ditched roads are also candidates for surface outsloping, thereby draining surface runoff to the outside and not into the ditch. The inside ditch will carry relatively clear water flows from seeps and springs, while the outsloped road surface ensures that turbid road runoff and fine sediment eroded from the roadbed will be drained to the outside edge of the road where it can be safely discharged into vegetation and onto undisturbed soils. Outsloping thereby minimizes flows in the inside ditch and reduces the potential for erosion and sediment delivery from the road surface.

Clearly, if conditions permit, roads should be constructed with an outsloped surface, no ditch and no berms along the outside edge of the road. If berms are needed for safety, they should be frequently breached along their length to allow for dispersed road surface drainage. Table 18 shows design criteria for the degree of outsloping needed to drain road surfaces on differing grades. The design of outsloped road surfaces, especially on steeper road grades, should also consider safety where the road surface may be slippery (e.g., in rain or snow conditions) during parts of the year.

Where fill slopes are stable, roads should be designed and constructed with minimum width and with a mild, 3 to 5% outslope (Figure 29). However, on most roads, especially those with grades in excess of eight percent (8%), outsloping is not always enough to get surface runoff out of wheel ruts and off the road quickly. Here, in addition to outsloping, **waterbars (for seasonal or temporary roads) or rolling dips (for permanent and seasonal roads) are necessary to divert surface runoff off outsloped roads.**

Where an outsloped road turns on an outside curve the outslope is frequently tapered to a flat or insloped road shape, depending on the direction of the turn, and then back to an outslope in the following straight stretch. These safety measures are commonly called super-inslope (turning around a ridge) or super-outslope (turning around a depression or swale). The shape of the road keeps vehicles slightly "banking" around turns in the road and allows them to maintain constant speeds without increasing the risk of skidding off the turning road. The short sections of alternating road shape also allow for dispersed road surface drainage.

TABLE 18. Outsloping "pitch" for roads up to 8% grade[1]

Road grade	Outslope "pitch" for unsurfaced roads	Outslope "pitch" for surfaced roads
≤ 4%	3/8" per foot	1/2" per foot
5%	1/2" per foot	5/8" per foot
6%	5/8" per foot	3/4" per foot
7%	3/4" per foot	7/8" per foot
≥ 8%	1" per foot	1 ¼" per foot

[1]California Department of Forestry and Fire Protection (2008)

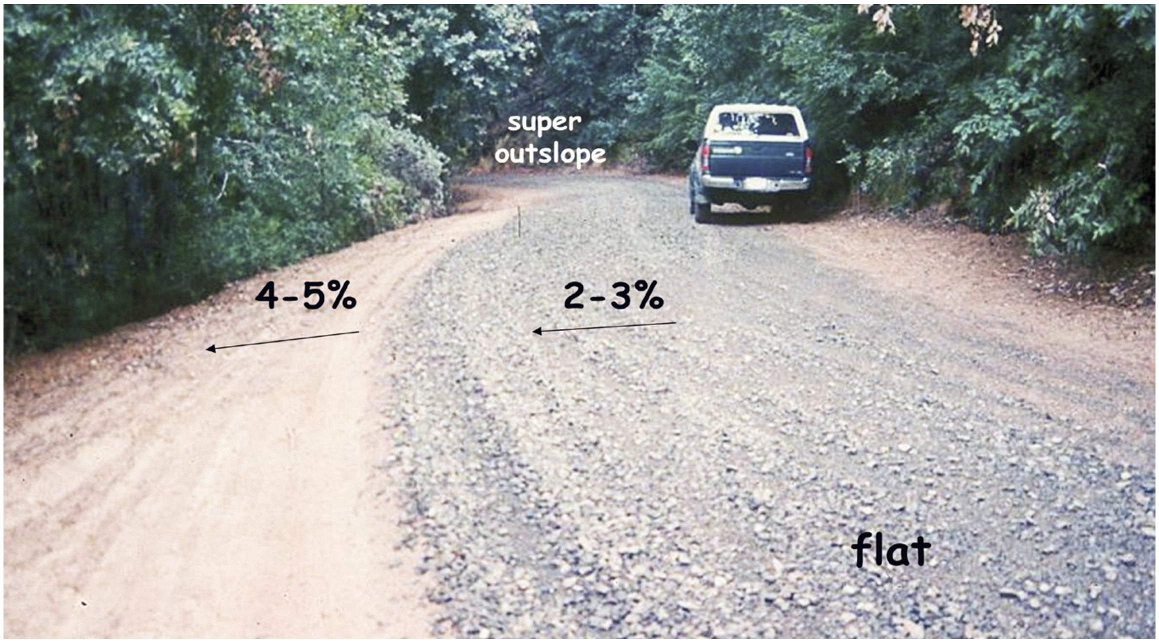


FIGURE 29. *Road shape changes as the road travels through the landscape. For example, an outsloped road will have a steep or "banked" outslope through inside curves, a consistent outslope through straight reaches and a flat or slightly insloped shape as it goes through an outside curve. The road may have an outslope of 2-3% across the travel surface while the shoulder is more steeply outsloped to ensure runoff and sediment will leave the roadbed.*

b. Crowned roads

A crowned road surface is one which traditionally slopes gently away from the centerline of the road and drains to both sides of the crown (Figure 30). Crowning is most commonly used where roads are wide enough for two lane traffic. Crowning may also be employed for safety purposes to keep traffic separated and where road grades are steep or snow is common; the crowned shape helps keep vehicles from sliding off the road.

The inside portion of a crowned road drains inward to the cutbank and ditch, while the outside portion drains out across the fill slope, thereby reducing the volume of road surface runoff (and fine sediment) that flows into the inside ditch. Crowning can be peaked at the center of the road, essentially dividing road surface drainage in half, or offset from the center so that more of the road surface drains to one side or the other. For example, crowning at the inside $^1/_3$ of the road surface results in most

FIGURE 30. *Crowned roads are peaked near the center of the roadbed and each side of the road surface drains to a ditch. This stable, crowned road reach is through cut into the hill and the ditches are drained frequently to prevent ditch erosion.*

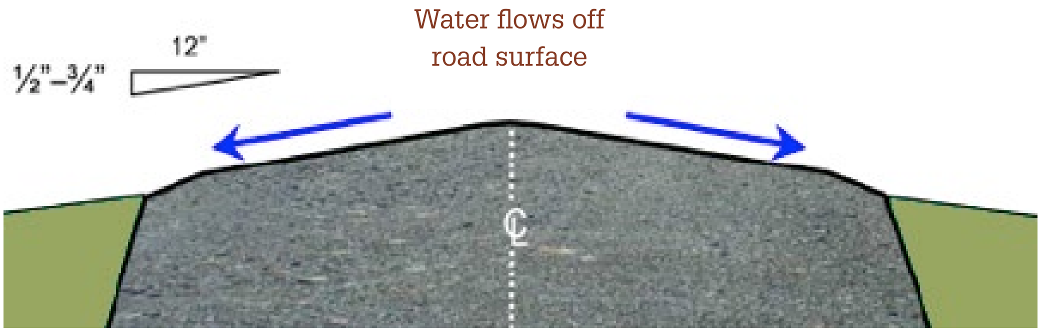


FIGURE 31A. *Centerline crown with proper cross-slope for an unpaved road. Road drainage flows without obstruction off the road surface into surrounding vegetation. Note the slight grade increase at the road shoulder to encourage off-road drainage (Center for Dirt and Gravel Road Studies, 2005).*

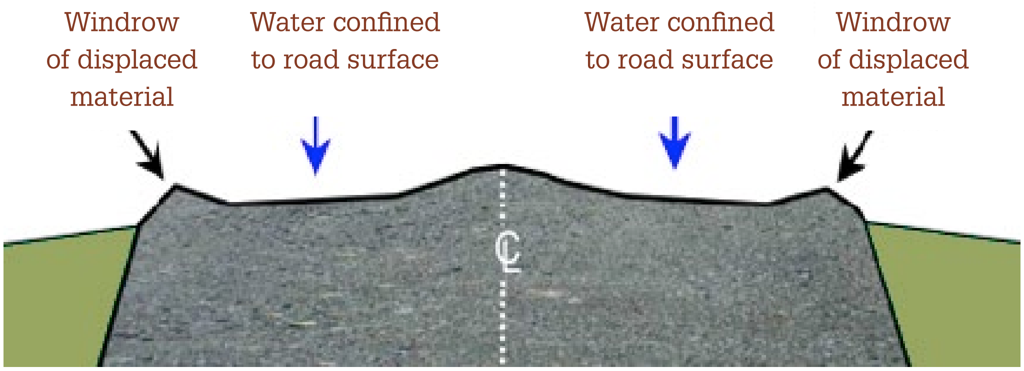


FIGURE 31B. *Centerline crown has become misshapen over time. Road surface drainage is trapped on the road by gravel movement, grader berms or by road rutting under heavy traffic. Road drainage travels down the rutted road surface causing erosion, loss of road material, and increased maintenance. The road can be reshaped to restore cross drainage, but rolling dips are needed for effective, permanent surface drainage (Center for Dirt and Gravel Road Studies, 2005).*

surface runoff and sediment being discharged to the outside of the road bench, much like an outsloped road. Regardless of the location of the crown, an inside ditch is still required.

On rock and native surfaced roads crowning requires frequent maintenance grading and/or the use of rolling dips to drain water off the road before it can produce ruts (Figures 31a, 31b). The recommended cross-slope is between 4% and 6%, or ½" to ¾" of fall per horizontal foot of width. The steeper cross-slope means less potential for water to penetrate and weaken the road and, therefore, longer intervals between maintenance grading operations.

c. Insloped roads

Insloped roads should be constructed only where road surface drainage needs to be kept off the fill slope (because it is unstable or the road is located right next to a stream), or where outsloping would create unsafe driving conditions. Insloped roads drain surface runoff to the inside of the roadbed, usually into a ditch, where it is combined with flow from the cut slope and upslope hillside areas and discharged to nearby stream crossing culverts or ditch relief culverts (Figure 32). The ditch causes the water table beneath the road to be lowered as it flows out of the soil and into the ditch.

Depending on the type of traffic and the road surfacing materials, roads steeper than about 8 to 10 percent may be too steep for safely outsloping. In this setting, insloping with a ditch may be necessary, although the potential for gullying in the ditch increases with road grade. Inside ditches should be drained at intervals sufficient to prevent ditch erosion and outlet gullying, and at locations where water and sediment can be filtered before reaching a watercourse. "Filtering" can be accomplished by thick vegetation, gentle slopes, constructed settling basins, or filter windrows of woody debris and mulch placed and secured on the slope.

As with outsloped roads, steep insloped road surfaces may be difficult to quickly drain. Rolling dips (for permanent roads and seasonal roads) or waterbars (for seasonal or temporary, unsurfaced roads) should be constructed at frequent intervals sufficient to disperse road surface runoff from steep road segments (Tables 3 and 19). Ditches and culverts need occasional maintenance to operate correctly and to carry the flows they were designed to handle. When

FIGURE 32. *This insloped ranch road drains to an inside ditch that shows evidence of past downcutting. Inside ditches need to be drained with ditch relief culverts frequently enough to prevent ditch erosion, as well as erosion of the slope where the culvert is discharged.*

TABLE 19. Recommended maximum rolling dip and ditch relief culvert spacing, in feet, based on road gradient and soil erodibility [1, 2]

Soil erodibility	Road gradient (%) and drainage structure spacing (feet)				
	0–3	4–6	7–9	10–12	>12
High to moderate	250	160	130	115	100
Low	400	300	250	200	160

[1]Based on Keller and Sherar, 2003. Also suggested by California Board of Forestry and Fire Protection in Technical Rule Addendum No. 5 (see Appendix C).

[2]Table distances are designed to prevent ditch erosion, not to eliminate hydrologic connectivity. If road surface drainage is hydrologically connected to a stream crossing, install first a rolling dip and/or ditch relief culvert close to the crossing, but such that it drains onto the fill slope or hillslope and will not deliver runoff to the watercourse. The next (second) drainage structure should be placed so that it too will not discharge to the stream. Add additional drainage relief treatments along the road according to the approximate spacing recommended in this table.

ditches become blocked by cutbank slumps, they need to be cleaned. However, excessive maintenance of ditches (mostly grading) can cause continuing and persistent erosion, sediment transport and sediment pollution to local streams during storm runoff.

3. ROAD DRAINAGE STRUCTURES

Road drainage structures include those features of a road, other than road shape, designed to drain road surface and cutbank runoff off or away from the road prism. Road drainage structures include rolling dips, waterbars, drainage berms, ditches and ditch relief culverts (Table 20). The purpose of all drainage structures is to get water off of, and away from, the roadbed as quickly as possible so roadbed materials do not become saturated, and roadbed/ditch erosion is minimized.

a. Rolling dips

Rolling dips and a smooth, sloped road surface are critical to maintaining a well-drained, outsloped road. On climbing (or falling) roads, especially on outsloped road shapes, the road surface can be drained using rolling dips or waterbars. Unlike abrupt waterbars, rolling dips should be able to be driven at prevailing speeds on the road where they are installed. Rolling dips are smooth, angled depressions constructed in the roadbed (Figures 33a, 33b). Typical design dimensions for rolling dips are shown in Table 21. **It is important to use rolling dips, rather than waterbars, on roads with even infrequent use because traffic will quickly break down and/or breach**

TABLE 20. Comparison of drainage structures used on dirt and gravel roads

Structure type	Ditch relief culverts	Rolling dips	Water bars	Cross road drains
Purpose	Drains the road's inside ditch	Drains the road surface; Only drains the ditch if dip is deep and intersects the ditch	Drains the road surface	Drains road surface, ditch and springs on decommissioned or closed roads
Construction costs	High	Medium	Low	Low to Medium
Maintenance	Medium Needs frequent inspection and inlet cleaning	Low Needs occasional repair or reshaping	High Needs frequent cleaning, reshaping and replacement	None Should not need any maintenance
When to use	On all road grades On high or low traffic roads with frequent maintenance	On low and moderate grades On high or low traffic roads	On all road grades On low traffic roads or seasonal roads	On all closed or decommissioned roads, especially at springs and seeps
When not to use	On infrequently maintained roads; or wherever they would discharge to streams or onto unstable areas Below unstable or raveling cut slopes	On steep grades (>12% to 18%), depending on traffic type On curves	On high traffic roads	Where the cross road drain would feed water onto an unstable area or deliver eroded sediment to a stream

waterbars. Waterbars should be reserved for unsurfaced seasonal roads that are to have little traffic and/or no wet season use.

Rolling dips are usually used on outsloped roads to drain road surface runoff to the outside of the road, but may be built on either insloped, crowned or outsloped roads to drain runoff in either direction. However, keep in mind the goal of effective road drainage is to disperse rather than collect and concentrate road runoff. Drainage structures that drain to the inside of the road will likely require a greater number of ditch relief culverts to prevent ditch erosion and/or the formation of hillslope gullies.

***Rolling dip design*—In general, broad rolling-dips are usually built perpendicular to the road alignment, with a cross slope of 3 to 5 percent greater than the grade of the road.**

FIGURE 33A. *Rolling dip constructed on a rock surfaced rural road. The rolling dip represents a change-in-grade along the road alignment and acts to discharge water that has collected on, or is flowing down, the road surface. This road was recently converted from a high maintenance, insloped, ditched road to a low maintenance, outsloped road with rolling dips.*

FIGURE 33B. *This side view of an outsloped road shows that the rolling dip does not have to be deep or abrupt to reverse road grade and effectively drain the road surface. This outsloped forest road has rolling dips that allow all traffic types to travel the route without changing speed.*

TABLE 21. Table of rolling dip dimensions[1]

Road grade (%)	Upslope approach[2] (distance from up-road start of rolling dip to trough) (ft)	Reverse grade[2] (distance from trough to crest) (ft)	Depth below average road grade at discharge end of trough[2] (ft)	Depth below average road grade at upslope end of trough[2] (ft)
<6	55	15–20	0.9	0.3
8	65	15–20	1.0	0.2
10	75	15–20	1.1	0.1
12	85	20–25	1.2	0.1
>12	100	20–25	1.3	0.1

[1]USDA-SCS (1981)
[2]See also Figure 36

The cross grade slope ensures proper drainage to the outside of the dip. If the outslope in the axis of the rolling dip is insufficient, water will not drain, sediment will be deposited, and puddles and potholes will form. The morphology of the dip results in an up-and-down or slight rolling movement when driven. Some rolling dips are built at a 30 to 45 degree angle to the road alignment, but if the road is to receive commercial truck and trailer traffic (e.g., log trucks or cattle trailers) this angle can cause a significant rocking and twisting action to heavy truck loads and trailers that may not be acceptable.

Rolling dips are built with a long, shallow approach on their up-road side and a more abrupt rise or reverse grade on their down-road side (Figure 34, Table 21). Dips should be constructed deep enough into the road subgrade so that traffic and subsequent road grading will not obliterate them. Their length and depth should provide the needed drainage, but not be a driving hazard (Figure 35).

Rolling dips can be broken down into three types, depending on the existing road gradient and conditions of the outboard edge of the road. Figure 36 provides the general design characteristics of the three rolling dip types.

- A Type 1 rolling dip is the standard rolling dip design for roads that do not have a through cut or large berm that would prevent the dip from draining onto the adjacent outboard fill slope. Type 1 rolling dips are built on roads with road gradients less than 12–14%, and with or without a small outboard berm that can be easily removed. If an outboard berm is present make sure to remove the berm through the entire length of the dip.

- Type 2 rolling dips are designed for roads with gradients less than 12–14% within a small through cut, or that have a large (i.e. tall and/or wide) berm on the outboard edge of the road. This type of dip requires "breaching" or excavating the outboard through cut or large berm through the axis of the dip. The width of the breach is dependent on the road conditions (e.g., width of berm, road steepness, and road subgrade materials).

- Type 3 rolling dips are suggested for roads with gradients that exceed 12–14% where road steepness prevents the construction of a rolling dip with a reverse grade. Instead of building a dip with a reverse grade, a Type 3 rolling dip is constructed by building an aggressive 6–8% outslope from the inboard to the outboard edge of road to ensure that runoff travels obliquely across the road and exits the road within the rolling outslope. This outslope is developed by ripping the roadbed and pushing road fill from the outboard half to the inner half of the road.

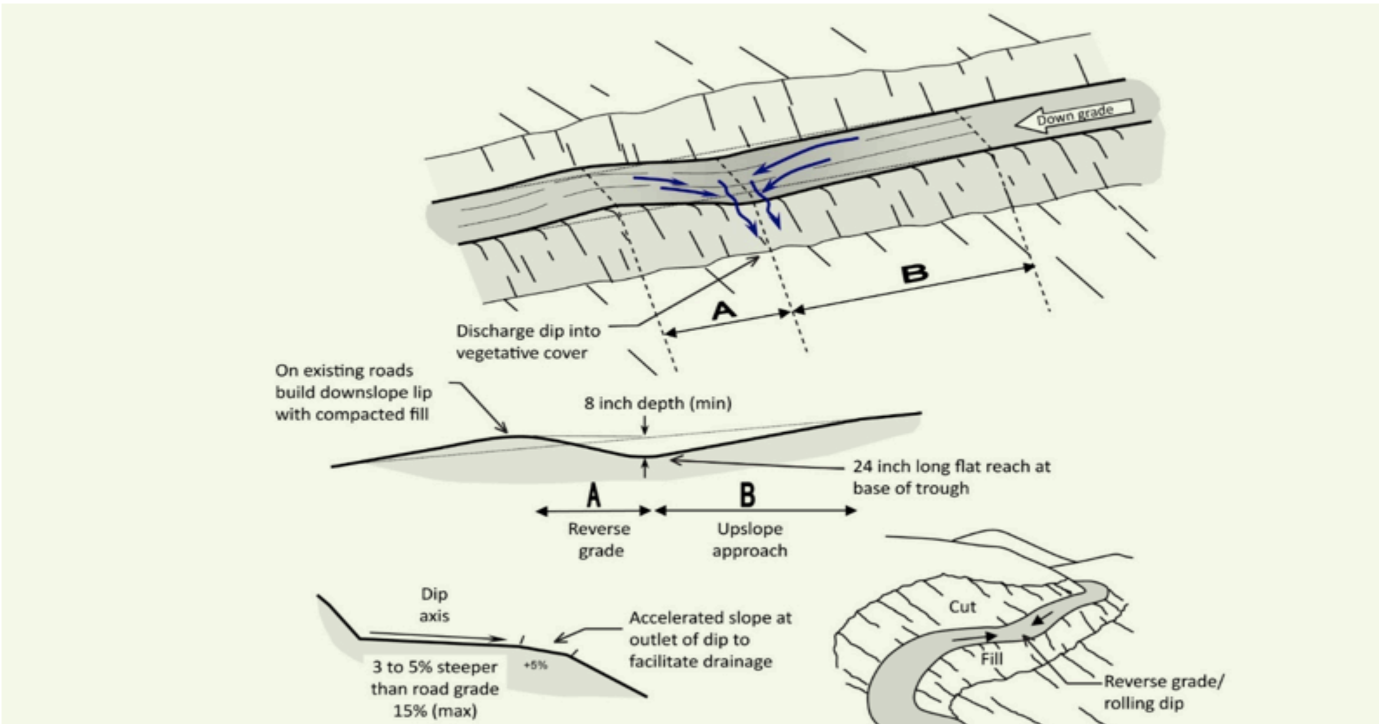
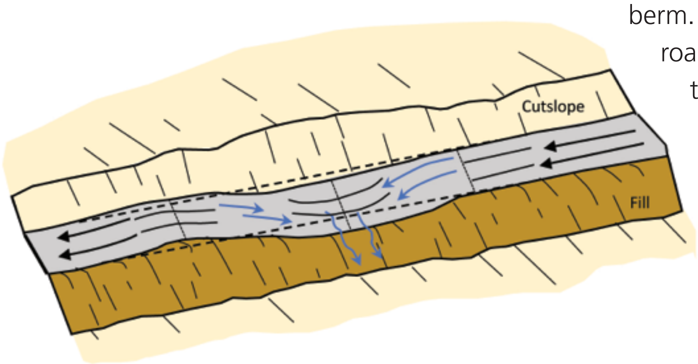


FIGURE 34. *A classic Type I rolling dip, where the excavated up-road approach (B) to the rolling dip is several percent steeper than the approaching road and extends for 60 to 80 feet to the dip axis. The lower side of the structure reverses grade (A) over approximately 15 feet or more, and then falls down to rejoin the original road grade. The dip must be deep enough that it is not obliterated by normal grading, but not so deep that it is difficult to negotiate or a hazard to normal traffic. The outward cross-slope of the dip axis should be 3% to 5% greater than the up-road grade (B) so it will drain properly. The dip axis should be out-sloped sufficiently to be self-cleaning, without triggering excessive downcutting or sediment deposition in the dip axis (Modified from: Best, 2013).*

FIGURE 35. *This outsloped forest road is used by commercial logging trucks and was constructed with frequent rolling dips to promote road surface drainage. The dips were built as a part of planned road construction for use by truck and trailer traffic. Note that the cutbanks are rocky, dry and stable, and there is no inside ditch.*

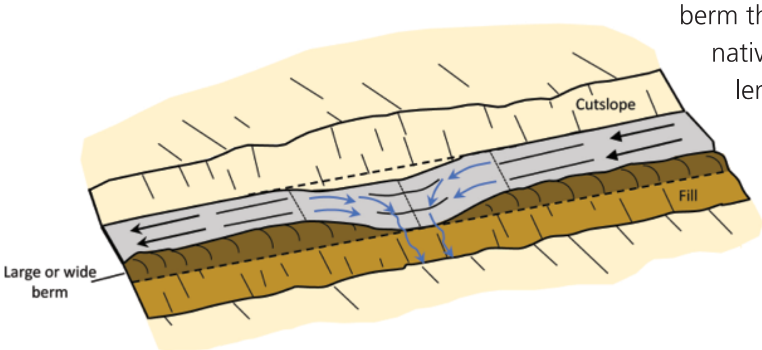
Type 1 Rolling Dip (Standard)

Type 1 rolling dips are used where road grades are less than about 12-14% and road runoff is not confined by a large through cut or berm. The axis of the dip should be perpendicular to the road alignment and sloped at 3-4% across the road tread. Steep roads will have longer and more abrupt dip dimensions to develop reverse grade through the dip axis. The road tread and/or the dip outlet can be rocked to protect against erosion, if needed.



Type 2 Rolling Dip (Through-cut or thick berm road reaches)

Type 2 rolling dips are constructed on roads up to 12-14% grade where there is a through cut up to 3 feet tall, or a wide or tall berm that otherwise blocks road drainage. The berm or native through cut material should be removed for the length of the dip, or at least through the axis of the dip, to the extent needed to provide for uninterrupted drainage onto the adjacent slope. The berm and slope material can be excavated and endhauled, or the material can be sidecast onto native slopes up to 45%, provided it will not enter a stream.



Type 3 Rolling Dip (Steep road grade)

Type 3 rolling dips are utilized where road grades are steeper than about 12% and it is not feasible to develop a reverse grade that will also allow passage of the design vehicle (steep road grades require more abrupt grade reversals that some vehicles may not be able to traverse without bottoming out).

Instead of relying on the dip's grade reversal to turn runoff off the roadbed, the road is built with an exaggerated outslope of 6-8% across the dip axis. Road runoff is deflected obliquely across the dip axis and is shed off the outsloped section rather than continuing down the steep road grade.

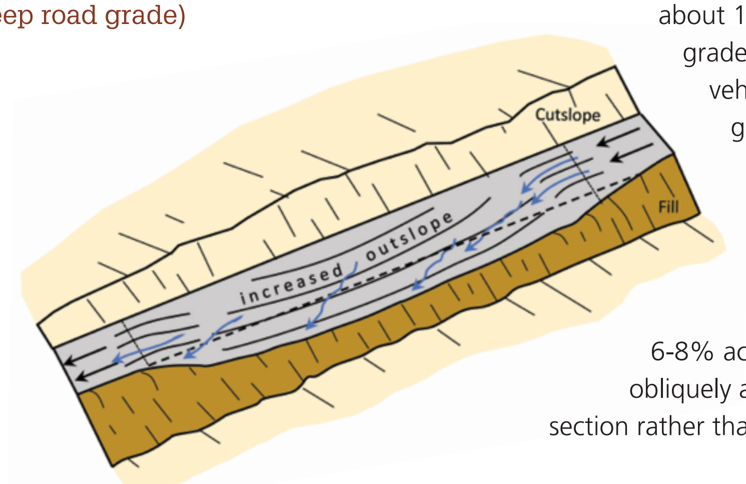


FIGURE 36. *Rolling dip types*

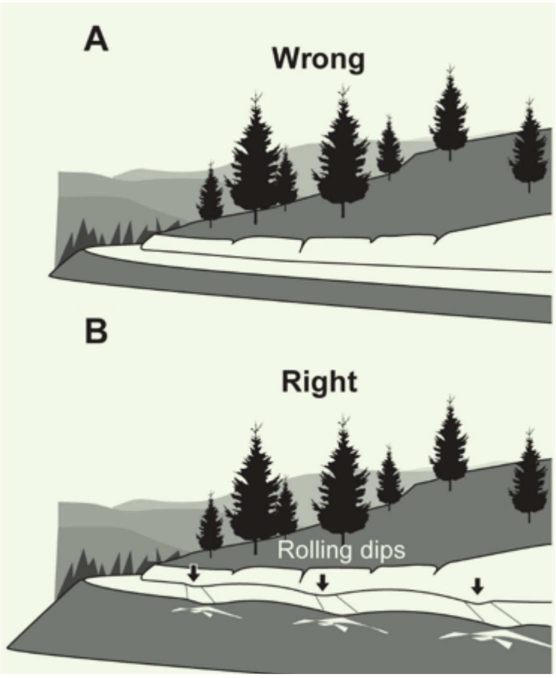


FIGURE 37.
Installing rolling dips, or "rolling the grade" of an outsloped road helps guarantee that surface runoff will not concentrate on the road surface and erode the roadbed, and that road runoff will be dispersed across the hillside. Spacing of rolling dips depends on road grade, soil erodibility and proximity to the nearest water body (Kramer, 2001).

Rolling dip spacing—The frequency or "spacing" of rolling dips and grade breaks (Figure 37), and the amount of "outsloping" needed to drain the road surface, depends on the grade of the road, as well as the road surfacing (Table 19). To design drainage structure spacing, it is useful to look at local roads to determine the maximum spacing that is likely to work for the soils and climate in your specific area. Example design criteria for drainage structure spacing to minimize road surface and ditch erosion (waterbars and rolling dips) are listed in Table 3 and, alternately, Table 19 (rolling dips and ditch relief culverts).

Drainage tables provide guidance and are common in the literature, but local observations are key to determining the most appropriate spacing in your particular area. In general, the spacing of road drainage structures is appropriate when you can observe minor rilling (incision) on the road fill slope where the road runoff is occurring, but hillslope rills and gullies are absent or do not extend continuously on native slopes below the drainage structure outlet (Figure 38).

The basic spacing guidance of Table 19 must be tempered by the proximity of the discharge points to streams and other waterbodies, and considering factors that might increase the probability of runoff and sediment being transported to the stream, lake or wetland. Those things that are likely to increase the probability of sediment delivery include such factors as: a short distance to the nearest stream or water body, steep slopes, unstable terrain, the presence of gullies or channels that could collect and efficiently transport road runoff and sediment, bare soils or low vegetation density, and shallow or clay rich soils with low infiltration rates. **To account for hydrologic connectivity in the suggested drainage spacing tables you must significantly and progressively reduce the spacing of drainage structures as you get closer to streams and other waters, accounting for the proximity of stream or lake, slope steepness and the other contributing factors.**

b. Waterbars, rubber waterbars and open top box culverts

Waterbars can also be used to drain a road surface. These are shallow, abrupt, excavated dips or troughs with an adjacent, downslope hump or mounded berm that are built at an oblique angle across the road (Figure 39). To maintain the greatest effectiveness, the axis of the waterbar (including where it drains onto the adjacent hillslope) should be constructed at a gradient slightly steeper than the road gradient it is intended to drain. This prevents deposition within or at the outlet of the structure and maintains flow and sediment transport along its length.

Waterbars are useful only on low standard seasonal or temporary, unsurfaced roads where winter or wet season use will not occur, because traffic easily cuts through the soft berm and fills the adjacent dip. Waterbars should be constructed at proper

FIGURE 38. *Rolling dips should be spaced on outsloped roads so that the road surface is well drained and free from erosion, and the slopes below each dip show minimal erosion. Three broad rolling dips (see arrows) are visible in this upgraded road reach used by both commercial and residential traffic.*

spacing according to the grade of the road (Figure 40; Tables 3 and 19). Waterbars are usually regraded (smoothed out) at the beginning of each operating season in which the road is to be used and opened to traffic, and then reconstructed prior to the beginning of each winter or wet season period.

Waterbars are high maintenance drainage structures that are prone to failure if not properly built and maintained. Unauthorized winter traffic is likely to break down waterbars and result in serious road surface erosion and water pollution. Roads that are drained with waterbars should be restricted from most traffic, especially during the wet season when soils are softest.

On seasonal rocked roads and roads where waterbars cannot be built and maintained each year, thick rubber flaps or "rubber waterbars" are occasionally constructed into the roadbed. The rubber waterbar is most useful where frequent road grading is not necessary but the road surface needs better drainage.

These drainage diversion devices are sometimes made of thick rubber strips or salvaged conveyor belt fabrics, and are dug at least 12

FIGURE 39.
Waterbars are often used to drain surface runoff from seasonal, unsurfaced roads. Because they are easily broken down by vehicles, waterbars are only used on unsurfaced roads where there is little or no wet weather traffic. In this photo, a waterbar and ditch relief culvert are used to drain all road surface and ditch runoff from the insloped road prism.

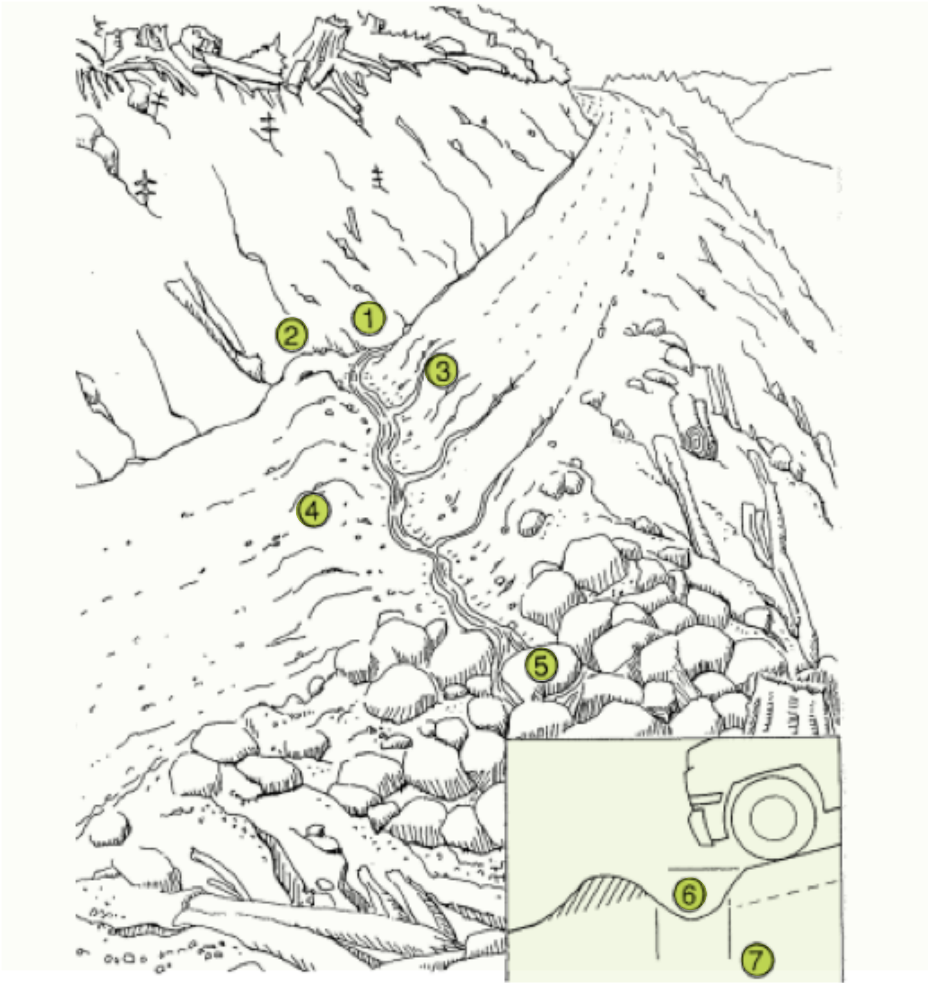


FIGURE 40. *Waterbars are constructed on unsurfaced forest and ranch roads that will have little or no traffic during the wet season. The waterbar should be extended to the cutbank to intercept all ditch flow (1) and extend beyond the shoulder of the road. A berm (2) must block and prevent ditch flow from continuing down the road during flood flows. The excavated waterbar (3) should be constructed to be self-cleaning, typically with a 30° skew to the road alignment with the excavated material bermed on the downhill grade of the road (4). Water should always be discharged onto the downhill side on a stable slope protected by vegetation. Rock (shown in the figure) should not be necessary if waterbars are spaced close enough to prevent serious erosion. (5) The cross ditch depth (6) and width (7) must allow vehicle cross-over without destroying the function of the drain. Several alternate types of waterbars are possible, including one that drains only the road surface (not the ditch), and one that drains the road surface into the inside ditch (BCMF, 1991).*

inches into, and anchored in, the roadbed at an angle oblique to the road alignment, much like a waterbar. They stick up about 4 inches above the running surface and divert surface runoff to the side of the road. The flap bends down as vehicles pass over the waterbar and then immediately springs back to deflect runoff. Unlike waterbars, vehicles can drive over the flap without having to slow down; it folds over and pops back up when the vehicle passes.

