TROPICAL FORESTRY

John Sessions
Editor

Forest Road Operations in the Tropics

Springer

Tropical Forestry

Tropical Forestry
Volumes Already Published in this Series

Forest Road Operations in the Tropics by Sessions, J. 2007
ISBN: 3-540-46392-5

Tropical Forest Genetics by Finkeldey, R., Hattemer, H. 2007
ISBN: 3-540-37396-9

Sampling Methods, Remote Sensing and GIS Multiresource Forest Inventory by Köhl, M., Magnussen, S., Marchetti M. 2006
ISBN: 3-540-32571-9

Tropical Forest Ecology - The Basis for Conservation and Management by Montagnini, F., Jordan C. 2005
ISBN: 3-540-23797-6

John Sessions (Ed.)

Forest Road Operations in the Tropics

With 57 Figures and 25 Tables

Springer

Volume Editor:

Dr. John Sessions
Department of Forest Engineering
Oregon State University
213 Peavy Hall
Corvallis
OR 97731-5706
USA

ISSN: 1614-9785
ISBN-10 3-540-46392-5 Springer-Verlag Berlin Heidelberg New York
ISBN-13 978-3-540-46392-4 Springer-Verlag Berlin Heidelberg New York

Library of Congress Control Number: 2006935980

Springer-Verlag is a part of Springer Science+Business Media

springer.com

Editor: Dr. Dieter Czeschlik, Heidelberg
Desk Editor: Anette Lindqvist, Heidelberg
Production: SPi
Typesetting: SPi
Cover Design: Design & Production, Heidelberg

Printed on acid-free paper 31/3152-HM 5 4 3 2 1 0

Preface

Forest road operations include all the activities to plan, design, construct, and maintain the infrastructure needed to move forest products from the roadside to the mill or port destination. Poor road management can jeopardize the economics of the forestry enterprise and can impact water quality and wildlife habitat.

Sustainable forest management is concerned with management of the transportation infrastructure in such a way that efficient transportation is provided while controlling adverse environmental impacts.

Much of the direct impact of forest roads can be reduced through proper planning and control of road location, design, construction, and maintenance using principles, systems, and techniques common to temperate forests. However, many areas of the tropics pose unique operating conditions: prolonged wet periods, high-intensity precipitation, swamps, and lack of rock for suitable road surfacing.

The purpose of this book is to bring together information on road planning, location, design, construction, and maintenance to support environmentally acceptable operations in tropical forests. It highlights the challenges of road operations in the tropics, includes techniques that have been shown to be successful, and discusses newer technologies. It is intended as a reference book for the forest engineer and others interested in the planning and management of tropical forests. Numerical examples, where appropriate, are included to provide clarity for interpreting graphs, procedures, and formulas. The book is divided into 11 chapters which cover the various facets of road management from design objectives through practices to control environmental impacts.

Chapter 1 summarizes the issues surrounding road development, the purpose of forest roads, including concepts of the design vehicle, design objectives, an overview of environmental effects, and best management practices.

Chapter 2 covers road standards suitable for forest road operations in the tropics, including geometric design for heavy vehicle use and safety.

Chapter 3 discusses the economic basis for forest road construction and identifies the cost components in road construction and maintenance, and procedures for identifying the road spacing and the most economical road standard.

Chapter 4 presents the elements of route selection from preliminary examination of documents, field reconnaissance, in-field road design, to staking the alignment on the ground, and construction staking.

Chapter 5 discusses the selection and use of road building materials in the tropics, including design of the road structure, location and improvement of road building materials, and opportunities for recycling of road aggregate. The importance of proper road structure design and the tradeoff between axle loading, vehicle tire pressure, and road surface thickness is examined.

Chapter 6 focuses on road construction techniques on gentle and steep terrain by tractor and excavator. The importance of adequate road drainage structures is emphasized, including design for high-intensity rainfall events. Simple retaining walls for special slope stability problems are discussed.

Chapter 7 focuses on special road structures for the tropics suitable for crossing swamps and wetspots. The design of buried corduroy and use of geotextiles is presented.

Chapter 8 addresses a range of stream crossing options from culverts to log stringer and portable bridges. Flow-estimating procedures are presented with examples. The advantages of various options are discussed. The elements of bridge location are presented. The importance of appropriate choice of log stringers for log plank decking and laterite decking is discussed.

Chapter 9 discusses elements of road maintenance needed to protect the road structure and permit safe and efficient road use. Elements of road maintenance include the importance of maintaining road drainage, protection of cut and fill slopes, dust abatement, erosion protection, safe sight distances, bridge condition monitoring, and economic determination of road surface maintenance frequency.

Chapter 10 provides an overview of road construction and maintenance equipment with consideration of special conditions in the tropics.

Chapter 11 summarizes relatively inexpensive actions that can contribute to environmental protection during the design, construction, and maintenance of forest roads if done in a consistent and disciplined manner.

The Appendix summarizes analog tools and digital tools available for road measurements in the tropics and their accuracies.

This book represents a compilation of available literature and the professional experiences of the authors. In particular we would like to recognize the long-term contributions of the Food and Agriculture Organization for promoting improved management of world forests, and their funding and documentation of many studies in tropical forest management and conservation.

September 2006 John Sessions

Contents

List of Authors

John Sessions
Department of Forest Engineering, Oregon State University, 223 Peavy Hall, Corvallis, OR 97331-5706, USA

Kevin Boston
Department of Forest Engineering, Oregon State University, 23 Peavy Hall, Corvallis, OR 97331-5706, USA

Michael G. Wing
Department of Forest Engineering, Oregon State University, 275 Peavy Hall, Corvallis, OR 97331-5706, USA

Abdullah Emin Akay
Forest Engineering Department, Faculty of Forestry, Kahramanmaras Sutcu Iman University, 46100 Kahramanmaras, Turkey

Paul Theisen
2231 NE Bridge Creek Ave, Vancouver, WA 98664, USA

Rudolf Heinrich
Via Gorgia di Leontini 260, 00124 Rome, Italy

Forest Roads in the Tropics 1

1.1 What Are the Issues?

In the public mind, few things signify change in tropical forests more than the construction of a road; machines versus nature, artificial versus a natural construct. Muted, in much of the dialogue, are the social importance of forest roads and the technical knowledge required to properly design, construct, and operate them. Road infrastructures in tropical forests are complex engineering structures which provide access to forests. These road infrastructures involve engineering design, field layout, construction, and maintenance. They include bridges and other stream-crossing structures. Road infrastructures are commonly associated with the extraction of industrial wood, but they also provide access to forests for management, development, conservation, and protection purposes. Moreover, the importance of forests for biological diversity, non-wood products, cultural, and spiritual values, as well as environmental services, is widely recognized by the world community. In the context of sustainable development, as stated by Agenda 21 of the United Nations Conference on Environment and Development (UNCED) in 1992, the use of natural, renewable resources is a key demand of environmentally sound development. Resource use depends on accessibility of the relevant areas which can only be provided by the construction of forest road networks.

As a result, road infrastructure development has become a more demanding and complex discipline: planning and executing road infrastructure has become a difficult task, as these infrastructures must be designed and implemented in ways that accommodate, and if possible, enhance the various functions of the forests. In some cases forest roads form part of the planned network of public roads connecting diverse parts of a country or region and are essential components of developed infrastructure. This is especially true in rural areas where these roads provide mobility for people living in and around the vicinity of forested areas and benefit local communities in their daily socioeconomic activities. An improved transportation system allows not only the existing forestry organization to increase its profit margins as transportation costs are reduced, but the surrounding area also benefits. Benefits for communities from an improved transportation system can come from several sources. Neighboring farms can have increased profitability as transportation costs are reduced. Labor will be better able to reach these areas, thus potentially lowering the labor costs or increasing its availability. Improved roads will allow for better access to health care and schools as vehicles will be more likely to reach isolated areas. Overall, the improved road network developed primarily for the forest enterprise may be a key element in the economic development of the area.

Forest roads may not be benign. Some argue that roads are the most significant cause of deforestation. Recent developments in road ecology consider the interactions of roads and the environment. These interactions can impact hydrology, vegetation, and animals. Roads can alter the hydrology of an area by often diverting subsurface flows to surface flows and increasing the amount and frequency of runoff to streams. They can cause significant increases in sedimentation from the cut and fill areas as well as the surface of the road, contributing to excessive river sedimentation, which could potentially have serious effects on water quality, aquatic life, and wildlife populations. Roads often provide a site for the establishment of noxious weeds that find recently disturbed cut and fill slopes ideal spots to occupy. Roads can impact wildlife habitat in multiple ways. Main roads with higher traffic volumes and travel speeds can increase mortality of animals owing to collisions with vehicles. Roads can alter habitat quality, as some species may avoid crossing well-traveled roads and suffer from increased predation on roads. Roads may enhance disruption of breeding areas or migratory routes of animal species. Roads, especially in primary forests, can lead to expansion of the agriculture sectors or allow for increased hunting.

Others, including the authors of this book, believe that road infrastructures that are properly designed, constructed according to environmentally sound engineering practices, and correctly maintained provide convenient, low-cost access to forest products and serve the needs for forest management conservation and protection. The revenue generated from the harvested forest products, notably industrial wood, provides the much needed resources to enhance sustainable forest management in the long term. It has been argued that the reason for improperly designed, constructed, and maintained roads is not so much a shortage of funds, lack of modern and suitable road building equipment, or the working methods, but far too little awareness of the negative impacts of poorly designed, planned, and constructed road systems on the entire forest ecosystem. Best management practices, if followed, will markedly reduce and control the negative environmental impacts of road construction and maintenance.

Roads do create a highly visible impact on the landscape, but they probably are not a direct cause of forest loss; rather they are the agent of change. The major causes of forest degradation and deforestation, among others, include overharvesting of high-valued species, excessive damage to the residual stands, overharvesting for fuel wood, illegal logging, overhunting, overgrazing and land conversion to agriculture and other rural development. Forest roads may be misused, attracting wood, game, and fish poachers and collectors of non-wood forest products from outside the forests, thus causing considerable negative impacts on the forest and the environment as well as on the local people. Although these activities are illegal, in many cases they cannot be controlled or stopped because of lack of capacity of the agencies responsible. All of these are made possible through road access, and thus roads become the *lightning rod* in a larger discussion of economic development and resource conservation.

This book is not intended to suggest appropriate forest development policies for a country or region. Its purpose is to present appropriate ways to plan, locate, design, and maintain tropical forest roads to maximize the benefits they create while controlling direct environmental impacts associated with construction, maintenance, and use. It is intended as a reference book for forest engineers and others interested in the design and management of forest roads. Although some methods and techniques discussed in this book may be appropriate for areas outside of the tropical forests and some may have originated in other regions, the focus is on techniques suitable for the special conditions found in tropical forests.

1.2 Overview of the Tropics

The tropics are bounded roughly to the north of the equator by the Tropic of Cancer and to the south of the equator by the Tropic of Capricorn. Although the tropics are often portrayed as an area that has remained unchanged for a long time, i.e., not subject to glacial activity and large climate swings, that does not mean that they are homogeneous. Differences can be described by elevation, topography, temperature, mean annual rainfall, seasonal rainfall, and soils. The tropics can be divided into the warm tropics and the cold tropics, wet tropics and dry tropics. There are three major tropical regions, America, Asia, and Africa (Fig. 1.1). Some generalizations can be made between regions and within regions. Southeast Asia is much more mountainous than Africa or South America and has many young, eroding landscapes. It also has substantial areas of volcanic rock and soils. In Africa and South America, recent volcanic rock and soils are much less common.

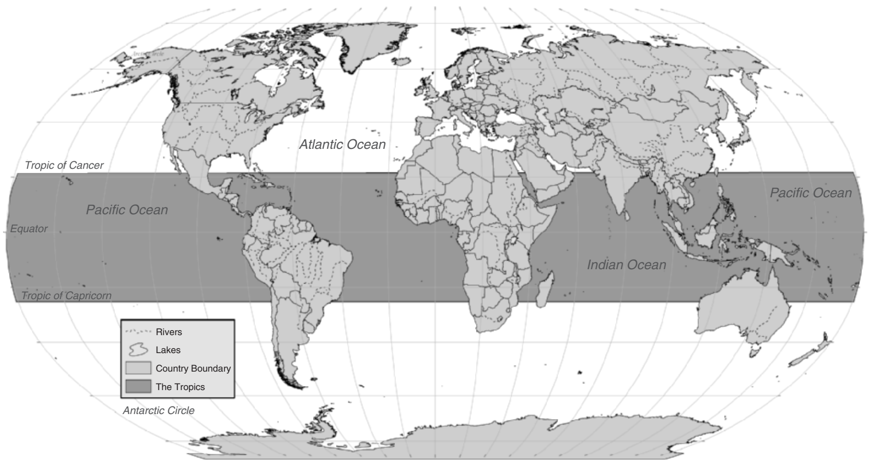


Fig. 1.1. Tropics of the world

Considering within-region variation, slightly more than 50% of tropical America, for example, has a mean annual precipitation of 1,600–3,200 mm/year and less than 5% receives more than 3,200 mm/year and less than 5% receives under 400 mm/year. Similarly, the majority of tropical America has pronounced seasonal rainfall, with most of the seasonal rainfall coming in summer, but some eastern coastal areas have the pronounced seasonal rainfall coming in winter. Other areas have rainfall well distributed throughout the year. One can generalize that tropical America is flat. Eighty-two percent is less than 8% slope, and 4% is greater than 30% slope. And one could generalize that tropical America is well drained, but about 25% of the flat terrain would be classified as poorly drained.

Much international interest focuses on that part of the tropics that supports tropical rainforests (Fig. 1.2). Tropical America has about 50% of that total, with the remainder concentrated in Southeast Asia and Africa (Table 1.1). Tropical rainforests are found in places that have no dry months or only a few dry months. Tropical evergreen rainforest occurs in places with no dry season, and tropical semievergreen rainforest forms where there is a dry season. Tropical evergreen rainforests differ from semievergreen rainforests in that semievergreen rainforests have some species that are deciduous. In general, the western Amazon rainforests are evergreen, and the eastern Amazon rainforests are semievergreen. Southeast Asian rainforest is almost entirely evergreen and African rainforest is almost entirely semievergreen.

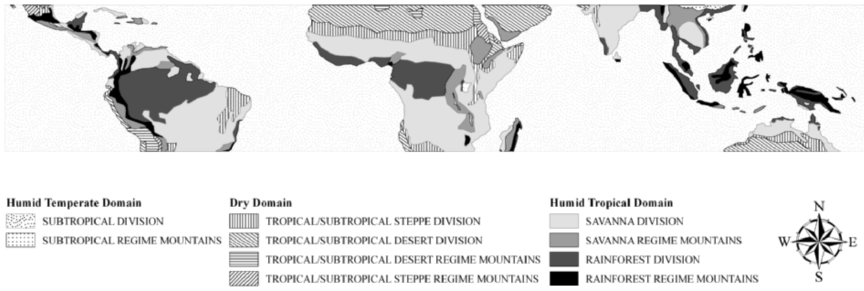


Fig. 1.2. Bailey's ecosystem classification of the tropics

Table 1.1. Distribution of tropical rainforest

Region	Rainforest area (million hectares)	Percentage of total	Primary location
South America	400	48	Amazon, Orinoco basins
Southeast Asia	250	30	Malesia, Asian subcontinent to India
Africa	180	22	Zaire Basin to Gulf of Guinea

1.3 Road Building Challenges in the Tropics

Tropical forest conditions pose special problems for forest transportation owing to several factors. These factors include (1) prolonged wet periods with high-intensity rainfall in many tropical forests, (2) scarcity and expense of good-quality rock in tropical areas, (3) swamps, and (4) harvest removals under the selective management systems designed to sustain natural tropical forests are usually low and may limit investments in roads. On the other hand, the tropics do have a number of very strong timber species which provide superior bridge-building materials for crossing the many streams and rivers in tropical forests.

1.4 Traffic Characteristics

Roads within the forest differ from general roads in that they serve a special purpose; efficient access for heavy vehicles associated with timber production. Their specialized function has three characteristics: low traffic volume, long, heavy trucks, and loaded trucks traveling mostly in one direction. Each road or section of road is not subjected to the same amount of traffic. The characteristics of each section of road depend on its function in the road system. At its extreme points, the forest road is an extension of the harvesting system. That is not to say that main forest roads do not alter the social and economical factors in an area, particularly as they leave the primary forest zone.

The traffic on forest roads is usually low, and is used primarily for extraction of logs and associated activities. Traffic in the case of native forests may be of short duration. With planted forests, transport may be seasonal. The number of trips past a given point on a collector road serving a logging area will never be excessive, even during periods of intense activity. A total of 20 vehicles a day in each direction could be considered a good average – in unusual circumstances, 30 vehicles. On the main roads of large planted forests, traffic may be as high as 100–200 vehicles in each direction.

Traffic levels remain such that the movement of vehicles is independent of each vehicle – too much traffic is not a problem. At most, safety rules may impose some control at special points, for example, at blind corners, approaches to bridges, and crests of hills. Generally speaking, for local and collector roads, only a single line of traffic is adequate with some widening at special points: on curves and crests of hills, and at intervals of 0.5 km or so for turnouts. On main roads, two lanes are necessary.

Almost all the loaded transport is in one direction, going from the forest to the points of conversion or redistribution. The tendency is for converging traffic of loaded trucks toward transfer points where the loads are sorted before transport to sawmills and factories. The transfer points are located at a wharf, a waterway, a junction on a main road carrying heavier traffic, or a station on a main railway. Therefore, the profile of a forest road can have different characteristics in the two directions. Vehicles returning empty to the forest can climb steeper gradients than those they climb when traveling loaded.

1.5 Design Vehicle

Identification of the design vehicle is important to provide information for design of road width, road surfacing, road gradient, and bridge design. Forest traffic is mainly concerned with light vehicles for personnel transport and with vehicles for transporting logs. Light vehicles, for staff or workmen, are usually some combination of jeeps, pickups, vans, or light trucks. These vehicles can normally go everywhere that trucks can go. The log-hauling truck normally determines the design of the road. These trucks are slow, heavy vehicles, usually composed of a truck with two rear axles pulling a special pole trailer or semitrailer or sometimes pulling a full trailer. Vehicles such as lowboys may affect curve widening requirements. In some special cases, such as bridge design, the passage of heavy construction equipment or tracked log loaders may influence the design.

A modern truck has an engine power of 250–400 kW with a semitrailer, giving an overall length of about 20 m and a gross load of 35–60 t. These heavy, articulated vehicles should be able to take curves and climb grades at a reasonable speed, and descend hills safely. Power-to-weight ratios for new log-hauling trucks have been increasing as have engine braking capabilities, permitting higher speeds on both favorable and adverse grades. However, many lower-powered vehicles are still in use in the tropics. The controlling gradients should remain low even at the expense of a certain increase in the length of the route, except in the case of extremely high road construction costs.

Gradients uphill in the direction of the forest (returning empty) can be considerably more than the downhill ruling gradients coming out (traveling loaded). Depending upon the terrain, empty trucks could climb 8–12% grades, while loaded trucks are normally limited to maximum climbing grades of 6–8%. Criteria are economics, safety and environmental impacts.

1.6 Design Objectives

For most forest roads, the objective is to find the design which results in the lowest total cost of design, construction, and maintenance for the intended use while providing for safe operation and environmental protection. Road builders concerned about constructing roads as economically as possible must find a solution which is a compromise between the natural conditions of the area and the actual needs of the expected traffic. Conversely, to construct a road for too low an estimated volume of traffic can result in high transport and maintenance costs. On the other hand, the cost of a road constructed to a standard that is too high cannot be justified by the value of the forest which this road serves. The development of the road network must be considered simultaneously with the extraction system to the roadside in order to reach an economical balance. The work of planning and constructing forest roads must always be carried out considering existing economic conditions. Expenditure for permanent construction of too high a standard should be carefully balanced against a more economic temporary solution adapted to the present needs.

1.7 Direct Environmental Impacts

The primary environmental impacts of roads differ depending upon terrain. In native tropical forests on gentle terrain, roads provide access to previously inaccessible areas. Roads are the basic infrastructure for development. In many areas, farmers and ranchers have followed roads into the forest, converting land to agriculture, pasture land, and communities. Roads can also function as linear barriers for wildlife and fragment the forest.

On steeper terrain in both natural and planted forests, roads can contribute significantly to erosion and mass movement of soil. They can also divert water flow, becoming artificial "streams" that can affect water delivery time to rivers. Cut slopes can intercept groundwater flow, and road drainage can accumulate water in areas where it has not been before or divert water to areas that have not previously had overland flow. Improperly located roads placed on unstable slopes can create soil mass movement, as can oversteepened fill slopes or buried organic material which later decomposes into slippery lenses within the road prism.

Improperly designed stream crossings can funnel sediment into streams, and poor equipment maintenance policies can introduce chemicals into streams. Sediment from roads can make its way to streams, affecting downstream water quality for aquatic life and human use.

Proper location, design, construction, and maintenance of roads can avoid or reduce many undesirable side effects of forest roads (Chap. 11).

1.8 Best Management Practices

Considerable progress has been made in recent years in the introduction of environmentally sound forest harvesting and road practices in many parts of the tropics. A number of tropical countries have developed harvesting codes of practice which also include guidelines for forest roads. The International Labor Office (ILO) and the Food and Agriculture Organization of the United Nations (FAO) have been active supporters.

One of the earliest national harvesting codes of practice in the tropics was adopted by Fiji in 1990 with the help of ILO. In 1996, FAO released its *Model Code of Harvesting Practice* (Dykstra 1996) which as of 2006 has been used as the template for at least 30 countries in the tropics. Several regional codes have been developed or are in development. Examples include the regional *Code of Practice for Forest Harvesting in Asia-Pacific* published by FAO in 1999 (FAO 1999a) and endorsed by the Association of Southeast Asian Nations (ASEAN) in 2001 and the *Regional Code of Practice for Reduced-Impact Forest Harvesting in Tropical Moist Forests of West And Central Africa* published in 2005 (FAO 2005).

The primary objectives of the harvesting codes are to promote forest harvesting practices that improve standards of utilization and reduce environmental impacts, thereby contributing to the conservation of forests through their wise use. Harvesting codes typically contain information on harvest planning, forest road engineering, cutting, extraction, landing operations, transport, postharvest assessment, and training, supervision, and safety for the forest workforce.

Road Standards 2

2.1 Basic Terminology

The terminology used in describing the road structure is shown in Fig. 2.1.

Travel way. The road surface design width designated for vehicle travel, both travel lanes of a double-lane road, or the single-lane width on a single-lane road.

Shoulder. The designated road shoulder width specified in a design, or any width in excess of the travel way width available as a usable shoulder adjacent to the travel way.

Subgrade. The road surfacing foundation.

Base course. The layer of material above the subgrade that supports the weight of traffic. On roads with only one layer on top of the subgrade, the layer has a dual function; providing for vehicle support and the vehicle running surface.

Surface course. The top layer of the travel way that provides a running surface for vehicles. On aggregate-surfaced roads no strength is assumed for surfacing when there is a base course under the surface course.

Roadside ditch. The ditch constructed at the bottom of a back slope parallel to the road subgrade for the purpose of keeping water out of the subbase or improved soil layer, collecting road-surface and cut-bank runoff water.

Intercept or catchwater ditch. A ditch located above a cut bank to collect runoff water and divert it from cut banks that will erode.

Subdrains. Any form of drain placed within the subgrade or under a roadside ditch for the purpose of collecting and removing underground water.

Cross slope. A general term for either the crown or the superelevation (degree of banking) of travel ways and/or shoulders.

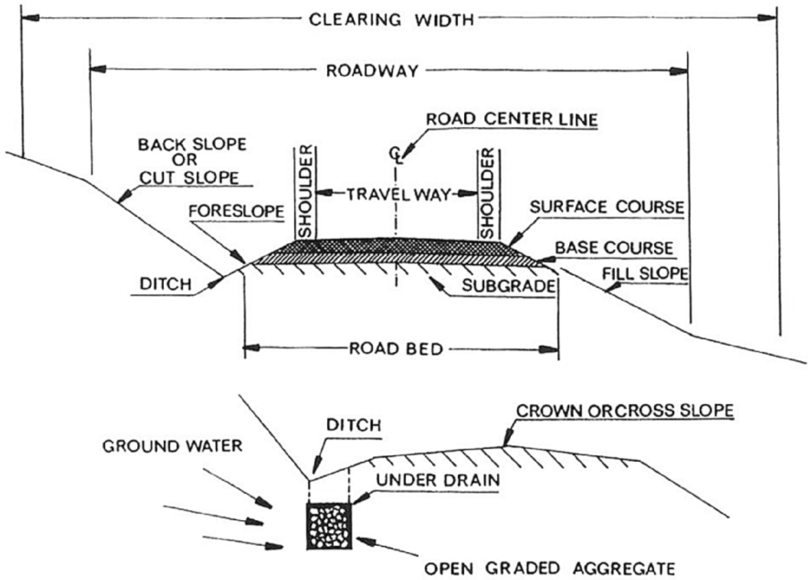


Fig. 2.1. Road cross section

2.2
Forest Road Classification

Forest roads are classified in the following way:

1. Access roads are permanent transport links between the forests and public roads. They serve for transport from villages to the forests, and from forests to the wood-processing sites. In some countries, wood of up to 100,000 m^3 or more may be transported annually on these rural access roads. These roads may also serve as public roads, although they may be maintained by private logging companies. Access roads and main forest roads usually are constructed to be all-weather roads. They are trafficable most of the year and are intended to be permanent roads. Secondary forest roads and skidding roads usually are suitable as dry-season roads. If they will be abandoned, they are referred to as temporary roads.
2. Main forest roads (branch roads, forest truck roads) form the basic forest road network. They allow all-year truck transport of wood. When needed for several years, these roads require higher-standard construction.

3. Secondary forest roads (spur roads, feeder roads, subsidiary roads) are connecting lines in the forest from the landings to the main roads. They are accessible by trucks in the dry season, but may be closed down during rainy seasons. Often they are abandoned after the logging operations; therefore, surfacing often is not required.
4. Terrain truck roads are roads that are specially built for all-wheel-drive, "off-road" truck use. These roads are special-purpose, low-standard roads, where high gradients and/or very weak subgrades exist. Other vehicles often cannot use them.
5. Skid roads are temporary earth roads between the trees. They serve as skidding or forwarding routes from the felling site to a landing constructed along a secondary forest road. For skid roads in mountainous terrain, earth moving may be done by hand, small bulldozers, or loaders. For skid roads in flat, easy terrain, earth moving usually is not needed. In mechanized transport, some logging residues may be left on the roads to protect the soil.
6. Skid trails in the forest are spaces between the trees, which are used to move wood from the stump area to the side of the skid roads. No dirt is moved to form the trails, but trees and underbrush may be removed. Stumps have to be cut as low as possible. In mechanized transport, logging residues are sometimes left on the skid trail to protect the soil.

