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Debris Flow Control Structures for Forest Engineering

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D.F. VanDine

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Prepared by
D. F. VanDine
for
B.C. Ministry of Forests
Research Branch
31 Bastion Square
Victoria, BC V8W 3E7

Copies of this report may be obtained, depending upon supply, from:
B.C. Ministry of Forests
Forestry Division Services Branch
Production Resources
1205 Broad Street
Victoria, BC V8W 3E7

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FIGURES

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1 INTRODUCTION

This report summarizes the results of a study on the use of debris flow control structures in forest engineering. The purposes of the study were:

- to review and assess the viability and limitations of such structures; and
- to provide a number of conceptual designs that are appropriate for forest engineering.

The results of the study have been used in the design and construction of a number of prototype debris flow control structures located on the Queen Charlotte Islands. A larger structure was designed for a site on Vancouver Island, but as yet has not been constructed.

The study was carried out by Doug VanDine, PEng, PGeo, of VanDine Geological Engineering, Victoria, B.C., during 1991 and 1992 for B.C. Ministry of Forests, Research Branch, and was funded by the Fish/Forestry Interaction Program (FFIP).

1.1 Scope of the Study

Definition of Debris Flow The generic term "debris flow" can be broadly divided into "open slope debris flow" and "channellized debris flow" (Evans 1982). This study addressed channellized debris flows only.

The term "channellized debris flow" follows the classification convention suggested by Pierson and Costa (1987). Other terms, however, have been used to mean the same thing. For example:

- in British Columbia and the United States Pacific Northwest, they are commonly referred to as "debris torrents" (Swanston 1974; Miles et al. 1979; VanDine 1985; Chatwin et al. 1994);
- in the Queen Charlotte Islands, they have been referred to simply as "debris flows" by Rood (1984, 1990)—the same term used in the *Gully Assessment Procedure Guidebook* of the Forest Practices Code of British Columbia (1995); and
- also in the Queen Charlotte Islands, they are called "debris torrents" (Wilford and Schwab 1982; Chatwin and Rollerson 1984; Krag et al. 1986; Tripp and Poulin 1986; Sauder et al. 1987; and Gimbarzevsky 1988).

For this study a channellized debris flow is defined as "a type of mass movement that involves water-charged, predominantly coarse-grained inorganic and organic material flowing rapidly down a steep confined, pre-existing channel" (VanDine 1985: p. 44). Additional characteristics of channellized debris flows are discussed in subsequent sections of this report.

Scope of the Study The study was limited to the review, assessment, and conceptual design of debris flow control structures located on the debris fan—otherwise known as the deposition zone of the channellized debris flow path. Although all types of debris flow control structures were reviewed and assessed, the emphasis for conceptual design was limited to the less expensive structures that can be built by forest company personnel using local materials, generally available construction equipment, and conventional construction techniques.

The primary function of debris flow control structures is to constrain or contain the coarse-grained portion of the debris flow. Fine-grained sediments, however, are also often associated with channellized debris flows, in the form of "afterflow," that is finer-grained material subsequently eroded by water from the coarse-grained deposits. Although debris flow control structures can partially constrain the movement of fine-grained sediment, sediment control structures are usually required to fully constrain and contain the movement of this material. These can be designed, located, and constructed either separate from, or in association with debris flow control structures.

Although sediment control structures were considered in this study, the emphasis was on debris flow control structures.

Many aspects of channellized debris flows were not addressed by the study, including: the production and nature of debris; the conditions conducive to the occurrence of channellized debris flows; failure mechanisms; and methods of hazard identification and assessment.

For discussions of these and other related matters, see Innis (1983); Takahashi (1983); Costa (1984); Eisbacher and Clague (1984); Johnson and Rodine (1984); VanDine (1985); Chen (1987); Church and Miles (1987); Hungr et al. (1987); Jackson (1987); Bovis and Dagg (1988); Takahashi (1991); and Maynard.[1]

1.2 Methods of Study

In 1984, Doug VanDine, while employed by Thurber Consultants Limited, prepared a report for B.C. Ministry of Transportation and Highways entitled "Debris Torrents: A Review of Mitigative Measures" (Thurber Consultants 1984). The information gathered for the report was based on: a comprehensive literature search; visits made in 1983 to research institutes, universities, government departments, and channellized debris flow sites in Switzerland, Austria, and Japan; and the experience of Thurber Consultants in British Columbia up to that time.

Following the preparation of the 1984 report, VanDine participated in debris flow conferences and visited channellized debris flow sites in the United States, Japan, and New Zealand. He was also involved in the preliminary design of several channellized debris flow control structures in the province (along the Howe Sound portion of B.C. Highway 99 [1983–1984]; on B.C. Highways 1 and 3 in the vicinity of Hope, and on Phase 1 of the Coquihalla Highway [1984–1985]); in the conceptual design of control structures (along B.C. Highway 1 from Sicamous to Revelstoke [1986–1987]); and in the functional design of control structures associated with the proposed 4-lane upgrading of the Sea to Sky Highway (Highway 99 [1990–1992]). All of this work was carried out for B.C. Ministry of Transportation and Highways.

The 1984 Thurber report formed the starting point for this present work. The results of that study have been updated to the present from a review of post-1984 literature and VanDine's additional experience.

Field work for this study was carried out in the Rennell Sound, located on the west coast of Graham Island in the Queen Charlotte Islands, and in the vicinity of Boat Launch Creek near Kennedy Lake on Vancouver Island.

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[1] D.E. Maynard. *Gully classification.* A report for Research Branch, B.C. Ministry of Forests. In preparation.

The effects of channellized debris flows can be reduced by a number of mitigative methods. Such methods lessen, but do not necessarily eliminate, associated hazards and risks.

2.1 Passive versus Active Mitigation

Mitigative methods can be broadly divided into two groups: passive and active (Figure 1). Passive methods involve essentially no direct engineering because no attempt is made to prevent, modify, or control the event. Instead, for example, once a channellized debris flow hazard has been identified and assessed, the area can be avoided, land use regulations can be applied, the public can be notified and educated, or, in certain circumstances, a warning system can be established. These are all examples of passive methods.

Active methods of mitigation require some engineering once the hazard has been identified and assessed. These methods can involve some form of prevention (including maintenance) of the hazard, remediation to reduce or eliminate the potential of a channellized debris flow from occurring, or the design and construction of some form of protection to reduce the effects of the event.

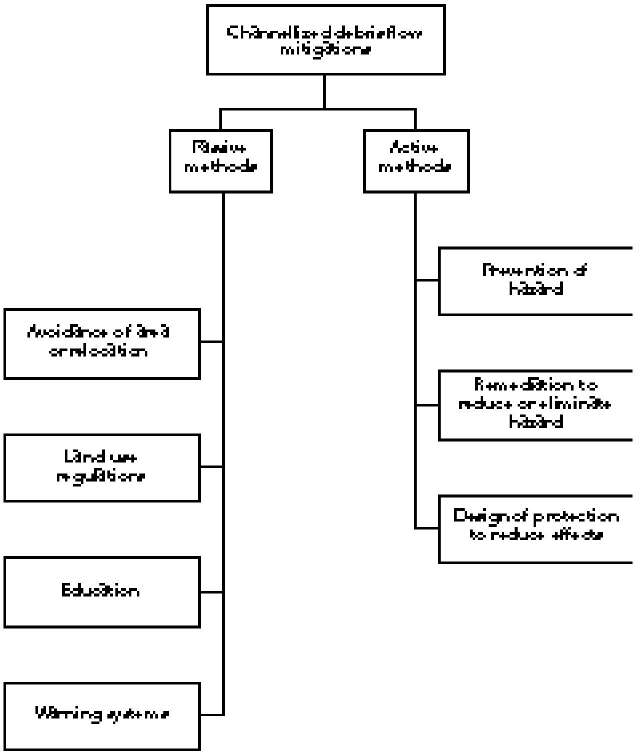


FIGURE 1 *Active versus passive mitigation.*

2.2 Active Debris Flow Mitigation on the Debris Fan

As noted earlier, this study was limited to the review, assessment, and conceptual design of debris flow control structures located on the debris fan. Such structures are obviously active forms of mitigation. Their purpose is to control the movement of coarse-grained debris across the fan to protect any roads, stream crossings, buildings and other structures located on the fan, and to minimize the amount of coarse-grained debris (and, in part, fine-grained sediment) from entering neighbouring bodies of water. Controlling the movement of debris across the fan involves controlling the volume and velocity of the debris, where on the fan the debris does and does not travel, and where the debris comes to rest.

There are three forms of hazards on debris fans from which roads, stream crossings, building and other structures require protection. Thurber Consultants (1983) and Hungr et al. (1987) described these hazards as follows:

- hazards from the direct impact of high-energy, generally coarse-grained debris that can destroy structures;
- hazards from the indirect impact of lower-energy, coarse-grained debris and fine-grained afterflow that can bury structures; and
- hazards from subsequent flood waters that are forced from the normal channel by debris deposits and have the potential to erode unprotected surfaces and cause flood damage.

The hazard associated with coarse-grained debris and fine-grained sediment entering a neighbouring body of water is primarily related to the degradation of the fish habitat.

3 DEPOSITION OF A DEBRIS FLOW

3.1 Gradient of the Depositional Debris Fan

The profile of a stream, gully, or channel that is subject to channellized debris flows can be broadly divided into three zones: initiation; transportation and erosion; and deposition (Figure 2). Initiation generally requires a channel gradient greater than 25° (47%); transportation and erosion generally require a gradient of greater than 15° (27%); partial deposition, in the form of levees, generally occurs at a gradient of less than 15° (27%); and deposition on the debris fan usually begins once the gradient flattens to less than a 10° (18%) gradient.

Actual gradients within each of the three zones are stream specific and depend on a number of factors, including:

- the relative confinement of the channel;
- the composition and gradation of the debris, which in turn depends on the geology of the area; and
- the ratio of debris to water.

As shown in Figure 3, from a study of the debris-flow-prone streams along Howe Sound, the gradients in each of the three profile zones tend to decrease with increasing drainage area (VanDine 1985).

Thurber Consultants (1983) found that the average fan gradient for 15 streams prone to debris flows along Howe Sound was 12° (21%) and ranged between 5 and 18° (9 and 32%). They found that the average fan gradient for 73 streams prone to debris flows in the Hope-Coquihalla area was approximately 13° (23%) and ranged between 4 and 24° (7 and 45%) (Thurber

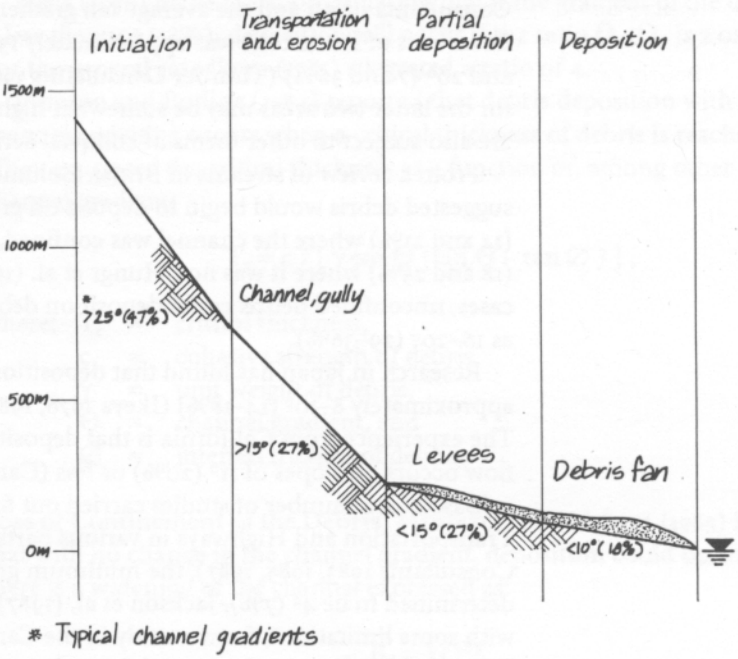


FIGURE 2 *Zones of channellized debris flow.*

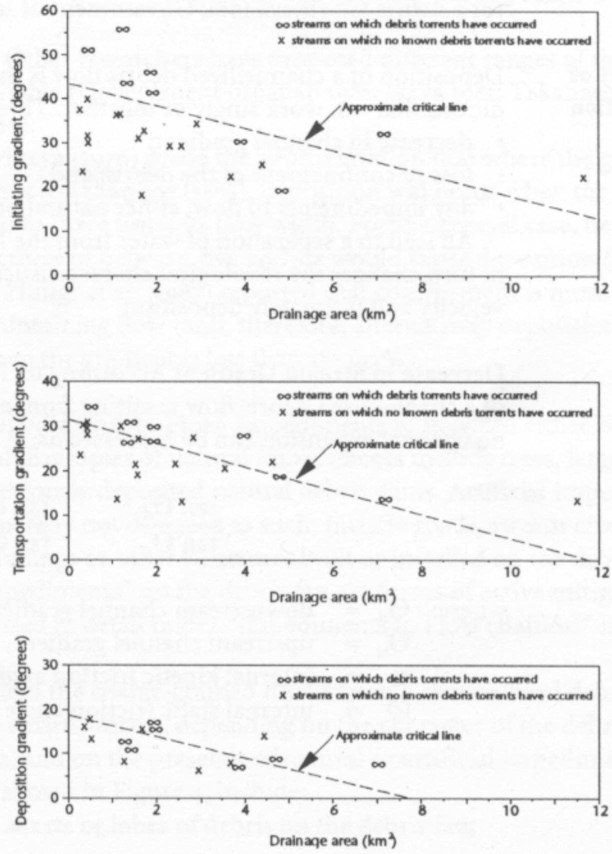


FIGURE 3 *Example of decreasing gradients in each zone with increasing drainage area.*

Consultants 1985); and the average fan gradient for 31 streams prone to debris flows west of Revelstoke was approximately 13° (23%) and ranged between 4 and 20° (7 and 36%) (Thurber Consultants 1987). (The averages and ranges for the latter two areas may be somewhat high because a number of the fans are also subject to other forms of colluvial activity.)

From a review of streams in British Columbia, Hungr et al, (1984) suggested debris would begin to deposit on gradients between 8 and 12° (14 and 21%) where the channel was confined, and between 10 and 14° (18 and 25%) where it was not. Hungr et al. (1987) mentioned that in certain cases, unconfined debris could deposit on debris fans with gradients as high as 16–20° (29–36%).

Research in Japan has found that deposition on a debris fan begins at approximately 8–10° (14–18%) (Ikeya 1976, 1981; Government of Japan 1981). The experience from California is that deposition of a channellized debris flow occurs on slopes of 11° (20%) or less (Campbell 1975).

Based on a number of studies carried out for the B.C. Ministry of Transportation and Highways in various parts of the province (Thurber Consultants 1983, 1985, 1987), the minimum gradient of a debris fan was determined to be 4° (7%). Jackson et al. (1987) determined a similar angle, with some limitations, from a study in the Canadian Rocky Mountains. Tripp and Poulin (1986) reported from their research in the Queen Charlotte Islands that 2° (3.5%) was the mean gradient recorded at the terminus of channellized debris flows.

Researchers in Japan consider 2–3° (3.5–5%) to be the minimum gradient for a debris fan (Ikeya 1981; Government of Japan 1981).

3.2 Causes of Deposition

Deposition of a channellized debris flow is the result of a number of conditions that can work singly or together. These include:

- decrease in channel gradient;
- loss of confinement of the debris; and
- any impediments to flow, either natural or artificial.

All lead to a separation of water from the flowing debris mass, which in turn changes the rheological characteristics of the mass, thus decreasing velocity and ultimately deposition.

Decrease in Stream Gradient According to Takahashi (1983), deposition of a channellized debris flow resulting from an abrupt change in slope with no channel expansion can be expressed as:

$$\frac{\tan \Theta_d}{\tan \Theta_u} < \frac{\tan \alpha}{\tan \varnothing'} \, ,$$

where: Θ_d = downstream channel gradient,
Θ_u = upstream channel gradient,
α = internal kinetic friction angle of debris, and
$\varnothing'$ = internal static friction angle of debris.

Ikeya (1976) made the approximation that if the gradient of the debris fan is less than 10° (18%), deposition will occur if the ratio Θ_u/Θ_d is 2 or greater. For the general case Ikeya (1981) suggested a ratio of 4.

Johnson and Rodine (1984) reported that debris deposition with no channel widening occurs when a critical thickness of debris is reached. They expressed the critical thickness as a function of, among other factors, channel gradient:

$$T_c = c / [\ \gamma \cos \Theta\ (\tan \Theta - \tan \varnothing\ )\ ]\ ,$$

where: T_c = critical thickness,
c = cohesive strength of debris,
γ = unit weight of debris,
Θ = channel gradient, and
$\varnothing$ = internal friction of debris.

Loss of Confinement of the Debris Mizuyama and Uehara (1983) found that with no change in the channel gradient, deposition could occur where there is a widening of the channel expressed as:

$$B_d = kQ^{1/2}\ ,$$

where: B_d = width of deposition in an unconfined downstream channel,
Q = discharge, and
k = a dimensional variable that can range from 3.5 to 7.

Other researchers have proposed different ranges of the dimensional variable (Government of Japan 1981; Ikeya 1981; Takahashi and Tsujimoto 1985).

Ikeya (1976) made the approximation that where the gradient of the debris fan is less than 10° (18%), deposition will occur when the flow widens out to two to three times its flow width. For the general case, he suggested that an increase of between five and six would cause deposition (Ikeya 1981).

Hungr et al. (1987) reported that confinement is more critical to maintaining flow (and, therefore, alternatively deposition) than gradient, when the gradient is less than 18° (32%).

Impediments to Flow Impediments to flow can either be natural or artificial. Examples of natural impediments include trees, large boulders, and previously deposited natural debris dams. Artificial impediments, though generally not designed as such, include roads, stream crossings, and any buildings or other structures built or installed on the debris fan. "Designed impediments" on the debris fan are forms of active mitigation and are discussed in detail under "Impediments to Flow (Baffles)" in Section 5.1.

3.3 Forms of Deposition

When the coarse-grained debris from a channellized debris flow stops, it can take many forms, depending on the character of the debris and the debris fan, and on the presence of natural or artificial impediments. These forms, as shown in Figure 4, include:

- sheets or lobes of debris on the debris fan;

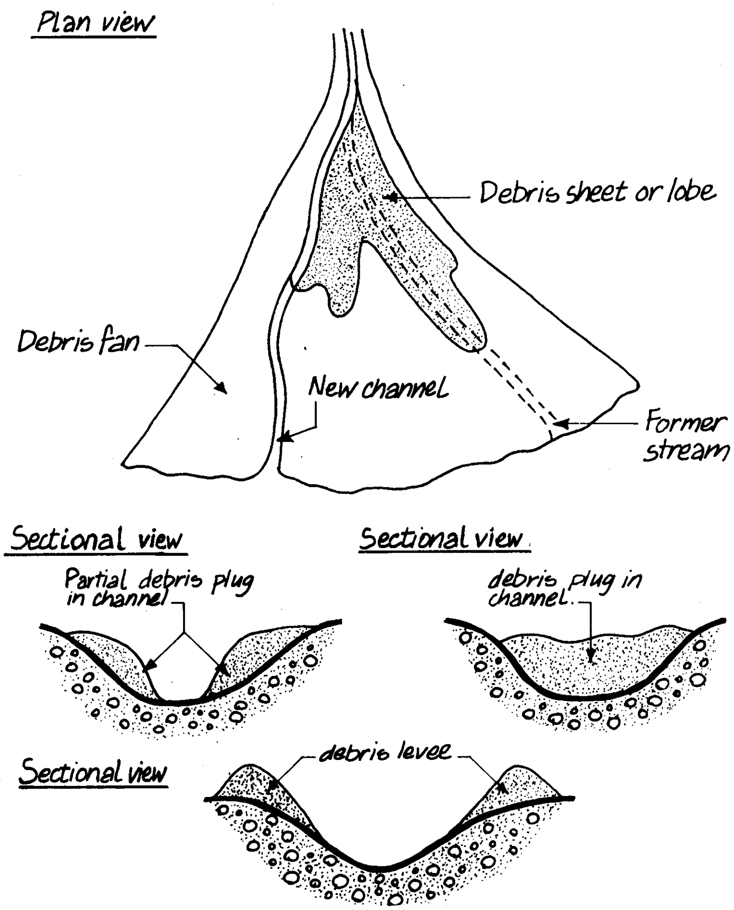


FIGURE 4 *Forms of channellized debris flow deposition.*

- plugs of debris deposited in the stream channel; and
- debris levees along the stream channel.