The main shortcomings include the labor intensive installation required to build each diversion device, and the difficulty of grading the road surface that contains frequent rubber waterbars.

Open top box culverts (usually made of wood or metal) can also be used to drain the road surface, but they often fill with soil and rock, are difficult to grade over, and usually require higher levels of maintenance to keep open and functional. They should have a relatively steep grade so they self-clean during runoff events, and are often fitted with a surface grate on top to prevent large rocks from entering the top of the culvert and obstructing flow.

Like waterbars, and for maximum effectiveness and minimal maintenance, these less common road drainage structures should be constructed obliquely across the road such that their slope is slightly greater than the grade of the road they are draining.

c. Drainage berms

Road berms are generally defined as a continuous row of fill and/or aggregate,

FIGURE 41. *This outside berm on a crowned road prevents road surface runoff from draining onto the adjacent hillslope. If the road was insloped, the berm would not interfere with road drainage.*

FIGURE 42. *Short road reach where a soil berm has been intentionally constructed along the outside edge of the road prism to prevent surface runoff from flowing over the highly erodible fill. To prevent the accumulation of too much runoff, the berm can be intermittently breached and a small flared inlet and culvert or sheet metal berm-drain installed to carry runoff downslope past the base of the erodible fill slope.*

usually on the outside edge of a road, which prevents surface water from leaving the road (Figures 41 and 42). Berms may be created in several ways and have several purposes, or they may be the result of poor grading practices. **Regardless of their origin, road berms can have the negative consequence of unintentionally collecting and concentrating road surface runoff.** Berms located along the outside edge of a crowned or outsloped road prevents road runoff from leaving the roadbed and may result in roadbed erosion or gully erosion where the concentrated runoff is discharged off the road.

Not all berms are bad. For example, where berms have formed or been built along the outside of an insloped road, and road surface runoff is flowing away from the berm and into the inside ditch, the berm will not have any negative hydrologic effects. Similarly, berms are sometimes used as a real or perceived safety measure to keep vehicles from sliding off outsloped or crowned roads that are steep or built in a snow-zone, or where the road is narrow and the adjacent hillside is extremely steep. In other locations, berms may be intentionally constructed on the outer edge of the road to keep drainage water from flowing into a stream or onto an unstable area (Figure 42). Berms are often used by grader operators as a temporary reservoir of road surfacing material that can be brought back onto the road surface during routine maintenance grading operations.

Many other road berms along forest, ranch and rural roads are unintentionally built as a consequence of routine road surface grading and maintenance, leaving a small (or large) berm of spoil material along the out edge of the road. Over time, these small berms become permanent as they are covered with vegetation. The largest berms are often the unintended end-product of years of routine grading. **Road berms on the outside of an outsloped or crowned road can have the same effect on road drainage as does a through cut; road runoff may be blocked by the berm and unable to drain off the road surface. It collects, diverts and then discharges runoff where it can cause fill slope and/or hillslope gullying.**

Berms may also form because of physical obstructions that prevent effective road surface grading. The growth of vegetation or young trees on the outside edge of a road, or the presence of a property boundary or livestock fence along the inside or outside road edge, may prevent effective surface grading, thereby causing formation of a residual berm. Road berms may also be created by road maintenance crews when they decide to store spoil materials, created elsewhere (e.g., by slide clearance work), along the outside edge of a wide section of road.

Berm treatments—It is generally a good practice to completely or intermittently remove berms that are blocking road runoff and preventing effective road drainage. If berms are not blocking or diverting road surface runoff they may be left in place with no adverse effects. **Simple treatments can often be used to minimize the hydrologic impact of berms on roads, road surface drainage and downstream water quality:**

- Keep the outside edge of outsloped or crowned roads free of berms unless they are intentionally placed to control water or for traffic safety.
- Where they are preventing road surface drainage, remove berms or breach berms at strategic non-erodible locations to allow drainage onto non-erodible, stable slopes.
- Where driving hazards do not exist, avoid creating a windrow or small berm of material along the edge of an outsloped or crowned road during maintenance grading which may form a barrier to dispersing road surface runoff.
- Consider installing a raised berm on the outside edge of the road over newly constructed stream crossings to keep road surface runoff from discharging onto and eroding newly built fill slopes until they are well vegetated.
- Berms are also good to use where a road closely parallels a stream, lake or wetland. Berms can be used to control and direct road surface runoff, and to intentionally discharge it where the sediment will not impact streams, lakes or wetlands.
- When outside berms are needed as a permanent safety measure, daylight (breach) them at frequent intervals (e.g., every 30 to 60 feet) to break up the length of the berm and the accumulated runoff that would otherwise occur.
- Road berms on insloped roads do not affect road drainage and can usually be left in place with little negative effect.
- If they are not needed, or if they are causing road drainage and erosion problems, road berms on crowned and outsloped roads can be either partially or completely removed.

- Depending on the slope steepness and proximity of the road to a stream, berms can be removed by excavation or sidecasting. Sidecasting should not be used if there is a possibility that spoil or eroded sediment could enter a watercourse and/or increase fill slope instability.

d. Ditches

Historically, many roads have been "automatically" constructed as insloped, with an inboard ditch. For decades, that was the default engineered design standard, whether or not hillslopes were wet and a ditch was really needed. Landowners should evaluate soil moisture, usually during the wet season, to determine what portion of the road actually requires a ditch for drainage and to maintain a firm and stable roadbed. Dry road sections should be constructed, or reconstructed, as outsloped, without a ditch. In wet areas, the road can still be outsloped even if an inside ditch is needed to drain emergent water (Figure 43).

Well-constructed and maintained ditches are important to the long-term stability of an insloped or crowned road. Backhoe and excavator constructed ditches are often superior to bladed ditches built by a bulldozer or grader because they can be cut out of the subgrade rather than gouged into the cutbank. However, they are more difficult and time consuming to construct and maintain. The ditch cross section should be designed to accommodate expected storm flows, with the base of the ditch at least 12 inches below the adjacent roadway in order to prevent water from entering and saturating the road surface material and reducing road strength. A relatively deep ditch also allows for faster drainage of the subgrade into the ditch and helps maintain high soil strength beneath the roadbed. If the cutbank and ditch are relatively dry for most of the year, the ditch can be shallower as roadbed saturation should not be an issue.

There are two types of roadside ditches; those that are hydrologically connected and delivering runoff and sediment to streams, and those that

FIGURE 43. *This rural subdivision road has been converted from an insloped, ditched road to an outsloped road shape with rolling dips and an inside ditch. Broad rolling dips have been built at regular intervals to accommodate all traffic types. The ditch has been retained to drain clear spring flow from the small cutbank. The road surface no longer drains to the ditch.*

are not. **Road ditches that drain directly to stream crossing culvert inlets are typically the most common and important source of hydrologic connectivity between roads and streams.** During runoff events they act much like an ephemeral stream, and serve as "conveyor belts," transporting road runoff and fine sediment to the natural stream channel network. **Connected ditch lengths should be minimized, and the ditches themselves should be constructed and maintained to minimize the amount of sediment that is delivered to the stream crossing.** Broad, low gradient, vegetated ditches immediately adjacent to the stream crossing will encourage sediment deposition (Figure 44). Connected ditches should be graded as infrequently as possible, and then seeded and revegetated after grading. Ideally, the roads draining to connected ditches should be rock surfaced (or paved) to minimize surface erosion or they should be outsloped so their runoff does not drain to the ditch.

In contrast, ditches that are not hydrologically connected to streams, lakes or wetlands should be maintained to be as efficient as needed to rapidly drain runoff away from the road and into adjacent downslope buffer areas. Ditch gradients on insloped roads should be steep enough to prevent excessive sediment deposition and allow rapid drainage, but not so steep as to result in ditch erosion. The road gradient usually dictates the ditch gradient. Outsloped roads do not drain to the ditch, so sediment accumulation is not an issue.

On steep roads over about 10% grade, even small volumes of ditch flow may have high enough flow velocities to cause erosion of the ditch. In this case, it may be necessary to armor the ditch to prevent erosion, although armoring the ditch will make it more difficult to maintain. Any armoring of channels or ditches also has to follow specific design criteria to be effective. Dumping loose rock in the ditch will likely cause erosion rather than prevent it. The rock armor needs to be formed into a channel shape, with a bottom and sidewalls to contain the expected volume of flow.

When inside ditches are used along a road, frequent ditch relief culverts should be installed to minimize the concentration of runoff in the ditch and to disperse runoff to downslope

FIGURE 44. *This insloped, gravel surfaced road drains to a vegetated ditch. The ditch is connected to a stream crossing culvert, but the heavy vegetation in the ditch prevents sediment from being delivered to the stream.*

FIGURE 45. *If ditches show excessive erosion, or long gullies form below the outlet of a ditch relief culvert, then the ditch is carrying too much flow and additional ditch relief culverts are needed up the road to break up the flow. Gullies below culvert outlets are a common source of hydrologic connectivity, delivering road runoff and eroded sediment to the downslope stream channel.*

areas. **If the ditch shows signs of erosion, it is likely that additional culverts are needed to break up and disperse the ditch flow. Likewise, if ditch relief culverts show extended scour at or below their outlets, that is a sign that there is too much flow being discharged onto the slope below the road and that one or more additional culverts are needed to drain the ditch and disperse ditch flow without causing erosion downslope from the road** (Figure 45).

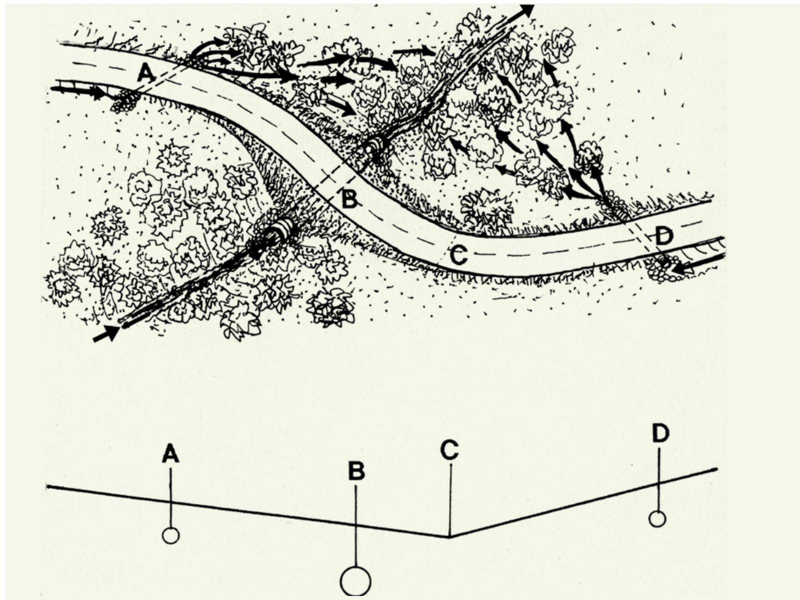
e. Ditch relief culverts

Hydrologically connected ditches which drain directly to watercourse crossing culverts should be treated and protected from disturbance and erosion, just as is an ephemeral stream or Class III watercourse. Ditch relief culverts should be installed sufficiently before watercourse crossings so that water and sediment can be filtered through a vegetated slope before reaching the stream. They should also be installed at intervals along the road that are close enough to prevent significant erosion of the ditch and below the culvert outfall on the native hillslope, and at locations where collected water and sediment is not discharged directly onto unstable areas or into watercourses (Figure 46; Table 19).[2]

Spacing tables for ditch relief culverts that are often found in the literature, or even derived for your particular area, can provide guidance on how frequently to install road drainage structures to minimize erosion. **However, an inflexible spacing distance or frequency, derived from a spacing table, is not recommended because conditions along all roads change and some locations are more suitable for receiving runoff than others. The performance of the ditch, the ditch drain outlet and the receiving area (including the potential for hydrologic connectivity) are the**

2 California's Forest Practice Rules do not prescribe the maximum or proper distance between inside ditch relief drains. Instead, they state that adequate drainage must be provided. Table 19 provides examples of suggested spacings, although it is important to remember that actual spacing is dictated by local conditions and proximity to a watercourse, with closer spacing near the channel (see Appendix C: California Department of Forestry and Fire Protection Technical Rule Addendum No.5). Indicators of inadequate relief drain spacing include: 1) gullying of the inside ditch, 2) gullying or sliding of the slope below the culvert outlet of a cross drain, 3) direct transport of sediment along an inside ditch to a watercourse, or 4) direct transport of road runoff and sediment from a drainage structure outlet to a stream.

FIGURE 46. *Where a road approaches a stream crossing (B), ditch flow should be culverted across the road (A, D) and discharged into a vegetative buffer that can filter the runoff before it reaches the watercourse. If the stream culvert plugs with debris or is topped by flood flows, flow will spill over the road at the change-in-grade (critical diversion dip, or critical dip) at location "C" and back into the stream channel (Modified from: MDSL, 1991).*



most important drivers for the placement of ditch relief culverts and other road drainage structures.

Ditch relief culverts do not need to be large, since they carry flow only from the cutbank, springs and sometimes from a limited length of road surface. **It is recommended that a minimum 18-inch diameter pipe be used for ditch relief culverts in forested locations (where woody debris is in transport).** Smaller culverts are too easily plugged, either by transported organic debris in the ditch or by cutbank slumps above the culvert inlet. If the cutbank above the inlet is unstable or rapidly eroding, a slotted drop inlet can be installed over the inlet to keep it from plugging. Where roads cross grassland areas, with no woodlands, the minimum culvert diameter can be reduced slightly but should never be less than 15 inches.

A general rule-of-thumb is to install the culvert at a grade at least 2% steeper than the ditch grade leading to it, and to skew the culvert at a 30° angle to the ditch line (Figure 47) to minimize inlet erosion and to efficiently transport sediment through the culvert (Figure 48). A minimum 10 percent grade through the culvert will usually be self-cleaning. Inlet protection, such as rock armoring or drop structures, can be used to minimize erosion, safely turn the flow, prevent inlet plugging and slow flow velocity as it enters the pipe. Culverts should be installed to discharge at the toe of the fill slope so their discharge does not erode the fill. If they are set shallower, they will need a full-round downspout, half-round/flume or properly sized, armored channel to carry the culvert flow to the base of the fill slope.

Culvert outfalls that show erosion can be protected with slash and/or rock armor to prevent erosion, but there is no reason to automatically armor the outlet of ditch relief culverts. **If erosion is isolated to the culvert outlet area, and does not extend downslope as a gully, then outlet armoring is probably not necessary. Where sedimentation at the inlet occurs because of over-steepened cutbanks, drop inlets can be installed to prevent culvert plugging.** Culverts should never be "shot-gunned" out of the fill, thereby creating highly erosive road drainage "waterfalls" and the resultant outlet gullies.

FIGURE 47. *Ditch relief culvert installed across a low volume, permanent road. The culvert is set at the base of this shallow road fill and angled approximately 30° to the road alignment.*

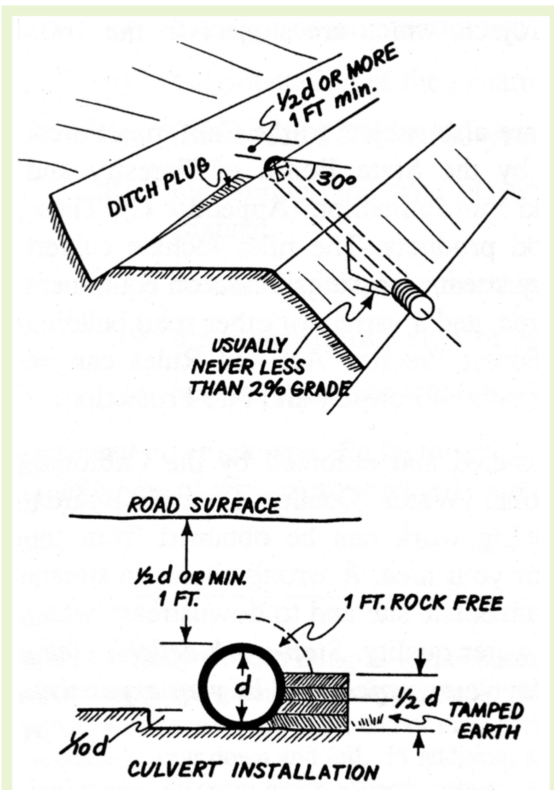


FIGURE 48. *The elements of a properly installed ditch relief culvert. The culvert is angled at about 30 degrees to the road alignment to help capture flow and prevent culvert plugging or erosion of the inlet area. It is set at the base of the fill (ideally) or with a grade slightly steeper than the grade of the contributing ditch (but never with a grade less than 2 percent). At a minimum, the grade of the ditch relief culvert should be sufficient to prevent sediment accumulation at the inlet or deposition within the culvert itself (it should be self-cleaning) (USDA-SCS, 1983).*

4. SPECIAL DESIGN CONSIDERATIONS

In forest, ranch and rural land settings, special design considerations may be required where roads cross unstable slopes, wet areas, watercourses and other potential hazards or obstacles. Some of these might involve using new, state-of-the-art subdrainage materials and methods. Other special designs may simply involve the application of time tested methods of equipment exclusion, excavation, endhauling, bridge installation, road surfacing or additional requirements to provide increased protection to water quality. Guides for special road design are often available from engineering geologists or geotechnical specialists specializing in road construction, from literature and manuals, and/or from suppliers of materials and supplies used in erosion control and road engineering.

a. Landing design and layout

Forest roads used for commercial timber harvest often have wide areas, or landings, built along their road systems where cut logs are loaded onto log trucks for transport to the mill. Log landings vary tremendously in size and frequency from one landowner to the next, but their design requirements differ little from other sections of a road system (Figure 17). Newer, mobile cable yarding machines can operate on narrow sections of road, with little more than a turnout required for their swing. Other yarders, including towers, may require an entirely separate "yarder pad" be constructed on a spur road above the main haul road where logs are landed and then loaded onto trucks.

Although such large yarding machines are becoming less commonplace, these legacy landings are found along many older forest road systems. Landowners who have purchased formerly logged lands to use for forestry or other purposes should identify and carefully evaluate landings for long term stability. For example, landings may be envisioned as good building sites for rural landowners, but most were built with little or no attention to proper compaction.

Tractor yarding requires moderate size landings that, over the years, may grow larger than needed as spoil and debris is carried down the converging skid trail network and then sidecast over the outside edge of the landing. In the Pacific Northwest, bulldozers were historically used to yard logs down small stream channels and steep slopes; creating large landings. Today, tractors are usually used only on gentle and moderate slopes and not in or near stream channels so their landings are less likely to impact streams.

Helicopter yarding requires the largest landings, but very few in number, and they are typically located high on slopes and ridge top areas. Their impact on hydrology and sediment delivery can be more easily mitigated.

The frequency of landings that need to be constructed is controlled, or influenced, by the type of yarding equipment, the slope of the land and the density of harvestable trees along the route. For example, on very steep slopes, stable landings might only be constructed on broad ridge crests (Figure 16). In general, landing construction should be limited to the fewest number and smallest size that are absolutely needed for yarding operations.[3]

Landing fills that are placed on steep slopes or near watercourses should be "keyed" or benched into the hillslope and compacted in shallow (1 foot) lifts from the bottom up. Sidecasting should be avoided. In addition, older landings that are being rebuilt or reused should not be enlarged by sidecasting of spoil or organic debris. Where roads are located far from the stream, maximum hillslope gradients for building small landings using sidecasting methods should be the same as for road construction: about 55 percent. It is recommended that benches or benches with keyways be constructed for catching sidecast and fill where landings are built on slopes steeper than about 40%.

The following terrain conditions should be avoided as sites for landings (Figure 16): 1) unstable slopes and soils, 2) open slopes steeper than about 55% with no natural benches, 3) steep headwater swales and inner gorge slopes, 4) narrow ridges between headwater swales, 5) any steep slopes (>50%) which lead without flattening to a watercourse and 6) areas underlain by steeply dipping sedimentary rock or highly fractured rock.

3 See Appendix C for California Forest Practice Rules regarding landing design.

Constructing full benches for landings on steep slopes produces tremendous volumes of spoil material. Although full benching might be necessary so that fills can withstand equipment vibrations and weight loads, spoil that is disposed of as sidecast can destabilize the hillside below. Sidecasting should be avoided during construction or enlargement work. Gully headwalls and swales are already naturally unstable sites and have little room for landing debris. Sidecasting into these steep headwater swales can trigger debris flows and torrents (Figure 49). Although steep, narrow ridges adjacent to these steep headwater channels provide good deflection for yarding, the sides of these ridges are often unstable and unsuitable for sidecasting.

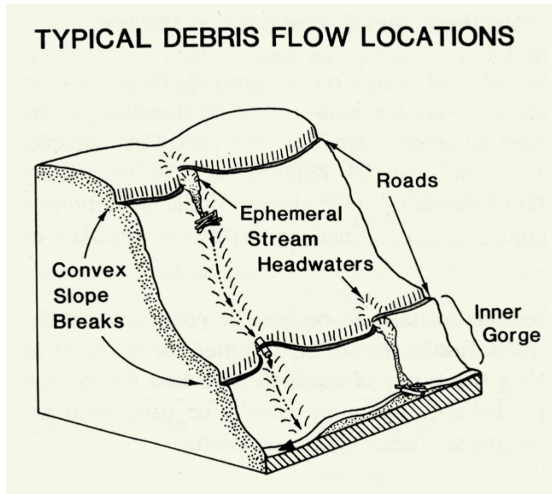


FIGURE 49. *Research in mountainous areas has shown that many destructive debris slides and debris flows caused by the construction of wildland roads occur at specific sites on a hillside. The most sensitive sites, and therefore those to avoid during road and landing construction, are steep inner gorge slopes, steep headwater swales or stream areas, and steep slopes immediately below a convex break-in-slope.*

b. Converging roads

Converging roads on steep slopes is one special case of road construction that commonly produces erosion and sediment problems. In this situation, a lower road may undercut and remove support for the upslope road. In addition, sidecast from the upper road can extend downslope to the lower road, with continuing sidecast from the lower road then extending the blanket of bare soil downslope even farther. These steep, bare soil areas are notably difficult to stabilize and revegetate.

The best planning and design solution for converging roads is to locate road junctions on gentler slopes, or to plan for them to occur on broad ridges separating steep gradient slopes (Figure 50). If steep slopes cannot be avoided, it is recommended that the upper road be constructed as a full bench road with all spoil endhauled to a stable location, and the lower road be built with an

FIGURE 50. *Where roads diverge or converge on a steep hillside, there is an increased likelihood for slope undercutting, instability, excessive sidecasting, and subsequent erosion. Road intersections should be located on benches, or on gentler terrain, underlain by stable, dry or rocky soils to minimize required excavation volumes and subsequent instability and erosion.*

engineered fill or as a full bench road to limit uncontrolled sidecasting. The road junction should be located sufficiently far upslope from watercourses such that water quality will not be affected. Full bench construction with endhauling, or other creative engineering solutions that minimize sidecast, may be designed for these "unavoidable" settings where the potential for sedimentation or slope failure is relatively high.

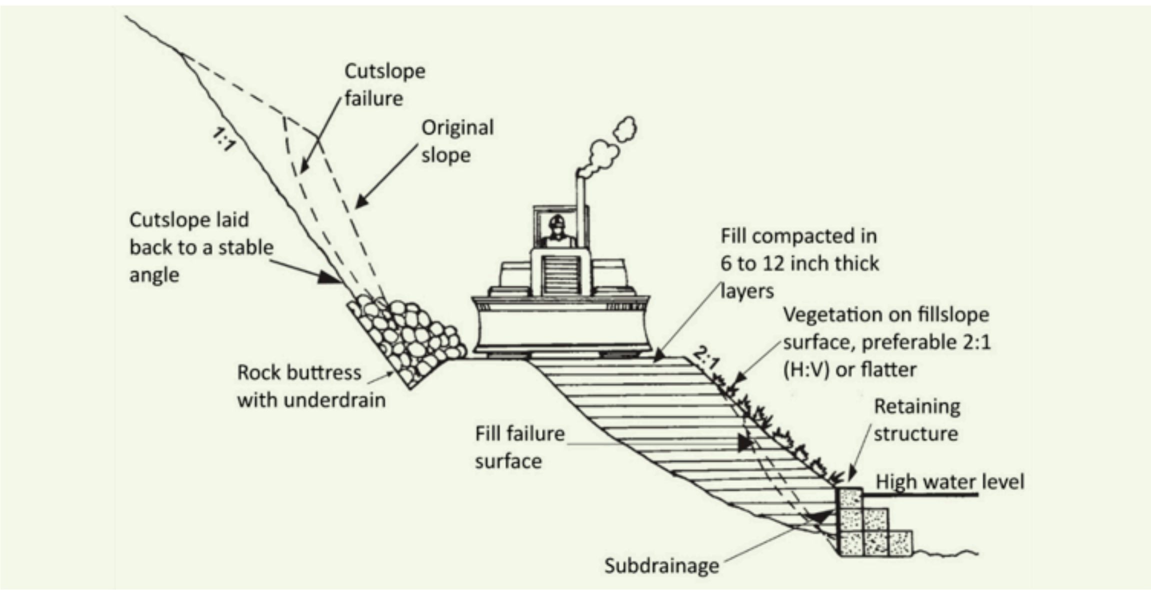
c. Developing stable cuts and fills

Roads are typically built across hillslopes using either cut-and-fill construction methods, or employing full bench (end-haul) methods. Balanced cut-and-fill road construction (no endhauling) is appropriate wherever slopes are moderate and stable, and slopes are less than about 40% to 50% gradient. As slopes steepen, balanced cut-and-fill methods become more difficult to employ and conditions may require benching and compaction to retain and control loose fill.

Roads built across steep slopes are generally more prone to failure than those on moderate or gentle slopes in the same soil types. Similarly, wet, unstable or fine grained soils are more prone to failure during storm events than are those constructed through dry, coarse and angular materials. Road fills in wet areas may appear stable for long periods, but they can still represent potential weak points along the road alignment even years after initial road construction.

General diagrams and guidance have been developed for creating stable cutbanks and fill slopes in typical soil materials (Table 17). However, stable cut slope and fill slope angles will be highly specific to the type and character of the soils and hillslope hydrology through which the road passes. Cuts into erodible, unstable or wet soils can cause instability in otherwise stable hillslopes, as road construction undercuts natural slopes, removes lateral support, and exposes springs and through-flow of near surface soil water. Similarly, unstable, erodible soils may not be suitable for fill slope construction. These special situations may require rerouting of the alignment or the use of special designs, including full bench endhauling, fill slope benching, or the construction of slope revetment (rock buttresses, reinforced (engineered) soils or retaining structures) (Figure 51). If these sites are unavoidable along a proposed alignment, or if an existing road alignment is experiencing continuing stability

FIGURE 51. *Slope stability solutions with a variety of stabilization measures. Other than simple excavation treatments, most slope stability solutions will require input and/or design by a qualified engineer or engineering geologist (Modified from: Keller et al., 2011).*



problems, a qualified and experienced geotechnical engineer or engineering geologist can assist with one or more special designs.

On slopes steeper than about 50% to 65%, or within 100 feet of a stream, full bench endhaul construction is almost always preferred. Higher cutbanks from full bench construction can increase the risk of cut slope failures, but most of these are caught by the road bench and do not travel past the road or into a stream. **If full bench construction is not possible (say, because of a solid rock bank) road relocation or the use of various retaining structures, buttresses and engineered fills can be employed where a fill slope is needed on steep slopes.** These structures require engineering and significantly increase the cost of road construction or reconstruction, so **they are infrequently used on low volume roads in forest, ranch or rural settings.**

Rock buttresses keyed into the basal slope are the simplest and least expensive slope retaining structure (Figure 52). Because of the large earth pressures involved, retaining structures typically require engineering design. Manufacturers of special application materials used for retaining wall structures will usually give engineering advice on the use of their products. Retaining structures should be reinforced and planted with live cuttings between the structural elements to provide for increased long term stability.

The simplest and most straightforward method of repairing unstable fill slopes is direct excavation of the unstable fill materials. If excavation would significantly reduce usable road width, widening the road into the cutbank may be a simple and low cost solution. **For unstable fills along the outside edge of a road where there are signs of instability (cracks and small scarps), but the road cannot be moved into the cut slope, a deep patch repair can be used.** This consists of excavating the unstable subsided materials, creating a stable bench in the native soils, and then backfilling the excavation with compacted

FIGURE 52. *This wet and potentially unstable cut slope on a newly constructed road was stabilized using a buttress of large rock armor. To assure their effectiveness, rock buttresses and other retaining structures should be designed by a qualified engineer or engineering geologist.*

lifts of soil. Several layers of geogrid or geotextile are placed to provide additional lateral support. **Common maintenance grading or paving over cracks or small scarps does not stop or repair a fill slope settlement problem.**

d. Through cuts

There are a number of road shapes and drainage structures or features that direct and control surface runoff on rural roads. These include rolling dips, waterbars, various road shapes (insloped, crowned or outsloped) and natural dips in the road alignment. Most of these are intentionally employed to direct road surface runoff to chosen locations where it will minimize potential impacts to water quality. **Through cuts are often an unintentional consequence of the initial road alignment, construction practices or subsequent maintenance activities.**

i. Location and characteristics There are two basic types of road cuts; sidehill cut and through cut (Figure 22). A sidehill cut is an excavation across a hillside that leaves a cut only on the inside of the road. Cut-and-fill as well as full bench road construction creates a sidehill cut, and the road surface can be drained either into a ditch on the inside of the road or onto the adjacent hillslope on the outside of the road. In contrast, **a through cut is defined as a road cut into a native hillslope with excavated slopes on both sides of the roadway.** They are characterized by excavations that range from tens of feet high down to as little as several inches (Figure 53). **They are commonly found where a road has been excavated through a hillslope or ridge or, more commonly, straight down a relatively gentle ridge or hillside.** Through cuts are sometimes designed or constructed to reduce the grade (steepness) or curviness of a road, and in other cases to reduce the length of a new road.

Low volume forest, ranch and rural roads should be built to follow the topography as much as is possible, not cut through it. The exception occurs where a road is designed

FIGURE 53. *Through cut road reaches can be short or long, and the degree of cut can vary from several inches to tens of feet deep. The road in this through cut section is well drained using a crowned shape, with ditches on both sides of the road. The road surface and ditch should be drained at the beginning and the end of the through cut road reach to minimize erosion.*

for high travel speeds or considerable commercial traffic is expected. In these instances, large sidehill cuts, or sidehill through cuts, are constructed to keep the alignment relatively straight and avoid having to weave in and out of the naturally undulating terrain. Everywhere a road is constructed through, rather than around, a ridge or hill, a through cut is often constructed (where there is a cut on each side of the road). Larger and taller ridges will have higher and longer cutbanks on each side of the road.

Other through cuts are sometimes unintentionally developed when a road is constructed straight down a gentle ridge or hillslope to reach a lower level or the valley bottom. These through cut road segments are typically constructed to shorten the road from one point to another (a road down a gentle or moderate fall-line gradient slope is much shorter than constructing a broad switchback that traverses back and forth across the hillside to get to the lower elevation point). When a road is constructed straight down a gentle ridge or hillslope, a shallow through cut is naturally formed.

All through cuts behave similarly, with runoff flowing straight down the excavated roadbed. The key component is that there is an excavated cut on both sides of the roadbed and road surface drainage is confined between the two cutbanks, either along the sides of the roadbed (usually ditches) or down the road surface itself where roads are flat in cross sectional shape. **Poor drainage is a characteristic of virtually all through cut roads and the longer the through cut, the greater will be the volume of water that collects within and concentrates along or on the road surface.**

Similarly, the steeper the grade of the through cut, the greater will be the erosive force of the water that is contained within it during runoff events. Long and/or steep through cut road segments can produce extensive rills, road ruts or gullies on or alongside the road surface, and this concentrated runoff and eroded sediment is discharged off the road at the end of the through cut. In addition to their potential to impact water quality, through cut road segments are locations requiring high levels of road maintenance.

ii. Treatment Several treatments can be employed to reduce the impacts of through cut roads. These include:

- Relocate or realign the road segment on a sideslope so that it can be effectively drained along its length.
- For shallow through cuts, where one or both cutbanks are less than several feet high, it may be possible to refill the through cut and redevelop effective sidehill drainage.
- Surface (rock or pave) the road and ditches within the through cut to reduce erosion rates and lower long term maintenance requirements.
- Make sure the roadbed has a distinct road shape that drains the road to one or both sides (rather than down the center of the road).
- Construct (excavate) "cutouts" in the downslope road cut to regularly drain the through cut onto the adjacent, stable hillslope. These drainage cuts or lead-out ditches can be many 10s of feet long.
- Install rolling dips and/or ditch relief culverts with outlet energy dissipation (rock armor) both above and below the through cut road reach, to drain the road surface before and after the through cut.

Fall line roads that are aligned straight down a hillslope, even if the hillslope

gradient is relatively gentle, are almost impossible to effectively drain. Runoff water wants to run straight down the road surface, creating rills and small gullies. The eroded road surface is regraded each year, and then re-erodes every wet season. **It is a self-perpetuating cycle of erosion and grading that slowly and persistently deepens fall line through cuts over time.** If an alternative alignment is not available, the most effective treatment for shallow through cuts includes road shaping to keep the runoff to the side(s) of the through cut roadbed, in concert with long "cutouts" or side drains that divert runoff onto the adjacent natural hillslope (Figures 54, 55). The deeper the through cut, the deeper and longer these cutout drains have to be excavated and the more difficult this treatment becomes.

e. Operations and treatments for unstable soils

Both soils and areas can be classified as "unstable." Typically, unstable areas are characterized by unstable soils, but the presence of unstable soils may not yet have been expressed on the landscape as an unstable area. Unstable areas are perhaps most easily and frequently recognized by expressions on the hillslope (cracks, scarps, leaning trees, etc.), while the presence of unstable soils may be masked by a number of site factors (e.g., gentle slopes, binding roots, rocky abutments, etc.) that have prevented the development of indicators of slope instability.