Depending on the means of transport, the roads may be named truck, tractor, or animal roads. Depending on their position, the forest roads in mountainous terrain may be valley, slope, or mountain ridge roads. Depending on their construction, the roads may be earth roads, graveled, or chemically stabilized roads, or roads with a permanently stabilized (e.g., concrete or asphalt) surface.

2.3 Geometric Design Specifications

In order to ensure driver safety, and efficient and economic movement of the trucks, the road alignment must satisfy certain geometric design specifications. The main elements of geometric design specifications are lane width, horizontal curves, vehicle off-tracking requirements, road gradient, and vertical curves.

Typical characteristics for forest roads in the tropics are shown in Table 2.1. Traffic speeds indicated in the table are also called design speeds. These speeds can be achieved only when the roads are properly maintained.

Table 2.1. Characteristics for forest roads in the tropics (Heinrich 1975)

Road type	Road use	Road width including shoulders (m)	Width of travel way (m)[a]	Minimum curve radius (m)	Maximum gradient (%)	Truck loads per day	Traffic speed (km/h)	Cost estimate (relative cost units per meter of road)
Access	Truck	9–12	7–10	50	6 (8)[b]	More than 50	50–60	10–15
Main	Truck	8–10	6–8	30	8 (10)[b]	Up to 50	25–40	7–10
Secondary	Truck	6–8	5–6	20	10 (12)[c]	Up to 6	15–25	1–7
Skidding	Tractor		3.5–4.5					0.05–1

[a]In steep and difficult terrain conditions the road widths given have to be reduced considerably
[b]Maximum gradient in steep, difficult terrain for unloaded trucks when driving uphill
[c]Maximum gradient in steep, difficult terrain for a short distance

2.3.1 Horizontal Curves

On low-volume forest roads, a circular horizontal curve is generally used to provide a transition between two tangents as spiral transition curves are not necessary at speeds typical of forest traffic (Fig. 2.2).

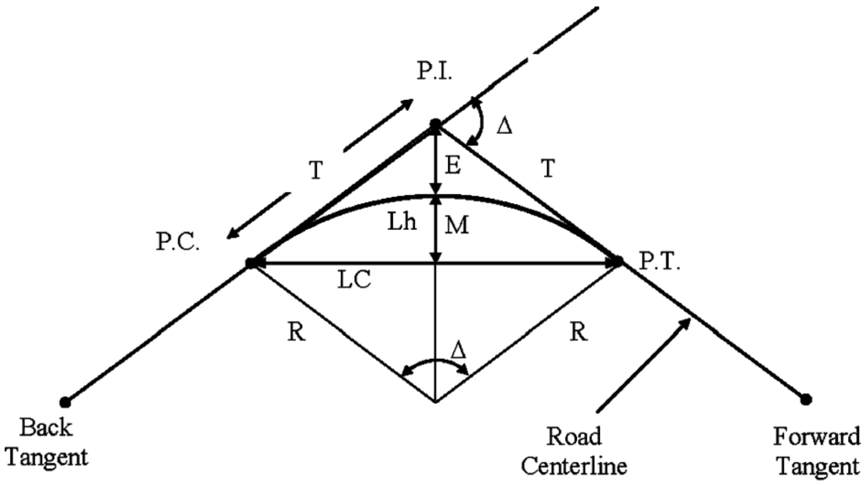
To design a feasible horizontal curve, the designer considers the minimum curve radius, acceptable road grade on the horizontal curve, and minimum safe stopping distance. The design speed for the truck is the minimum of the:

- Maximum speed limited by stopping sight distance (SSD)
- Maximum speed limited by overturning
- Maximum speed limited by sliding
- Maximum speed limited by dust or road roughness

2.3.1.1 Speed Limited by Stopping Sight Distance

The objective is to provide a sufficient sight distance for the drivers to safely stop their vehicles before reaching objects obstructing their forward motion. The SSD (in meters) for two-lane roads is computed as

$$\text{SSD} = \frac{v^2}{254\,(f \pm g)} + 0.278 v t_{\text{r}} ,$$



Definitions:

P.I. = Point of intersection
P.C. = Beginning point of the curve
P.T. = Ending point of the curve
Lh = Curve length
Δ = Central angle
M = Middle ordinate
R = Radius
T = Tangent distance
L.C. = Long chord
E = External distance

Equations:

$$Lh = \frac{\Delta \pi R}{180^{\circ}}$$

$$T = R \tan \frac{\Delta}{2}$$

$$LC = 2R \sin\left(\frac{\Delta}{2}\right)$$

$$E = T \tan \frac{\Delta}{4}$$

Fig. 2.2. Geometry of a circular horizontal curve. The central angle is also numerically equal to the deflection angle, i.e., the angle between the back tangent and the forward tangent

where v is the design speed in kilometers per hour, t_r is the perception–reaction time of the driver in seconds (generally 2.5 s), f is the coefficient of vehicle braking friction, which is a function of the road surface and braking efficiency, and g is the road grade in decimal percent (negative in the downhill direction). On two-directional one-lane roads, the SSD is approximately twice the SSD for a two-lane road. The required SSDs applicable to two-lane roads for various vehicle speeds and braking coefficients are shown in Table 2.2.

Table 2.2. Stopping sight distances (*SSD*) on two-lane roads including 2.5 s reaction time

Design speed (km/h)	Braking coefficient	SSD (m)
30	0.40	30
40	0.38	45
50	0.36	65
60	0.34	85
70	0.32	110
80	0.31	140

The middle ordinate distance must be visually clear so that the available SSD is sufficient for the driver's line of sight (Fig. 2.3). Road maintenance must maintain the line of sight through vegetation control.

Experience has shown that a driver should be able to see from an eye height of 1,070 mm and stop before hitting an object of 150-mm height at the middle ordinate point. On forest roads, 600 mm of object height at the middle ordinate point is generally used. Middle ordinate distance in meters is computed as follows:

$$M = R\left[1 - \cos\left(28.65\,\frac{\mathrm{SSD}}{R}\right)\right],$$

where R is the radius of horizontal curve (in meters). It is a straightforward task to compute M, once R and SSD have been determined.

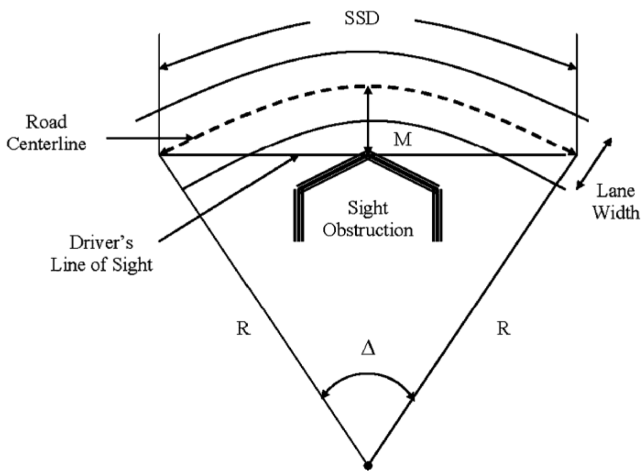


Fig. 2.3. Middle ordinate distance (M) around a horizontal curve

2.3.1.2
Speed Limited by Overturning

Having high centers of gravity and narrow track width (the distance between the outside faces of the wheels at opposite ends of an axle), logging trucks may overturn owing to an inadequate radius. Design speed, lateral acceleration, and vehicle weight must be considered. Although the design speed for truck turnover is a function of truck configuration, the minimum radii in Table 2.3 provide a reasonable guide.

2.3.1.3
Speed Limited by Sliding

The limiting speed V (in kilometers per hour), to avoid sliding around a horizontal curve, can be formulated considering vehicle weight, side friction force, centrifugal force, curve radius, side friction coefficient, and superelevation:

$$V = 11.27\sqrt{R(f_s + e)},$$

where f_s is the coefficient of side friction, R is the radius of the horizontal curve in meters, and e is the superelevation of the horizontal curve in decimal percent if it exists.

2.3.1.4
Speed Limited by Dust and Road Roughness

These speeds will be a function of the maintenance policy and may vary by season (Chap. 9).

2.3.2
Off-Tracking

When traveling around the horizontal curve, the rear wheels of slow-moving vehicles do not track in the same path as the front wheels; a condition referred

Table 2.3. Minimum radius for various vehicle speeds to avoid overturning

Speed (km/h)	Speed (m/s)	Minimum radius (m)
30	8.33	47
40	11.1	84
50	13.9	131
60	16.7	189
70	19.4	257
80	22.2	336

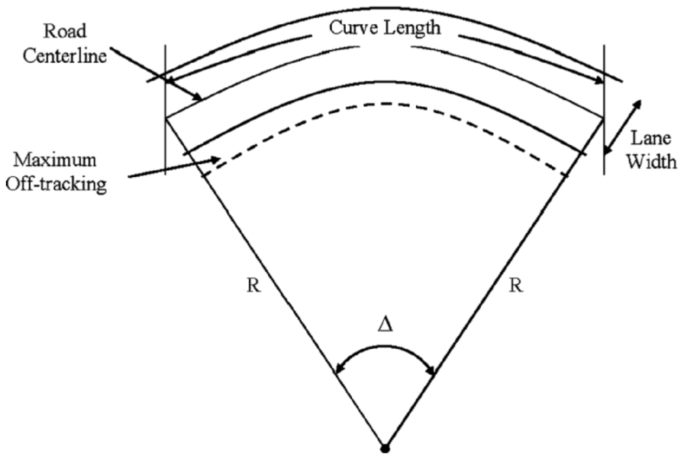


Fig. 2.4. Maximum off-tracking on a horizontal curve

to as off-tracking. To accommodate the off-tracking of the rear wheels, extra road width is required on the inside of the curve (Fig. 2.4). The required curve widening depends on various factors such as vehicle dimensions, curve radius, and the central angle of the curve (Δ). To predict off-tracking, an empirical method is generally employed and provides designers with quick, easy, and relatively accurate results:

$$\mathrm{OT} = (R - \sqrt{R^2 - L^2})\left[1 - \exp\left(-0.015\Delta\frac{R}{L} + 0.216\right)\right],$$

where OT is the off-tracking. L is computed for a stinger-steered trailer (Fig. 2.5) as

$$L = \sqrt{L_1^2 - L_2^2 + L_3^2},$$

where L_1 is wheel base of the tractor, L_2 is the length of the stinger measured from the middle of the tractor tandem axles to the end of the stinger, and L_3 is the extended reach, which, when at its shortest length, can be approximated by the

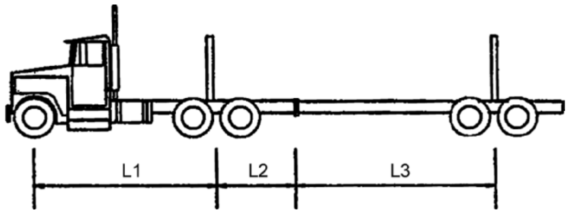


Fig. 2.5. Geometry for the stinger-steered trailer and tractor with a lowboy or conventional trailer

bunk-to-bunk distance minus the length of the stinger. For the lowboy or conventional trailer, the length of the stinger is zero, so the bunk-to-bunk distance in Fig. 2.5 is equal to L_2+L_3.

For a conventional trailer,

$$L = \sqrt{L_1^2 + \left(L_2 + L_3\right)^2}. \text{ (see Fig. 2.5)}$$

Example for a stinger-steered trailer and lowboy or conventional trailer: L_1=6.10 m, L_2=3.00 m, L_3=6.30 m, R=30 m, Δ=90°.
For a stinger-steered trailer, L = 8.24 m, and the off-tracking is 1.14 m:

$$\text{OT} = (30 - \sqrt{30^2 - 8.24^2})\{1 - \exp[-0.015 \times 90 \times (30/8.24) + 0.216]\} = 1.14 \text{ m}.$$

For a conventional trailer, L = 11.12 m, and the off-tracking is 2.07 m:

$$\text{OT} = (30 - \sqrt{30^2 - 11.12^2})\{1 - \exp[-0.015 \times 90 \times (30/11.12) + 0.216]\} = 2.07 \text{ m}.$$

For a truck pulling a trailer (Fig. 2.6),

$$L = \sqrt{L_1^2 + L_2^2 + L_3^2 + L_4^2},$$

where L_1 is the wheelbase of the tractor, L_2 is the distance from the middle of the tractor tandem axles to the pintel hook, L_3 is the drawbar length of the trailer, and L_4 is the wheelbase of the trailer.

Example for a truck pulling a trailer: L_1=6.10 m, L_2=3.00 m, L_3=4.5 m, L_4=4.50 m, R=30 m, Δ=90°.

For a truck pulling a trailer, L=9.31 m, and the off-tracking is 1.46 m.

For a truck tractor with a jeep and lowboy or a B-train combination (Fig. 2.7),

$$L = \sqrt{L_1^2 - L_2^2 + L_3^2 - L_4^2 + L_5^2}.$$

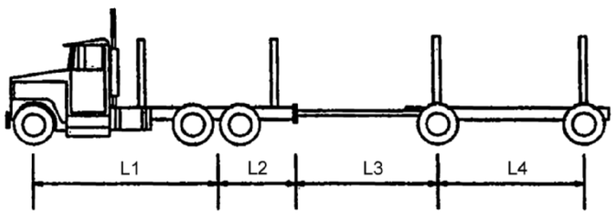


Fig. 2.6. Geometry for truck pulling a trailer

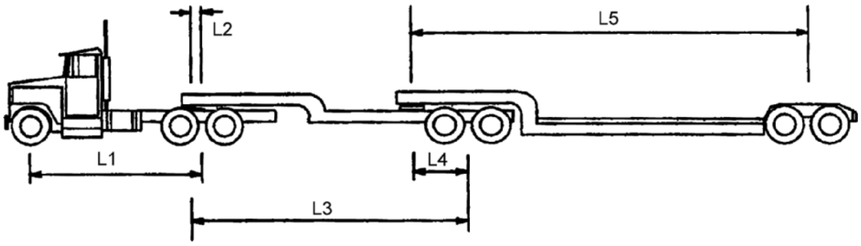


Fig. 2.7. Truck pulling a jeep and a lowboy or a B-train combination

Example for a jeep and lowboy or a B-train combination: L_1=6.10 m, L_2= 0.70 m, L_3=6.10 m, L_4=1.00 m, L_5=10.60 m, R=30 m, Δ=90°.

For a jeep and lowboy or a B-train combination, L=13.61 m, and the off-tracking is 3.06 m.

2.3.3 Road Gradient

Road gradient (in percent) is calculated in units of vertical rise divided by the horizontal distance. The minimum road gradient is limited by the minimum acceptable road grade to provide proper drainage. Having a minimum 1–2% longitudinal gradient along a road section helps prevent ponding of water on the surface. The maximum road gradient is determined based on the design vehicle. A list of recommended maximum gradients for light trucks is shown in Table 2.4. Since trucks lose speed rapidly on climbing grades, and ultimately reach an equilibrium speed, vehicle performance should be taken into account to minimize overall transportation costs. In current vehicle performance models, the road alignment and surface type are taken as inputs, and alignment-specific results (ground speed, engine speed, gear-shifting requirements, fuel consumption, and round-trip time) are determined. Detailed information on these models can be obtained from the "References" and "Further Reading."

Table 2.4. Maximum road gradient (%) for various design speeds and topography for light trucks

Speed (km/h)	Rolling topography (%)	Mountainous topography (%)
30	11	16
40	11	15
50	10	14
60	10	13
70	9	12
80	8	10

Sometimes a steep gradient is needed to reach a control point. The maximum adverse grade will depend upon the coefficient of traction (surface condition), number of driving wheels, normal force on the driving wheels, weight of the vehicle, pressure in the tires, and configuration of the vehicle. Since the maximum adverse grade is most highly dependent on the surface condition at the time of transport, local experience is the best guide, but there are some guides that create conditions to permit a vehicle to climb the steepest possible grade, all other things being equal:

- Loading the butts forward onto driving wheels increases the normal force on the drivers, increasing drive traction. Care must be taken not to overload the drive axles, or exceed bridge loadings.
- Powering the front wheels in addition to the rear truck tractor wheels can provide approximately a 4% increase in gradeability, for example, if a 6×4 power train could climb a 12% grade, a 6×6 power train could climb a 16% grade.
- Reducing tire pressures on the drive tires of the truck will increase gradeability. The tires must be radial tires, not bias ply tires (Sect. 3.7).
- Using an assist vehicle such as a grader, front-end loader, or rubber-tired skidder to push or pull the truck.

The maximum gradeability of a truck going around a curve of given radius is lower than that of a truck climbing on a tangent for a number of reasons:

- Part of the available traction is used for cornering resistance.
- The cornering resistance of the tires, particularly tandem axles, creates an additional drag force.
- The redistribution of normal forces between the right and left driving axles as the vehicle goes around the curve limits the available traction to twice the traction that can be developed on the side with the lowest normal force owing to the action of the differential.

The smaller the radius of the curve, the more significant is the reduction in gradeability relative to the tangent. A number of rules of thumb exist. One example is Table 2.5. Introducing a superelevation into the road to adjust the distribution of forces on the drive axles may offset some negative effects of the curve on gradeability, but that will depend upon vehicle speed and configuration.

Example: A loaded truck is traction-limited to a 12% adverse grade on a tangent. Find the maximum grade through a horizontal curve with a 20-m centerline radius.

From Table 2.5, the suggested maximum gradient through the curve would be 12%–3.5%=8.5%.

Table 2.5. Suggested gradient reductions around horizontal curves with no superelevation relative to the maximum adverse grade on a tangent

Curve radius	Grade reduction
Tangent	No reduction
50 m	0.5%
40 m	1.0%
30 m	2.0%
20 m	3.5%
15 m	4.5%

2.3.4 Vertical Curves

Vertical curves are used to design transitions between gradients along roads. Forest road engineers customarily use parabolic vertical curves (Fig. 2.8) with a constant rate of change of gradient, because (1) they result in alignments comfortable to drive, (2) they are easy to lay out, and (3) the SSD is constant along the curve. The vertical curves should have a sufficient curve length that permits a log truck to pass a curve without bottoming out in the sag or breaching the crest and provides an adequate SSD.

In determining a feasible curve length, crest and sag vertical curves are considered separately on the basis of the assumption that the curve length (meters) may be greater than or less than the SSD. If the SSD is greater than the curve length Lv, (Fig. 2.9),

$$\text{Lv} = 2\text{SSD} - \frac{200\left(\sqrt{h_1} + \sqrt{h_2}\right)^2}{A},$$

where h_1 is the distance from the road surface to the level of the driver's eye, h_2 is the height of the object on the road, and A is the absolute value of the difference between gradients (in percent). If the SSD is less than the curve length (Fig. 2.10),

$$\text{Lv} = \frac{\text{SSD}^2 A}{200\left(\sqrt{h_1} + \sqrt{h_2}\right)^2}.$$

The length of a sag curve, for a required SSD depends on two cases. If the SSD is greater than the curve length,

$$\text{Lv} = 2\text{SSD} - \frac{200\left(h_3 + \text{SSD}\tan\alpha\right)}{A},$$

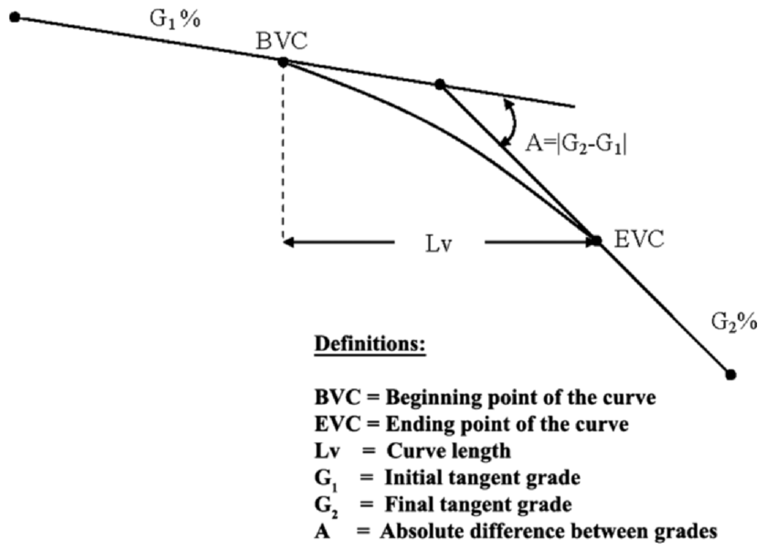


Fig. 2.8. Geometry of a crest vertical curve (symmetrical)

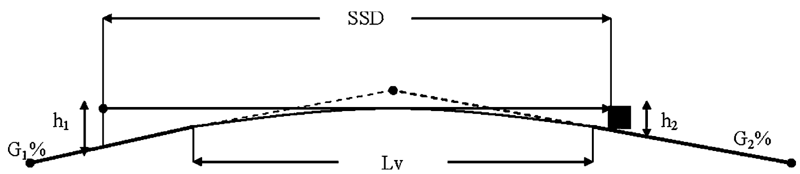


Fig. 2.9. Stopping sight distance (*SSD*) is greater than the length of a vertical curve

where h_3 is the distance from the road surface to the level of the vehicle headlights and α is the angle (in degrees) of the headlight beam above axis of the vehicle. If the SSD is less than the curve length,

$$\mathrm{Lv} = \frac{\mathrm{SSD}^2 A}{200\,(h_3 + \mathrm{SSD}\tan\alpha)}\,.$$

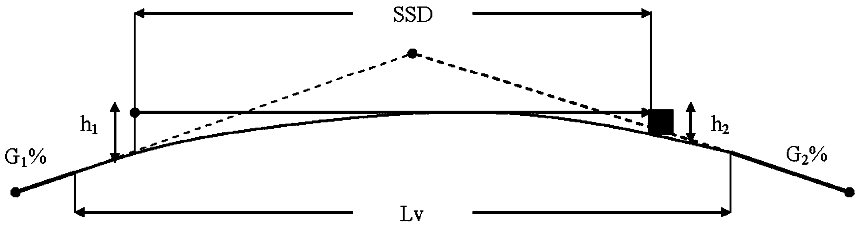


Fig. 2.10. SSD is less than the length of a vertical curve

2.4 Cut and Fill Slope Design

Cuts and fills are designed to accommodate geometric design, remain stable over time, not be a source of sediment that reduces water quality, and minimize long-term costs. Landslides and failed road cuts can close the road or require major repairs, can greatly increase road maintenance costs, and can be a major source of sediment. Vertical cut slopes should not be used unless the cut is in rock or in cemented soil. Examination of local cuts can provide valuable information about cut slope stability. Long-term stable cut slopes are made with about a 1:1 or 0.75:1 (horizontal-to-vertical) slope. Fill slopes should be constructed with a 1.5:1 or flatter slope. Oversteepened fill slopes, commonly formed by sidecasting loose fill material, may continue to ravel with time, and are difficult to stabilize. Cut and fill slopes should be made so that they can be revegetated. Common stable slope ratios appropriate for rock and soil types are shown in Table 2.6.

In steep areas where it is not practicable or cost-effective to achieve a stable slope ratio, a retaining structure is necessary. These include gravity walls, crib

Table 2.6. Common slope ratios for varying soil and rock conditions

Soil/rock condition	Slope ratio (Horizontal to vertical)
Most types of rock	0.25:1 to 0.5:1
Very well cemented soils	0.25:1 to 0.5:1
Most in-place soils	0.75:1 to 1:1
Very fractured rock	1:1 to 1.5:1
Loose coarse granular soils	1.5:1
Heavy clay soils	2:1 to 3:1
Soft clay-rich zones or wet seepage areas	2:1 to 3:1
Fills of most soils	1.5 to 2:1
Fills of hard, angular rock	1.33:1
Low cuts and fills (<2–3-m high)	2:1 or flatter (for revegetation)

walls, gabions, and reinforced earth walls. If retaining walls are used, the structures must be placed on a good foundation such as firm, in-place soil. Road locations in very steep terrain (more than 60%) should use full bench construction. Excavation should be placed in a stable location.

2.5 Cross Slope

Sufficient cross slope (camber) is necessary to assure proper drainage of the road surface. Cross slopes should be a minimum of 5% on earth roads and 4% on graveled roads. On centerline gradients greater than 4%, the cross slope should be as large as the centerline grade to move water quickly off the road.

2.6 Terrain Truck Roads

Terrain truck roads are a separate class of road used in very difficult situations where steep grades, poor traction, and low-bearing surfaces exist. Special trucks are used. These trucks are referred to as terrain or off-road trucks. Terrain trucks are normally all-wheel drive, high clearance, with large-diameter, wide-base, low-pressure tires. Gradeability of these trucks is in the range 30–40%. They can operate under situations of very heavy rolling resistance, with tire penetration as much as 60 cm, so a significant part of the gradeability is used to overcome rolling resistance. Often road conditions where terrain trucks are used cannot be used by other vehicles.

In Southeast Asia one popular terrain truck is a converted 6×6 military transport truck. In other situations, in Indonesia and West Africa, trucks designed for off-road construction or mining have been fitted with a fifth wheel, log stakes, and a pole trailer. Terrain trucks are used between the log landing and a transfer yard along the main road. In some situations, they are used to haul directly from the landing to the mill or riverside. The economics of using terrain trucks should consider differences in road standards and the extra cost of reloading the logs if a transfer yard is required, and increase in hauling season. In areas of expensive road construction, where steep grade road locations could avoid large excavation, landslides, and potential erosion, the use of terrain trucks could be a viable alternative to limit environmental impacts. In some cases, landing size can be reduced as the terrain trucks can jackknife in the road to be loaded by a front-end loader. An additional advantage of terrain trucks is the ability to remove logs cut from the road right of way that normally would have to wait until road construction is complete.

Economic Basis for Forest Road Construction 3

In order to determine the most economical alignment, standard, and density of the road system, it is necessary to be able to calculate the cost of the vehicles which use the roads and the cost of the roads themselves. The optimal design is one that minimizes the combination of logging, transport, construction, and maintenance costs while providing for safe operation and controlling environmental impacts.