Whatever the form, debris flow deposits are typically coarse grained, poorly to very poorly stratified, and very poorly sorted.

Debris sheets or lobes are usually deposited over an areal portion of the debris fan. They are often characterized by a number of arms, each ending in a "snout." Hungr et al. (1987) reported that the mean thickness of debris lobes in British Columbia, resulting from events with magnitudes between 10 000 and 50 000 m^3, can range from approximately 1.0 to 1.5 m. Innis (1983), from research in Europe, determined that the thickness of debris would be between 1.1 and 1.7 m for events of the same magnitude.

Debris plugs usually partially or completely fill the stream channel. Where they partially fill the channel, they are commonly deposited along the channel sides or at the outside bends of a sinuous channel. Where debris plugs completely fill a channel, they often end in a confined snout or lobe. The formation of a debris plug in a stream channel often results in an avulsion, an abrupt change in flow direction.

Debris levees are steep-sided ridges that can be up to several metres in height. They lie outside and above the sides of a pre-existing stream channel, and can extend for many tens of metres along a channel.

The resulting debris deposits, which over time form the debris fan, are usually deposited on land. If the stream discharges into a larger drainage or into a lake or the ocean, however, a portion of the debris may be deposited under water. Researchers have only recently begun to investigate the character of subaqueous channellized debris flow deposits (see, for example, Prior and Bornhold 1988).

4 DESIGN CONSIDERATIONS FOR DEBRIS FLOW CONTROL STRUCTURES

When designing debris flow control structures, many parameters must be addressed including those associated with the character of the channellized debris flow on the debris fan and those associated with the character of the debris fan itself.

4.1 Character of the Channellized Debris Flow on the Debris Fan

Design considerations associated with the character of the debris flow on the debris fan include:

- frequency of occurrence;
- design magnitude or volume;
- maximum discharge and flow depth;
- size and gradation of debris;
- likely flow paths;
- potential runout distance;
- potential impact forces;
- potential run-up and superelevation; and
- probable storage angle.

Although some of these characteristics can be determined through rigorous methods, measuring and assessing, the determination of some of them is not an exact science and often involves field estimates and rules of thumb.

The following summarizes some of the methods now being used in British Columbia and elsewhere.

Frequency of Occurrence The occurrence of a channellized debris flow does not depend solely on rainfall intensity or streamflow discharge. Also affecting it are: local weather cells, antecedent rainfall and snowfall, channel profile, the existence of debris in the stream, and a wide variety of triggering mechanisms (see, for example, VanDine 1985; Church and Miles 1987). Applying a simple recurrence interval or return period to a channellized debris flow is therefore not all that is required in determining frequency of debris flows.

Rather than attempt to assign an absolute probability of debris flow occurrence, it has been more common to assign a relative probability of occurrence for a number of streams in a particular geographic area. Factors considered include the frequency of past events, and the character of the drainage basins, streams, and debris fans in question compared to those on

TABLE 1 *Categories of relative probability of occurrence*

Category	Description
4	Very high probability of occurrence; indicates that debris flows of less than the design magnitude can occur frequently with high runoff conditions, and the design debris flow should be assumed to occur within the short term. It is applied to creeks that have a history of more than one event involving greater than 500 m^3 or have physical characteristics that are comparnable to these creeks.
3	High probability of occurrence; indicates that debris flows of less than the design magnitude will occur less frequently than under category 4, but the design debris flow should still be assumed to occur within the short term. It is applied to creeks that have a history of a single debris flow. It is also applied to creeks that have no known history of events but possess several significant physical characteristics that are comparable to category 4 creeks.
2	Moderately high probability of occurrence; indicates that the designdebris flow should be assumed to occur during the life of a significant long term structure (such as a bridge or house). It is applied to those creeks that have significant physical characteristics that fall well within the threshold where debris flows are possible, although not in the range of category 4. To date these creeks have no recorded history of debris flows, or have experienced events of uncertain origin.
1	Low probability of occurrence; indicates a low potential for the design debris flow. It is applied to those creeks whose physical characteristics place them at or close to the threshold where debris flows are possible. Although a significant debris flow is possible during the life of a long term structure, it would require an unusually high (and thus infrequent) runoff condition.
0	No risk; indicates that there is virtually no potential for large debris flows to occur although small and local debris flows may occur, and debris flows of varying magnitudes may develop in upper reaches and tributaries. It is applied to channel reaches whose physical characteristics fall well below the threshold where debris flows are possible.

which past events have occurred. Examples of where and how this approach has been applied are found in Thurber Consultants (1983, 1985, 1987) and VanDine (1985). Table 1 summarizes the five categories of relative probability used by Thurber Consultants.

The application of absolute probability methods to large debris flows when downstream consequences are high is discussed by Morgan et al. (1992) and Thurber Engineering and Golder Associates (1992).

Design Magnitude or Volume Over a period of time, a stream may experience channellized debris flows of a wide range of magnitudes. The design magnitude is defined as the reasonable upper limit of the volume of material that is likely to be involved in an event and thus to ultimately reach the debris fan. It depends on the available debris in the streambed, plus any additional material that may be contributed to the stream from the valley walls during an event. The magnitude estimate arrived at should be tempered by the magnitudes of past debris flows on that particular stream.

VanDine (1985) reviewed 11 different methods of estimating the design magnitude from around the world. Many of these methods involve the detailed inspection of each stream upstream of the debris fan, and the recording of factors such as channel gradient and width of stream, size and gradation of material, potential scour depth of the streambed, and stability of the banks.

In British Columbia, the unit volume technique has been the most commonly used method for estimating design magnitude. This technique estimates a unit volume of debris along distinct reaches of the stream (volume of debris per unit stream length, or stream width times estimated scour depth per unit stream length), then sums the products to arrive at the potential debris volume. This volume can be adjusted to reflect specific characteristics of the stream and estimated volumes of known past events, to arrive at the design magnitude (VanDine 1985). Modifications to this unit volume technique are described by Hungr et al. (1984); Thurber Consultants (1987); and Fannin and Rollerson (1993).

Attempts have been made to predict debris flow magnitude from drainage basin characteristics. For example, VanDine (1985) tried to correlate design magnitude with drainage area for the streams along Howe Sound, but met with only moderate success (Figure 5). And Thurber Consultants (1987), as part of a study for the B.C. Ministry of Transportation and Highways, carried out a multiple regression analysis of factors affecting the design magnitude.

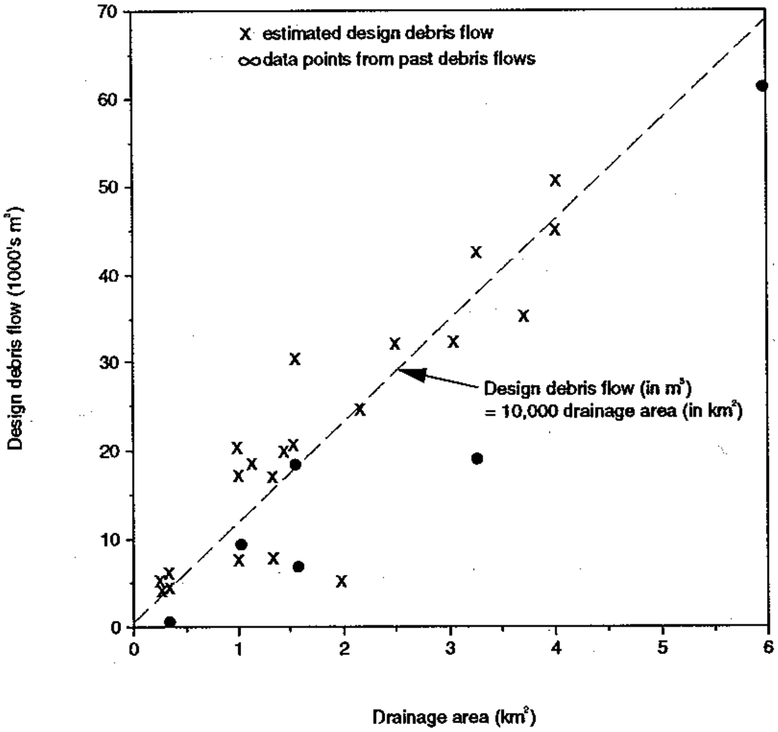


FIGURE 5 *Estimated design magnitudes and recorded magnitudes versus drainage area.*

That study found that "data on the watershed characteristics in the study area do not have a strong statistical relationship with design debris torrent volumes as calculated in the field" (p. 128).

Maximum Discharge and Flow Depth The discharge of a channellized debris flow past any one location depends on the geometry of the stream channel and the velocity of the flow. The velocity of the flow is determined by the gradient and geometry of the channel, and the dynamic viscosity and unit weight of the debris mass. For a given channel geometry, the discharge and velocity will determine the depth of the flow in the channel. The maximum discharge and flow depth usually occur soon after the front of the debris flow passes and, although generally of short duration, are critical to know for design purposes.

Hungr et al. (1984) reviewed several methods of estimating debris flow discharge. For a number of channellized debris flow events in British Columbia, they correlated the maximum debris flow discharge with the magnitude or volume of the event (Figure 6), and recommended that the upper bound of this data be used for design purposes.

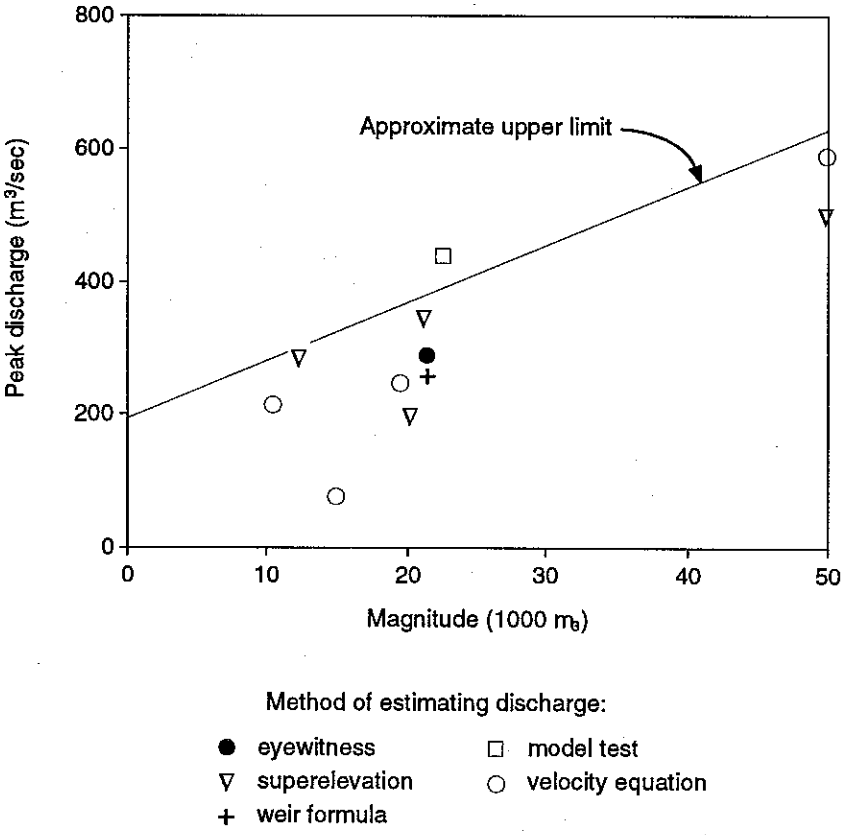


FIGURE 6 *Peak debris flow discharge versus design magnitude for debris flows in British Columbia.*

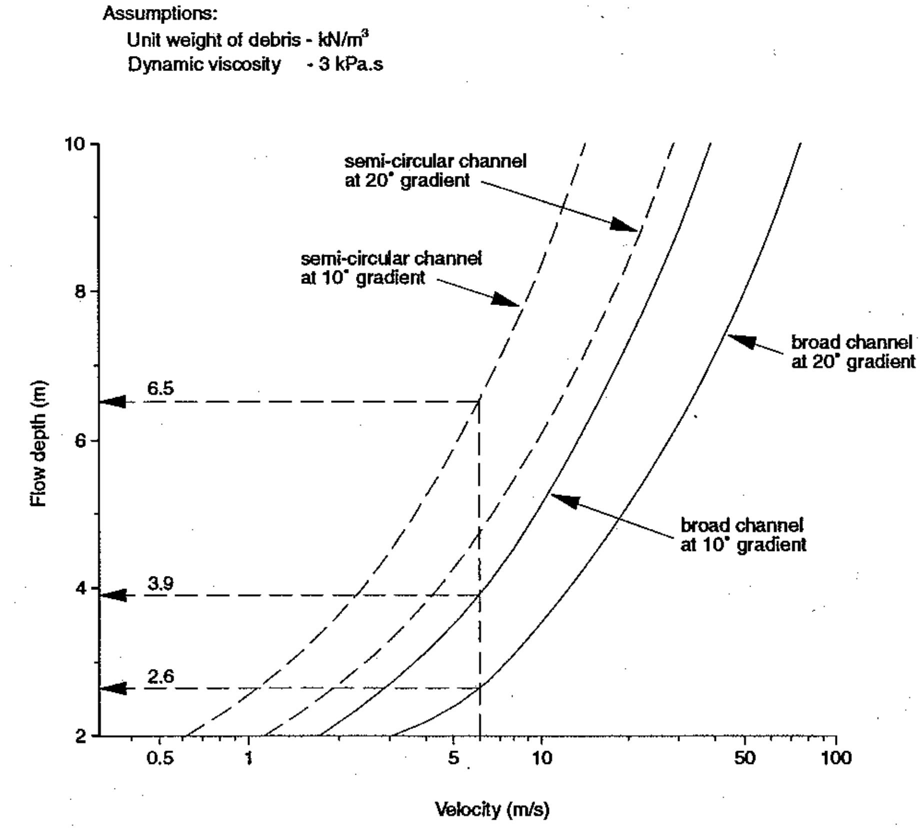
The Poiseuille Equation can be used to relate the velocity of the flow to the gradient and geometry of the stream, and the dynamic viscosity and unit weight of the debris mass:

$$v = \frac{\gamma \sin \Theta\, h^2}{l\, \nu},$$

where: v = velocity,
Θ = channel gradient,
h = flow depth,
γ = unit weight of debris mass,
ν = dynamic viscosity of debris mass, and
l = a constant based on the cross-sectional shape of the channel (= 3 for a broad channel, = 8 for a semi-circular channel).

With this equation applied, Figure 7 shows several examples of how flow depth varies with velocity, channel gradient, and geometry.

In Japan, efforts have been made to correlate debris flow discharge with water flood discharge (e.g., Government of Japan 1984), but this method has not been calibrated to the debris flows in British Columbia. VanDine (1985) correlated the same parameters for 22 streams along Howe Sound and found the debris flow discharge could be 5–10 times greater than that for the



Example 1

At a velocity of 6 m/s, flow depth in a semi-circular channel at 10° is 6.5 m, and in a broad channel at the same gradient is 3.9 m.

Example 2

At a velocity of 6 m/s, flow depth in a broad channel at 10° is 3.9 m, and in a broad channel at 20° is 2.6 m.

FIGURE 7 *Examples of flow height (flow depth) versus velocity, based on Poiseuille Equation.*

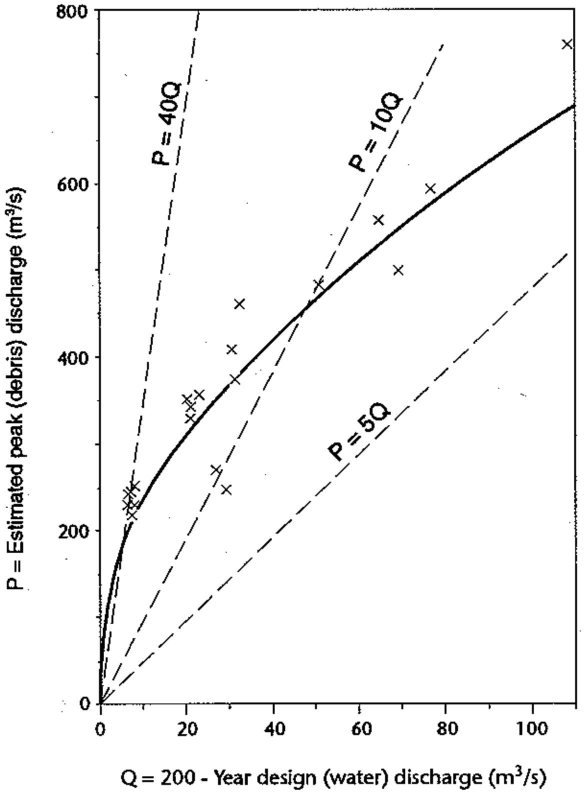


FIGURE 8 *Estimate peak debris flow discharge versus estimated 200-year design water flood discharge*

200-year flood for large streams and up to 40 times greater for small streams (Figure 8). To complicate matters further, channellized debris flows do not generally flow down a channel as a single event, but rather in a series of surges.

Size and Gradation of Debris Estimates of the mean and maximum sizes of both the inorganic and organic coarse-grained debris, and the gradation of each, are useful for the design of certain types of control structures. These estimates can be derived from an examination of the debris that is exposed on the debris fan, any that makes up the streambed, and any that lies along the sides of the stream upslope of the debris fan.

The size and gradation of the inorganic debris is a function of the bedrock and surficial geology of the area. The character of the organic debris depends on the vegetation along the stream.

Likely Flow Paths Once a channellized debris flow reaches the debris fan, its flow path across the fan is very difficult to predict. The flow path depends on many factors, the most important of which is the morphology of the fan. Other factors include the magnitude of the debris flow, the character of the debris, whether the original stream channel on the debris fan becomes plugged and an avulsion occurs, and the existence of natural features or artificial structures that could impede the natural flow path. Conservatively, and without any impediments, by definition, the entire debris fan must be considered as the likely flow path.

For the streams along Howe Sound and Highway 1 west of Revelstoke, Thurber Consultants (1983, 1987) determined the likely flow path based on: an estimate of the design magnitude; 1:2000 and 1:2500 scale topographic maps of the debris fans that included all artificial structures on the fan; engineering judgement; and, where available, previous channellized debris flow paths. Not dissimilar to this method is an empirical method used in Japan and summarized by Ikeya (1981).

Sophisticated modelling was used to determine the likely flow path of future debris flows on the fan at Port Alice, B.C. (Nasmith and Mercer 1979).

In Japan, extensive research has attempted to predict the hazard zones on the debris fan. For these methods, see papers by Takahashi et al. (1981); Takahashi (1983); Takahashi and Tsujimoto (1985); and Takahashi (1991).

Hungr et al. (1987) suggested that where adequate topographic mapping is lacking, a ratio of 1 (width) to 2 (length) can be assumed for the flow path. This follows the Swiss practice of estimating the widening of a debris flow on a debris fan (Thurber Consultants 1984), but overestimates the potential length to width ratio of debris flows on debris fans used in Japan and discussed under "Loss of Confinement of the Debris" in Section 3.2.

Potential Runout Distance Regardless of the stream or drainage area, the potential runout distance of a debris flow on a debris fan must be conservatively estimated as occurring at the distal end of the debris fan. Care should be taken, however, to differentiate between the colluvial portion of the fan (the debris fan) and the alluvial portion. Jackson et al. (1987), from research in the Canadian Rocky Mountains, reported that, with some limitations, fan slope and a relationship between drainage basin area and basin relief can be used to distinguish between debris fans and alluvial fans.

Hungr et al. (1987) outlined a simplified method for estimating the potential runout. First, once the design magnitude or volume has been estimated and an average thickness of debris on the fan assumed, a deposit area can be determined. Judgement should then be used to account for the influence of the fan morphology or, lacking adequate mapping, the suggested ratio of 1 (width) to 2 (length) should be used to determine the flow path, as discussed above. The distal limit of the deposit defines the runout distance.

A number of empirical methods for estimating runout have been developed in Japan (for example, Ikeya 1981; Takahashi et al. 1981), but these have not been verified for British Columbia conditions.

