



*of*  
BRITISH COLUMBIA

# Forest Road Engineering Guidebook

Second edition

June 2002



BRITISH  
COLUMBIA  
Ministry of Forests



FOREST PRACTICES  
  
*of*  
BRITISH COLUMBIA

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**Second edition**

June 2002

**Authority**

*Forest Practices Code of British Columbia Act*

*Forest Road Regulation*

*Operational Planning Regulation*

**National Library of Canada Cataloguing in Publication Data**

Main entry under title:

Forest road engineering guidebook. -- 2nd ed.

(Forest practices code of British Columbia)

Previously published: 1995.

Includes bibliographical references: p.

ISBN 0-7726-4806-9

1. Forest roads - British Columbia - Design and construction. 2. Forest roads - British Columbia - Maintenance and repair. 3. Forest roads - Environmental aspects - British Columbia. I. British Columbia. Ministry of Forests. II. Series.

SD389.F57 2002

634.9'3'09711

C2002-960150-9

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**Citation**

B.C. Ministry of Forests. 2002. Forest road engineering guidebook.

For. Prac. Br., B.C. Min. For., Victoria, B.C. Forest Practices Code of British Columbia Guidebook.

<http://www.for.gov.bc.ca/tasb/legsregs/fpc/fpcguide/guidetoc.htm>

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## Foreword

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This guidebook provides forest road practitioners with advice on road design and field practices to assist them to achieve the statutory and regulatory requirements in the *Forest Practices Code of British Columbia Act*, the *Forest Road Regulation*, and the *Operational Planning Regulation*.

The practices contained in this document are not mandatory and are not to be interpreted as the only acceptable options. However, as the Chief Engineer for the Ministry of Forests, I believe that by using the suggested procedures, a proponent will more likely be successful in addressing his or her legal responsibilities, at least where the actual site situation matches the conditions contemplated by the documented practices. The practices described in the document have been prepared and reviewed by experts in their field, including both public and private sector technicians and professionals. Accordingly, I believe this guidebook is a reasonable reflection of acceptable standards of practice in the forest sector of British Columbia.

Where a range of options or outcomes apply, such ranges have been given. Where these are not provided, some flexibility may be required in applying the guidebook practices, particularly where the proponent believes that such variance is warranted based on site-specific conditions.



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## Introduction

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The materials presented in this guidebook are intended primarily for skilled, experienced, and knowledgeable technical personnel who are responsible for locating, designing, building, maintaining, and deactivating forest roads. It is aimed at those personnel who are already carrying out technical operations related to forest road engineering, but who may require guidance on how to interpret and meet the requirements of the *Forest Practices Code of British Columbia Act* (Act), and associated regulations. This guidebook is a result of many contributions from ministry staff and forest company practitioners, as well as a number of consultants.

Throughout this guidebook, emphasis is placed on compliance with operational and safety requirements and the need to ensure protection of forest resources, while meeting the requirements of the Forest Practices Code statutory obligations in an effective, efficient manner. The guidebook materials are grouped into six subject areas that correspond to the following work phases:

1. **Road Layout and Design**—This section describes route selection and layout, field investigation, surveying, and associated engineering practices to provide site-specific road location, design, and construction specifications.
2. **Design and Construction of Bridges and Stream Culverts**—This section outlines the general design requirements for bridges and stream culverts, and discusses non-professional and professional design responsibility, site and site survey information requirements for bridges and major culverts, preparation of construction drawings, specifications for bridges, major culverts, and stream culverts, and methods to estimate design flow discharge for streams.
3. **Road Construction**—This section presents information to assist technical personnel responsible for forest road construction and modification in constructing roads appropriate for the expected service life while minimizing any adverse impacts on other forest resources.
4. **Road Drainage Construction**—This section covers drainage system construction, the purpose of which is to maintain natural surface drainage patterns while intercepting, collecting, and controlling flows to minimize any adverse impacts to the environment.
5. **Road and Structure Inspection and Maintenance**—This section provides information to assist those responsible for the inspection and maintenance of roads and associated structures.
6. **Road Deactivation**—This section describes the objectives, levels, and techniques of forest road deactivation to provide practitioners with administrative and process-oriented guidance.



# 1. Road Layout and Design

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## Introduction

Forest road layout and design is a process that includes route selection, field investigation, surveying, and analysis to provide a site-specific road location and design. Road design provides construction specifications, road prism geometry, stream crossing site information, and information necessary for construction control.

The detail and information required for each phase in this process varies with the type of road required, the complexity of terrain, the size and complexity of stream crossings, and other resource values.

This chapter:

- describes the types of projects for which the district manager's approval of road layout and design for construction and modification is mandatory
- provides information on route selection and layout, and describes the content requirements of a reconnaissance report
- provides criteria for survey level selection, and explains the types of survey (field traverse and location survey), and the suitability and application of different survey levels
- provides procedures for field traverses and location surveys
- explains general and geometric road design requirements
- provides example correction factors to convert compacted volume to bank volume for road design purposes
- discusses slope stability considerations if a proposed road will cross areas with a moderate or high likelihood of landslides
- provides road design specifications and parameters.

## District manager approval of road layout and design

The Ministry of Forests has developed a package of road layout and design forms and administrative procedures that incorporate the statutory contents for road layout and design. This information can be found at an appropriate Ministry of Forests website.

The district manager approves road construction and modification for forest roads under various permits. In general, unless the district manager requires it, the following types of projects are exempted from needing his or her approval of road layout and design:

- in-block roads, unless they cross areas with a moderate or high likelihood of landslides as determined by a terrain stability field assessment (TSFA), or unless they are in community watersheds and surface soil erosion potential or hazard is high or very high;
- stream-crossing modifications, unless the work consists of replacement or new construction of bridges or major culverts; and
- emergency works.

## **Route selection and layout**

Decisions made at the route selection stage may have long-term effects on road construction and maintenance costs, user safety, and other resources. Routes must be selected and located to meet the objectives of higher-level plans within the constraints of any approved operational plans or permits. It is essential that adequate time and resources be allocated to route selection.

The route selection stage begins with the collecting and analyzing of all available information for the development area, focusing on the route corridor. This information may include aerial photos, topographic maps, soil erosion potential maps, land alienation maps, and reconnaissance terrain stability or detailed terrain stability maps and other assessments for the area.

The method of harvesting and constraints of the harvesting system should also be considered if the road will traverse (1) a harvesting area or (2) an area that could be harvested in the future. Road drainage flows and drainage structures and road and clearing widths could all be affected by harvesting.

Control points (physical features that may influence road location or design) should then be plotted on the aerial photos and/or topographic maps of a suitable scale.

Control points include:

- stream crossings, rock bluffs, benches, passes, saddles, and other dominant terrain features
- road grades and switchback locations
- harvesting system landings
- potential endhaul or waste areas
- alienated lands, including powerline, gas pipeline, or railway crossings
- current access and junction to existing roads.

Route selection should then be made based on an analysis of all of the available information, and the route should be field verified.

The route selection field phase is an on-the-ground check of the proposed route or potential routes, taking into consideration control points or other constraints. This field traverse is also known as a Level 1 survey (measurements are not usually accurate enough for detailed road design) and is run along a proposed route to confirm that the horizontal and vertical alignment are suitable. Adjustments to the line may be necessary, and often several iterations are needed to establish the alignment and confirm the choice of route.

The person carrying out the field traverse should make sufficient notes to prepare a detailed reconnaissance report to assist the location surveyors, road designers, and road builders.

The reconnaissance report should identify and or confirm:

- terrain conditions and road sections that are in unstable or potentially unstable terrain
- road sections with side slopes over 60% or where slope instability is found
- control points and topographic features (e.g., rock bluffs, swamps, avalanche paths, landslides, and debris slides), including those that may be used as photo ties
- the sections of road that encroach on public utilities
- the sections of road that are adjacent to or cross private property, Crown leases, or mineral and placer claims or leases (where possible, alienated lands should be avoided)
- all continuous and intermittent drainage flow channels, springs, seeps, and wet areas
- riparian areas
- stream crossings where channel and bank disturbances can be prevented or mitigated, locations that require site plans, and data required for minor stream crossings
- forest cover (species composition, timber quality, and volume per hectare)
- recommended slash and debris disposal methods and additional clearing widths required for the slash and debris disposal
- soil types based on visual observations of exposed cuts, shallow hand-dug test holes and probing, and the location of these soils on maps or aerial photos (see Appendix 1 for a method of identifying soils)
- maximum road grades and minimum curve radii
- location and extent of bedrock, if rippable, and the potential as ballast
- location and extent of gravel sources and the potential for use as sub-grade and surfacing materials

- endhaul sections and potential waste areas
- recommended construction methods and potentially appropriate alternatives
- recommended survey level or levels appropriate for the terrain.

The field reconnaissance report should also record the characteristics of existing roads in the vicinity of the proposed road location by identifying and recording soil types, stable cut and fill slope angles, and existing sources of road surfacing materials.

Field reconnaissance is an appropriate stage to evaluate the need for any additional information or assessments that may include:

- TSFAs
- riparian classification of streams, wetlands, and lakes
- identification of fish streams in community watersheds
- visual impact assessments
- archaeological impact assessments
- soil erosion field assessments.

### **Survey level selection**

There are two general types of surveys: a field traverse and a location survey. There are also four levels of survey intensity: Survey Levels 1, 2, 3, and 4. These survey types and levels are briefly explained below.

To determine which survey type and level to recommend in the reconnaissance report, the physical characteristics of the terrain, design complexity, and desired road prism geometry should be considered.

#### ***Types of survey***

##### **Field traverse**

A field traverse is required for road layout and design and is conducted to collect data and measurements for the road location. A field traverse is also sometimes referred to as Survey Level 1 (see “Survey levels” below).

##### **Location survey**

A location survey is carried out to obtain information and measurements necessary for detailed design, or to obtain information when geometric road designs are required. Compared to a field traverse, a location survey is carried out at a higher level of survey intensity (i.e., Survey Level 2, 3, or 4).



If as-built surveys are required for volume determination or to check conformance to the design, the location survey level should be suitable for accurately re-establishing the road centreline location.

If construction surveys are required, the location survey level should be suitable to accurately re-establish the construction control points.

The accuracy achieved with any survey level depends, in part, on the type and condition of survey equipment used, the competence of the crew, and the field methods used. Global Positioning System (GPS) receivers, like other survey equipment, are acceptable when they can achieve the required horizontal and vertical accuracy for the appropriate survey level.

Stream crossings require special consideration. Site information requirements for bridge and culvert planning and design are provided later in this chapter.

Winter-constructed roads require special layout considerations to identify the location of cross-drains and stream crossings. Long continuous grades should be avoided, since they easily become conduits for meltwater and groundwater seepage. Steep cut banks should be avoided because they may slough or fail, blocking ditches and sending ditchwater onto the road surface and creating the potential for major surface erosion.

## **Survey levels**

The following criteria are used to determine the appropriate survey level for a field traverse (Survey Level 1) or location survey (Survey Levels 2, 3, or 4).

### **Survey Level 1 (for field traverses)**

*Application:* For field traverses on stable terrain with a low likelihood of landslides and where geometric road design, construction surveys, and as-built surveys are not required. The necessary accuracy of survey may be achieved with basic field equipment such as hand compass, clinometer, and hip chain.

*Horizontal accuracy:* Turning points are established to a relative accuracy of 1:100.

*Vertical accuracy:* Not applicable.