3.1 Determination of Truck Costs

The operating cost of a truck is the sum of several components:

- Depreciation or capital write-off
- Interest on average investment
- Insurance: public liability and property damage, fire, etc.
- Annual taxes, including licensing cost
- Operating labor
- Fuel, including fuel taxes
- Oil and lubricants
- Servicing and repairs (except tires for hauling vehicles)
- Tires for hauling trucks and trailers

Truck hourly costs can be calculated using the form shown in Table 3.1. This form can be used for compiling the estimated operating cost per unit for all equipment, including the operators. For trucks and trailers, the time units should be divided between "standing hours" and "traveling hours." For comparing alternative road standards, the cost per traveling hour is usually the most appropriate hourly cost to use.

Table 3.1. Machine Operating Cost Estimates (FAO 1977)

Machine:	Description ____________
	Gross hp ____________ Delivered Cost ____________
	Life in Years ________ Hours (days): per year ________ life ________
Fuel:	Type ____________ Price per litre ____________
Tires:	Size ________ Type ________ Number ________
	Cost of replacement set ____________
Operator:	Rate per hour (day) ____________ Fringe benefits ________%

Cost Component		*Cost per hour (day)*
a) Depreciation	$= \dfrac{\text{delivered cost} \times 0.90}{\text{life in hours}}$	________
b) Interest	$= \dfrac{\text{delivered cost} \times 0.60 \times \text{interest rate}}{\text{average hours per year}}$	________
c) Insurance	$= \dfrac{\text{delivered cost} \times 0.60 \times 0.03}{\text{average hours per year}}$	________
d) Taxes	$= \dfrac{\text{annual tax amount}}{\text{average hours per year}}$	
e) Operating Labour	$= \dfrac{\text{labour cost per period} \times (1 + f)}{\text{machine hours in period}}$	________
where f = cost of labour fringe benefits expressed as % of direct labour cost.		
	Sub-total[a]	________
f) Fuel = GHP × X × CL		________
where GHP = gross engine horsepower; CL = fuel cost per litre in dollars; X = 0.12 for diesel fuel, 0.175 for gasoline		
g) Oils and greases	$= \dfrac{\text{GHP} \times \text{X} \times 3.4^{c}}{100}$	________
where X = 0.20 for tractors, skidders, front end loaders and trucks; X = 0.30 for feller-bunchers and knuckle boom loaders; X = 0.50 for processors, harvesters and forwarders.		
h) Servicing and Repairs(*)	$= \dfrac{\text{Delivered Cost}}{\text{life in hours**}}$	________
* include tires except for haulting rigs; ** use lifetime travelling hours in case of haulting rigs.		
i) Tires for hauling rigs = 0.0006 × CST		________
where CST = cost of set of replacement tires.		
	Total[b]	________

[a]This represents the *cost per standing hour* of a hauling rig.
[b]This represents the *cost per travelling hour* of a hauling rig, and cost per productive machine or effective hour for other machines.
[c]Cost multiplication update to 2006.

3.2 Truck Travel Times

Truck travel time is affected by the vertical and horizontal alignment, the gross vehicle load, the truck's power plant and drive train characteristics, the volume of traffic, the conditions of the road surface, operator training, and weather conditions. Truck travel times over a section of road can be derived from tables or figures using (1) data from local observations or (2) by mathematical models. Figure 3.1 illustrates the effect on truck speed as a function of vertical alignment for a loaded truck with a power-to-weight ratio of 2.9 kW/t and an unloaded truck with a power-to-weight ratio of 8.2 kW/t. Figure 3.2 illustrates the effect of horizontal alignment on truck travel time. Procedures to use the information outlined in Figs. 3.1 and 3.2 are described in Byrne et al. (1960).

3.3 Determination of Road Construction and Maintenance Costs

Understanding road construction and maintenance costs is important to evaluate roading strategies including (1) alternative choices of road location, (2) tradeoffs between harvesting costs and roading costs, (3) choices of road standards, (4) choice of transport mode, (5) selection of dry season and wet season

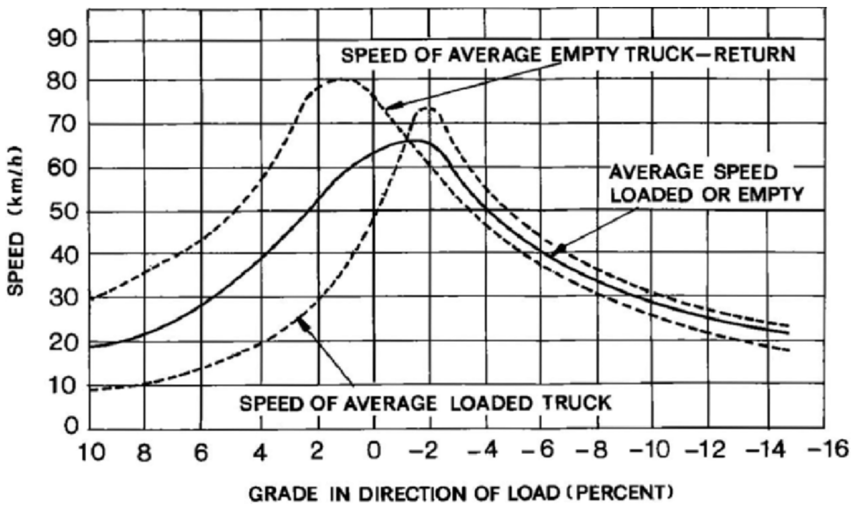


Fig. 3.1. Example of truck travel speed as a function of grade. (After Byrne et al. 1960)

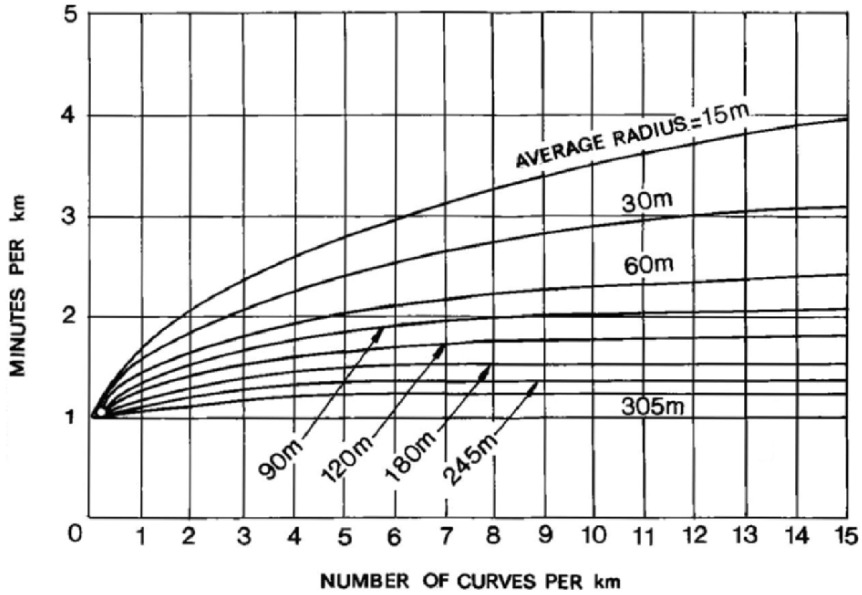


Fig. 3.2. Example of loaded truck travel time as a function of road alignment for single-lane roads. (After Byrne et al. 1960)

harvesting areas, and (5) understanding whether bids on road projects or subprojects that are to be contracted are reasonable.

Road construction and maintenance costs are often calculated using the "engineer's" method. First, the quantity required for each road element, such as construction staking, clearing and piling, earthwork, finish grading, surfacing, and drainage structures, is estimated. Then, the estimated quantities are multiplied by the unit costs for each element (i.e., cost per kilometer of constructed road).

The unit cost for each the road element is derived from local experience or by estimating the daily cost of the equipment and labor used for that element and dividing it by the estimated daily productivity.

The following sections provide examples for estimating unit costs for the main elements of a forest road: construction staking, clearing and piling, earthwork, finish grading, sufacing, and drainage.

3.3.1 Construction Staking

Construction staking costs depend on the type and size of the job, access, terrain, and job location. One method of estimating production is to estimate the number of stakes which can be set per hour and the number of stakes which must be set per kilometer. The surveying production rate (in kilometers per hour) is equal to the number of stakes the crew sets per hour divided by the number of stakes required per kilometer. A typical five-point section consists of two reference stakes, two slope stakes, and one final centerline stake. Staking costs will increase in heavier vegetation, on steeper slopes, and are proportional to the number of staking sections per kilometer. Long walk-in times or working in terrain with large amounts of brush will shorten the work day, increasing the effective cost per crew hour.

Example: A two-man survey crew is setting 300 stakes per kilometer at a rate of 15 stakes per hour. The cost of a survey crew including transport is $15 per hour.

Surveying production rate=(15 stakes per hour)/(300 stakes per kilometer) =0.05 km/h.

Surveying unit cost=($15 per hour)/(0.05 km/hr)=$300 per kilometer.

3.3.2 Clearing and Piling

Clearing can be accomplished in a number of ways, including men with axes or power saws or heavy equipment such as tractors. The clearing and piling cost can be calculated by estimating the number of hectares of right of way to be cleared and piled per kilometer of road. The clearing and piling production rate in kilometers per hour is the number of hectares per hour which can be cleared and piled per hour divided by the number of hectares per kilometer to be cleared and piled. Merchantable logs may be removed by skidder or tractor and the remainder piled by tractor for burning or decay. Felling and skidding productivity and costs for logging can be used for determining the cost of the removal of merchantable logs.

On gentle terrain, if a wide right of way is being cleared to permit sunlight to dry the road surface after frequent rains, the project can be estimated as a land-clearing project. Production rates are available from sources such as the *Caterpillar Performance Handbook* (Caterpillar 2003) or Sessions (1992). Important variables are tractor size, number of trees, and tree size.

Example: Five hectares per kilometer of right of way in hardwoods is being cleared for a road (including extra width to help the road dry after rains). Of the 5.0 ha/km, 1.2 ha/km will need to have the stumps removed. The tractor machine rate is $120 per hour. All material will be piled for burning. Using this input and the methodology from Sessions (1992), the estimated tractor time is 26 h/km of right of way.

Work is being done by a 224 kW bulldozer. The number of trees by size class is:

Diameter class (cm)	Number of trees per hectare
<30	1,100
30–60	35
61–90	6
91–120	6
121–180	4
>180	1

Clearing and piling productivity=1 km/26 h=0.039 km/h.

Unit cost of clearing and piling=($120 per hour)/(0.039 km/h)=$3,077 per kilometer.

3.3.3 Earthwork

The earthwork quantity (in cubic meters per kilometer) is calculated by estimating the volume of common material and rock which must be excavated to construct the road. It is usually estimated as the bank volume. The volume can be estimated using formulas or tables for calculating earthwork quantities as a function of sideslope, road width, and cut and fill slope ratios. The earthwork production rate is calculated as the number of cubic meters per hour which can be excavated and placed divided by the number of cubic meters per kilometer to be excavated. Production rates (in cubic meters per hour) for bulldozers and hydraulic excavators are available from handbooks. Alternatively, road construction superintendents can often estimate the productivity of their equipment on the basis of local experience after looking at the topography.

Example: A 6.0-m subgrade on a 30% slope with a 1.5:1 fill slope and 0.5:1 cut slope with a 0.3-m ditch and a 20% shrinkage factor would be approximately 2,100 bank m^3/km for a balanced section. An average production rate in common material (no rock) from an equipment performance handbook might be 150 bank m^3/h for a 224 kW power-shift tractor with a ripper. The tractor cost is $120 per hour. The rate of excavation would be

Earthwork productivity=(150 m^3/h)/(2,100 m^3/km)=0.07 km/h.

Unit cost for earthwork=($120 per hour)/(0.07 km/h)=$1,714 per kilometer.

Earthwork placed or sidecast within 50 m of the cut is usually not tracked separately. If the earthwork is being placed or sidecast outside of 50 m of the cut, a production rate for pushing the material to the placement location is usually made. Scrapers or excavators and dump trucks may be used to move the excavated material to the embankment site. If compaction effort above that provided by the construction equipment is needed, a unit cost for rolling and any necessary watering are added.

Excavation rates in rock vary with the size of the job, the hardness of rock, and other local conditions. Often there is a local market price for blasting. Estimates of blasting production can be made by knowing the size of the equipment and the type of job. For example, a 10-cm track-mounted drill and 25-m^3/min air compressor may prepare 40 m^3/h for small, shallow blasts and 140 m^3/h for larger, deeper blasts, including quarry development to produce rock surfacing. A major cost will be explosives. For example, 0.8 kg of explosive such as Tovex might be used per cubic meter of rock at a cost of approximately $2 per kilogram.

3.3.4 Finish Grading

Finish grading cost of the subgrade can be estimated by determining the number of passes a grader must make for a certain width subgrade and the speed of the grader. This number can be converted to the number of hours per hectare of subgrade.

Example: A 90 kW grader costing $60 per hour requires about 10 h/ha of subgrade or 0.1 ha/h.

The production rate for final grading of a 6.0-m subgrade would then be: Productivity for finish grading=(0.1 ha/h)/(0.6 ha/km)=0.17 km/h.

Unit cost for grading=($60 per hour)/(0.17 km/h)=$353 per kilometer.

The rate for ditch construction per kilometer can be estimated similarly.

3.3.5 Surfacing

Surfacing costs are a function of the type of surfacing material, the quantity of surfacing material per square meter, and the length of haul. Local information is the best guide in constructing surfacing costs owing to the wide range of conditions that can be encountered. Natural gravel from streams may require only loading with front-end loaders directly to dump trucks, transporting, spreading, and may or may not be compacted. Laterite may be ripped by crawler tractor, loaded by front-end loader, transported, spread, and grid-rolled with a sheep's-foot roller to produce a sealed running surface. Rock may have to be blasted, loaded into one or more crusher(s), stockpiled, reloaded, transported, spread, and compacted. The costs for each of these operations can be developed by estimating the equipment production rates and machine rates.

Example: A surfacing operation requires developing a 20,000 m^3 solid rock source (26,400 m^3 in the road considering swell of the blasted and crushed rock) to surface 26.4 km of road including shooting and crushing rock, loading, transporting, and spreading rock as follows.

To open up the rock source, the equipment time can be estimated from the quantities for clearing and common excavation:
To clear and excavate to rock:

Equipment	Machine hours	Machine rate	Cost
Tractor	27	72	1,944

Cost per cubic meter of solid rock=\$1,944/20,000 m^3=\$0.10 per cubic meter.

To drill and blast at a production rate of 140 m^3/h:

Equipment	Machine hours	Machine rate	Cost
Drills	1.0	60	60
Compressor	1.0	55	55
Explosives	.8 kg/m^3×\$2.0 per kilogram×140 m^3		224
			339

Cost per cubic meter solid rock=(\$339 per hour)/(140 m^3/h)=\$2.42 per cubic meter.

To crush 225 t/h at 2.6 t/solid m^3:

Equipment	Machine hours	Machine rate	Cost
Tractor	0.5	72	36
Loader	1.0	90	90
Crusher	1.0	100	100
Generator	1.0	25	25
			251

Productivity for crushing rock=(225 t/h)/(2.6 t/solid m^3)=86.5 m^3/h.

Cost per cubic meter of solid rock=(\$251 per hour)/(86.5 solid m^3/h) =\$2.90 per cubic meter.

To load, transport, and spread 20,000 m^3 of rock:

1 truck×3 loads per hour×20 t per load/load×(cubic meters/2.6 t)=23 m^3/h.

If four trucks are used:

Equipment	Machine hours	Machine rate	Cost
4 trucks	870	50	43,500
Loader	218	90	19,600
Tractor	218	72	15,700
Grader	30	60	1,800
			80,600

Cost per cubic meter of solid rock=$80,600/20,000 m^3=$4.03 per cubic meter.

The total unit cost per cubic meter of rock spread on the road is:

Activity	Solid ($/m^3)	In Place ($/m^3)	Cost ($/km)
Develop pit	0.10	0.08	80
Drill and blast	2.42	1.83	1,830
Crush	2.90	2.20	2,200
Load, transport, and spread	4.03	3.05	3,050
	9.45	7.16	7,160

Equipment balancing plays an important role in obtaining the minimum cost per cubic meter for surfacing. In some areas, market prices for various types of surfacing may exist and tradeoffs between aggregate cost, aggregate quality, and hauling distance will have to be evaluated. Since surfacing is often expensive, a surveying crew is sometimes added to stake and monitor the surfacing operation. If the surfacing is to be compacted, a roller is added to the equipment mix.

3.3.6 Drainage

Drainage costs vary widely with the type of drainage being installed. The costs of drainage dips (water bars), culverts, and bridges are often expressed as a cost per lineal meter, which can then be easily applied in road estimating. Local values for cost per lineal meter for culverts and different types of bridges are generally available. If not, costs can be developed from time study data.

Example: A 45-cm culvert, 10 m long, is being installed. Experience indicates that a small backhoe and operator, and two laborers can install three culverts per day. The culvert crew uses a flat-bed truck to transport themselves and the pipe each day.

To install three culverts:

Equipment	Machine hours	Machine rate	Cost
Backhoe	6	60	360
Truck/crew	9	15	135
Pipe cost	30 m×$20 per meter		600
			1,095

The cost per installed culvert is $365. If an average of four culverts per kilometer were required, the unit cost for drainage could be expressed as $1,460 per kilometer.

3.4 Selection of Road Spacing

Depending on the level of existing road development, decisions may need to be made regarding spacing and standards of main roads, collector roads, and spur (feeder) roads (Fig. 3.3). Often main roads are in place, or are limited by topographic controls other than the theoretical economic road spacing based on gentle terrain. Network analysis techniques are usually used to identify the location and standards of main and collector roads in uneven terrain. However, in gentle terrain, the use of economic models to determine the spacing of spur roads can be a useful guide for the road planner (Fig. 3.4). Spur roads form the fingers of the road network branching from the collector roads or sometimes the main (primary) roads and penetrating to the landings to which skidding and forwarding systems deliver the harvested wood. For skidders, forwarders, or agricultural tractors the most important factors which can be controlled are load size and distance. In general, the heavier the load that can be pulled or carried without excessive wheel or track slip, the more economical is the skidding operation. Similarly, the shorter the skidding distance, the more economical the skidding operation. However, the logging manager is responsible for both skidding costs and road construction costs. Placing the roads too close together, although good for production, is not good for overall costs. No discussion of log skidding is complete without an introduction to the spacing of roads to minimize the sum of spur road (feeder road) costs and skidding costs. When using a specific skidding or forwarding machine, there is a spur road density (meters per hectare) or a spacing which will result in the lowest combined cost of constructing the spur road and skidding or forwarding. This is called the optimum spur road density (ORD) or optimum spur road spacing (ORS). For skidding costs which are linear with skidding distance, it is attained when the travel portion of the skidding or forwarding cost equals the cost of building the spur road and maintaining it during the hauling period.

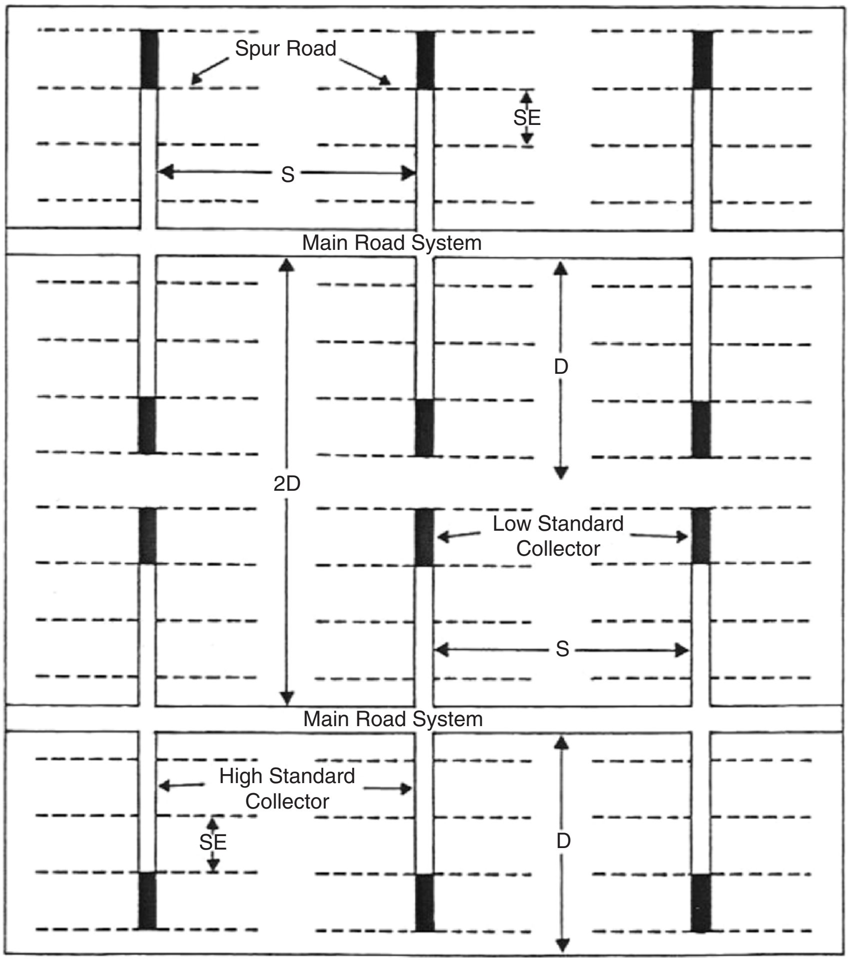


Fig. 3.3. Theoretical layout of main roads, collector roads, and spur roads in gentle terrain. *SE* is the distance between spur roads, *S* is the distance between collector roads, and 2*D* is the distance between main roads

Under ideal forest conditions on flat or gently rolling terrain where spur roads are straight and parallel, skidding or forwarding is carried on perpendicularly to the road and equidistantly on both sides, and the loads are offloaded where the road is reached, the average skidding or forwarding distance is one quarter of the spur road spacing. However, this situation rarely, if ever, occurs in practice. Sometimes a spur road may follow the border of a swamp, lake, river, or other topographic feature, so skidding or forwarding is done from one side only.

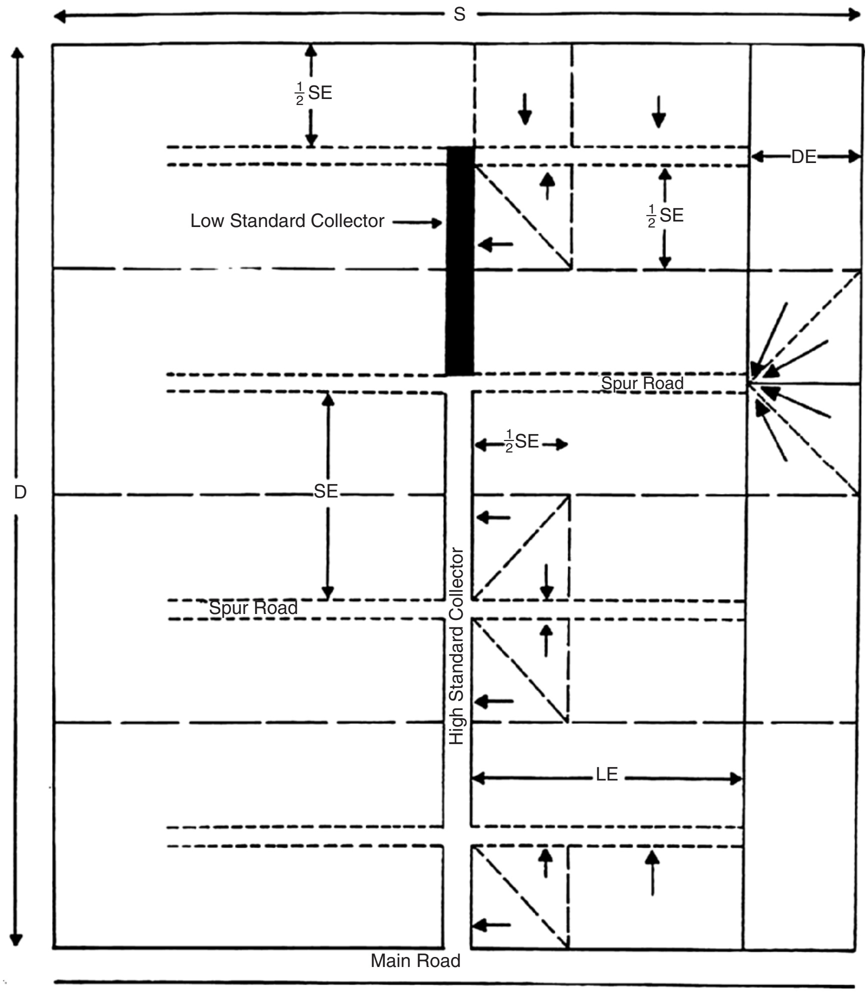


Fig. 3.4. Spur road spacing on gentle terrain showing skidding pattern. *SE* is the spur road spacing, *LE* is the length of the spur road, and *DE* is the distance that the logs are skidded to the end of the spur road

3.4.1 Optimum Road Spacing

While spur road density, expressed in meters per hectare, is easier to use in calculating spur road cost per cubic meter, spur road spacing is the more practical guide for the forest engineer laying out a spur road network in a forest.

The ORS may be found with the formula

$$\text{ORS} = k\sqrt{\frac{40RL}{qct(1+p)}},$$

where ORS is expressed in meters, R is the cost per kilometer of constructing and maintaining the spur road, L is the average skidder or forwarder load in cubic meters, q is the quantity of wood harvested, expressed in cubic meters per hectare, c is the operating cost per minute of the skidder or forwarder including the operator, t is the time in minutes for the skidder or forwarder to travel 1 m loaded and return 1 m empty, k is a correction factor, with a normal value between 1.0 under the ideal conditions when skidding or forwarding is done equidistantly on both sides of the spur road, and 0.71 (or $\sqrt{0.50}$) when skidding or forwarding is done from one side only – it is also used in situations where the spur roads are winding, meet in junctions or terminate as dead-end roads, and p is a correction factor, normally with a value between 0 and 0.5, to be used in situations where skidding or forwarding trails, i.e., the strip roads, are winding or do not end at the closest point on the spur road, or where an allowance is made for delays along the route due to low-bearing soils, hang-ups, and so on.