A rigorous method of estimating runout has also been developed by Takahashi and Yoshida (1979) and Takahashi (1991). It is based on momentum and requires an estimate of peak discharge of debris flow, debris flow depth, and channel geometry at the point of transition between the zone of transportation and the zone of deposition (assumed to be 10°, or 18%). This method was adapted by Hungr et al. (1984) and Thurber Consultants (1984) as:

$$X_L = \frac{V^2}{G} \ ,$$

where: X_L = runout distance,
V = $V_u \cos(\Theta_u - \Theta_d) \frac{(1 + g h_u \cos\Theta_u)}{2V_u^{2},}$

and G = $g\,(S_f \cos\Theta_d - \sin\Theta_d)$,

where: Θ_d = runout, or downstream, gradient,
Θ_u = upstream channel gradient,
V_u = upstream velocity,
h_u = upstream flow depth,
g = acceleration due to gravity, and
S_f = friction slope (refer to Hungr et al. 1984).

The "lag rate" method of determining the potential runout distance in Colorado has been summarized by Cannon (1989). The method assumes the Johnson and Rodine (1984) critical thickness theory for the deposition of debris, as discussed under "Decrease in Stream Gradient" in Section 3.2.

Potential Impact Forces The design of many types of debris control structures should consider the potential impact forces, both dynamic thrust and point impact forces, at various locations on the debris fan. Hungr et al. (1984) and Thurber Consultants (1984) summarized the calculations for these parameters.

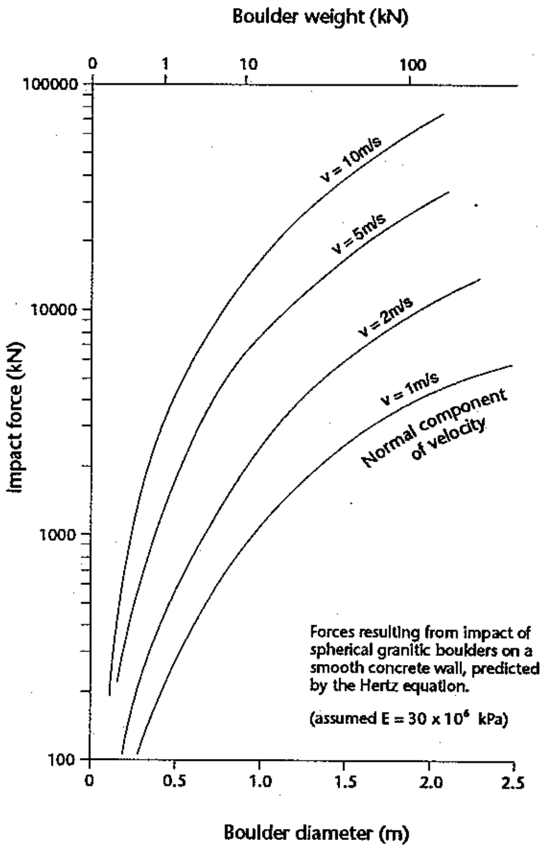
The momentum equation, which incorporates the entire estimated peak surge of the debris flow travelling at a uniform velocity, is used to calculate dynamic thrust. The momentum equation is:

$$F = \rho\, A\, v^2 \sin\beta \ ,$$

where: F = dynamic thrust,
ρ = density of debris,
A = cross-sectional area of flow,
v = velocity of flow, and
β = the angle between the flow direction and face of the structure.

Hungr et al. (1984) recommended that the thrust calculated by the above formula be distributed over an area as wide as the expected debris front and approximately 1.5 times the front height. This added height accounts for the build-up of debris behind a structure.

In Japan, it has been estimated that when a surge front collides with a structure, the dynamic impact force may be up to twice that calculated for the steady force from the momentum equation above (Government of Japan 1981).



Forces resulting from impact of spherical granitic boulders on a smooth concrete wall, predicted by the Hertz equation.

(assumed $E = 30 \times 10^6$ kPa)

FIGURE 9 *Point impact forces, based on Hertz contact force equation.*

From empirical observations made in California, Hollingsworth and Kovacs (1981) determined that the dynamic thrust of debris flows was approximately equivalent to 125 lb/ft^3 (approximately 20 kN/m^3). Baldwin et al. (1987) recognized that this 20 kN/m^3 decreases very quickly once deposition begins. One Japanese study measured the dynamic thrust of a channellized debris flow on a 150 × 150 mm metal plate to be 60 kN^3 (Thurber Consultants 1984).

Point impact forces, such as those resulting from a single boulder against a particular structural member, can be calculated by the Hertz contact force equation. This equation is discussed more fully in Hungr et al. (1984), and shown in Figure 9.

In a study conducted by Thurber Consultants and Ker Priestman (no date), the design point impact force for the structures constructed on Harvey, Charles, and Magnesia creeks was estimated for a 2 m diameter boulder hitting the structure at 7 m/s and allowing a deflection of 175 mm.

Potential Run-up and Superelevation When a control structure is located in the path of a debris flow, its design height should be greater than the height of the potential run-up flow. A method of estimating potential run-up (which is similar to estimating the potential runout distance) is described by

Hungr et al. (1984) and Thurber Consultants (1984). It involves the same formula as is used to calculate runout (refer to "Potential Runout Distance" above), but assumes the run-up gradient (the slope of the face) is equivalent in magnitude to the runout gradient, but negative.

An estimate of superelevation is required to determine the height of a debris flow on the outside bend of a curve. Superelevation can be predicted using a forced vortex equation as outlined by Hungr et al. (1984), Thurber Consultants (1984), Chen (1987), and others:

$$\Delta h = j \frac{bV^2}{r\,g} ,$$

where: Δh = elevation difference between the two sides of the flow,
j = a correction factor related to viscosity and vertical sorting that exists in coarse-grained debris and varies between 1 and 5,
b = surface width of flow,
V = mean velocity,
r = mean radius of curvature, and
g = acceleration due to gravity.

Probable Storage Angle The storage angle of the debris is an important factor in the design of the area over which a channellized debris flow will deposit. In several Japanese studies, the storage angle is estimated to be approximately half of the angle on which deposition occurs (Government of Japan 1981, 1984). The relationship between storage angle and storage capacity behind a barrier is shown in Figure 10.

4.2 Character of the Debris Fan

The methods of determining the characteristics of the debris fan are relatively straightforward compared to those for determining the character of the channellized debris flow.

The characteristics of the debris fan include:

- size,
- gradient,
- geometry,
- morphology, and
- existence and location of artificial structures.

For the most part, these characteristics can be determined relatively easily in the field, or from topographic maps or plans at an appropriate scale and with an appropriate contour interval. For design purposes, a scale of 1:2500 with a contour interval of 5 m was found to be most practical (Thurber Consultants 1983, 1987), although a larger scale and a smaller contour interval would improve the design capabilities.

Some of the factors associated with these characteristics, and how they influence the design of debris flow control structures and the movement of fine-grained sediment are discussed below.

Size The size of a debris fan is usually an indication of the past magnitudes and frequency of channellized debris flows on that stream.

A large debris fan allows for more flexibility in the type of debris flow control structure that can be used and its location on the fan. In general,

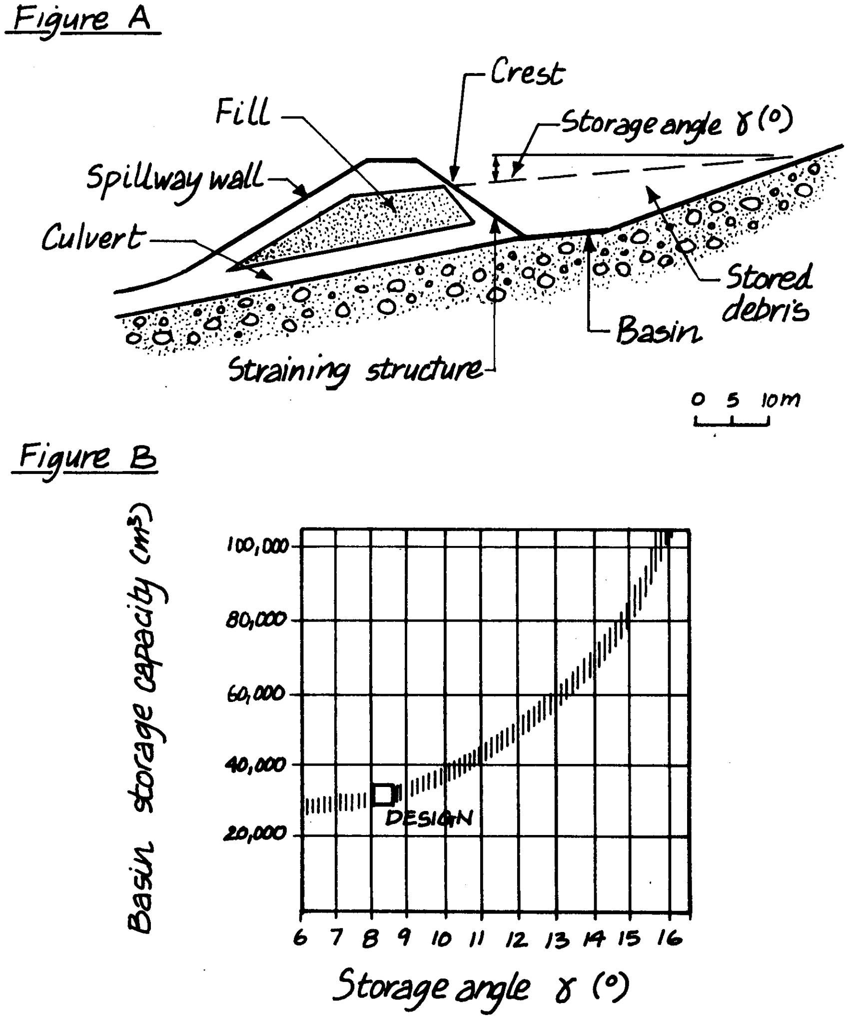


FIGURE 10 *Storage angle definition (A) and the relationship with storage basin capacity (B).*

the lower the fan gradient, the farther downstream from the apex of the debris fan the control structure can be located, and the less energy the control structure will be subject to from the debris flow. The possibility of avulsions, however, increases downslope from the apex of the fan, and therefore the likely flow path becomes more difficult to predict.

As the size of the debris fan increases, the amount of fine-grained sediment that can be deposited before reaching the distal end of the fan also increases. This may influence the design of any associated sediment control structures.

Gradient The gradient of the debris fan is a function of the gradation of the debris involved in past flows, the debris flow discharges and the intervening water flood discharges, and other geomorphic processes active on the fan. These factors also influence the sinuosity of the stream across the fan. The gradient is usually steepest at the apex of the fan and decreases down gradient.

The gradient of the debris fan often determines whether it is more practical in the design to encourage the debris to deposit or to encourage it to keep moving to another portion of the fan. As discussed previously, fine-grained sediment requires much gentler gradients for deposition.

The more sinuous the stream, the longer its flow path, the gentler its gradient, and the slower its velocity. All these factors increase the possibility of deposition of both coarse-grained debris and fine-grained sediment. An abrupt bend in the stream increases the likelihood of an avulsion.

Geometry The geometry of a debris fan depends on the character of past debris flows, and on the geomorphic confinement of the depositional area. Fan geometry influences the likely flow paths across the fan and the location and geometric layout of any control structures.

Morphology The morphology of the debris fan depends on the character of past debris flows, and on any other geomorphic processes active on the fan. Morphological characteristics of the fan include: the depth of incision of the stream; the existence of older flow paths; and the roughness of the fan surface.

The fan morphology determines, among other things, how easily the flow in the channel can avulse and how fast and how far debris will travel before it comes to a stop. A rougher surface retards the movement of both the coarse-grained debris and fine-grained sediments.

Existence and Location of Artificial Structures Unless the artificial structures, such as roads, stream-crossings, or buildings can be moved, they may inhibit the location of any proposed debris flow control structure. There are examples, however, where such structures have been incorporated into the design of the control structure.

5 DEBRIS FLOW CONTROL STRUCTURES

Consider an ideal hypothetical situation: a very large debris fan deposited on land where there are no artificial structures. In this ideal case, it is possible that debris flow control structures would not be required, because there are no structures to protect and essentially all of the coarse-grained debris would deposit on the debris fan. If a very large alluvial fan existed farther downstream of the debris fan, it is also possible that sediment control structures would not be required because all the fine-grained sediment would deposit on the alluvial fan before entering any neighbouring bodies of water. Anything less than this ideal case, however, may require some control structures to achieve the desired mitigation.

The type of debris flow control structure that is used on a debris fan must be site specifically suited to the character of the channellized debris flow, the character of the debris fan, the purpose of the mitigation, and the monies, resources, and equipment available for design, construction, and maintenance of the structure. Several different types of debris flow control structures are sometimes used in conjunction with one another.

In general, debris flow control structures can be divided into two basic types: open and closed. Open control structures are designed primarily to *constrain* the flow of a channellized debris flow; closed control structures are designed primarily to *contain* a channellized debris flow.

Sediment control structures, although often associated with both open and closed debris flow control structures, are considered separately in Section 5.3.

Briefly described here is each type of control structure and the main design considerations for it. For a number of these structures, conceptual designs that are particularly appropriate for forest engineering purposes are presented in Section 6 and Appendix 1.

5.1 Open Debris Flow Control Structures

Open debris flow control structures include:

- unconfined deposition areas;
- impediments to flow (baffles);
- check dams;
- lateral walls (berms);
- deflection walls (berms); and
- terminal walls, berms, or barriers.

Unconfined Deposition Areas Unconfined deposition areas, referred to as "debris flow deposition works" in a Japanese study (Government of Japan 1984), are areas on the debris fan that are designed and prepared to receive a portion or all of the debris from a channellized debris flow. To encourage the coarse-grained debris to deposit, the gradient of the fan is reduced or the debris is allowed to spread out and lose its confinement (Figure 11).

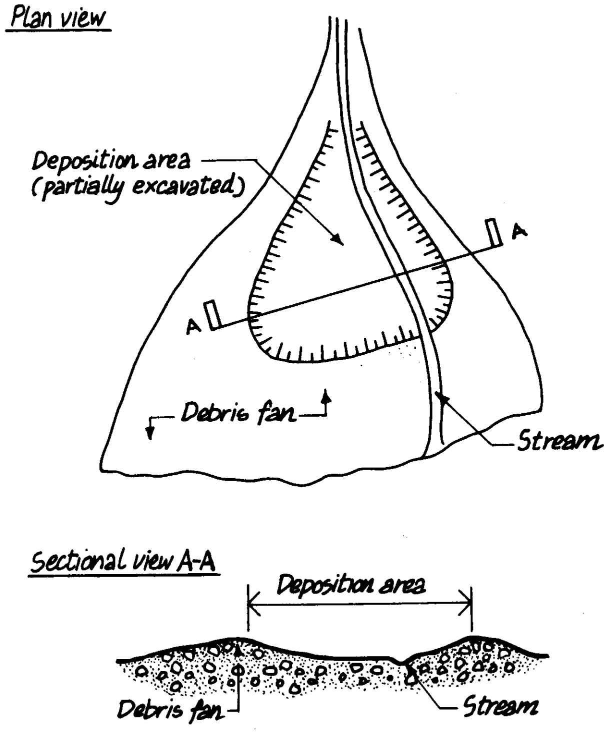


FIGURE 11 *Plan and sectional view of an unconfined deposition area.*

Several unconfined deposition areas have been constructed along Phase I of the Coquihalla Highway (Thurber Consultants, no date).

Design considerations include the design magnitude or volume of the debris flow; the likely flow paths, including length to width ratio of the flow on the fan; the potential runout distance; and the probable storage angle.

This method of debris control is best suited to larger debris fans that have relatively low gradients and few artificial structures. The geometry and morphology of the debris fan can be used to optimize the location of the area.

An excavated, or partially excavated, deposition area can be prepared and shaped to further decrease the gradient and thereby decrease the potential runout distance and increase the potential storage volume. This form of control can be accompanied by some form of flow impediment within the deposition area or by a terminal berm or barrier at the downstream end (refer to “Impediments to Flow (Baffles)” and “Terminal Walls, Berms, or Barriers”). Some method of channelling the fine-grained sediment and water from the debris flow, and from subsequent stream flows downstream of the area, may be required.

After a debris flow has occurred, the coarse-grained debris that has collected in the deposition area must be cleaned out in preparation for subsequent flows.

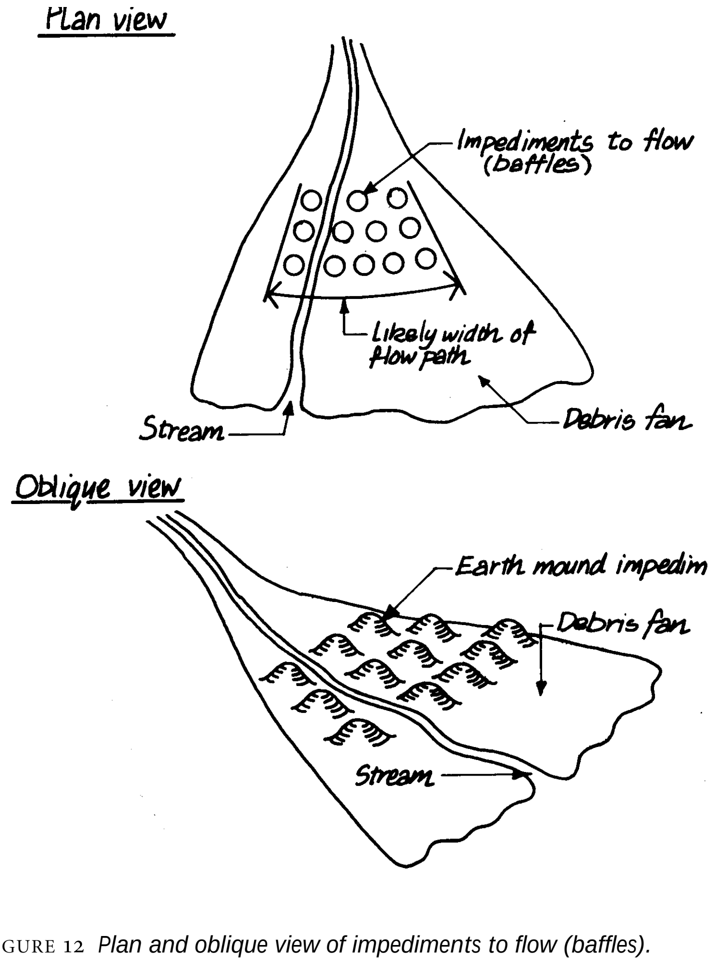


FIGURE 12 *Plan and oblique view of impediments to flow (baffles).*

Impediments to Flow (Baffles) Impediments to flow, or baffles, are used primarily to slow down a debris flow and thereby encourage it to deposit. In some instances they are used to deflect the flow.

Impediments can be either natural or artificial. When trees are used, they have been referred to as "debris flow dispersing forest zones" (Government of Japan 1984).

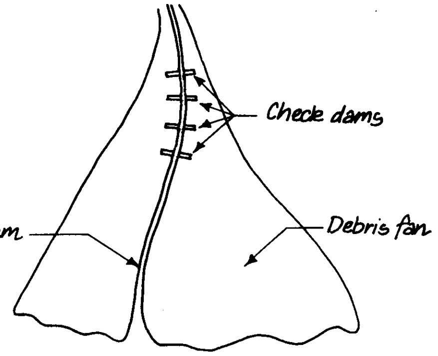
Artificial impediments can be constructed of earth berms, timber, or steel, and function in much the same way as snow avalanche retarding structures. They can be placed as single units, in lines or staggered (Figure 12). Although they can be used by themselves, they are more commonly used in concert with other forms of control, often unconfined deposition areas (described above). Impediments to flow should not be confused with debris-straining structures (discussed below).

Design considerations include the design magnitude or volume of the debris flow, likely flow path, potential runout distance, impact forces, and run-up. Although they are often designed to be sacrificial, and replaced or rebuilt after use, they should be designed so that they do not add to the mass of the debris flow.

Earth mounds, designed for use against both channellized debris flows and snow avalanches, were constructed along Phase I of the Coquihalla Highway (Thurber Consultants, no date).