Location and characteristics—*Unstable soils* have various definitions depending on the use to which they are likely to be subjected. Sometimes these soils show natural instability in the undisturbed setting. More often (e.g., on soils maps), they are classified as

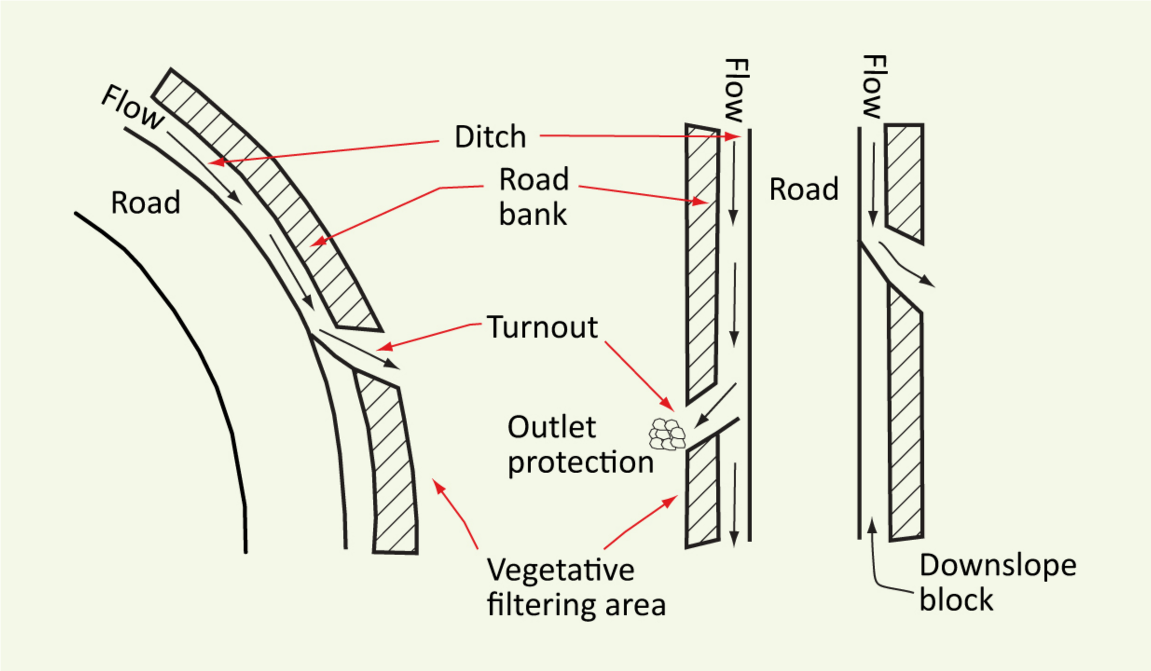


FIGURE 54. *Typical locations for "turnouts" or lead-out ditches used to drain bermed or minor through cut road reaches. To be self-maintaining, lead out ditches must have a grade at least 2-3% steeper than the road surface or ditch that drains to them; otherwise they'll plug with sediment deposits (U.S. EPA, 2000).*

FIGURE 55. *Steep roads that go straight up or down a hillside are very difficult to drain. This steep, fall line road developed a through cut cross section that was drained using lead out ditches to direct runoff off the road and onto the adjacent, vegetated hillside. The road was "outsloped" to drain runoff to the right side, and the lead out ditch was built slightly steeper than the road grade, to be self-cleaning. Four lead out ditches have been constructed at 100-foot intervals to the bottom of the hillside.*

poor quality soils that become unstable when disturbed by construction (Figure 56). In the context of roads, unstable soils are less likely to support cutbanks without buttressing or special measures. Unstable soils are often characterized by weak, non-cohesive soils or colluvium containing sand, gravel, rock fragments or weathered granitics, as well as expansive clays.

Unstable areas are characterized by mass movement features, typically developed in areas of unstable soils. Unstable areas are often characterized by hummocky topography, tension cracks and/or slope scarps, headwall and lateral scarps, and irregular bowl-shaped slopes suggesting previous slope failure. The hillslope may also exhibit indirect evidence (e.g., leaning trees) or contributing factors (very steep slopes) that can lead to slope instability. Many unstable areas are often found in combination with areas of emergent groundwater (springs and seeps) and zones of saturated soils that suggest impaired groundwater movement. **Water in and on hillslopes is usually**

FIGURE 56. *This forest road was constructed through wet, unstable soils and subsequently experienced shallow slope failures and rapid erosion rates for a number of years following road building.*

a key contributing factor to the occurrence of slope instability and landslides.

Road construction and management activities that cause or increase slope instability in areas of unstable soil include undercutting (developing slope cuts), loading (including spoil disposal or sidecasting onto steep slopes), and the addition of water (road drainage diverted or discharged onto unstable or potentially unstable slopes). Roads intercept subsurface flow paths when they cut into the soil profile, with water either emerging from the cutbank (contributing to cutbank failures) or being blocked by overburden and uncompacted earthen materials disposed of where the road crosses (and fills) steep swales or where loose spoil is sidecast downslope off the road. Road building in wet areas may cause subsurface damming of groundwater that, in turn, contributes to fill slope failures and to larger debris slides and debris flows.

***Avoidance*—As with operations on or near wet areas, the first and best option is to locate the road to avoid sensitive areas such as headwalls, steep slopes (slopes >60%, especially those known to be prone to debris slides in nearby areas), and areas of known unstable soils and slope instabilities.** Road planning and road location are invaluable tools used to avoid unstable areas. Vulnerable slopes include those where roads cross geologically unstable or highly erodible materials, steep slopes or steep channels subject to debris flows, wet slopes, or areas subject to flooding. New roads should be planned to avoid these high hazard locations and unstable areas, such as slumps, landslides, debris flow tracks, earthflows and other instabilities, and to have a qualified geologist find another suitable alignment. Existing roads that cross this type of terrain will likely require high maintenance and be subject to regular and costly storm damage repairs.

Treatment—A variety of slope stabilization measures are available to solve road-related slope stability problems and to cross unstable areas. **In most cases, relatively gentle cut slopes, good compaction, minimal sidecasting and good surface and subsurface drainage will eliminate routine stability problems.** General treatment strategies may be employed to minimize a road's impact on hillslope stability, but most problems are site specific and a qualified geologist or engineering geologist should be consulted for the best treatment design. The initial assessment and design of the road often requires continued professional observation and guidance as the road construction, road upgrading or road decommissioning project progresses.

Roads built in steep and/or unstable areas should contour the landscape, minimizing cuts and fills, and be kept as narrow as possible. Where possible, design minimum standard roads as outsloped with no ditch. Road runoff should be drained away from known unstable areas and unstable soils. Sidecasting should be avoided on steep slopes, and roads should be built using either full bench endhaul construction techniques, or benched construction to minimize sidecasting.

Roads themselves often develop cut slope or fill slope instabilities when constructed on steep slopes or through unstable soils. Minor cutbank instabilities can be treated using a variety of buttressing, drainage and revegetation measures. Unstable fill slope treatments can range from the direct excavation of unstable fill materials to more complicated, deep patch embankment repairs.

Because it may not be feasible to build, mitigate, or maintain a road where slopes are steep and the rock or soil material is weak, alternative road locations should be considered. Existing roads built on steep, unstable inner gorge or streamside slopes should be considered for permanent decommissioning. Consult with a qualified geologist or engineering geologist to determine the best decommissioning design.

f. Operations and treatments for wet areas

Constructing, maintaining or decommissioning forest, ranch and rural roads becomes significantly more challenging when you operate on wet or unstable soils. If at all possible, wet areas, especially large wet areas, should be avoided when constructing or relocating low volume roads. Avoidance is always the preferred option. Road crossings in wet areas are problematic and undesirable, usually requiring special designs to remove water, stabilize the road surface and prevent road damage.

Not only are many wet areas ecologically valuable and should be avoided if at all possible, they are challenging places to build and maintain roads for logging, ranching or other operations where commercial traffic, heavy loads or high levels of vehicle traffic are common. Soils in these areas are often weak, quickly deteriorate under traffic, and require considerable subgrade reinforcement to guard against damage and deformation (Figure 57). Not all treatments

FIGURE 57. *This seasonal road was built on fine grained soils that exhibited poor drainage and high rates of soil erosion. Even minor traffic during the wet season caused damage to the roadbed and rapid erosion clogged and filled ditches, waterbars and rolling dips.*

are effective and road reaches built across wet areas generally require a long term commitment to continued maintenance and repair.

Location and characteristics—Wet areas may be wet because of long term snow cover, long rainy seasons, or because of emerging groundwater (springs and seeps). Slopes with abundant slope instabilities and high fractured geologies are locations where emerging groundwater is likely to be common. Wet areas are also prevalent in lower slope, riparian and valley bottom areas, where groundwater is near or at the soil surface and expressed as wetlands, marshy areas, or by the presence of water loving plants. Soil maps can be used to help identify the location of wet and poorly drained soils.

Road design and construction in areas of wet soils is typically more difficult and expensive than in dry soil conditions. The road may require intermittent or continuous subsurface drainage and thicker surfacing to support traffic without deterioration and rutting. Wet, fine grained soils are susceptible to deformation, rutting and erosion and have low shear strength. Expansive, clay rich soils are difficult to work and cannot be easily driven in wet conditions. Wet conditions on cutbanks and fill slopes are also likely to cause stability problems and high maintenance requirements, and make road construction and maintenance more expensive. Similarly, cut-and-fill road construction may bury springs and seeps; thereby causing elevated subsurface pore water pressures and triggering fill slope failures.

Avoidance—Road cuts and fills are highly susceptible to springs, seeps and saturated soil conditions. Roads should be located or realigned to avoid sensitive areas such as headwalls (steep bowl- or swale-shaped depressions near the headwaters of small watershed areas), wet areas and unstable soils. In addition to avoiding obvious obstacles, like rock outcrops and landslides, roads should be located to avoid riparian areas; saturated, unstable soils; expansive soils; wetlands; bogs; marshes; springs; and other environmentally sensitive wet areas. These should be identified as control points along a road alignment that are mapped during field layout and avoided during construction. Roads should be located where road construction costs and stability can be achieved, and where the impact on streams, water quality and aquatic habitat can be kept to a minimum.

Treatments—If wet areas must be crossed and cannot be avoided, special drainage or construction methods should be used to reduce impacts from road construction and use. Localized wet zones usually require comparatively low gradient cut slopes of 2:1 or gentler to reduce the risk of failure. Experience shows that a stable wet slope angle may be roughly half the angle of the same stable dry slope. Low, gentle cut slopes will show less instability and lower erosion rates.

Simple slope buttressing can also be employed along the base of a wet, unstable cut slope (Figure 52), but unless it involves a mainline road, the more expensive engineering measures are rarely used on low volume forest, ranch and rural roads. Soil buttressing and armoring of small slumps, planting, and other simple erosion control techniques can be employed on cutbanks but instabilities will continue to occur until the slope has naturally stabilized. Maintenance of the cut and the ditch will be a continuing requirement for some time.

Subdrainage is used to carry subsurface or emergent subsurface water from the roadway. Seepage can occur along the cutbank, beneath the roadbed and/or beneath the road fill along the outside edge of the road. This can cause several problems if subsurface water is not drained from the road prism and construction area, including 1) excessively wet fills and subgrade materials, leading to road surface rutting or the need for large quantities of rock as base-course, 2) cutbank slumping, 3) mass wasting of the fill due to unrelieved pore water pressures, and 4) continual mud pumping at the road surface,

leading to failure of the surfacing and the need for regular re-surfacing, possibly with filter fabric.

Special subsurface drainage measures (subdrains) are not frequently used on forest and ranch roads, but it is important they be employed where needed. Some relatively simple subdrain techniques can be used to drain water before it adversely affects roadbed strength and integrity or causes slope stability problems (Figure 58). Ditches and French drains (sometimes called trench drains) excavated along the inside edge of the road, at the base of the cutbank, are common methods of draining emergent, upslope groundwater before it can saturate roadbed materials. Horizontal drain pipes can be installed to drain water from within the cutbank, but this stabilization technique is expensive and not always effective.

If the roadbed crosses an intermittent or perennial spring, soils beneath the road surface may need extra drainage. For water which will emerge beneath the road, gravel drainage

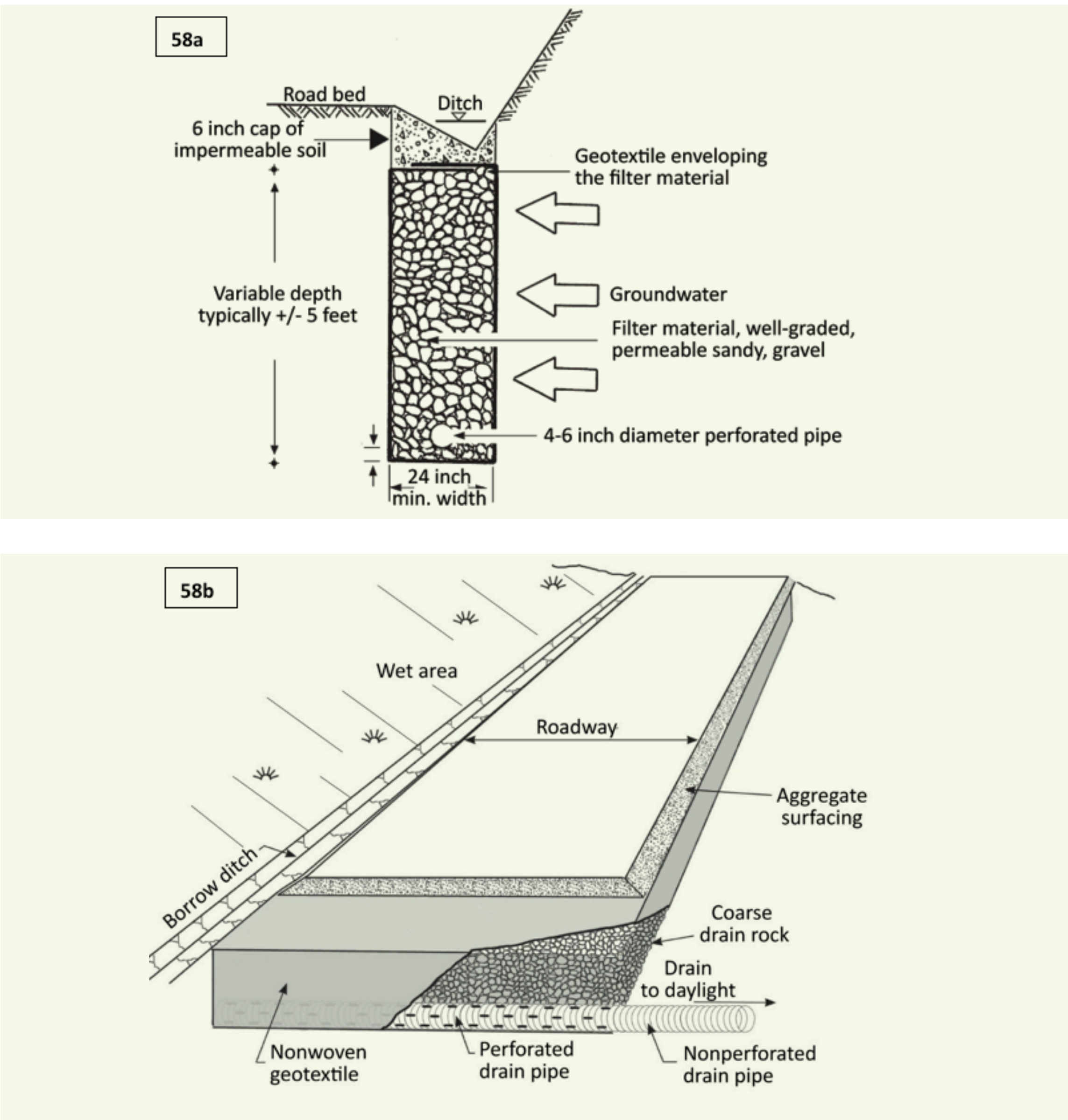


FIGURE 58. *Roads which are built across small springs, seeps or wet areas can be kept dry and stable by the use of subsurface drainage techniques. Vertical underdrains or French drains (a) and horizontal drainage blankets (b), using graded rock and synthetic fabrics (geotextiles), are two common methods for draining or dewatering wet subgrades (subsurface soil and rock materials) (Modified from: Keller et al., 2011).*

blankets can be used to drain the water laterally to the toe of the fill slope (Figure 58a). Filter fabrics (geotextiles) are used to maintain separation between the native hillslope materials and the overlying base course or surface course materials (Figure 58b). Where fills are thin, and where surfacing is placed directly on native soils, geotextiles can also be used on the subgrade to maintain soil separation and prevent soil pumping into the surfacing materials.

5. MATERIALS AND MATERIAL SOURCES

a. Road rock and riprap

i. Rock quarries, rock pits and borrow sites Quarries, rock pits and borrow sites are developed to obtain rock for various uses on rural roads (Figure 59). A **quarry** is an open excavation site where stone, riprap, aggregate, and other construction materials are developed and extracted from a bedrock surface or rock outcrop. Rock material is usually developed by ripping or blasting and often needs to be processed by crushing, sorting or screening to produce the desired stone sizes for a project. In a **rock pit or borrow site**, soil or rock is mechanically ripped or excavated to produce construction materials or fill for use on a project, such as rock from outcrops for armoring or road surfacing, aggregate from river deposits, or fill material from native soils. Screening and/or crushing may be required to produce the needed shapes and size grades.

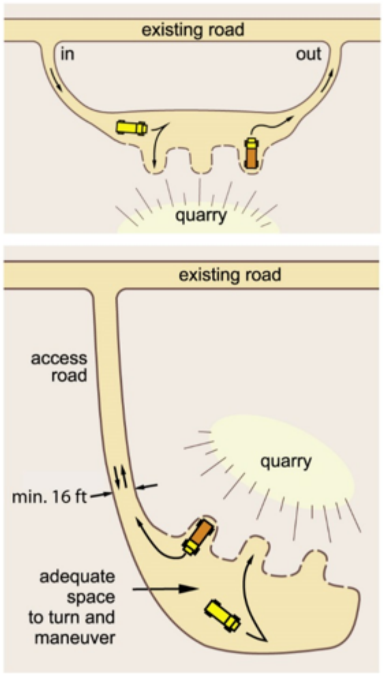


FIGURE 59. *Access roads are required in new quarry locations or borrow sites that allow for efficient transport into and out of the rock development area. Sufficient space must be provided for quarrying, processing, loading and transport. The drawing shows two possible quarry access routes that maximize efficiency (Johannessen, 2008).*

Regulations—Local development, use and abandonment of quarries and rock pits/storage areas in California, and in many other states, normally follow regulatory requirements for forest management (e.g., California's Forest Practices Act and Rules) or mining. The rules for developing rock sources for forestry generally focus on maintaining stable slopes and protecting water quality. Where quarry operations involve relatively large areas or where commercial products will be sold for use off-property, more stringent surface mining regulations may apply. State and/or federal regulatory agencies usually oversee surface mining operations. For example, California's Surface Mining and Reclamation Act of 1975 (SMARA) provides a comprehensive surface mining and reclamation policy to minimize environmental impacts and to make sure mined lands are reclaimed to a usable condition (California Office of Mine Reclamation, 2013). **Anyone engaged in surface mining operations, including quarrying, borrow pitting or gravel skimming from river beds, is affected if the disturbed area exceeds one acre in size or the cumulative volume of material mined exceeds 1,000 cubic yards per location.**[4] Most other states have similar regulations.

4 In California the mining site is exempt from SMARA where the excavation is done exclusively for obtaining materials for use on timber harvest roads or in forest management activities on the property where forestry is occurring, and if the footprint of surface mining disturbance is further than 100 feet away from any Class I watercourse or 75 feet away from any Class II watercourse. If any part of the mining disturbance falls within the stipulated stream buffer, or any portion of the material produced at the site is used for commercial purposes, the mining activities are subject to SMARA. Mining for on-property forest operations is regulated by the California Forest Practice Act and Rules.

Naturally occurring asbestos, common in ultramafic rocks and soil throughout the U.S. and globally, can pose serious health risks when airborne and inhaled. In areas where naturally occurring asbestos is present, road construction activities, as well as the development of quarry, borrow, or rock pit locations can generate airborne dust that must be mitigated for air and water quality, and worker safety. Asbestos emissions are regulated by federal, state, and local laws for construction, earthwork, and mining. Contact your state air quality regulatory agency (e.g. California Air Resources Board; Oregon/Washington/Montana Air Quality Program) for regulatory compliance requirements.

Rock source development and management—After the need is determined, and a possible rock source has been identified, projects are normally developed in four stages: reconnaissance, feasibility, design, and construction.

1. *Reconnaissance*—Initial exploration involves field reconnaissance using topographic maps, geologic maps and reports, and aerial photographs. Any projects that have previously used the rock source should be examined and evaluated in the field. You will need both an adequate quantity and quality of rock for your project!

2. *Feasibility*—Feasibility includes determining the size and physical character of the rock outcrops and rock materials, including general hardness and likely fragment sizes that could be made. Feasibility is analyzed to prepare preliminary designs and cost estimates for permitting, mining, processing and transportation, as well as other factors required for quarry or pit development.

3. *Design*—Rock pit or quarry design is needed to assure that the developed rock will meet your needs, including quantities, rock sizes, rock quality and expected waste. Field tests or service records of the same rock used elsewhere may be used in conjunction with, or instead of, laboratory testing.

4. *Construction*—Investigations during actual excavation of the rock materials provide field and design personnel with detailed information for how to best develop the rock source.

The use of local rock sources, such as borrow pits and quarries, can produce major cost savings for a project compared to the cost of hauling materials from commercial sources or distant locations. However, the quarry or borrow pit material quality must be adequate for your needs.

ii. Evaluating rock quality **Use of local high quality materials, even in small amounts from a variety of sites, can be very desirable and cost-effective, but only if it performs well.** Poor quality materials will require more road maintenance and may break down quickly; eroding, polluting water sources, affecting air quality and requiring re-surfacing. Haul distance strongly affects the delivered cost of rock so it is best to use small, high quality local quarries or borrow pits whenever possible.

Rock quality can be determined or judged from both in-situ characteristics and conditions of the rock mass, as well as from field and laboratory tests of the actual rock material.

In-situ tests of rock suitability—

- Naturally durable rocks are often identified and defined on geologic maps. Most rocks that are durable and resistant will form prominent outcrops that stand above the surrounding landscape. These often include massive igneous, metamorphic and well cemented sandstone rock types. Clay rich siltstones, shales and other thin bedded sedimentary rocks, or rapidly weathering rock (e.g., deeply weathered, decomposed granitics) usually do not make good, durable rock.

- Past performance is a good indicator of rock quality. **Nearby or similar rock that has been quarried and used in the field for an extended period of time can provide an excellent measure of future rock performance on a newly opened quarry or pit.** This may be a better indicator of future rock performance than many field and laboratory tests, although both measures are preferred.

- **Simple field tests can be used to gauge basic rock strength and suitability.** For example, sandstones can be examined using a hand lens to see if the grains are hard and shiny or dull and soft. Finally, a rock hammer is a good tool for field testing. If you break off a piece of rock, and the break actually fractures the cement and mineral grains, then it is well cemented and likely to be durable. **The hardest and most durable rock will have a distinctive "ring" when struck with a hammer and the hammer will quickly rebound.** Rocks that give a lower pitch "thud" rather than a higher pitch ring will likely be softer and less durable. These are qualitative indicators, so it is useful to try this on rocks of known durability so you can gauge the relative responses.

- Rock particle sizes needed for your project (e.g., road rock versus riprap) must also be readily available, or easily produced, from the pit or outcrop without excessive effort or development of large volumes of waste material.

Laboratory tests of rock suitability— Laboratory tests or field results can be used to quantitatively determine rock quality, and to predict a rock material's suitability for use as a base course or surfacing material. Laboratory tests center around those designed to determine resistance to abrasion, freeze-thaw cycles, and strength in relation to durability. However, laboratory tests for forest, ranch and rural road applications are costly and not frequently used in these applications.

If laboratory testing is to be employed, the most marginal quality rock should receive the greatest number of tests. **The ultimate goal of all testing is to accurately predict durability and prevent erosion hazards. That's why performance in the field under actual conditions and for extended periods may provide a more accurate picture of rock suitability than field or laboratory tests that are designed to predict performance.** Qualified geologists and engineering geologists can provide guidance on the suitability of rock aggregate for various road uses, and local road managers and maintenance crews often have excellent knowledge of the suitability of local aggregates.

iii. Rock development and production Rock is most frequently developed from a quarry or pit by blasting, or ripping and excavating.

Blasting—Production methods that include drilling, blasting, hammering, ripping, excavating, processing, and hauling play an important role in the sizes of rock that can be obtained. When blasting solid, unfractured bedrock, make sure to obtain any required permits and employ only qualified, trained and licensed experts. Rock quarried from blasting is often the best material available and is not severely fractured or weathered, but it is likely to require further processing and sorting before it can be used.

Ripping and excavating—Where bedrock outcrops contain sufficient natural fractures, you can usually excavate rock materials by ripping or hammering instead of blasting. **Hydraulic rippers mounted on larger crawler tractors, or hydraulic hammers on excavators, are frequently used to generate rock from fractured bedrock outcrops.** In-channel gravel deposits or river terrace deposits are often used as material sources for fill and road surfacing. They are produced by direct excavation of gravels using heavy equipment. The river rock is often screened and crushed to develop more angular material from the largest rounded rock particles. **Ideally, unless these gravel sources are permitted, deposits in or near streams or rivers should not be used. Instead, geologic river terrace deposits are often used to produce river-run gravels for road surfacing and other road-related uses, and they are often located farther away from active river channels.**

iv. Rock waste It is important to estimate and plan for the amount of waste that can be expected from rock production, whether by blasting, or ripping and excavation. Waste material from quarrying and borrow operations should be endhauled and placed at an approved, stable location where it will not enter a watercourse or adversely affect the environment (Figure 60). Simple sidecasting of waste debris at the excavation site is generally not acceptable. A qualified geologist may be required to identify appropriate spoil disposal sites and to evaluate sites for stability before they are developed or used. The waste debris and original groundcover soils should be recycled and reused during reclamation of the rock pit or quarry.

v. Rock riprap Riprap, used along roads and where roads cross streams, most commonly consists of an arrangement of large rocks, typically graded with smaller rocks filling in the voids. Riprap is generally used to protect a slope from erosion. Sometimes referred to as rock slope protection (RSP), it works by absorbing and deflecting the energy of flowing water and is installed for energy dissipation and for preventing erosion along shorelines, streambeds, bridge abutments, stream crossings and at culvert inlets and outlets. It is employed in various sizes for these project types, and is designed to resist the forces it is expected to encounter. In forest, ranch and rural road applications, riprap is often "field designed" by experienced personnel, but consulting with a qualified engineer or engineering geologist will take the guess work out of

FIGURE 60. *This rock pit is easily worked by an excavator, but the material contains abundant fine grained particles. Here, a Grizzly rock screen is used to separate high quality rock armor from fine grained waste materials. As in this photo, waste materials should be endhauled to a stable spoil disposal site rather than sidecasting onto steep, unstable or streamside slopes.*

the design, ensure the rock sizes are appropriate for the intended purpose, and likely save time and money. Large rock is also designed and used to buttress potentially unstable fill slopes or cut slopes against failure and, because of the large earth forces involved, these designs are also best developed by a qualified professional.

Rock for riprap should be hard, dense, durable, and resistant to abrasion, displacement by flowing water or exposure to various environmental conditions. Like other rock products, the best tests of rock suitability are those in which the rock materials have been successfully in use for long time periods in similar conditions. Riprap stones should not be thin and platy, nor should they be long and needle-like. "Angularity" is often used as a qualitative descriptor of shape, because it improves the ability of rock armor particles to "lock together" and be stable on a slope.

vi. Road rock (base-course and surfacing) The pavement of a forest, ranch or rural road is a structural system comprised of a surface course and a base course, all overlying the prepared subgrade (native) soil. Ideal aggregate has hard, dense angular fragments with at least 3 sharp edges, but not sharp enough to puncture vehicle tires. It is well graded (contains a variety of particle sizes) with a compact, blocky (not elongated or platy) shape.

Road surfacing rock must be hard enough (not brittle and not soft) to withstand vehicle tire pressure without fracturing and with minimal wear under repeated tire loads. The aggregate should also contain sufficient fines to fill voids and allow for good compaction. River gravel, sometimes known as "river-run," is often too rounded to compact adequately. It can be crushed to improve the angularity of the largest particles but still contains mostly rounded particles and is less suitable.

Durable aggregate road surfacing must be used for active roads and road segments that drain to streams so as to minimize erosion, fine sediment production and transport, and turbidity (muddy water). Marginal, lower durability aggregate that will break down and erode should not be used as a surface course, especially on high traffic roads and on road segments that drain to streams.

While surfacing can double the cost of a road (Table 22), the rock or gravel cover provides a stable surface that can be used to extend the operating season while limiting damage to water quality. For rural residential roads, a good rock surfacing is required for all-season traffic. However, if water is reaching the roadbed from subsurface flow beneath the road fill (rather than from rainfall), measures in addition to surface rocking will likely be required to maintain surface stability and control erosion.

TABLE 22. Estimated cost distribution for constructing a typical low volume road[1]

Construction phase	Average cost (%)
Equipment and material	10%
Clearing grubbing, slash disposal	20–25%
Excavation	20–25%
Culverts	10%
Rock surfacing	30–40%

[1]USDA - SCS/USFS (1981)

vii. Reclamation (rehabilitation) of quarry and borrow sites Reclamation is the process by which adverse impacts of mining are minimized so that mined lands can be used for a beneficial land use after they are closed and reclaimed. Some key components of reclamation include slope stabilization, erosion control, flood and drainage control, avoidance or mitigation of impacts to sensitive species and habitats, minimizing water and air degradation, revegetation and safety. The reclamation process may extend to affected lands surrounding mined lands, and may require backfilling, grading, re-soiling, soil compaction, stabilization, drainage control, erosion control, revegetation, or other measures.

Reclamation consists of activities and treatments that reclaim, repair, or improve part or all of an existing road, borrow pit, quarry or disturbed area and restore it to its original or some desired final condition. Site reclamation is typically needed after materials extraction, and regulations usually dictate how reclamation is conducted and the final configuration and restoration of the site. Reclamation work on larger sites may be dictated by regulation (e.g., SMARA) and should always be defined in a *Reclamation Plan*. Small pits and quarries may not need a plan but will still benefit from certain restoration practices that ensure it will not adversely affect the environment.

Reclamation usually consists of discrete steps, starting with salvage and stockpiling topsoil from the initial site clearing work. Unused top soil and subsequent waste products from rock development can be stockpiled or temporarily stored so they can be used to fill and reshape the final pit or quarry site. The recontoured site is designed with either a dispersed internal drainage system or external drainage that prevents eroded sediment from discharging to nearby streams or lakes. Once the final topography has been achieved, the site is capped with salvaged or imported topsoil, treated with temporary and permanent erosion control measures including seeding and replanting, and required safety measures (e.g., restoring the site to minimize danger from overhangs, loose rock and waste material heaps; installing gates, barriers, signs, etc.).

b. Geotextiles

Geotextiles are synthetic, permeable fabrics which are used to separate, filter, reinforce, protect, and/or drain rock, soil and other related materials. They are usually made from synthetic polymers which do not decay under biological or chemical processes. This makes them useful in road construction and maintenance.

Geotextile fabrics come in three basic forms: woven, needle punched (felt-like), or heat bonded (ironed felt). Woven geotextile is a sheet made of two sets of parallel strands interlaced to form a thin, flat fabric. Non-woven geotextile fabric is more likely to stretch than woven geotextile and has the increased ability to let water flow through or along the plane of the geotextile. **For general road applications, the two most important geotextile specifications are permeability and strength.** Woven fabrics have a high tensile strength, but they have a lower abrasion resistance, less permeability and lower frictional resistance than non-woven fabrics. **In contrast, nonwoven fabrics offer superior resistance to abrasion damage and provide excellent characteristics for soil separation, as well as filtration and drainage.**

Geotextile variants include geosynthetics and geomembranes. Geosynthetic composites such as geogrids, mats, webs, nets, meshes or formed plastic sheets have been developed primarily for structural reinforcement and/or to contain particles. A geogrid is a non-woven geosynthetic with large holes on a rectangular layout used to constrain internal particle movement and consequent rutting, while stiffening the soil mass over its complete depth so as to improve (spread) the load distribution from vehicles. A geomembrane is a continuous membrane-type liner or barrier that acts as a complete moisture barrier, but allows lateral transmission of water within the membrane so that it can be transmitted away from the site.

i. Geotextiles for common road applications Geotextiles and geosynthetics have a number of applications in the forest, ranch and rural road setting. For example, geotextiles keep the layers of subgrade and base materials separate and manage water movement through or off the roadbed (Figure 61). Other uses include:

- drainage and filtration, including trenched or French drains;
- underdrains and filter blankets, to capture spring and seepage flow beneath a road;
- subgrade reinforcement, to provide additional tensile and compressive strength;
- subgrade or base containment, to resist lateral displacement of surfacing materials;
- structure reinforcement, to provide lateral tensile strength to soils;
- in retaining walls and reinforced soil walls, to provide lateral strength to emplaced and engineered fills; and
- erosion control, including sediment traps (silt fences, silt curtains, etc.), riprap bank protection, diversion ditches, and slope protection.

Manufacturers of these products will usually provide expert professional advice on the proper use and installation of their products and this advice should be sought.

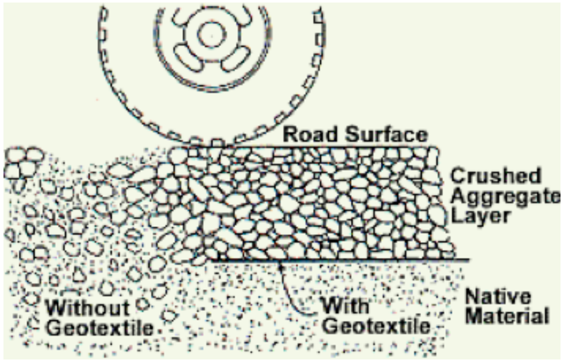


FIGURE 61. *Geotextile in separation application (Wiest, 1998).*

In forest, ranch and rural road systems, geotextiles have four basic functions (Figure 62):

- *Separation* is the main benefit of stabilization work with geotextiles. Inserting a properly designed geotextile will keep layers of different sized particles separated from one another, thereby preventing intermixing of the two soils and preventing fine subgrade soils from pumping up into and contaminating the overlying, clean base rock.
- *Filtration* is the process of allowing water to pass through the fabric while preventing soil migration. Water can be transmitted either downward (drainage) through the geotextile into the subsoil, or laterally (transmission) within the geotextile.
- In *reinforcement*, a geotextile can actually strengthen earth materials. Under load, non-woven fabric typically exhibits high tensile strength and broadens (spreads out) subgrade loads.
- Geotextiles can also provide aggregate *confinement* above the fabric (keeping road rock in place) and good frictional resistance (so aggregate won't slide off the fabric). Geotextiles with superior frictional characteristics, such as needle punched unwoven fabrics, aid in "locking" the aggregate in place.