The spacing distance derived with the formula may be considered only as an approximate value because of the imprecise values of several of the factors in the formula. For example, if the formula gives an ORS of 1,000 m, a road spacing between 700 m and 1,300 m will often give quite satisfactory results. This allows some leeway in locating spur roads to avoid obstacles that might increase the cost of constructing the road. An examination of the ORS formula will show that quadrupling the quantity of wood harvested per hectare will halve the spur road spacing; this will (1) require twice as much road to be built but at half the cost per cubic meter and (2) halve the skidding distance and therefore the traveling portion of the skidding cost, thus bringing about an overall reduction in the logging cost.

Example 1: What is the optimal road spacing if the road construction cost is \$10,000 per kilometer, the average skidder load is 4 m^3, the volume to be harvested is 30 m^3/ha, the operating cost is \$0.80 per minute, and the skidder travels 5 km/h unloaded and 3 km/h loaded? Skidding is equidistant from each side and a correction factor of 0.2 is used to account for delays.

The time to travel 1 m empty and to travel 1 m loaded is 60/5,000 + 60/3,000 = 0.032 min per round-trip meter.

The ORS is then

$$\text{ORS} = 1.0\sqrt{\frac{40 \times 10000 \times 4}{30 \times 0.8 \times 0.032 \times (1+0.2)}} = 1318\,\text{m}.$$

Example 2: What is the optimal road spacing if the road construction cost is \$10,000 per kilometer, the average forwarder load is 14 m^3, the volume to be harvested is 130 m^3/ha, the operating cost is \$1.20 per minute, and the skidder travels 3 km/h unloaded and 3 km/h loaded? Forwarding is equidistant from each side and a correction factor of 0.2 is used to account for delays.

The time to travel 1 m empty and to travel 1 m loaded is 60/3,000 + 60/3,000 = 0.04 min per round-trip meter.

The ORS is then

$$\text{ORS} = 1.0\sqrt{\frac{40 \times 10000 \times 14}{130 \times 1.2 \times 0.04 \times (1 + 0.2)}} = 865\,\text{m}.$$

The total cost per cubic meter in example 2 (Fig. 3.5) is a minimum at a road spacing of 865 m, but the total cost per cubic meter changes little between 500 and 1,400 m, even though the skidding cost and road costs are quite sensitive to change. This has important environmental and tactical implications. If it is environmentally desirable to minimize road construction, the roads can be spaced toward the upper end of the range (i.e., 1,400 m) without having much effect on total cost. But increasing road spacing has other environmental implications. If fewer roads will be built, the skid trails will be longer and there will be more trips per skid trail, increasing the potential for rutting and compaction. On the other hand, if there is a shortage of skidding equipment, or a risk of a shortage in the operating season for the skidders, then shortening the skidding

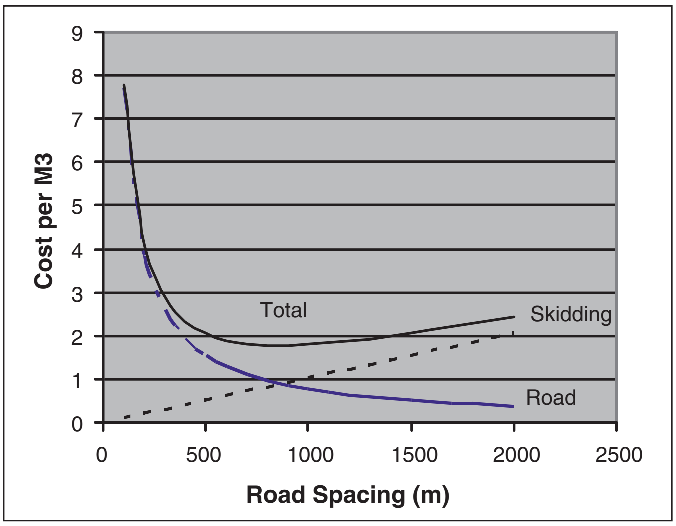


Fig. 3.5. Road cost, skidding cost, and total cost per cubic meter as a function of road spacing for the data in example 2

distance toward the lower end of the range (i.e., 500 m) will greatly increase skidding productivity while not increasing total production cost. And, at the shorter end of the road spacing range, there will be fewer trips per skid trail as the skid trails will be shorter.

3.4.2 Optimum Spur Road Density

Having determined the ORS as in the previous section, the ORD may be found with the formula

$$\text{ORD} = \frac{10000}{\text{ORS}},$$

where ORD is in meters per hectare and ORS is in meters.

The ORD may also be found directly with the formula

$$\text{ORD} = 50\sqrt{\frac{qct \times 1000TV}{RL}},$$

where ORD is in meters per hectare, q is the quantity of wood harvested in cubic meters per hectare, c is the operating cost per minute of the skidder or forwarder, including the operator, t is the time in minutes for the skidder or forwarder to travel 1 m loaded and return empty, T is a correction factor, normally with a value between 1.0 and 1.5, to be used in the same situations as the factor k in the ORS formula in the previous section, V is a correction factor, normally between 1.0 and 2.0, to be used in the same situation as the factor p in the ORS formula in the previous section, R is the cost of constructing and maintaining the spur road in US dollars per kilometer, L is the average skidder or forwarder load in cubic meters.

Example for calculating ORD: What is the optimal road density for example 2 from the previous section if the ORS is 865 m?

ORD = 10000/ORS = 10000/865 = 11.6 m/ha.

If the ORS is not available, then the ORD can be calculated as

$$\text{ORD} = 50\sqrt{\frac{130 \times 1.2 \times 0.04 \times 1000 \times 1.2}{10000 \times 14}} = 11.6 \text{ m/ha}.$$

3.5 Selection of Most Economical Road Standard

The determination of the most economical road standard for a given road location and level of traffic can be based on a comparison of combined annual costs of road construction, road maintenance, and transport. The formula for annual cost is

$$A = R + M + T,$$

where A is total annual cost, R is the annual cost of road construction for the amortization period, M is the annual road maintenance cost, and T is the transport cost for the annual log volume to be hauled out over the road. To compute the correct annual cost of road construction, the appropriate interest rate and capital recovery formula is used. The route and road standard with the lowest annual cost is the most economical. Costs are separated into variable costs and fixed costs. Variable costs include vehicle operating costs and maintenance costs that are proportional to vehicle use. Fixed costs are costs that are not a function of vehicle use, such as construction and reconstruction costs. We discuss the choice of road standards for several special cases.

3.5.1 Temporary Roads

3.5.1.1 Traffic Increasing Linearly Along a Roadway

Given the choice of two road standards, with the lower road standard with variable cost H_L (in dollars per vehicle-kilometer) and fixed cost R_L (in dollars per kilometer), and the higher standard with variable cost H_H and fixed cost R_H, an initial volume of traffic entering the road segment of V_o (i.e., cubic meters, tonnes) and an increase of traffic of ΔV per kilometer of road, the length of road to build at the lower standard is

$$S = \frac{(R_H - R_L) - V_O(H_L - H_H)}{\Delta V(H_L - H_H)}.$$

If the actual length of road, measured from the point where V_o enters the road system is greater than S, then build the initial length S to the lower standard and then switch to the higher standard at length S.

3.5.1.2 Traffic That Is Constant Between Two Points

If traffic is constant between two points, the road standard will not change between the two points. Evaluate the sum of the fixed and variable costs for each standard and choose the road standard that has the smallest total sum of fixed and variable costs.

3.5.2 Permanent Roads

3.5.2.1 Traffic Increasing Linearly Along a Roadway

For the case where traffic is increasing linearly between two points and the road will provide service over a number of years, the formula for temporary roads can be used, but each term is replaced by the discounted sum of the series of costs. For example, replace H_L by sum of the haul cost for the low-cost road in period 1 divided by $(1+i)^{t1}$ plus the haul cost for the low-cost road in period 2 divided by $(1+i)^{t2}$ +.... Similarly replace the fixed costs by their discounted sum. For example replace R_L by the initial cost of the low-standard road plus the discounted sum of the road construction costs during the planning horizon.

3.5.2.2 Traffic That Is Constant Between Two Points

For the case where traffic is constant each time period between two points and the road will provide service over a number of years, the same approach as used for temporary roads can be used, but the fixed and variable cost terms are replaced by their discounted equivalents.

3.5.3 Change of Transport Mode

In some situations the choice of road standard must include considering a change of transport mode, for example, small trucks to large trucks, or agricultural tractor plus trailer to large trucks. Small trucks and agricultural tractors with trailers have the advantage of being able to use narrower, less expensive roads. Large trucks have the ability to carry larger loads at a lower transport cost but require wider roads and, depending upon axle loads and subgrade strength, a deeper aggregate course. For longer-distance transport, larger trucks are more economical, particularly once major roads are reached. To choose the appropriate road standard it may be necessary to consider reloading costs as well as transport, maintenance, and construction costs.

For the case where two modes of transport are considered along a road with a constant tributary volume to be transported (Fig. 3.6), the appropriate length of the lower standard road (S) to be constructed before upgrading to a higher standard can be calculated by

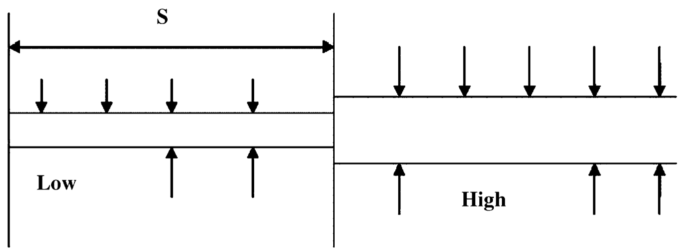


Fig. 3.6. Low-standard road is built for a length of *S* before upgrading to a high-standard road when a constant volume of timber per unit length tributary to the road is being accessed

$$S = \frac{(R_H - R_L) - V_O(H_L - H_H) - F_L \Delta V}{\Delta V(H_L - H_H)},$$

where R_H and R_L are the construction costs (in dollars per kilometer), of the high- and low-standard roads, V_o is the initial traffic volume (in cubic meters), at the beginning of the low-standard road, ΔV is the increase in volume tributary to the road(in cubic meters per kilometer), H_H and H_L are the sums of the transport and maintenance costs for the high- and low-standard roads (in dollars per cubic meter per kilometer), and F_L is the difference in loading costs (in dollars per cubic meter) between loading the small truck plus the transfer cost of loading on to the large truck compared with loading the large truck initially.

Example: Construction of the high-standard road costs $25,000 per kilometer, construction of the low-standard road costs $15,000 per kilometer, transport plus maintenance on the high-standard road costs $0.20 per cubic meter per kilometer, transport plus maintenance on the low-standard road costs $0.50 per cubic meter per kilometer, the tributary volume is 1,500 m^3/km, the initial volume is 0 m^3, the loading cost for a small truck is $1.00 per cubic meter, and the loading (or reloading) cost for a large truck is $1.00 per cubic meter, then

$$S = \frac{(25000 - 15000) - 0\,(0.50 - 0.20) - 1\,(1500)}{(1500)\,(0.50 - 0.20)} = 18.9\,\text{km}.$$

To minimize the total sum of construction, maintenance, and transport, a maximum of 18.9 km of lower-standard road should be constructed and the remainder should be of high standard. If the tributary volume were doubled, the maximum length of low-standard road would be reduced to 7.8 km. If the road will be used more for than 1 year, then appropriate discounting procedures should be used. The total cost curves are usually fairly insensitive near the low point, so other factors may control the final decision.

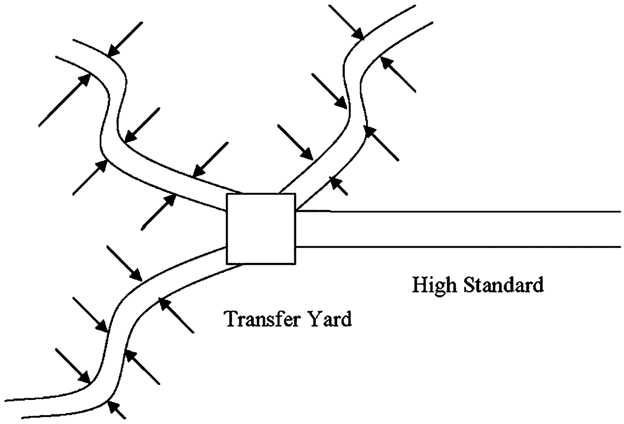


Fig. 3.7. Low-standard roads terminating at a transfer yard where timber is transferred from one mode of transport to another mode for transport along a higher-standard road

In a situation where more than one lower-standard road is being evaluated, a single transfer point could serve several roads (Fig. 3.7). The location of the sort yard is determined by the minimum cost of the road construction, maintenance, transport, and transfer yard construction cost and operation.

3.6 Seasonal Timing of Transport

In many tropical forests, surfacing material is scarce and expensive. Consideration needs to be given to selection of which roads need to be surfaced and which roads will be used during the dry season. Considerations include mill demands, length of season, variability of soils within the harvest area, alternative wood supplies, and reserve areas for prolonged wet weather. To reduce the amount of surfaced roads, storage (surge) yards have been used successfully. A surge yard is a storage area along a surfaced road (all-weather road) where logs can be stored. Trucks haul on unsurfaced roads to the surge yard in dry weather. During heavy rains, logs are taken from surge yards to the mill.

3.7 Variable Tire Inflation

Tropical forest conditions pose special problems for forest transportation owing to several factors. These factors include (1) prolonged wet periods with high-intensity rainfall in many tropical forests, (2) scarcity and expense of good-quality rock in tropical areas, (3) swamps, and (4) harvest removals under the selective management systems designed to sustain natural tropical forests are usually low and may limit investments in roads. The use of radial tires and reduced tire inflation pressure is one method that can be used to increase the season of operation, improve traction, reduce road maintenance, reduce the depth of aggregate surfacing, reduce vehicle operating costs, and improve environmental performance of forest roads. At reduced tire pressure the footprint of the radial tire will increase (Fig. 3.8). The longer footprint reduces shear stresses for powered tires as well as for all tires during braking, improving traction, and reducing the tendency to washboard. The longer footprint also increases the bearing area of the tire so that vertical stresses are reduced (Fig. 3.9).

The objective is to match tire inflation pressures with specific operating conditions defined by speed, terrain, load, and road surface strength. The aggregate design section discusses road structure design requirements as a function of tire inflation pressure. At lower pressures, impact loads to the road surface are reduced and washboarding and rutting are reduced. With less rutting, surface erosion from roads is reduced. Reports of crushed rock savings of 25% have been reported by reducing tire pressure from 690 to 345 kPa. Under severe road roughness conditions, travel speed can actually increase owing to reduced truck vibrations, and reduced tire pressures have been reported to smooth and flatten existing washboards.

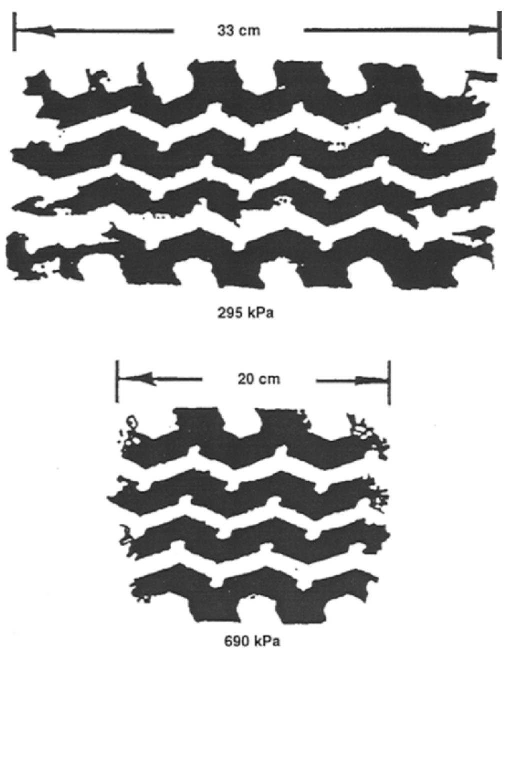


Fig. 3.8. The footprint of a radial tire will change size with different inflation pressures

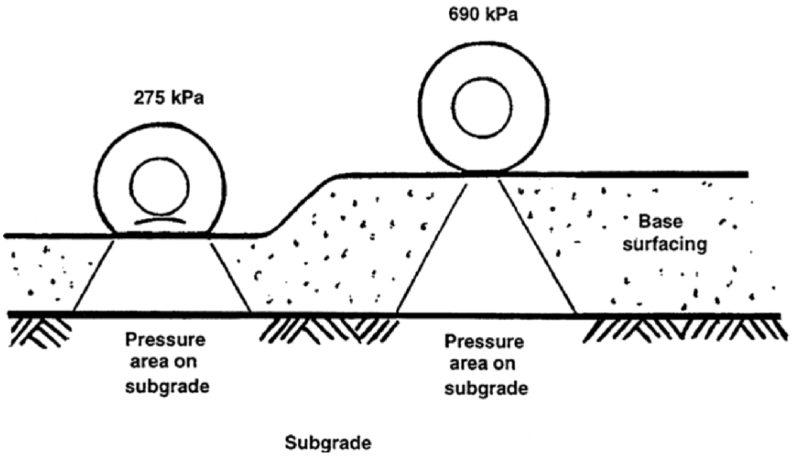


Fig. 3.9. Reduced pressure in a radial tire requires less surfacing to distribute loads to the subgrade

Many radial-type truck tires can be safely operated at pressures 50% less than on-highway tires if speeds are reduced to 60 km/h or less. Tire pressures can be adjusted manually when trucks enter the forest road system or trucks can be equipped with compressors, airlines, and controls that permit air pressure to be adjusted while vehicles are moving. On-board truck inflation systems can increase truck purchase costs by 10–20%. Costs for adjusting tire inflation, whether manually or automatically, must be balanced against savings in road surfacing costs, road maintenance costs, truck maintenance costs, and driver productivity. For situations where trucks only operate within the forest at speeds of 60 km/h or less, the tire pressures can be permanently reduced without purchase of additional inflation systems or controls. However, the benefits of reduced tire inflation require the use of radial tires as bias ply tires deflect differently under reduced pressure. Reduced tire pressure should be considered not only for log-haul trucks, but also for dump trucks.

Route Selection 4

A fundamental principle guides all road planning: the main lines of road alignment are decided in advance by a method of successive approximations on maps, plans, or rough sketches on an increasing scale, which are later checked by reconnaissance carried out on the ground. Many construction, maintenance, and operating problems with forest roads in the tropics could be avoided by systematic planning.

There are five phases in the systematic and increasingly detailed study of the terrain:

1. Examination of general information from maps, aerial reconnaissance, and aerial photographs to select a proposed route corridor
2. Drawing up of preliminary alignments using the information collected
3. Detailed ground reconnaissance to locate preliminary alignment possibilities
4. Establishing the final alignment by correcting the preliminary one using information gained by the ground reconnaissance
5. Marking out and staking the selected alignment with regard to the actual ground conditions to guide construction

4.1 Examination of Documents

The first phase consists in making a rough sketch of the general direction of the alignment. All available cartographic documents on the region must be used for this purpose.

4.1.1 General Maps and Mapping Tools

Any existing maps of the area should be acquired. In spite of any imperfections, these maps can be a considerable help in the initial planning stages.

Some information will be found in them which will be quite easy to check, such as existing transportation networks, ridge lines, principal rivers, and hydrologic features, including waterfalls or rapids on important rivers. Although some agencies may include accuracy assessments of the maps they produce, the actual number of control points checked is likely to be small and reconnaissance will usually be necessary to confirm map feature locations. Mapping documents vary from one country to another, but generally include:

- 1:200,000 quadrangle maps with or without contour lines
- 1:200,000 thematic maps: hydrology, geology, soils, physiographic features, vegetation, political boundaries
- 1:50,000 quadrangle maps with contour lines (20-m intervals), special area maps of reserves or parks
- 1:50,000 Landsat or SPOT satellite imagery
- 1:200,000 radar imagery
- Historic and recent aerial photo coverage at a scale of 1:20,000 to 1:50,000

Increasingly, hard-copy maps are often converted into a digital format through scanning processes and can be accessed and analyzed through a geographic information system (GIS). Maps produced from remote-sensing techniques are typically georeferenced. Hand-held and survey-grade GPS receivers with digital data loggers are now widely used to georeference points during aerial and ground reconnaissance. Outside of tropical forests, digital terrain models (three-dimensional digital images of the terrain) are becoming available. Digital terrain models will undoubtedly become more available in tropical forests as lidar (light detection and ranging) technology continues to improve and drives costs down.

4.1.2 Aerial Reconnaissance

Aerial reconnaissance is often valuable when possible. The advantage is that the whole forest zone can be seen. Helicopters are best in rough topography because speed and elevations can be varied. A detailed plan of the different flights should be made beforehand. These flights should be plotted on a small-scale map or rough sketch, even if they are not very accurate. The plan can be for flights of two kinds: either for a grid with a spacing of 5–10 km, or for flights between two points consisting of prominent landmarks which are easy to identify, such as the corner of a forest, a waterfall or rapid, a river junction, crossroads, isolated homesteads, or a village. If even small-scale aerial photographs of 1:50,000 are available, they should be used to plan reconnaissance trips. They are complete pictures of the terrain on which all the important topographical details can be marked. Each photograph can be examined and angles for direction can be measured on it.

With vertical photographs of fairly even ground, it is possible to obtain a good assembly of several adjacent strips. These photographs can be joined together to create a photo mosaic and provisional map. This mosaic can be photographed, but it must not be forgotten that the errors in putting individual photographs together can be considerable.

Stereoscopic examination of a pair of photographs is essential to understanding the terrain and the forest. The stereo pair represents the common ground area of two aerial photographs which have been taken from different viewpoints, either along a flight line, or from adjacent flight lines. Stereoscopic examination of terrain provides a three-dimensional image that reveals the topographic nature of a landscape. It gives the impression of examining a small rough model of the ground. This examination, though fairly easy, requires some preliminary training. Training consists of learning to use a stereoscope correctly and to interpret the stereographic picture obtained.

4.1.3 Special Inventory Maps

A sketch map of the harvest area is necessary. Often large-scale maps are not available for native forest. Information for a sketch map can be recorded at the time of the inventory when inventory lines were cut across the forest. The whole section of forest to be inventoried can be divided into rectangular compartments with the principal lines running north and south and the secondary ones from east to west. The compartments have a rectangular shape and an area which varies according to the distances between the lines: it may be 1,000 m×250 m (i.e., 25 ha) or 500 m×200 m (i.e., 10 ha). This system of lines makes up a topographical grid on which you can reference and locate topographical features and the position of harvestable trees. The usual scale is 1:5000 to 1:20,000.

A preliminary examination of the inventory map makes it possible to pick out the best zones in the forest in which a road of predetermined specifications can later be constructed. Marked on this sketch may be:

- The areas to be harvested that will require roads
- Positive control points, such as a narrow part of a stream for a crossing or a saddle to cross a ridge, and potential landings
- Negative control points (places to avoid): marshy land, or land under water in the rainy season which would need an expensive embankment and which might often be unstable
- Areas where food crops have been grown in the past and without commercial trees, but where the absence of stumps would make crossing easier

Usually the inventory map is only concerned with the area covered by the property lines, license, or concession within the property boundary or affected by easements or regulations. There may be little information about the areas outside the boundaries of the property over which the main harvesting road has to cross until it meets either the public highway or a waterway. Aerial observation or aerial photographs can be useful in providing this information.

4.2 Preliminary Alignment

4.2.1 Route Location

Terrain familiarity is an essential part of route location. The first stage is to become thoroughly familiar with the terrain. The surface relief of the ground must be studied and understood. It is convenient to mark the position of significant landscape features, i.e., the lines of ridges and of valleys. The watersheds or ridge lines are the upper intersection of two adjacent slopes. Valley bottoms or lines where water running off the surface join, and which are often followed by streams or watercourses, are the lower intersection of two adjacent slopes. Lines of the same nature divide and change direction rather like a roof. The convergence of water toward the lowest points causes the valleys to flow into each other and thus form a network. Between two valleys there is a ridge line; these lines form a system enclosing the network of valleys.

If the details of the valley lines and the ridge lines are marked in systematically, a picture of the ground emerges (Fig. 4.1). From this picture, the essential features of the land can be delineated to increase terrain familiarity.

It may not be known at the time of the inventory how much delay there will be in planning the haul roads, but it often happens that, as work cannot be carried out under the best conditions, the inventory operations immediately precede the planning of the alignment. In this case, these two operations can be given to the same person. When marking in topographical data, the head of the survey party gives special attention to any information which could be useful for planning the road. He notes rocky places, swamps, and very steep places unsuitable for an inexpensive alignment. He will be especially careful to mark the easy places, such as the lower saddles on ridges, rock outcrops, and riverbanks suitable for bridge sites. This information will facilitate planning by indicating the parts of a preliminary alignment needing further study and will reduce the time taken subsequently in future detailed reconnaissance.

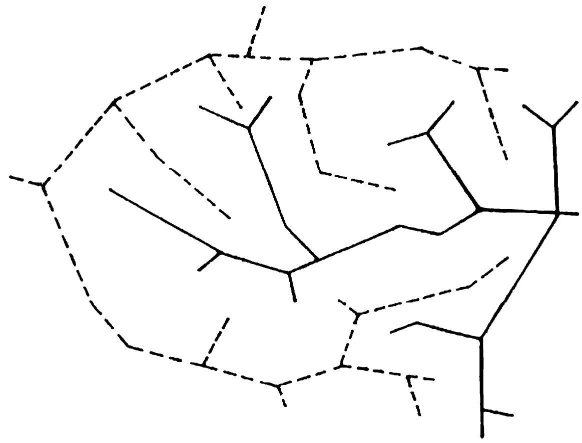


Fig. 4.1. Lines showing features of the terrain. *Solid lines* are ridge lines, *dashed lines* are valley lines

4.2.2
Preliminary Logging Plan

In the second stage, a preliminary logging plan is prepared for the area. In flat terrain, optimal road spacing provides guidelines for design of secondary roads. In mountainous terrain, an iterative process identifying landings which are then connected by spur or secondary roads is usually used. The secondary roads are then connected by a mainline road. The routes of the secondary roads are dictated by the logging plan. It cannot be overemphasized that the roads and the yarding are interdependent and must be integrated. The logging plan must be feasible for economical road construction and log-truck operation. The roads must serve the landings and economical yarding distances. Compromise is often necessary to arrive at the minimum total combined cost of yarding, trucking, and roads with regard to protection and silvicultural considerations. The efficient plan is that which allows for the lowest overall extraction costs.