### **Survey Level 2 (for location surveys on stable terrain)**

*Application:* For location surveys on stable terrain with a low likelihood of landslides and where a geometric road design, construction surveys, or as-built surveys are desired.

*Horizontal accuracy:* Turning points to be established to a relative accuracy of 1:300.

*Vertical accuracy:* =  $\sqrt{\text{total horizontal distance measured in kilometres}}$ , expressed in metres. For example, the vertical accuracy for a 1-km road is 1 m. For a 2-km road, the vertical accuracy is 1.41 m.

### **Survey Level 3 (for location surveys within areas of moderate or high likelihood of landslides)**

*Application:* For location surveys, construction surveys, geometric road design, and as-built surveys in areas of moderate to high likelihood of landslides as determined by a TSFA. Appropriate level of survey for material volume determination and detailed-engineered estimates. This level of survey may also be used for bridge and major culvert planning and design, but greater vertical accuracy would possibly be necessary.

*Horizontal accuracy:* Turning points to be established to a relative accuracy of 1:1000.

*Vertical accuracy:* =  $0.5 \times \sqrt{\text{total horizontal distance measured in kilometres}}$ , expressed in metres. For example, the vertical accuracy for a 1-km road is 0.5 m. For a 2-km road, the vertical accuracy is 0.71 m.

### **Survey Level 4 (for high-order survey requirements)**

*Application:* A high-order survey for location surveys, construction surveys, construction contracting on a cost-per-unit basis, check surveys, placement of permanent bridges, as-built surveys through Crown leases, mineral and placer claims, and leases, private property, and surveys to re-establish private property lines.

*Horizontal accuracy:* Turning hubs are to be established to a relative accuracy of 1:5000.

*Vertical accuracy:* =  $0.3 \times \sqrt{\text{total horizontal distance measured in kilometres}}$ , expressed in metres. For example, the vertical accuracy for a 1-km road is 0.3 m. For a 2-km road, the vertical accuracy is 0.42 m.

## **Procedures for field traverses and location surveys**

This section outlines the minimum requirements for field traverses and location surveys. Although considerable gains have been made in survey instrumentation technology, use of the technology does not preclude the need to follow standard survey practices. Standard practices are outlined in the *Manual for Roads and Transportation* (BCIT 1984).

**Survey Level 1 (for field traverses)**

Where no location survey is required (e.g., where a proposed road will **not** cross areas with a moderate or high likelihood of landslides as determined by a TSFA):

1. Clearly identify the beginning and end of the road.
2. Clearly flag the proposed centreline of the road.
3. Using an appropriate method (such as aluminum plaques and tree blazes), mark and record control points, noting the control point number, station, bearing, and horizontal distance from the proposed centreline.
4. Record notes on forest cover, vegetative types, soil types, rock, ground water seepage, streams, etc.

**Survey Levels 2 and 3 (for location surveys)****Traverse**

1. Clearly identify the beginning and end of the road.
2. Establish intervisible stations called turning points (TPs) if using a compass or traverse hubs if using a transit—along the preliminary centreline (P-Line). Use manufactured stakes or local material (blazing of saplings) driven into the ground.
3. Measure the bearing, slope gradient, and distance between TPs and mark the cumulative chainages and/or point number in the field.
4. Measure the slope gradient and distance to additional grade breaks between TPs as intermediate fore shots to facilitate taking cross-sections at those locations.
5. Using an appropriate method (such as aluminum plaques and tree blazes), mark and record control points, reference points and bench marks, noting the number, station, bearing, and horizontal distance from the P-Line.
6. Record notes on forest cover, vegetative types, soil types, rock, ground water seepage, streams, etc. that were not identified on the reconnaissance report.
7. Obtain enough information to ensure that road junctions can be designed and constructed. Switchbacks located on steep slopes also require detailed data for proper design and construction.
8. The final designed road location centreline (L-Line) should be close to the P-Line and generally within 3 m of the P-Line if the road will cross areas with a moderate to high likelihood of landslides as determined by a TSFA, or if bedrock is present or switchbacks are encountered.

## Cross-sections

1. Take cross-sections at all TPs and intermediate fore shots perpendicular to the back tangent or bisecting the interior angle of two tangents. Ensure that the recorded information is compatible with computer design software requirements.
2. Cross-sections should not be more than 15 m apart in rock or 30 m apart in other material. A longer spacing will not provide sufficient cross-sections for the accurate earth volume calculations required for geometric design. Exceptions to this guideline may be considered for Level 2 surveys conducted in uniform terrain.
3. Extend cross-sections at least 15 m horizontally on either side of the location line or farther to accommodate the road prism and in areas considered for waste disposal.
4. Measure and record slope breaks (over 10%) on the cross-section profile to the nearest 0.1 m in distance and nearest 1% in slope gradient.
5. Take additional cross-sections to record features that may affect the road prism on each side of the proposed centreline. Examples of such features are rock outcrops, flat topography (benches), lakeshores, fences, streams, back channels, and existing roads.

## Referencing and benchmarks

A reference tree or other fixed object (e.g., bedrock outcrop) is used for the horizontal control, and a benchmark is used for the vertical control of the road traverse. Both are important for re-establishing the designed location line (L-Line), and are required for construction surveys and those surveys necessary to complete as-built documentation.

1. Reference the beginning and end of the location line traverse. When switching from one survey level to another, reference this point in accordance with the higher survey level accuracy.
2. Establish references at least every 300 m, and at control points established during the field traverse.
3. Use two trees to establish references outside the proposed upslope clearing limit. Set the angle from the TP to the two reference trees between  $60^\circ$  and  $120^\circ$  from the centreline tangent. Make horizontal measurements to the centre of the reference marker (plaque). (The use of two reference trees improves the accuracy of relocating the traverse station and provides for a back-up if one tree is destroyed.) Use the same level of survey accuracy to establish references and benchmarks.
4. Record the diameter at breast height (dbh) and species of the reference trees so that they can easily be found.

5. Establish benchmarks outside the clearing width no more than 1 km apart, at major structures and at existing references for control points established during the field traverse.
6. A typical benchmark and road survey reference information is shown in Figure 1.

### **Ties to existing property boundaries**

Traverse-tie the location survey to existing property markers or other evidence of legal boundaries that may be near the location survey. Sufficient investigation should be completed to establish the location of the property line and determine whether the road right-of-way will encroach on the property line. If possible, the centreline and right-of-way should be relocated if there is an encroachment.

### ***Survey Level 4 (for high-order survey requirements)***

As noted earlier, this high-order survey is also suitable for alienated lands such as private property. Before starting work on alienated lands, contact the owners and explain the nature of the work. The owner may be able to provide the location of corner pins and other useful information.

When working on alienated lands, keep the clearing (tree falling, line slashing, etc.) and marking of lines to a minimum. The following information should be recorded and tied to the location line traverse:

- all existing legal markers
- improvements and utilities that may be affected by the right-of-way
- fences and buildings
- parts of the existing road if applicable, including the top of cut, toe of fill, grade, and ditchline.

If possible, close traverses onto at least two legal posts to ensure accuracy and establish correct orientation of the survey with respect to the legal lot or lots.

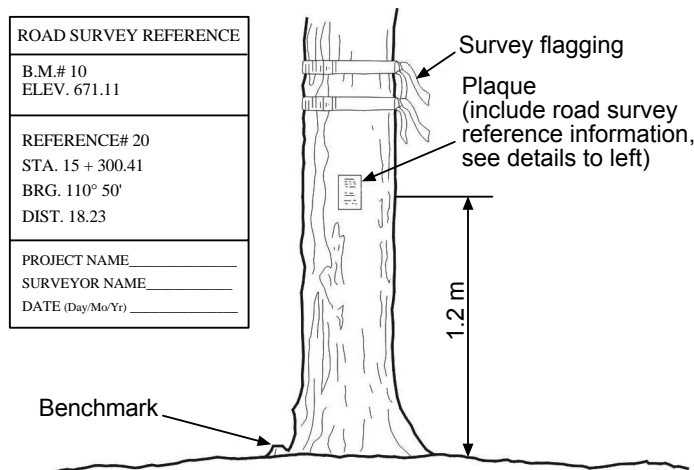


Figure 1. Typical benchmarks and reference.

## Road design requirements

The purpose of road design is to produce design specifications for road construction by determining the optimum road geometry that will accommodate the design vehicle configuration for load and alignment, and traffic volume, and provide for user safety, while minimizing the cost of construction, transportation, maintenance, and deactivation. The optimum road design should minimize impacts on other resources by minimizing clearing and road widths, minimizing excavation, using rolling grades, and installing proper drainage structures.

Road design software has been developed to replace manual drafting and repetitious design calculations so that various alignment alternatives can be quickly evaluated. Once the location survey data have been entered into the road design program, select and input appropriate design parameters for the specific project. Ensuring this requires direction from a skilled and knowledgeable designer familiar with forest road layout, design, and construction practices. As each phase of road layout and design builds on the previous phase, the quality of the final design depends on the appropriateness of the road location, field data, and survey—and the competence of the designer.

### General design requirements

This section provides road design requirements common to all levels of road layout and design. Construction techniques, road width, cut and fill slope angles, and horizontal and vertical control angles are selected according to terrain and soil conditions for the required road standard. Forest road standards are defined primarily in terms of stabilized road width and design speed.

Road design specifications consist of alignment elements (e.g., horizontal curvature, vertical curvature, road grade, and sight distance) and cross-section elements (e.g., full or partial bench construction, sidecast construction, road width, angles of repose for stable cut slopes, ditch dimensions, drainage specification, and clearing widths).

Geometric road designs include plans, profiles, cross-sections, and mass haul diagrams showing the optimum balance of waste, borrow, and endhaul volumes. The designs are generated from the route selection process and the location survey. From the location survey information, a road centreline (L-Line) is designed for vertical and horizontal alignment, earthwork quantities are calculated, and a mass haul diagram is produced to show the optimum placement of excavated material.

Figure 2 shows a typical road cross-section and the terminology used to describe cross-section elements.

### **Factors to consider in road design**

Road design should consider the following factors:

#### *General considerations:*

- intended season and use of the road (design vehicle configuration for load and alignment, and traffic volume)
- climate (heavy snowfall areas, heavy rainfall areas, etc.)
- design service life of the road
- user safety
- resource impacts
- economics
- road alignment (horizontal and vertical geometry)
- junctions with existing roads
- road width (turnouts and widenings).