Check Dams Check dams, usually constructed in series in the transportation zone of a channellized debris flow, are used to reduce steep channel

Plan view



Oblique view (after Eisbacher and Clague, 1984)

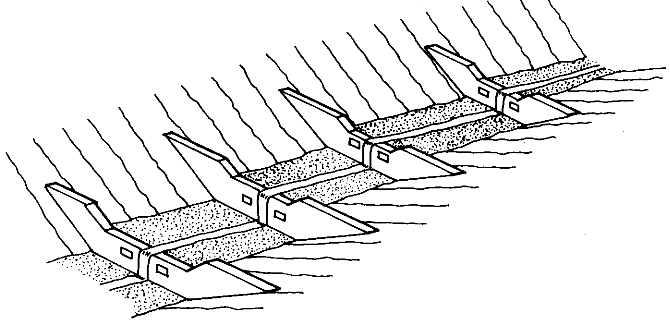


FIGURE 13 *Plan and oblique view of series of check dams on a debris fan.*

gradients locally and to minimize scour along the bottom and sides of the stream. They can, however, also be constructed on the debris fan (Figure 13), usually near the apex. This can artificially lower the gradient of the upper portion of the fan or help maintain flow within a particular channel on the fan. When constructed immediately upstream of a storage basin, where they are intended to minimize degradation of the streambed, a check dam is referred to as an inlet structure (Zollinger 1985).

Although we are not aware of any Canadian examples of check dams constructed on a debris fan, we do know that reinforced concrete check dams have been used in the transportation zone on Alberta Creek (Hungr et al. 1987; Martin 1989) and Newman Creek along the Howe Sound portion of Highway 99.

Design considerations for check dams include the likely flow path immediately upstream of the structure, and the maximum discharge of the channellized debris flow past the location of the structure. Check dams, similar to gravity-retaining structures, are usually designed to withstand dynamic and point impact forces, sliding, overturning, uplift pressures, and foundation and abutment loadings.

Debris that collects behind a check dam is not usually removed. Excess debris deposited behind a check dam is removed over a period of time by water flow after the debris flow (Ikeya 1976; Thurber Consultants 1984).

In Austria, Japan, and Switzerland, manuals have been published for the design of such structures (respectively, Leys and Hagen 1971; Government of Japan 1984; Switzerland,[2]). In these countries, check dams are commonly less than 5 m in height, but can extend up to 15 m. They have been constructed as timber and steel rock-filled cribs, and as stone masonry and

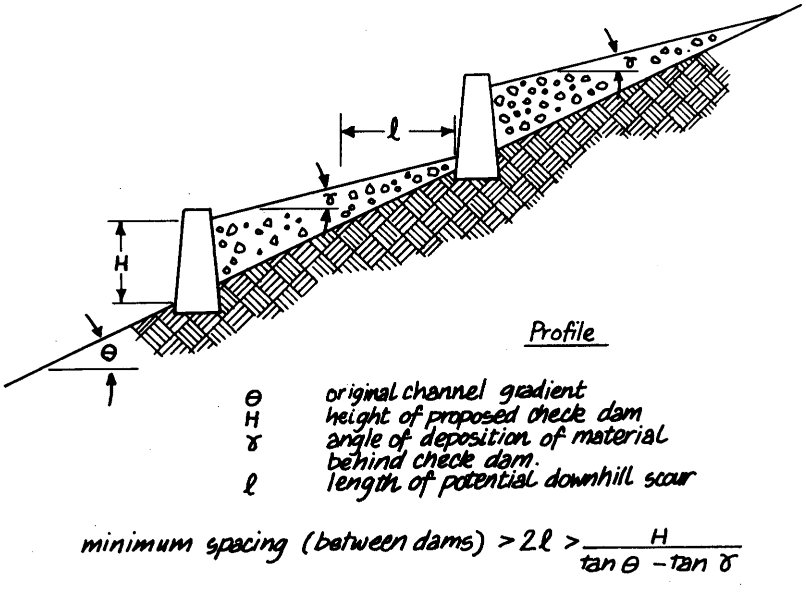


FIGURE 14 *Factors that influence spacing of check dams, and formula for spacing of check dams.*

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[2] Switzerland, Eidgenossisches Amt fur Strassen-und Flussbau. 1973. Dimensionierung von Wildbachsperren aus Beton und Stahlbeton. Bern. Unpubl. 121 p. (in German).

gabion structures, but are now more commonly constructed of concrete and reinforced concrete.

The weir portion of the check dam must be designed to pass both flood water discharges and channellized debris flow discharges, the latter being potentially much larger than the former (Thurber Consultants 1984; Government of Japan 1984; VanDine 1985).

Drainage holes or galleries are incorporated into the check dam to allow passage of normal stream flows during construction, and to allow drainage of water from the entrapped material afterwards.

As shown in Figure 14, the spacing between check dams depends on stream gradient, dam height, angle of deposition of material behind the dam, and downstream extent of potential scour. Chatwin et al. (1994) provides a formula for the spacing of check dams (Figure 14).

The most common causes for check dam failure include:

- abrasion of the structure;
- impact on the "wings" of the structure;
- scouring beneath the front face;
- outflanking of the abutments; and
- inadequate spillway capacity (Thurber Consultants 1984).

Refer to Leys and Hagen (1971); Eisbacher and Clague (1984); Government of Japan (1984); Thurber Consultants (1984); Heierli and Merk (1985); Whittaker et al. (1985); Chatwin et al. (1994); and Switzerland[3] for further details on the design of check dams.

Lateral Walls (Berms) Lateral walls or berms, referred to as "guiding walls" by Eisbacher and Clague (1984) and "training walls" in a Japanese report

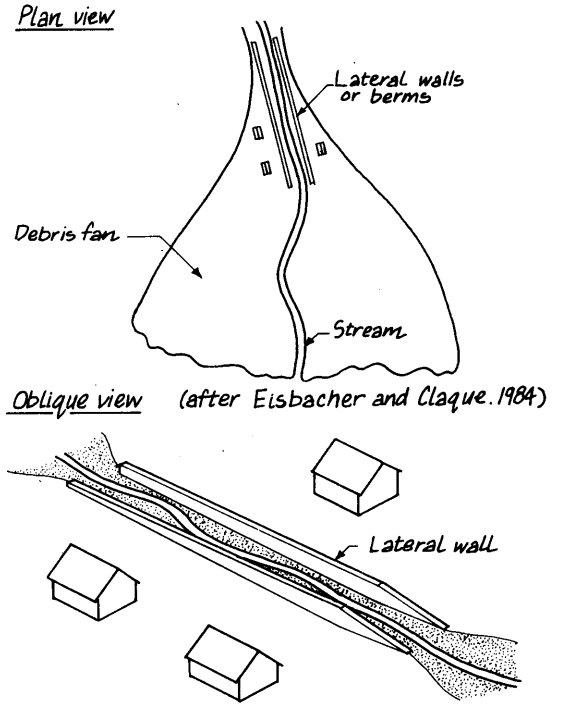

FIGURE 15 *Plan and oblique view of lateral walls and berms.*

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[3] Ibid.

(Government of Japan 1984), are constructed parallel to the desired path of the debris flow. They are used to constrain the lateral movement of a debris flow, encourage the debris to travel in a straight path, and thereby protect an area of—or a structure on—the debris fan (Figure 15).

They can be constructed of earth berms, concrete, or composite structures. Eisbacher and Clague (1984) mentioned that "forest belts," left or grown on both sides of the flow path, can perform a similar function.

We know of no Canadian examples where lateral walls or berms have been located on a debris fan. Reinforced concrete walls have been constructed in the transportation zone on Alberta Creek along Howe Sound (Hungr et al. 1987; Hawley 1989; Lister and Morgan 1989) and in the Hope-Coquihalla area (Hungr et al. 1987; Thurber Consultants, no date).

To be most effective on the debris fan, lateral walls or berms should be located immediately downslope of the apex of the fan, where the gradient is greatest and the flow path is known with some certainty. Usually they are located and designed so that the debris will not be deposited adjacent to them, but will keep travelling. If deposition does occur, the coarse-grained debris must be removed.

The main design consideration for lateral berms or barriers is the maximum discharge and flow depth of the debris flow at the location of the structure. The structure should be designed with a freeboard above the estimated flow depth. As a rule of thumb, one study used 0.6 m of freeboard for discharges less than 200 m^3/s and 0.8 m of freeboard for discharges of 200–500 m^3/s, although these heights were somewhat dependent on the gradient (Government of Japan 1984). In the design of the lateral walls along the lower portion of the transportation zone of Alberta Creek, a freeboard of 1.0 m was used for an estimated discharge of 350 m^3/s (Lister and Morgan 1989).

The front face of these structures must be designed for both stability and flow hydraulics, and some form of erosion protection or armouring must be included in the design to minimize erosion and the addition of material from the structure to the debris flow mass. Erosion protection from coarse-grained debris can be in the form of rip-rap, dimension stone, concrete, or fibre reinforced shotcrete.

Deflection Walls (Berms) Deflection walls or berms are referred to as "deflection dams" by Eisbacher and Clague (1984) and "debris flow direction controlling works" in Japan (Government of Japan 1984). They are similar to lateral berms in that they are usually built immediately downslope from the apex of the debris fan, and parallel to the desired path of the debris flow whose lateral movement they are used to constrain. They differ from lateral walls or berms in that they deflect the flow path and prevent it from going straight. They can be used to protect a structure, deflect the flow to another area of the fan, or increase the length of the flow path, thereby decreasing the overall gradient and encouraging deposition (Figure 16). In California, deflection walls are used to decrease the angle of impact on a structure (Hollingsworth and Kovacs 1981).

Walls are usually constructed of reinforced concrete; berms are usually constructed from local materials, but can be a composite. A number of earth deflection berms have been constructed in British Columbia. Examples include those at Port Alice on Vancouver Island, near Agassiz in the Fraser Valley, at Ted Creek west of Hope, and at Boulder Creek along Phase I of the Coquihalla Highway (Nasmith and Mercer 1979; Martin et al. 1984; Hungr et al. 1987; Slaymaker et al. 1987; Hawley 1989; Martin 1989). The deflection berms constructed at Port Alice (Nasmith and Mercer 1979) have the distinction of being the first debris flow control structures to have been constructed in British Columbia.

As for lateral walls or berms, the main design consideration for deflection structures is the maximum discharge and flow depth of the debris flow past the location of the structure. In addition, because of the curvature of the stream, potential impact forces, run-up and superelevation must be considered. To take these into account, the front face of the structure is designed for stability and with an appropriate slope and height. The freeboard heights discussed for lateral walls or berms can be used as well, but an additional height for superelevation is required. A freeboard height of 1.5 m was used for the deflection berms used at Port Alice, B.C. (Nasmith and Mercer 1979).

Some form of erosion protection or armouring must also be included in the design of these structures to minimize the addition of material from the structure to the debris flow mass. At Boulder Creek, along the Coquihalla Highway, Class 250 rip-rap was placed up the lower 8 m of a 1.5(H):1(V) slope on the outside bend of the earth deflection berm.[4]

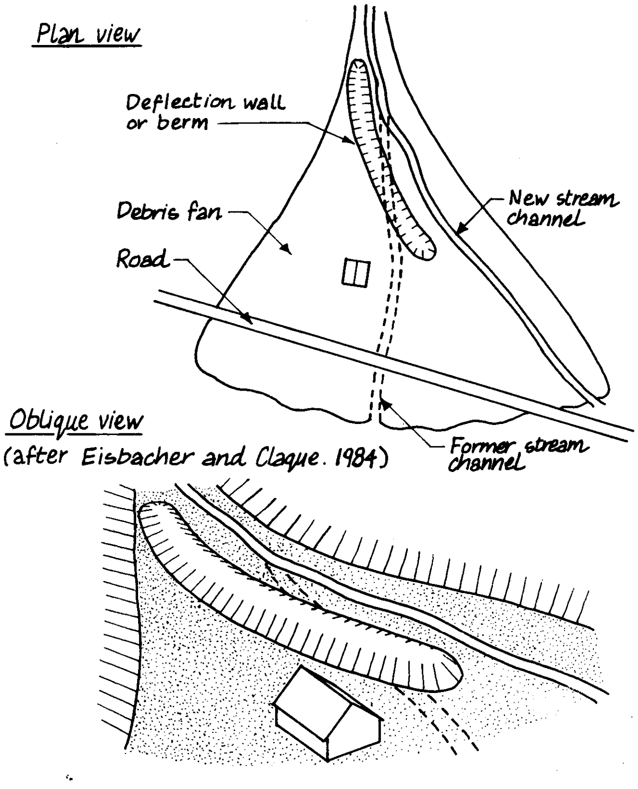

FIGURE 16 *Plan and oblique view of deflection wall or berm.*

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[4] British Columbia Ministry of Transportation and Highways. 1984. Contract construction drawings for various debris torrent structures between Ted Creek and Berkey Creek, Highways 1 and 3 near Hope, and Phase 1 of Coquihalla Highway. Prepared by the Ministry and various consultants. Unpubl.

Where deposition is encouraged, the likely flow path of the fine-grained sediment, water from the debris flow, and subsequent water flows must be considered. If deposition does occur, the coarse-grained debris must be removed from the stream channel.

Terminal Walls, Berms, or Barriers Terminal walls, berms, or barriers are constructed across the path of a debris flow to encourage deposition by presenting a physical obstruction to flow. They do this by increasing the length of the flow path. They are built with a finite length so that normal water flows and fine-grained sediment and water from the debris flow can find their way around either end of the berm (Figure 17). Once a debris flow has been deposited upstream of a terminal structure, the coarse-grained debris must be removed from the area.

A number of terminal berms or barriers have been constructed in British Columbia. Examples exist near Agassiz and in the Hope-Coquihalla area (Martin et al. 1984; Thurber Consultants, no date).

Design considerations include the design magnitude or volume of the debris flow, the likely flow paths, potential runout distance, impact forces, run-up, and probable storage angle.

Terminal walls, berms, or barriers are usually located as far as possible downstream from the apex of the fan to maximize the runout distance and deposition area, and to minimize the impact forces and run-up. These structures are often built with a deposition area or partial deposition area upstream. The excavated deposition area artificially lowers the gradient,

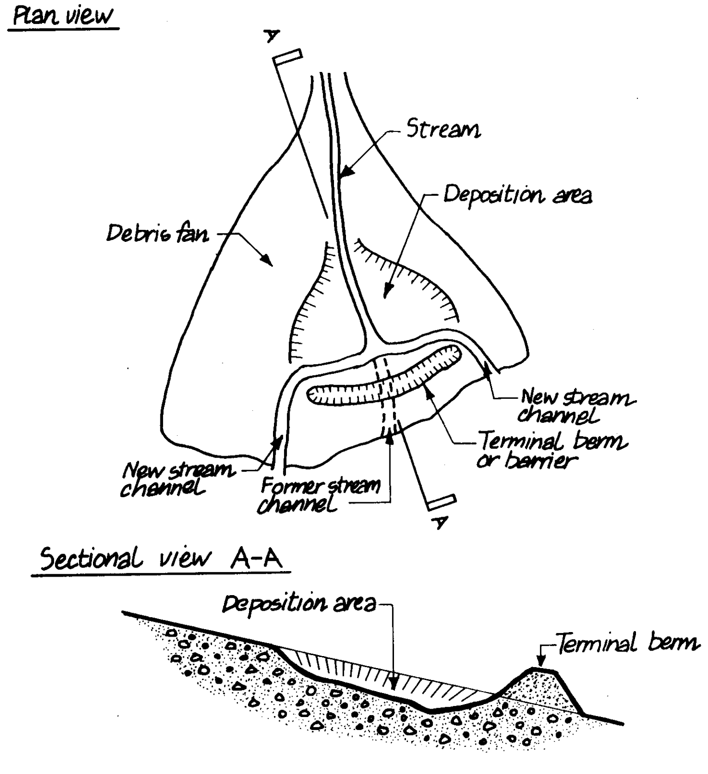

FIGURE 17 *Plan and section of a terminal berm or barrier.*

increases storage capacity, and decreases runout distances, impact forces, and run-up.

In British Columbia, terminal structures have usually been constructed as massive gravity earth structures, so as to withstand the impact forces and the external forces of sliding and overturning. Impact forces and run-up can be reduced by decreasing the slope angle of the front face and by installing a sand cushion in front of the structure. For smaller magnitude debris flows in California, Baldwin et al. (1987) described terminal walls as "impact walls," built as concrete walls, soldier pile walls, and soil and rock gravity walls, including gabions.

5.2 Closed Debris Flow Control Structures

Examples of closed control structures include:

- debris racks, grizzlies, or some other form of debris-straining structure located in the channel; and
- debris barriers and storage basins with some form of debris-straining structure incorporated into the barrier.

Debris Racks, Grizzlies, or Other Debris-straining Structures Debris racks, grizzlies, or other forms of debris-straining structures are used to separate the coarse-grained debris from the fine-grained debris and water of the debris flow, thus encouraging the coarse-grained portion to be deposited (Figure 18). In Japan (Government of Japan 1981, 1984), these sorts of structures are referred to as "slit dams," "separating dykes," or "drainage screens."

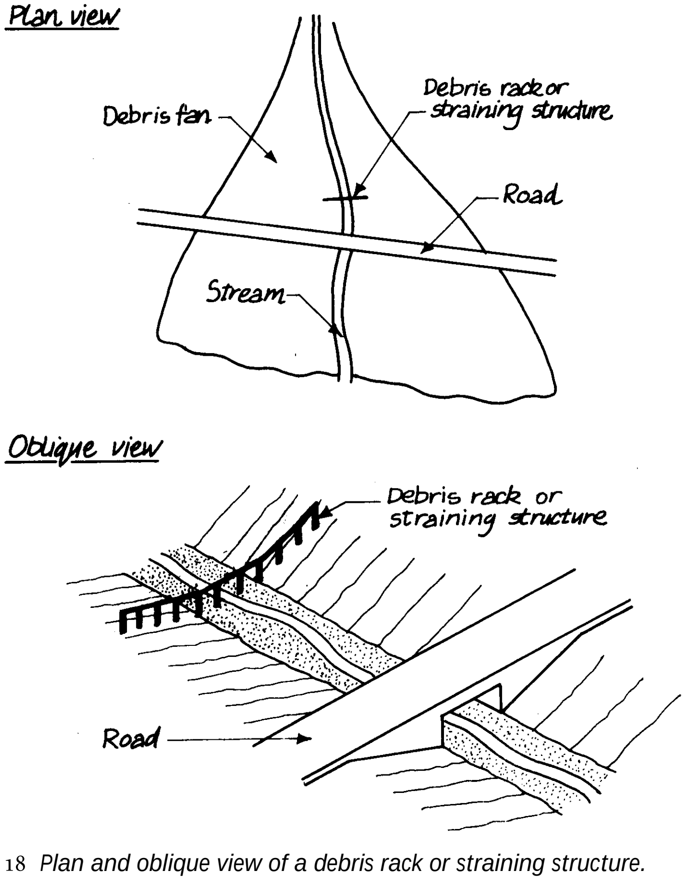

FIGURE 18 *Plan and oblique view of a debris rack or straining structure.*

In the United States, they are referred to as "debris fences" (Mears 1977; Hollingsworth and Kovacs 1981; Baldwin et al. 1987; Morris 1989).

Debris racks, grizzlies, and other forms of straining structures are used commonly in British Columbia (Thurber Consultants 1984, no date; VanDine 1985; Hungr et al. 1987).

Often used to prevent culvert openings and bridge clearances from becoming blocked with debris, debris racks and grizzlies are also often used as an integral component of debris barriers. To remain effective, the coarse-grained debris must be removed from behind the straining structure on a regular basis.

Design considerations include the design magnitude or volume of the debris flow; the likely flow path so that the debris flow remains in the channel until it reaches the structure; the size and gradation of the debris; potential impact forces; and probable storage angle.

When located within a stream channel (with its storage volume constraints), this system of control is limited to small volumes of debris. Debris-straining structures located within a channel must be designed to allow the normal water flows and stream bedload to pass at all times, and should redirect fine-grained sediment flows and water from the debris mass back into the channel after the coarse-grained debris has been stopped. For this purpose, a weir is often incorporated into the design of the straining structure.

As a rule of thumb, Japanese researchers design the slit interval at 1.5 to 2 times the maximum diameter of the boulders (Ikeya 1981, 1985; Government of Japan 1984). The openings used for the straining structures associated with the debris barriers and storage basins along Howe Sound were 0.45 m (Thurber Consultants and Ker Priestman, no date). For the debris racks in the Hope-Coquihalla area, the openings ranged between 0.75 and 0.91 m.[5]

Debris racks can be constructed of a wide variety of materials. Reishen (1964) lists materials that have been used successfully for such structures:

- railroad rails;
- structural steel sections, such as I-beams;
- timbers;
- pre-cast concrete beams;
- cables;
- culvert pipes; and
- fencing materials.