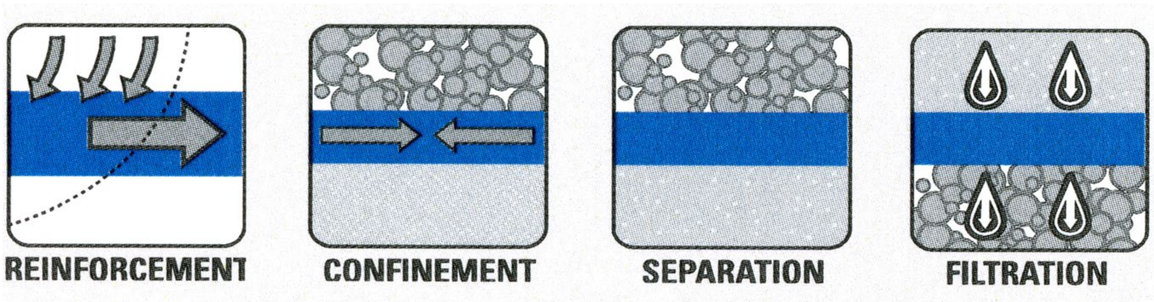


FIGURE 62. *Four basic functions of geotextiles (TenCate Geosynthetics).*

Where aggregate is unlikely to remain in place even under normal traffic (e.g., on a steep road grade, within a ford, or where you have rounded "river-run" aggregate) a geomatrix or geogrid can be used to physically contain soil materials (containment), add tensile strength and prevent lateral movement of the aggregate. However, these specialized geosynthetics do not have the ability to separate materials or to provide filtration.

When using geotextiles, you can often reduce the thickness of required road aggregate by up to 30% because of its strengthening properties. This is important and can save money if you don't have a nearby or affordable source of high quality road rock.

ii. Geotextiles for erosion control Geotextiles can be used in many ways for erosion control. One of these is with riprap along stream banks, lake shores, and other bodies of water to keep finer soils beneath the riprap from eroding (Figure 63). Geotextiles are also employed in protecting the sloped banks of diversion ditches, and in controlling surface erosion (erosion control blankets) or retaining eroded sediment in the project area (e.g., silt fences). Geotextiles recommended for erosion control should have permeability, resistance to abrasion, and high resistance

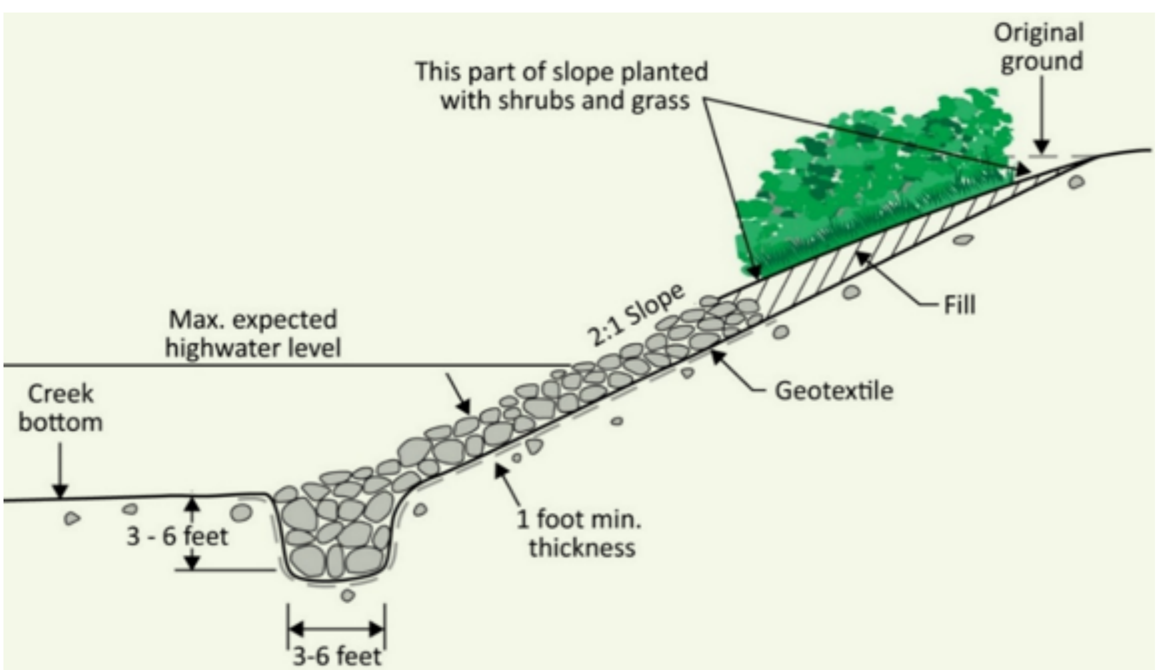


FIGURE 63. *Geotextile used beneath riprap for erosion control, filtration and material separation. Whether in a streamside, lakeside or slope buttressing application, the permeable fabric protects fine grained soils beneath the armor from erosion and sapping, and allows soil water to filter through the fabric and into the armored area without increasing pore water pressures (Modified from: USDA—NRCS, 2007).*

to ultraviolet rays as primary considerations. Erosion control covers a variety of conditions from high velocity stream flow to heavy wave action, to less severe conditions.

C. STREAM CROSSING DESIGN

Where a road crosses a natural watercourse, provision must be made to carry the water under or across the road. The selection of the best and most appropriate stream crossing design depends on a number of factors, and a poor design choice can result in a costly installation that is subject to failure and significant environmental damage.

Streams can be crossed with bridges (including arches) or culverts (flow beneath the roadbed), or armored fills or fords (where streamflow travels over the road surface). Culverts are the most common stream crossing structure and bridges and arches are best for large streams or where migratory fish are present. Fords work well on small to medium sized streams where there is a stable stream bottom, vehicle traffic is light, and fish passage is not required, but their use can cause persistent downstream turbidity and fine sediment pollution. Armored fills, where the stream flows over the top of the fill and down the protected outside fill face, are employed on relatively small, non-fish bearing streams that flow only occasionally during the wet season. Because they cannot plug with debris, they are used in places where winter or wet season maintenance is difficult or impossible.

1. LEGAL REQUIREMENTS

All private landowners constructing temporary or permanent stream crossings need to obtain proper permits and follow applicable laws and regulations of state and federal agencies. Prior to conducting road building or timber operations, or to modifying the bed or banks of a stream channel for any purpose, it is important to determine the legal requirements of your work (see Chapter 1, Section I).

All states and countries have regulatory requirements regarding working in or around streams and lakes, and most have standards and/or suggested best management practices (BMP) for stream crossing installations and for road building operations in these areas. These often include culvert sizing requirements, requirements for removal of temporary stream crossings, limits on equipment operations near stream channels, road construction standards, and a variety of other road building and erosion control requirements (e.g., see Appendix B).[5] You will need to check with regulatory agencies to determine the requirements in your area before undertaking similar project work. Such regulations always have the same broad goals: provide for sustainable forest or land use operations while providing maximum feasible protection to the environment.

It will be less expensive and certainly more effective to learn what best management practices (BMPs) are applicable and required in your area before planning, designing and conducting a road construction, road upgrading or decommissioning project that involves stream crossings. Thus, in California most federal and state water pollution regulations are administered and enforced by the California State Water Resources Control Board, through their Regional Water Quality Control Boards. A wrong choice in stream crossing method can result in major damage to both the immediate site and to downstream water quality. There are strict legal requirements for protecting water quality. **Stop-work orders, clean up and abatement orders, and heavy penalties for pollution can delay or terminate your project and be very expensive. Do it right the first time!**

5 Information on the complete Forest Practice Act and Rules in California can be obtained from Ranger Unit offices of the California Department of Forestry and Fire Protection.

No matter where you are located, ask your local regulatory agencies for assistance in determining what permits you may need and what practices are required before initiating a proposed project. In California, ask your local California Department of Fish and Wildlife biologist, a forester from the California Department of Forestry and Fire Protection, a geologist with the California Geological Survey, your Regional Water Quality Control Board inspector or a Resource Conservation District (RCD) specialist for assistance and information about requirements for your project. **Prevention is always the best course of action in conducting progressive land stewardship and resource conservation.**

2. STREAM CROSSING DESIGN AND REDESIGN CONSIDERATIONS

Classifying the stream (e.g., California Class I, II, III or IV watercourses) and the road (temporary, seasonal or permanent all-weather) is the first step in defining the type of stream crossing to be installed. **Stream crossings should be designed (or redesigned) for adequate fish passage (even where fish could be seasonally present), minimum impact on water quality, and to handle peak runoff and flood waters.** Fish passage is now expected and required in most areas of the country, and you must consider and provide for passage requirements for all life stages of migratory and resident fish encountering the crossing site. Stream crossings can be classified as either "permanent"[6] or "temporary."

6 There is really no such thing as a "permanent" culverted stream crossing. Culverts are subject to a variety of processes which guarantee their eventual failure unless they receive regular, periodic and storm maintenance, and they are replaced and rebuilt at the end of their normal life span. Metal culvert pipes have a limited life span and will eventually wear down and fail. In addition, since culverts are designed to pass a "design flood," a larger flood may eventually occur which exceeds culvert capacity and washes out the stream crossing.

There are three basic subcategories of both permanent and temporary stream crossings: 1) bridges and arches, 2) fords and armored fills, and 3) culverts. Culverts include not only the traditional corrugated metal pipe (CMP), but also includes plastic HDPE pipes, concrete culverts, log/culvert temporary crossings, and other temporary structures that pass streamflow through or beneath the road fill.

The type of crossing facility selected will depend on a number of factors. Each of these elements should be considered before selecting the final design or location for the stream crossing installation. Design considerations include:

- whether fish, amphibians or other wildlife of any life stage use the channel as a migration route at the crossing site,
- whether the crossing will be temporary (used for only a single entry) or permanent (to be used for more than a single season or a number of years),
- the types of vehicles that will use the crossing,
- the slope, configuration and stability of the natural hillslopes on either side of the channel (soil foundation conditions),
- the slope of the channel bed,
- the orientation of the stream relative to the proposed road,
- the expected 100-year flood (peak) discharge (i.e., stream size),
- the amount and type of sediment and woody debris that is in transport within the channel during flood conditions,
- the installation and subsequent maintenance costs for the crossing,

- the expected frequency of use, and
- limitations and designs imposed by permits and other legal requirements.

These and other site-specific factors play a role in determining the best crossing location and most suitable type of stream crossing to be used.

As recently as the 1960s and 1970s, culvert sizing and simple stream crossing design on low volume roads was often done by subjective methods, using the best knowledge and experience available from the crews actually performing the work. This was most common on non-public forest and ranch roads where public safety was less of a concern. For public roads it was once standard practice that when a stream crossing failed and washed out during a large flood event, federal emergency monies would be made available to reconstruct the crossing or failure. Unfortunately, reconstruction was required to be to the same standards as existed in the original facility, thereby "reloading" the gun for the next storm of equal of greater magnitude. This has largely been corrected so new installations can be designed to current standards, making future failures less likely to occur.

a. Reducing stream crossing vulnerability

Culverted stream crossings are naturally susceptible to failure. That is why it is somewhat of a misnomer to call culverted stream crossings "permanent." In reality, a fill crossing is really an earthen dam, placed across a stream channel, that has a small hole (culvert) in the bottom. If the culvert is too small, or if it gets plugged with sediment, vegetation or wood, the "dam" (stream crossing fill) may be overtopped and wash out. **That's why culverted stream crossings need to be properly designed, constructed and maintained to prevent loss of the fill and discharge of large volumes of eroded soil into the stream.**

FIGURE 64. *Eroding stream crossing after a single storm on an unmaintained road. The culvert plugged and flood flow overtopped the fill, initiating a headcut. In addition to being undersized, the culvert was installed at a flat gradient that is more prone to inlet plugging with debris. If left uncorrected, the crossing fill would continue to erode and deliver the eroded sediment downstream.*

Washed-out stream crossings are a common occurrence on abandoned, poorly maintained and/or improperly designed forest, ranch and rural roads (Figure 64). However, culvert plugging can result in much more damage than a washed-out stream crossing fill. If flow from a plugged culvert is diverted down the adjacent road (instead of flowing over the fill and immediately back into the stream channel), the diverted streamflow can create large gully systems, cause natural stream channels receiving the diverted flow to greatly enlarge, or trigger landslides as it flows over nearby unprotected hillslopes.

Stream crossings with a diversion potential (DP) occur wherever the road climbs through the crossing site and one approach slopes away from the stream crossing (Figure 65). If the culvert plugs, the backed up flood waters will be diverted down the road alignment (Figures 66a, 66b). If the crossing has no DP, backed up flood waters will flow onto the road surface, over the low point in the fill and back into the natural channel (Figure 67).

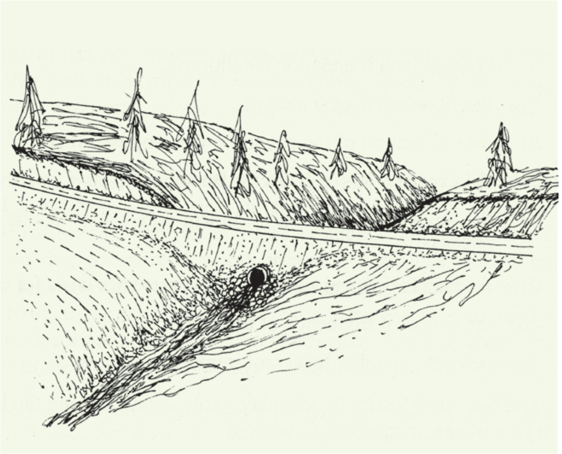


FIGURE 65.
Stream crossing with diversion potential. Streamflow would be diverted down the road toward the right side of the picture if the culvert inlet plugged and streamflow reached the road surface.

The fill may be partially eroded or completely washed-out, but streamflow is not diverted out of the channel and onto adjacent, unprotected roads and slopes. **Flood research in mountainous areas of the western USA has shown that, on average, stream diversions cause from 2 to 10 times the volume of erosion and downstream sediment delivery (through gullying and landsliding) compared to simply eroding and washing out a stream crossing fill.**

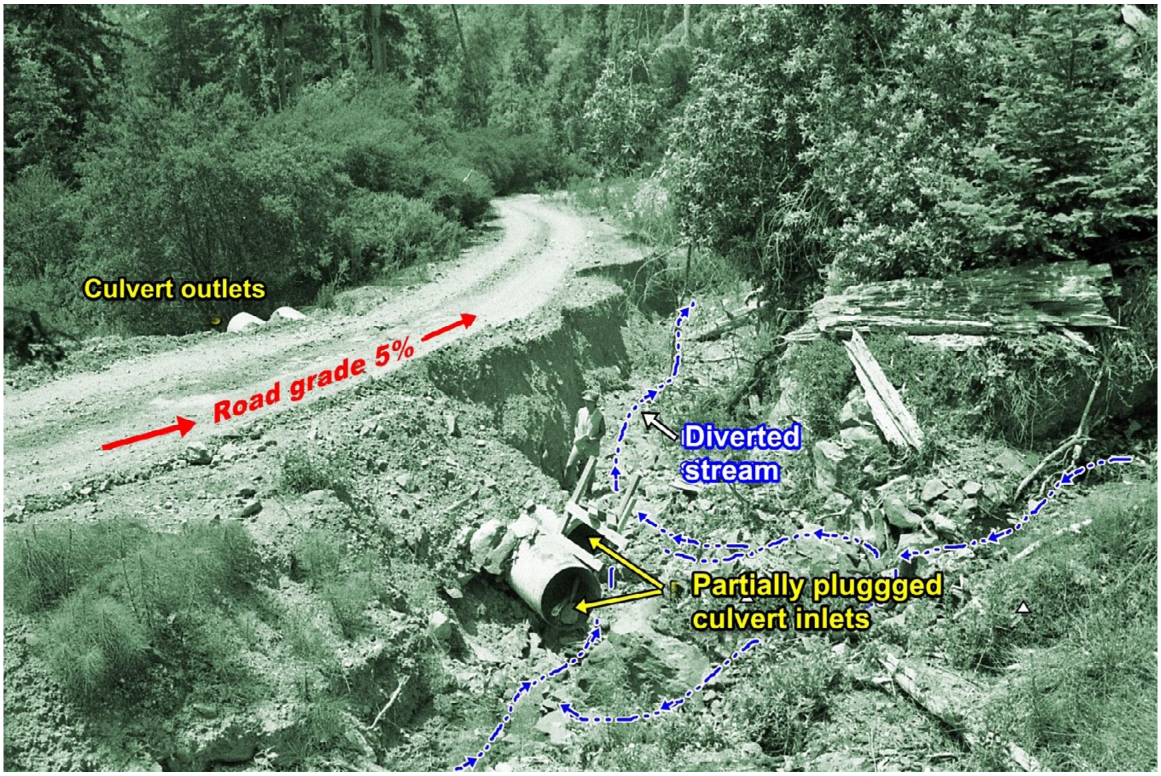


FIGURE 66A.
Double culvert stream crossing showing the result of a stream diversion that occurred during a winter storm. The road slopes to the distance at about 5 percent. When the culverts plugged with debris, streamflow diverted down the inboard ditch and created the large diversion gully. Note the person for scale.

FIGURE 66B. *This large hillslope gully was caused during a single storm event when a culvert plugged and a stream diverted at a stream crossing located 400 feet up the road to the left of the vehicle. The eroded sediment from this gully was delivered to the same stream channel downslope.*

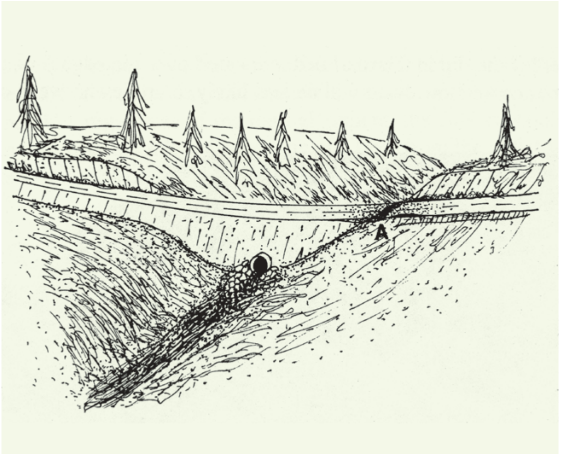


FIGURE 67. *Stream crossing with no diversion potential. If the crossing was overtopped, flood flow would reach the road surface and flow back into the channel at location "A," where the road changes grade. This is called the hinge line of the fill, where the crossing fill intersects the natural slope.*

i. Reducing the risk of stream crossing failure and stream diversion

Stream crossings fail by one of two mechanisms: 1) they partially or completely erode or gully (washout) when they are overtopped by floodwaters, or 2) floodwaters are diverted down the adjacent road alignment instead of flowing over the road and washing out the crossing fill. Either way, significant environmental damage can occur when flood flows exceed the ability of a stream crossing drainage structure to pass the required design streamflow and material in transport.

Although bridges and arches may be locally undersized and prone to failure, culverted stream crossings are the most common, and most susceptible, type of stream crossing likely to fail during flood events. Most of these failures result from culvert plugging, and the subsequent ponding of flood flows behind the stream crossing fill.

***Reducing the risk of culvert and stream crossing failure*—In-channel and drainage structure treatments can be applied to existing culverted stream crossings to reduce the chance that a culvert will become plugged, with subsequent flood flows overtopping or diverting down the road.** They are aimed at reducing the likelihood of culvert plugging rather than physically preventing a subsequent stream diversion, but both techniques reduce the vulnerability of a stream crossing to failure and to possible stream diversion. These measures are often employed on steep road grades where it may not be physically possible to dip the road or construct a critical dip on the road surface to prevent stream diversion (e.g., see Figure 68), but they are appropriate as preventive measures on most culverted stream crossings.

The most common measures used to reduce the risk of culvert and stream crossing failure include:

- upsizing the stream crossing culvert beyond the 100-year flood design diameter (e.g., by one or two sizes) so that floating woody debris is less likely to plug the inlet;
- installing debris barriers (also called trash racks) to capture floating woody debris slightly upstream of the culvert inlet before it can plug the culvert;
- installing wing walls and/or a flared culvert inlet to either direct wood and sediment more easily through the culvert inlet or to cause it to be trapped above or before reaching the inlet;
- installing an emergency overflow culvert higher in the fill (above the main culvert) as a "relief valve" in case the main culvert becomes plugged; and/or
- removing the road fill and replacing the culverted stream crossing with a bridge.

Reducing the risk of stream diversion—Reducing the risk of culvert failure is not enough, as there are times when culvert failure will occur despite the best design. **Except where physically impossible or where not compatible with existing traffic types, all new and reconstructed (upgraded) stream crossings should be designed and built to prevent the diversion of flood flows if (when) the culvert becomes plugged.** If the designs and treatments are done correctly (i.e., they can accommodate the 100-year peak flow), these preventive treatments can

FIGURE 68. *Culverted stream crossing with a diversion potential. If this culvert inlet plugs with sediment or floating debris during a flood event, streamflow will be diverted down the road into the distance. Because the culvert is close to the road surface in this shallow fill, a critical dip could be installed immediately to the right of the fill, to direct flood flow back into the channel.*

completely eliminate the risk of future stream diversions, and their erosional consequences.

With new construction, the most effective road prism design is to dip the road into and back out of the stream channel (a dipped crossing), so that when the culvert plugs flood flow will spill over the low point in the fill and back into the natural stream channel. The erosion prevention treatments for road upgrading are similar to those for new construction; either physically lower the existing fill over crossing or construct a deep, broad rolling dip to prevent flood flow from ever diverting down the road (Figure 69). Where the stream channel is not incised into the landscape (i.e., it can't be dipped) or the culvert has a thin overlying fill and is too close to the road surface, the new road can be constructed, or the existing road can be reconstructed, with a broad, deep rolling dip on the down-road side of the crossing (over the fill's hinge line) to direct flood flows over the fill and back into the channel (Figure 67).

This dip in the road is called a "**critical dip**" because of its critical importance in protecting the watershed and its streams from storm impacts. Although somewhat like a rolling dip, it has to be designed to have sufficient capacity (width and depth) to carry flood flows from the stream without itself overtopping and diverting down the road. Stream crossings with no diversion potential are said to be designed as "diversion-safe" because a dip in the road fill, or a critical dip in the road grade, prevents flood flows from ever flowing down the adjacent road to do damage elsewhere. The placement of this dip on the fill's down-road hinge line also minimizes the volume of erosion that is likely to occur when and if the fill is overtopped.

Preventing future stream diversions is one of the most important and cost effective measures that can be applied to the existing road network to protect downstream water quality and aquatic habitat from catastrophic damage. The steeper the hillslopes, the more erodible the soils, and the larger the diverted streams, the greater will be the potential for

FIGURE 69. *A gradually climbing road changes grade over the small stream crossing, thereby eliminating the possibility for future stream diversion. The dip is broad and gentle to accommodate all traffic, and designed to carry peak flood flows across the road and back into the channel with minimal erosion and sediment delivery.*

significant erosion and downstream impacts from a diversion. However, even small streams, when diverted onto steep, unstable hillslopes, can cause large debris slides and debris flows that can severely impact rivers and streams in downslope areas far removed from the actual diversion site. In some locations (such as valley bottoms and low gradient basal slopes) culvert plugging and stream diversion is less likely to cause significant erosion or water quality impacts. Some judgment is required to correctly identify these low threat settings.

ii. Reducing the magnitude of stream crossing failures When a stream crossing culvert plugs, and flood waters overtop the stream crossing fill, the road prism and fill will begin to gully as the streamflow cascades back down the outside fill face. The magnitude of stream crossing erosion (partial or complete washout) depends on the volume, velocity and duration of the overflow event, as well as the erodibility of the fill materials.

Three basic treatments can be designed into a stream crossing to minimize the magnitude of the erosion that will occur during an overflow event.

1. *Minimizing erodible fill volume*: **Minimizing the erodible fill volume is done by dipping the road grade into and out of the stream crossing, rather than having the road run at a smooth, even grade across the crossing fill.** For shallow fills (e.g., Figure 69), or for steep road grades which cross a fill (e.g., Figure 68), you might be able to dip the road only a small amount. For deep stream crossing fills with gentle road approaches, the amount of the dip that can be constructed (excavated) is controlled by the steepness of the resulting road grade on each approach. Deeply dipped stream crossing fills means there is less fill to erode in an overtopping event and guarantees that the stream will not be diverted down the adjacent road when overtopping occurs.

2. *Minimizing overtopping erosion rates:* **To minimize the amount of erosion that would occur in an overtopping flood event, and to minimize damage to the crossing, flood overflow can be intentionally directed to a hardened or more resistant location on the fill.** By locating the axis of the deep road dip, or the critical dip for shallow fills, on the down-road hinge line of the crossing fill, only a small amount of fill will erode until denser native soils or bedrock is encountered. This will minimize the rate and volume of erosion created by the overtopping event. If the dip were located over the center of the stream crossing fill, erosion would proceed more quickly down through the easily erodible fill and potentially exposing the culvert.

3. *Armoring the overflow spillway:* Finally, in channels where debris flows or other culvert plugging events are relatively common, an armored overflow channel can be constructed on the outside fill face across the axis of the road dip. The armor will protect the underlying fill from erosion during an overflow event. Although it is difficult to correctly design the required armor size for use on a steep fill slope, the rock can also be grouted or locked in place with concrete. It is important to design a channel cross sectional form to contain the predicted flood overflow and prevent it from flanking the rock armor. This type of spillway armoring treatment will be needed on only a small percentage of stream crossings, where overtopping is a common occurrence, or where failure is likely (e.g., the basal culvert is greatly undersized), erodible fill volume is high and downstream resources are especially sensitive or valuable.

Overtopping events are rare, so you have to balance the expense of the protective design with the probability of its occurrence. **Properly located**

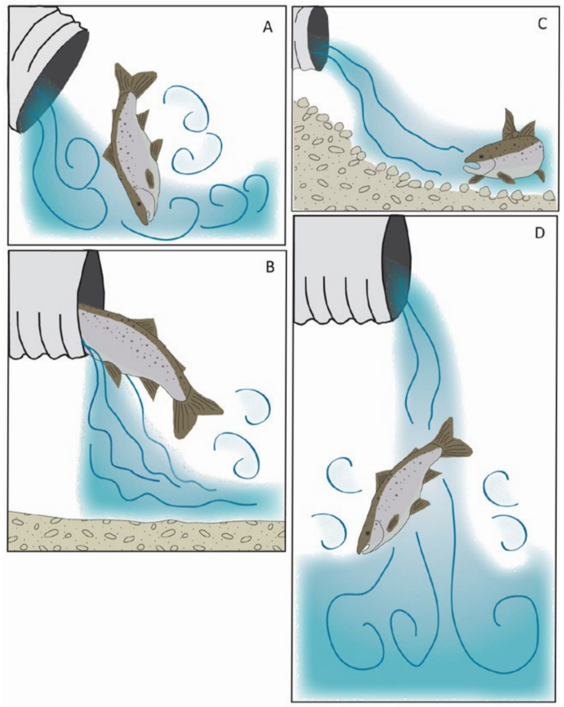


FIGURE 70. *Incorrect culvert installation can impede or prevent fish passage through a stream crossing. Culvert conditions that block fish passage include: A) water velocities too great, B) water depths too shallow, C) insufficient resting area or jumping pool depth at culvert outlet, and D) culvert outlets that are too high above the streambed (Modified from: Furniss et. al., 1991).*

and designed stream crossing dips (the most cost effective design change) will minimize erosion and damage to stream crossing fills in most overtopping events. The armoring and construction of an overflow channel to convey flood waters is not usually required.

b. Fish passage designs

For fish bearing streams, designing crossings with proper fish passage is equally as important as sizing the stream crossing for the 100-year design flood flow and to pass sediment and debris.[7] Stream crossings that are not properly designed for the upstream and downstream migration of anadromous or resident fish species can combine to result in the overall loss of important fish habitat and ecological productivity.

Of all the types of stream crossing designs and structures, culverts are most commonly identified as impeding fish passage. Compared to the natural channel, poorly designed culverts in fish-bearing streams often result in (1) replacing natural spawning gravels with pipe materials, (2) straightening and shortening stream channels, thereby resulting in reduced natural channel complexity and increased stream velocities, and (3) impeding fish passage due to channel scour at poorly designed culvert outlets (Figure 70). In addition, construction activities in fish bearing streams can also result in the modification of stream channel hydraulics and release fine sediment, resulting in embedded spawning gravels and reduced pool depths.

There are obvious benefits, but also potential impacts, to removing a barrier to fish and organism passage. Impassable crossings may occasionally provide an ecologically beneficial function. For example, elevated culverts provide elevational (grade) control by creating a rigid boundary against the upstream migration of channel incision in an unstable channel system.

Removal of a culvert that controls base level could allow channel incision to progress upstream, contributing to reduced habitat quality throughout the upstream reach. In a few instances, it may even be preferred to install or maintain a fish passage barrier. Thus, a culvert that is impassable to an invasive species protects upstream native species from predation and unwanted competition. You should consult a qualified fisheries biologist, and the appropriate regulatory agencies, before deciding to remove a known fish migration barrier.

Proper fish crossing design should be aimed at minimal impact on habitat while improving "ecological connectivity" for salmonid and other native fish, amphibians, reptiles, macroinvertebrates, insects, and other organisms that make up the aquatic food web. Fish require the ability to move throughout a watershed to access spawning grounds, to migrate in the summer to avoid warm water temperature and low flows and to escape to side channel refugia during winter flood flows.

7 See Appendix C for specific California Forest Practice Rule language for this requirement.

i. Fish passage at stream crossings Many forest, ranch and rural roads were constructed decades ago, before fish passage was considered an important design consideration. Even on small fish bearing streams, old culverts are typically undersized, installed at steep gradients or installed high in the stream crossing fill so as to partially or completely block passage. These sites are increasingly becoming the focus of road improvement projects, to make the stream crossing more resilient to storm damage and flood flows, while also reestablishing or improving fish passage.

The National Marine Fisheries Service (NMFS, 2001) has suggested the following alternatives and stream crossing types/structures for fish bearing streams, in the order of preference:

1. **Preferred**: *No stream crossing structure in a fish-bearing stream*. The best design for fish passage is not to install a stream crossing that disrupts the nature stream channel characteristics. Decommission or permanently remove existing stream crossings that act as fish barriers and realign roads to avoid crossing the stream.

2. *Bridge* that spans the stream to allow for long term dynamic channel stability. Bridges are an expensive option, but when installed properly, they are the best crossing structure for maintaining stream integrity and natural channel characteristics, as well as preserving ecological connectivity.

3. *Bottomless arch, embedded culvert, embedded ford*, or ford that simulates the natural streambed characteristics. These crossing designs incorporate the natural streambed at the base of the structure and across the entire width of the road.

4. On low gradient channels, use a *non-embedded culvert or "hydraulic design"* that incorporates more traditional culvert design.

5. **Least preferred**: on steeper gradient channels, install *baffled culvert* or a structure with a designed fishway.

When culverted stream crossings are upgraded for fish passage, they can be replaced with bridges or bottomless arch installations. For existing stream crossings, **bridges that do not affect the channel bed and have their**

FIGURE 71. *This 45-foot railroad flatcar bridge was installed to replace an undersized culvert that had been a barrier to fish migration. The channel width was maintained and a minor amount of armor was used to protect the abutments from erosion.*

abutments outside the channel are the least likely to adversely affect fish and organism passage. In replacing a culverted stream crossing, a bridge installation is generally a highly effective but potentially costly project. On private, low standard roads, use of salvaged rail flatcars and affordable I-beam bridges can be a highly cost-effective option (Figure 71).

Bottomless arches, with natural channel beds and abutments at least as wide as the channel, are also considered generally favorable for providing or improving aquatic passage (Figure 72). Because of their high rate of success, and not having to precisely design grade control and culvert embedding at the crossing site, a number of commercial timber companies have made it

FIGURE 72. *This bottomless plate arch was installed to provide fish access through the stream crossing. Each abutment is comprised of a concrete foundation and the stable streambed ensures continuous aquatic passage.*

FIGURE 73. *Embedded culverts are another type of stream crossing structure that allows continuous fish passage. This 10-foot diameter embedded culvert has a natural gravel and cobble streambed. It was installed to replace a small diameter culvert that was a barrier to fish migration.*

their policy to upgrade to bridges rather than install embedded culverts or arch structures.

The simplest fish-friendly culvert installation is the embedded culvert that contains a natural streambed through a wide, oversized pipe (Figure 73). For many landowners, this is the most cost-effective solution. The old culvert is removed and replaced at channel grade with a culvert that is embedded in the stream channel gravels. An embedded culvert can be any shape, but is most often a circular, box or pipe arch that has been buried into the ground typically 20–40% of its height (Figure 74).

Ideally, embedded fish passage culverts are wide and as close to the natural channel width as possible, so flows are not accelerated through them and downstream scour is avoided. Embedded culverts are typically installed in stable, low gradient stream channels that are unlikely to experience significant channel changes (i.e., heavy aggradation or channel downcutting). One advantage of an embedded culvert is the culvert invert (bottom) can provide grade control and protection against extreme scour compared to an open-bottom arch.

Many existing low-water crossings (fords) and culverts create passage problems for aquatic organisms. However, like other crossing structure types, low-water crossings can be effectively designed to: (1) enable passage of aquatic organisms, (2) protect endemic species from invasive competitors, and (3) provide grade control in an incised stream system for protection or restoration of upstream reaches. Fords, particularly vented fords, can be constructed to pass large flows and large amounts of debris, and still provide suitable aquatic organism passage.