#### *Soils, road prism geometry, slash disposal:*

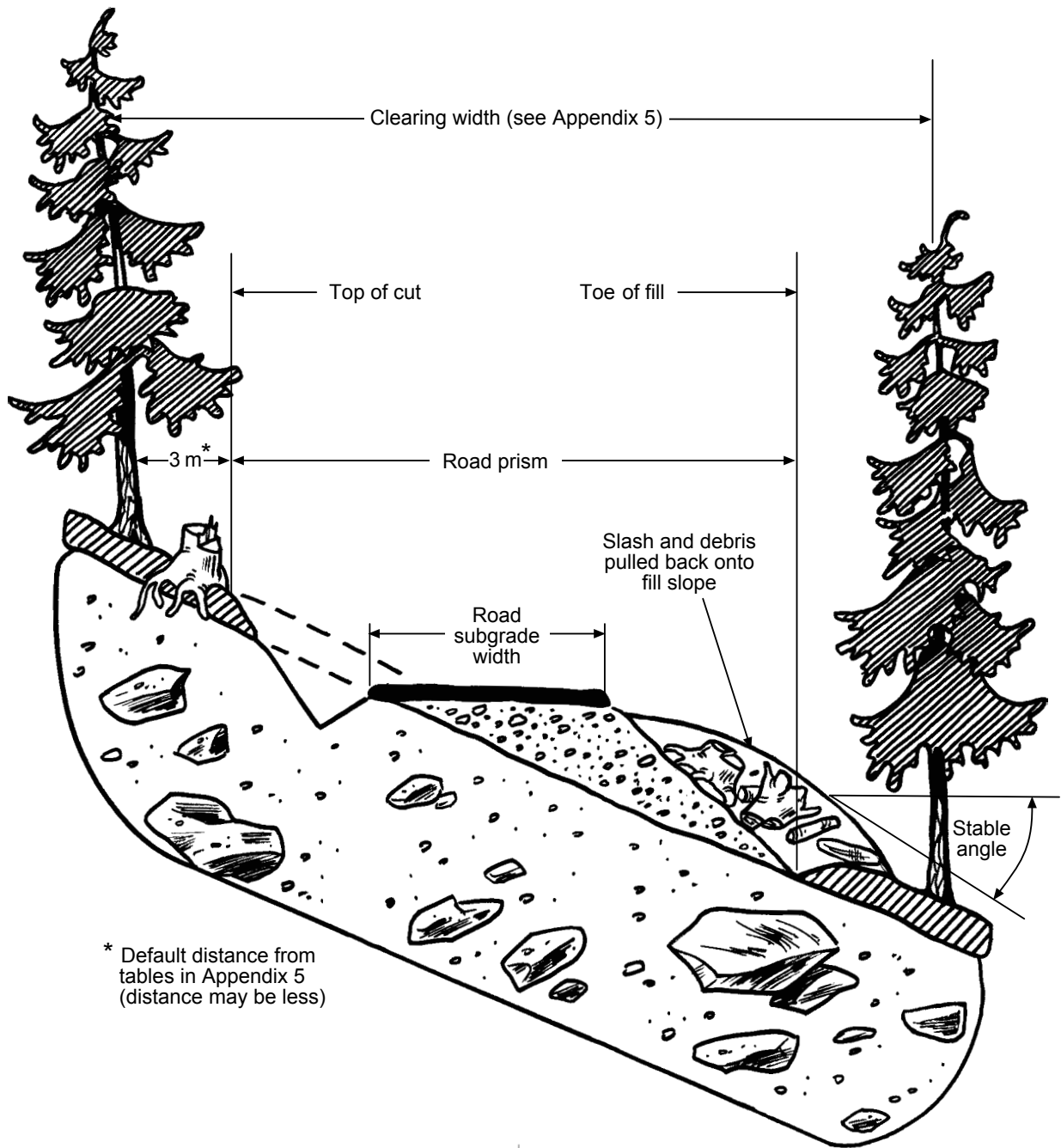
- the measures to maintain slope stability if the road will cross areas with a moderate or high likelihood of landslides (also see “Geometric road design requirements” below)
- soil types (including the use of appropriate conversion factors to adjust for swell and shrinkage of materials)
- cut and fill slope angles
- clearing widths
- slash disposal methods

- planned movement and placement of materials (balancing of design), including waste areas and endhaul areas.

*Drainage, construction techniques, sediment prevention, road deactivation:*

- culverts (locations, type, size, and skew angles)
- drainage and ditch (including depth) locations
- rock blasting techniques to optimize usable rock
- anticipated construction problems
- measures to mitigate soil erosion (including vegetative requirements and prescriptions)
- measures to maintain water quality
- future deactivation requirements.





\* Default distance from tables in Appendix 5 (distance may be less)

Figure 2. Typical roadway on moderate slopes with no additional clearing.

## ***Geometric road design requirements***

A geometric road design is mandatory for all roads that will cross areas with a moderate or high likelihood of landslides as determined by a TSFA. In these areas, it is also mandatory that measures to maintain slope stability be incorporated into the geometric road design. These measures rarely allow for the most optimum balance of waste, borrow, and endhaul volumes.

In geometric road design, specifications such as road width, cut and fill slope angles, and horizontal and vertical control angles are selected to match the required road standard. A road centreline location (L-Line) is designed based on information from the location survey and reconnaissance report. Earthwork volumes or quantities are then calculated.

In addition to the information described under “General design requirements” above, a geometric road design should also provide:

- plans and profiles (see Appendix 3 for recommended content and layout)
- cross-sections with road prism templates
- mass diagrams with balance lines
- correction factors used in the design to convert compacted volume to bank volume
- a schedule of quantities and units of measure for clearing, grubbing, excavating (other material and rock), and gravelling
- planned movement and placement of materials (balancing of design)
- the location and size of required drainage structures such as culverts and bridges
- the location and size of retaining walls or specialized roadway structures
- clearing widths
- typical construction equipment required, and any equipment recommended for specialized construction techniques
- estimated material and construction costs
- location survey alignment and designed centreline (L-Line) offsets, and clearing width offsets shown on the site plan
- slope stake information (note that this information is only a guide and slope/grade stakes should be calculated and placed based on design or re-design of cuts and fills at centreline)
- measures required for reducing potential impacts on other resource values
- site-specific design and construction notes and prescriptions on, for example, the location of endhaul sections, borrow pits, waste and slash disposal areas, and full bench cut areas, and any other information that the designer considers useful to the road builder

- measures to maintain slope stability if the road will cross areas with a moderate or high likelihood of landslides as determined by a TSFA
- information that the designer considers useful to the road builder or owner.

Whenever possible, the design should allow for the use of waste or spoil material in ways that reduce endhauling requirements. For example, some material types may be used for the road subgrade, base course, turnouts, curve widenings, and embankment (fill). If these options are not available, or if the excess material consists of overburden and debris, then spoil sites should be identified as close to the construction area as possible. Abandoned quarries, gravel pits, and roads are some possibilities. Alternatively, stable areas in gentle or benched terrain can be evaluated for use as spoil sites.

## Correction factors to adjust for swell and shrinkage of materials

### *Material volumes (bank, loose, and compacted)*

The volume of natural in-place material usually expands (swells) or contracts (shrinks) after it is excavated and reworked. Figure 3 illustrates how the volume of a material can change during excavation, handling, placement, and compaction in a fill. Soil and rock volumes can be expressed in different ways, depending on whether they are measured in the **bank**, or measured in **loose** or **compacted** conditions.

**Bank volume** (sometimes referred to as **excavation volume**) is the volume of material in its natural, or in-place, condition.

**Loose volume** (sometimes referred to as **trucked volume**) is the volume of material in a loose, broken, blasted, or otherwise disturbed state that has been excavated and stockpiled or loaded into trucks and hauled (handled). As shown in Figure 3, both soil and rock increase in volume (swell) when they are excavated and handled. This occurs because air voids are created in the material during these processes.

**Compacted volume** (sometimes referred to as **embankment volume**) is the measured volume of material after it has been placed in a fill and compacted. As shown in Figure 3, when loose material is placed and compacted, a reduction in volume occurs. The amount of this decrease may be greater or less than the increase in volume due to excavation, depending on several factors explained below. If the compacted volume is greater than the bank volume, the volume increase is called **swell**. If the compacted volume is less than the bank volume, the volume reduction is called **shrinkage**.

The amount of swell and shrinkage depends on several factors:



The correction factors in Table 1 do not include any effects due to wastage or loss of material. The road designer should consider the need to separately account for other potential material losses that might affect achieving a balanced cut and fill design. Typical important sources of material loss, among others, can include:

- material lost (spilled) in transport from cut to fill, and
- subsidence, compression, or displacement of the prepared subgrade or original ground surface caused by the weight of the overlying embankment.

**Table 1.** Example correction factors to convert compacted volume to bank volume for various materials.

Example Correction Factor	Swell or Shrinkage	Example Material When It Was IN THE BANK
0.75 to 0.85	Swell	<b>Solid rock.</b> Assumes drilling and blasting is required, resulting in large fragments and high voids.
0.9 to 1.0	Swell	<b>Dense soil or rippable rock.</b> In the case of dense soil (e.g., glacial till) or rippable rock, typical compaction during conventional forest road construction will result in swell.
1.0 to 1.15	Shrinkage	<b>Compact to loose soil.</b> Lower correction factors are more appropriate for coarse-grained soils (e.g., sand, sandy gravel, or mixtures of gravel, sand, silt, and clay). Higher correction factors are more appropriate for fine-grained soils (e.g., silt and clay). It is more possible to achieve shrinkage during conventional forest road construction if the soil in the bank was in a loose condition. For example, a correction factor of 1.0 (i.e., no shrinkage) may be appropriate for compact sands and gravels, whereas a correction factor of 1.15 may be appropriate for very loose silts.

**Notes:**

1. The “example correction factors” are applicable to forest road design purposes only. They assume compaction typically achieved during conventional forest road construction, and different correction factors could apply for engineered fills, placed and compacted to achieve the highest material density possible. Because of the variability of natural materials and their conditions in the bank, the potential for material loss during handling, and the range of road construction methods, correction factors are best determined from experience and local knowledge.
2. The example correction factors are based on swell or shrinkage effects due to an increase or decrease in the density of the soil or rock materials, and do not include any effects of potential wastage or loss of material from other sources.

## Example

Bank volume = compacted volume  $\times$  correction factor.

Example: If the compacted volume of shot rock is 12 m<sup>3</sup> measured from drawings, how much bank volume needs to be drilled, blasted, and excavated to achieve this volume? Assume a correction factor of 0.75.

Solution: Bank volume = 12 m<sup>3</sup>  $\times$  0.75 = 9 m<sup>3</sup>

## Slope stability considerations

Roads should be designed, constructed, maintained, and deactivated so that they will not contribute directly or indirectly to slope failures or landslides.

If a proposed road will cross areas with a moderate or high likelihood of landslides as determined by a TSFA, the person required to prepare the road layout and design must address, among other requirements, **measures to maintain slope stability**. (The term “measures” means prescriptions or recommendations.) For roads that cross such terrain, a conventional cut and fill road construction technique may not be an adequate type of measure to maintain slope stability, and alternative measures incorporated into the geometric road design may be needed to prevent road-induced slope failures and landslides.

Examples of types of prescriptions or recommendations include:

- road relocation, or a decision not to build
- **road construction techniques**
- methods to cross gullies and fish streams
- cut and fill slope angles
- location and design of spoil or waste areas and endhaul areas
- drainage control or installation of subsurface drainage
- road modification, maintenance, and deactivation strategies.

Examples of different **road construction techniques** include:

- for single season use of the road,  $\frac{1}{2}$  bench construction with no endhaul, followed by full pullback of road fill after harvesting
- oversteepened fills for single-season use of the road
- use of wood for fill support for short-term roads
- oversteepened cuts with modified drainage control to manage minor sloughing

- $\frac{3}{4}$  bench construction with endhaul and replacement of finer material with coarse rock fill
- full bench construction with 100% endhaul and water management following harvesting
- designed retaining wall structures to support cut or fill slopes
- designed fills that incorporate special requirements for compaction of the fill or reinforcement of the fill with geosynthetics.

### ***Involvement of qualified registered professionals***

If a proposed road will cross areas with a moderate or high likelihood of landslides as determined by a TSFA, the measures to maintain slope stability must be prepared by a **qualified registered professional** as defined in the Forest Road Regulation. Additionally, a qualified registered professional must sign and seal a statement that indicates that the proposed measures to maintain slope stability have been incorporated into the geometric road design. Obviously, the qualified registered professional should have the training and/or experience to be able to determine if the measures have been incorporated into the geometric road design. This individual may or may not be the same person who prepared the measures.