Zollinger (1985) found that when the structural members were placed vertically rather than horizontally, inorganic coarse-grained debris jammed more easily. Organic debris was found to jam more easily with structural members placed horizontally rather than vertically.

Placing several culverts at different elevations through an embankment was a form of debris-straining structure used along the Coquihalla Highway.[6]

Numerous drawings and photographs of European debris-straining structures are included in Thurber Consultants (1984).

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[5] B.C. Ministry of Transportation and Highways, 1984.

[6] Ibid.

Debris Barriers and Storage Basins with Debris-straining Structures Incorporated into the Barrier Debris barriers and storage basins, with some form of debris-straining structure incorporated into the barrier, are referred to as "open dams" in Japan (Government of Japan 1984; Ikeya 1985) and "transverse debris retention dams" and "detention basins" by the Europeans (Eisbacher and Clague 1984; Zollinger 1985).

This system of debris flow control is similar to that achieved by a terminal berm or barrier, in that both are located across the debris flow path and designed to encourage deposition. Unlike terminal berms or barriers, however, debris barriers are designed as a closed barrier, or "dam," so that all the coarse-grained debris is contained within the storage basin located upslope of the barrier. The debris-straining structure must be designed so that during normal conditions, stream water and bedload can travel through the structure and, after a debris flow, the water that was in the flow and some of the fine-grained sediment can escape (Figure 19).

As for a terminal berm or barrier, the area upstream of the debris barrier can be excavated to reduce the gradient and to increase storage capacity. Depending on the site, an inlet structure may be constructed upstream of the storage basin to minimize erosion of the streambed. After a debris flow has occurred, the coarse-grained debris trapped behind the debris barrier must be removed.

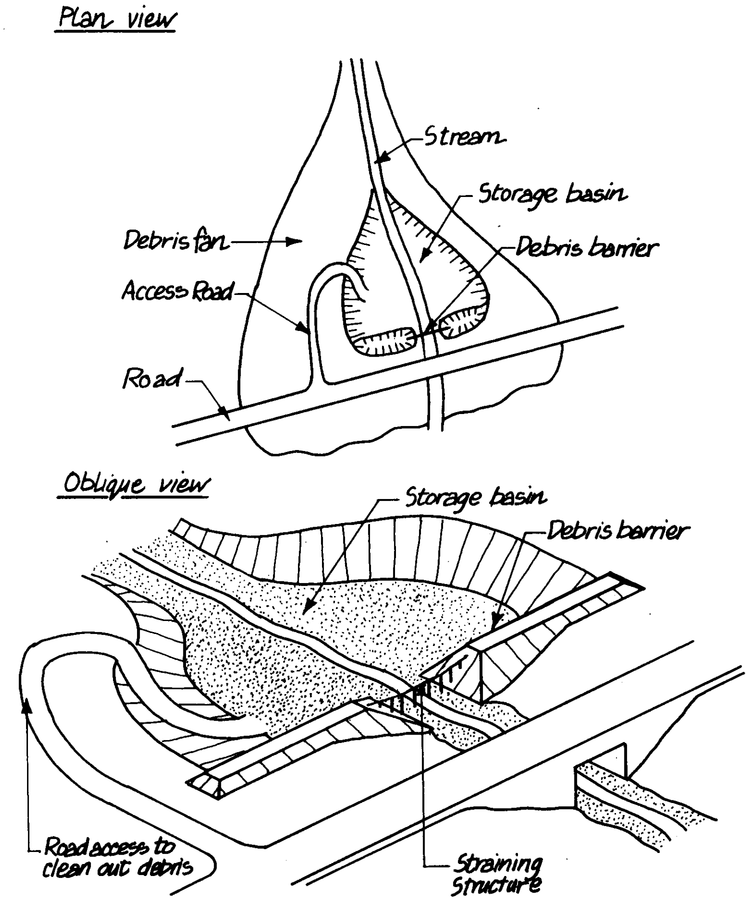

FIGURE 19 *Plan and oblique view of typical components of a debris barrier and storage basin.*

This form of debris flow control is generally considered to be the most sophisticated and generally the most costly. Design considerations include: design magnitude or volume of a debris flow, size and gradation of the coarse-grained debris (pertinent to designing the straining structure), potential runout distance, impact forces, run-up, and probable storage angle. Properly located, designed, and constructed, a debris barrier and storage basin, with an appropriate form of debris-straining structure incorporated into the barrier, is probably the most positive form of debris flow control.

As well, this form of control structure is best suited to a larger debris fan with a relatively low gradient. The geometry and morphology of the debris fan can be used to optimize design and minimize construction costs.

Very sophisticated storage basins were designed and constructed in the mid-1980s for the B.C. Ministry of Transportation and Highways on the Charles, Harvey, and Magnesia creeks along the Howe Sound portion of Highway 99. These structures are described by Price (1986), Lister and Morgan (1989) and Thurber Consultants and Ker Priestman (no date). A total of seven less-expensive debris barriers and storage basins were also designed and constructed in the Hope-Coquihalla area (Thurber Consultants, no date; B.C. Ministry of Transportation and Highways[7]) associated with Phase I of the Coquihalla Highway. Appendix 1 includes an example of a design for a 30,000 m^3 storage basin and associated structures on Vancouver Island.

Most of the storage basins constructed in British Columbia to date have been built as variations of earth berms or earth dams. In Europe and Japan, concrete and reinforced concrete gravity and arch-dam type structures have also been used. Unlike traditionally designed water-retaining structures, debris barriers are usually designed with the curve downstream to maximize the volume of debris storage. It is imperative to incorporate a weir or spillway into the structure to allow debris, fine-grained sediment, and water to safely overtop the structure should the storage basin be filled when a subsequent debris flow occurs. Other design considerations include external forces such as sliding, overturning uplift, and foundation and abutment loadings.

5.3 Sediment Control Structures

Sediment control structures are used by themselves or in concert with debris control structures to control the movement of fine-grained material across a debris fan or alluvial fan, thereby minimizing the amount of fine-grained sediment entering a neighbouring body of water. In general, their design can be divided into two types:

- energy dissipation or settling basins; and
- sediment control fences constructed of natural or artificial materials.

The location of sediment control structures is very important. Located too close to the apex of the debris fan, they are subject to a large volume of coarse-grained debris and large impact forces. When located at the distal end of a debris fan or on the alluvial fan, they must face the possibility of an avulsion of the stream channel and flow path farther up the fan, which might result in the structure being bypassed.

Because the emphasis of this study was on debris flow control structures, sediment control structures are not discussed here further.

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[7] Ibid.

6 CONCEPTUAL DESIGNS

This section provides sketches and discussions of conceptual designs for seven debris flow control structures. These designs are based on actual sites and field conditions. The seven sites, selected specifically as part of this study, are located in the Rennell Sound area of Graham Island in the Queen Charlotte Islands.

The design of an eighth site near Kennedy Lake on Vancouver Island is included in Appendix 1. It was part of a separate study for the B.C. Ministry of Forests (VanDine Geological Engineering 1992).

The seven designs for the Queen Charlotte Islands have been prepared as field designs; the one from Vancouver Island has been prepared as a preliminary functional design.

These designs are intended as examples only. As stated in Section 5, the type of debris flow control structure that is used on a debris fan must be site specifically suited to the character of the channellized debris flow, the character of the debris fan, the purpose of the mitigation, and the monies, resources, and equipment available for design, construction, and maintenance of the structure.

To date, four of the structures on the Queen Charlotte Islands have been constructed. Ground photographs and the approximate labour and equipment-hours and costs are provided for these structures.

The conceptual designs for the debris flow control structures on the Queen Charlotte Islands are discussed in point form under the following headings:

- reference figure
- type of mitigative control structure
- location
- history of past debris flow activity
- design philosophy
- design details to note
- reference photographs (where applicable)

The information on the preliminary functional design for the Kennedy Lake site on Vancouver Island (Appendix 1) has been taken from Section 4 of VanDine Geological Engineering (1992).

6.1 Conceptual Design 1

Reference Figure Figure 20.

Type of Mitigative Control Structure A series of small log crib check dams near the distal end of the fan.

Location A small tributary stream to Bonanza Creek (locally referred to as Creek 4.5) in the Rennell Sound area of Graham Island in the Queen Charlotte Islands.

History of Past Debris Flow Activity Debris on this fan perennially migrates downstream and blocks the Bonanza Mainline.

Design Philosophy To trap debris behind the check dams, thereby artificially reducing the fan gradient and encouraging deposition higher up the fan. A natural log jam, approximately 100 m upstream of the mainline, is currently accomplishing this to some extent. The trapped debris is not to be removed.

Design Details to Note The log cribs are approximately 10–12 m long, 3 m wide, and 2.5 m high. For stability, the logs are keyed into the stream banks to approximately 2 m, and the cribs are filled with boulders as large as are available. The top row of logs forms a weir in the middle of the structure to help keep discharge away from the sides of the channel, thus minimizing erosion.

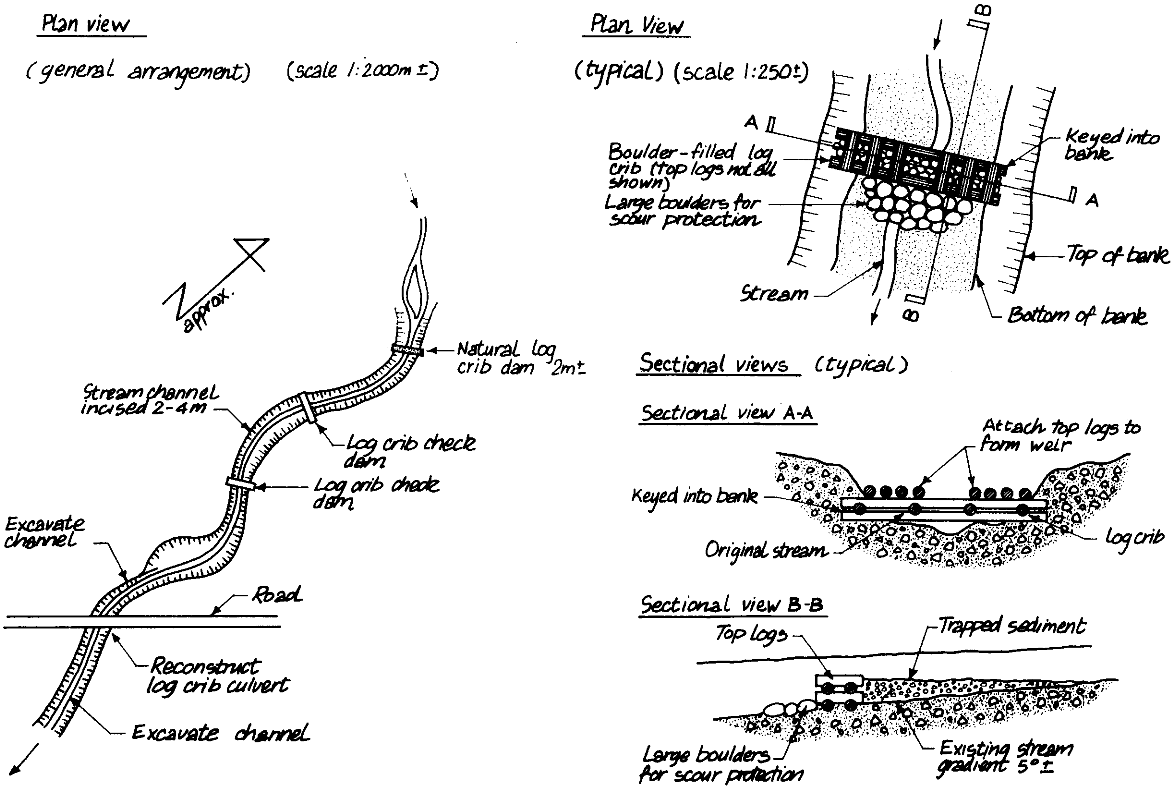


FIGURE 20 *Mitigative control structure, Creek 4.5, along Bonanza Mainline.*

6.2 Conceptual Design 2

Reference Figure Figure 21.

Type of Mitigative Control Structure Deflection berm.

Location A small tributary to Hangover Creek at approximate Station 0+050 along the Hangover Mainline in the Rennell Sound area of Graham Island in the Queen Charlotte Islands.

History of Past Debris Flow Activity A steep colluvial fan provides evidence of past activity.

Design Philosophy To encourage the debris to deposit before it reaches the road, by lengthening the flow path. Should a debris flow occur, the material should be cleaned out from the upslope side of the berm.

Design Details to Note The berm is constructed from material excavated on the upslope side, and is tied into a bedrock face on the upstream end.
The upslope face is armoured by large rocks to minimize erosion. The concept could have been improved if the berm and runout zone could have been increased in length and if the gradient were gentler.

Construction Details Constructed in approximately eight hours during March 1992 using a Hitachi UH-181 Excavator. Total construction costs were approximately $1300.

Reference Photographs Plate 1.

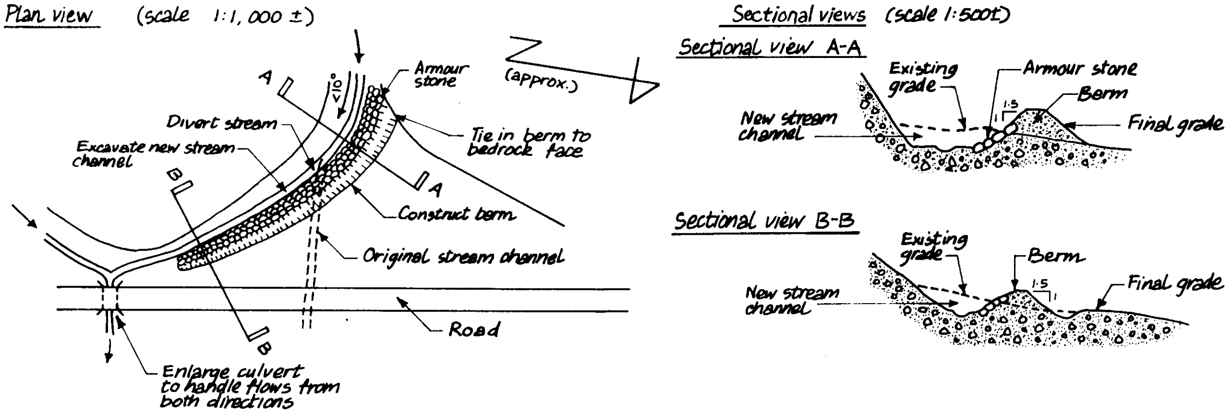


FIGURE 21 *Mitigative control structure, approximate Station 0+050, Hangover Mainline.*

Looking downstream. Deflection berm is on left. Upslope side of berm has not yet been armoured.

PLATE 1 *Hangover Mainline, approximate Station 0+050.*

6.3 Conceptual Design 3

Reference Figure Figure 22.

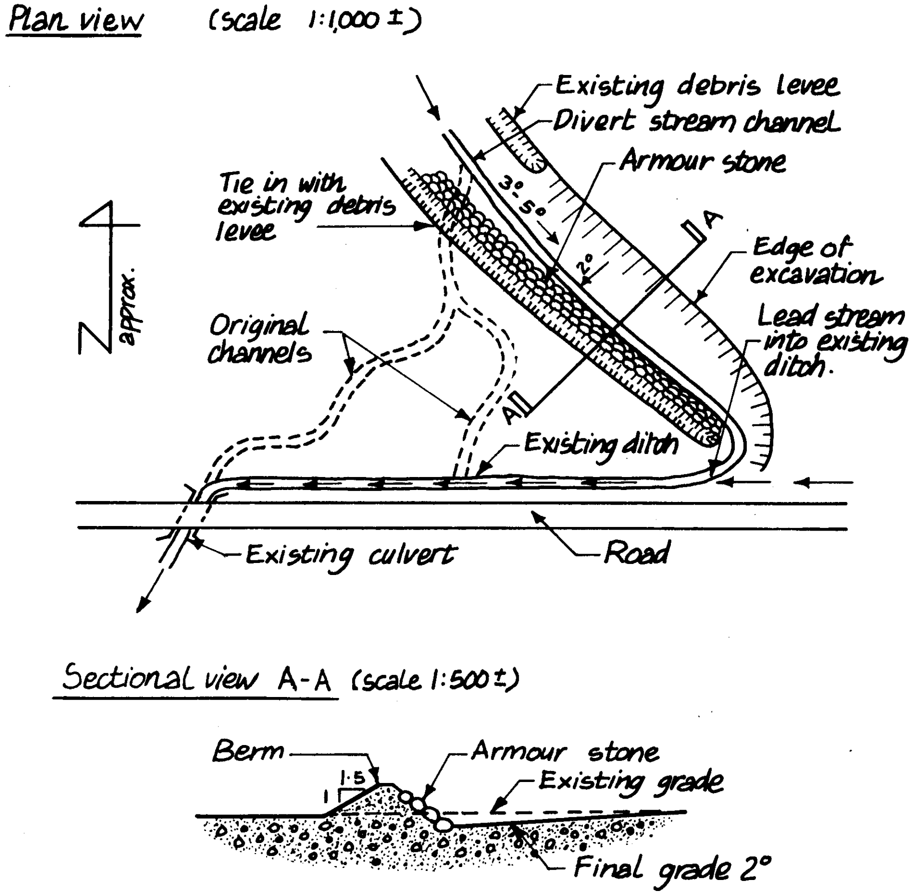
Type of Mitigative Control Structure Deflection berm.

Location A small tributary at approximate Station 0+600 on the proposed Gregory Creek Mainline in the Rennell Sound area of Graham Island in the Queen Charlotte Islands.

History of Past Debris Flow Activity There is evidence of at least two small debris flows in the recent past.

Design Philosophy To encourage the debris to deposit before it reaches the road, by lengthening the flow path. Should a debris flow occur, the material should be cleaned out from the upslope side of the berm.

Design Details to Note The berm is constructed from material excavated from the upslope side, and is tied into a former debris flow levee on the upstream end. The upslope side of the berm is armoured with large rocks to minimize erosion.


Plan view (scale 1:1,000 ±)

Sectional view A-A (scale 1:500 ±)

FIGURE 22 *Mitigative control structure, approximate Station 0+600, Gregory Creek Mainline.*

6.4 Conceptual Design 4

Reference Figure Figure 23.

Type of Mitigative Control Structure Small debris basin with deflection/terminal berm.

Location A small tributary to Riley Creek along the Riley Mainline in the Rennell Sound area of Graham Island in the Queen Charlotte Islands.

History of Past Debris Flow Activity A debris flow descended this tributary in the winter of 1989. A branch of the flow also followed a parallel flow path to the north of the tributary. Debris from both these flow paths were deposited on the Riley Mainline. An inspection of the source area of the 1989 debris flow indicates that further debris flows are very likely.

Design Philosophy To excavate a relatively flat area to encourage debris deposition, and to use the excavated material to construct a deflection/terminal berm to deflect and halt additional debris. The deflection berm is tied into the bank on the upstream end, and is continued past the former debris flow path to the north to act as terminal berm in this area.
The size of the debris basin, the curvature of the deflection berm, and the height of the terminal berm are not as large as required, but are designed to be as large as the area would allow. Some debris, but only a reduced volume from future debris flows, will likely reach the road. Debris from behind the berm should be cleaned out after a flow occurs.

Design Details to Note The apex of the basin is excavated to bedrock to provide an upstream sill against erosion. The upstream side of the berm is armoured with large rocks to minimize erosion. The basin is graded so that the stream flows around the inside of the curve during low flows.

Construction Details Constructed in 40 hours during March 1992 using a Hitachi UH-181 Excavator. The total construction costs were approximately $6500. During construction, it was found that the former debris flow material, which was required to be excavated and used to build the berm, was much finer-grained and much wetter than anticipated. The basin was therefore not excavated as deeply, and the berm was not constructed at the design height.

Reference Photographs Plate 2.