The passage conditions and obstacles for ford crossings are similar to those of a culvert, except at higher water conditions when passage over the structure is unimpeded. There should be at least one culvert set deep into the streambed of a hardened ford structure so that passage during low flow conditions is possible. For fish or aquatic species passage, uniform stream channel gradients and acceptable flow velocities must be achieved and maintained through the crossing. Just as wide, embedded culverts are preferred for fish passage, a high Vent-Area Ratio (VAR) structure for a vented ford is much better for

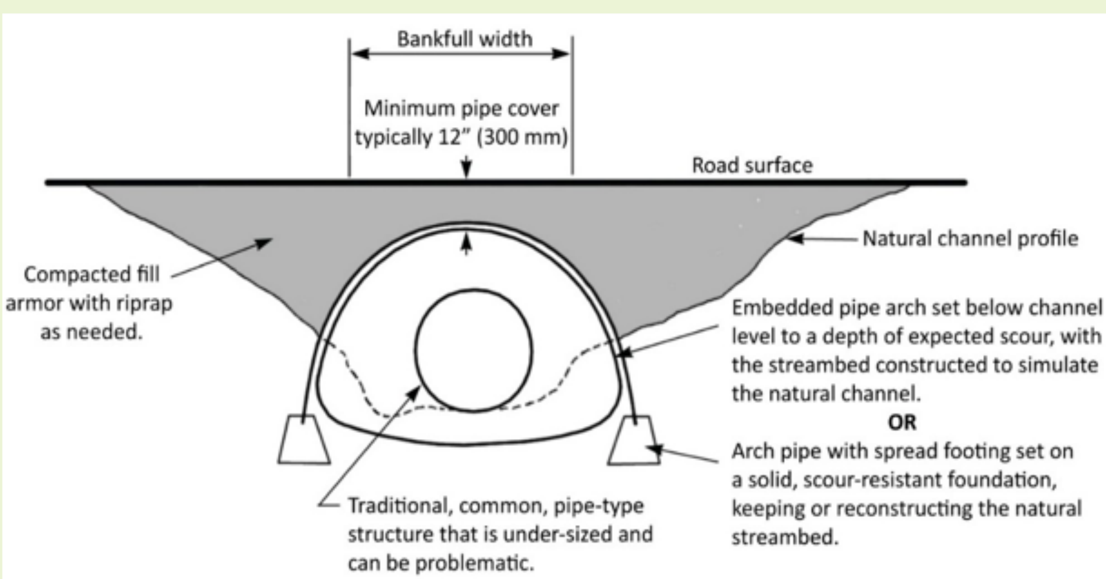


FIGURE 74. *Example of a stream simulation culvert (showing preexisting round culvert, embedded arch culvert and bottomless arch or plate arch) (Modified from: Keller et al., 2011).*

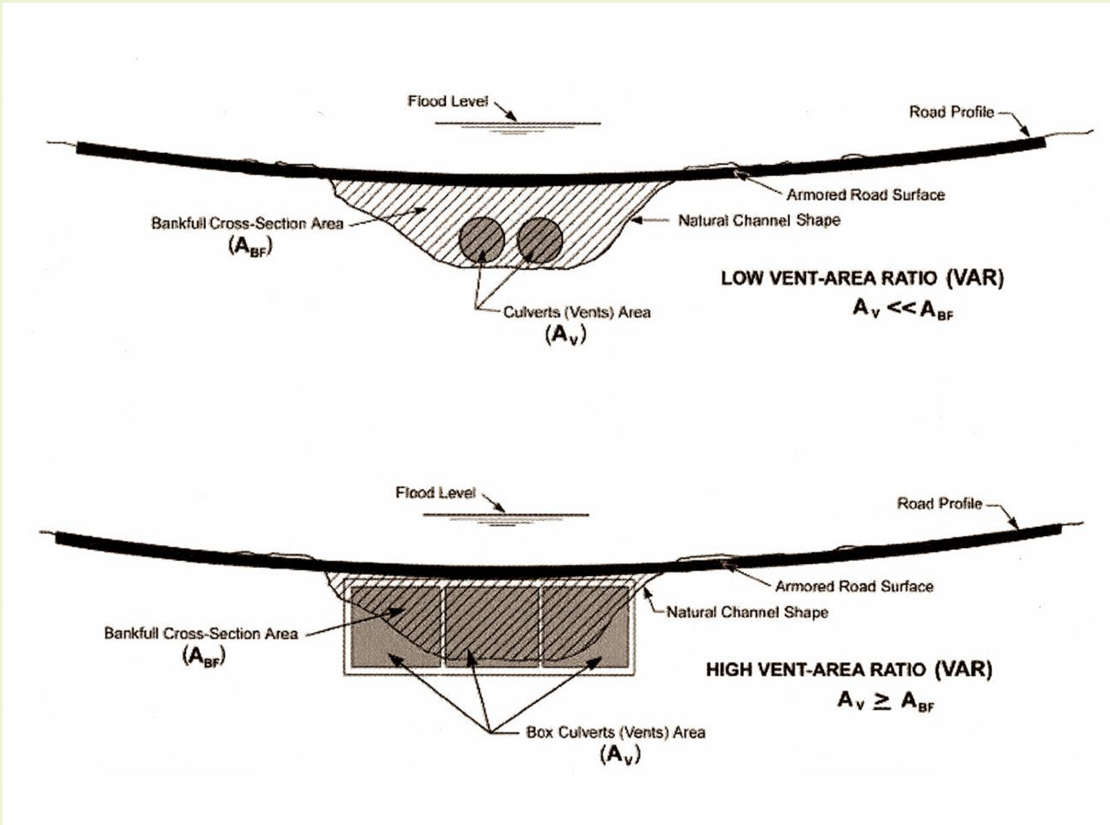


FIGURE 75. *Examples of fords with low and high Vent-Area Ratio (VAR). The high vent-area crossing is preferred for fish passage (Keller and Ketcheson, 2012).*

aquatic organism passage and to maintain the natural function of the stream (Figure 75).

In general, unstable, eroding stream channels should not be chosen for stream crossing arches, fords or low water crossings, especially where fish passage is required. In a degrading reach, hardened fords and other fixed-bottom crossing structures (like culverts) may be undermined when an advancing headcut reaches them, and this could eliminate fish passage. At the same time, low-water crossings and culverts can function as grade-control structures, preventing the headcut from moving headward and protecting the stability and aquatic habitat of upstream reaches. It may be necessary to install a bridge or an open bottom arch, or otherwise provide alternative passage (such as a roughened channel) for aquatic organisms if impassible grade drops occur on the downstream side of a ford, or if energy dissipation structures cannot accommodate passage. This is especially important for concrete slab ford crossings.

ii. Grade control for fish passage When installing or replacing stream crossing culverts, fords, vented fords and other in-channel stream crossing structures in fish bearing streams, channel grade (slope) and channel structure (roughness and drops) become important design elements. Installation techniques that might be applicable and effective for non-fish bearing channels may no longer be suitable. For example, 1) wide, flat bottom box culverts may not provide for low flow juvenile passage; 2) rock armor at the outlet of a culvert may not allow passage or provide for an adequate holding or jumping pool; and 3) downstream cutoff walls, roughened energy dissipation slabs, splash aprons, or energy dissipation pools might reduce outlet erosion and channel scour, but such measures can also create fish

passage barriers. Likewise, simply removing or replacing an existing culvert with a larger culvert could trigger channel downcutting and the creation of a new fish passage barrier.

Grade control structures may be necessary upstream and/or downstream of a newly installed or removed drainage structure (especially culverts) to control the longitudinal profile and water surface elevations, and thereby provide for continuous fish passage (Table 23). Channel grade controls may be needed to provide for steepened or stepped fish passage through the affected channel reach. Channel grades can be stabilized using a series of small grade control structures to produce small steps in the channel to raise it to the required level or elevation. Alternately, the channel can be "roughened" with coarse rock to provide for a continuous steepened section that will not erode and yet can still provide for fish passage. In essence, roughened channels are permanent features designed to resist channel changes during the design, 100-year flow event.

Designing grade control to provide for unimpeded fish passage in a stream will likely require special permitting and/or the use of a qualified, experienced professional (hydraulic engineer or engineering geologist). These projects need to accommodate passage of all life stages (e.g., juvenile and adult salmonids) and still function well during both low flow periods and during flood flows. Designs require an uninterrupted, uniform (or acceptable) gradient, natural bottom stream bed at the crossing site, extending from the natural channel bed below the stream crossing to the same natural channel bed above the drainage structure. **Grade control may be required to control the integrity of the longitudinal profile and water surface elevations through the**

TABLE 23. Comparison of channel profile design structures used to control grade either upstream or downstream of a stream crossing culvert for fish-bearing streams[1]

Grade control	Advantages	Disadvantages	Limitations
Log sills	Downstream bed elevation control	Limited to <5% final gradient (affects length to catch channel grade).	Minimum spacing of 15 ft. Limited to <5% gradient. Allowable drop depends upon fish requiring passage. No wet/dry cycles between.
Baffles	Increase hydraulic roughness	Turbulence, hydraulic profile raised, debris and structural problems. No small fish passage.	Slope ≤3.5%
Plank sills	Hand labor	Less durability	Limited to streams with <5% gradient; small streams.
Roughened channel	Natural appearance, flexible, can provide passage for all fish	Technical expertise required. Technical fish-passage analysis required.	Limited to <3% gradient streams.
Boulder controls	Flexible, allowing channel to regrade slowly	Should only be used for downstream use if culvert is sufficiently embedded.	Maximum drop of 0.75 ft.
Fishway	Can provide passage for most fish	Expensive. Technical expertise and site-specific, flow-regime data required. Debris and bedload problems.	Narrow range of operating flow. Difficult to provide passage for all fish, all of the time.

[1]Hotchkiss and Frei (2007)

stream crossing and, where necessary, trained personnel should be consulted.

iii. Design guidelines **In most cases, fish passage is designed for juvenile fish, considered to be the most vulnerable and "least able" life stage of migratory and resident fish.** Designing crossings with proper fish passage for juvenile fish is more difficult, but ensures that all life stages, and ultimately the health of the watershed's fisheries, will be maintained. This handbook is not a guide to designing fish passage and organism passage at road stream crossings, but knowledge of the basic criteria and elements of grade control is provided so that users can determine when and where they may need to consult with specialists about their particular project or site.

Determining the proper fish passage design for your stream crossing requires a site-specific assessment by qualified and experienced fish biologists, civil engineers, and engineering geologists or geologists. Designs are developed utilizing federal and state-accepted methodologies to identify the species at risk, quality and quantity of existing or potential fish habitat, potential or existing fish barriers, physical environmental conditions, and hydraulic and hydrologic conditions upstream and downstream of the proposed stream crossing. Contact your local state fish and wildlife office, Resource Conservation District or similar organization to obtain a list of fish passage design professionals in your area.

Federal and state agencies have developed specific guidelines for evaluating the site suitability of fish passage crossings and specific design techniques. **It is important to re-emphasize that the evaluation and design of fish passage stream crossings should be conducted by qualified professionals, as defined by federal or state laws.** It is important that the landowner understand their responsibility and role in proper road design in fish-bearing streams. Table 24 provides a list of available reference documents that may be used to inform landowners, road project managers, and road design professionals about federal and state guidelines and techniques for proper fish passage stream crossing evaluation, design, and construction. At the same time, there is no substitute for qualified, experienced professionals.

c. Designing stable stream crossing fill slopes

i. Slope gradient Slope gradient is one of the key factors that influence the stability of fill slopes. **Stable fill slopes are a product of stable fills, and that requires good compaction.** Properly designed culverted stream crossings also require careful attention to design fill slope gradients that will not structurally fail and will stabilize and revegetate quickly. Stream crossing fill slopes should be designed and constructed at gentle angles (e.g. maximum 2:1 (horizontal:vertical) slope ratio) unless that is infeasible or cost prohibitive. Stream crossing fill slopes constructed with a 2:1 slope ratio are typically stable and not prone to fill slope failure (if they are compacted under proper moisture conditions), and respond the best to revegetation (Figure 76).

Obtaining a stable fill slope gradient is dependent on:

- *The type of fill used to backfill crossing.* **To ensure stable crossing fill slope gradients, avoid using clay-rich soils, or cohesionless soils such as fine sands and silts.** Aim for backfill materials that are moist but not excessively wet or unstable (see also "Chapter 5: Construction, Section I (3). Culvert Installation" and Table 17).

- *Compaction measures applied during backfill.* Uncompacted fill materials allow water to fill the soil pore spaces, thereby reducing soil density and shear resistance. Lack of soil shear strength makes it difficult to

TABLE 24. List of federal and state fish documents and handbooks related to fish passage stream crossing evaluation and design

Agency	Title	Year published	Citation
			Federal
USDA Forest Service	Stream Simulation: An Ecological Approach to Providing Passage for Aquatic Organisms at Road-Stream Crossings	2008	Stream-Simulation Group, Forest Service. 2008. Stream Simulation: An Ecological Approach to Providing Passage for Aquatic Organisms at Road-Stream Crossings. 0877 1801P. San Dimas, CA: U.S. Department of Agriculture, Forest Service, San Dimas Technology and Development Center
Federal Highway Administration (FHWA)	Culvert Design for Aquatic Organism Passage	2010	FHWA, 2010, Culvert Design for Aquatic Organism Passage, Publication No. FHWA-HIF-11-008, U.S. Department of Transportation, Federal Highway Administration, Office of Infrastructure Research and Development, McLean, VA, 234 p. Available at: http://www.fhwa.dot.gov/engineering/hydraulics/pubs/11008/hif11008.pdf
National Marine Fisheries Service (NMFS)	Guidelines for Salmonid Passage at Stream Crossings	2001	NMFS, 2001, Guidelines for salmonid passage at stream crossings, U.S. Department of Commerce, National Oceanic and Atmospheric Administration. Available at: http://swr.nmfs.noaa.gov/hcd/NMFSSCG.PDF
			State
California Department of Fish and Wildlife	Fish Passage Design and Implementation	2009	Love, M., and Bates, K., 2009, Chapter XII: Fish Passage Design and Implementation, in California Salmonid Stream Habitat Restoration Manual, Third Edition, Inland Fisheries Division, California Department of Fish and Wildlife, Sacramento, CA, 189 p. Available at: http://www.dfg.ca.gov/fish/resources/habitatmanual.asp
California Department of Fish and Wildlife	Chapter IX: Fish Passage Evaluation at Stream Crossings	2003	Taylor, R.N. and Love, M., 2003, Chapter IX: Fish passage evaluation at stream crossings, in California Salmonid Stream Habitat Restoration Manual, Third Edition, Inland Fisheries Division, California Department of Fish and Wildlife, Sacramento, CA, 100 p. Available at: http://www.dfg.ca.gov/fish/resources/habitatmanual.asp
Oregon Department of Forestry (ODF)	Fish Passage Guidelines for New and Replacement Stream Crossing Structures	2002	ODF, 2002, Fish Passage Guidelines for New and Replacement Stream Crossing Structures, Forest Practices Technical Note No. 4, version 1.0., Oregon Department of Forestry, Salem, OR., 14 p. Available at: http://www.oregon.gov/odf/privateforests/docs/fishpassguidelines.pdf
Washington Department of Fish and Wildlife	Design of Road Culverts for Fish Passage	2003	Bates, K., Barnard, B., Heiner, B., Klavas, J. P. and Powers, P. D., 2003, Design of Road Culverts for Fish Passage, Washington Department of Fish and Wildlife, Olympia, WA, 112 p. Available at: http://wdfw.wa.gov/publications/00049/wdfw00049.pdf

FIGURE 76. *This newly upgraded 36-inch diameter culvert was installed in-line with the natural channel and at the base of the road fill. The road fill was graded to slightly less than 2:1 (50% slope) that was easily and rapidly revegetated. The culvert outlet extends at least 6 feet beyond the fill and discharges into the natural channel bed.*

construct or maintain proper fill slope gradients. **Stream crossing fill materials should be compacted during optimal (moist, not overly dry or wet) soil conditions in 6" to 12" lifts (layers) to increase soil density and shear resistance and reduce the potential for fill and fill slope instability.**

- *Compaction equipment.* A variety of compactors can be used for various soil types and site conditions, including: *sheepsfoot rollers* (which are usually towed); *pneumatic-tired rollers* (which use rubber tires to "knead" the soil or subgrade); *vibratory rollers* (smooth drum) (typically used for granular and mixed soil materials); and *tamping foot compactors* (which combines the advantages of a vibratory roller with a sheepsfoot). All compactors are used in building up a stable fill. **Vibratory rolling compactors should be used on cohesionless soils, such as sand and gravel while sheepsfoot rollers are best suited for cohesive soils such as silts and clays.** True compaction equipment usually produces the best results but **field compaction using rubber tired heavy equipment or even dozer tracking can often provide adequate soil strength if done uniformly and under proper soil moisture conditions.**

- *Compaction of the fill slope faces.* Compaction is most easily obtained on horizontal surfaces; it is much more difficult to obtain proper soil compaction on the slanting outer fill slope faces. **Ideally, if the design stream crossing fill slope is to be steeper than 2:1, the fill should be built slightly wider than desired and compacted in thin vertical lifts. The excavator can then use its bucket to excavate back the fill slope face to remove the outer 6" of loose, uncompacted soil material until the internally compacted soils are exposed. This provides the best compacted fill slope.**

Even under ideal moisture conditions, only moderate compaction on angled fill slope faces can be attained using a sheep's foot roller winched up and down the fill slope, or an excavator fitted with a quick-release sheep's foot roller attachment used to compact the fill face. Short, gently sloping fill faces can often be mulched, either with small diameter angular rock (road rock) or with a straw mulch to control erosion until the surface has naturally compacted and stabilized with vegetation.

For locations where stream crossing fill slopes require steeper gradient design (e.g., steeper than 2:1 or 1½:1), a qualified civil engineer, engineering geologist, or geologist should be consulted. They will help you determine if simply rock armoring will help stabilize the fill slope surface, or if other slope revetment measures need to be applied to prevent potential fill slope instability. Slope revetments might include riprap blankets keyed into the base of the stream crossing fill slopes; gabion structures[8]; engineered fills; or other fill slope retaining structures (Figures 51 and 77).

ii. Culvert outlet extensions Stream crossing culverts should be installed so that both culvert ends extend sufficiently beyond the base of the fill slope to prevent erosion or undercutting of the fill, and that the culverts are long enough to allow construction of a gentle and stable fill slope. **Preferably, the culvert outlet should extend at least 6 feet beyond the base of the fill** (Figure 76)**, and the inlet approximately 2 feet upstream of the base of the fill, to protect the stream from soil erosion or soil movement off the newly constructed fill slope.** If stream crossing culvert installations require riprap protection at the inlet or outlet, several additional feet of culvert can be added to protect the exposed pipe from crushing or burial.

8 Gabion wire baskets should not be used in fish-bearing streams.

FIGURE 77. *Road crossings of steep stream channels require fill slopes that often exceed a 2:1 slope gradient. This steep fill slope was stabilized with coarse rock armor embedded in a basal keyway.*

Landowners have sometimes tried to save money by minimizing culvert length during construction, by installing short culverts, constructing steep fills and "shot-gunning" culvert outlets near the top of the fill. A culvert installed too short in the fill can cause culvert inflow or outflow to scour and potentially undercut and destabilize the fill. The additional pipe length beyond the base of the fill ensures that streamflow is transported beyond the fill slope and is released into the natural channel. In addition, the extended pipe length is added insurance that the pipe inlet/outlet will not be buried or blocked in the case of small fill failures, sidecast during grading, or culvert damage during maintenance activities.

iii. Armoring and riprap

Introduction—Rock armor and riprap can be used at stream crossings to provide erosion control at the inlet and outlet of culverts, on fill slope surfaces, along stream channel bottoms and stream banks, and along ditches leading to stream crossings. As an erosion control measure, riprap is effective for energy dissipation by providing roughness that slows water velocities or turbulent flow along stream channels, at culvert inlets and outlets, and along ditches. Finer rock materials can also be applied as non-erodible "mulch" on fill slopes that lack vegetation and will not respond well to vegetative erosion control measures (e.g., in arid or semi-arid areas). Used as mulch, riprap prevents surface erosion by protecting the soil surface from raindrop erosion and by dispersing and slowing concentrated surface runoff. It also acts to trap eroded sediment within rock particle spaces.

Riprap is also used as a stabilization measure for steep fill slopes or along unstable stream banks; although, riprap can be become unstable when placed on slopes steeper than 2:1 if it is not properly selected and installed. For this reason, the landowner or road project manager should consult with a qualified professional for design specifications and installation instructions when riprap is planned as a stabilization or revetment measure.

Riprap specifications—The effectiveness of rock riprap as an erosion control measure is based on (1) stone or particle size and weight, (2) stone durability, (3) slope gradient, (4) thickness of riprap application, and (5) its use in conjunction with underlying filter fabric or geotextile. At stream crossings, riprap should be sized according to expected stream velocities and slope gradients. Riprap that is undersized for site specific stream velocities and slope steepness will be subject to particle erosion, where the riprap cannot withstand the stream hydraulic forces and becomes dislodged or the slope steepness exceeds the riprap angle of repose.

Riprap should consist of a well-graded mixture of larger and smaller hard rock sizes in order to minimize void space and create a dense layer of interlocking rock. Interlocking riprap forms a flexible, yet durable and self-adjusting erosion resistant surface. Avoid using uniformly sized riprap due to its reduced frictional resistance, large pore space voids and sensitivity to individual particle movement. However, recent published documents suggest that a coarse, uniformly sized riprap surface may be advantageous along stream environments to create increased roughness and flow resistance, improved diverse habitat, suspended sediment deposition and increased oxygenation. Table 25 provides ten of the standard riprap classes and the associated gradation by size and weight.

In general, riprap should be installed with an underlying layer of geotextile or gravel separating the riprap from compacted fill material. Geotextiles are used to prevent winnowing of fines, scour, slumping, piping, or the movement of fill or subgrade soils into the overlying riprap. Care should be taken when using equipment to place riprap on geotextile so that it is not damaged or torn.

Culvert inlet and outlet armoring, and energy dissipation—Rock armor at culvert inlets and outlets has three functions; 1) as inlet and outlet protection used to protect the base of the fill from spash and surface erosion, 2) to trap sediment eroded from the upper portions of the newly constructed fill slope before it is delivered to the stream, and 3) as energy dissipation below the culvert outlet to protect the channel against high velocity flood flows.

Riprap installed to protect the inlet and outlet of a stream crossing culvert from erosion or for energy dissipation should be keyed into the natural channel bed and banks to an approximate depth of about 1.5x the maximum rock thickness (Figures 78, 79).

TABLE 25. Standard classification and gradation of riprap by size of rock[1]

Riprap size class	Median particle weight[2]	Median particle diameter[2] (in)	Minimum and maximum allowable particle size (in)[2]						
			D_{15}		D_{50}		D_{85}		D_{100}
			Min	Max	Min	Max	Min	Max	Max
Class I	20 lb	6	3.7	5.2	5.7	6.9	7.8	9.2	12.0
Class II	60 lb	9	5.5	7.8	8.5	10.5	11.5	14.0	18.0
Class III	150 lb	12	7.3	10.5	11.5	14.0	15.5	18.5	24.0
Class IV	300 lb	15	9.2	13.0	14.5	17.5	19.5	23.0	30.0
Class V	¼ ton	18	11.0	15.5	17.0	20.5	23.5	27.5	36.0
Class VI	3/8 ton	21	13.0	18.5	20.0	24.0	27.5	32.5	42.0
Class VII	½ ton	24	14.5	21.0	23.0	27.5	31.0	37.0	48.0
Class VIII	1 ton	30	18.5	26.0	28.5	34.5	39.0	46.0	60.0
Class IX	2 ton	36	22.0	31.5	34.0	41.5	47.0	55.5	72.0
Class X	3 ton	42	25.5	36.5	40.0	48.5	54.5	64.5	84.0

[1]Lagasse et al. (2006)
[2]Equivalent to spherical diameter

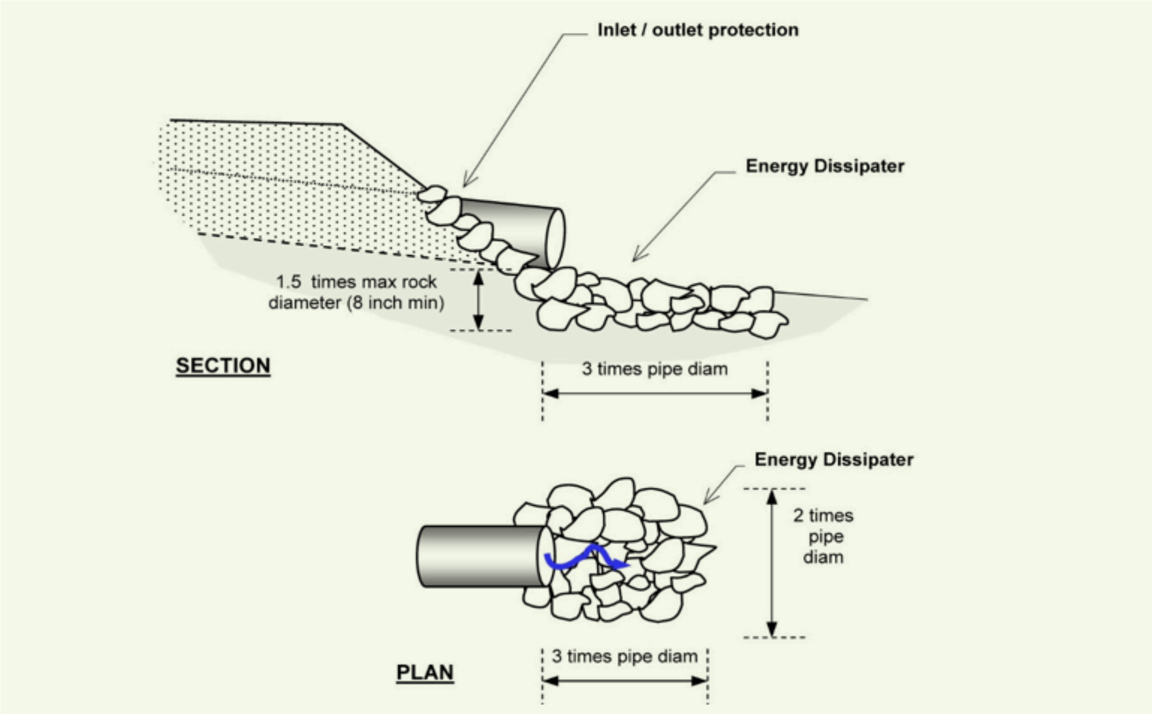


FIGURE 78. *Riprap as outlet energy dissipation (Best, 2013).*

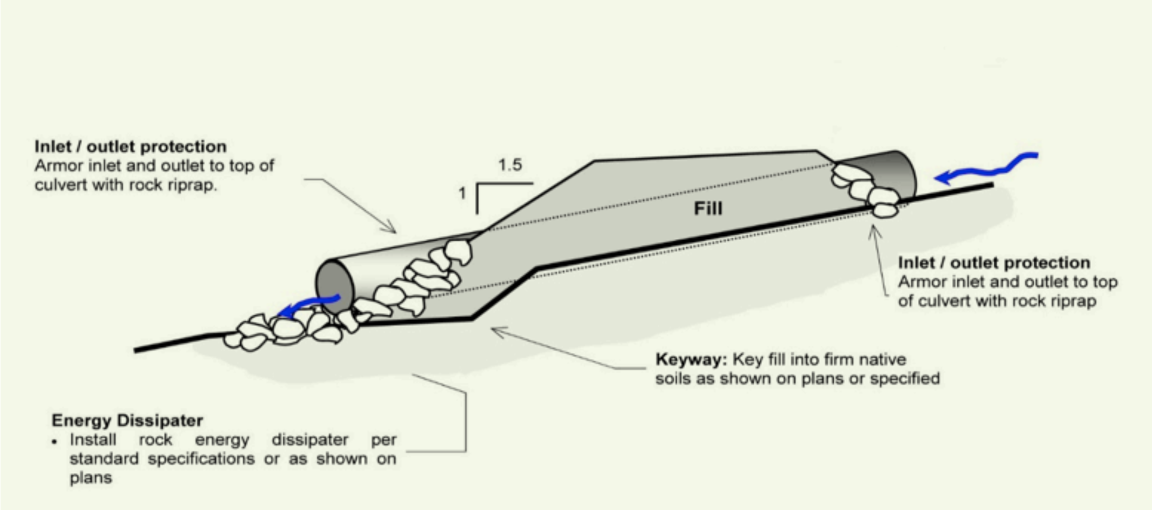


FIGURE 79. *Riprap as inlet protection and outlet energy dissipation (Modified from: Best, 2013).*

Riprap should be placed at least up to the top of the culvert at both the inlet and outlet to protect them from splash erosion and to trap any sediment eroded from the newly constructed fill slope above (Figure 79).

Rock armor used for inlet and outlet protection (i.e., not as energy dissipation) does not have to be sized to protect against high velocity scour. If the culvert is properly sized and its length is adequate, it should be able to transmit flood flows without scouring the inlet or eroding the outlet around the culvert. Armor here is designed to protect the culvert outlet and basal fill from splash erosion and from occasional submergence and currents within standing water (at the inlet) when the culvert plugs. Importantly, inlet and outlet armor also serves to trap sediment that has been eroded or slides down the new constructed fill face in its first several years, until the slope becomes well vegetated (Figures 73, 80).

FIGURE 80. *Rock armor placed around this culvert where it emerges from the fill slope was used to protect the stream from unexpected erosion of the new, erodible fill slope until it stabilized with vegetation.*

If energy dissipation is necessary below the culvert outlet, rock armor size should be designed for the peak flood flow. The riprap apron should extend a length of about three culvert diameters downstream from the end of the outlet and in line with the natural channel, and span a width of at least two culvert diameters in order to reduce the potential for outlet scour or flanking of the rock armor during flood flows (Figure 78). Riprap size should be based on the design stream velocities to ensure rock will stay in place and not be mobilized, causing potential erosion and destabilization of the stream crossing. However, outlet velocities are not easily estimated for sloping culverts at peak flood flows.

Armored fills and armored spillways—Riprap armor is employed to protect the outer fill slope of an armored fill (see Armored fills, below) and less frequently as overflow "chutes" for culverted stream crossing fills that are prone to overtopping during flood events. Both designs require rock armor to be centered at the low point in the stream crossing fill, where the flood flow would overtop the fill and flow down the fill face during any storm or culvert plugging event. The spillway should be constructed with a broad overflow dip (like an armored channel; with a bed and two gently sloping banks and sufficient capacity to contain flood overflows) directly over the low point in the crossing.

Some general design parameters for rock placement on an armored fill might include the following: Riprap should be keyed in to the fill slope or overflow channel to an approximate depth of 1.5x the maximum rock thickness. Riprap should be placed with a minimum of 2x the D50 thickness and extend to the top of the fill slope. In general, the width of the spillway should be at least 5x the design stream bankful stage width. We would also suggest a range of rock sizes be used in order to lock the rock riprap together, and a geotextile fabric beneath to protect the underlying erodible fill. Riprap placed on a steep fill slope can not be guaranteed against erosion during a flood flow or overtopping event. For this reason, the rock can be grouted or secured with concrete as a stabilizing measure.

Slope revetment—Anything but the smallest slope revetment (such as a small boulder pile) require specific designs that are best developed by a licensed professional so as to provide the most stable, functional and safe structure. A qualified and experienced engineer or engineering geologist evaluates existing site conditions, geology, and soils to determine the best design that will provide critical slope stabilization. In general, building stream crossing fill slopes at slope ratios greater than 1½:1 is discouraged. In some cases, steep fill slopes are buttressed using riprap blankets or gabion baskets that are keyed into the channel bed and extend upslope. Because of the variable nature of fill materials and the difficulty of attaining stable and consistent compaction, a qualified professional should be consulted for design advice before constructing steep stream crossing fill slopes, road and cutbank fill slopes, bridge abutments or engineered fills.

Streambank stabilization—In some cases, it may be necessary to protect steep streambanks upstream, downstream or, in the case of bridges, through the entire length of a stream crossing, from high velocity stream flows that may cause bank instability or scour. Riprap can be used alone in riprap blankets or gabion baskets, or it may be used in combination with live plants and structures (biotechnical measures) or dead vegetation (root wads, large woody debris, etc.) (Gabion baskets are not recommended for fish bearing streams).

Wherever rock armor has to resist flowing water, the size and weight of riprap is based on the stream velocity and channel slope. The nomograph illustrated in Figure 81 provides the relationship between riprap particle diameter, particle weight, stream velocity, and slope ratio. It is a useful tool for helping you estimate the proper size riprap for the design stream crossing or stream bank stabilization project. Advice from an experienced and qualified hydraulic engineer or engineering

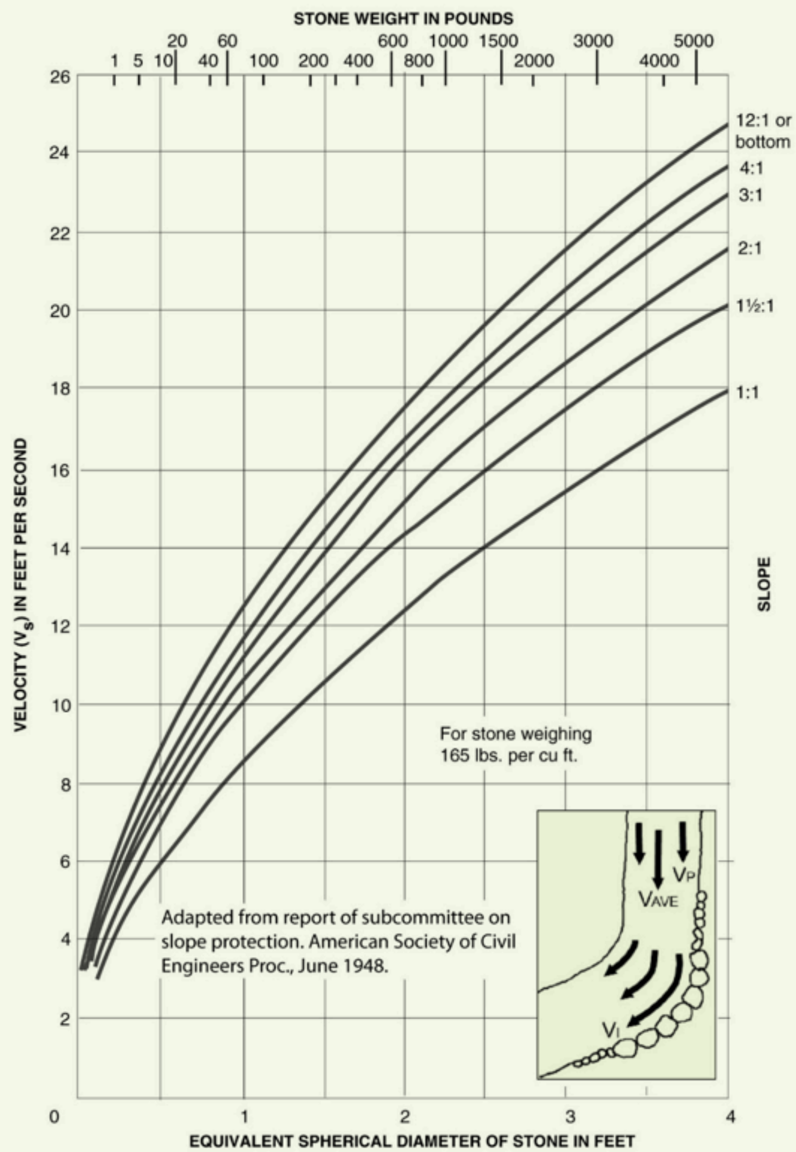


FIGURE 81. *Nomograph for determining riprap stone size and weight based on velocity and side slope steepness. While this nomograph provides an estimate of the required stone sizes, a qualified engineer or engineering geologist should be consulted for specific design work prior to constructing a streambank protection structure (Johnson and Stypula, 1993).*

geologist should be sought when designing streambank stabilization works that are protecting roads, buildings or other infrastructure.