A qualified registered professional should ensure that his or her prescriptions or recommendations are site specific and precise so that the road designer cannot misunderstand them. He or she should also provide the results of the measures to maintain slope stability as they apply to the road prism, or adjacent to the road prism, separately from other recommendations. For example, recommendations for bridge foundations, walls, or deep approach fills should be provided in a separate report or, alternatively, in distinct sections or under separate headings in the same report, so that the two sets of recommendations cannot be confused.

Specific measures should be referenced to road traverse survey stations marked in the field.

### ***Statement of construction conformance***

The prescriptions or recommendations must state whether or not a qualified registered professional should prepare a **statement of construction conformance** after construction to confirm that the measures were incorporated into the construction. Such a statement may be necessary if the measures are technically complex or if they are not readily discernible after the construction is complete. It may require a qualified registered professional, or his or her designate, to be on site during construction. The statement of construction conformance does not have to be prepared by the same qualified registered professional who prepared the prescriptions or recommendations.

Refer to the Ministry of Forests package of road layout and design forms that incorporate the above statutory content requirements. This information can be found at an appropriate Ministry of Forests website.

Additional guidelines for preparing and implementing measures to maintain slope stability are available in several Forest Regions.

**Criteria for measures to maintain slope stability**

If a proposed road will cross areas with a moderate or high likelihood of landslides as determined by a TSFA, the person required to prepare a road layout and design must ensure that it includes measures to maintain slope stability that satisfy either **Criterion 1 (hazard-based) OR Criterion 2 (risk-based)**. These criteria are explained below, and are consistent with the requirements of Section 6 (1)(n)(i) and (ii) of the Forest Road Regulation.

**Criterion 1**

Code Requirement: In this criterion, the selected measure is the **least likely measure to result in a landslide**, and a qualified registered professional provides a statement to this effect. (See Section 6 (1)(n)(i) of the Forest Road Regulation.)

Criterion 1 is considered to be hazard-based (hazard being the likelihood of landslide occurrence). It requires consideration of a limited number of **road construction techniques** that are likely to result in the lowest likelihood of landslide occurrence. Meeting this criterion would be justified in areas where the likelihood of landslide occurrence is high, and where any measure other than the “least likely measure to result in a landslide” would be unacceptable to a district manager.

A measure that would satisfy the above criterion is any prescription or recommendation for a road construction technique that will result in **at least a low likelihood** of a landslide occurring. A qualified registered professional must provide a statement to this effect to accompany the prescriptions or recommendations. No other road construction techniques other than the ones that provide for at least a low likelihood of landslide occurrence should be considered. There are usually only a few methods of road construction that fit this criterion, and most involve higher road costs. Obviously, the selected measure should be considered in the context of conventional practices for forest roads.

Examples of least likely measures to result in a landslide include any road construction technique that has a low or very low likelihood of landslide occurrence, such as:



- full bench construction in competent bedrock and 100% endhaul of the excavated material
- construction of an engineered retaining wall structure to fully support a road embankment fill or a cut slope
- the application of an engineered reinforced earth section to strengthen and maintain the stability of a deep embankment fill.

In this criterion, the optimization of total costs for road building, maintenance, and deactivation over the life of the road is typically secondary to providing assurance to the district manager that the road construction technique will result in a low or very low likelihood of a landslide occurring.

Appendix 10 shows a procedure for assessing and reporting landslide hazards. **Note:** *The Landslide Hazard table in Appendix 10 is an illustrative example only and should not be considered a procedural standard.*

## Criterion 2

Code Requirement: In this criterion, the selected measure is based on an analysis (i.e., landslide risk assessment) made by a qualified registered professional. (See Section 6 (1)(n)(ii) of the Forest Road Regulation.)

Criterion 2 is considered to be risk-based (risk being the product of hazard and consequence:  $\text{Risk} = \text{Hazard} \times \text{Consequence}$ ). This criterion considers measures that are likely to result in the **lowest risk of damage to one or more elements at risk**. In this criterion, there is usually a broader range of possible types of measures and different combinations of measures to consider than that permissible under Criterion 1.

The selected measures are based on a **landslide risk assessment** (see the definitions below) made by a qualified registered professional. A landslide risk assessment involves identifying reasonable road construction technique options and other potential mitigative measures that could be incorporated into the design, construction, maintenance, or deactivation of the road. The alternatives should focus on achieving an optimum balance between road costs and level of risk—a balance that is satisfactory to the district manager.

For each road construction technique or other type of measure, a **qualitative landslide risk assessment** involves the comparison of:

1. likelihood of landslide occurrence (hazard)
2. potential consequences of a landslide (consequence)
3. resultant risk ( $\text{Risk} = \text{Hazard} \times \text{Consequence}$ )
4. all direct and indirect costs.

Items 1, 2, and 3 are the **landslide risk analysis**; item 4 is the **evaluation of landslide risk**. Items 1 through 4 together make up the **landslide risk assessment**.

Appendix 10 provides a procedure for carrying out a **qualitative landslide risk analysis** to determine landslide hazard, landslide consequences for various elements at risk, and landslide risk. *The tables and matrix in Appendix 10 are illustrative examples only and should not be considered a procedural standard.*

For most projects, the entire landslide risk assessment, including the selection of the optimum measure, can be carried out in the field. For less routine projects, and in addition to the fieldwork, it may be necessary to carry out a detailed office-based cost comparison of each alternative (**evaluation of landslide risk**). For effective and efficient risk management decisions to be made, such comparisons should also take into account the residual risk (the risk that remains after the measures have been implemented) and the costs of road maintenance and deactivation over the expected life of the road.

For some special projects, it may be necessary to determine the nature and costs of any remedial actions required should a landslide occur. Such actions might include any potential rehabilitation of aquatic habitats, recovery of timber values, and replacement of road or other infrastructure damaged from a landslide. The costs for these actions would be added to the other costs described above.

It is important that users realize that decisions with respect to hazard, consequence, and risk may need to be undertaken by a team of individuals familiar with the various parameters and factors involved in landslide risk assessment. For example, a qualified registered professional alone may not always have enough knowledge (e.g., about all the elements at risk and associated costs) to carry out a complete landslide risk assessment. Sometimes the qualified registered professional will only be able to estimate and describe the likelihood of landslide occurrence and the potential **landslide characteristics**, such as the likely path of the landslide, dimensions of the transportation and deposition areas, types of materials involved, and the volumes of materials removed and deposited. In these cases, it is often the role of the person responsible for the road layout and design to use the landslide characteristic information to determine the landslide consequences, with assistance from specialists as necessary. For example, where the element at risk is a fish stream, a fisheries specialist may have to assess the consequences and risks associated with a potential landslide.

See the “Suggestions for further reading” at the end of this chapter for helpful references on landslide risk assessment.

**Definitions**

The following definitions have been adapted from the CAN/CSA-Q850-97.

**Landslide risk analysis** is a systematic use of information to determine the landslide hazard (likelihood of landslide occurrence) and consequence of a landslide at a particular site, thereby allowing an estimate of the risk to adjacent resources from a landslide occurrence.

**Evaluation of landslide risk** is the process by which costs or benefits of various road construction options are compared by the proponent and evaluated in terms of tolerable risk considering the needs, issues, and concerns of those potentially affected by the landslides.

**Landslide risk assessment** is the overall process of landslide risk analysis and the evaluation of landslide risk (landslide risk assessment = risk analysis + evaluation of risk). Landslide risk assessment is an essential component of assessing the advantages and disadvantages of various road construction options and other measures to maintain slope stability.

## Design specifications and parameters

### *Road alignment*

Road design incorporates horizontal and vertical road alignments that provide for user safety. This involves establishing:

- appropriate travel speeds
- suitable stopping and sight distances
- road widths
- turnouts
- truck and trailer configurations
- appropriate traffic control devices.

Designed travel speeds often vary along forest roads due to terrain conditions or changing road standards. The cycle time or distance from the logging area to the dump or processing area may be an important economic factor to consider in establishing an overall design speed, and may be derived from a transportation study and stated in the overall plan for the area. In other cases, topography and terrain will dictate alignment, with little impact from other factors. In general, the safe vehicle speed for a road should be based on:

- horizontal and vertical alignment of the road
- super-elevation on curves
- coefficient of friction between tires and road surface

- type and condition of road surface
- road width
- sight distance and traffic volume.

Tables 2 and 3 and Appendix 2 can be used to determine appropriate travel speeds and stopping and sight distance requirements along the road and at road junctions.

Turnouts should be located in suitable numbers (intervisible and often three or more per kilometre) on single-lane roads to accommodate user safety. The recommended lengths and taper widths for turnouts, based on stabilized road width, can be determined from Table 4.

The *Manual of Geometric Design Standards for Canadian Roads*, published by the Roads and Transportation Association of Canada (RTAC) provides design standards that can be used for forest roads.

**Table 2.** Summary of alignment controls for forest roads.

Stabilized Road Width (m)	Design Speed (km/h)	Minimum Stopping Sight Distance <sup>a</sup> (m)	Minimum Passing Sight Distance for 2-Lane Roads (m)	Minimum Radius of Curve (m)	Suggested Maximum Road Gradient <sup>b,c</sup>				
					Favourable		Adverse		Switchbacks
					S	P <sup>d</sup>	S	P <sup>e</sup>	
4	20	40		15	16%	18% for distance <150 m	9%	12% for distance <100 m	8%
5–6	30	65		35	12%	14% for distance <150 m	8%	10% for distance <100 m	8%
	40	95		65					
8+	50	135	340	100		10% for distance <200m	6%	8% for distance <100m	
	60	175	420	140	8%				6%
	70	220	480	190					
	80	270	560	250					

**NOTE:** These are suggested alignment controls for average conditions on forest roads. Variations can be expected, depending on, for example, site conditions and time of use.

- <sup>a</sup> For two-lane and single-lane one-way roads, multiply the minimum stopping sight distance by 0.5.
- <sup>b</sup> There are no absolute rules for establishing maximum road gradient. Maximum grades cannot generally be established without an analysis to determine the most economical grade for the site-specific conditions encountered. The maximum grade selected for design purposes may also depend on other factors such as: topography and environmental considerations; the resistance to erosion of the road surface material and the soil in the adjacent drainage ditches; the life expectancy and standard of road; periods of use (seasonal or all-weather use); and road surfacing material as it relates to traction, types of vehicles and traffic, and traffic volume. Apply other grade restrictions in special situations. For example:
- On horizontal curves sharper than 80 m radius, reduce the adverse maximum grade by 0.5% for every 10 m reduction in radius.
  - As required at bridge approaches, and at highway and railway crossings.
- <sup>c</sup> S – sustained grade; P – short pitch
- <sup>d</sup> Design maximum short-pitch favourable grades so that they are followed or preceded by a section of slack grade. The average grade over this segment of the road should be less than the specified sustained maximum.
- <sup>e</sup> Design maximum short-pitch adverse grades as momentum grades.

**Table 3.** Minimum subgrade widths for roads on curves, for pole and tri-axle trailer configurations, and for lowbed vehicles.