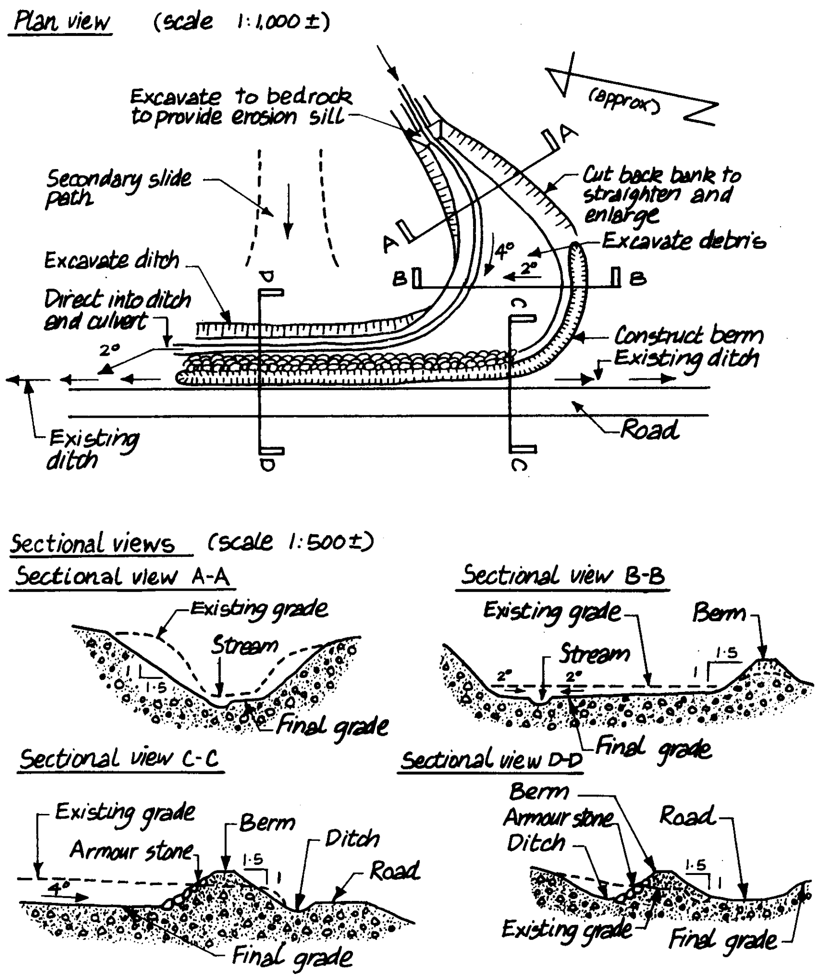


FIGURE 23 *Mitigative control structure, small tributary along Riley Mainline.*

Looking northwards. Deflection/terminal berm is on left. Upslope side of berm has not yet been armoured. Excavated basin is in foreground.

PLATE 2 *Riley Creek Mainline.*

6.5 Conceptual Design 5

Reference Figure Figure 24.

Type of Mitigative Control Structure Debris basin with a terminal berm.

Location A small tributary (locally called Heli Creek) to Hangover Creek along the Hangover Mainline in the Rennell Sound area of Graham Island in the Queen Charlotte Islands.

History of Past Debris Flow Activity No known history of past events. The stream appears to have a high potential for debris flows once the watershed above is logged.

Design Philosophy To excavate a relatively large and flat debris basin to encourage deposition, and to use the excavated material to construct a relatively large terminal berm. Also, to divert the original drainage path to the edge of the terminal berm to minimize the probability of a debris flow blocking the outlet.

Design Details to Note The apex of the basin is excavated to bedrock to provide an upstream sill against erosion. The terminal berm is located so as to incorporate two small hillocks. The upstream side of the berm is armoured with large rocks to minimize erosion. The debris basin is graded to direct normal water flows around the end of the terminal berm and then along a new stream channel. An access road is provided to allow for the future clean-out of debris, should a debris flow occur.

Construction Details Constructed in 48 hours during March 1992 using a Hitachi UH-181 Excavator. The total construction costs were approximately $8000.

Reference Photographs Plate 3.

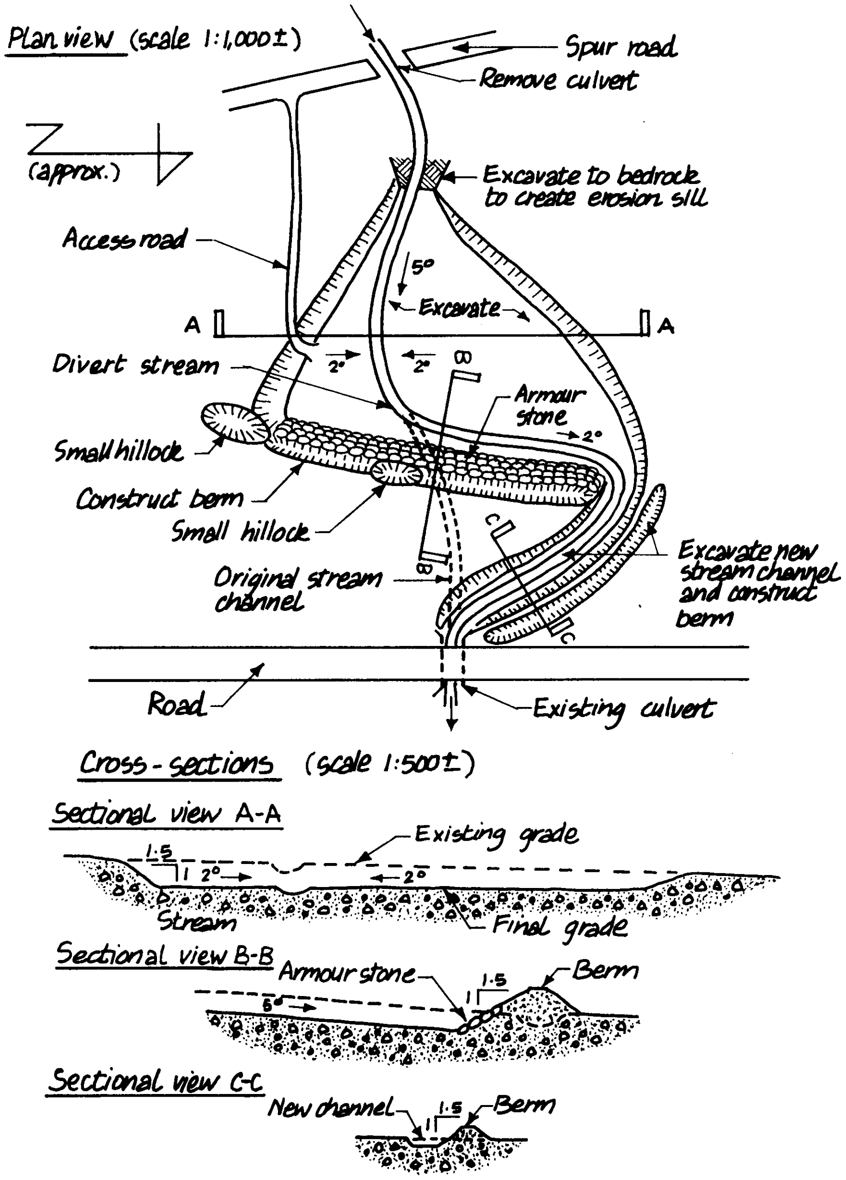


FIGURE 24 *Mitigative control structure, Heli Creek along Hangover Mainline.*

Looking downstream from apex of debris basin towards terminal berm. For scale, berm is approximately 5 m high.
Note armouring of upslope side of berm.

New creek channel on right of photo, old channel on left.
Looking upstream from mainline.

PLATE 3 *Heli Creek along Hangover Mainline.*

6.6 Conceptual Design 6

Reference Figure Figure 25.

Type of Mitigative Control Structure Small debris basin.

Location A small tributary to Hangover Creek at approximate Station 0+325 along Hangover Mainline in the Rennell Sound area of Graham Island in the Queen Charlotte Islands.

History of Past Debris Flow Activity At least two small debris flows have occurred on this stream in the past 50–100 years.

Design Philosophy To shift the original proposed road alignment downslope, thereby creating a larger area for the debris to deposit before reaching the road; to use the excavated material from the basin to construct the road embankment; to use the road embankment as the downstream berm for the debris basin; and to divert the original drainage path to the edge of the basin to minimize the probability of a debris flow blocking the outlet. Should a debris flow occur, the material should be cleaned out from the basin.

Design Details to Note The apex of the basin is excavated to bedrock to provide an upstream sill against erosion. The upstream side of the road embankment/berm is armoured with large rocks to minimize erosion.
The debris basin is graded to direct normal water flows to the side of the basin and through the culvert. For a larger debris basin, a secondary culvert should be included at the side of the road embankment opposite the primary culvert.

Construction Details Constructed in 10 hours during March 1992 using a Hitachi UH-181 Excavator. The total construction costs were approximately $1700. The proposed debris basin was somewhat larger than the basin that was actually constructed. This occurred because the road was shifted downslope less than proposed, and because bedrock was encountered in the bottom of the basin.

Reference Photographs Plates 4 and 5.

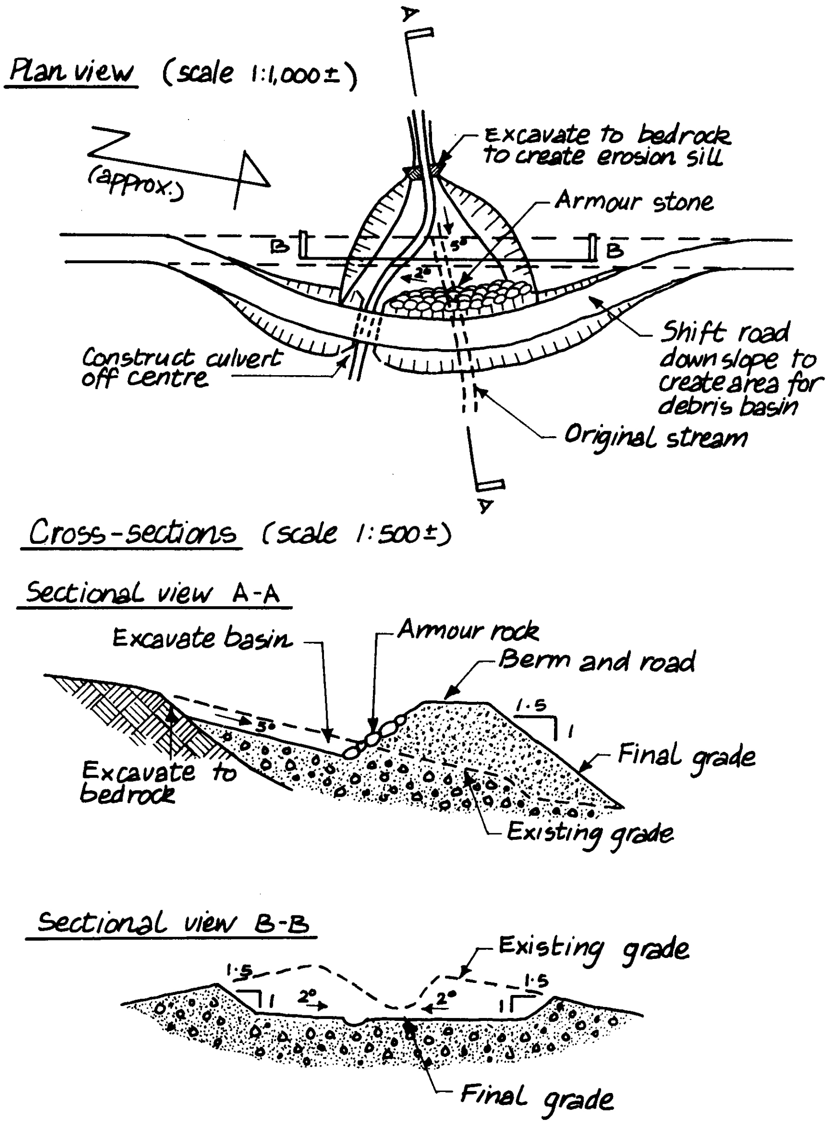


FIGURE 25 *Mitigative control structure, approximate Station 0+325, Hangover Mainline.*

Road on left forms terminal berm for small debris basin. Note armouring on upslope side of road.

PLATE 4 *Hangover Mainline, approximate Station 0+325.*

Looking downstream towards terminal berm. Note armouring.

PLATE 5 *Hangover Mainline, approximate Station 0+325.*

6.7 Conceptual Design 7

Reference Figure Figure 26.

Type of Mitigative Control Structure Small debris basin.

Location A small tributary at approximate Station 0+910 along the proposed Gregory Creek Mainline in the Rennell Sound area of Graham Island in the Queen Charlotte Islands.

History of Past Debris Flow Activity Evidence of at least one former debris flow.

Design Philosophy To excavate a small debris basin so that a relatively flat area is provided to encourage deposition, and to construct small lateral containment berms and a small terminal berm to aid in containing the flow material. Should a debris flow occur, the material should be cleaned out from the basin.

Design Details to Note The upstream ends of the containment berms are tied into the existing stream banks. If bedrock is not found at the apex of the debris basin, very large rocks must be placed across the apex to form a sill that minimizes upstream erosion.

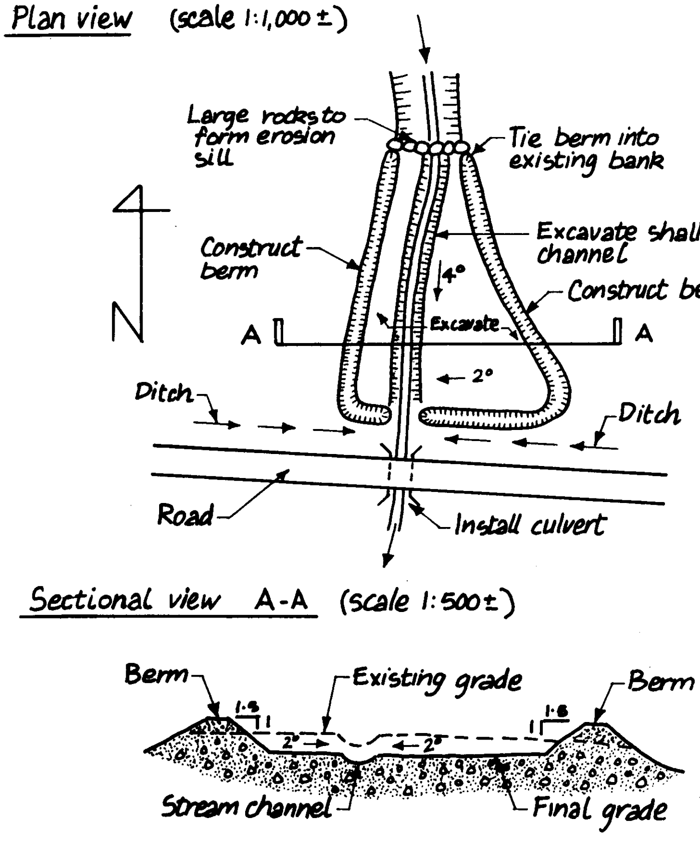


FIGURE 26 *Mitigative control structure, approximate Station 0+910, Gregory Creek Mainline.*

Reference Figures Figures 4.1–4.8 from VanDine Geological Engineering (1992).

Type of Mitigative Control Structure A relatively large debris basin with a terminal berm and debris-straining structure.

Location Boat Launch Creek, a stream flowing into the south side of Kennedy Lake on the west coast of Vancouver Island.

History of Past Debris Flow Activity There is some geomorphic evidence of debris flow activity before development of the area in the 1950s. Since then, there have been several minor debris flows along the stream and two major debris flows. The first major flow in October 1987 is estimated to be approximately 30 000 m^3, and the second major flow in August 1991 is estimated to be approximately 10 000 m^3 (VanDine Geological Engineering 1991 and 1992).

Design Philosophy The following discussion is adapted from VanDine Geological Engineering (1992) Chapter 4.

Preliminary Design for Debris Flow Mitigative Works

DESIGN CRITERIA

Two preliminary designs for debris flow mitigative works on Boat Launch Creek have been prepared: a basic low-cost design and an enhanced low-cost design. The criteria agreed upon and used for both designs are as follows:

- To construct a relatively low-cost structure, maximizing the use of site topography and local materials. This is interpreted to mean that mitigative works should be more closely related to the types of mitigative works constructed along the Coquihalla Highway in the mid-1980s, as opposed to those constructed along the Squamish Highway in the mid-1980s.
- The mitigative works should minimize the risk to users of Highway 4 and minimize the risk of damage to the Highway 4 Boat Launch Creek bridge from future debris flows. This means that Highway 4 should not be subject to any direct impact from a debris flow, but could be subject to subsequent indirect impacts, such as debris floods and water floods that could result in minor damage, but not sever the highway structure.
- The mitigative works should minimize the amount of coarse-grained sediment that enters Kennedy Lake from future debris flows.

For design purposes it was assumed that the Eastmain in the vicinity of the Boat Launch Creek fan will be abandoned by MacMillan Bloedel Limited (J. Smith, pers. comm.). The possible future realignment or upgrading of Highway 4 in the vicinity of Boat Launch Creek were not considered in the designs.

DESIGN CONCEPT

To achieve the above criteria, the proposed design concept is similar for both designs. The mitigative works would be constructed on the fan of Boat Launch Creek upstream of Highway 4. They would consist of a terminal gravity berm, a debris-straining structure across an opening in the berm, a debris basin upstream of the berm, and road access for cleaning out any debris that enters the basin from future debris flows. The Eastmain log bridge over the stream would be removed. A general arrangement of these features is shown on Figure 4.1.

The basic and enhanced designs only differ somewhat in detail and these differences are described in "Design Parameters."

The berm would be constructed in the form of an arc, convex downstream, and would extend from bedrock on the west side of the fan to bedrock on the east side of the fan. The berm would have an opening where it crosses the existing Boat Launch Creek. A debris-straining structure would be constructed across this opening. Two secondary culverts, one on either side of the stream, would be constructed through the berm to act as emergency outlets for water. The debris basin upstream of the terminal gravity berm would be cleared, shaped, and graded. Two access roads for debris clean-out would be provided, one on either side of the stream.

The effectiveness of the above concept depends on a number of factors:

- The debris, once it reaches the relatively broad and gently sloping debris basin, will spread out, slow down, and lose most of its energy before it reaches the berm.
- Any debris still moving when it reaches the terminal gravity berm will be stopped by the berm, or will lose all remaining energy by overtopping the berm.
- The water accompanying the debris flow will be encouraged, by the shaping and grading of the debris basin, to return to the stream and pass through the debris-straining structure.
- The debris-straining structure will minimize coarse-grained inorganic and organic debris from moving past the structure, while allowing some fine-grained debris and the accompanying water and subsequent water flows to continue down Boat Launch Creek.
- Should water be trapped behind the berm and not be able to get to the stream and debris-straining structure, it will flow through one of the secondary culverts.
- As soon as possible after a debris flow, the debris will be excavated and removed from behind the terminal berm.