Riprap should be installed on top of geotextile fabric or a clean mixture of coarse gravel and sand. The riprap should be keyed into the streambed and extend below the maximum expected scour depth with an adequately sized key base width at a thickness of a minimum of 2x the median (D50) rock diameter with the largest stone sizes placed at the base of the riprap structure. The armor should be set into the streambank so it does not significantly protrude into, or constrict, the natural channel, or otherwise reduce channel capacity. The riprap should extend along the length of unstable or oversteepened bank and up the bank sufficiently to encompass the existing bank instability and/or design flood elevations. Site-specific conditions will dictate the exact specifications and installation techniques that are chosen for your site. Because of environmental restrictions, regulatory (permitting) agencies may also provide specifications or restrictions on riprap installation at most sites.

iv. Road surface drainage Uncontrolled chronic road surface drainage can produce and deliver significant amounts of fine sediment to streams via ditches and road surfaces, and if it is discharged onto a stream crossing fill slope it can deeply gully or destabilize the fill. In general, roads over and adjacent to stream crossing fills should be designed to disperse runoff quickly and not allow concentration of runoff. **Designing roads to disperse and shed water on stream crossing approaches, before the road runoff reaches the crossing, can help maintain slope stability, reduce erosion and minimize sediment delivery.**

Road surfaces can be de-watered before reaching the crossing utilizing a variety of road shaping treatments including outsloping, insloping, and crowning; or road drainage structures such as rolling dips and ditch relief culverts (Refer to "Chapter 4, Section B: Road Prism and Road Surface Drainage" for specific information regarding road drainage techniques, design, spacing, and construction). Depending on site and road conditions, a rolling dip and/or ditch relief culvert installed just up road (e.g., 50 to 100 ft) from the stream crossing can help reduce the amount of road surface runoff reaching the crossing, as well as drain the runoff onto stable terrain away from the stream crossing fill slope. If the ditch is wet and flows water, ditch relief culverts (not rolling dips) should be used to drain the ditch.

In addition to de-watering the road approaches to a stream crossing, it is important to drain the roadbed through the crossing so runoff does not threaten the fills with erosion or instability. As long as the road has been hydrologically disconnected before reaching the stream crossing, local road surface drainage can be controlled by outsloping, insloping and/or berms. To minimize erosion, make sure any fill slope that receives local runoff is stable and mulched with vegetation or rock. If slopes are long, steep or susceptible to surface erosion, a low earthen berm can be used to take local runoff beyond the crossing fill and then discharge it onto stable terrain alongside the crossing (Figure 82). In some instances, rock armor or a flume may be required to carry flow to the base of the fill. When the fill face has completely revegetated the berm can be removed. **Insloping the road fill and road surface is probably the preferred method for controlling road surface runoff over the crossing and maintaining a stable fill**, especially where commercial truck and trailer traffic is common. If the road is insloped to drain onto the shorter inboard fill slope of the stream crossing, light surface armor or heavy mulch may be all that is required to prevent erosion until it is revegetated.

FIGURE 82. *This newly upgraded stream crossing fill was protected from road runoff and erosion by the installation of a drainage berm along the road. Once the fill is vegetated and stabilized, the berm can be safely removed.*

v. Erosion control Stream crossing construction results in the removal of vegetation and the creation of a bare road surface and two bare fill slopes that are highly susceptible to erosion. Although vegetation will usually reestablish over time, it is important to mulch and rapidly re-vegetate the bare fill slopes immediately after construction to establish a protective vegetated surface prior to the wet weather season. **All bare soil surfaces at newly constructed stream crossings should be straw mulched and seeded, or covered with an erosion control blanket.** The hydrologically connected road surface should be rock surfaced, or paved. If revegetation is not likely to develop quickly, the fill surfaces can be covered with a thin rock mulch to control raindrop impact and rill erosion.

In order to properly seed and mulch bare soil areas, make sure to use local, native seed with two or more shade tolerant, well rooted, aggressive perennial grass, forb, legume, or woody species. Seed should be applied to fill slopes immediately after construction when seed will have direct contact with soil and weed species have not had time to establish. After seeding, cover the slope with protective mulch, such as weed-free straw, wood chips, bark, or other similar materials to protect and encourage seed growth and reduce the potential for surface erosion. Cover the surface uniformly, but not too thick or you may inhibit germination and growth.[9] For additional protection on steeper fill slopes (steeper than 1½: 1), it may be necessary to tack erosion control netting (e.g., jute or coir netting) over the seeded and mulched surfaces in order to protect the slopes from surface erosion and provide a stable environment for vegetative growth.

vi. Critical dip placement A critical dip should be constructed at newly built or upgraded stream crossings that would exhibit a diversion potential.[10] If a stream crossing culvert plugs and flood flow overtops the

9 A good rule of thumb is "no bare soil visible."
10 See Appendix C for specific California Forest Practice Rule language for this requirement.

road fill, a properly constructed critical dip can convey flow over the crossing and back into the natural channel, usually with far less erosional impact than if it had been diverted down the road and into another stream or onto an unprotected hillslope (Figure 83).

If road conditions allow, critical dips should be built on the down gradient side of the crossing (near the stream crossing hinge line) and not along the centerline where the fill is the deepest and the where a culvert is typically aligned. If the culvert plugs and the crossing fill is overtopped, a critical dip installed over the centerline of the crossing risks the development of a deep gully that would likely compromise or damage the existing culvert. A critical dip installed along the stream crossing hinge line would result in a smaller gully (shallower depth of fill at the crossing hinge line) and would not likely damage the existing culvert, thereby causing less environmental damage and making crossing reconstruction less difficult or costly (Figure 84).

The critical dip should intercept the ditch and the ditch should be physically plugged at the down road side to prevent any diverted flow from discharging down the ditch. For additional protection, and for use only at stream crossings with a history of frequent culvert plugging and overtopping, an armored overflow channel can be constructed at the outfall of the critical dip extending down to the stream channel (Figure 84). This will ensure that the fill slope is protected from potentially erosive streamflows.

A second strategy to prevent stream diversions is to dip the entire stream crossing fill, with the low point in the dip at the down-road hinge line (Figure 84)**.** This prevents the stream from diverting and flowing down the adjacent road, and also reduces the volume of erodible fill in the crossing itself.

FIGURE 83.
Critical dip at a stream crossing. Note reverse grade that directs flow over the road and back into the natural channel in this climbing road grade. Prior to installation of the critical dip, the culvert plugged and the stream diverted down the road and completed washed out the road in the foreground.

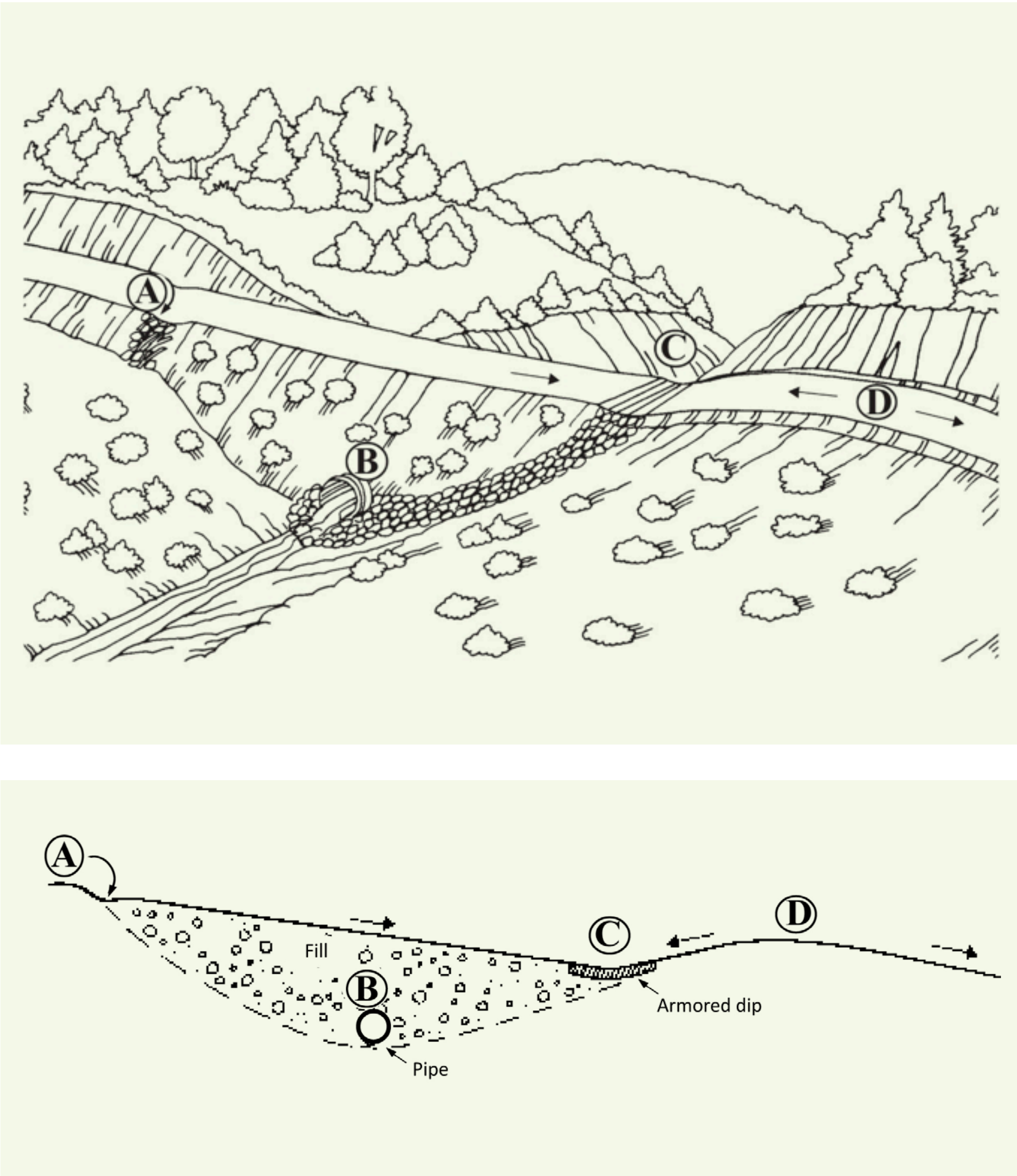


FIGURE 84. *Critical dips or dipped crossing fills should be centered near a stream crossing's down-road hingeline, not over the centerline of the crossing where overtopping could cause washout or severe erosion of the fill. If the stream crossing culvert (B) plugs, water will pond behind the fill until reaching the critical dip or low point in the crossing (C) and flowing back down into the natural stream channel. The down-road ditch must be plugged to prevent streamflow from diverting down the ditch line. For extra protection in this sketch, riprap armor has been placed at the critical dip outfall and extending downslope to the stream channel. This is only required or suggested on stream crossings where the culvert is* ***highly likely*** *to plug and the crossing fill overtopped. The dip at the hinge line is usually sufficient to limit erosional damage during an overtopping event. Road surface and ditch runoff is disconnected from the stream crossing by installing a rolling dip and ditch relief culvert just up-road from the crossing (A) (Keller and Sherar, 2003).*

d. Treating hydrologically connected stream crossing approaches

For maintained forest, ranch and rural roads, hydrologic connectivity can rarely be completely eliminated. Unless recently constructed, most untreated road systems have connectivity values ranging from 30% to 50%. Preferably, the goal should be to have <10% hydrologic connectivity along your roads.[11]

Stream crossings usually represent the most common location where road reaches are hydrologically connected to adjacent streams. A reasonable goal would be to have no more than a total of 200′ of connectivity at each stream crossing (less would be better) and ideally less than 100′ of connectivity per approach (Figure 85). Some situations will allow you to achieve even less connectivity, where road approaches can be outsloped with no inside ditch and almost none of the road drains to the stream.

Minimizing hydrologic connectivity depends on having frequent road and ditch drainage structures collecting and discharging runoff onto stable slopes where it can infiltrate into undisturbed forest soils before it reaches a watercourse (Figure 85).

Insloped roads with ditches are the most common way in which roads are hydrologically connected to streams in a watershed. Most hydrologic connectivity typically occurs on the approaches to stream crossings and secondarily at ditch relief culverts with gullies below their outlets. Thus, insloped roads should be frequently drained onto the adjacent, stable hillslope using ditch relief culverts or rolling dips, where runoff will not enter a stream channel.

11 See Appendix C for specific California Forest Practice Rule language for this requirement and TRA #5 for additional information on this topic.

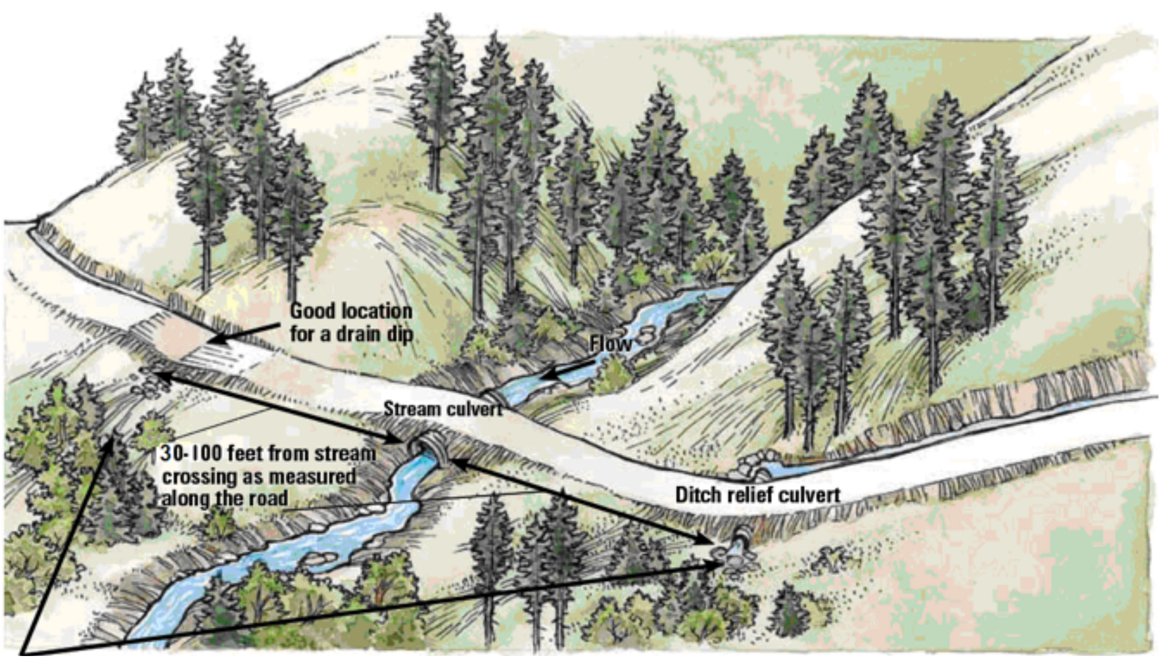


FIGURE 85. *Diagram showing hydrologic disconnection on the approaches to a stream crossing. Note the absence of an apparent critical dip at the crossing. (Modified from: Adams and Storm, 2011; see Appendix C for use in TRA #5).*

FIGURE 86. *Rolling road grade is one method used to effectively drain a road and disconnect road runoff from streams. This road was dipped and then rises to the bridge crossing, ensuring that road runoff is drained off the road and onto the vegetated hillslope prior to reaching the crossing.*

Choose from a variety or combination of surface drainage techniques including berm removal, waterbars, road surface shaping (outsloping, insloping or crowning), ditch relief culverts, rolling dips, and other measures that effectively disperse road surface runoff (Figure 86). It is critical that all road surface drainage techniques adequately drain the road surface while still being drivable for the expected traffic.

A number of road drainage tools or practices can be employed to cost-effectively reduce hydrologic connectivity of forest, ranch and rural road systems. These include:

Road Shaping (outsloping, crowning and insloping)

- Road outsloping, with or without an inboard ditch, is the preferred method of road surface shaping for protecting water quality, reducing hydrologic connectivity, and minimizing fine sediment delivery to streams.
- The degree of outslope is typically at least 2% for low gradient roads (<4% road grade) but increases up to about 5% as road grade steepens.
- Outsloping alone is insufficient to drain the roadbed unless it is paved. The road surface must be drained with rolling dips or waterbars.
- Outsloped roads may or may not have an inside ditch. If the cutbank is wet or has seasonal springs, a ditch is used to drain emergent water to a ditch relief culvert or rolling dip that intercepts the ditch. The road surface can be, and still should be, outsloped.
- Steep roads (greater than about 14%) are difficult to drain, so crowned or insloped road shapes are employed. Ditch relief culverts and rolling dips must be frequent to prevent road and ditch gullying.
- Crowned roads drain both to the outside fill slope and to the inside ditch. The crown or high spot is often the center of the road, but it can be shifted to the inside third of the road to reduce road runoff delivered to the ditch.
- Insloped roads normally need a ditch to carry road runoff and spring flow to the nearest ditch relief culvert or rolling dip where it can be discharged to a stable hillslope.

- Insloping is typically 3% to 4% towards the ditch, but the degree of inslope will increase as the grade of the road increases to quickly drain road runoff off the road and into the ditch.

- Insloped roads can be converted to outsloped roads to reduce hydrologic connectivity.

  - For roads needing a ditch, outslope the road so runoff drains off the outside road edge while the ditch drains relatively clear spring flow to the nearest stream crossing or ditch relief culvert.

  - If there is no spring flow in the ditch, the ditch can be filled (eliminated) while the insloped road is ripped and regraded to drain to the outside half of the road.

- Insloped roads are used where water cannot be discharged over the outside fill slope because of soil erodibility, fill slope instability or the proximity of a stream. This often includes newly constructed stream crossing fill slopes.

Road drainage structures

- Use rolling dips and road shaping to drain the road surface. Even if you increase the frequency of ditch relief culverts, you *must* also drain the road surface (using rolling dips or waterbars) and either get the road runoff into the ditch where it can be delivered to a ditch relief culvert, or drain it to the outside of the road (using rolling dips or waterbars) so it is discharged onto a stable, buffered hillslope. **In hydrologically disconnecting roads from streams, you must account for BOTH road surface runoff AND ditch flow.**

- Rolling dips on outsloped roads are recommended:

  - For mainline roads less than 7–10% grade if used by lowboys or other low clearance vehicles or trailers. Rolling dips must be broad and shallow.

  - For logging roads with log trucks, rolling dips are generally suitable on road grades up to 12% to 15%.

  - On road grades up to 10 to 12% when in the snow zone or where unsurfaced roads are used when wet and/or slippery.

  - On road grades up to 18% or more used by pickup trucks or other high clearance or 4-wheel drive vehicles.

- Ditch relief culverts or other road/ditch drainage structures that currently have gullies at their outlets, even if those gullies are stable, should be closed and relocated. Existing gullies are highly efficient corridors for continued connectivity, even if the gullies themselves are not actively eroding.

- Spacing of road surface and ditch drainage structures should be partially based on proximity to the watercourse, not just on road grade and soil erodibility. **The closer you are to a stream, the more closely spaced will be the drainage structures—so that no single drainage structure carries enough flow to connect to the nearby stream during a design runoff event.**

- **The closest drainage structure to a stream crossing is important, but the location of the *next* structure up the road is equally important. That spacing determines how much road and/or ditch runoff reaches the closest drainage structure, and hence its ability to connect to the watercourse.**

Other methods and considerations

- Install sediment retention basins where a connected ditch is likely to carry substantial runoff and eroded sediment. The sediment basins require maintenance.
- Road reaches that cannot be disconnected (e.g., the immediate approaches to stream crossings) should be well rocked, paved or otherwise surfaced. This is especially important for roads with significant traffic (they generate the most fine sediment) but is also important for native surfaced roads that are easily eroded.
- The connected road surfaces (i.e., road approaches) of native surfaced roads can be stabilized with mulch and grass as long as there is little or no traffic during the wet weather season. Otherwise, rock surfacing should be employed.
- Erosion and sediment delivery on seasonal roads can be further reduced by utilizing seasonal closures or traffic restrictions.

Connectivity goals should be established for individual driveways, as well as large ownerships, complete watersheds, and entire road systems. Everyone, from small landowners to large property owners, is responsible for reducing man-caused cumulative watershed effects. The ultimate goal would be to have roads where there was no hydrologic connectivity; hence, ridge roads or upper slope roads with no stream crossings and no connected road drainage structures. That's unrealistic in most areas. **Set a goal of 10% to 15% (or less) connectivity in a watershed or over a road network. Set targets of having 1) no more than 100 feet of connectivity (ideally 50 feet) per connected approach to each stream crossing wherever possible, 2) disconnecting all ditch relief culverts and rolling dips, and 3) surfacing (rocking, paving, etc.) those road reaches that are to remain connected.**

3. STREAM CROSSING CULVERTS

a. Culvert materials and durability

Culvert materials—The selection of culvert material type should be based on a combination of factors that will determine its suitability and longevity for the environment where it will be used. These factors include:

- durability (service life),
- structural strength,
- hydraulic roughness,
- bedding conditions,
- durability and abrasion resistance,
- corrosion resistance,
- expected wildfire frequency, and
- water-tightness requirements.

The pipe material used in a project may also depend on cost, required span, discharge, topography, soil chemistry, and climate.

The four most common culvert materials include steel (including galvanized steel), aluminum, plastic (HDPE) and concrete. Each material has advantages and disadvantages.

- **Steel culverts** are the most common culvert material used in the field and are available in a large range of shapes, diameters, and lengths. They are used in both corrugated pipe and plate forms (e.g., multi-plate culverts assembled by bolting). Corrugated metal pipes (CMP) are constructed from a single piece of galvanized steel and can be custom made in many lengths; 20 to 30-foot lengths are standard and easily transported. Single pipes with a diameter greater than 12 feet usually have special traffic requirements for delivery or shipping.

Steel culverts are strong, relatively lightweight, easy to place, have a moderate service life (estimated 20–50 years) and are readily available. Sections are joined together by metal coupling bands with neoprene gaskets that provide good tensile strength. Their disadvantages include their susceptibility to corrosion (rusting) and abrasion, even with a galvanized coating. They have a shorter life than concrete. Steel culverts are also available as aluminized steel, where an aluminum protective coating is applied on both sides. The aluminized protective coating is more expensive but more resistant to corrosion than galvanized steel. Aluminized Steel can be considered equivalent to galvanized steel for abrasion resistance.

- **Aluminum culverts** are light weight (for a metal), have a long life, resist corrosion (do not rust) and are available as standard corrugated 20' sections. Aluminum culvert pipes are also corrugated and can be constructed as either structural plates or as pipes from a single piece of aluminum. Due to their high resistance to corrosion, aluminum pipes are often used in high corrosion environments such as saltwater applications. However, because of the "softness" of the metal they require special care when backfilling and can be damaged during handling (loading, unloading, etc.). Under similar conditions, aluminum culverts will abrade faster than steel culverts, so aluminum culverts are not recommended in highly abrasive environments with angular bedload and high stream velocities. Aluminum culverts have not been used as much since the mid-1980s because of their comparatively higher cost.

- **Plastic (HDPE) culverts** have the advantage of being lightweight, with the standard 20-foot section manageable by one person, and can be installed by smaller equipment than metal or concrete pipe. Because of its light weight, plastic pipe is easier to ship, handle, and install. Another advantage of plastic pipe during backfill is that it can be cut with a conventional chainsaw. Check locally to compare costs of plastic and steel culverts, as one may be preferable over the other in various size ranges. Currently, because of higher raw material costs, plastic pipe is more expensive than galvanized steel culverts for sizes over 24" diameter, but that could change over time.

Plastic pipe can be corrugated or double sided, although double sided pipe is greatly preferred for its strength. They are corrugated on the outside and smooth on the inside and commonly used for road projects with sizes (diameters) ranging from 24 to 120 inches (10 feet). The most common sizes are 18 to 48 inches diameter. Plastic pipe culverts exhibit good abrasion resistance and are virtually corrosion free (even in low pH soils), permitting a 50-year maintenance-free service life under most conditions. Plastic culverts are now available with steel reinforcing for extra durability and strength. Because of their smooth inside surface, they are hydraulically efficient (i.e., greatly increasing stream velocities in the pipe). Due to increased flow velocities, energy dissipation structures may be needed below steeply sloped HDPE pipes.

Plastic culvert sections are coupled by snap-on or slip-on bell ends, or strap-on coupling bands. These couplers provide adequate pull-apart resistance but are less secure than metal bands used for joining steel and aluminum culverts. Differential settlement under a new culvert can bend them and cause them to separate, so it is important to provide a well compacted foundation. Plastic culverts are problematic in areas subject to burning and wildfires because they can burn and melt while

in the ground if one end catches fire (Figure 87). End treatments using metal, concrete or masonry (flared end sections or headwalls) will limit the possibility of fire damage.

Solid wall HDPE pipe is a special-use culvert employed in trenchless culvert installations (pipe ramming) and a few other situations where strength is critical. This type of pipe is engineered to provide balanced properties for strength, toughness, flexibility, wear resistance, chemical resistance and durability. The pipe can be joined using several conventional methods, but the preferred method is by heat fusion (melting) which produces a leak-proof seal that is as hard as the pipe.

- **Concrete** culverts are strong, resistant to corrosion, resistant to abrasion, and have the longest life span of common culvert materials (about 75 years). Concrete (reinforced) box culverts are commonly used on county- and state-maintained public roads. Circular pipes that are precast in segments and grouted together are sometimes used, but are more commonly employed as low flow drain pipes and sewer lines. Concrete and reinforced concrete pipes are composed of cement, aggregates, and possibly reinforcing material, and are available in circular, arch, and elliptical shapes. Concrete arches are increasingly used for new projects designed for fish passage. The main disadvantages include their high cost, weight, and the requirements for special handling and careful placing. They require rubber O-ring gaskets at joints to prevent leakage. Concrete pipes require a uniform, well compacted bed and backfill because the joints are held together only by friction and are more easily disjoined. Concrete pipes are not as readily available in all areas and typically come in maximum 8-foot sections because of their heavy weight.

FIGURE 87. *This plastic culvert was melted and burned out during a forest fire in central California. In fire-prone areas, metal culverts may be more suitable, or plastic culverts can be fitted with metal inlets and outlets that prevent burning (Pete Cafferata, Calfire).*

TABLE 26. Abrasion and corrosion potential of common culvert materials

Material	Abrasion Potential	Corrosion Potential	Comment
Steel	Low to Moderate	Low to High	Low abrasion potential assuming zinc galvanizing is present and steel is not exposed. Once exposed, steel will corrode in most environments. Corroded steel is subject to accelerated abrasion. Aluminized steel is more resistant to abrasion and corrosion. Coatings decrease abrasion and corrosion potential. Corrosion is high in acidic environments.
Aluminum	Varies	Low	Aluminum generally does not corrode easily. Its abrasion potential is relatively low but highly dependent upon velocity and discharge as well as amount, size, shape and hardness of bedload.
Plastic	Generally Low	Low	HDPE and PVC may experience greater abrasive wear in an acidic environment. Both are relatively corrosion resistant.
Concrete	Low to High	Generally low	Abrasion potential for concrete is dependent upon the quality, strength, and hardness of the aggregate and density of the concrete as well as the velocity of the water flow coupled with abrasive sediment content. There is a correlation between decreasing water/cement ratio, increasing compressive strength and increasing abrasion resistance.

TABLE 27. Estimated increase in metal pipe service life based on metal thickness[1]

Gauge	Multiply life by this factor
16	1.0
14	1.3
12	1.7
10	2.2
8	2.9

[1]Johansen et al., 1997

Culvert durability—Pipe durability and corrosion resistance can be enhanced by several techniques, including protective coatings and treatments (Table 26), as well as increased gage thickness (Table 27). Under most conditions plain galvanizing of steel pipe is all that is needed; however, the presence of corrosive or abrasive elements may require additional protection. The metal pipe invert may be buried in the streambed or under concrete and other lining materials to reduce or eliminate the impact of heavy sediment loads that can cause abrasion and subsequent corrosion. To use a round pipe with a buried invert, the size of the round pipe should be selected so that its capacity will be equivalent to that of the required unburied pipe-arch.

FIGURE 88. *Abrasive bedload transport has worn through this aluminum culvert invert.*

Corrugated steel pipes are typically the most susceptible to the combined actions of abrasion and corrosion, and this has led to a wide range of protective coatings. Some protective coatings meant to protect metal culverts from abrasion and corrosion can be abraded and discharged into the stream and therefore may not be allowed for culverts in perennial, highly abrasive or fish bearing streams. A variety of special coatings have been developed to extend pipe life under various environmental conditions.

Metal pipe may be protected with an asphalt coating to insure corrosion resistance throughout the pipe design life, and research has shown this can add 15 to 35 years of life in certain conditions. However, highly abrasive bedload can remove the asphalt coating relatively quickly, eliminating any corrosion resistance benefit. As an alternative to asphalt protective treatments, the thickness (gage) of corrugated steel pipes can be increased to compensate for loss of metal due to corrosion or abrasion. **While increasing the pipe's metal thickness to offset corrosive or abrasive effects can be specified, coatings are typically more cost effective.**

Abrasion is a metal culvert's worst enemy. Abrasion is the wearing away of pipe material by water carrying sands, gravels, and rocks (Figure 88). This also exposes steel culverts to increased

FIGURE 89.
Steel plates have been welded onto the lower 25% of the invert of this 6 ft diameter galvanized culvert. The steel provides protection against abrasion by coarse bedload transport.

corrosion when galvanized and aluminized coatings are worn off. However, all types of pipe material are subject to abrasion and can experience structural failure around the pipe invert if not adequately protected (Table 26).

A liner or bottom reinforcement utilizing excess structural material is one option to repair or extend culvert life with minimal reductions in flow capacity. **Welded steel plate is one viable alternative for use as an invert lining to extend culvert life (Figure 89). Concrete or bituminous lining of the invert of corrugated metal pipe is a more commonly employed method to minimize abrasion.** Sometimes, an asphalt coating can be used in combination with an asphalt or concrete paved invert. Simple repairs might include protecting the invert of the culvert with reinforced concrete. **Invert linings should cover the lower 25% of the periphery of circular pipes, and about 40% of pipe arches** (Figure 90). Visual examination of the size of the materials in transport in the stream bed and the average stream slopes will give you some idea of the expected level of abrasion and the paving you might need. You can also learn a lot by observing the condition of culvert inverts in similar streams nearby.

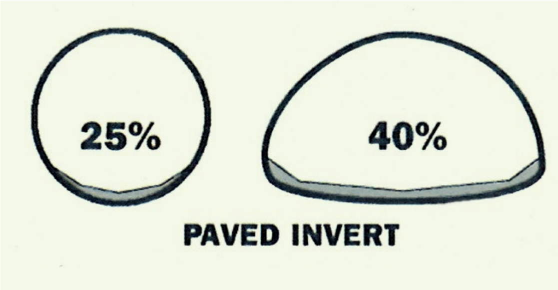


FIGURE 90.
A paved culvert invert can add protection and extend culvert life in an abrasive stream environment without causing much reduction in flow capacity.

Where fish passage is required, culverts are often embedded into the alluvial streambed. This effectively covers the invert during most flow conditions and may help protect the invert from abrasion. However, in streams with significant bedload, placing culverts on flat grades (<3%) to encourage bedload deposition and protection against abrasion may also increase the failure potential of the pipe. The deposited sediment can substantially decrease the hydraulic capacity, ultimately leading to plugging or potential roadway overtopping on the upstream side of the culvert. **As a standard practice, culvert diameters should be increased two or more standard sizes over the required hydraulic opening in situations where abrasion and bedload concerns have been identified and the culvert has been embedded.**

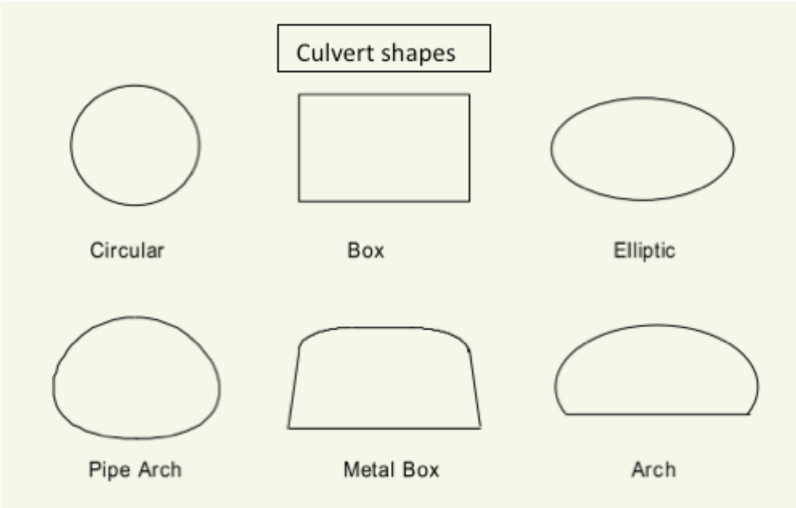


FIGURE 91. *Common culvert cross-sectional shapes. Each shape has advantages and specific uses that reflect their hydraulic capabilities and site conditions. Circular culverts are described by their diameter. Box culvert shapes are described by their width and depth. The other four culvert shapes are defined by a* ***span*** *(widest dimension) and a* ***rise*** *(tallest dimension). The* ***crown*** *is the top of the culvert and the* ***invert*** *is the bottom of the culvert.*

b. Culvert shapes

Selection of culvert size and shape should be based on engineering, stream morphology, biologic requirements, site conditions and economics. For example, migratory fish passage may indicate use of a specific culvert shape (e.g., an embedded, flat bottom arch) that conforms to passage requirements rather than round culverts. While round shapes are strongest, other shapes are sometimes required for specific designs or situations.

Culverts come in a variety of shapes, but the six depicted in Figure 91 are the most common. By definition, culverts are completely enclosed forms, with tops and bottoms. A circular culvert is the most efficient shape because of its higher ratio of cross sectional area to the wetted perimeter, relative to other shapes with identical cross-sectional areas. **Circular culverts are by far the most common culvert shape. They are the most easily manufactured and usually the lowest in unit price (price/foot).** They are available in multiple sizes and materials, with a variety of thicknesses (gage). Circular metal culverts are usually ribbed or corrugated (annular or spiral) to increase strength; are structurally sound with no directional weaknesses; and are easy to handle, load, transport and install.

A narrow but high rectangular culvert is less expensive than a wide, low culvert of the same area. However, **the wider culvert has several advantages that are very important. The wider culvert spreads the outlet flow more; the outlet flow is shallower and has slightly slower velocity, causing less outlet erosion damage. The lower culvert is necessary where clearance is minimal and headwater depths are limited. However, a wide shallow culvert may not be suitable for fish passage during low flow conditions.**

Box culverts are usually made from concrete. Multiple box culverts are sometimes secured together, side by side, and partially embedded in stream channel sediments to act as a vented ford. Unless embedded, box culverts have relatively wide bottoms with shallow flows and are not suitable for fish passage during low flow conditions.