If a main forest road is to be built primarily for hauling logs, the first consideration in selecting the route of the main road is to serve the secondary branch and spur roads. The main route should reach suitable junction points where there is room for the branch roads to turn off from the main road. Such junction points include flats, benches, and saddles where there is space for the double width required for grade separation without excessive excavation. If the branch road gradient is steeper than that of the main road, adequate length is required for an easy vertical curve to allow for a safe transition between the two road segments. The junction should be staked and constructed to the point where the branch road subgrade clears the main road at the time the main road is built. The route which will give the minimum combined hauling distance over the secondary road and the main road from the center of the timber volume will generally be the most economical route.

The topography often will determine the selection of the route for the main road. Since the main road usually follows up the main drainage paralleling a sizeable river or stream, the route possibilities which may be encountered and relative advantages and disadvantages are as follows:

- Wide valley bottom. This condition affords the advantages of a downhill gradient, good alignment, and relatively low earthwork. Good landings are available for settings to be logged along the route. Disadvantages are flood hazard and the cost of bridges to maintain good alignment and to avoid rock cuts if the stream meanders. Protection of recreational resources, such as camping sites and fishing streams, requires special consideration. Stream channel changes are objectionable to fisheries agencies.
- Narrow valley bottom. This condition offers a downhill gradient and advantages over a hillside route of less excavation and better alignment, since the mouths of a side stream usually can be crossed on tangents with fills. Fewer but larger culverts may be needed. Disadvantages are flood hazards, bridges when it is necessary to cross the stream to avoid rock cuts or sharp curves, and the difficulty of avoiding interference with the stream channel.
- Hillside route. Locating a main road on hillsides well away from the creek will eliminate flood hazards and stream damage to the road. Bridges are usually eliminated since side streams can be crossed with fills and culverts. Steeper and more variable gradients are often required. Alignment on the hillside route is poorer since the route following the grade contours around ridges and draws. This also makes the road longer. Excavation is larger as the sidehill is steeper than the valley bottom. Takeoffs for branch or spur roads are more difficult. Higher cut banks expose more soil to erosion.
- Ridge crest. A ridge crest route offers the advantages of good alignment, light excavation, good drainage, and few culverts. If the ridge profile is uneven, more adverse pitches are encountered, although the possibility of making momentum grades is good. The principal disadvantage is that a main road above the bulk of the timber necessitates adverse grade spurs. A hillside segment of road is required to reach the ridge, and the total length of haul may be longer.

4.2.3
Positive and Negative Control Points

In the third stage a preliminary alignment is made, step by step. In practice, it is a matter of fixing points and in planning a preliminary section between two successive points. The positive control points are advantageous parts of the terrain to locate the road, such as:

- Stream crossings suitable for bridges and culverts
- Gentle slopes in steep terrain
- Saddles or passes on ridges
- Benches in slopes suitable for curves, switchbacks, and road junctions
- Suitable sites for landings
- Suitable deposits of road-building materials
- Suitable log landings

Negative control points are the places to be avoided, such as:

- Terrain with low bearing capacity
- Steep and/or unstable slopes; landslide-prone areas
- Cliffs (with heavy blasting requirements)
- Swamps
- Flood plains

Determine the terminal control points that define (1) where to begin from an existing road or location survey and (2) where to end the present project. If the road may be extended in the future, the upper terminal should be at a point suitable for continuing the road. This may necessitate projecting the road beyond the present project, to ensure that it does not "dead-end." The lower terminal is usually the more flexible, and is subject to change when intermediate control points are found, and the grade contour is projected.

Look for major control points between the terminals. These are usually saddles or passes, benches for spur road junctions, and suitable crossings of large streams, where bridges or large plate culverts are required. Construction of switchbacks on steep ground can be prohibitively expensive as well as involve large earthwork and potential environmental impacts. In some situations, locating suitable switchback areas can be the most important control point on the road. If a logging plan is involved, landings along the road route may be control points. If projecting a main road from which stub spurs to landings will take off, suitable junction points for the spurs are controls. Work from the top down, as the valleys and control points tend to constrict at the higher elevations and to widen out at the lower elevations.

Look for minor control points along the probable route between major control points. These include points at which obstacles can be passed, such as above or below cliffs, rock outcrop or slides, and either side of the swamps. Look for evidence of soft or poorly drained ground, and the best places to cross or avoid them, and for the best crossings of side streams.

Where the route will follow a water grade along a main stream, study both sides of the valley to determine whether to project alternate routes paralleling the stream on each side of the valley, or, in the case of a meandering stream or a valley with cliffs or steep sideslopes alternating from one side to the other, to project a route which would cross the creek at intervals. It may be necessary to project alternate routes and compare costs to determine the preferable route.

Other factors being equal, a route which gets the most sun is preferred. A road along the slope which gets the most sun will dry out faster after rain. Consequently, it will be subject to less damage from traffic and will result in lower maintenance cost. After selecting the control points, the next step is to connect the positive control points by feasible road corridors.

4.2.4 Connecting Control Points on Flat Ground

On flat ground the major difficulties come from obstacles, not considerations of gradient and earthwork. It is better to shift the alignment immediately outside the area of obstacles to avoid a succession of deviations. Usually an arc M–P–N (Fig. 4.2) is not much longer than the direct route represented by the chord M–T–N. It is often better to avoid a group of obstacles at one stroke

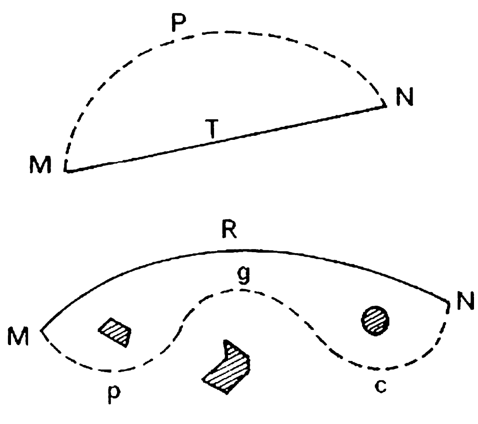


Fig. 4.2. Avoiding obstacles on flat terrain. A curve of large radius is preferable to smaller-radius curves

(e.g., rocks or stumps) rather than to go around each obstacle. Thus, the line M–R–N is preferable to the line M–p–g–c–N.

4.2.5 Connecting Control Points on Uneven Ground

On uneven ground, where there are marked ridges or valleys, the choice of road line must be tentative. If the control points are all obvious, then the solution follows naturally, but this is rare. In practice, the determination of the alignment is always a compromise between the length to be constructed, the maximum gradient, and a limited amount of earthwork. In uneven or mountainous terrain, a topographic map is essential. The biggest challenge is to avoid exceeding the maximum gradient allowed for the road.

4.2.5.1 Technique for Plotting Grade Control

Preliminary road corridors can be checked by the method of divider setting on a topographic map, whereby a gradeline for the road with the required gradient is plotted on the contour map (Fig. 4.3).

A cross section between two contour lines is illustrated below. The divider setting in meters is d_s, the gradient in percent is g, and the vertical interval of the contours in meters is v. The divider setting in conformance with the proportions is

$$d_s = \frac{100 \times v}{g}.$$

The divider setting has to be adjusted to the scale of the map. It can be done according to the following example where $g = 10\%$, $v = 20$ m, and the map scale, M, is 1:10,000.

By putting these values in the formula, we can derive the divider setting:

$$d_s = \frac{100 \times v}{g \times M} = \frac{100 \times 20}{10 \times 10000} = 0.02.$$

Thus, the divider setting in this case is 0.02 m=20 mm.

The drawing of a gradeline on a contour map with a divider is illustrated in Fig. 4.3. If the trial gradeline does not hit the terminal contour, the divider end is set to mark off a second trial line. A gradeline with a constant grade can be easily and quickly drawn by means of this simple method.

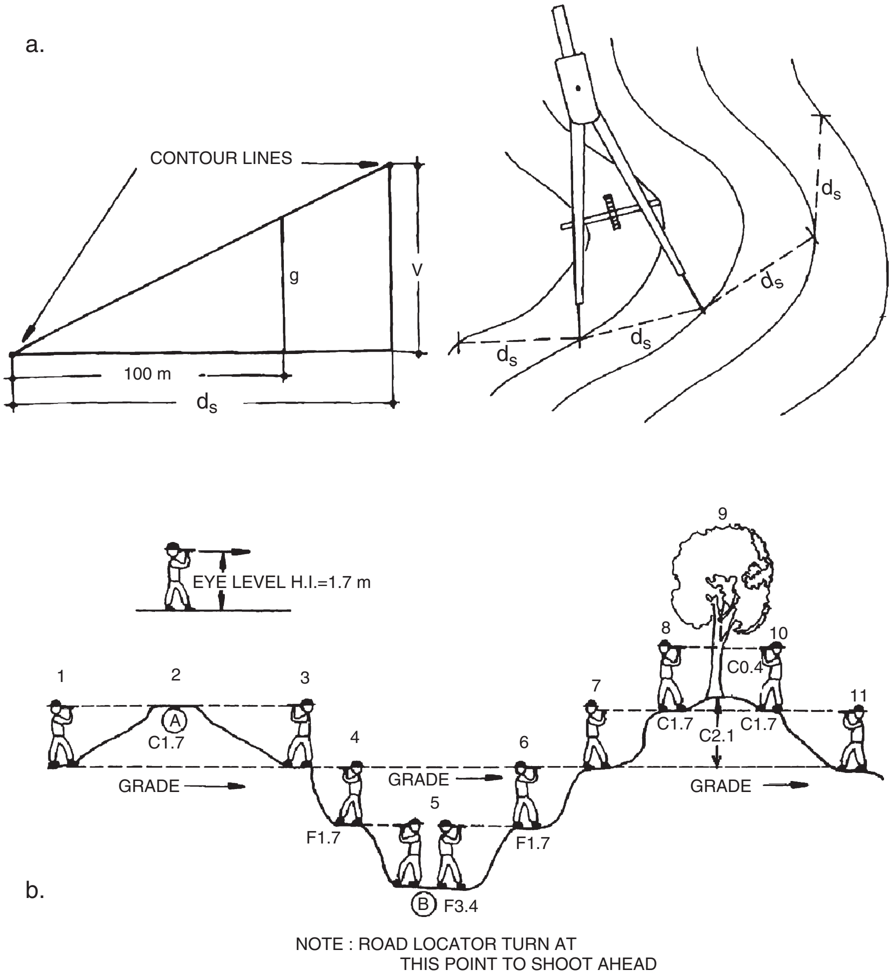


Fig. 4.3. Making a grade projection. **a** Determining the divider setting (*left*) and projecting the route at a constant grade (*right*). **b** Carrying the gradeline forward over uneven terrain through differential leveling

4.2.5.2
Practical Considerations in Grade Projection

Gradelines for forest roads are set using an Abney level or clinometer. Abney levels have the advantage that the grade can be locked on the instrument, which allows a more precise measurement of gradient than does the clinometer (see Appendix A.1). Both instruments need to be periodically checked to ensure that they are properly calibrated. This is necessary if running against maximum permissible grades.

A common problem encountered by route locators during preliminary route location in mountainous terrain is maintaining adequate vertical control. The three major factors contributing to improper running of gradelines in the field are:

1. Instrument out of adjustment
2. Misreading of the instrument
3. Neglecting to make grade adjustments for curve length

Proper adjustment of the instrument, particularly the Abney level, is easily done in the field and requires about 10 min. The "two-peg" method is usually used and the procedure is documented in many elementary surveying texts. Instrument adjustments should be checked at least once per day. Misreading of the instrument can be avoided or at least detected by the use of double Abney level readings. This procedure involves the use of Abney levels by both the headman and the chainman, who make independent observations. Improper adjustments of instruments can also be detected by the use of double Abney level readings. Neglecting to make grade adjustments for curve length, however, is a persistent problem, troubling even experienced route locators.

4.2.5.3 Grade Adjustments for Outside Curves

When running gradelines around outside curves such as around the nose of a sharp ridge, the road locator often runs the gradelines along the tangents of the curve neglecting to take into account that the actual curve length will be shorter than the tangent lengths and the resulting grade will be higher than intended. The seriousness of the problem is proportional to the radius of curve and the deflection angle. Two options are available. One option is lower the grade 1–2% for the entire gradeline in broken terrain to allow for horizontal curves and any grade adjustments necessitated by adverse grades in the curves; another option is to adjust the gradeline at each point of curvature. A simple relationship exists between the tangent lengths and the curve length which allows calculation of a multiplication factor to correct for this change of length.

Instructions for use:

1. Determine the deflection angle from compass readings.
2. Select the appropriate multiplication factor from Table 4.1.
3. Multiply the grade by the multiplication factor.
4. Reset the Abney level and run the grade along the estimated tangent lengths.

Table 4.1. Adjustment factors for outside curves

Deflection angle	Multiplication factor
10	1.00
30	0.98
50	0.94
70	0.87
90	0.79
100	0.73
110	0.67
120	0.60
130	0.53
140	0.44
150	0.35
160	0.25
170	0.13

Example: What grade should be run along the tangents of a curve to maintain a 6.0% grade along the constructed curve? The deflection angle of the curve is 110°. The multiplication factor for a deflection angle of 110° is 0.67. Multiplying 0.67 by 6.0% gives 4.0%. A 4.0% grade along the curve tangents will result in a 6.0% grade along the constructed curve. If the 6.0% grade had been run along the curve tangents, as is often mistakenly done, the resulting grade along the curve would have been 9.0%.

4.2.5.4
Grade Adjustments for Inside Curves

When running gradelines around inside curves, such as across a gully, situations arise when neither the point of intersection of the curve tangents nor the actual curve length is accessible. The vertical alignment for this situation can be controlled by running an adjusted grade across the long chord of the curve.

Instructions for use:

1. Determine the deflection angles from compass readings.
2. Select the appropriate multiplication factor from Table 4.2.
3. Multiply the grade by the multiplication factor.
4. Reset the Abney level and run the grade across the estimated long chord.

Example: What grade should be run across the long chord of a curve to maintain an 8.0% grade along the constructed curve? The deflection angle for the curve is 90°. The multiplication factor for a deflection angle of 90° is 1.11.

Table 4.2. Adjustment factors for inside curves

Deflection angle	Multiplication factor
10	1.00
30	1.01
50	1.03
70	1.06
90	1.11
100	1.14
110	1.17
120	1.21
130	1.25
140	1.30
150	1.35
160	1.42
170	1.49

Multiplying 1.11 by 8.0% gives 8.9%. An 8.9% grade along the long chord will result in an 8.0% grade along the constructed curve.

Other points to remember are the following. Flatten the grade at intervals on a long sustained favorable grade to allow release and cooling of the service brakes. Although this is not as important with trucks with modern engine brakes or retarders, you may need to take local equipment into account. Avoid frequent changes of grade on adverse grades which necessitate changing gears with consequent shock to the truck power train. When changing to a steeper grade, reduce the lesser grade 1 or 2% for 30 or 40 m to facilitate gear shifting.

4.3 Special Reconnaissance on the Ground

Each uncertain area and each control point should be the subject of a detailed reconnaissance. The best time to do this is during the rainy season. It is then that characteristics of the soil, the limits of marshy places, and the width and level of watercourses can best be learned.

The following equipment is necessary: a map of the district with the provisional alignments, a compass, an Abney level or clinometer, 20-m measuring tape, a barometer, and flagging tapes. The few stakes which will be needed can be easily cut from material in the forest.

4.3.1 Essential Points to Remember

When considering a crossing over a watercourse, a check must be made that there is not another place nearby which had been overlooked when the map was studied and which would be more suitable. To determine the highest flood level of the water, look for masses of debris brought down by the floods and also traces of slime left on the stems of plants on the slopes. If it is likely that the route will cross the line of a ridge or a watershed between two valleys, the line of the main ridge and the lines of the secondary ridges or spurs should be walked over systematically. It is often essential to work up the valleys with the reconnaissance equipment to discover the highest part suitable for a crossing. The relative heights of high and low points are read on the barometer.

The nature of the terrain should be looked at from the objective of carrying out earthwork. Among things to look for are:

- Limits of seasonal swamps on which embankments may sink
- Loose ground which can cause a fall of rock or local landslides when opened up
- Rocky areas which would need explosives
- Springs which could indicate a clayey outcrop to avoid
- Sand, fluvial deposits, or lateritic outcrops which might be potential construction materials.

Cross over the watercourse at right angles to the stream channel to minimize culvert or bridge span and to have minimum impact on the riparian zone.

4.3.2 Alignment on a Given Gradient

Do not try to plan a profile with a uniform gradient without the aid of a topographical instrument. Anyone who has tried to walk over a slope following a horizontal line or a line with a low gradient of from 3 to 5% has soon realized that there is always a tendency to climb toward the top of the slope describing a line where the gradient easily rises to 20% and more.

This gradient nearly always exceeds the maximum acceptable on a forest road. Instead, use a clinometer to control grade. For direction, a compass is used, and a 20-m tape is used for measuring distance. In native forest, the survey party often consists of an assistant forester, a foreman, and four laborers, two carrying the chain and two to clear a path. It is often convenient to start work from the highest point on the road to be made, whether it is on a saddle or some point on a ridge. As mentioned before, the lowest point is often not absolutely fixed and in a forest it is easier to see more of the terrain looking toward the bottom of a slope.

The head of the party, carrying the Abney level or clinometer, begins by measuring the height of his eye above the ground when he is using the instrument to measure a gradient. He then marks the same height on a staff or he may note on the man carrying the staff the point of his hat or of his face which corresponds to the same height of the clinometer. This avoids using a staff which is not always easy to hold upright. The line of sight between the clinometer at eye height and the marked staff is then parallel to the line which joins the two stations.

As soon as the limits of this line on a given gradient are laid out, it is a good idea to mark each station by a stake or a small pole with flagging so that the line will not be lost.

4.4 Selection of the Final Alignment

The comprehensive map completed from sketches and information of all kinds gathered from the ground is now used as a basis for deciding on the final location. When making the choice of the final alignment, the party chief should bear in mind the following general observations which are dictated by experience:

- On fairly even ground it is always better to build the road on a ridge or near it. Earthwork is minimized, drainage is made easier, the need for culverts is reduced, and embankments are avoided.
- On uneven ground, the main road will pass from one valley to another. Each secondary road will serve a compartment corresponding to the whole of a secondary valley. This avoids crossing the intermediate ridges, which is always expensive.
- On a hillside, especially in regions of steep topography, the flattest slopes should be identified. Where plateaus exist, roads should be built along the edge of the plateau, particularly if there is to be uphill extraction to the roadside. Near the base of steep slopes, especially in valleys with a flat bottom, the road can be made immediately below or close to the foot of the slope.
- In a valley alignment, on the other hand, it is better to keep the road as low as possible, but above the flood plain. In a wide flat valley, instead of crossing numerous watercourses near their confluences and where they are widest, it is better to economize with culverts or small bridges. If, however, the road has to go through a narrow valley with steep sides, fewer deep depressions should be crossed and the cut will be less deep.
- On the side of a hill, when a constant gradient has to be kept, a balanced section where the material removed from the cut just equals that needed for the fill minimizes the earthwork. However, if the hill is steep, a full bench construction may be necessary and the excess excavated material should be placed where it will not create landslides.

- A deep cut has several disadvantages. First, it is expensive to construct. Second, it may require special construction to divert water from the top of the cut and face of the fill. Third, the bottom of the cut is shut in, less sun reaches it, and it is slower to dry. Fourth, it may be expensive to maintain. Fifth, it can create landslides which endanger the road and the surrounding area. The solution may be to change the alignment and reduce the depth of the cut.
- To facilitate the making of an embankment, especially for the approach to a bridge, it is most economical to choose a place where extra earth is easily available on the approach to the embankment.
- All other things being equal, it is better to plan a low embankment on marshy ground and as shallow a cutting as possible on rocky ground.

4.5 Staking out the Alignment on the Ground

Staking out consists of marking on the ground the exact position of the road to be built. Several methods are used. If terrain is irregular or difficult the centerline and limits of excavation should be marked on the ground. Sometimes only the gradeline is marked if the terrain is not irregular or difficult.

The gradeline is the point on the original ground line where the excavated material just equals the fill material. This gradeline will be used as a guide by the construction equipment operator. Instead of following carefully surveyed curves, the operator constructs "free bends" which are close to the shape of the terrain. Staking only the gradeline may be satisfactory when curves are not tight and where the gradeline is not crossing valleys or ridges. In these more difficult cases, additional design is appropriate to control construction costs and reduce environmental impacts.

4.5.1 In-Field Design Methods

Designing forest roads in steeper and more difficult areas can be completed using traditional civil engineering approaches that begin with the establishment of a P-line (preliminary line) survey with plan, profile, and cross-sectional data. The road can then be designed using well-established manual techniques or using a variety of computerized road design programs. Once the design has been completed, it can be applied to the site through either the surveying of the L-line (final location line) or offsets from the original P-line survey. However, for many forest roads, this level of design is not warranted as the design can be completed in the field using a series of equations that can be programmed into a handheld computer or by using a set of tables. These field methods can be used to set the slope stakes to guide excavation in the field, thus reducing the likelihood of either excavating slopes too steep that will result in slope failures that can cause additional maintenance costs or excavating flatter slopes that will result in unnecessary excavation.

The process begins by locating the gradeline and establishing the centerline for both the horizontal and the vertical alignment (Fig. 4.4). Once the segment has been successfully located, the design team can locate the top of the excavation and the bottom of the fill section. The design team will be able to better visualize the road's location and make adjustment to the design as well as to guide construction activities to ensure that the design has been properly implemented. The method used to locate these segments can vary depending on the design being used.

4.5.1.1 Nonbalanced Sidehill Section

Generalized slope staking equations based on the allowable steepness of the cut slope and road width will allow the designer to locate the top of the cut and the bottom of the fill (Fig. 4.5).

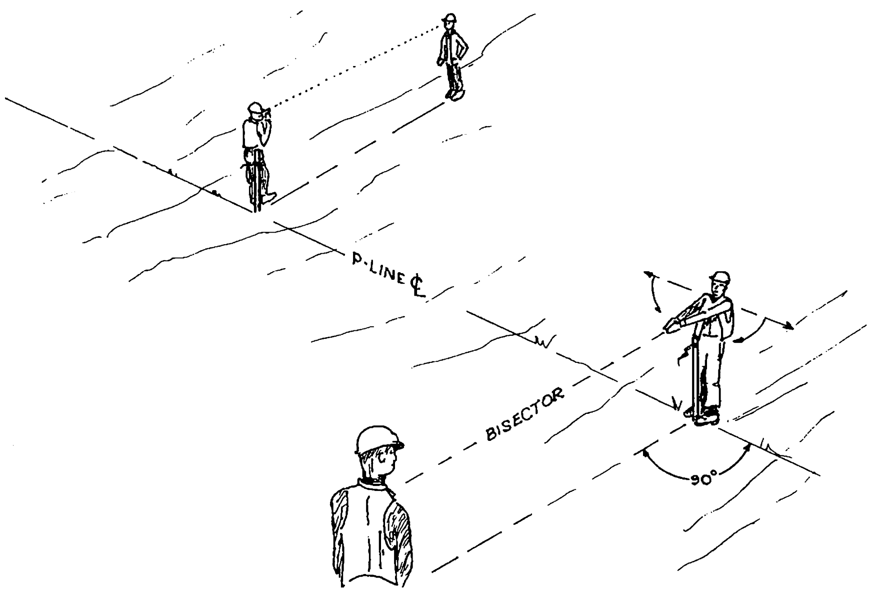
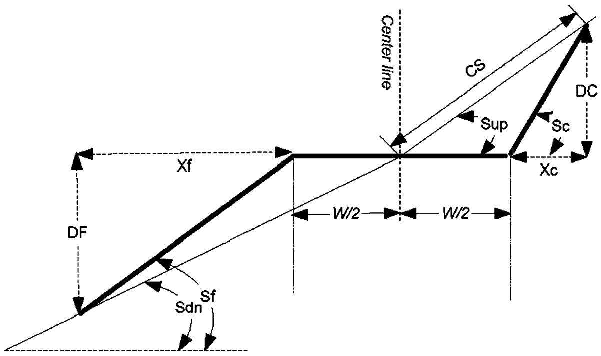


Fig. 4.4. Field crew taking cross-section data along the P-line (preliminary line). (Adapted from Waldbridge 1991)



W = subgrade road width
DF = depth of fill
DC = depth of cut
CS = slope distance from centerline of road to top of cut
W = subgrade width, m
Sc = cut slope ratio, tangent of cut slope angle, i.e. Sc =1.333 for a rise of 4 for a run of 3
Sf = fill slope ratio, tangent of fill slope angle, i.e. Sf =.667 for a rise of 1 for a run of 1.5
Sup = ground slope ratio, tangent of ground slope angle in direction above gradeline, i.e. Sup =.35 for 35%
Sdn = ground slope ratio, tangent of ground slope angle in direction below gradeline, i.e. Sdn =.45 for 45%

Fig. 4.5. An example of a nonbalanced road cross section on a sidehill

When the cut slope angle or fill slope angle is known in decimal percent (i.e., a 1:1 cut has a value of 1.0 and a 40% sideslope has a value of 0.4) the top of the cut can be computed using simple geometry. For the simplest example when the roadway elevation intersects the ground point the slope distance can be computed with the following equation

$$\mathrm{SD} = \frac{(W/2 \times S_c)/(S_c - S_{up})}{\cos(\arctan S_{up})},$$

where SD is the slope distance, W is the subgrade road width, S_c is the cut slope ratio, and S_{up} is the sideslope.

Example: For excavated area with a cut ratio of 1:1 on a 40% sideslope with a subgrade road width of 7.0 m, find the slope distance from the road centerline to the top of the cut:

$$\mathrm{SD} = \frac{(7/2 \times 1.00)/(1.00 - 0.40)}{\cos(\arctan 0.40)} = 6.28 \text{ m}.$$

A common design standard is to find the point where the volume in the fill section equals the volume removed in the cut section. This design minimizes the amount of earth movement. The process involves shifting the centerline location left or right until the volume removed from the cut balances the amount of fill needed to provide a subgrade of a desired width. This is referred to as a balanced section. It assumes that the fill section will be sufficiently compacted to provide the needed bearing strength to support the wheel load of the design vehicle. For forest roads on steeper slopes, this generally requires an excavator (Sect. 6.2). In order to provide this bearing strength, the density of the compacted material in the fill will often be higher than in its original unexcavated state, so 1 m^3 from the cut will occupy less than 1 m^3 in the compacted fill section. This apparent "loss" of material due to the difference in density is referred to as "shrinkage" and is taken into account during the design. It requires that the shrink factor, the ratio of the volume of the material in its compacted state (in the fill) to the volume of the material in its natural state (before excavation in the cut), be estimated. For example, a shrink factor of 0.8 means that 1.0 m^3 of material in the cut will provide 0.8 m^3 of compacted fill, or 1.25 m^3 of material in the cut will be required for each 1.0 m^3 in the compacted fill. See Sect. 5.4 for additional discussion of the selection of a shrink factor.