DESIGN PARAMETERS

Volume and Character of Debris The re-estimated volume of material deposited on the Boat Launch Creek fan during the 1987 event, approximately 30 000 m^3, is considered to be a reasonable upper limit of the quantity of material that could be involved in a future large event. The character of the debris, its size and gradation, and proportion of inorganic

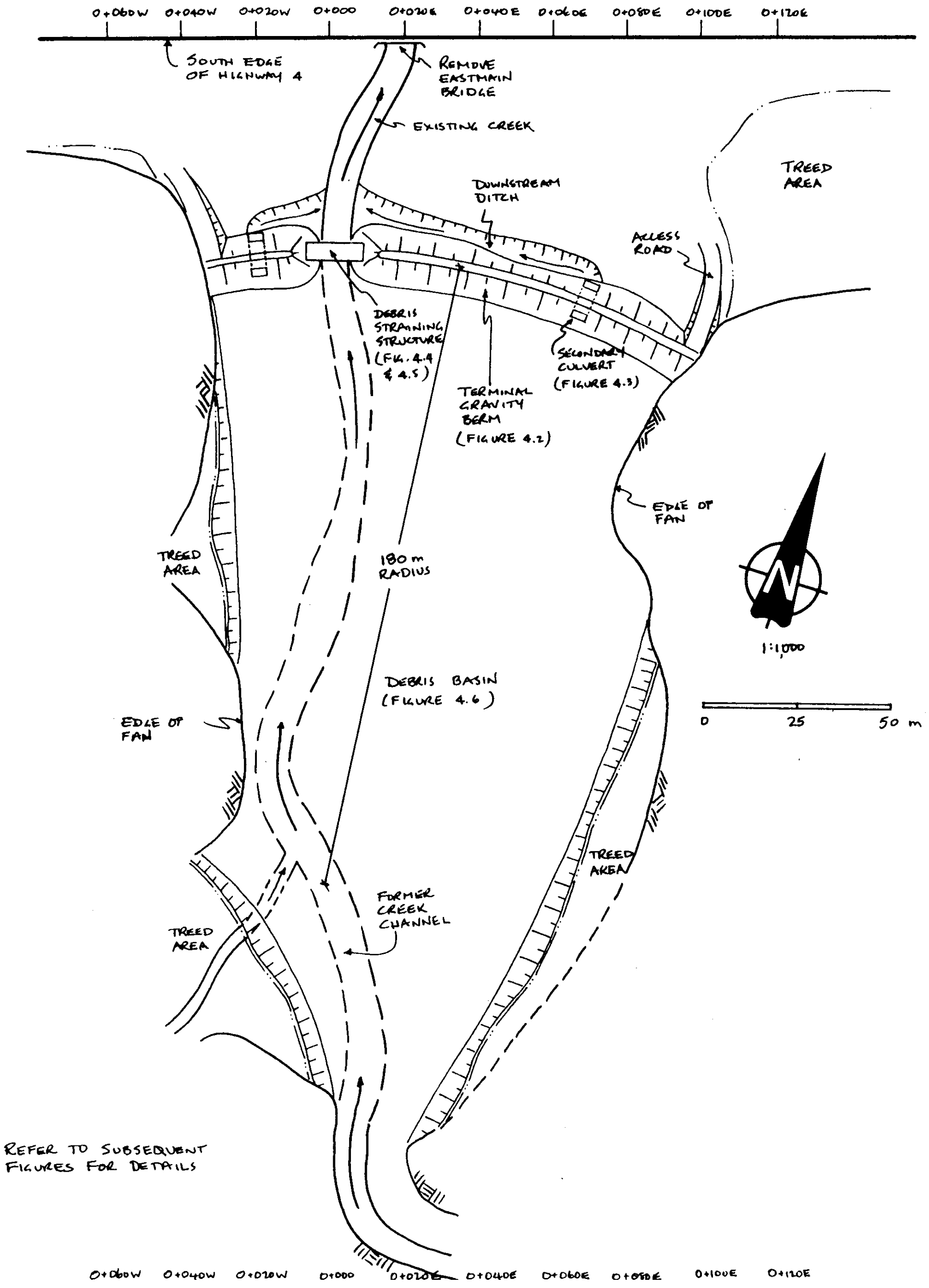


FIGURE 4.1 *Proposed mitigative works, general arrangement.*

versus organic, have been qualitatively assessed from the debris involved in the 1987 and 1991 events.

Location of the Berm The proposed location of the terminal gravity berm is approximately 60 m upstream of the existing Highway 4. This location, close to the distal end of the Boat Launch Creek fan, maximizes the size of the debris basin upstream, allows much of the debris to slow down or stop before it reaches the berm, takes advantage of the location of the bedrock on both sides of the fan, and allows a buffer between the crest of the berm and the highway.

The approximate length of the 180 m radial arc of the berm, between the west and east bedrock abutments, is 130 m (Figure 4.1). Where proposed, the abutment/berm structure interface, on both ends of the berm, is relatively protected from direct debris flow impact. There is an approximately 60 m buffer between the crest of the berm and the highway.

Terminal Gravity Berm The proposed cross section and longitudinal sections of the terminal gravity berm are shown on Figure 4.2. The berm is 5 m high from the base of the debris basin, 3 m wide at the top, with 1.5(H):1(V) side slopes, both on the upstream and downstream faces of the berm. It is proposed that the longitudinal section will have a 3% (1.7°) slope towards the existing stream.

It is proposed the berm be constructed of granular material excavated from the upstream side of the berm in conjunction with excavation of the debris basin. It will be properly compacted by bulldozer during construction. Logs and stumps will not be incorporated into the berm.

The height was selected to provide an adequate height for the estimated run-up of debris and to provide an adequate mass against any moving debris. Five metres is also a practical limit for construction by excavators and bulldozers. Rigorous design calculations for run-up, hydrodynamic and point impact forces, and a structural analysis of the berm, were not carried out for this study. These aspects of the design should be reviewed by a structural engineer.

To minimize erosion, at least the lower 4 m (measured vertically) of the upstream face of the berm will be covered by 100–250 kg rip-rap to minimize erosion. For the enhanced low-cost design, it is proposed that this rip-rap be grouted in place to aid cleaning debris away from this face. Drainage holes should be placed through the grout to prevent the berm from acting as a dam.

Debris-straining Structures Two different debris-straining structures are proposed. For the basic low-cost design, the straining structure would be constructed entirely from local log cribbing. The enhanced low-cost design would consist of a row of vertical and angled railway rails set in a concrete base. The enhanced debris-straining structure design should last longer than the timber cribbing and require less maintenance. Details of the two different designs are presented on Figures 4.3 and 4.4, respectively. Variations to these two proposed structures are possible.

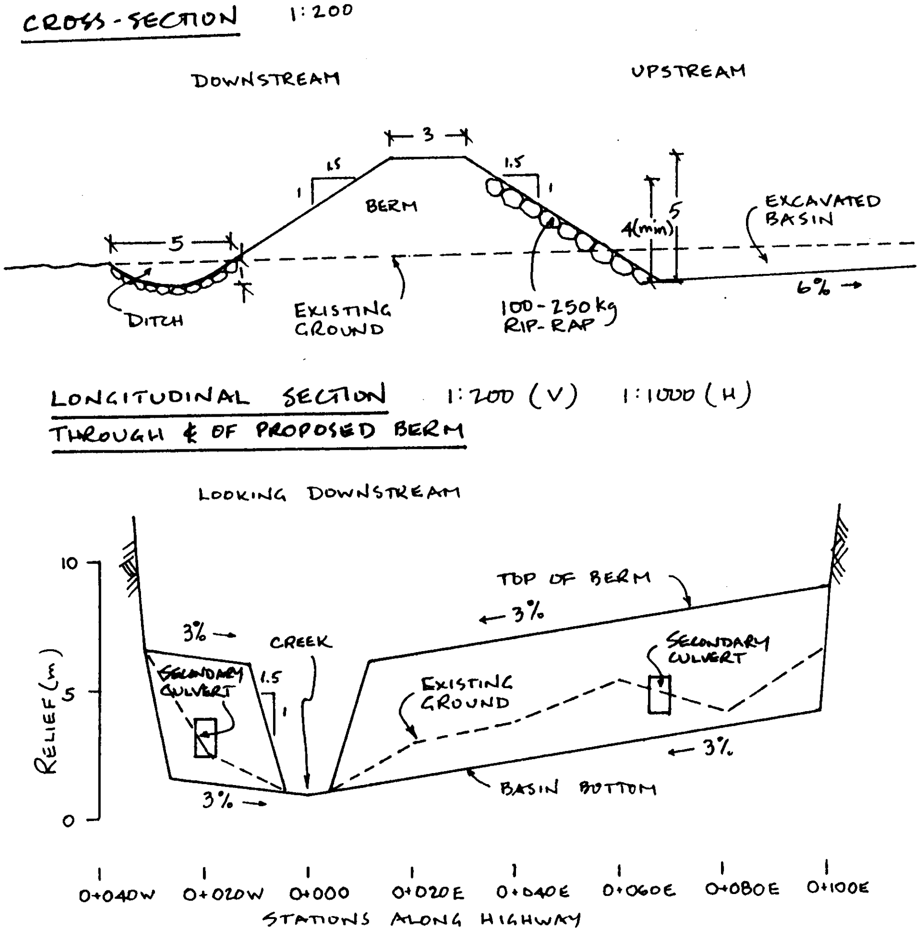


FIGURE 4.2 *Sections across and along proposed berm.*

The debris-straining structures must be designed to allow for a 200-year water discharge. These designs should be reviewed by both a structural and hydraulics engineer.

For both designs, the ends of the berm adjacent to the debris-straining structure should be protected by grouted 100–250 kg rip-rap to minimize erosion.

Secondary Culverts For the basic low-cost design, two secondary log culverts, approximately 1.5 × 4 m, are proposed to be placed through the berm, one on each side of the stream. Details of the culverts are presented on Figure 4.5. For the enhanced design, two parallel 2 m diameter corrugated steel pipe culverts are proposed for each side of the stream. The sizes provided are estimated to handle a 200-year discharge, but should be reviewed by a hydraulics engineer.

Because these culverts are intended as emergency outlets, the inlet elevations are placed 2 m above the bottom of the debris basin. The inlets of these culverts should be protected by debris racks. The outlets for these culverts should be protected from erosion, and the potential downstream

APPENDIX 1 *Continued*

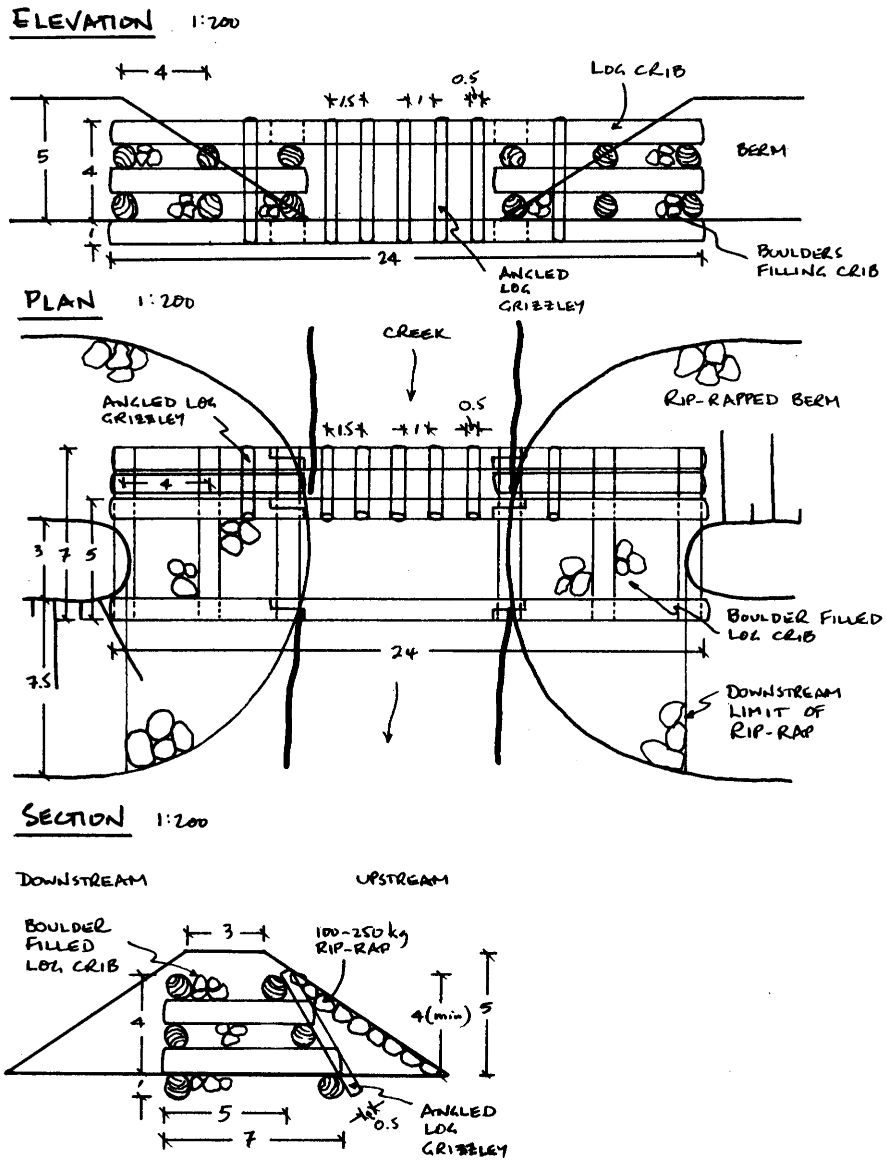


FIGURE 4.3 *Details of log crib debris straining structure.*

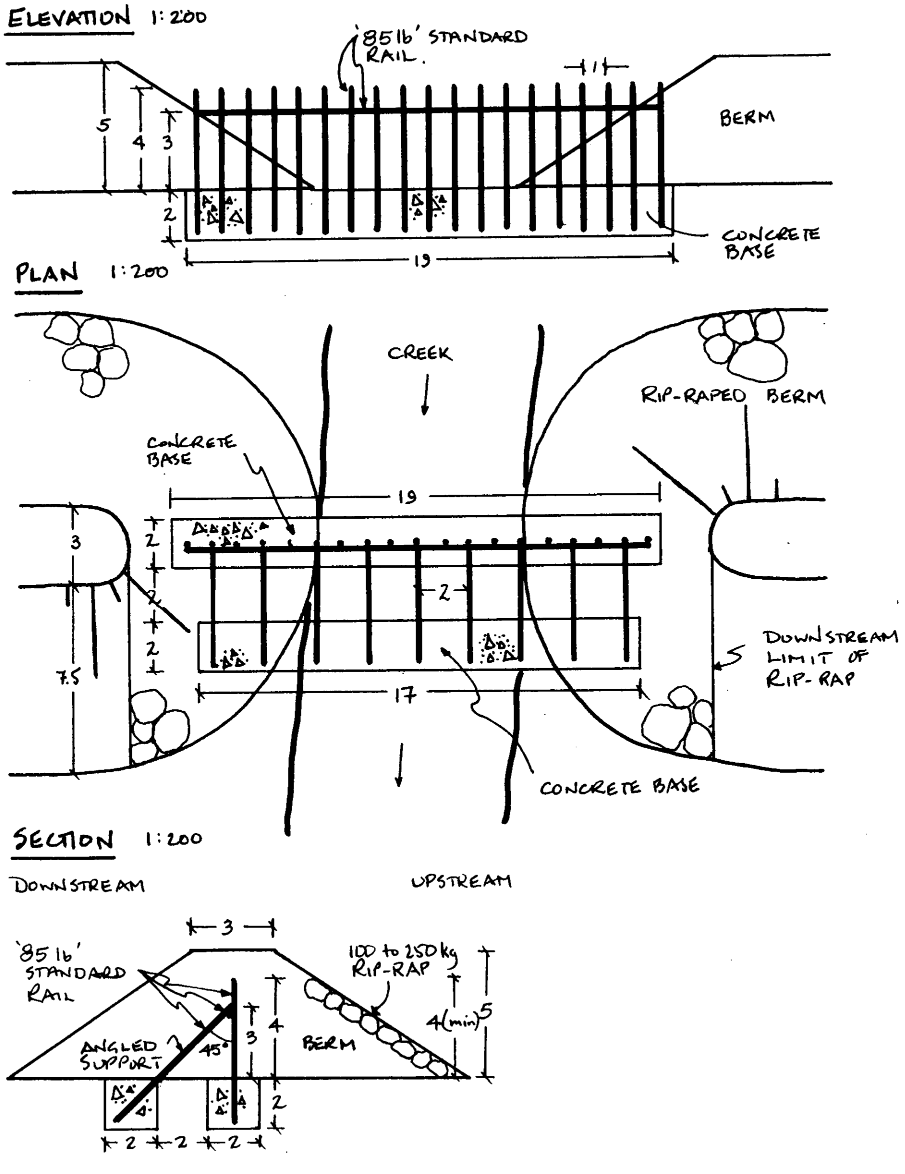


FIGURE 4.4 *Details of rail and concrete debris-straining structure.*

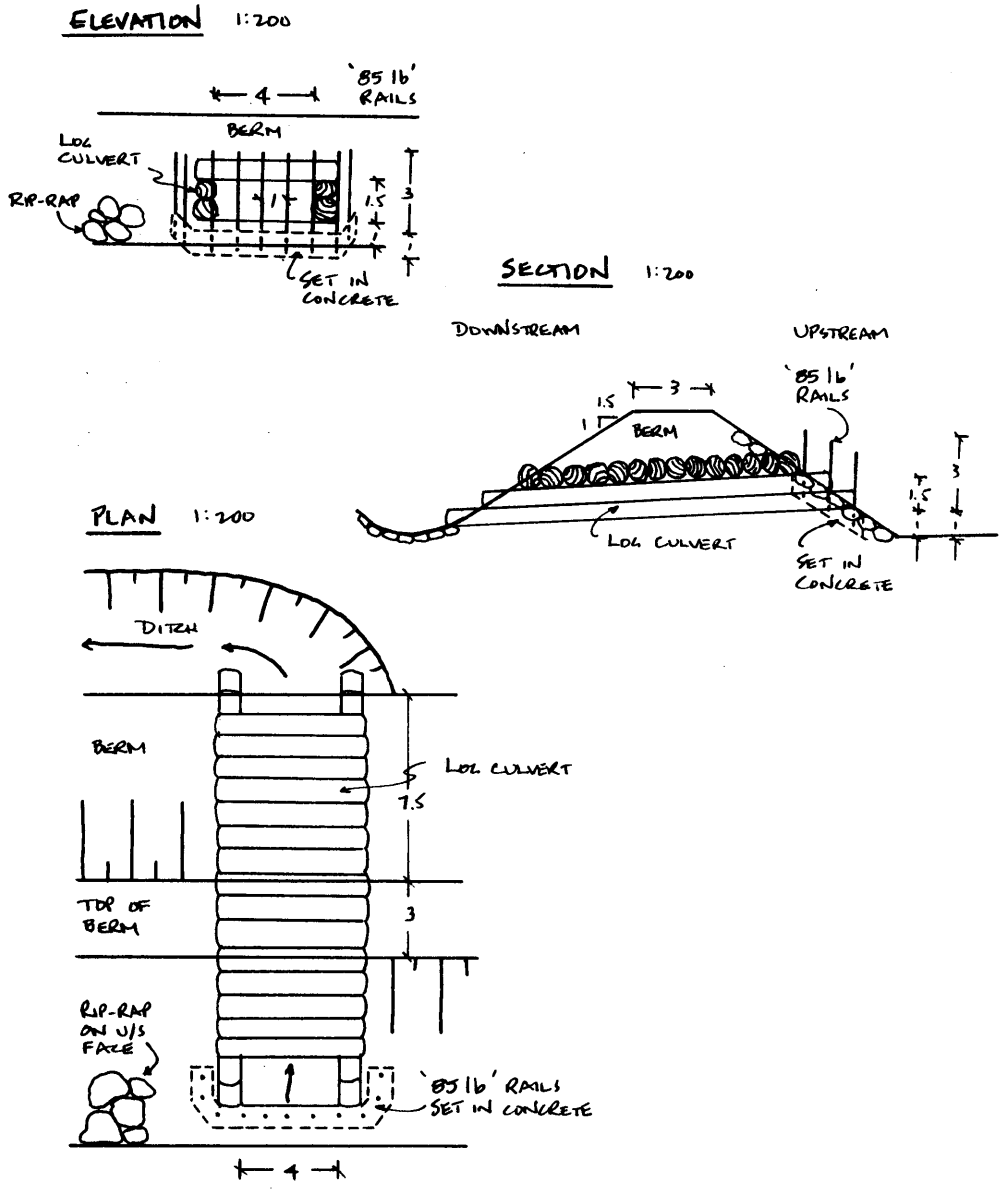


FIGURE 4.5 *Details of secondary culvert (only log culvert shown).*

flow path should be ditched to lead the water flow back into the stream (Figures 4.1 and 4.5).

Debris Basin For both designs it is proposed to clear the entire basin area of trees, trim the sides of the basin to increase width and improve hydraulic flow, and shape and grade the bottom of the basin to encourage water to return to the main stream.

The resulting cleared, shaped, and graded debris basin will have an approximate area of 15 000 m^2. The elongated triangular shape of the proposed debris basin will have an approximate length to width ratio of approximately 260 to 130 m, or 2:1.

The present average gradient of the fan surface is approximately 6% (3.4°). A range of profile gradients from 6 to 7%, and a range of cross-section gradients from 3 to 4% were investigated. It was determined that the optimum gradients should maintain the 6% (3.4°) gradient for the bottom of the debris basin in the direction parallel to the stream and slope the sides of the debris basin toward the stream at 3% (1.7°). Refer to Figure 4.6 for details of the clearing, shaping, and grading in plan, Figure 4.7 for details of the grading along the profile lines, and Figure 4.8 for details of the grading across the cross-section lines.