Elliptical culverts are often used where the road fill is shallow and a circular culvert of the correct diameter would not fit. They have a squished cross section and are wider than high. **Because of their shape, elliptical culverts are not as strong vertically as circular pipes.** Their structural strength requires thorough compaction of the bed and the sides of the pipe to provide confining pressures to counter vertical loads of the overlying fill and traffic.

Pipe arches, arches and metal box culvert shapes are designed to provide a wide cross section and a maximum span near the channel bed. Often, these culvert types are embedded into channel gravels to provide a natural substrate channel bottom within the pipe. These culverts are commonly used where fish passage is a requirement. They are also used to maximize culvert width and thereby allow larger floating debris to pass through the structure. While time consuming to assemble, multi-plate culverts are easier to transport and are generally used for culverts that have a diameter greater than 12 feet.

Except when concrete is used, each of these culvert designs are considered flexible pipes. As vertical loads are applied, a flexible culvert attempts to deflect. The vertical diameter decreases while the horizontal diameter increases (Figure 92a). **A flexible pipe will be stable as long as adequate soil support is achieved around the pipe.** When using flexible pipes, the bedding should be shaped to provide support under the haunches of the pipe (Figure 92b). The foundation must be able to uniformly support the pipe at the proposed grade and elevation without concentrating the load along the pipe. Establishing a suitable foundation requires removal and replacement of any hard spots or soft spots that would result in load concentration along the pipe. Bedding is needed to level out any irregularities in the foundation and to insure adequate compaction of the backfill material. In addition to providing structural support for a pipe, the bedding and backfill must be installed properly to prevent piping from occurring (Figure 92c).

Another type of stream crossing structure is sometimes called a bottomless arch culvert, open bottom arch or plate arch (Figure 93) as it is typically assembled on-site from individual plates bolted together to form the arch. In reality, it is an arch supported by lateral foundations and not a true culvert.

A prefabricated or poured concrete foundation is usually used to secure the arch within the streambed. It is actually more like a short span bridge than a culvert, although its "feet" are usually in or alongside the channel bed. It is often used in situations where fish passage is a requirement because the stream flows on the natural streambed beneath the arch, and the bed can contain the same type of channel complexity as upstream or downstream from the crossing. Bottomless culverts can fail by undermining if the concrete footings are not placed on a solid rock base or below the expected depth of scour, and if the streambed is unstable and subject to scour.

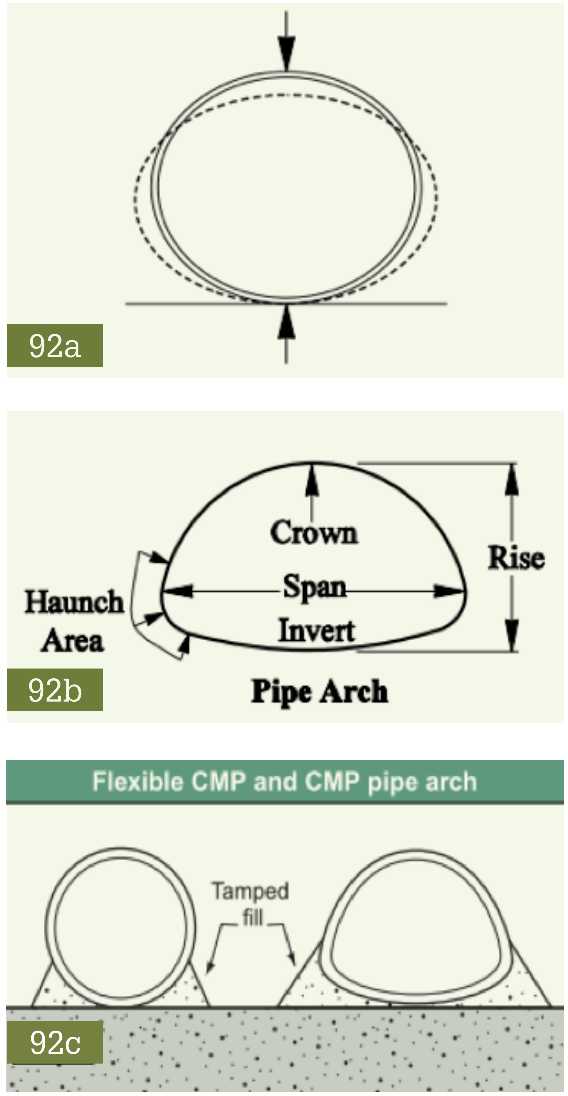


FIGURE 92. *Flexible metal pipes, showing the effects of loads on unconfined shape (92a) and the requirements for proper compaction on non-circular culverts to provide confining strength (92b) and to prevent piping (92c).*

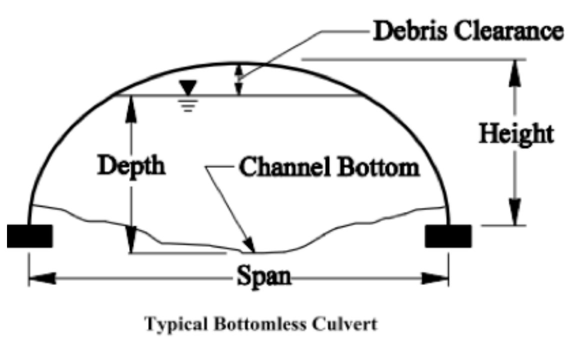


FIGURE 93. *A "bottomless culvert" or plate arch is often used to meet fish passage requirements. Not a true culvert (culverts are closed conduits), it has lateral foundations that support the span and the natural channel bed carries streamflow through the structure.*

FIGURE 94. *The inlet of this 30-inch diameter culvert shows considerable rust where bedload abrasion has worn away the galvanized coating and exposed the steel to corrosion (rusting). A rule-of-thumb for evaluating culvert sizing in the field is if the rust line in a galvanized steel culvert is higher than about 20% of the culvert diameter (i.e., active bedload transport is occurring high up in the culvert), then the culvert is probably undersized. This culvert displays a 50% rust line, suggesting it is very undersized.*

FIGURE 95. *Woody debris does not have to completely plug a culvert inlet to significantly reduce its flow capacity. This culvert is at increased risk of plugging because of the large inlet basin that was excavated and because the inlet is not aligned with the approaching stream channel. These conditions encourage debris to float against the inlet rather than pass through it.*

c. Culvert sizing

Flow capacity is one of the most important factors in stream crossing design, especially when using culverts. Culverts need to be large enough to meet design flood discharge requirements, not just normal flows (Figure 94). Permanent stream crossings to be built as a part of forestry operations in many areas are now required to pass at least the 100-year flood flow for that channel, including debris and sediment loads, even if they are to remain in the channel through only one winter season.[12] However, even a 100-year flood flow design does not mean that a culvert will not fail. **Woody debris and sediment transported down a stream channel can substantially increase the risk and likelihood of culvert plugging and failure occurring** (Figure 95). Stream crossing design should account for the possibility of culvert failure from both flow exceedance and inlet plugging. **However, research has clearly shown that culvert plugging by wood and/or sediment, and not flow exceedance, is by far the most common cause of stream crossing culvert failure** (Figure 96).

Culverts are typically sized using the estimated 100-year design flood flow and a culvert sizing nomograph that relates culvert size to design discharge, culvert inlet type, and headwater depth ratio. Methods for determining the 100-year design discharge include the Rational Method, USGS Magnitude and Frequency Method, and Flow Transference Method (Table 28).

The accuracy of each method is dependent on the size of the design watershed, and available precipitation and runoff data. Prepared culvert sizing tables may already be available for your area where someone has calculated peak flows and appropriate culvert sizes using one or more of these or other methods and culvert nomographs. Weather conditions change quickly, especially in mountainous terrain, so it is often useful and more accurate to perform the calculations and size culverts yourself. Culvert sizing methods are described in more detail in Appendix A.

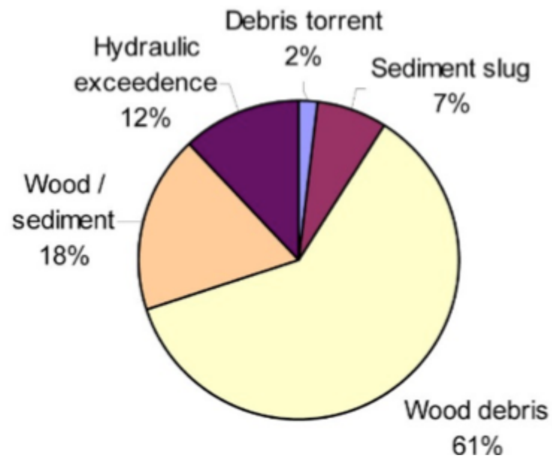


FIGURE 96. *Failure mechanisms for culverts occurring along forest roads in northwestern California associated with storm events with recurrence intervals less than approximately 12 years (Flanagan 2004; n = 57). Note that the specific distribution of failure mechanisms will vary depending on factors, including storm intensity and watershed characteristics. For example, see Furniss et al. (1998) for additional information on failure mechanisms following very large floods in the Pacific Northwest (Cafferata et al., 2004).*

Except for the very smallest of crossings (<5 acres), it is generally not sufficient or adequate to estimate (guess) culvert sizes for stream crossings along forest, ranch and rural roads. Most field personnel have little personal experience or expertise with which to correctly estimate or visualize a 100-year flood flow, and many stream channels may no longer display physical evidence of large floods which may have occurred decades ago.

The culvert sizing methods used to determine culvert size for a given peak flow are based on culvert hydraulic flow capacity, and do not consider the influence of woody debris and sediment. Even small streams have the potential to transport debris and sediment and smaller culverts, such as 12″ or 18″ diameter culverts, are easily plugged with sediment and woody debris. **In addition to invaluable local observations and experience, there are several guidelines or measures that can be employed to reduce the risk of culvert exceedance and/or culvert plugging during peak flow events:**

12 See Appendix C for specific California Forest Practice Rule language for this requirement.

TABLE 28. Methods for calculating the 100-year design discharge.

Culvert sizing method	Suggested watershed area limit	Advantages	Disadvantages	Reference
Rational Method	<200 acres (preferred 100 acres or less)	Commonly used Uses local data	Local precipitation data may be difficult to obtain Accuracy is limited to drainage areas <200 acres	Kuichling, 1889 Dunne and Leopold, 1978 Cafferata, et al., 2004
USGS Magnitude and Frequency Method	>100 acres	Easy to use Equations are tailored to specific geographic areas Designs for rain-on-snow events Required data is readily available	Generalizes geographic areas Accuracy is limited to drainage areas >100 acres	USGS, 2012 Cafferata, et al., 2004
Flow Transference Method	Accuracy limited to distance (climatic differences) between gaged & ungaged streams	Easy to use More accurate than other methods if local stream data is used	Requires >20 years of gaging data Less accurate if ungaged stream is in different location or watershed	USGS, 2012 Skaugset and Pyles,1991 Cafferata, et al., 2004

- Where possible, install culverts whose diameter or span is equal to, or greater than, the active channel width.

- Design culverts for no more than barrel-full capacity (HW/D = 1.0) in the design flow event (100-year flow), provided there is *no* significant floating debris or bedload sediment.

- Design culverts for no more than 2/3 barrel-full capacity (HW/D = 0.67) wherever debris and bedload sediment are likely to be present.

- Alternatively, where debris is present, it has been suggested that culvert diameters be increased one or two size diameters (12 to 24 inches) over the barrel-full design capacity to reduce the risk of plugging; and crossings of small streams should be designed with a minimum 24″ diameter culvert (nothing smaller) to reduce plugging potential.

d. Culvert alignment and length

In the past, forest, ranch and rural road managers often attempted to minimize stream crossing costs by installing the shortest possible culverts needed to take streamflow across the road. These culverts were often installed at a narrow point in the road, and set at a flat gradient, rather than sloping a long culvert down to the base of the fill. Gently sloped stream crossing culverts are easier to install and replace, but they require more maintenance, cause extensive gullying of the fill slope and have a higher likelihood of plugging and washing out or diverting down the road.

Culverts should be aligned vertically with the natural channel. During construction, culverts are generally installed on or close to the natural stream bed so the outlet exits the fill at the level of the natural channel downstream from the crossing (i.e., mimic the natural channel gradient). **Steep channels will have steeply sloped culverts.**

To function properly, culverts should also be installed in-line with the channel's natural orientation. It is best for the road to cross at right angles to the stream channel, but regardless of the road alignment, the culvert should be placed parallel to the natural channel. In this manner, the inlet naturally receives the flow, plugging potential is reduced and flow from the outlet is directed

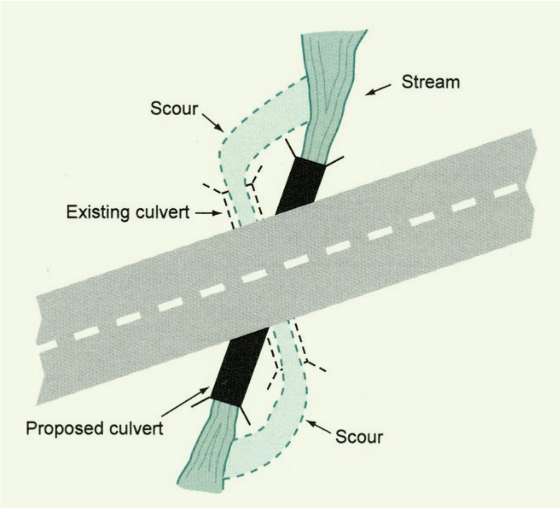


FIGURE 97. *Culvert alignment should be in relation to the stream and not the road. It is important that the stream enters and leaves the culvert in a relatively straight horizontal alignment so streamflow does not have to turn to enter the inlet or discharge into a bank as it exits. This figure shows a redesigned culvert installation that replaces the bending alignment that previously existed. Channel turns at the inlet increase plugging potential because wood going through the turn will not align with the inlet. Similarly, channel turns at the inlet and outlet are often accompanied by scour against the channel banks (Wisconsin Transportation Information Center, 2004).*

back into the natural channel and not against either of the channel banks (Figures 97 and 98).

Culvert length should also be estimated so that correct quantities of pipe will be available on the job site when stream crossings are being installed, and so the culvert can be installed to the base of the fill with the recommended barrel extension lengths (Chapter 5). Culvert length can be estimated based on the slope of the stream channel and the designed width of the road. A procedure for determining the correct length of culvert needed for stream crossings or ditch relief drains is outlined in Appendix E. Culverts that are too short for the crossing cause erosion of the fill and severe sediment pollution in the stream channel.

e. Culvert inlet and outlet treatments

i. Trash barriers and screens Even if a culvert is correctly sized for the design flow, small amounts of debris lodged against the inlet can significantly reduce its flow capacity. Debris may consist of anything from limbs and sticks or orchard prunings, to logs and trees floating down the channel. Silt, sand, gravel, and boulders can also be classified as debris and can partially or completely block culvert inlets (Figure 96). Typically, especially in forested environments, woody debris that lodges against the culvert inlet slows

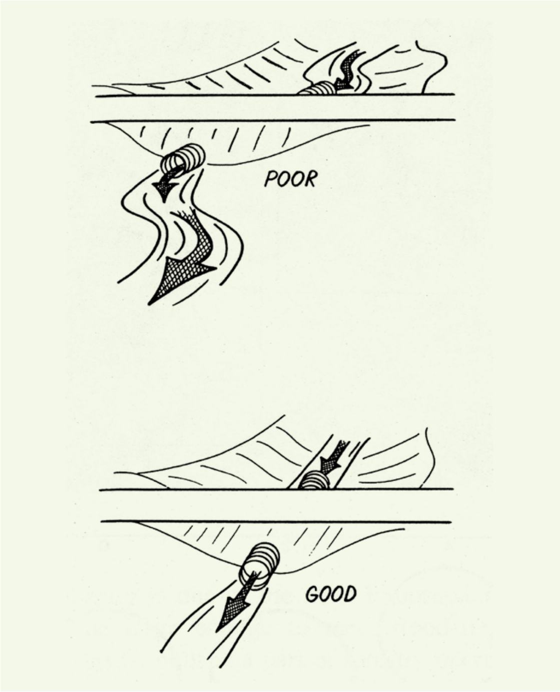


FIGURE 98. *Culverts should be aligned with and placed in the bed of the natural channel so that flow enters and exits the culvert without having to turn or change gradient (USDA-SCS, 1983).*

inlet velocities and sediment drops out of the water column and adds to or completes the blockage. The culvert site is a natural place for these materials to settle and accumulate.

Debris control structures (trash racks) at culvert inlets, and energy dissipaters at culvert inlets and outlets, are key components of stable culvert design, but winter maintenance of these structures is critical for success. The design of these protective structures is varied, and there are as many successful designs as there have been failures.

Debris control is best obtained by some type of grate or filtering structure of vertical or inclined poles dug into and built across the channel just upstream from the culvert inlet (Table 29). Creativity and experience can be used to develop a successful design. Drop inlet, slotted riser pipes have also proven to be effective in trapping debris without allowing the culvert to plug. However, **care must be taken on fish-bearing stream channels to make sure passage is not blocked by such designs.**

Culvert trash racks should not be constructed right over or against the culvert inlet because they can easily plug and, in turn, prevent streamflow from entering the

TABLE 29. Debris classification and appropriate debris control structures[1]

Debris classification	Debris deflector	Debris rack	Debris riser	Debris crib	Debris basin and dam
Light floating debris		✓		✓	
Medium floating debris	✓	✓			
Heavy floating debris	✓				
Flowing debris			✓		✓
Fine detritus			✓		✓
Coarse detritus			✓	✓	✓
Boulders	✓				

[1]San Diego County DPW, 2012

FIGURE 99. *This 6-foot diameter culvert with concrete head- and wing-walls has a trash screen built over the inlet to catch floating debris. The design is flawed because it screens and catches small woody debris that would otherwise easily pass through the culvert. During a flood event, debris will quickly cover the trash screen and effectively plug the drainage structure. Screen bars should be more widely spaced and the trash rack should be installed in the stream channel somewhere upstream of the culvert inlet.*

culvert inlet (Figure 99). **This is a common design flaw seen in culvert inlets on forest, ranch and rural roads everywhere.** If constructed incorrectly, wooden crib boxes or metal grates built around or over the culvert inlet easily become clogged with debris and plug the pipe or significantly reduce its capacity to pass flood waters. **The most common problem with trash racks and screens placed over the culvert inlet is that small debris is often trapped rather than being allowed to pass through the culvert.**

Floating woody debris is one of the most common causes of culvert plugging and stream crossing failure during storm and flood events on forest, ranch and rural roads. Debris barriers and control structures can also be used to reduce the risk that floating debris will adversely affect culvert flow capacity. Both treatments reduce the risk of a culverted stream catastrophically failing. Debris control should be considered where experience or physical evidence indicates the stream transports a heavy volume of floating debris that could plug the inlet. **Not all streams are candidates for debris control structures, but active channels in steep mountainous areas, streams with tall, large volume fills, and stream crossing culverts that show evidence of past culvert plugging are places especially at risk.** Examining the maintenance history of each site is the most reliable way of determining potential problems, but maintenance records for both public and private low volume roads is usually sparse. Landowners, land managers, road managers and maintenance crews sometimes have the best local knowledge of the most problematic culverted crossings.

The most common treatments used to reduce the threat of culvert plugging include culvert upsizing so the culvert can pass larger debris, adding flared or mitered inlets, or constructing debris screens or debris barriers that block large wood before it can reach the inlet area.

Debris Deflectors—A debris deflector is usually V-shaped and designed to deflect large floating debris or boulders carried as bedload in moderate to high velocity streams (usually found in mountainous or steep terrain) that might otherwise be trapped against the pipe inlet (Figure 100). It is located immediately in front of the culvert entrance with the vortex of the V placed upstream to deflect floating debris. **The horizontal spacing(s) of the vertical members should not exceed the diameter of a circular culvert or the smallest dimension of a non-circular culvert.** During large flood flows the culvert inlet is still susceptible to plugging if water and floating debris rises above the vertical members and debris is carried over the structure and into the culvert inlet. The addition of horizontal members on top of the structure can help prevent overtopping. Care must also be taken to ensure that woody debris

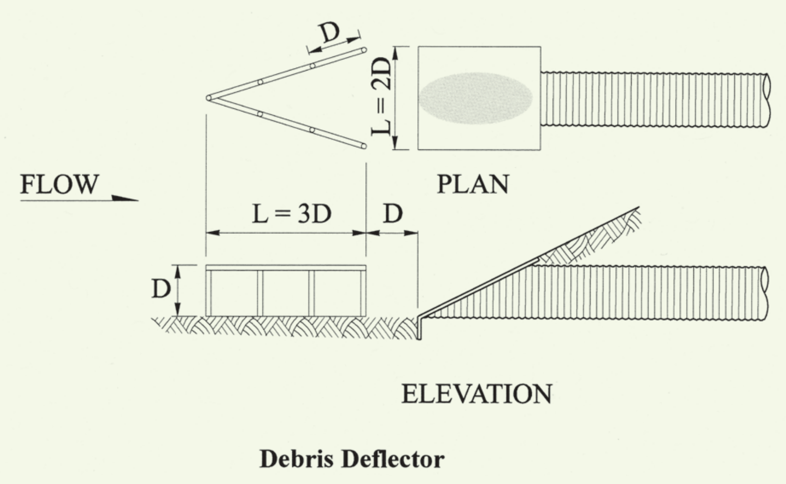


FIGURE 100. *Debris deflector installed in front of a mitered culvert inlet with a sloping headwall. A deflector, by itself, cannot protect a culvert inlet from plugging with floating wood if the pipe is significantly undersized and flow ponds over the top of the deflector. The culvert should be properly sized for the design flow event (WDOT, 2010).*

cannot float around the deflector and lodge against the culvert inlet. Frequent maintenance will be required to remove woody debris.

A recently developed alternative to the multi-post V-shaped debris deflector is a sturdy single-post debris deflector installed immediately upstream of the culvert inlet (Figure 101). Initial performance observations suggest this deflector is effective at turning debris so some can pass through the culvert and capturing the longest materials before the inlet can plug. A single metal post is embedded or pounded into the center of the streambed one culvert diameter distance upstream and directly in front of the culvert inlet. To be effective, it is important to increase the diameter and strength of the post, and the depth of installation into the streambed, because as stream size increases so does the size of the floating debris and the hydraulic forces. If necessary, the post can be strengthened using one or two support bars fastened to the top of the culvert or embedded back into the fill face. The vertical bar should extend at least one culvert diameter above the streambed. Floating debris that hits the post is turned lengthwise and parallel to the stream and culvert so that it will float into and through the pipe. If debris is longer than the culvert is wide, it will be turned and then be wedged between the post and the adjacent stream bank, fill slope, or the outside edge of the culvert. The inlet will remain open. Sediment will also stack up against the retained wood and behind the post, rather than directly against the culvert inlet. As with all styles of debris barriers and deflectors, the woody debris can then be cleaned out by hand or with heavy equipment after the storm is over to restore full channel capacity. **Although experimental, this design has shown promise for protecting all sizes of culvert installations and additional observations, case studies and research is needed.**

Debris Racks—A debris rack is a screening structure placed across the stream channel upstream from the culvert inlet to be protected

FIGURE 101. *Single post debris deflector placed one culvert diameter in front of the culvert inlet is intended to turn short debris parallel to the stream flow, so it can pass through the culvert, while trapping long debris against the banks before it can plug the inlet.*

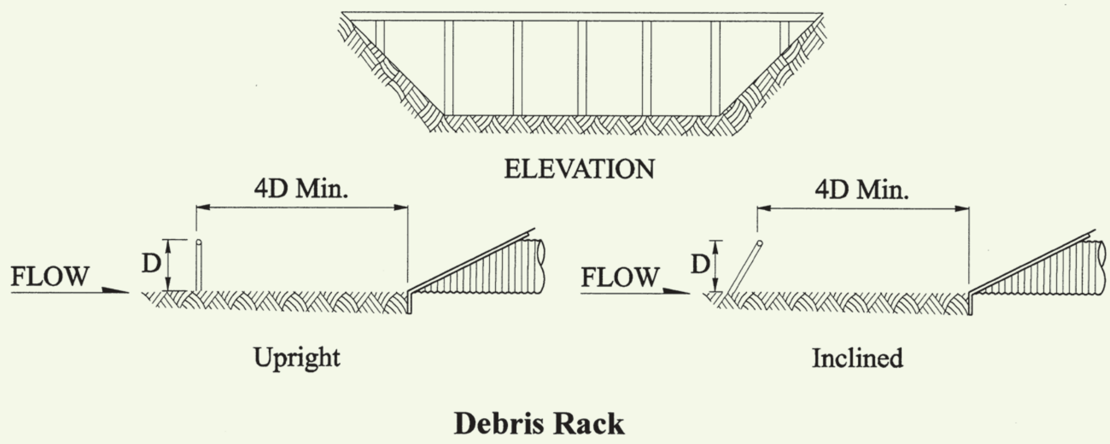


FIGURE 102. *Multi-bar debris rack with vertical or sloping bars embedded in or wedged against the streambed. Bars should be spaced one culvert diameter apart (WDOT, 2010).*

(Figure 102). It should be constructed with screening bars in an upright or downstream-inclined position attached to a horizontal support member. **The bars should be spaced at approximately the diameter of a circular culvert or the smallest dimension of a non-circular pipe.** The intent is to allow smaller debris to pass through the screen and through the culvert inlet while screening and retaining all longer pieces that would be more likely to plug the inlet.

Debris racks should be placed far enough away from the culvert entrance so that debris will not block the pipe itself and yet not so far that falling limbs and other debris sources could enter the channel between the debris rack and the culvert (Figure 103). Floating debris and sediment backed up behind it will frequently be trapped behind the rack and require cleaning after storm events (Figure 104). Preferably, there should be access for work crews and/or a backhoe to clean it and perform repairs. Like debris deflectors, debris racks trap most of the floating wood in the

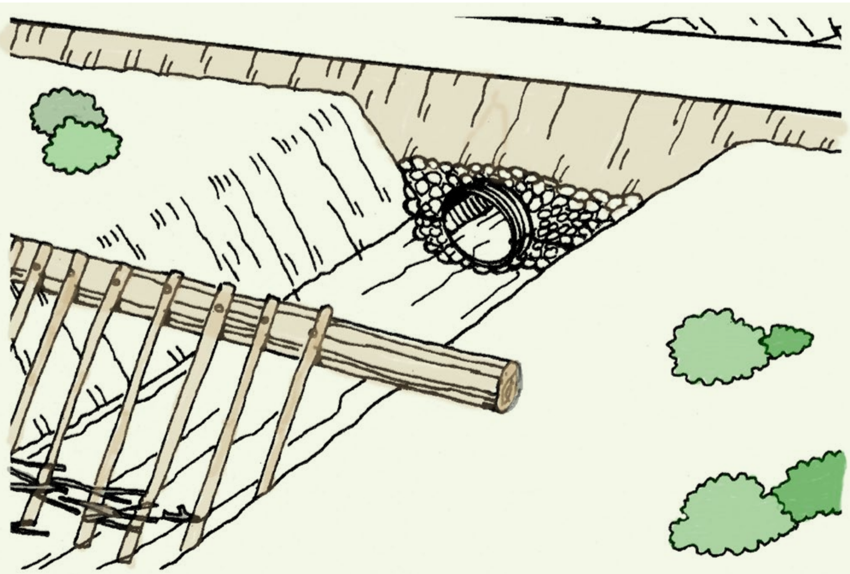


FIGURE 103. *Sloping debris rack on a non-fish bearing stream channel (Keller and Sherar, 2003).*

FIGURE 104. *The most effective trash rack or screen is one placed across the channel slightly upstream of the culvert inlet, with the spacing of the vertical posts approximately equal to the span or diameter of the culvert. Closer post spacing catches too much debris, and wider spacing lets large debris through that could plug the culvert inlet. The 4 posts on this debris rack are a little too closely spaced and one more post should be added to each side to prevent flanking during a flood event.*

FIGURE 105. *In larger streams, debris racks may need to be placed farther upstream from the culvert inlet. Limbs and branches floating down the channel are caught by the screen, but flow will back up and flood around the structure (as in this photo) if it is not extended into the bank. Debris racks or screens need regular maintenance to remove the accumulated debris. They should be made of durable metal posts and I-beams sized to resist the expected stresses and sunk deeply into the streambed for long term, secure installations.*

stream and will therefore require regular maintenance to prepare them for each storm event.

Debris control devices are often unsightly and expensive and they often require considerable maintenance after each flood occurrence (Figure 105). If the storage capacity of the debris trap is too small for a major storm, water may be diverted over or around the debris barrier and into the culvert entrance causing additional channel bank erosion and damage from stream crossing failure. Regardless, they can save a large stream crossing fill from failing, prevent loss of access and save thousands of dollars in reconstruction costs.

ii. Culvert Inlet Treatments The type of end treatment used on a culvert inlet depends on many interrelated and occasionally conflicting considerations. They can be designed to increase culvert flow capacity and to provide some protection against culvert plugging. The designer must evaluate safety, debris capacity, hydraulic efficiency, scouring, and economics against the potential beneficial effects the end treatment might have on stream crossing stability.

The most common inlet treatments include the standard projecting barrel along with mitered inlets that are cut to the same slope as the adjacent fill, and flared inlets that are attached to the barrel of a standard culvert; each with or without rock armor along the fill slope (Figure 106). Flared inlets are available for most culvert shapes and culvert materials, but they are usually more expensive than mitered inlets.

Armor is also commonly used around the inlet and outlet of culvert pipes, where the ends emerge from the fill slopes (Figures 79,

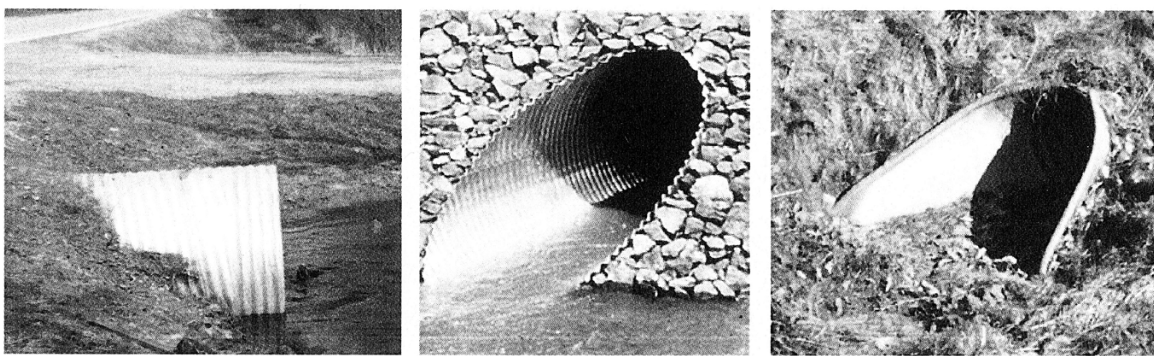


FIGURE 106. *Three common types of culvert inlet treatments include: projecting barrel, mitered or beveled inlet, and tapered or flared inlet. The most common, least costly, but least efficient inlet is the projecting barrel inlet.*

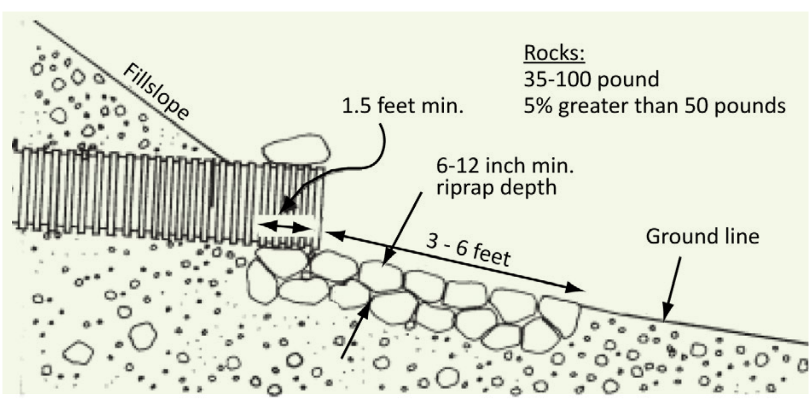


FIGURE 107A. *Riprap armor at culvert outlet (Modified from: Kellar et al., 2011).*

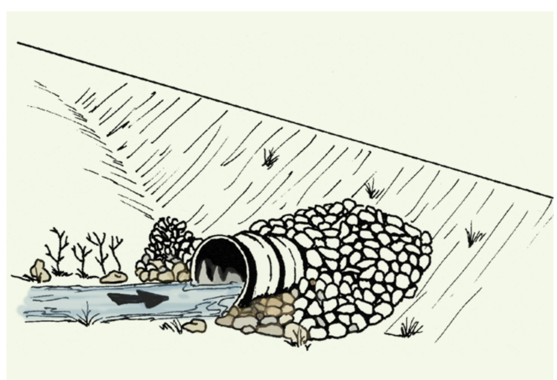


FIGURE 107B. *Riprap armor at culvert inlet (Keller and Sherar, 2003).*

106, 107a and 107b). This armor serves to protect the culvert from erosion during high water (at the inlet) and from splash erosion (at the outlet). Placed at the base of the slope it also serves to trap sediment that is eroded from newly constructed stream crossing fills until they revegetate and stabilize.

Projecting Ends—A projecting end is a treatment where the culvert barrel protrudes out of the embankment (Figure 108). It is by far the most common type of inlet configuration and works well for almost all stream channels. The primary advantage of this type of end configuration is that it is the simplest and most economical of all treatments. Projecting ends also provide excellent strength characteristics since the pipe consists of a complete ring structure out to the culvert opening. The simplest and least expensive way to fortify a projecting culvert is to apply rock armor to the fill slope around and above the inlet (Figure 107b)

There are several disadvantages to projecting ends. For metal, the thin wall thickness does not provide flow transition into or out of the culvert, significantly increasing head losses and reducing flow capacity. The projecting inlet is also considerably more susceptible to plugging with floating debris or sediment, but this can be addressed with the installation of a debris deflector.

Tapered and Mitered Inlets—A **tapered inlet** is a flared culvert inlet with an enlarged face section and a hydraulically efficient throat section (Figure 109). It can be a side tapered inlet (where the culvert widens at the inlet) or a slope tapered inlet (where the bed slope increases into the culvert inlet). Tapered inlets improve culvert performance (discharge capacity) by up to 25% for side tapered culverts inlets, and up to 100% for vertical tapered inlets, by providing a more efficient control section (the throat). The wing walls deflect or trap large floating debris before it can plug the inlet and the concrete floor provides for a smooth surface that encourages rocks and sediment to pass through the culvert rather than be deposited at the inlet.