Radius of Curve (m)	Pole and Tri-axle Trailer Configuration	Lowbed Vehicles
	Minimum Subgrade Width (m)	Minimum Subgrade Width (m)
180	4.0	4.3
90	4.5	5.3
60	5.0	5.8
45	5.0	6.0
35	5.5	6.5
25	6.0	7.5
20	7.0	8.0
15	8.0	9.0

**NOTES:**

- The subgrade widths in this table do not allow for the overhang of long logs or any slippage of the truck or trailer due to poor road conditions.
- Apply the widening to the inside of the curve unless the curve has a 60 m long taper section on each end. For widening on the inside, provide a minimum 10 m section on each end of the curve.
- For two-lane roads or turnouts, it is assumed that the second vehicle is a car or single-unit truck. Add 4.0 m for logging trailer configurations and 4.5 m for lowbed vehicles.
- Double-lane any blind curves or provide adequate traffic control devices.

**Table 4.** Recommended turnout widths, based on stabilized road widths.

Stabilized Road Width <sup>a</sup>	Description	Turnout Width <sup>b</sup> (m)
9+	2-lane off-highway	none
8	2-lane on-highway	none
6	1-lane off-highway	10
5	1-lane on/off-highway	8 to 10
4	1-lane on/off-highway	8

<sup>a</sup> Where no road surfacing is used, the stabilized road width is the width of the road subgrade. Sufficient room should be left on the low side to accommodate debris.

<sup>b</sup> Turnout width includes stabilized road width.

## ***Fill slope and cut slope angles***

Stable cut slopes, road fills, borrow pits, quarries, and waste areas should be designed and constructed in a manner that will not contribute directly or indirectly to slope failures or landslides over the expected design life. Table 5 provides general guidelines for cut and fill slope angles for use in forest road design.

### **Fill slopes**

The stability of a fill slope depends on several variables, including the forces that tend to cause instability (gravitational and water pressure forces), and the forces that tend to oppose instability (e.g., shear strength resistance of the soil or rock materials expressed as an internal friction angle or cohesion).

The stability of an embankment fill can be increased several ways:

- Construct the side slopes of fill embankments at a gentle angle, and usually not steeper than the “angle of repose.” The term “angle of repose” should be used in the context of loose, cohesionless soils only (e.g., non-plastic silt, sand, sand and gravel). Constructing flatter side slopes in all types of soil will reduce the gravitational forces that tend to cause slope instability. For a fill slope in cohesionless material, the angle of repose is about the same as the *minimum* value of that material’s angle of internal friction. Steeper fill slopes are more likely to cause a road-induced slope failure or landslide than flatter fill slopes.
- Compact the fill materials to make them more dense and increase the shearing resistance of the soil. The angle of internal friction depends primarily on the relative density (loose versus dense), the particle shape (round versus angular), and the gradation (uniformly graded versus well graded). For relatively loose cohesionless soils, the minimum value of the angle of internal friction will range from about 27 degrees (2H : 1V) for rounded uniform soil grains to 37 degrees (1½ H : 1V) for angular, well-graded soil grains. For relatively dense cohesionless soils, the maximum value of the angle of internal friction will range from about 35 degrees (1½ H : 1V) for rounded uniform soil grains to 45 degrees (1H : 1V) for angular, well-graded soil grains.

**Note:** Fill slopes that are constructed at or less than the angle of repose (minimum angle of internal friction) will not necessarily remain stable if partial or full saturation of the fill occurs. Such saturation can result from surface and subsurface water flows during spring melt or after heavy periods of rainfall.

- Where necessary, provide good drainage of the fill to reduce the build-up of water pressure forces along potential planes of sliding within the fill. Expect that poorly drained fill materials will be prone to a greater likelihood of slope failure or sloughing than well-drained fill materials. Additionally, the slopes of poorly drained fills at locations of significant

zones of ground water seepage may experience larger and greater frequency of slope failures or sloughing problems. The significance of observed seepage zones might dictate the application of special drainage measures to reduce the likelihood of slope failure during construction and the intensity of maintenance activities over the operating life of the road. As a general rule, without special drainage measures, the side slopes of poorly drained fills (e.g., fills composed of silty soils) should be constructed at angles that are flatter than the angle of repose to minimize the likelihood of slope failures.

### **Cut slopes**

The design of cut slopes should consider and address factors such as the desired performance of the cut slopes, types of cut slope materials, issues about overall terrain stability, engineering properties of soils, seepage conditions, construction methods, and maintenance. In general, cut slopes will remain stable at slightly steeper angles than fill slopes constructed from like soil materials. The reason for this is the undisturbed soil materials in a cut (1) are often in a denser state than similar type materials placed in a fill, and (2) may contain sources of cohesive strength that further increases the shearing resistance of the soil.

Cut slopes constructed at too flat an angle can be uneconomical in steep ground because of the large volumes of excavation. Steeper cut slopes may be more economical to construct in terms of reduced volumes of excavation. However, they can also be more costly from an operational standpoint because they require more road maintenance.

For most forest roads, cut slope angles are generally designed to favour steeper angles to reduce the length of cut slopes, to minimize visible site disturbance, and to reduce excavation costs, provided that a somewhat higher level of road maintenance and likelihood of slope destabilization is acceptable for the site.

In the latter case, prepare and implement a maintenance schedule that addresses the erosional processes acting on the exposed cut slope face (such as splash, sheet, rill, and gully erosion) and reduces the threat to drainage systems (as a result of cut bank slope failure redirecting ditchwater flows onto potentially unstable fill or natural slopes), user safety, and the environment.

It may be necessary to construct flatter cut and fill slopes, or to build retaining wall structures to support cut slopes or fill slopes, in cases where slope stability problems are expected to be difficult to manage with maintenance measures alone.



**Table 5.** General guidelines for cut and fill slope angles for use in forest road design.

Cut Slopes			Fill Slopes	
	Examples of Material Types <sup>a</sup>	Suggested Cut Slope Angles <sup>b</sup> for Cut Bank Height < 6 m <sup>c</sup>	Examples of Material Types <sup>a</sup>	Suggested Fill Slope Angles <sup>b</sup>
Coarse-grained Soils <sup>d</sup>	Road cuts in loose to compact SANDS or SANDS and GRAVELS (not cemented and non-cohesive)	1½ H : 1 V	Road fills composed predominantly of SANDS, or SANDS and GRAVELS, or drained <b>mixtures</b> of coarse-grained and fine-grained soils	1½ H : 1 V
Fine-grained Soils	Road cuts in loose SILTS, or soft cohesive soils such as SILTY CLAYS or CLAYS (not consolidated and not cemented)	1½H : 1V for lower cuts to 2H : 1V for higher cuts	Road fills composed predominantly of SILTS or CLAYS <sup>e</sup>	2H : 1V
	Road cuts in hard cohesive soils such as SILTY CLAYS or CLAYS (consolidated)	1H : 1V or flatter		
Dense Glacial Till / Cemented Sands and Gravels	Road cuts in dense to very dense GLACIAL TILL (i.e., basal till), or cemented SANDS or SANDS and GRAVELS	¾H : 1V or flatter	See above for coarse-grained soils	See above for coarse-grained soils
Rock <sup>f</sup>	Road cuts in strong, good quality ROCK masses with no significant weaknesses	¼H : 1V to vertical	Road fill composed predominantly of individually placed and locked together (not dumped) good quality angular blasted or ripped ROCK	1H : 1V
	Road cuts in other ROCK types should be flatter to include any weaknesses from the effects of structural discontinuities in the rock mass, and other factors such as the strength of the rock material, and the spacing, aperture, roughness, filling, weathering, and orientation of discontinuities	¼H : 1V to 1¼H : 1V	Road fill composed predominantly of dumped angular ROCK or placed rounded ROCK	1¼H : 1V to 1½H : 1V

### Notes for Table 5:

- <sup>a</sup> Not all material types in the soil groups are represented in the table.
- <sup>b</sup> For the design of roads located in domestic watersheds, on sensitive terrain, or in other areas where transport of sediment or landslides may adversely affect resources, it may be necessary to use flatter cut and fill slope angles to reduce the hazard of erosion or failure of cut and fill slopes. During construction of roads, it may be necessary to build flatter slopes where the road prism exhibits signs of distress, such as, for example: (1) cracks or scarps within original ground above the top of cut slopes, in the road surface, or within the fill slope on the downslope side of the road; and (2) significant zones of ground water seepage such that localized failure of cut or fill slopes are expected. Alternatively, installation of retaining wall structures may be needed to reduce excavation, contain bank material, or prevent slope failure. The significance of observed seepage zones might dictate application of other special measures to reduce the likelihood of slope failure during construction and over the operating life of the road.
- <sup>c</sup> Consider the need to obtain advice from a qualified registered professional for cut heights greater than 6 m. The advantages of steeper cuts may include: less area occupied by road; less excavated material; less sidecast; and shorter slope lengths exposed to erosion processes. The disadvantages of steeper cuts may include: increased difficulty to establish vegetation; increased chance of slope raveling, tension crack development and slope failure; and increased road maintenance costs. The disadvantages of steeper cut slopes can be reduced if high banks are avoided.
- <sup>d</sup> Erosion control may be particularly problematic for slopes composed of sand, silty sands, or silts. Consider the need for erosion protection measures for cut slopes, fill slopes, and ditches, such as revegetation, soil bioengineering and biotechnical slope stabilization techniques, rip rap, or other special slope treatments.
- <sup>e</sup> If significant compaction of the road fills can be achieved, then fill slopes (of limited height) may be placed steeper than 2H : 1V.
- <sup>f</sup> If potential problems are anticipated for rock slopes either during design, construction, maintenance, or deactivation, consult with a geotechnical engineer or other rock slope specialist. It may be necessary to address the need for special rock slope stabilization measures (e.g., rock-fall catch ditch, wire mesh slope protection, shotcrete, rock bolts).

### ***Clearing widths***

Clearing widths should be as narrow as possible, to minimize impacts on other resources, but wide enough to accommodate:

- the road prism
- user safety
- turnouts
- subgrade drainage
- subgrade stability
- waste areas and endhaul areas
- pits and quarries
- landings
- slash disposal
- equipment operation
- snow removal
- fencing and other structures
- standing timber root protection, especially on cut banks.

Organic debris, rock, or any other excess material that cannot be placed in the road prism and within the clearing width because of terrain stability or other factors should be moved to waste areas. Such areas should be of suitable size to accommodate the estimated volume of waste material and should be identified in the road design.

Clearing widths are calculated on a station-by-station basis as part of a geometric road design. In situations where geometric road design is not required, other methods can be used. For further details, see Chapter 3, “Road Construction” and clearing width tables in Appendix 5.

### ***Culvert drainage design***

Refer to Chapter 4, “Road Drainage Construction,” for guidance on culvert drainage design.

### ***Other structures***

A professional engineer must take design responsibility for cattleguard fabrication, the construction or modification of retaining walls greater than 1.5 m high, and the design of other specialized structures that fall within the practice of a professional engineer.

## Suggestions for further reading

- British Columbia Institute of Technology (BCIT). 1984. *Manual for Roads and Transportation*. Vol. 1 and 2. Burnaby, B.C.
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- Canadian Standards Association. 1997. *Risk Management: Guideline for Decision-makers*. National Standard of Canada CAN/CSA-Q850-97.
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## 2. Design and Construction of Bridges and Stream Culverts

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### Introduction

This chapter describes some of the activities and practices that precede and follow the construction of forest road bridges and stream culverts. These include:

- design requirements for bridges and stream culverts
- bridge and major culvert design responsibility
- site data and survey requirements for bridges and major culverts
- construction drawings and specifications for bridges, major culverts, and stream culverts on fish streams
- site data and survey requirements for culverts on non–fish-bearing streams
- estimating design discharge for streams
- statement of construction conformance and documentation.