Assuming a storage angle parallel to the bottom of the contoured debris basin, the theoretical storage volume behind the berm is approximately 15 000 m^3/m height of the berm, or approximately 75 000 m^3. The effective storage volume is estimated to be less than half that volume.

Road Access for Clean-out The proposed access for debris clean-out, following a future debris flow, involves constructing road ramps at the extreme west and east ends of the berm (Figure 4.1). These roads will allow access to both sides of the stream and the shortest haul distance to the highway. The roads should have a minimum width of 5 m and a maximum grade of 15% (8.5°). When not in use, to prevent public vehicular access to these roads, large boulders should be placed at the start of each road.

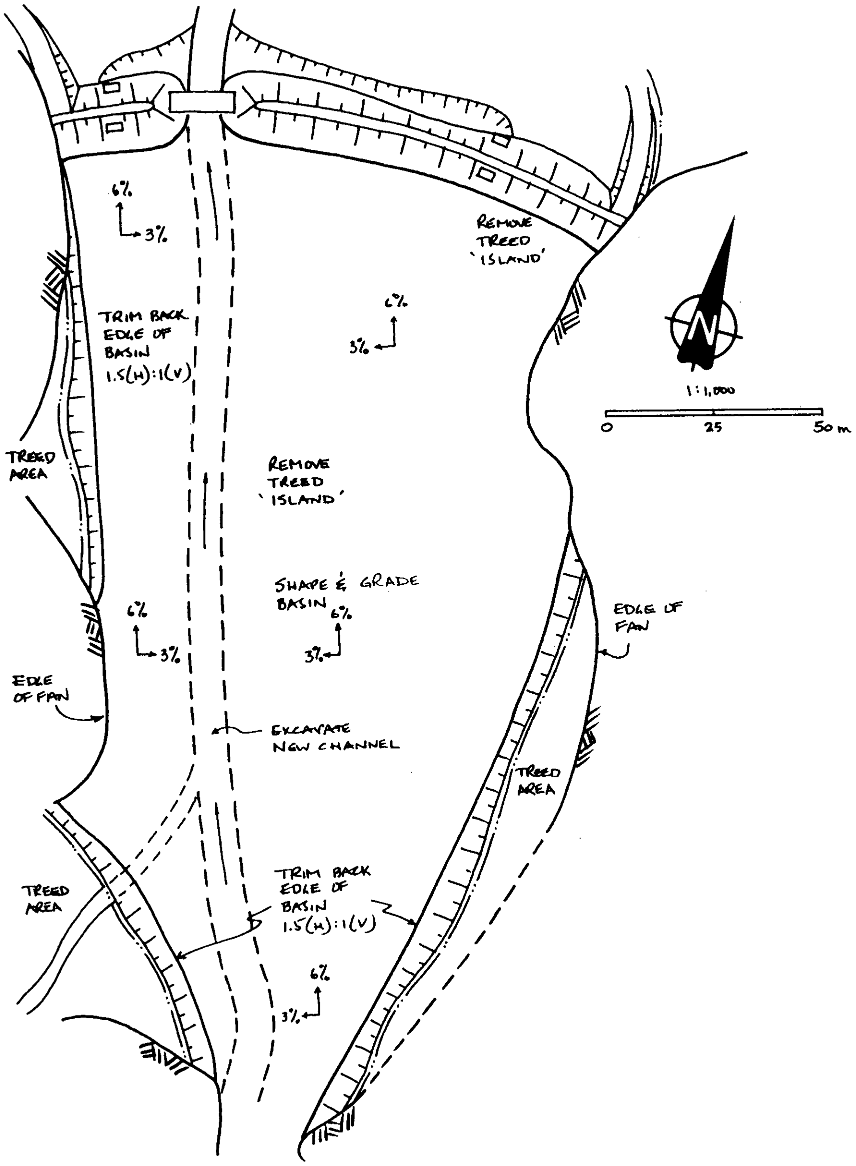


FIGURE 4.6 *Details of debris basin clearing, shaping and grading.*

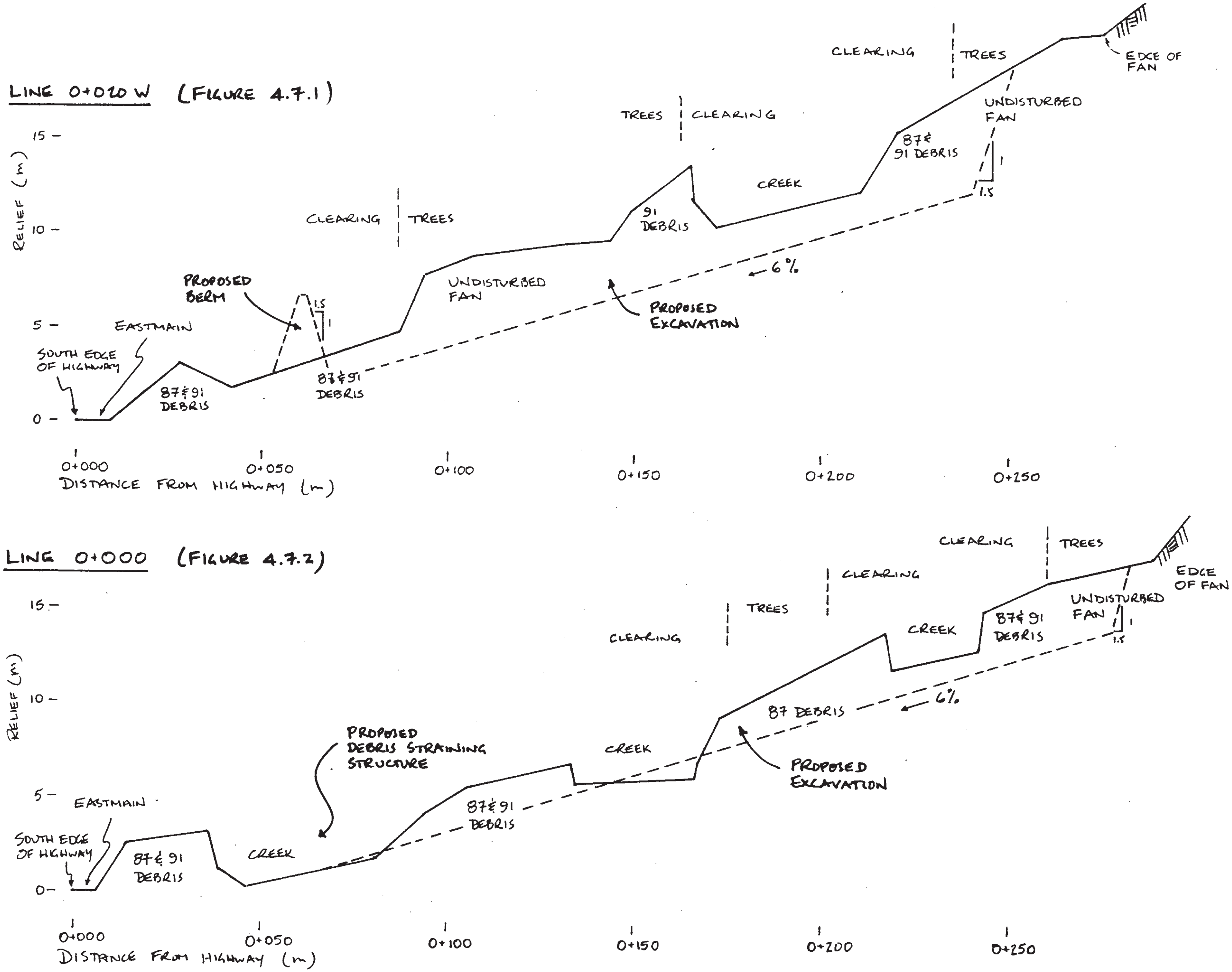


FIGURE 4.7 *Grading along profile survey lines.*

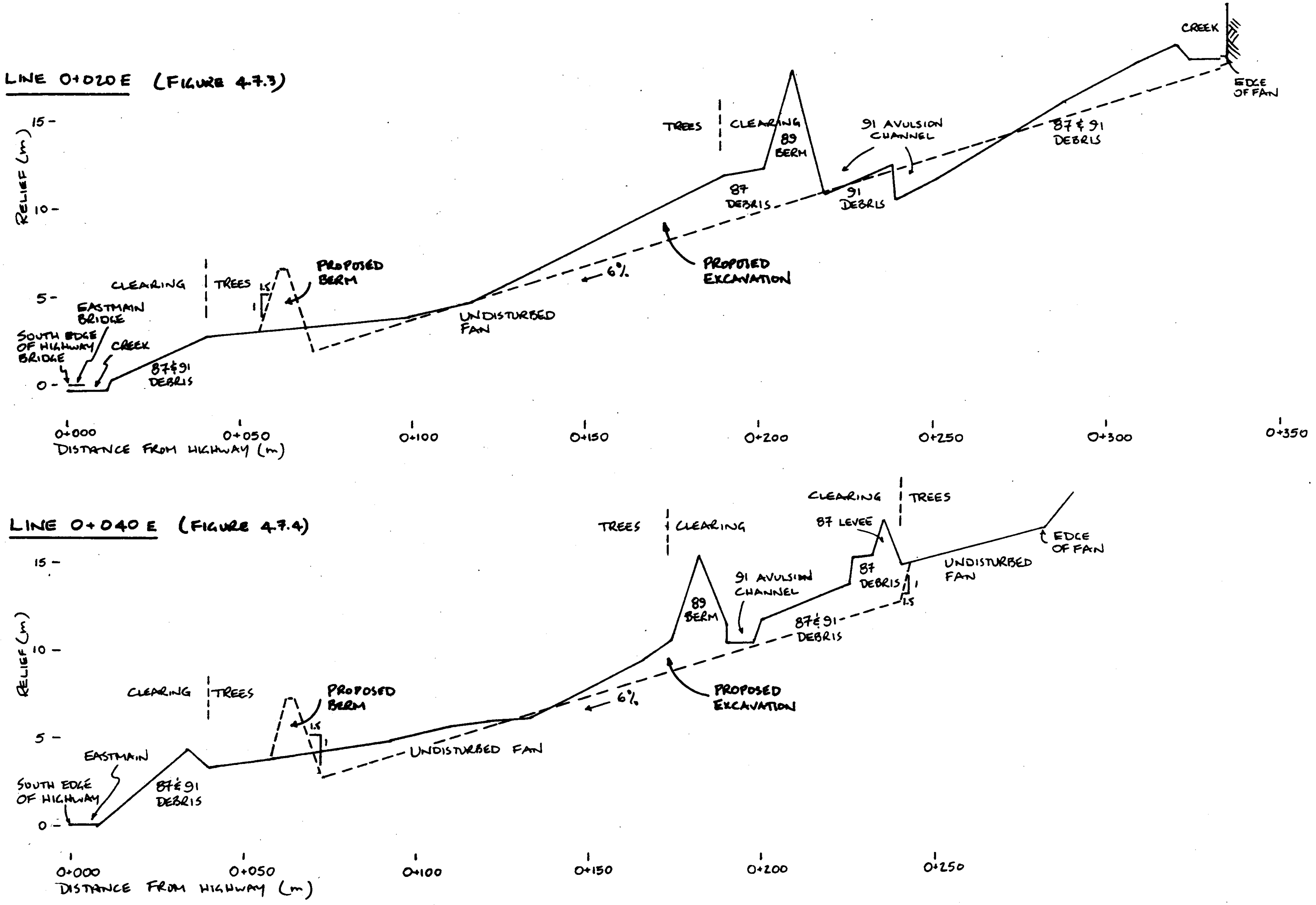
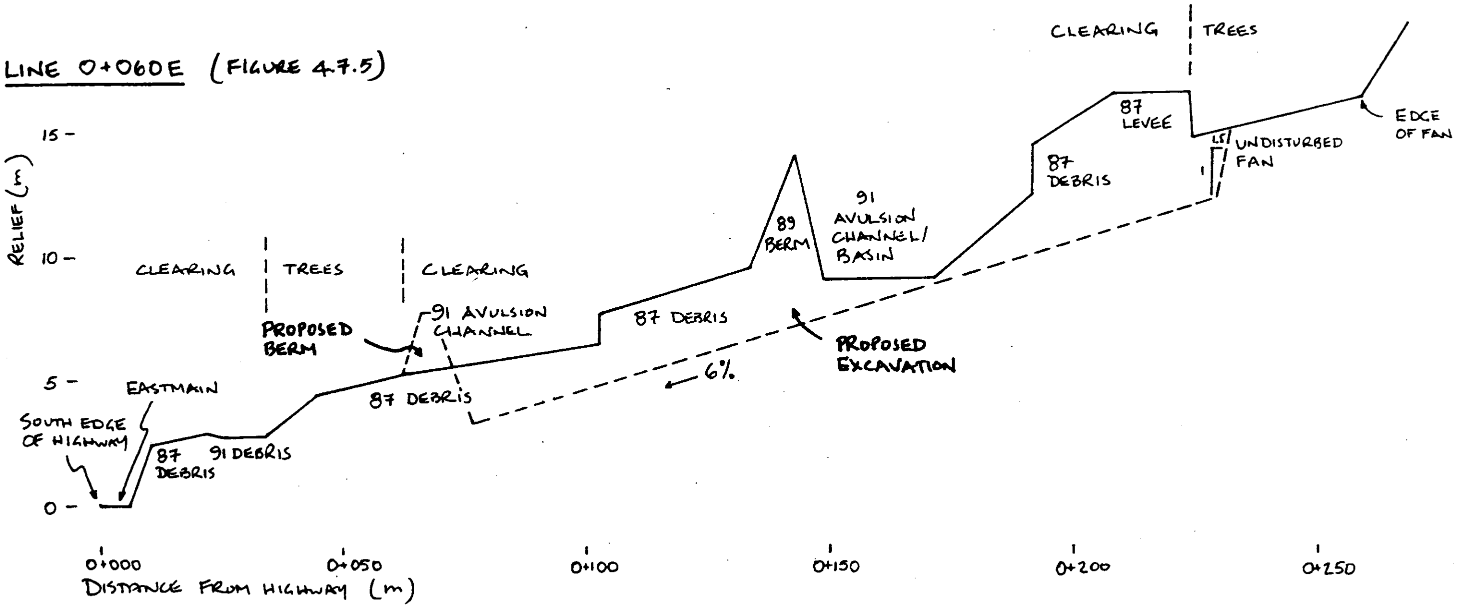


FIGURE 4.7 *Continued.*



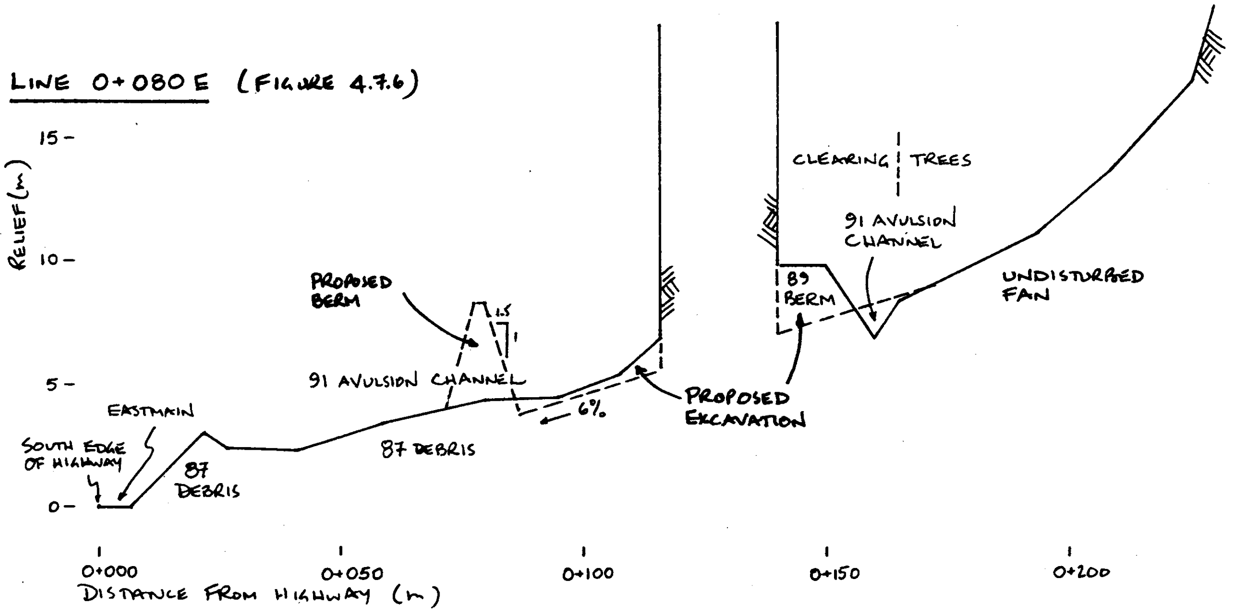


FIGURE 4.7 *Continued.*

APPENDIX 1 *Concluded*

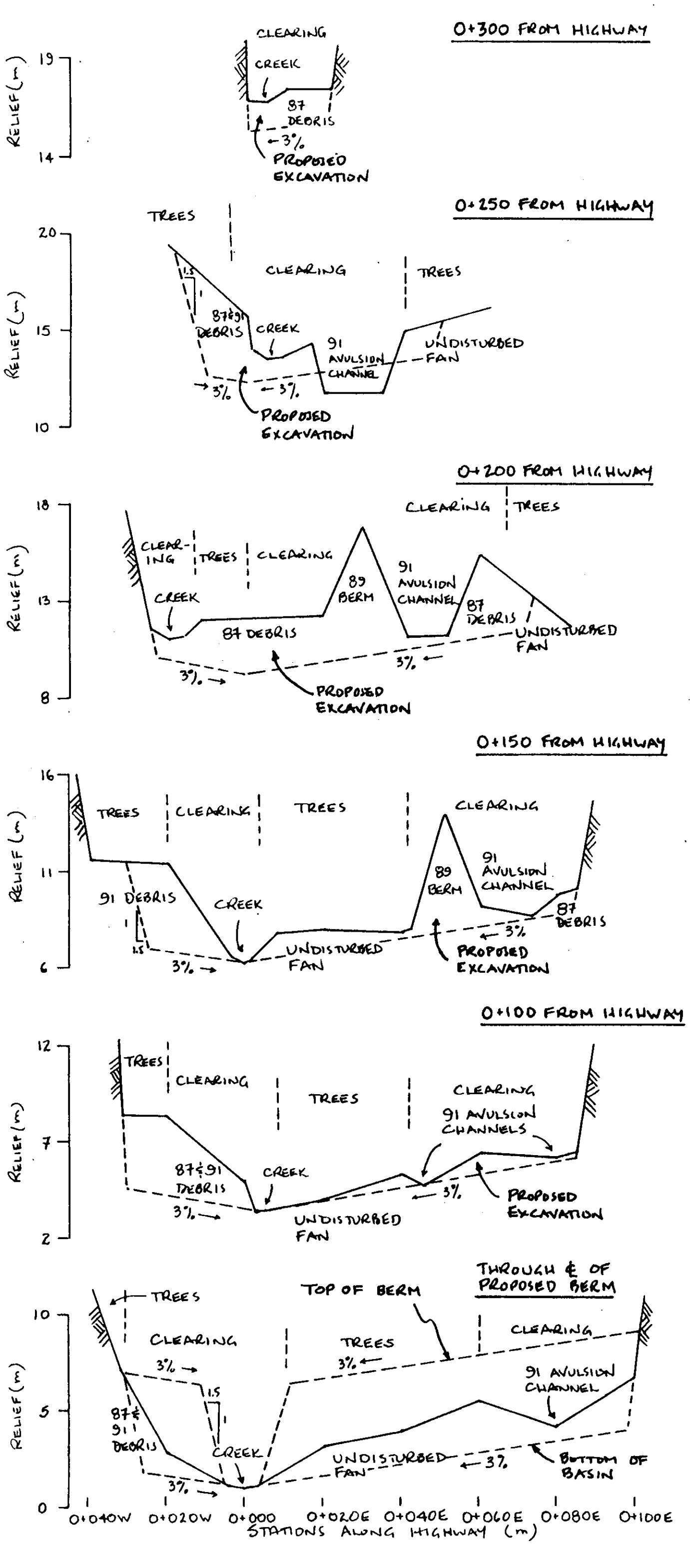


FIGURE 4.8 *Grading along cross-section survey lines.*

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