A **mitered inlet** consists of cutting the end section of a projecting culvert at an angle to match the embankment slope surrounding the culvert, thereby significantly increasing the effective area of the culvert inlet opening (Figure 106). It is relatively easy to either retrofit an existing projecting inlet and/or convert it to a mitered configuration.

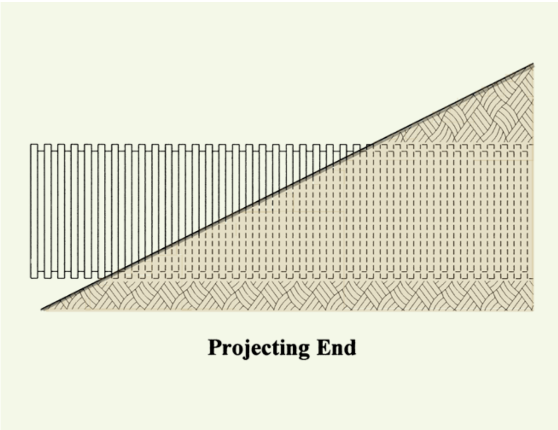


FIGURE 108. *The projecting barrel inlet is the least efficient but the strongest, least costly and most common culvert inlet type.*

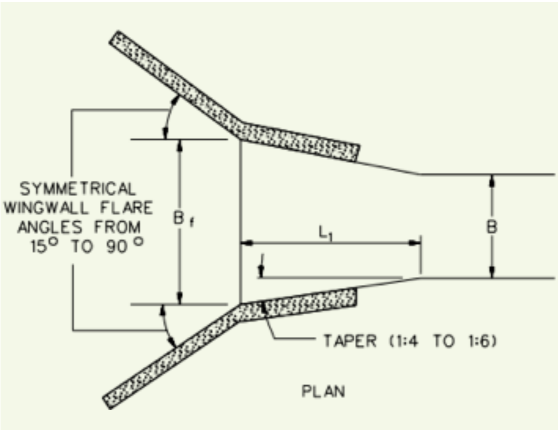


FIGURE 109. *Side tapered culvert inlet with wing walls added.*

A mitered end provides a larger, hydraulically more efficient opening than a projecting end, provides some measure of protection against plugging with floating organic debris, and is relatively cost effective to make. **Mitered ends should be considered for culverts about 6 feet in diameter and less, but can be constructed on larger diameter culvert ends if they are reinforced with a headwall, slope collar or fill slope armoring up to the height of the inlet** (Figures 103 and 107b). Unless they are of heavy gage steel, unsupported miters on larger culverts can weaken the inlet structure and make it susceptible to deformation during high flows.

The standard mitered end section should not be used on culverts placed on a skew of more than about 30 degrees from the perpendicular to the centerline of the road and fill. It is critical to have the mitered inlet be within about 6 inches of the fill face; a mitered pipe extending 1–2 feet has lost its hydrologic efficiency advantage by 25 to 50%. Wing walls may be needed to turn flow into the mitered inlet. Cutting the ends of a corrugated metal culvert structure to an extreme skew or miter to conform to a gentle embankment slope reduces the strength of the end section, in comparison to a round pipe. Headwalls, riprap slopes, slope paving, or stiffening of the pipe may be required to stabilize the ends.

Flared End Sections—A metal flared end section, or flared inlet, is a very economical and easily installed, manufactured culvert end that is bolted to the culvert barrel and provides a simple transition between the culvert barrel and the streambed (Figure 110). Flared inlets increase culvert capacity the same as side tapered inlets (from 25% to 50% greater flow capacity than a projecting barrel inlet) by allowing flow to smoothly constrict into the culvert entrance. **Flared culvert inlets are often installed on culverts where the streams exhibit high rates of sediment transport that could otherwise cause culvert plugging.** The sheet metal bottom provides a very smooth surface at the inlet where sediment and rocks cannot come to rest and are easily flushed onto and through the culvert. Flared culvert inlets also act like mitered inlets by either wedging and trapping woody debris before it can plug the inlet, or allowing longer pieces of wood to ramp up over the inlet while streamflow enters the culvert barrel.

Flared end sections are typically used only on circular pipe or pipe arches. Flared ends are generally constructed out of steel and aluminum to match the existing culvert

FIGURE 110. *This 52-inch diameter culvert has been fitted with an attached flared inlet. Bolt-on, flared culvert inlets are available for most sizes and shapes of culverts, as well as for most culvert materials. The side flare improves hydraulic efficiency of the inlet, and the sheet metal bottom ensures that sediment is not able to accumulate or potentially plug the culvert entrance. The funneled sidewalls act to turn debris so it can enter the culvert, and its sloping sides causes larger debris to ramp up above the inlet, thereby reducing it plugging potential.*

material. However, either type of end section can be attached to concrete or plastic pipe with special attachments. HDPE plastic inlets are available, but less common.

A flared inlet is usually the most feasible option in smaller pipe sizes and should be considered for use on culverts up to 48 to 60 inches in diameter. For larger diameters, end treatments such as beveled (mitered) openings, prefabricated or poured concrete headwalls, wing walls and aprons may be more economical than the flared end sections.

Headwalls and Slope Collars—A headwall is a rock, masonry or concrete frame around a mitered or barrel culvert inlet (Figure 111). It provides structural support to the culvert and eliminates the tendency for buoyancy. It also increases the hydraulic efficiency of the inlet, especially compared to projecting barrel inlets. A headwall is generally considered to be an economically feasible end treatment for metal culverts that range in size from 6 to 10 feet, but can be used on smaller culverts to shorten the fill slope and improve hydraulic efficiency (Figure 111). Metal culverts smaller than 6 feet diameter generally do not need the structural support provided by a headwall. Headwalls are structurally beneficial on plastic culverts larger than 3 feet. A typical headwall on a mitered culvert is shown in Figure 112.

iii. Snorkels and risers **The objective of culvert snorkels and riser inlets is to prevent sediment and floating debris from plugging culverts and causing subsequent overtopping, fill failure or stream diversion.** Risers are also used to trap sediment, reduce sediment concentrations and sediment discharge, and protect downstream water quality. They are often used in recently burned watersheds where you expect significant soil erosion, and sediment and debris transport during a runoff event. They might also be used in retention basins downstream from a large earth moving project where unavoidable erosion and sediment transport is expected to enter the stream. Risers and snorkels are sometimes used where storm patrols and maintenance is uncertain and they serve as safety valves to alleviate the effects of culvert plugging.

FIGURE 111.
This concrete vertical headwall was installed on a ranch road stream crossing. The headwall increases culvert efficiency compared to a projecting barrel inlet, but is still prone to plugging by floating organic debris.

FIGURE 112. *This sloping concrete headwall was constructed around a mitered culvert inlet. The mitered headwall inlet improves culvert inlet efficiency, and the concrete counters the potential buoyancy effects a weak plastic pipe would be subject to at peak flow events.*

Snorkels are designed to provide a second inlet into the stream crossing culvert that will be used only when and if the main culvert inlet becomes plugged with sediment or woody debris (Figure 113). If that occurs, rising waters will eventually pour into the snorkel riser pipe through the slotted sides or into the open top. Snorkels are installed as a vertical riser welded over the top of the existing stream crossing culvert, usually at least several feet back from the current culvert inlet.

It is preferable for the vertical snorkel riser to have the same diameter as the main culvert so that it can accommodate design flood flows if the main inlet becomes completely plugged. The snorkel extends vertically usually 5 to 8 feet, but no more than about half the headwall height, and terminates in an open pipe. Snorkel risers may or may not be slotted along their length to allow for inflow when the main culvert plugs and water rises. The top of the vertical riser on a snorkel pipe is often screened for safety purposes and to prevent plugging by floating debris. However, this screen also increases the likelihood that the riser will be plugged too.

FIGURE 113. *The slotted culvert inlet snorkel on this small stream crossing culvert is designed to provide emergency overflow protection in case the main culvert becomes plugged with debris. Unfortunately, because of the small spacing of bars on the top of the riser, the snorkel could also become plugged with floating debris. To be effective, the top inlet or "glory hole" at the top of the snorkel riser must be lower than the adjacent road and ditch.*

In contrast, drop inlet riser pipes are usually extended vertically from a 90 degree elbow fitted over the culvert inlet. The drop inlet riser should be the same diameter as the stream crossing culvert, but no smaller than 36″ diameter to provide the needed flow capacity and to prevent plugging. Very tall risers (over 8 feet) in larger drainages may require anchors to keep them from moving with the expected currents and flow velocities. Risers can also be toppled by high flows or debris flows if they are not well secured. However, **risers should not be higher than about half the fill height to prevent developing hydrostatic head and saturation in the fill.**

Risers take advantage of the basin behind the fill to store both water and sediment. Slotted riser pipes function to encouraging temporary ponding of water while sieving out most debris and transported sediment (Figure 114). A riser pipe is usually slotted over its vertical length to allow water passage during rising water levels. Slotted risers are open at the top or the top has a debris screen for safety that is also intended to prevent plugging of the riser. Sediment that accumulates in the basin behind the road fill will need to be excavated and hauled away during the dry season so the basin has full capacity to trap sediment the next wet season.

Risers do not increase the flow capacity of the stream crossing culvert. It is critical that the opening at the top (the glory hole) is not plugged with floating debris as this is the only significant opening from which to release flood flows into the culvert. If it plugs, water levels may continue to rise until they overtop the road fill and erode the crossing.

Risers should only be employed in specific circumstances and settings. Risers are sometimes used on small streams that carry excessive sediment loads and pollute downstream areas; where trapping and removing the sediment is desired. Risers are sometimes used to protect transportation infrastructure on roads with large fills where access and road use must be maintained.

FIGURE 114. *This culvert inlet in a recently burned watershed has been fitted with a slotted riser so that flood flows pond in the large inlet basin, the stream drops its coarse sediment load, and flood waters gradually recede. If ponded streamflow reaches the top of the riser pipe it will pour into the top opening. Basins with slotted risers are sometimes used where sediment delivery from upstream areas is expected to be high (e.g., after a wildfire) and sediment needs to be retained to protect downstream areas. All sediment basins need to be intermittently cleaned of accumulated sediment to maintain needed capacity.*

However, by design, risers reduce the hydraulic efficiency of the culvert, so they may increase the vulnerability of some culverted stream crossings to excessive ponding and potential overtopping. Risers cannot be used in areas where fish or other aquatic passage is required.

f. Emergency overflow culverts

In situations where a culvert is placed at the base of a very high fill (over 20 feet) on a stream with significant debris problems, it may be necessary to install an emergency overflow or bypass culvert in case the main culvert becomes plugged with debris. A plugged culvert in a high embankment can impound a tremendous volume of water. The sudden failure of a high fill is possible, and this could result in either catastrophic road failure (via deep gullying of the fill), or a debris flow traveling great distances downstream. The overtopping and failure of large stream crossing fills can overwhelm downstream channels, destroy aquatic habitat in valuable streams and rivers, and potentially endanger downstream property owners and roadway users. **In deep fills an emergency bypass culvert will limit the level of impounded water behind a stream crossing fill to a safer level, so the fill is less likely to become saturated or overtopped. This is a risk reduction measure that provides significant protection.**

Emergency overflow culverts should be installed on large, deep stream crossing fills where the main culvert at the base of the fill is either 1) too difficult to clean and maintain, or 2) undersized, but funds are not available to properly upgrade it to current design standards. The reach of the excavating equipment may dictate the maximum depth to which the overflow culvert can be installed. In general, the overflow culvert should be installed half way down the fill from the road surface or, where possible, no more than 5 to 10 feet above the crown of the main culvert (Figure 115). Ponding should be minimized to the extent possible. If the fill is very deep, the emergency overflow pipe should be installed by trench excavation about 15 vertical feet below

FIGURE 115. *Where stream crossing culverts may not be adequately sized for the design flood flow, and they are not scheduled for immediate replacement, they can be fitted with more efficient entrances (such as the headwall seen here) as well as emergency overflow pipes installed higher in the fill. The overflow pipe provides relief during the large flow events or when the main culvert becomes plugged with debris. This overflow culvert experienced flood flow during the first winter after it was installed (See Figure 111).*

the elevation of the road surface, so it can be cleaned using a backhoe during a storm event.

Bypass culverts may also be used on stream crossings where it is not feasible or desirable to construct a critical dip at the crossing fill (perhaps the road grade is too steep for a functional dip), thus serving as an alternative to a critical dip. Although emergency overflow culverts may not be as effective at preventing stream diversions as a dipped crossing fill, they still offer increased protection to overtopping and/or stream diversion, at a greatly reduced cost, whenever the main culvert becomes plugged with debris. **Ideally, a stream crossing fill with an emergency overflow (bypass) culvert should also have a dipped road fill, or be fitted with a critical dip, so there are multiple layers of potential protection against catastrophic stream diversion or crossing failure.**

There is no magic formula for calculating the proper size (diameter) of an emergency overflow culvert. A reasonable estimate is that it should be about 50 to 60 percent of the diameter of the main culvert, and not less than 36 inches diameter for streams with large fills. The large ponded reservoir behind the fill will significantly reduce and broaden the timing of peak flood flows in the stream channel, so design-size culverts are not likely to be needed. If possible, the bypass culvert should be placed out of the main flow path so that the risk of it also plugging due to floating debris is minimized. In addition, the overflow culvert must be fitted with an anchored, full round downspout on the outside fill face to carry flow to the base of the fill slope and back into the natural channel without causing fill slope erosion.

4. BRIDGES

Bridges almost always have less environmental impact than culverted stream crossings. They usually provide much better clearance for extreme floods and floating debris, and bridges are the ideal crossing structure for meeting fish passage requirements. **The cost of portable bridge installation is now highly competitive with the installation of plate arches and large size culverted (filled) stream crossings in many situations.**

Bridges may be temporary or permanent. Temporary bridges can be constructed across a stream channel, and then removed upon the completion of operations. Because little soil is disturbed in or along the stream channel, the crossing site can easily be returned to its original condition. **Surplus railroad flatcars are the most common, low-cost alternative to conventional bridge construction used for forest and ranch roads.** They can also be easily hauled on low-boy trailers from site-to-site and require little preparation prior to installation.

Railroad flatcars can also be left in-place and used as permanent bridges (Figure 116). The bridge abutments may be made more permanent by the use of precast or poured concrete supports. Permanent bridges were once commonly constructed out of log stingers (large diameter logs extended across the stream channel), but this type of bridge is difficult to engineer and large logs are hard to find. Heavy duty portable bridges are now constructed of prefabricated steel I-beams with a steel or concrete driving surface and pre-made abutments that can be lowered in place (Figure 117). Portable, pre-fabricated, truss bridges, more commonly known as Bailey Bridges, are also commonly used and can be used for both temporary and long term installations.

Bridges used for commercial hauling and public vehicle traffic typically require an adequate engineering design and a qualified structural engineer should be consulted. Private roads built or converted for use to access homes or residential developments may also require

FIGURE 116.
Low cost railroad flatcar bridges can be used for temporary crossings of incised stream channels, or they can serve as permanent watercourse crossings. This 65-foot bridge spans the entire channel and was placed on large log abutments. The sideslopes have been protected with heavy rock riprap, and the natural channel width has been maintained through the crossing.

engineering certification. In wildland areas those bridges must be capable of supporting fire trucks, water trucks, heavy equipment and other emergency vehicles. Most public roads, even low volume roads in state and federal forests, are required to have an engineering design for bridges, no matter how few cars use it or how light the vehicles are. **At a minimum it is wise to have a qualified and experienced structural engineer certify a bridge's weight bearing load limits prior to installation, and to post that load limit at the entrances to the bridge.**

If the bridge is prefabricated it has been constructed and delivered with known specifications. If you are using a refurbished flatcar, it may have unseen structural weaknesses from an earlier accident and should be inspected.

Not every stream crossing is equally suited to bridge installation. Generally, bridges should be installed at right angles to the channel with enough clearance beneath the structure to pass the design flood flow (including floating organic debris—usually considered to be 3 feet of freeboard). Incised stream channels with relatively flat or low gradient approaching slopes are well suited to bridges. **Wherever possible, the stream channel should be spanned without using center supports that could alter channel capacity or be subject to channel bed scour or floating debris during flood events. Abutments should be placed well out of the flood zone of the stream, and**

FIGURE 117.
This 50-foot bridge is constructed from steel I-beams spanning the channel and secured to the slopes on either side of the channel using steel sheet pile abutments. I-beam bridges can be constructed on-site or they can be specified, prefabricated and assembled elsewhere, and then shipped and installed as a complete unit.

they should not constrict the natural channel's flood capacity. Abutment areas exposed to flood waters should be armored to protect them against erosion, but the placed armor should also not constrict the channel cross sectional area and flood flow capacity. Finally, the surface of the bridge should be slightly elevated above the adjacent road approaches to ensure the approaches are hydrologically disconnected.

Because bridges are generally straight and fairly narrow, all the vehicle turning needed to cross the channel must be incorporated into the approaching road segments. Crossing deeply incised stream channels with steep sideslopes may require extensive excavation (and endhauling) of material from the approaches before a bridge can be installed across the channel. One method of avoiding some excavation is to install dual, side-by-side flatcar bridges, or double wide I-beam bridges so that some vehicle turning can be performed on the deck of the bridge, or to utilize special construction techniques which allow some turning on the structure (Figures 118a, 118b).

The simpler, less expensive bridges are usually less than 100 feet long. For example, railroad flat cars generally come in standard lengths of about 55 feet and 90 feet. It is important to be sure the bridge is able to support the design loads that

FIGURE 118A. *This railroad flatcar bridge has been structurally modified to allow for some truck turning on the bridge deck. Deeply incised stream channels with steep sideslopes would require extensive hillslope excavation if a straight approach was utilized.*

FIGURE 118B. *Turning on the bridge can also be accomplished by using a double-wide flatcar bridge (two flat cars welded together), where the bridge width is sufficient to accommodate some turning by trucks with long trailers.*

will be passing over the road. Longer bridges may require added superstructure supports, or a center pier to support the extra length (Figure 119). Where such complications are present, an engineer should be consulted before fabricating and installing a bridge structure.

5. ARMORED FILLS

An armored fill crossing is built to convey stream flow directly across the roadbed and down an armored fill slope to the natural channel below (Figure 120). A vented porous rock fill is a special case of an armored crossing, where most low discharge streamflows pass through a porous fill rather than over the road surface. Armored fill crossings and porous rock fills are not technically ford crossings. Ford crossings are built directly across the natural streambed in low gradient settings and do not contain any road fill material. As stream gradients increase, it is impossible to build a stable roadbed across the stream channel without raising up the road with fill materials for a level or dipped driving surface into and out of the crossing.

Armored fills—Generally, an armored fill crossing is intended for low–volume traffic areas, such as ranches, seasonal logging roads, utility access routes, open space districts, and parklands. Armored fills are a good design for ephemeral and intermittent streams when the majority of traffic will be crossing during low flow or dry conditions. They should not be built in perennial streams or in fish-bearing streams. When designed and properly built, armored fill crossings are a good option for a low maintenance, remote access routes. If rock armor is locally available they will be less expensive to install than culverts and bridges, and they require less frequent inspection and maintenance.

Constructing an armored fill crossing involves a multi-step process (Figures 121a through 121f). In general, armored fill crossings are constructed with a wide dip through the road

FIGURE 119. *It is important that all bridges used to transport vehicles and equipment be properly designed or evaluated by a structural engineer before they are put into use. This long, truss-reinforced bridge was fabricated from two 90-foot long railroad flatcars with a center pier support that can be folded up under the bridge during winter flood flows. The center pier must be put down to haul heavy loads across the bridge.*

FIGURE 120. *This armored fill crossing of a steep, ephemeral stream was constructed to provide a low maintenance crossing. The crossing has been deeply dipped to reduce the volume of road fill and to eliminate the potential for stream diversion. The fill slope has been heavily armored through the axis of the crossing to contain flood flows and prevent downcutting. Armored fills cannot be used on fish bearing streams.*

FIGURE 121A. *The following photos depict the typical steps for constructing an armored fill. The original undersized, perched culvert on this intermittent stream was prone to inlet plugging and outlet erosion and it was located on a road that received only intermittent maintenance.*

FIGURE 121B. *In the first step, the stream crossing culvert is removed and the fill is broadly dipped out in a U-shape using a dozer. The dip must have enough capacity to pass the 100-year design flow without diverting. Spoil material is either endhauled to a stable disposal site, or it is bladed down the road approach(s) where it will not erode and enter the stream. Some fill is left in the crossing so vehicles will have a level roadbed to cross the channel.*

FIGURE 121C. *An excavator or backhoe is used to dig a broad keyway across the base of the fill, where the fill intersects the natural channel, and another broad keyway at the top of the fill, where the top edge of the road surface is planned. The largest rock goes in the lower keyway, and coarse armor is also placed in the upper keyway across the full width of the design spillway where streamflow will flow over the fill and down the armored fill slope. Filter fabric, or a filter layer of small rock, is placed on the underlying soil to prevent erosion or winnowing of soil beneath the armor.*

FIGURE 121D. *Well graded rock armor is then backfilled into the structure and spread across the breadth of the U-shaped stream crossing, and about one-third the way up the roadbed, so that streamflow will only flow over or come in contact with resistant armor material. The armor must be spread and compacted across the design width of the expected flood flow channel width so peak flows will not flank the armored structure.*

FIGURE 121E. *Two weeks after this armored fill was constructed, a storm flow event occurred and the structure maintained its function and integrity. The road approaches had not yet been compacted or surfaced with road rock.*

FIGURE 121F. *The same armored fill as it appeared after the first winter flood flows. No maintenance was required to reopen the road. It is also clear that no stream diversion is possible at this stream crossing site, and the volume of fill within the crossing has been reduced to the minimum amount needed to maintain a relatively smooth driving surface on this low volume road.*

and a riprap armored spillway. The first step involves removing any existing drainage structures (e.g., culverts or buried logs). A large "U" shaped dip is then constructed through the crossing that is wide and deep enough to accommodate the expected 100-year peak storm flow and to prevent stream diversion.

A general rule of thumb is that the width of the armored channel at the outboard edge of the dipped road should be at least 5 times the estimated design peak flow wetted perimeter in the upstream natural channel, and the depth should be at least 1.5 times deeper than the average flood flow depth in the natural channel. Thus, a natural stream channel with an estimated peak flow width of 6 feet and depth of 1.5 feet should have an armored fill that is at least 30 feet wide and 2.5 feet deep at the outboard edge of the road crossing. This is intended to keep flood flows confined within the armored portion of the dipped crossing. When constructing an armored fill, these estimates should be tailored to your particular setting.

Next, a trenched keyway prism is excavated into the outer third of the roadbed and down to the base of the fill. It needs to be wide enough to contain the design 100-year flood flow. A keyway slot is then dug across the channel at the base of the fill to hold anchor rocks. Another keyway slot is dug across the outer edge of the roadbed, where large rock will be placed to prevent headcutting into the road prism. The keyway slots are first packed with rock armor that will help hold upstream armor in place. The largest armor pieces will be placed in the keyway at the base of the fill and slightly smaller pieces in the keyway slot at the outboard top edge of the road's fill slope. Well graded rock armor is then backfilled into the excavated prism areas on the outer third of the roadbed and on the fill face.

Riprap sizing for armored fill crossings requires considerable professional judgment, as well as the utilization of published empirical methods that incorporate existing stream channel conditions, such as stream channel slope and estimated discharge at high flows. Because armored fills are similar to rock chutes, in that they are typically constructed on steeper streams with more turbulent, impinging flows; the ARS rock chute design technique is a good method for rock size determination. This method is outlined in the National Engineering Handbook: Technical Supplement 14C: Stone Sizing Criteria (USDA-NRCS, 2007). Most riprap sizing techniques only design rock armor for slopes less than 40% and therefore when designing on steeper slopes it is important to apply a factor of safety of 1.1 to 1.5 to rock size, depending on site conditions.

If soils are fine grained it will be necessary to install geotextile fabric in the keyways prior to backfilling with armor. The final road shape through the armored fill crossing should be a broad "U" shaped dip with a flat gradient from the inboard to outboard edge of fill. The flat road gradient is important to prevent the initiation and headward migration of rills or a small gully through the road fill.

Other structures, including gabion baskets, jersey barriers, concrete walls, and logs have been used for the construction of "armored fill" crossings. These structures are typically placed vertically at the outboard edge of the road and create a cascading waterfall to the channel below. Any such grade control structures must span the width of the design flow and have a stream-centering spillway sufficiently sized for the design discharge. It is important that the structures are properly placed and embedded in the channel to prevent undercutting and failure of the crossing, and incorporate rock armor energy dissipation at the base in order to prevent scour and undercutting. Although these structures may seem like a "quick, cheap fix" they are not recommended as a stable support for armored fill crossings and typically require regular maintenance and monitoring. These structures

should only be used in low-gradient settings with low stream velocities, and minimal fill.

Vented fills—A porous rock fill crossing (a vented fill) is a specialized type of armored fill crossing that is useful in crossing steep stream channels that are prone to debris flows or torrents. They are constructed of coarse rock and transmit low water streamflows through embedded culverts and through their porous, coarse rock fills. Higher streamflows that exceed culvert and porous rock capacity are carried over the hardened top and downstream fill face of the armored fill.

The same basic steps are used to construct a vented fill, except that a porous rock fill crossing is usually excavated deeper into the road (e.g., ½ the road is excavated) and backfilled with the largest (D_{95}) angular, well graded rock available. This type of armored fill crossing is intended to be porous and pass water through the fill. Over time, the voids in the large rock armor will be silted-in so that it becomes impermeable and most flows are directed over the top of the structure. The road surface may be capped with concrete or other non-erodible material, and armor on the fill face grouted in place, so that overtopping will not seriously erode the road fill or the fill face during overtopping.

Even if the crossing washes out, the amount of fine sediment delivery would be minimal and have minimal impact on downstream fish habitat. It is important that porous rock fill crossings (vented fills) are installed in upslope or headwater locations where stream flows are lower and crossings are likely to remain intact and unlikely to wash out.

6. FORDS

Fords are stream crossings where vehicles drive on the bed of the stream channel (i.e., no man-placed fill in or on the streambed). Fords work well on small to medium sized streams where there is a stable stream bottom and traffic is light. However, "construction" of fords and other unimproved stream crossings on well-traveled roads should be avoided where water regularly flows because of their potential to impact water quality. In certain situations, where flash floods, high seasonal flood peaks or floating debris are problems, fords may be a practical answer for low volume roads.

FIGURE 122. *Wet ford on a Class II (non-fish) perennial stream. Coarse rock armor that has been grouted in place provides energy dissipation and protects the outer edge of the hardened roadbed. Fords should not be used if high wet season flows would cut off access to inspect and maintain drainage structures further out the road. Unvented, hardened fords may also obstruct fish passage.*

Fords of live streams, called "wet fords," are typically composed of streambed gravels or concrete structures built in contact with the streambed so that vehicles can cross the channel (Figure 122). If possible, a stable, rocky (or bedrock) portion of the channel should be selected for the ford location. **The simplest of fords are those on low volume roads where occasional traffic drives over a naturally hardened streambed composed of bedrock or cobbles.**

Where the streambed at the crossing site is not sufficiently hard, fords can also be fortified or constructed of permeable trench drains of coarse, imported cobbles and boulders. Low summer flows seep through the fill, and higher water discharges flow over the top without scouring or removing the armor layer. Some post-winter or post-wet season maintenance may be needed. During extreme events, however, the ford may be completely washed-out and need reconstruction. Permeable or concrete fords are likely to be a barrier to migrating juvenile or resident adult fish and should not be used in fish-bearing channels.

Paved (hardened) fords across live streams may be necessary to maintain water quality if there is to be regular traffic. These are sometimes called "Arizona Crossings" for their prevalent use as ford crossings of dry streambeds in the USA's desert southwest. Paving, if used, usually consists of a concrete, slightly dish-shaped slab built across the stream channel that extends sufficiently up each streambank to contain design flood flows (i.e., the wetted perimeter for the design (100-yr) flood flow).[13] These may sometimes contain enough fill material beneath the concrete to maintain a level driving surface. A discharge apron or energy dissipater is constructed on the downstream side of the ford to prevent scour and undermining during high flows and this must also extend the entire width of the 100-yr flood flow wetted perimeter (Figure 123).

Fords are designed to pass both sediment and debris during high flows. Unfortunately, concrete fords are often plagued by scour around their edges because of a lack of capacity (depth and width) or because armor was not placed to the full width of the flood flow channel, sometimes leaving the ford elevated and impassable. Hardened ford structures are sometimes even moved downstream by large flood flows after the outfall has been eroded and the structure undermined.

Vented fords can also be constructed with a culvert embedded in the concrete or hardened structure to handle low seasonal flows. Fords, particularly vented fords, can be constructed to pass large flows and large amounts of debris while still accommodating fish passage. On streams that contain fish during some part of the year, fish passage is frequently obstructed at low flows unless venting culverts have been embedded into the basal concrete. Unless the vent/area ratio is large (Figure 75), vented fords typically require regular maintenance to clear debris from the culvert inlets. The larger the venting culvert, as compared to the stream width, the less likely they will become plugged with debris.

Unless it has a bedrock foundation and hardened approaches, most ford crossings are vulnerable to erosion and can create pollution from several sources. High traffic levels and/or high water flows can cause erosion of both natural and artificial streambed materials (Figure 124). Material placed in the stream or moved about by vehicle traffic can create a barrier to fish migration. Vehicle passage through fords with fine sediment channel bottoms creates plumes of turbidity with every passage. Deep water ford

13 It is rare to observe a hardened ford that has been constructed to contain the 100-year flood flow, or even the 20-year flood flow. Most hardened fords are overtopped and flanked by large runoff events due to the lack of depth in the axis of the stream, and the limited width of the hardened, dipped crossing. Many such fords are found in valley bottoms and floodplain settings where channels are not deeply incised and floods may be valley-wide.

FIGURE 123. *Flow in this hardened ford is from right to left. Low flow energy dissipation has been built into the center of the structure, but high flood flows have scoured to the base of the concrete ford in the foreground. Both the hardened ford and the downstream energy dissipation must be broad enough to encompass and contain the expected 100-year design flood flow.*

FIGURE 124. *This unimproved ford crossing of an intermittent stream was poorly located in a channel reach that had a fine, erodible bed. Efforts to stabilize the channel bottom with rock and concrete chunks have been unsuccessful. A plume of turbidity is released in this fish bearing channel with each crossing.*

FIGURE 125. *In addition to the actual ford crossing, the road approaches also contribute to sediment pollution unless they are paved or heavily rock surfaced. Fords are always low points in the road, so runoff from the connected approaches is delivered directly to the stream channel.*

crossings can cause oil products to be released from vehicles as they pass through a wet ford.

Fords are always the low point in a road alignment, where each road approach drops into the channel and then climbs back out. Unless the approaches are heavily rocked or paved, and hydrologically disconnected, rainfall and runoff will erode the roadbed and deliver fine sediment directly to the stream at the crossing site (Figure 125). Incised stream channels with high streambanks require the excavation of substantial ramps to get vehicles down to the streambed. Unless they are similarly protected, these through cut ramps are often sites of substantial surface and rill erosion that causes eroded sediment and turbid runoff to enter the stream during periods of heavy rainfall.

On small, poorly incised, ephemeral or intermittent streams a ford may be needed if there is insufficient channel depth to install a culvert. In fact, a rock lined rolling dip with a rock apron face may be preferable to a permanent culvert on some swales and small watercourses. **Fords and armored fills have the advantage, over culverted fills, of never plugging.** Fords on small streams should be rock armored to prevent erosion of the road surface during runoff events. **What are sometimes referred to as "unimproved" fords, where a stream channel has been filled with a substantial quantity of soil and left unprotected by armor or rock surfacing, is a high maintenance crossing that is a hazard to water quality and should not be constructed.**

7. TEMPORARY STREAM CROSSINGS

Temporary stream crossings are used to provide short term access to an area. Temporary crossings should be installed wherever a proposed temporary road crosses a stream channel, regardless of its size. **Any stream channel or water source that would be fitted with a drainage structure on a permanent road should receive a temporary drainage structure on a temporary road.** The structure should be capable of passing the expected discharge of the channel during the season(s) that it is to remain in place. **If a stream crossing**

is to remain in-place during the winter or wet season (beginning October 15 in Northern California), it must be designed and constructed to pass flood flows from the 100-year design runoff event, as well as debris and sediment loads, just as though it was a permanent stream crossing structure. Specific techniques for constructing temporary stream crossings are discussed in Chapter 5.

For temporary roads, only temporary crossings are acceptable. Dry fords that are removed following land use operations and before beginning of the wet season are appropriate for dry channels. For live streams, a more substantial crossing is needed. They can be constructed of a variety of materials including culverted fills, log crossings, combinations of logs and pipes, straw bales over pipes and logs, and temporary log or railroad flatcar bridges (Figure 126). Where channels are wet or incised, temporary culverts, temporary log fills or temporary bridges should be used. Log fills (with or without culverts) and portable bridges can often be installed, used and removed with little damage to the streambanks or channel bed.

It is important that the original base level of the stream channel be maintained when a temporary crossing is removed following operations. For this, a "marker" consisting of several inches of straw, or another distinctive marker placed in the bed of the channel, is often used to identify the natural channel bed before any logs or fill for a temporary crossing is placed in the channel. Re-excavation of the crossing down to this horizon is then relatively simple.

FIGURE 126. *This small, temporary log crossing is constructed with a culvert at its base, with logs, straw bales and finally road surfacing material on top. A geotextile fabric can be used instead of straw to provide separation between the stream and the overlying road materials. Ideally, the road surfacing materials should be clean road rock or gravel (not dirt) that will not adversely affect water quality if some makes its way into the stream. Temporary crossings should be removed before each wet weather season.*

A special category of temporary stream crossing is the low water crossing that is often installed to provide summer vehicle traffic across larger perennial streams and small rivers during summer low flow conditions (e.g., Figures 127a, 127b). These crossings are typically composed of streambed gravels that have been ramped up on both approaches to the low flow channel with one or more culverts or a temporary bridge used to carry streamflow. Only clean gravels are used in its construction and no new soil or fine sediment is introduced into the channel or floodplain. The low flow crossing and culverts (or bridge) are then removed prior to the first fall rains which would raise flows in the river. Fish passage should be considered and designed into the low flow crossing of fish-bearing streams so that juveniles and adults can pass through the structure. A temporary flatcar bridge is frequently used to span all or part of the low flow channel instead of culverts where fish are present. Like culverts, the temporary bridge is then removed prior to the rainy season.

FIGURE 127A. *Summer low-water crossing of a Class I (fish bearing) perennial river. Coarse, clean streambed material has been used to ramp up and over the flowing water. Two embedded culverts have been installed at water level to allow for uninterrupted flow and the migration of young fish.*

FIGURE 127B. *A temporary bridge crossing should be used where migrating adult or juvenile fish need to pass beneath the crossing. This temporary bridge crossing spans the active summer channel and the abutment in the channel is composed entirely of clean stream gravels. All temporary low water crossings should be removed before the first seasonal rains.*