The distance which the centerline of the road is shifted (Fig. 4.6) to create a balanced section can be computed using the following equations that can be written into a programmable calculator and implemented in the field by the engineer or surveyor.

$$B = (W/2)(k - 1)/(k + 1),$$

where

$$k = \{(1/S_{up} - 1/S_c)/[SF \times (1/S_{dn} - 1/S_f)]\}^{0.5},$$

where W is the subgrade road width (in meters) S_c is the cut slope ratio—the tangent of the cut slope angle, for example, $S_c = 1.333$ for a rise of 4 for a run of 3, S_f is the fill slope ratio—the tangent of the fill slope angle, for example,

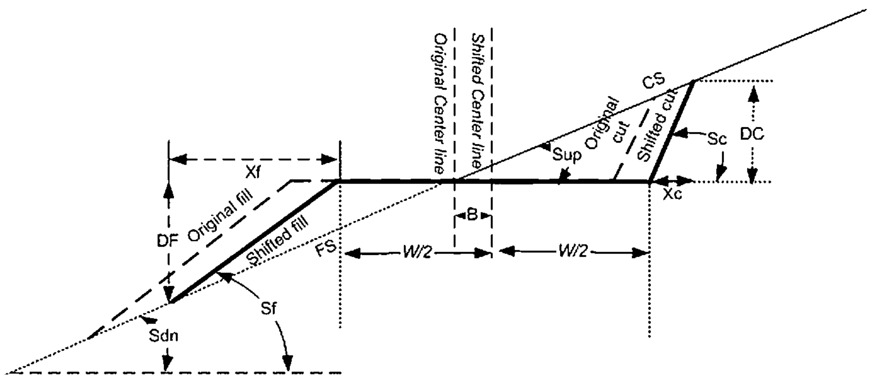


Fig. 4.6. An example of a balanced road cross section on a sidehill

S_f =0.667 for a rise of 1 for a run of 1.5, S_{up} is the tangent of the ground slope angle in a direction above the gradeline, for example, S_{up}=0.35 for 35%, S_{dn} is the tangent of the ground slope angle in a direction below the gradeline, for example, S_{dn}=0.45 for 45%, and SF is a shrink factor for example, SF=0.8 for 0.8-m^3 compacted fill per cubic meter in bank cubic meters of cut.

The depth to the toe of the fill, D_f, is

$$D_f = \frac{W/2 - B}{(1/S_{dn} - 1/S_f)}.$$

The height to the top of the cut, *D*c, is

$$D_c = \frac{W/2 + B}{(1/S_{up} - 1/S_c)}.$$

The slope distance to the toe of the fill is FS=D_f/sin(arctanS_{dn}) and the slope distance to the top of the cut is CS=D_c/sin(arctanS_{up}).

Use care with these formulas: In some countries the cut and fill slope convention is run/rise rather than rise/run.

Example: For a 7.0-m subgrade width with S_c=1.333 and S_f=0.667 with a shrink factor of 0.8 on a 40% sideslope above the road and a 50% sideslope below the road, the centerline shift for

$$k = \{(1/.40 - 1/1.333)/[0.8 \times (1/.50 - 1/.667)]\}^{0.5} = 2.091$$

will be

$$B = (7.0/2)(2.091-1)/(2.091+1) = 1.236 \text{ m},$$

and the information to place the construction stakes will be

$$D_f = \frac{7.0/2 - 1.236}{(1/.50 - 1/.667)} = 4.53 \text{ m},$$

$$D_c = \frac{7.0/2 + 1.236}{(1/.40 - 1/1.333)} = 2.71 \text{ m},$$

$$\text{FS} = 4.53/\sin(\arctan 0.50) = 10.13 \text{ m},$$

and

$$\text{CS} = 2.71/\sin(\arctan 0.40) = 7.29 \text{ m}.$$

If it is anticipated the compaction will not provide a fill of adequate strength at the outer edge, a wider subgrade can be designed so that the loaded vehicle remains primarily but not completely on the excavated portion of the subgrade. This results in a wider road, but there is less chance of a subgrade failure under a wheel on the outer fill section.

The setting of slope stakes during road design will result in the placement of the stakes that will not only allow the road designer to see the design and make needed changes in the field, but it will also be a benefit during construction to reduce the likelihood of road design being misinterpreted during construction. It will also reduce environmental impacts and construction costs.

4.5.1.2 Limits for Constructed Fills on Sideslopes

Although balanced sections reduce cut slope height and excavation and can technically be constructed across very steep sideslopes using excavators, slope failures can result from overloading the slopes below the road. Local experience in the area should be a guide. Geotechnical advice should be consulted before placing fills on sideslopes greater than 60%. Full bench construction with transport of the excavated material to a safe embankment site will reduce the potential for landslides and maintain road integrity if very steep slopes must be crossed.

Simple methods for identifying the centerline and limits of excavation are described in the following sections.

4.5.2 Laying out a Straight Alignment

Straight alignments can be laid out by eye with the help of posts put in three at a time. Care must be taken to see that the general alignment keeps as closely as possible to the gradient allowed. Experience has shown that the actual layout always has a tendency to be slightly shorter than that staked out; therefore, it is often good to remain at least 1% less than the ruling gradient. In order to maintain the gradient in uneven terrain, the gradeline can be carried forward in a series of incremental measurements at eye height as shown in Fig. 4.3b.

4.5.3 Laying out a Curve

Several methods exist for laying out a curve exactly, but they have the disadvantages of requiring the use of special tables and of having to either stand at the point where the tangents intersect or to walk over the chord AB joining the two transition points A and B. These different points are not always easily accessible before earthwork has begun. Two alternative methods are shown here: (1) by chord offset and (2) by deflection angles.

4.5.3.1 Chord-Offset Method

This method requires only a survey tape (or chain) of 10 or 20 m and a graduated staff of 2 m. First, set a post or stake at the chosen point, for example, the entry point of a curve (Fig. 4.7a, point A). Then, choose a distance to separate two successive posts. Posts must be nearer together on curves of small radius than on curves of large radius. In practice, a distance of between 10 and 20 m is chosen between posts for a main road. For demonstration, let us assume a 10-m distance and establish the extension of line BA a point C such that the distance AC is 10 m. Put a post at D along the graduated staff placed perpendicular to AC. Point D will be on the curve; its position is determined by the lengths of AC and CD which are chosen in advance in relation to the radius (Table 4.3). To obtain a new point on the curve establish a line DE where DE=CD, put a provisional stake at E, and extend AE to F so that EF=AE=AC. Point F is the second point of the curve. A further point H is found on the curve by putting a post at G so that FG=DE=CD and then establishing a stake at H, making GH=DG=AC. By repeating this operation until the other straight alignment C′A′B′ is reached, a curve is described which is an arc of a circle of the required radius.

At the first attempt, it is unlikely that the point of contact A′ will be exactly on the alignment C′B′. All that is needed is to begin again using a slightly different length on the graduated staff. With a little experience, the curve required can be found at the second attempt. Table 4.3 shows what lengths to choose on the tape (or chain) and the graduated staff in relation to the radius of the curve which is required.

4.5.3.2 Deflection-Angle Method

This method involves the use of a hand compass and a tape. First, the deflection angle based upon the desired radius of curve and a suitable length of chord is selected (Table 4.4). Then, points on the curve are sequentially identified by turning an angle from the tangent and measuring off the chord distance. The angles turned on the first and last sightings are equal to half the deflection angle. All others are equal to the deflection angle. If the point of tangent intersection is not accessible, then several trials will be needed from different starting points on the tangent (Fig. 4.7b).

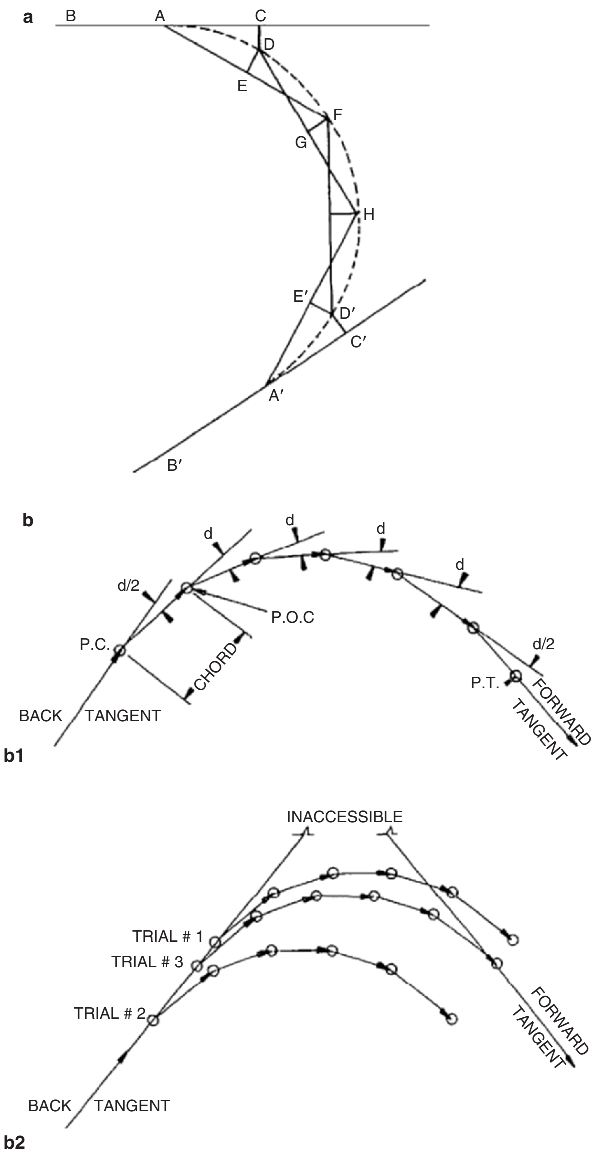


Fig. 4.7. **a** Laying out a curve using the chord-offset method. **b** Laying out a curve using the deflection-angle method if the beginning and the end of the curve points are *1* known *2* not known

Table 4.3. Measurements for laying out a curve. The chord-offset method as a function of curve radius and chord length

Radius of the curve (m)	Length of the half chord read on the tape. AC=AE (m)	Length of the offset read on the staff. CD=DE (m)
30	5	0.42
	7	0.83
	10	1.72
40	5	0.31
	7	0.61
	10	1.27
50	5	0.25
	7	0.49
	10	1.01
75	7	0.33
	10	0.66
	15	1.52
100	7	0.23
	10	0.51
	15	1.11
125	7	0.19
	10	0.40
	15	0.90
150	10	0.33
	15	0.75
	20	1.34
175	10	0.29
	15	0.65
	20	1.15
200	10	0.25
	15	0.57
	20	1.00

4.5.4 Staking for Construction

The final road location line on level ground is marked by centerline stakes (central pegs) 1.8-m high. They are inserted along the centerline of the road at intervals of 15–20 m. The edges of the road (e.g., 2.4-m wide) can be measured with a long stick (1.2 m) on both sides from the centerline. The edge lines of the road are marked with side pegs, also called multipurpose pegs, by inserting 1-m stakes firmly. Their position from the beginning of the road is marked through the method of station numbering or stationing by numbers written in kilometers and meters, e.g., 1+300, as shown in Fig. 4.8. In this system units of thousands of meters or hundreds of meters are designated by a single digit and a plus sign indicates additional units to be added. A station distance of 1,323 m

Table 4.4. Deflection angles and chord lengths

Radius (m)	10-m chords		15-m chords		20-m chords	
	1/2*d* (°)	*d* (°)	1/2*d* (°)	*d* (°)	1/2*d* (°)	*d* (°)
14	21	42	–	–	–	–
16	18	36	–	–	–	–
18	16	32	–	–	–	–
20	14	29	22	44	–	–
25	12	23	17	35	24	47
30	10	19	14	29	19	39
35	8	16	12	25	17	33
40	7	14	11	22	14	29
45	6	13	10	19	13	26
50	6	11	9	17	12	23
55	5	10	8	16	10	21
60	5	10	7	14	10	19
65	4	9	7	13	9	18
70	4	8	6	12	8	16
80	4	7	5	11	7	14
90	3	6	5	10	6	13
100	3	6	4	9	6	11
125	2	5	3	7	5	9
150	2	4	3	6	4	8
175	2	3	2	5	3	7
200	1	3	2	4	3	6

is represented as 1+323 if kilometers is being used, or a distance of 562 m is represented as 5+62 if hundreds of meters is being used.

On uneven terrain, reference stakes called excavation and survey pegs are used to indicate the desired horizontal and vertical alignment of the road, and thereby the excavations and fills needed. They are inserted 0.5 m outside the area of excavation or fill. Cut and fill stakes (multipurpose pegs) are inserted on the exact lines where the excavation or fill begins (Fig. 4.8).

Measurements to indicate surface level are written on the excavation and survey pegs. The future level of excavation is provided by a minus sign and the depth of excavation marked in meters (e.g., −1.3), measured from the top of the peg. The future level of the fill is provided by a plus sign and the height of the fill marked in meters (e.g., +0.9).

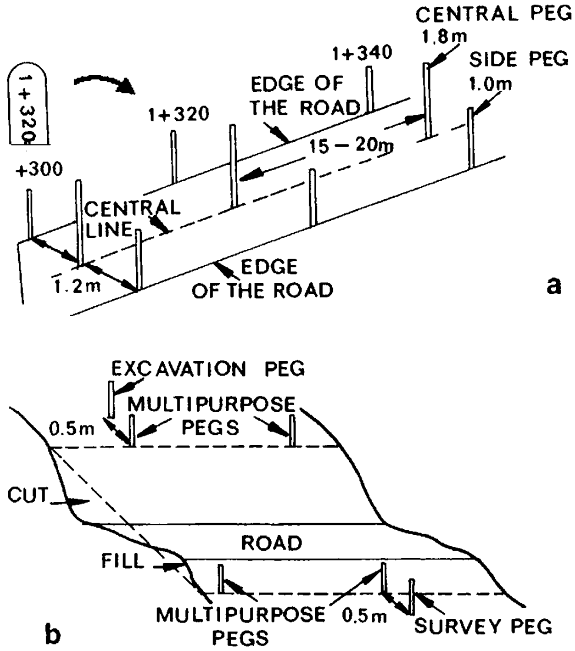


Fig. 4.8. Staking for construction. **a** Staking for level terrain. **b** Staking for uneven terrain. (From Karlsson and de Veen 1981)

Road Building Materials 5

5.1 General Road Structure

On a public road built to carry heavy traffic, the road is built up of several different layers, each of which has a definite purpose. From the top to the bottom, these layers consist of the surface layer, the road base, and the subbase (Fig. 5.1a).

5.1.1 Surface Layer

The surface takes the vertical forces caused by the load and the horizontal forces caused by braking. It must resist shearing and have great cohesion. As a rule, it is made with a bituminous binder to which the wheels adhere well.

5.1.2 Base Layer

The road base should be 10–20 cm in thickness. It must be resistant to all vertical and lateral forces exerted upon it and be dense and cohesive.

5.1.3 Subbase

The subbase, which is thicker than the road base, and which has to resist moderate vertical forces, is generally made from a cohesionless material. It is also possible to place a lower layer between the subbase and the natural earth to stop water rising by capillarity from a water table and to drain away water infiltrating from above.

In practice, this succession of three layers of material chosen to resist different forces is not found in forest roads which have been made of compacted soils.

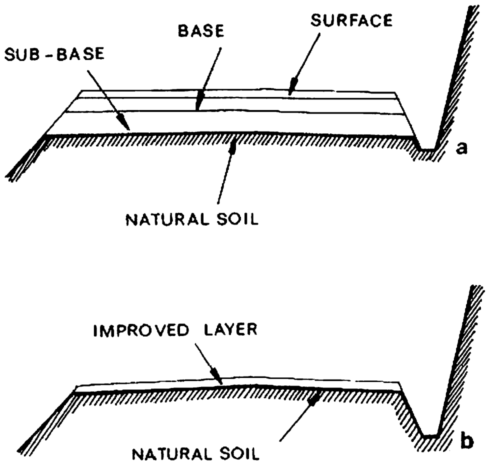


Fig. 5.1. Road cross sections. **a** Main public roads. **b** Forest roads

Two different layers can barely be distinguished: the natural earth and an improved layer (Fig. 5.1b).

5.1.3.1
Natural Earth

Once the organic material has been removed and the surface raised by pushing in material from the sides, natural soil is often used for making the subbase and is thus a continuation of the natural earth. Most soils which can be readily compacted and which are not very sensitive to water are suitable for the subbase. The soils are easier to compact when composed of particles of various size. In this case the distribution of particles of different sizes makes it possible by compaction to have greater density and fewer voids. The fewer the small particles, especially clay, that the soil contains, the less sensitive it is to water. Thus, the following soils are particularly suitable (Table 5.1):

- Coarse-grained soils composed of a mixture of coarse and fine gravels with little or no fines
- Gravel with fines which are more or less silty or clayey
- Sandy soils with little or no fines

Fine sands, slightly silty, are satisfactory. The principal quality essential for this standard of road is low sensitivity to water. Good drainage by ditches and evaporation must be ensured.

Table 5.1. Soil characteristics

Characteristics	Gravel	Sand			Silt	Clay
		Coarse	Medium	Fine		
Grain size (mm)						
Maximum	60	2.0	0.6	0.2	0.06	0.002
Minimum	2	0.6	0.2	0.06	0.002	0.0005
Shape	Various	Angular			Angular	Plates, sometimes rods
Cohesion	None	“Apparent” when damp			Very slight	Considerable
Plasticity	None	None			Slight to medium	High
Permeability	High	High to medium			Medium to low	Low
Consolidation	Little	Slight			Slight	High
Volume change	None	Slight			Medium	Considerable
Effect in soil mixture	Contributes to stability and strength	Contributes to strength and stability			Contributes to instability especially when vibrated or wet	Contributes to strength by cohesion, but to plastic movement under pressure

5.1.3.2 The Improved Layer

Above the compacted natural soil there is an improved layer, which corresponds to the road base on main roads and surface layer on forest roads. The material to be used should be carefully chosen so that it can resist the local forces which can be developed under traffic. Rocks greater than 3–4 cm should be avoided for surfacing. Smaller rocks are easier to spread, level, and compact, and prevent the surface from being torn up by the traffic. As in the case of the subbase, a good particle size distribution makes it possible to stabilize this surface by compaction. The material should be sufficiently hard not to be crushed by the traffic. The best roadbed surfacing materials have some plasticity and are well graded (Fig. 5.2). The thickness of the improved layer depends on traffic loading and subgrade characteristics usually vary from about 15 to 20 cm before consolidation, but may need to be greater in soft subgrades. It is composed of a mixture of natural gravel comprising pebbles, gravel, sand, and a few fines. In the tropics, this layer is often composed of unsorted laterite consisting of coarse particles and some fine material. The laterite is easily compacted by

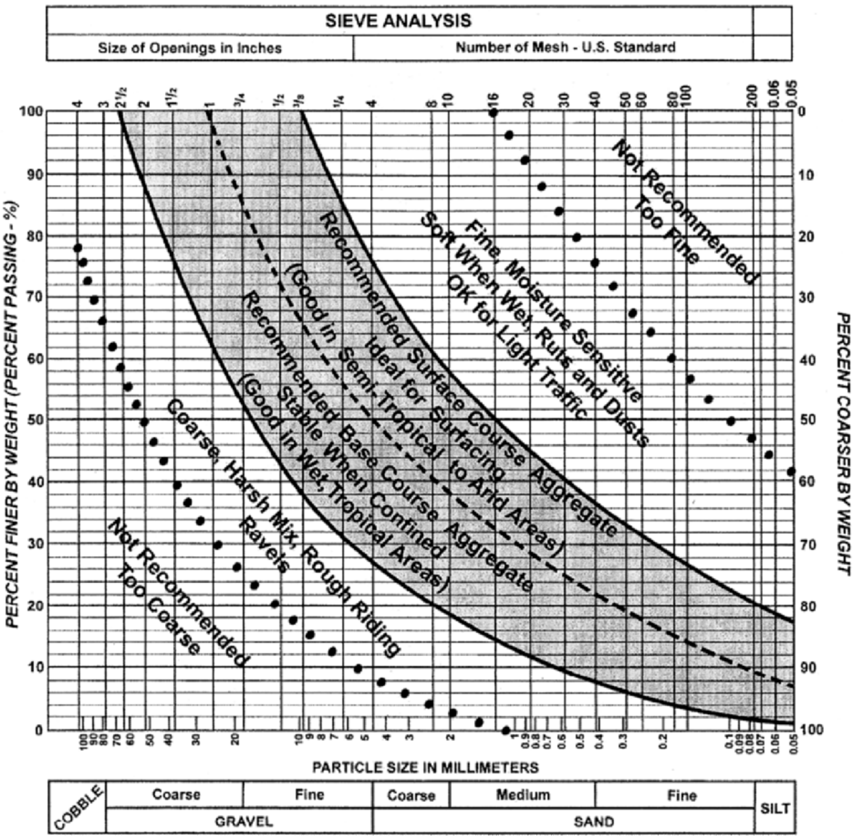


Fig. 5.2. Performance characteristics of roadway surfacing materials. Gradation ranges are approximate. The best road surfacing materials have some plasticity and are well graded. They have gradations parallel to the curves shown, and are closest to the "ideal" *dashed curve* in the middle of the gradation ranges shown. (From Keller and Sherar 2003).

rubber tires or simply by the traffic flow. Moreover, it is often the only hard material available in tropical regions.

5.1.4 The Ditch

The ditch serves two purposes: (1) to allow the subbase or improved layer to drain and (2) to move water from the adjacent hill slope or road surface to where it can be safely diverted from the road. The ditch must be deep enough to drain the subbase or the improved layer. The top water level in the ditch must not rise above the bottom of the subbase or improved layer. Road subgrades can fail because of ditches of insufficient depth, road designs that do not permit adequate gradients to drain the ditch, or poor maintenance that permit ditches to fill. The depth of the ditch should be at least 45 cm below the surface of the subgrade. Ditches can be parabolic (round bottom), trapezoidal (flat bottom), or triangular (V-shaped bottom). The triangular ditch is the most easily constructed, requires the most maintenance, has the lowest water-carrying capacity, and is the most susceptible to erosion. Backhoe or excavators most easily construct trapezoidal or parabolic ditches. Running the wheel of the road grader in the ditch can be used to compact the ditch bottom (see Sect. 6.4.1 for more on side ditches).

5.1.5 Capillarity

Some soils have a substantial capillary attraction. These are mainly silt soils containing a large percentage of very fine sand. To drain capillary water directly is almost impossible, but its source can be controlled, which can keep it from coming up into the upper subgrade. Two ways to do this are by (1) lowering the water table through deep ditches or installing subdrains and (2) placing an insulating layer of coarse sand or gravel in the subgrade between the water table and the upper subgrade to break the capillary rise (Table 5.2). Subdrains and insulating courses of material are expensive and probably can only be justified on main access roads.

5.2 Aggregate Surface Design

A number of design procedures and guides have been developed for determining the minimum required compacted depth for aggregate surfacing. One method uses a formula developed by the US Army Corps of Engineers. The formula relates the rut depth (in centimeters) that will be created with a thickness

Table 5.2. Capillarity in different soils (Zaremba 1976)

Soil type	Capillary rise (cm)
Coarse sand	5–15
Medium sand	15–50
Fine sand	40–100
Very fine sand	100–150
Coarse and medium silt	150–560
Fine silt	400–1,000

of the top layer, t (in centimeters), after a number of equivalent axle passes, R, of an equivalent single wheel load, P_k (in tonnes), with a tire at a pressure t_p (in kilopascals) where the strength of the aggregate surface C_1 and that of the subgrade C_2 are determined by the California bearing ratio (CBR) test. The formula is valid for values of C_1 between 20 and 100, C_2 between 3 and 30, and a ratio of C_1/C_2 of 1–7. The CBR should reflect the conditions when the road is to be used. For wet season transport a soaked CBR represents the worst-case condition, while for dry-season transport one can use the dry CBR. For subgrade values with a CBR less than 3, geotextiles should be considered. Design maximum rut depths should be limited to half of the structural thickness or less. A common design guide is a maximum rut depth of 5 cm.

$$\mathrm{RD} = 0.2136 \frac{P_k^{0.4704}\, t_p^{0.5695}\, R^{0.2476}}{[\log(t/2.54)]^{2.002}\, C_1^{0.9335}\, C_2^{0.2848}}$$

The easiest way to use this formula is given wheel loading, tire pressure, number of repetitions, and the CBR values, substitute different values of thickness, t, until you arrive at the target rut depth. Note log refers to base 10. A running surface course should be added to this depth and replaced after traffic use.

Example 1: RD=5 cm, t_p=600 kPa, P_k=3.92 t, C_1=40, C_2=10, and R=30,000. Solving for the compacted aggregate thickness by trial and error gives t =17 cm

Example 2: RD=5 cm, t_p=500 kPa (tire pressure reduction), P_k=3.92 t, C_1=40, C_2=10, and R=30,000. Solving for the compacted aggregate thickness by trial and error gives t=15 cm.

Example 3: RD=5 cm, t_p=600 kPa, P_k=3.92 t, C_1=30, C_2=10, and R=30,000. Solving for the compacted aggregate thickness by trial and error gives t =22 cm.

Alternative aggregate designs can be evaluated using this procedure. In example 1, the minimum compacted aggregate base should be 17 cm to keep the rut depth to 5 cm after 30,000 equivalent axle loads. If the tire pressure is reduced to 500 kPa, in example 2, the minimum required aggregate base is reduced to 15 cm. In example 3, if a weaker base material is used, the aggregate depth increases to 22 cm. If the weaker base material is sufficiently less expensive than the higher-quality base material, it may be more efficient to use it, even though more material must be transported.