The *Forest Service Bridge Design and Construction Manual* (B.C. Ministry of Forests 1999) provides further discussion on planning, design, and construction of forest road bridges.

Consistent with the Forest Road Regulation, in this chapter:

- “bridge” means a temporary or permanent structure carrying a road above a stream or other opening
- “culvert” means a transverse drain pipe or log structure covered with soil and lying below the road surface
- “cross-drain culvert” means a culvert used to carry ditchwater from one side of the road to the other
- “major culvert” means a stream culvert having a pipe diameter of 2000 mm or greater, or a maximum design discharge of 6 m<sup>3</sup>/sec or greater
- “stream culvert” means a culvert used to carry stream flow in an ephemeral or perennial stream channel from one side of the road to the other.

Refer to Chapter 4, “Road Drainage Construction” for further information on forest road drainage systems including; temporary stream crossings, ditch construction and cross-drain culverts, log culvert design and construction, and ford design and construction.

## Design requirements for bridges and stream culverts

The design of bridges and stream culverts encompasses more than the design of structural components. A bridge or stream culvert design should consider the composition and interaction of all the components, as well as their relationship and impact to the users, road, and stream. A bridge comprises the superstructure, substructure, connections, vertical and horizontal alignment controls, approach road fills, and scour protection works. Similarly, a stream culvert comprises the culvert materials, compacted backfill, scour protection, and roadway. Bridge or stream culvert designs include, but are not limited to, consideration of:

- user safety
- site selection
- environmental integrity
- fish habitat and passage
- impact of proposed structure on stream during and after construction
- site revegetation requirements
- structure alignment and location (vertical and horizontal) relative to the road and stream channel
- complete structure combination (substructure, superstructure, connections, and scour protection)
- suitability of selected foundations for the specific site
- design flood development
- navigation (*Navigable Waters Act*)
- debris potential and passage
- scour protection
- design vehicle configuration for load and alignment
- design service life influence on selection of bridge type and composition
- construction layout, methodology, and timing
- economics.

## Bridge and major culvert design responsibility

Bridge designs should clearly identify who is taking overall design responsibility (whether a professional engineer, professional forester, or non-professional) for ensuring that all aspects of the design have been appropriately addressed. In addition, a person required to prepare a road layout and design must ensure that a professional engineer takes design responsibility for major culverts.



### ***Non-professional and professional forester bridge design***

Subject to specified constraints, a role is recognized for non-professionals and professional foresters with considerable experience in designing and constructing shorter, single-span structures. These are non-complex, standard width, non-composite structures, with relatively straight road alignments. They are constructed with conventional materials, on simple abutment supports, founded on excavations in original ground or on a shallow ballast layer. A professional engineer should assume responsibility for design of longer spans, higher abutments, and more complex bridge structures.

#### **Bridge design limitations**

Design by non-professionals is limited to single spans with a maximum of 6 m centre-to-centre of bearing. Professional foresters are limited to single-span bridges with 12 m centre-to-centre of bearing or less.

For non-professional design, rip rap should not be required, as all bridge components (including rip rap or scour protection) are located outside of the design flood wetted perimeter. Where any components infringe or potentially infringe on the design flood wetted perimeter, design flood forces on these components should be considered and this part of the design must be completed by a professional engineer.

The stream should be historically stable, in a well-defined channel, with erosion-resistant banks, which are not subject to erosion or shifting in flood flows, such as would be the case on an alluvial fan.

The bridge abutments must be constructed on or below original ground or on a shallow ballast layer. This shallow ballast layer is intended to act only as a levelling surface to provide full bearing.

Note that the bridge superstructure must be non-composite. A composite bridge is one where a deck and girders are intimately connected such that they act as a unit to support the design load. These complex structures require a greater level of technical knowledge with respect to design and installation. Other structures included in this category are those with components that do not act independently of each other, such as concrete slab or box girders with welded or grouted shear connectors, or structures requiring field welding during installation.

Note also that welding is influenced by many factors, including: welder training and experience, type of weld (such as: rectangular groove, flat, vertical overhead, fillet, butt), welding equipment, welding rods, welding rate, ambient temperature and moisture, materials being welded, and so on. It is not possible to fully gauge the adequacy of a weld through only visual inspection. Since many structures require field welds, anyone considering design and erection of welded structures should ensure that persons with adequate

training and experience are involved and responsible for all aspects of weld design and welding procedures.

Where shop or field welding is required, designs should indicate the minimum qualifications required. Use of Canadian Welding Bureau (CWB) certified firms and qualified welders is recommended.

Abutment heights, from the foundation level to the top of the abutment on which the superstructure would bear, are limited to log cribs less than 4 m in height or sills or pads up to 1.5 m in height. For log cribs, the 4 m height limitation is measured from the bottom of abutment where it bears on the ground to the top of the bearing sill or bridge soffit (underside of bridge superstructure).

Abutments that are not log cribs are limited to 1.5 m in height. Sills and caps are transitions to connect the superstructure to the substructure. They are not considered part of the maximum allowable abutment height, provided the transition depth is not excessive (a maximum sill or cap height of 400 mm is suggested), and that the sills, caps, and the connections have been produced from design aids prepared by a professional engineer for use in the proposed configuration.

Note that abutment heights are not cumulative; for example, a 1.5 m abutment is not intended to be designed to bear on top of a log crib or its fill. Binwalls are not considered log crib equivalents. Binwall abutments are more complex, requiring bearing of sills or pads on significant compacted fill depths, and must be designed by a professional engineer.

Bridge designs by non-professionals and professional foresters must be prepared using structural details provided in drawings, tables, charts, and other design aids that have been prepared by a professional engineer. Each bridge or major culvert must have its own site-specific design. The bridge components (superstructure, substructure, connections) must all have been designed to be used in the specific combination and configuration shown in the design. Any design aids used should be referenced on the design drawings or attached documentation.

Where portable bridges are used, the structure must have been designed or structurally analyzed by a professional engineer. The design or analysis should demonstrate adequacy for the intended use. Once the structure has been reviewed and approved by a professional engineer, the structure may be reused at new sites without specific professional engineer review, provided that:

- a qualified inspector has inspected the bridge at the new site before any use and detects no damage or deterioration of the structure;

- the design loads to be carried should be equal to or lower than original design loads; and
- the bridge is suitable and has been specifically designed for the new site, and the superstructure has been fabricated and constructed in compliance with the Forest Road Regulation.

The professional engineer, professional forester, or person assuming responsibility must sign off on the design for the bridge or major culvert and becomes the designer of record.

## **Site data and survey requirements for bridges and major culverts**

The person assuming design responsibility for a bridge or major culvert requires site-specific information for the proposed crossing. A detailed site survey (see Appendix E, “Bridge and Major Culvert Site Plan Specifications” in the *Forest Service Bridge Design and Construction Manual*) is recommended for all bridges and major culverts. The survey information is used to produce site plan and profile drawings for planning, developing, and evaluating the crossing design. Direction for the type and quality of site information to be collected and the site survey to be completed should be obtained from the designer. Included should be:

- the riparian class for streams or lake classification
- the apparent high water elevation of the stream, based on visible evidence of recent flooding
- a description of the composition and size of stream bed materials
- a description of stream bank materials and stream stability
- cross-sections and a profile of the crossing
- the stream flow velocity and direction, if the flow may influence the size or layout of the structure
- a description of the soil profiles and foundation soil conditions, based on soil explorations appropriate to the level of risk
- presence (or absence) of bedrock, and depth to, bedrock
- a description of any evidence of stream debris or slope instability that could affect the crossing, based on upstream observations
- any existing improvements or resource values in the vicinity that may influence the size or layout of the structure.
- if there is an existing structure, location and dimensions of the structure, including roadway, abutment, superstructure, and stream information
- the date of the survey
- the locations and dimensions of any upstream structures, and a note about whether they are problem-free

- any other pertinent information: Is the site currently accessible by road? Are there road or bridge restrictions on load length or weight? How can these be overcome? If test drilling seems likely, how much work is required to get a drilling truck (usually not all-wheel drive) to the site?
- if equipment fording will be necessary for construction, information about possible ford locations and other considerations such as depth of stream at that point, bottom material, and access gradients

If a fish stream is involved, the *Fish-stream Crossing Guidebook* (B.C. Ministry of Forests 2002) should be consulted for additional site requirements.

## Construction drawings and specifications

General arrangement drawings are the outcome of the design process and show the location, composition, and arrangement of the proposed structure in relation to the crossing. Site plan and profile drawings are design aids from which a proposed design is developed; they are not general arrangement drawings.

A set of construction drawings consists of the general arrangement drawings supplemented with detailed superstructure and substructure drawings and other fabrication, material, and construction specifications. Shop drawings are prepared by material fabricators to detail, and in many cases complete the structural design of bridge structure components. These drawings will form part of the construction drawing set and should be retained as part of the as-built documentation. The complete construction drawing set should provide comprehensive details on the location, composition, arrangement, design parameters, and fabrication, materials, and construction specifications for the specific proposed structure and is intended to be an integral part of the planning process, completed before construction begins.

Typical scales for bridge and major culvert design and construction drawings are 1:200, 1:100, and 1:50. The construction drawings should clearly show all construction details and enable installation in general conformance with the design intent. Where appropriate, a smaller scale should be used for greater detail.

### **General bridge arrangement drawing requirements**

General arrangement drawings should clearly depict the proposed components and configuration of the bridge or major culvert in relation to the forest road, stream, and stream banks. These drawings may also be used during the agency referral process. Further details can be found in the *Forest Service Bridge Design and Construction Manual*.

Recommended contents for bridge and major culvert general arrangement drawings comprise:

- designer's name (and seal, if applicable)
- name of the stream, road, and station (km) and adequate information to detail the location of the structure
- design vehicle configuration for load and alignment
- design code references—specifically, those from the most recent version of the *Canadian Highway Bridge Design Code* and the *Canadian Foundation Engineering Manual*
- expected life of the structure in place (temporary or permanent)
- design high water elevation for bridges
- clearances between the design high water level and soffit (low point of underside of superstructure) of bridges
- details of debris passage or management strategies, if required
- road approaches, including width requirements (including allowance for vehicle side tracking) and side slopes, to a sufficient distance back from the bridge to show problems, or to the end of the first cut or fill
- dimensioning and labelling of component parts
- drawings scales
- relevant site plan and profile data; for suggested contents see above section on “Site data and survey requirements for bridges and major culverts” (sample general arrangement drawings are shown in Figures 4 and 5)
- location (vertical and horizontal) of proposed structure relative to field reference points
- possible ford locations
- special provisions related to the unique nature of the site and crossing, including specific instructions to bidders related to process or results, as appropriate
- references to specific design drawings or design aids used.