The CBR has been frequently used in road structure design. Unfortunately, it is a difficult test that requires a significant amount of work by trained laboratory technicians. To obtain the soak value requires 96 h submerged in a water bath. As an alternative, light-weight drop hammers have been developed by Zorn-Stendal in Germany and Clegg in Australia to measure the deflection in the soil from a dropped load. These drop hammers are easy to use and provide immediate results. There have been correlations between values obtained from these hammers and other soil strength measurements. One relationship from temperate soils relating the CBR to the Clegg impact value, CIV, is

$$CBR = 0.1085 \times CIV^{1.863}$$
$$(R^2 = .787)$$

For tropical soils, one can either develop the relationship using both the CBR and Clegg values for local use or measure Clegg values for roads and develop local guidelines for the acceptable Clegg values for surface and subsurface measurements.

Another tool that has been used to measure subgrade strength is the dynamic cone penetrometer (DCP). This tool has been tested by a variety of organizations, including at least one in the tropics. Like the Clegg hammer, a number of relationships have been developed relating it to the CBR for granular soils, cohesive soils, as well as aggregate base layers. The relationships have the form

$$\log CBR = a + b \log DCP.$$

The coefficient for the intercept value (a) ranges between 2.44 and 2.60, while the coefficient for the slope (b) ranges from −1.07 to −1.16.

Although these tools are not exact substitutes for the CBR, they provide an opportunity for immediate feedback to the forest engineer as to the strength of a section of road. It will allow the engineer to take corrective actions immediately, such as (1) additional compaction, (2) windrowing the soil to dry, (3) addition of water to improve the subgrade strength, or (4) modifying the aggregate design to account for the weaker subgrade on that section.

5.3 Locating Road Building Materials

5.3.1 Gravel

Hard rock is rare in many areas of the tropics and, if it exists, a bulldozer may be needed to dig for it. Aerial photographs may be useful to find gravel. These sites may be found by looking for abnormal landforms which may be underlain by weather-resistant rock such as clifflike, domed, or knoblike topographic features or areas of shallow soils. Signs include dry areas where the vegetation vigor and form are different from those of the surrounding forest. Study the topographic and vegetative characteristics where rock has been found in the area or adjacent land holdings.

If you find rock, probe around it with a bulldozer to determine whether sufficient rock is present to warrant pit development. Expose the rock source by removing the overburden soil, stumps, and other materials so they will not interfere with rock pit operations. Stream gravel deposits are suitable for roads if precautions are observed. Stream rocks are often like marbles, making it difficult to build a hard and firm surface.

Two approaches are common in using stream gravel:

1. It is best to crush the rock. This produces sharp edges and flat sides. A strong, binding road can be developed.
2. Success can be achieved by using a mixture of all particle sizes. The mixture must have particles ranging from sands to small rocks so that small particles can fill the voids between the rocks.

The second method will be the most economical. Do not remove gravel from or adjacent to streams – use only old floodplain deposits unless you have a permit from the appropriate regulatory agency.

5.3.2 Laterite

Often, lateritic materials derived from granular laterites are used for the improved layer. The materials which make up the improved layer are taken from natural deposits that are always heterogeneous. Very often beds, which appear suitable, are not thick and the clay content increases in the lower levels until these become no longer suitable. Supervision is important to prevent operators from unknowingly introducing unsuitable material into the surfacing material. Lateritic deposits can sometimes be found on ridge breaks. They can often be ripped by a tractor with a ripper and later crushed by a grid roller.

5.4 Improving Local Materials

All natural soil in place, as well as loose soil, contains many empty spaces which are filled with air; these spaces lead to shrinkage when under pressure. To be able to use any soil as the base of a road, it must be stabilized. That is to say, it must be improved so that it can carry traffic even under unfavorable conditions of wetting or drying. This improvement can be carried out by several methods: (1) by compaction, (2) by altering the particle size distribution, or (3) by changing the properties of the matrix. In practice, compaction is the most general treatment on forest roads. Compaction consists of reducing the apparent volume of the soil, i.e., by reducing the empty spaces and increasing the density of the soil. It attempts to arrange the particles in such a way as to give the greatest density so as to reduce the possibility of absorption. Compaction can be carried out by sheep's foot rollers, pneumatic tired rollers, or vibratory rollers, depending on the compaction material. A fair degree of compaction is achieved by the passage of construction equipment if the layers are thin. This can often be achieved by hauling a substantial volume of timber over a new road in the dry season to compact a lateritic improved layer before the wet season.

The water content of the soil to be compacted has an important influence on the compaction results. A small quantity of water acts as a lubricant and helps in arranging the particles in relation to each other and the expulsion of the air from the voids. With every soil there is an optimum moisture content at which compaction is easiest. In the field, the water content of soil is likely to vary considerably and it is desirable for a water content near the optimum. Laboratory tests can be used to determine the optimum moisture content. If other methods are not available, the following empirical test can be applied. The optimum moisture content is reached if, when a handful of soil is squeezed firmly, the imprint of the fingers can be seen, but water does not ooze out through the fingers. The ball of earth should become smooth when it is rolled once or twice in the hand. According to its conditions, the soil has either to be scarified to aerate it and facilitate evaporation or to be watered to increase the water content.

Improvement of local materials through compaction increases their density and the resulting bearing strength. If the materials come from excavation and are to be placed in compacted fills, the volume of excavation will usually need to be greater than the volume of compacted fill. The greater the amount of specified compaction, the greater the shrink factor (Table 5.3). In practice, the shrink factor is also affected by fill placement related to equipment type, sideslope, and length of fill. The steeper the sideslope; the more material that will roll beyond the toe of the fill. Hydraulic excavators can place fill material more precisely than bulldozers, so an excavator will lose less material, particularly if it starts with a fill foundation. On steeper slopes, the bulldozer working alone will not be able to achieve the compaction specification for much of the fill. If the toe of the fill is beyond the reach of the excavator (9–12 m), the excavator cannot place or compact the fill and the compaction specification may not be achievable with normal forest road construction equipment.

5.5 Gravel Recycling

Where crushed rock is placed on temporary roads, or roads that will not be reused for long periods of time, crushed rock can be recovered from these roads using graders, scrapers, or excavators. For gravel thicknesses of 20 cm or more, 70% or more of the rock can be recovered and reused. If geosynthetics

Table 5.3. Approximate shrink factors for various soil types, moisture levels, and compaction specifications. (Adapted from Burch 2000)

Soil type moisture level	Compaction requirement	Shrink factor	Soil type moisture level	Compaction requirement	Shrink factor
Dry sand	In bank	1.00	Dry clay	In bank	1.00
Dry sand	95% SP	0.83	Dry clay	90% SP	NA
Dry sand	100% SP	0.77	Dry clay	100% SP	0.94
Dry sand	95% MP	0.78	Dry clay	90% MP	0.94
Dry sand	100% MP	0.72	Dry clay	100% MP	0.82
Damp sand	In bank	1.00	Dry dirt	In bank	1.00
Damp sand	95% SP	0.98	Dry dirt	90% SP	0.95
Damp sand	100% SP	0.93	Dry dirt	100% SP	0.83
Damp sand	95% MP	0.94	Dry dirt	90% MP	0.90
Damp sand	100% MP	0.88	Dry dirt	100% MP	0.78
Damp gravel	In bank	1.00	Damp dirt	In bank	1.00
Damp gravel	95% SP	0.93	Damp dirt	90% SP	NA
Damp gravel	100% SP	0.87	Damp dirt	100% SP	0.93
Damp gravel	95% MP	0.84	Damp dirt	90% MP	1.00
Damp gravel	100% SP	0.78	Damp dirt	100% MP	0.89

SP standard Proctor test, *MP* modified Proctor test, *NA* in-bank density is greater than compaction specification

are used, the recovery rate can be 90% or more owing to good separation between the rock and the subgrade. The decision to recycle gravel considers the cost of recovery, reprocessing costs (if any), the distance to transport the recycled rock versus the cost of fresh gravel and the distance to transport the fresh gravel, and any royalties of pit costs for the new rock. If the road from which the rock has been recovered will be used again, the cost of replacing the rock must be included using the appropriate discount rate and return interval. Depending upon the transport costs for fresh rock, the savings can be substantial.

Forest Road Construction 6

6.1
Clearing and Grubbing

6.1.1
Clearing Width

Evaporation from the surface of the road depends directly on the amount of exposure to the sun. In the forest, the sun's rays are screened by large trees bordering the road. Their long shadows prevent the road from drying, particularly in the early morning. If these trees are felled, the period of exposure to the sun is increased and the aeration of the surface is improved. The larger the clearing in the forest, the better the air circulation. Avoid having trees with crowns covering a road. This causes shade on the road, and drops of water continue to drip onto the surface long after each rain.

It is difficult to specify the minimum width for clearing to open up the road and to give adequate light. Some road builders are of the opinion that the clearing on each side should be at least equal to width of the roadway. At the time of construction, they plan an opening in the stand 3 times the width of the road including ditches. Another rule is that after 8:30 or 9 a.m. there should be no shade on the road between the side ditches.

When building a road, it is best to clear only as much roadway as can be completed before the rainy season. This prevents the site from becoming too wet to build the road properly, avoids unnecessary erosion, and reduces delays.

6.1.2
Clearing Methods

There are two methods:

1. To cut down, with an axe or a chainsaw, all the large and small trees to a height of 1–2 m above the ground and then remove the stumps with a

bulldozer or excavator. If the stumps are to be cleared by bulldozer then they are usually cut higher than if they are to be removed by excavator to improve leverage.
2. To start in the first place with a bulldozer which clears a way for itself through the vegetation

The tractor crew generally consists of three men; the operator, and two helpers. The helpers cut down the creepers obstructing the operator's machine, pull off branches which get caught in the radiator or around the tracks, and more particularly cut back the roots protruding from the earth and slip the winch cable over the stumps.

6.1.2.1 Operator Protection and Machine Guarding

Cab guards are essential to do this work safely. In addition, daily production has been estimated to increase 20% when cab guards are used.

Cabs designed specifically for clearing are available from equipment manufacturers. The radiator, engine, and underside of the tractor must be well protected. Perforated hoods, screens, and crankcase guards as well as hydraulic cylinder guards are generally recommended. Generally speaking, lower-cost clearing can be done with larger tractors (more powerful than 225 kW) if the amount of clearing involved is sufficient to merit the initial investment in the bigger machine. Because of the need for constant changes in direction in most clearing work, a power shift transmission should be standard equipment. The direct drive transmission tractor is recommended when the tractor is used principally in constant drawbar work such as chaining or pulling a disc harrow. In most applications, a winch should also be considered on one of every three tractors in a fleet.

6.1.2.2 Use of Explosives

A large stump, from a tree 0.8–1.5 m in diameter which has been felled, is nearly always a problem. It can take 1 or 2 h of exacting work by a bulldozer to get it out. Leaving stumps 0.8–1.2 m in height provides added leverage if bulldozers are being used. If an excavator is being used to clear the right of way, there is no need to leave as high a stump as the excavator will dig the stump out. If a small change in alignment can avoid the obstacle, all the better, both for road construction efficiency and for the environment. When this cannot be done, there is the alternative of using a few kilograms of a high explosive in order to lay bare the root from the surrounding soil; and eventually to split the root into two or more parts.

6.2 Earthwork

Earthwork must begin by taking off the humus or top layer of the soil, which contains organic matter. In practice, this is completed in the process of clearing.

6.2.1 Methods

6.2.1.1 Flat Ground

On flat ground, an embankment must be constructed to keep the road structure dry. Work with the bulldozer proceeds from each side if the material is suitable (Fig. 6.1a).

6.2.1.2 On a Hillside

On a hilllside, the bulldozer beginning at the top of the section of road should be started as high up as possible to obtain the advantage of working downhill in moving earth from cuts to fills. The bulldozer begins at the top of the cut slope, excavating and sidecasting material until it reaches the gradeline (Fig. 6.1b). The location of the cut slope stake, which marks the top of the cut, and the cut slope steepness are critical. If the design calls for a 1:1 cut slope (1 m horizontal for each 1 m vertical) and the operator constructs a steeper cut slope, for example, 0.5:1, the road will reach the design road width before the desired grade is achieved. This will require further excavation to get down to grade producing excessive road width, increased construction cost, and the oversteepened cut slope may fail.

Backhoe tracked excavators are preferred for road construction in steeper terrain because of their ability to more closely control the earthmoving operation (Table 6.1). They can be used to load logs, excavate and deposit soil, shape slopes, dig side drains, load rock and gravel, and position culverts. Since the excavator undercarriage of the backhoe remains still during the excavation work, the machine can be used on fairly adverse slopes. Excavated soil materials and boulders can be precisely deposited into the road fill, minimizing the risks

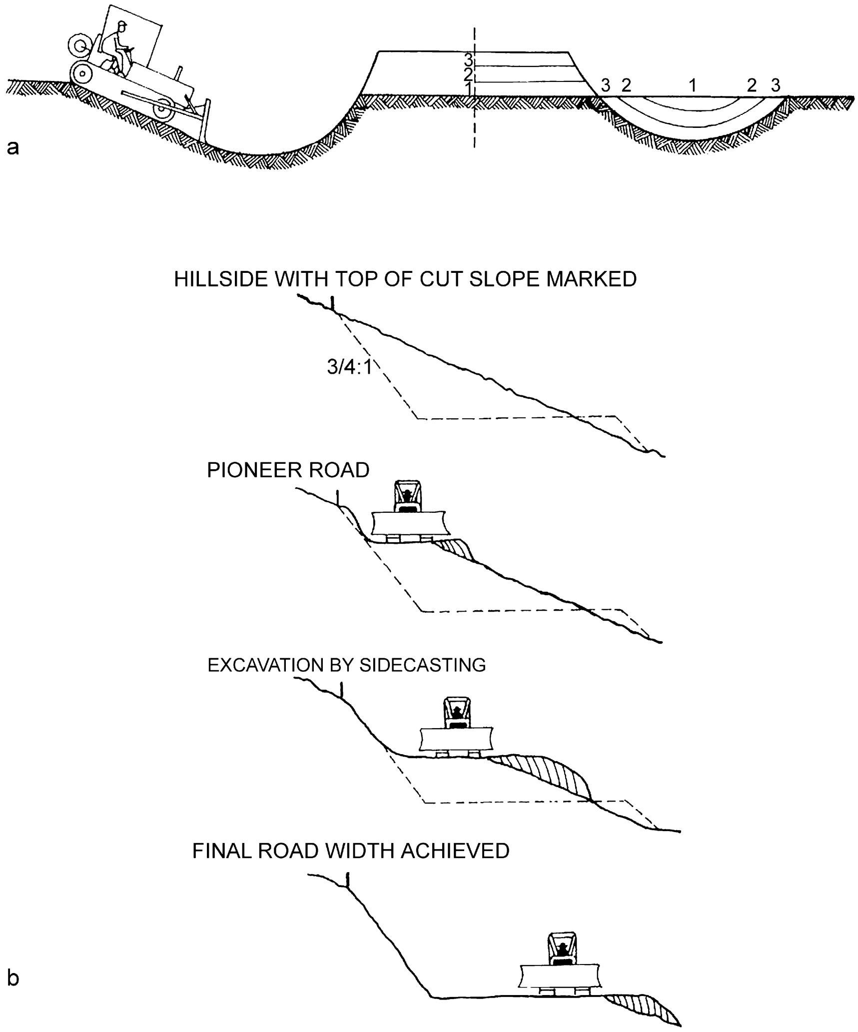


Fig. 6.1. Earthwork by tractor. **a** on level ground and **b** on steep terrain. (Courtesy FAO 1964; Garland 1983)

of erosion. Tree stumps, crowns, and other debris can be extracted and placed at the foot of the earthfill to form a filtration barrier, preventing sediment from reaching a watercourse. Earth can be placed in successive 30–50 cm layers that are easier to form and better compacted. Each layer is compacted by several excavator passes before being covered by the next layer of material. The fill slope is compacted with the excavator's bucket. Where terrain permits, earthfill can be laid on a foundation of stones, rocks, or resistant tree trunks

Table 6.1. Advantages of road construction by an excavator versus a bulldozer in steep terrain. (Adapted from FAO 1999b)

Road construction by excavator	Road construction by bulldozer
Subgrade width can be kept to the absolute minimum determined by safety and anticipated use as the excavator operates from a fixed position or by movement parallel to the road centerline	Bulldozer is difficult to use at construction sites where minimum subgrade width is required owing to its need to maneuver
A balanced road design where suitable excavated material is incorporated in the road structure will result in significantly less excavation when compared with full bench construction of road; in road construction by the excavator the bench construction needs only be applied on slopes where rock faces are to be crossed	On steeper slopes, full bench construction will be applied as the sideslope increases where the entire subgrade is cut into the hill and material will be sidecast or wasted rather than incorporated
Excellent control in the placement of excavated material as the excavator basically operates by digging, swinging, and depositing material with accuracy and care	Poor control in placement of material as the bulldozer operates by pushing or drifting material in front of the blade to areas where fill is needed and/or sidecasting excess material
Excavated material can be separated and temporarily piled by the excavator taking account of its anticipated use in building up the fill	Material from cuts cannot be separated to build up the fill in layers of suitably sized material
Length of fill slope can be reduced owing to the fill foundation established by the excavator; a solid fill foundation facilitates building a road in steep terrain	Length of fill slope increases dramatically as sideslope increases
Construction width is minimized as subgrade width and length of fill slope is reduced	Area dedicated to forest roads and disturbance of the landscape are higher when compared with those for road construction by an excavator
As excavated material is incorporated in the road it is exposed less to erosion	Full bench construction provides a uniform subgrade but also a high potential for erosion by loose, unconsolidated sidecast material
Different types of buckets available enable the excavator to carry out specific construction work and ensure highest performance; the use of a rock bucket substitutes for other equipment as long as the rock can be ripped	Adequate road construction performed solely by the bulldozer is considered to be restricted to construction sites where the road can be full benched or on moderate slopes
The use of a hydraulic hammer which can easily be attached to the excavator results in less need for blasting and, consequently, in avoidance of blast-related damage	If rock outcrops cannot be bypassed, rock blasting will be specified
As excavators enable the operator to efficiently dig, swing, and place material with accuracy and care, damage to stands alongside the road is minimal	Material escaping during construction operation or excess material wasted downhill might cause considerable damage to forest stands alongside the road
Satisfactory water drainage and erosion control can be ensured from the start of work as culverts can be installed and retaining walls built at any time	Culverts and retaining structures will be established after completion of bulldozer work

put in place by the excavator. The cut slope can be better shaped to match the natural slope, reducing the risk of erosion and landslide, and the fill slope can be shaped and covered with branches to facilitate regeneration. Medium-sized excavators have an operating weight of about 24 t and engine power of 100 kW.

Several approaches can be used. One approach is described here. The stages of the backhoe excavator operation, when constructing a forest road on a steep slope, are as follows (Fig. 6.2):

- Organic top soil is removed in front of the machine and distributed on the rear back slope and fill slope for better revegetation.
- A trench or bench is dug along the downhill edge as a deposit for the fill.
- The material is excavated and deposited in the fill. Single big rocks are deposited in the trench. The machine constructs primitive retaining walls in this way.

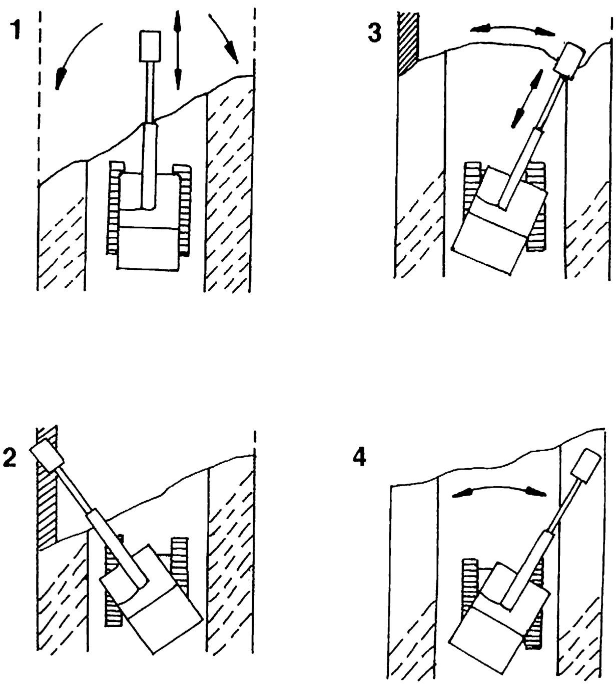


Fig. 6.2. Earthwork by excavator (Sedlak 1982). **1** Organic top soil is removed in front of the machine and spread on the rear back and fill slope. **2** A bench is excavated along the lower fill edge as a basis for the fill. **3** The material is excavated and deposited in the fill; boulders are deposited in the bench as revetment. **4** Subgrade and cut slope are finally shaped

- Excavation and fill continues until the coarse subgrade is completed.
- Excavation of the ditch is made and the material is used for crowning the subgrade.
- Final shaping of the cut slope is completed.
- Any excess material is then used on the next section or left to be spread by the grader.

The construction of the bench at the toe of the fill is a critical element for success of road building on steep terrain. The establishment of a fill foundation reduces the length of the fill slope by providing a solid foundation for the fill. To build up the fill foundation requires highly skilled and experienced operators. Fill failures not only destroy parts of the road, but may also trigger landslides in steep terrain, making large areas unproductive and delivering sediment to streams.

While the final finishing work is being done to the road surface, the hillside ditch can be formed. This allows for immediate draining of the road structure. As excavating the ditch interferes with the cut, final shaping of cut slope to provide the desired angle will depend upon completion of the coarse subgrade and ditch. The edge of the top of the cut is rounded to prevent downhill drifting of loose cut slope material after completion of the road. Material that later erodes or rolls into the ditch increases maintenance costs as well as obstructs drainage.

If the road is routed through a saddle to reduce the gradient, excavations are made on both sides of the road. First a rectangular U-cut cross section is excavated, and then the sideslopes are made. If the excavation is deeper than 1 m, it is done in several steps.

6.2.1.3 Excavation in Rock

If rock outcrops cannot be avoided there are three options: ripping, hammering, or blasting. The ripability of the rock will depend on the type of rock and on the degree of fracturing and weathering. If the rock can be ripped, ripping can be done by the blade or a ripping tool on the bulldozer, or by the bucket on an excavator. If ripping is not possible, but the rock still has enough planes of weakness for use of a hydraulic hammer, then a hydraulic hammer attachment on the excavator can be used. If rock is too difficult to be hammered, blasting is the last recourse. Although sophisticated blasting techniques have been developed, rock blasting is best avoided as the use of rock drilling equipment and explosives increase road construction cost and there are substantial risks in using explosives. If blasting is specified, excavators with drilling equipment can place both horizontal and vertical holes.

6.2.2 Embankments

Embankments typically are used to cross stream drainages, flat areas, and swamps, and are used as waste areas for extra excavation in sensitive steep areas. Fills across drainages are especially critical because they may act as dams during severe storms.

The bulldozer constructs an embankment in a succession of layers about 20-cm thick. The tractor has to make numerous journeys on the embankment, pushing the material in front of it to the end of the embankment. At the end of each trip the operator raises the blade to make a shoulder across the width of the line of discharge. This edge is pushed back on each trip, thus avoiding the danger of tipping the machine over the face of the embankment while it is being made. Passes over the loose earth cause considerable compaction by the tractor's weight and its vibrations.

Sometimes it may be necessary to haul material farther than an economic distance for the tractor. In these cases, a scraper may be necessary. If longer-distance transport is necessary, the tractor may roughly pile material for a front-end loader to place it in dump trucks or a backhoe may excavate it and load trucks directly. The following guidelines can be used to keep earthmoving machines in their most productive and economical zones. Use track-type tractors for distances up to 120 m, towed scrapers for distances up to 350–400 m, self-propelled scrapers for distances up to 900–1,000 m, and dump trucks for longer distances.

6.2.3 Methods of Compaction

The work of compaction must be done concurrently with the earthwork in the construction of embankments and in road building, even in building roads with simple stabilized foundation, such as earth roads. Earth is put on in thin layers along the length of the embankment. The bulldozer or grader keeps these thin layers to a maximum thickness of about 20 cm; these layers can undergo a regular mechanical compaction, which is obtained by the circulation of the bulldozer and, when necessary, by a few passes with a roller. Compaction needs to be adequate to meet the aggregate design goals for the subgrade (Sect. 5.2). If possible, the compacted subgrade should be used for some log haul before placement of surfacing, for example, to remove right-of-way logs. Normal use with logging trucks will compact the surface if the trucks do not repeat each trip in the same tracks. Soft spots and oversights during fill construction will become evident with use and can then be fixed.

6.2.4 Swamps

The backhoe's low ground-bearing pressure, reach, and mobility are an advantage in swamps. The main problems are poor soil condition and high water table. The backhoe with its low bearing pressure is able to navigate over most swampy ground by building a mat out of nonmerchantable logs, branches, small stumps, and other debris and then walking on the mat. Its ability to ditch allows it to scoop up nearby material that can be heaped on the built-up surface. This material, if it has the ability to drain, will firm up on its own. The result is an elevated roadbed. Once drained and hardened, ballast can then be placed on the mat. See Chap. 7. for corduroy design procedures.

6.3 Surfacing

A distinction has already been made between the natural soil and the surface layer. The surface layer is very often made up of unsorted gravel extracted from selected natural deposits and transported directly to the compacted and leveled natural soil.

Ideally surfacing should not be applied until the subgrade has an opportunity to dry and consolidate. Prior to surfacing, check that the subgrade has been constructed with a strong base. Eliminate or reduce sharp humps or depressions in the subgrade. Do not use expensive surfacing material to fill in local depressions if less expensive material close at hand would work.

An important control activity is to stake the width of the surfacing to be applied and to control its depth. Surfacing regardless of the source is usually expensive and scarce. Unnecessarily wide surfacing serves no purpose and drives up cost. Too little surfacing risks the integrity of the subgrade.

The surfacing operation can be done in several ways. One method is for the dump trucks to drop their loads in small heaps at regular intervals along the shoulders of the road. This gravelly material is often unsorted laterite, rich in gravel of less than 4 cm in diameter. The grader can spread material which has been supplied either in heaps or in a line along the road. It is best to leave the site at the end of the day with an even top surface, to avoid damage due to erosion and to soaking of the soil which is in the process of being handled and compacted.