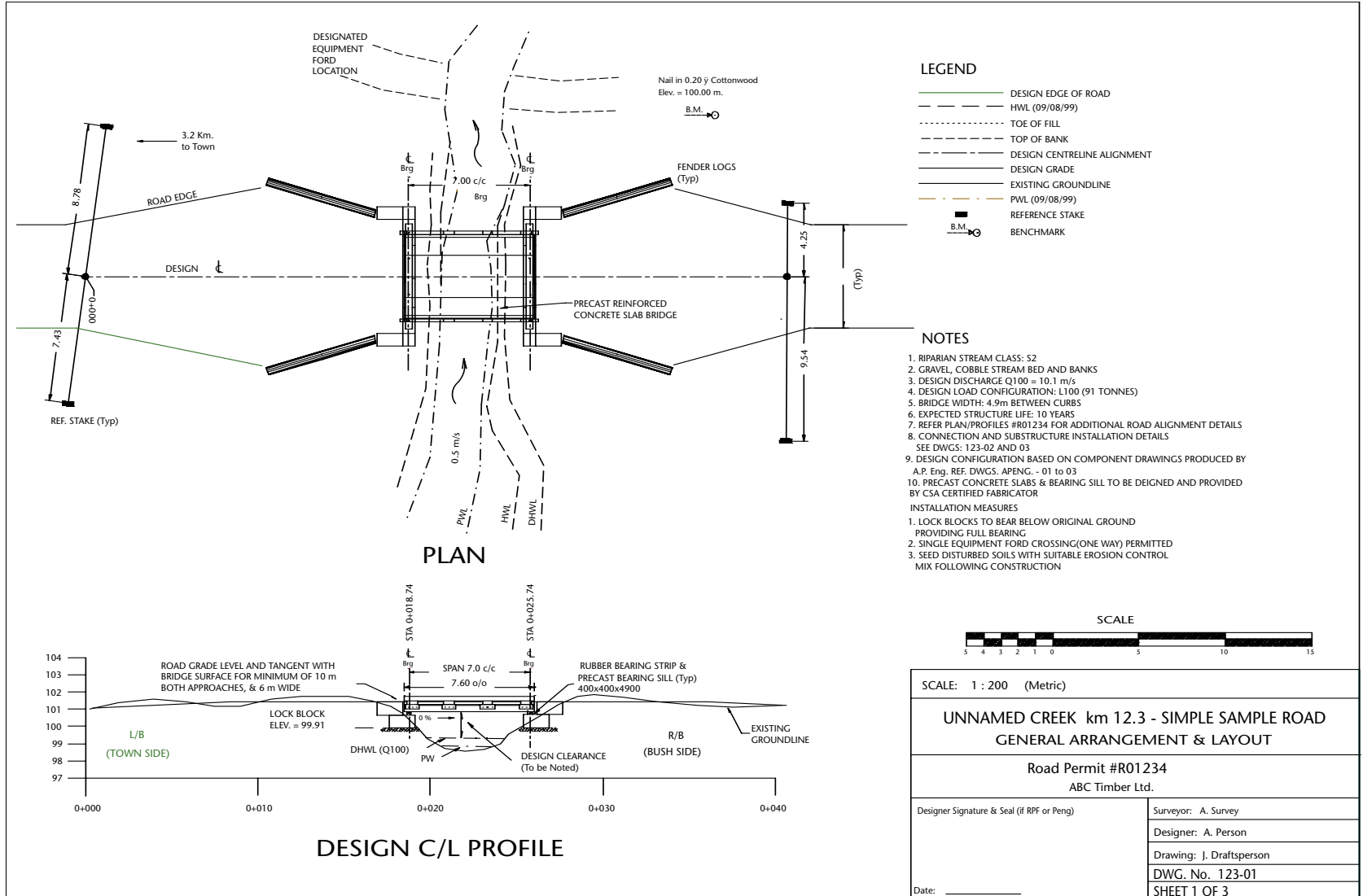


Figure 4. Sample of general arrangement and layout (simple creek crossing).

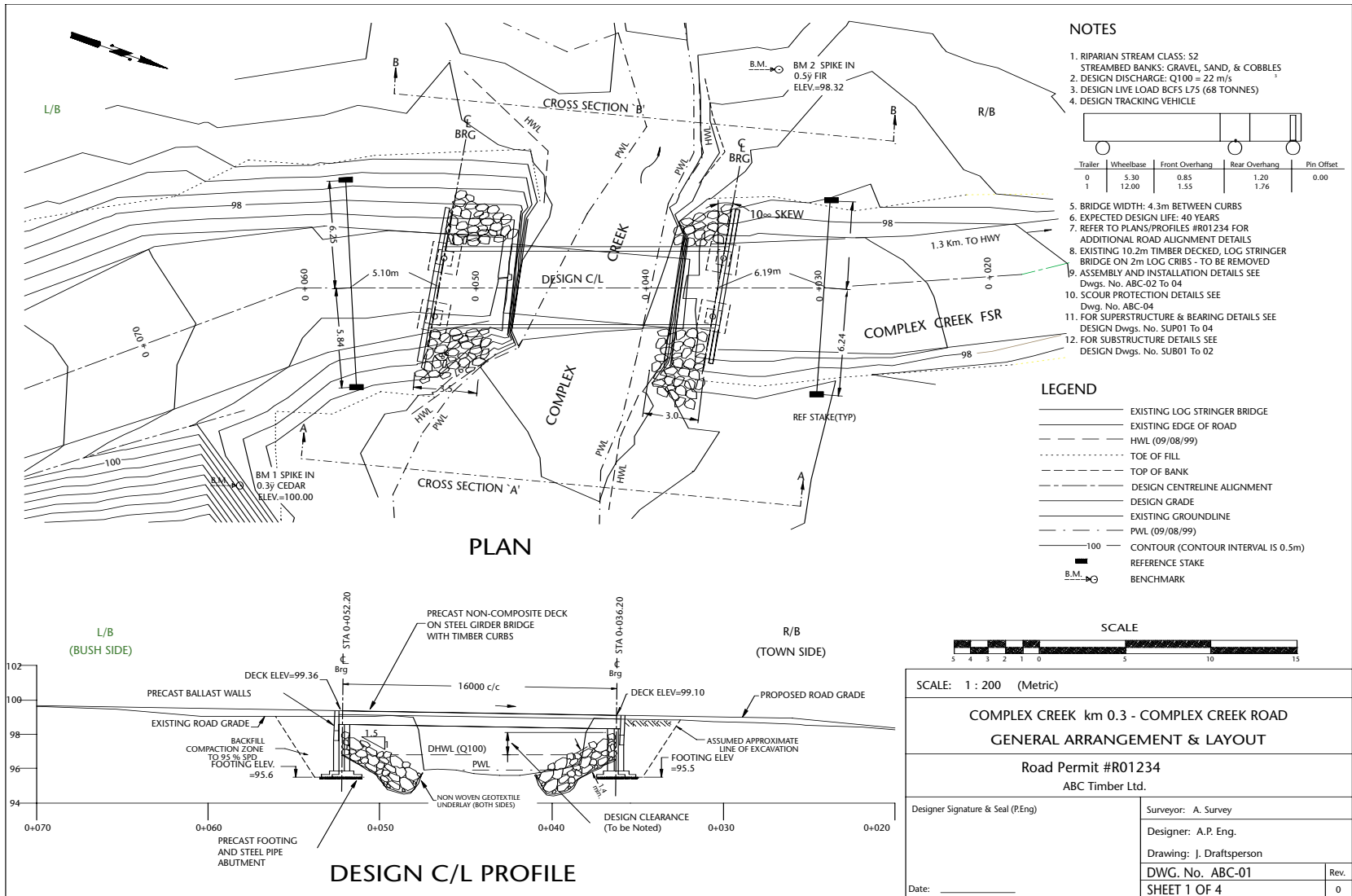


Figure 5. Sample of general arrangement and layout (complex creek crossing).

### ***Bridge superstructure drawing requirements***

In addition to the general drawing requirements, the following elements should be detailed on bridge superstructure drawings:

- design code references—specifically, those in the latest edition of the *Canadian Highway Bridge Design Code* and the *Canadian Foundation Engineering Manual*
- materials specifications and CSA references, including but not limited to:
  - steel grades, impact category, finish
  - timber species, grades, preservative treatment
  - concrete strength, slump, and air entrainment
  - rip rap and geosynthetics
  - bearing materials and connections
- superstructure elements, configuration, and connections
- dimensions and sizes of components
- girder or stringer arrangements and connections
- span lengths
- bridge and road width
- deck elevations at bridge ends
- road and bridge grades and alignment
- deck configuration, connections, and component elements
- curb and rail configuration, connections, and component elements
- field fabrication details.

### ***Bridge substructure drawing requirements***

The following information on foundation requirements should be detailed on the bridge substructure drawings:

- abutment elements, configuration, and connections
- dimensions and sizes of components
- critical elevations of substructure components
- scour protection: dimensions, composition, extent of placement, design slope, and other considerations
- piers
- location and sizes of piles or posts
- pile driving specifications, minimum expected pile penetrations, set criteria, and required service level capacities
- bracing and sheathing configurations.



### ***Log bridge superstructure on log crib drawing requirements***

Since log stringer and crib materials are variable in nature and finished dimensions are not uniform, log bridge drawings will be somewhat schematic. Drawings should address layout, required component sizing, and connection details.

The following should be indicated on the log bridge superstructure and log crib drawings:

- schematic layout indicating width and span
- reference source for stringer and needle beam sizing
- minimum stringer, curb, and needle beam dimensions
- stringer, curb, needle beam, and crib logs specifications, including species, quality characteristics of acceptable logs, and seasoning
- stringer to cap bearing details, including shim types and stringer and cap bearing width and surface preparation
- dap details at log connections
- needle beam locations and connection details, if applicable
- space to add stringer, curb, and needle beam sizes as part of the as-built record
- deck layout, indicating tie sizes and spacing, plank thickness, and connections
- other materials specifications, including sawn timber, hardware, and shims
- excavated depth relative to scour line for mudsill or bottom bearing log
- general layout and arrangement of front, wing wall, deadman, and tieback logs, and their connections to each other and to the bearing log or cap
- description of crib fill material
- layout and description of in-stream protection, if applicable
- rip rap protection layout and specifications (as required).

### ***Major culvert and fish stream culvert drawing requirements***

Drawings and notes for major culverts, and for stream culverts not classified as major culverts and installed on fish-bearing streams, should portray and describe the following:

- site plan (see previous section on “Site data and survey requirements for bridges and major culverts”)
- location of the culvert, such as a key map
- design vehicle load

- fill height, depth of cover, and maximum and minimum cover requirements
- design slopes of fill and rip rap
- culvert invert elevations at the inlet and outlet
- culvert specifications and dimensions—opening dimensions, length, corrugation profile, gauge, and material type
- site preparation requirements
- embedment requirements, including a description of the substrate and any rock used to anchor the bed material in the pipe
- backfill and installation specifications
- installation camber
- culvert slope
- special attachments or modifications
- inlet requirements (rip rap layout, stilling basin, etc.)
- outlet requirements (rip rap layout, stilling basin, backwater weir for fish passage)
- rip rap specifications, including dimensions and configuration
- design high water elevation and design discharge
- connection details for pipe sections
- any existing improvements and resource values in the vicinity of the culvert that would influence or be influenced by the structure.

Any of the foregoing requirements can be combined. For example, drawings for a log stringer bridge on timber piles can include the details from “Log bridge superstructure on log crib drawing requirements,” plus those from “Bridge substructure drawing requirements.”

Any additional requirements for a fish stream culvert should be included as specified in the *Fish-stream Crossing Guidebook*.

## **Culverts on non–fish-bearing streams**

A detailed site plan is usually not required for stream culverts not classified as major culverts or those installed on non–fish-bearing streams. However, a minimum amount of information should be recorded during the road location survey to assist in sizing such a stream culvert for the 100-year flood return. Where conditions are such that there are complex horizontal and vertical or other control issues requiring higher-level design and installation procedures, detailed site plans are recommended.

In planning the layout of the structure:

- Choose an appropriate location, along a stream reach with uniform or uniformly varying flow close to the proposed crossing, to measure a cross-section. Sketch the cross-section of the stream gully, showing evidence of the high water level, present water level, and the depth of the stream across the bottom. The cross-section should extend back from the stream an appropriate distance to show the terrain that affects the proposed crossing and road alignment.
- Note any visual evidence of high water.
- Measure and record the average gradient of the stream at the crossing and at the cross-section if the two are taken at different locations.
- Record the soil type, soil profile, parent material, and substrate material at the crossing and describe the stream bottom.
- Describe the stream channel (debris loading, bank stability, crossing location on a fan, bedload problem, etc.).

If the site is a fish stream or a potential fish stream, the *Fish-stream Crossing Guidebook* should be consulted for site and design requirements.

## **Estimating design discharge for streams**

The following guidelines apply to determining the design discharge for streams for a particular recurrence interval. Establishing a return period provides a benchmark of the relative risk to be attached to any particular design.

These guidelines should not preclude use of other reasonable and accepted methods for determining the design discharge. Professional engineers, who in the course of carrying out their professional functions as designers of a bridge or a major culvert (2000 mm or greater in diameter or with discharges of 6 m<sup>3</sup>/sec or greater), are ultimately responsible for establishing the design discharge for that structure. Others determining stream discharges should be familiar with methods and their limitations, or consult those with training and experience in stream discharge determination.

### ***Factors affecting runoff***

The runoff and behaviour of a stream depends on many factors, most of which are not readily available or calculable, such as:

- rainfall (cloudbursts; hourly and daily maxima)
- snowpack depth and distribution, and snowmelt
- contributory watershed area, shape, and slope
- topography and aspect
- ground cover

- soil and subsoil
- weather conditions
- harvesting and road or other upslope development
- drainage pattern (stream order, branchiness; lakes and swamps)
- stream channel shape, length, cross-section, slope, and “roughness.”

Because topography, soil, and climate combine in infinite variety, drainage for specific sites should be designed individually from available data for each site. In addition, the designer should consult those who have long experience in maintaining drainage structures in the area.

### Some methodologies to estimate design flood discharge

There are too many analytical and empirical methods for estimating stream discharge to be discussed at any length in this guidebook. Methodologies commonly used involve:

- working from available evidence of flood flows in the specific stream;
- gathering evidence of flood flows in other streams, relating these to their drainage basin characteristics, and then, from the characteristics of the basin under consideration, estimating a flood flow; or
- relating meteorological data to stream basin characteristics and estimating flood flow through empirical methods.

The necessary data for these methodologies can be obtained from several sources:

**Site information:** Site data at and adjacent to the proposed crossing can be used to determine the maximum flow. Records of culverts and bridges within the vicinity that have successfully withstood known flood events can be used to develop flood flows.

**Stream basin characteristics:** Stream basin characteristics such as length, slope, order, roughness, vegetative characteristics, and elevation band, combined with meteorological data, can be used in empirical approaches to determine design flood flows.

**Data on other streams:** Studies done on other streams in the vicinity, with similar characteristics, can provide relationships and comparative values.

**Hydrometric records:** The Water Survey of Canada provides, in its Surface Water Data, annual reports of readings on hydrometric stations throughout the province. In addition, it publishes Historical Stream Flow Summaries in which mean values and annual peaks are tabulated. These stream flow records can be used to project design flood flows from theoretical analysis.

### ***Comparing discharges using hydrological information***

Determining design flood discharge usually involves applying several different methods and then using judgement to select an appropriate design value. In all stream flood discharge determinations, it is prudent to compare the proposed opening size with historically problem-free existing stream crossings serving similar drainages in the same area.

The designer should compare the flood discharge estimates derived from the site information with other data and theoretical derivations. The final selection of design discharge and resulting bridge opening or major culvert size should then be based on the designer's judgement, taking into account these comparisons, together with consideration of debris potential, ice jams, or other local factors that might influence the structure opening.

### ***High water estimation method for stream culverts***

Application of this method for determining the  $Q_{100}$  from site information should be limited to non-major stream culverts—less than 2000 mm in diameter or less than 6 m<sup>3</sup>/s design discharge. It is not appropriate for use as the sole method for “professional” designs.

This method assumes that the high water width represents the mean annual flood cross-sectional flow area for the stream ( $Q_2$ ); and that the  $Q_{100}$  cross-sectional flow area is three times this. It also assumes that the discharge is not sensitive to influences from pipe slope, roughness, or other factors. These assumptions are not truly representative of all situations, but, within the accuracy expected for establishing design discharge, should be acceptable for sizing stream culverts smaller than 2000 mm diameter or 6 m<sup>3</sup>/s on forest roads.

The high water width is defined as the horizontal distance between the stream banks on opposite sides of the stream, measured at right angles to the general orientation of the banks. The point on each bank from which width is measured is usually indicated by a definite change in vegetation and sediment texture. Above this border, the soils and terrestrial plants appear undisturbed by recent stream erosion. Below this border, the banks typically show signs of both scouring and sediment deposition. The high water width should be determined from recent visible high-water mark indicators, which would approximate the mean annual flood cross-section. This point is not necessarily the top of bank, particularly in the case of an incised stream.

- Locate a relatively uniform stream reach in close proximity to the proposed culvert location. Note that this not an averaging process that would be used for determining the stream channel width for the purpose of assessing stream habitat impacts. A uniform stream reach would have a consistent cross-section, bed materials, and channel slope. It would also be relatively straight.

- Estimate the visible high water stream width and cross-sectional area.
  - a) Measure (in metres) the high water width at a relatively uniform reach of the stream, representative of the mean annual flood ( $W_1$ ) and at the stream bottom ( $W_2$ ) (see Figure 6).
  - b) Measure the depth of the stream at several spots across the opening to obtain the average depth ( $D$ ) in metres.
  - c) Calculate the cross-sectional area of the stream,  $A = (W_1 + W_2)/2 \times D$ .
- Calculate the area of the required culvert opening,  $A_c = A \times 3.0$ .
- Size the pipe (see Table 6), using the smallest pipe area that exceeds the required area, or select an opening size for a log culvert that will be greater than  $A_c$ .

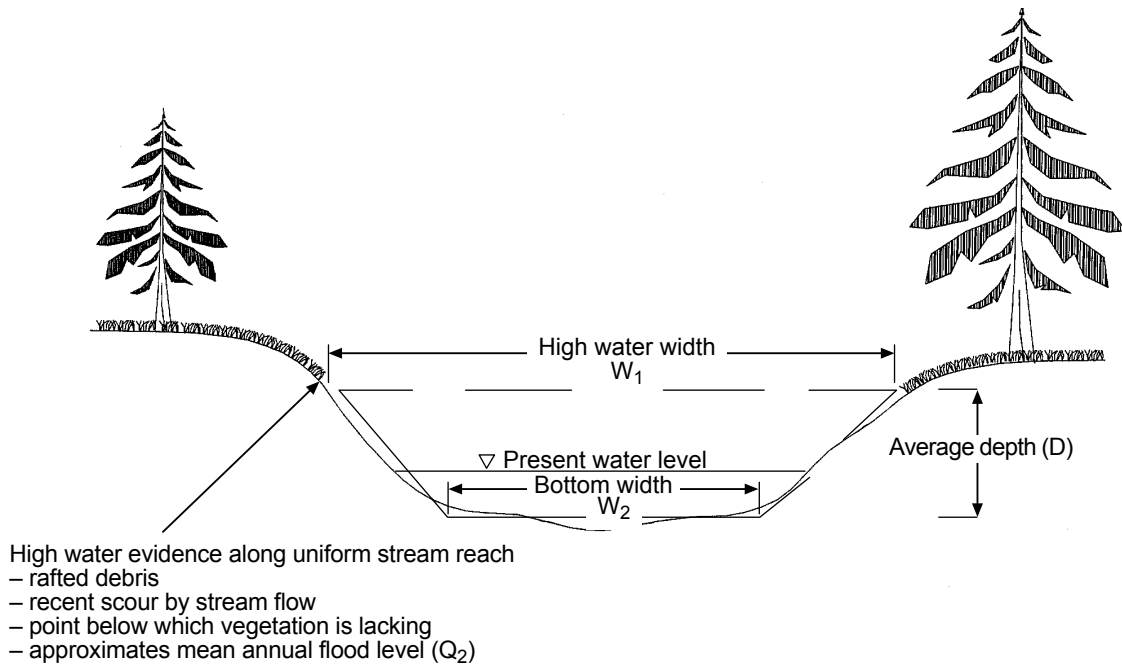
The high water width method can be cross-checked if field or other evidence of an approximate 10-year flood is available. In this case, the area of the  $Q_{10}$  flood can be multiplied by 2 to estimate the minimum culvert area for the  $Q_{100}$  flood.

### Example

If  $W_1 = 1.2$  m  
 $W_2 = 0.8$  m  
 $D = 0.5$  m  
stream cross-sectional area  $A = 0.5$  m<sup>2</sup>

Then  $A_c = 0.5 \times 3.0 = 1.5$  m<sup>2</sup>

Therefore (from Table 6), the required pipe culvert size = 1400 mm.



$$\text{High water width cross-sectional area} = \frac{(W_1 + W_2)}{2} \times D$$

Figure 6. High water width cross-sectional area.

Table 6. Round pipe culvert area ( $A_c$ ) versus pipe diameter.

$A_c$ (m <sup>2</sup> )	Pipe Diameter (mm)
0.13	400
0.20	500
0.28	600
0.50	800
0.64	900
0.79	1000
1.13	1200
1.54	1400
2.01	1600
2.54	1800

### General conformance and construction documentation

After construction of a bridge, major culvert, stream culvert, or other specialized structure, the person responsible (non-professional, professional forester, or professional engineer) must sign (and seal, as appropriate) a statement indicating that the entire structure is in general conformance with the design drawings and specifications.

Where a professional forester has taken design responsibility for a bridge, a professional forester or a professional engineer must provide a signed and sealed statement that the bridge is in general conformance with the design drawings and specifications.

Where a professional engineer has taken design responsibility for a bridge, a professional engineer must provide a signed and sealed statement that the bridge is in general conformance with the design drawings and specifications.

A sample statement of construction conformance is located in Appendix 4.

Documentation of materials used, and as-built records for the bridge or major culvert, should be obtained during fabrication and construction. The person responsible for construction should obtain and retain as-built records, including:

- any pile driving records, hammer type, penetration, set criteria, etc.
- fabrication plant inspection reports, including mill test certificates, concrete test results, etc.
- shop or as-built fabrication drawings
- concrete and grout test results
- field compaction results
- other pertinent fabrication, field, and construction data.

As-built drawings are the “approved for construction” drawings—which may be the approved design drawings—marked up to show all significant variations from the original design. For example, mark-ups would show as-constructed details such as precise location in plan, finished pile depths, footing elevations, deck and other finished elevations, finished dimensions, and configurations of components. The as-built drawings should be signed (and sealed, where applicable) by the individual taking responsibility for the as-constructed structure being in general conformance with the design. Where the original design has been modified, these drawings should have been amended by the designer, before inserting the as-built notes and details.

The as-built drawings, materials records, fabrication documentation, and other field and construction documentation must be retained for the life of the structure.



## Suggestions for further reading

- American Iron and Steel Institute. 1984 (3rd Printing, May 1995). *Handbook of Steel Drainage & Highway Construction Products*. Canadian Edition. New York, N.Y.
- British Columbia Ministry of Forests. 2002. *Fish-stream Crossing Guidebook*. Victoria, B.C.
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