An alternative to dumping the surfacing material in heaps along the road is to begin the surfacing at the point nearest the pit. Repeated trips of the dump trucks will compact the surfacing. A grader or tractor spreads each load, extending the surfaced road. Each subsequent load is dumped on the newly spread material. By dumping each load on the previously spread rock, a continuous layer will develop – not a patchy surface. Larger rocks are maneuvered to the subgrade as both truck and tractor operate on the rock. Smaller rocks fill voids between the larger rocks. Placing the rock can be controlled by marking the length of roadway each dump truck load should be spread.

Finally following up the grader should be a vibratory roller for proper compaction. Compaction needs to be adequate to reach the aggregate design goals for the improved surface (Sect. 5.2). Proper compaction of the road surface builds its strength as well as sealing the surface, preventing the washing away of loose silts and fine gravels when there is heavy rain.

6.4 Drainage

Water is the principal destructive agent of the road, particularly in the tropics where runoff may be very heavy (e.g., up to 10 times greater than amounts common in many temperate areas). When constructing the road, ensure that there is a crown in the road of 3–4 cm/m to eliminate standing water which causes the road to break up under heavy loads.

Ditches are used to collect water falling on the road and to carry it toward the streams or rivers. There are several kinds of ditches, each one having a well-defined role (Fig. 6.3). They can facilitate drainage by creating a hydraulic gradient between the road and water in the ditch. These drainage devices are:

- Side ditches
- Drainage outlets
- Catchwater or intercepting ditches
- Culverts under the roadway
- Dips or rolling grades

6.4.1 Side Ditches

Side ditches collect the water which falls on the road as well as reduce the water table in the vicinity of the ditch. The camber of the road is designed for runoff of water toward the side ditches.

6.4.1.1 Ditch Depth

The water in the side ditches must not remain in the ditches or it will penetrate into the subgrade and reduce its strength. Ditches reduce the water table in the vicinity

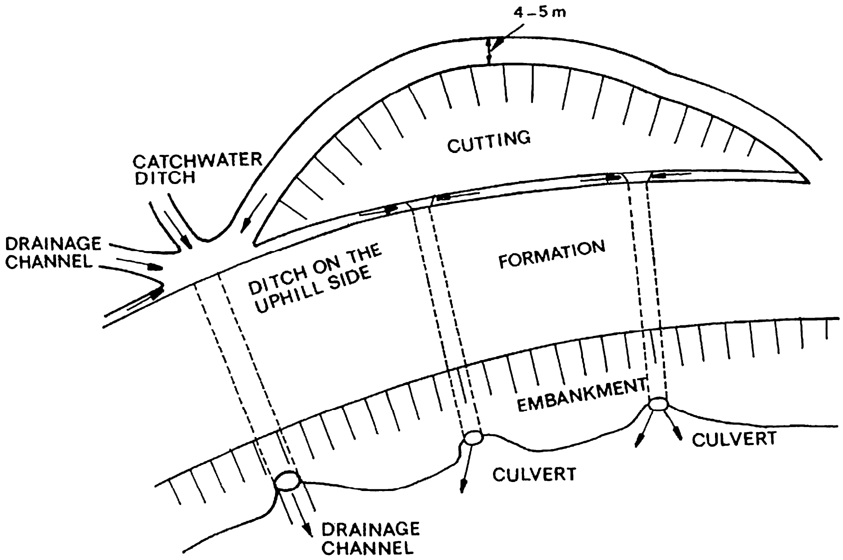


Fig. 6.3. Various types of ditches. (From FAO 1964)

of the ditch, helping to maintain subgrade strength. The deeper the ditch, the more impact on the water table. To be effective the tops of the ditches must be below the level of the road shoulder and the bottom of ditch should extend preferably at least 45 cm below the subbase or improved layer. In wet areas or swamps the ditches may need to be 75 cm or deeper, particularly on the up-swamp side of the road.

6.4.1.2
Ditch Gradient

If roads do not have a sufficient grade, the ditches will not drain well and will collect deposits. In practice, the minimum slope is from 0.5 to 1%. The maximum slope is determined by the erodibility of the ground. It can be less than 4% in some soil types. Road grades may need to be rolled to maintain adequate ditch drainage.

6.4.1.3
Ditch Cross Section

In tropical climates, rainfall is often intense, so the ditches should have a discharge or a cross section which will allow a considerable flash flow. In dense forest areas, there is often more than 100 mm of rainfall in a day and every few years there could be storms resulting in rainfall as high as 100 mm in an hour. In practice, a more or less uniform cross section is kept, but the outlets are increased so that the water running in the side ditches can be readily discharged toward the outside of the road. When sufficient outlets are not provided, there is the risk of the side ditches being rapidly eroded.

6.4.1.4 Ditch Construction

Ditches can be dug by a grader, backhoe, or hand. It is important, regardless of the method, that these ditches are dug as soon as possible and at latest immediately after the earthwork has been completed.

6.4.2 Drainage Outlets

The function of drainage outlets is to carry water in the side ditches toward the natural drainage channels. Although spacing guides exist as a function of ditch erodibility, road grade, and rainfall intensity (Tables 6.2, 6.3), there is one universal rule. The more drainage outlets the better, particularly if the road gradient is steep. Inspections should be made during the first storms to check if additional outlets are needed. To avoid the silting up of an outlet, it should have a steeper slope than the adjoining side ditch, and a slope which increases from the ditch down the hillside or toward the drainage channel. Side ditches should not be drained directly onto fill slopes. Armoring of outlet areas with rocks, wood, or other available materials may be needed to avoid erosion.

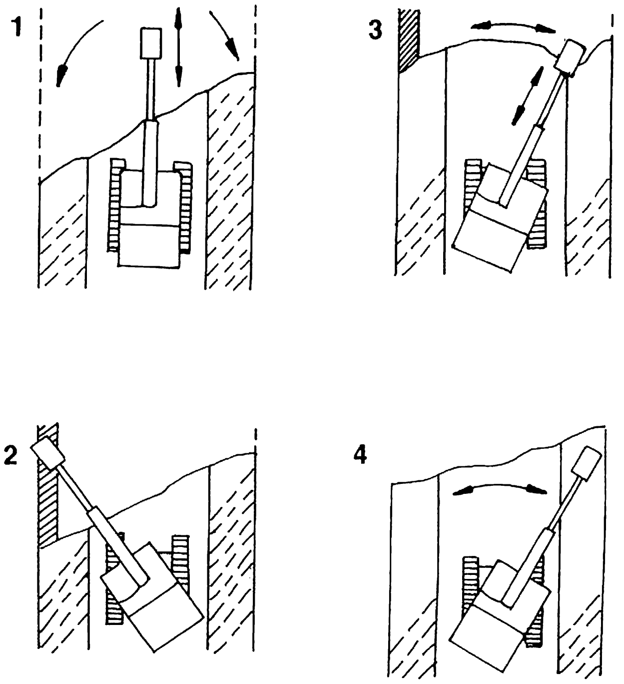
The construction of the outlets is carried out at the same time as that of the ditches. In fairly even ground, when an artificial outlet ditch has to be opened between the road and the neighboring drainage channel, it is better to use the equipment carrying out the principal earthwork of the road when it is working at the level of these outlets.

6.4.3 Catchwater Ditches

It is often useful to make a catchwater or intercepting ditch above a cut to stop the water before it reaches the face of the cut slope and to lead it to a drainage channel, preventing it from reaching the road. A catchwater ditch is made in the same way as the side ditch.

Its size depends on the steepness of the slope situated above it. It should not be constructed too close to the top of the cut slope to prevent possible seepage

Table 6.2. A guide for placing common soil and geologic types into soil erosion and soil infiltration classes to space lateral road drainage culverts (USDA Forest Service 1966)



which could be dangerous to the stability of the slope it is protecting. The minimum distance must be at least 4–5 m.

6.4.4 Culverts

In sloping ground, a culvert is often required to carry water across the road in order to drain a side ditch. When there is no culvert, the water must pass over the road during storms. The road then acts as spillway, sometimes leading to a

Table 6.3. Table of ditch outlet spacing, meters, as a function of erosion class, road grade, and rainfall intensity

Road grade (%)	Erosion class/Erosion index									
	I/10	II/20	III/30	IV/40	V/50	VI/60	VII/70	VIII/80	IX/90	X/100
2	274	373								
3	183	248	326	367						
4	137	186	244	276	309					
5	110	149	195	221	247	264	305			
6	91	125	163	184	206	219	254	308		
7	78	107	139	157	177	189	218	264	314	369
8	69	93	122	137	154	165	190	230	274	322
9	61	82	108	122	137	146	169	204	244	286
10	55	75	98	110	123	133	152	184	219	258
11	50	67	88	101	113	120	139	168	200	235
12	46	62	81	93	104	110	126	154	183	215
13	43	58	75	85	94	102	117	142	169	198
14	40	53	70	79	88	94	108	131	157	184
15	37	50	66	73	82	91	102	123	146	172
16	35	47	61	69	78	85	94	116	137	162
17	32	44	58	66	73	81	90	108	129	152
18	30	41	55	61	69	76	85	102	122	143

The table is based on rainfall intensities of 25–50 mm/h falling in a 15-minute period with an expected interval of recurrence of 25 years. For areas having intensities other than 25–50 mm/h, divide the values in the table as follows: for a rainfall intensity of 50–80 mm/h use a divisor of 1.50; for a rainfall intensity of 80–100 mm/h use a divisor of 1.75; for a rainfall intensity of 100–130 mm/h use a divisor of 2.00

rut in the road. In addition, the water remaining in the side ditch at the end of the storm seeps into the soil and reduces the strength of the roadway.

When a road must remain serviceable for more than a dry season, a culvert should be installed at each low point along the road. Intermediate culverts should be placed according to local experience. In areas of heavy rainfall, culverts may need to be fairly large and numerous. In mountainous areas, care should be taken to not concentrate the water at the top of slumps or fills where landslides could be created.

Proper ditch inlet conditions are provided by angling the culvert across the road in the direction of ditch water flow. Ditch dams can be used to block the ditch and channel water through the culvert (Fig. 6.4a). Culverts should not empty water directly upon a fill slope as excessive erosion can occur as well as failure of the road fill. Down spouts, full round or half round culverts, and energy dissipaters can be used to protect the slope below the road (Fig. 6.4b).

Culverts can be built of different materials of varying durability according to the length of time it is expected that the road will be used and the materials

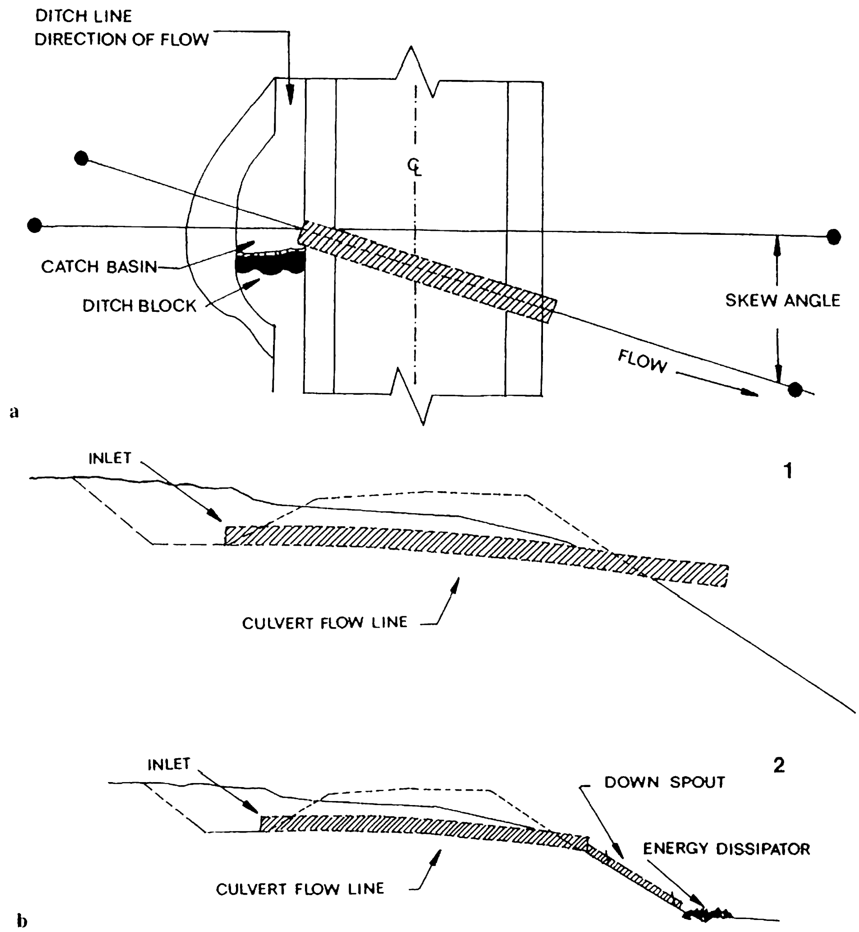


Fig. 6.4. a Proper culvert design. **b** Culvert outlet design: **1** improper outlet; **2** proper outlet with downspout and energy dissipater

available. They can be made using hollow logs, rejected sawmill planks, salvaged metal pipes, or pipes made from cement, steel, or plastic. If hollow logs are used, the narrower end should be placed at the inlet to avoid obstruction.

Galvanized culverts will have short lives where water is acidic. For longer lives, concrete structures may be more suitable. Prefabricated steel culverts are superior to articulated concrete pipes as concrete pipes could collapse under the load of heavy hauling during periods of weakened road strength and obstructed or blocked water passage.

For temporary roads, where drainage structures will be removed after harvesting operations, hollow logs, closed-top log culverts (Fig. 6.5a), stacked-log

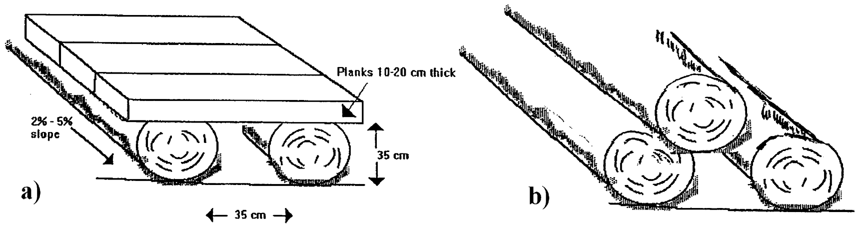


Fig. 6.5. **a** Closed-top log culvert and **b** Stacked-log culvert

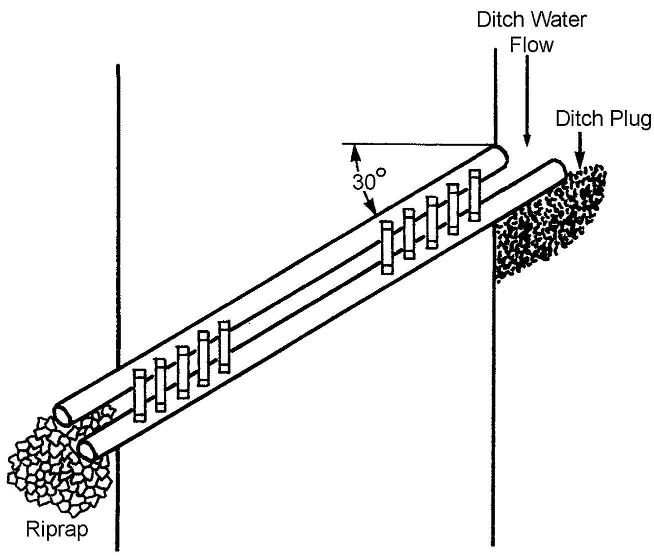


Fig. 6.6. Open-top log culvert

culverts (Fig. 6.5b), and open-top culverts (Fig. 6.6) are often economical. Gradients should be 2–5% to facilitate water flow, but not so much as to create scour at the outfall. Even so, flow through log culvert structures is often limited.

When possible, the culverts should be placed into the subgrade owing to its higher stability. It is important that they are placed on the same level or below the level of the stream. Open-top culverts can be installed to provide cross drainage immediately above steep grades, below bank seepages, or where water will run onto roads or log landings. Open-top culverts need to be cleaned frequently as they can easily fill with debris.

6.4.5
Broad-Based Dips or Rolling Grades

Sometimes it is impractical to use cross-drain culverts. Careful construction of rolling dips, outsloping, and armoring of selected portions of dips and fills can be used for drainage while also minimizing erosion. Drainage dips work well for taking surface runoff of outsloped roads without a ditch. Broad-based dips usually cost less than culverts and require less maintenance. Dips should be designed with a sufficient curve length and depth to permit vehicle passage. Drainage dips should not be built on fills greater than 2 m. A surface of crushed rock should be placed on the dip and mound for soils and conditions where rutting may occur. Spacing for broad-based dips is the same as for other drainage outlets.

Where tractor-trailers must be accommodated, a relatively long horizontal drainage dip transition permits easy passage. On grades less than 9% where at least a 64-m tangent exists and the road outlet spacing requirements are met, the design in Table 6.4 has worked well. The length, depth, and height of the sag and crest vertical curves are high enough to prevent obliteration by road maintenance activities (Fig. 6.7). On steeper grades, the dips may need to be more closely spaced and a shorter horizontal transition will be required.

6.4.6
Water Bars

A water bar is a shallow trench with a mound or berm which provides cross drainage and intercepts overland flow from inactive or closed roads. Constructing a water bar will minimize erosion and provide conditions for revegetation. Water bars are placed at 30–45° to the road with a cross-drainage grade of 2–5%. A water

Table 6.4. Drainage dip design and construction staking data (m)

Road grade (%)	Drainage dip construction stakes using stationing				
	0+000	0+021	0+034	0+043	0+064
	Cut	Cut	Cut	Fill	Fill
2–3	0.00	0.40	0.00	0.30	0.00
4	0.00	0.60	0.00	0.43	0.00
5	0.00	0.70	0.00	0.55	0.00
6	0.00	0.82	0.00	0.60	0.00
7	0.00	0.91	0.00	0.70	0.00
8	0.00	1.10	0.00	0.85	0.00

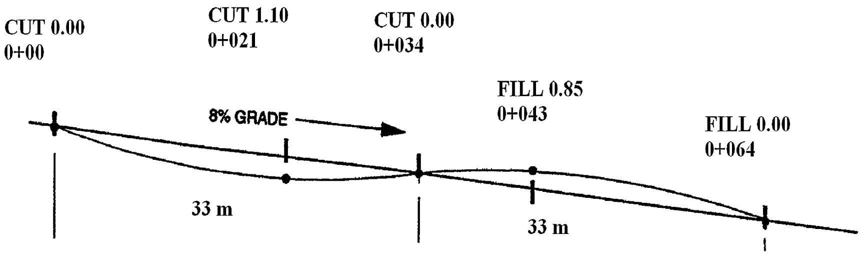


Fig. 6.7. Broad-based dip example for 8% grade (not to scale)

bar is about 3-m long with a 0.3-m mound (Fig. 6.8). Water bar spacing would follow Table 6.3.

6.4.7 Retaining Walls

Occasionally retaining walls are needed to deal with special slope stability issues, including steep fills, bridge abutments, and repairing fill or cut failures. A number of retaining wall types are available, some of which can be constructed from local materials (Fig. 6.9). Retaining wall types include gabions, cribs, cantilever, and counterfort walls, welded-wire walls, and various types of mechanically stabilized earth structures. The basic requirements for the wall are that it be able to resist the

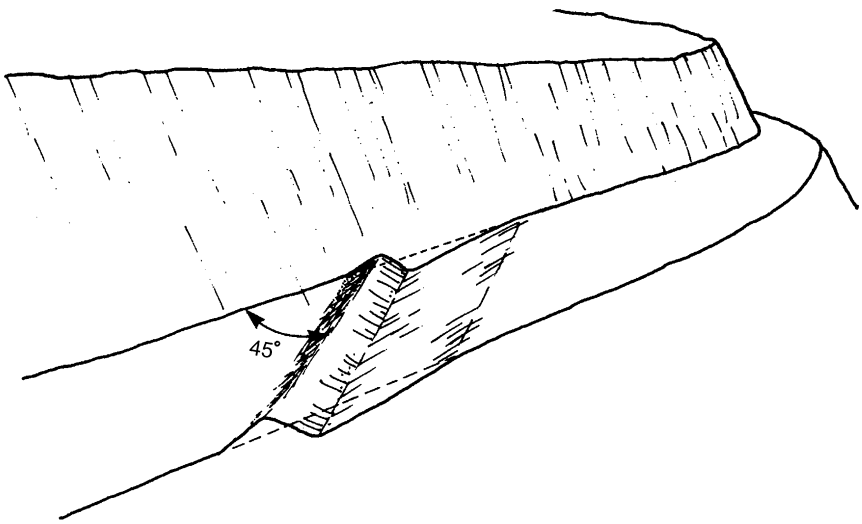


Fig. 6.8. Water bar

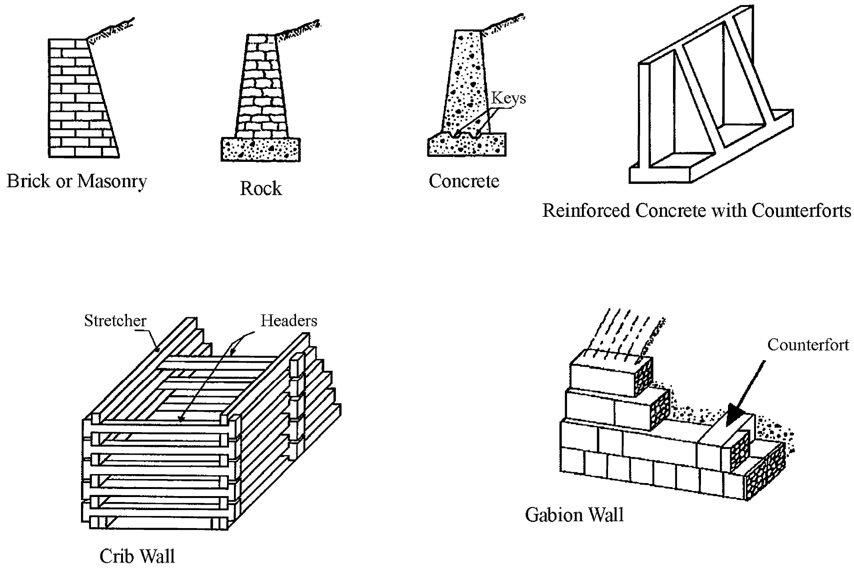


Fig. 6.9. Common retaining walls

forces of the soils behind it and have an adequate bearing foundation. All of the examples above can be considered gravity walls. Stiff walls such as monolithic concrete structures can be designed using conventional stability analysis. Other structures, if they are less than 6 m or so in height, can be designed satisfactorily as if they were stiff, monolithic structures, even though they behave differently.

Given basic soil parameters (Table 6.5) a design can be readily checked to see if it is stable. The three criteria for stability are (1) the wall will resist overturning, (2) it will resist sliding, and (3) it will not exceed the bearing capacity of the underlying soil. There are several approaches to estimating the soil

Table 6.5. Typical ranges of soil angle of internal friction and bearing capacity. Laboratory and field tests should be done to identify soil properties for significant installations

Type of soil	Angle of internal friction (°)	Consistency in place	Bearing capacity (kN/m^2)
Sand and gravel	30–40	Compact	380
		Loose	190
Sandy loam	20–30	Compact	290
		Loose	145
Clay	10–20	Stiff	190
		Soft	50

forces acting on the wall. Here Coulomb's formula is used. Soil cohesion, if any, is ignored, and wall height should not exceed 6 m. The wall must be water-permeable through use of weep holes or other drains. Walls sitting on clay may need to be anchored by construction of a narrow trench filled with 15 cm of gravel. If gabions are used in clay, arranging them in a counterfort structure (crosswise) each 5–7 m will provide drainage as well as additional structural support.

The forces acting on the gravity retaining wall are assumed to be concentrated at a height equal to one third of the height of the wall (Fig. 6.10) with a force equal to

$$P_a = \frac{1}{2}\gamma H^2 K_a,$$

where P_a is the active earth force per unit length of wall, γ is the unit weight of the retained soil, H is the height of the wall, and K_a is the coefficient of active earth pressure given by

$$K_a = \left(\frac{\sin(\alpha - \phi)/\sin\alpha}{\sin(\alpha + \phi_w)^{1/2} + \left(\frac{\sin(\phi + \phi_w)\sin(\phi - \beta)}{\sin(\alpha - \beta)}\right)^{1/2}} \right)^2,$$

where, β is the angle of inclination of the backfill or slope, α is the batter angle of the wall, ϕ is the angle of internal friction of retained soil, and ϕ_w is the angle of wall friction. Note the backslope angle cannot be larger than the angle of internal friction.

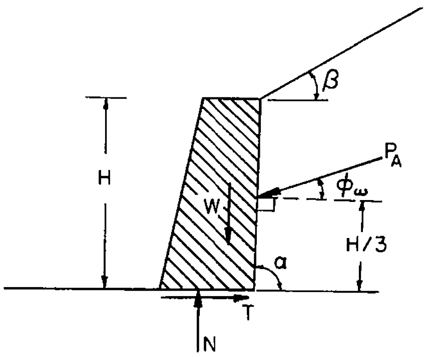


Fig. 6.10. Forces acting on a gravity retaining wall

Resolving P_a into vertical and horizontal components gives $P_{av}=P_a \sin \phi_w$ and $P_{ah}=P_a \cos \phi_w$. The total vertical force the bearing surface under the wall must support is

$$N = W_1 + W_2 + P_{av}.$$

The sum of the restoring moments around the toe of the wall (Fig. 6.11, point PTO) is

$$M_r = W_1 \times (2/3)\, B_1 + (B_1 + B_2/2) W_2 + P_{av}\, (B_1 + B_2).$$

The overturning moment, M_o, around the toe of the wall is

$$M_o = P_{ah}\, (H/3).$$

Check the three conditions for stability; the resistance to overturning, sliding, and bearing failure for adequate factor of safety:

1. To have an adequate resistance to overturning requires that M_r/M_o is greater than the factor of safety (FS), for example, 1.5.
2. To have an adequate resistance to sliding requires that $N \tan\phi / P_{ah}$>FS, for example, 1.5.
3. To spread the bearing load and keep the entire base under compression requires the resultant of the normal force, *N*, is in the middle third of the base. This requires that $0.33(B_1+B_2)<x<0.67(B_1+B_2)$. For the check on bearing capacity, we require the ratio of bearing capacity to bearing pressure to be greater than FS, for example, 2.5.

Example: Check the adequacy of a wall 6-m tall that tapers from a base of 4 m to a top width of 1 m (B_1=3 m and B_2=1 m) with the following soil

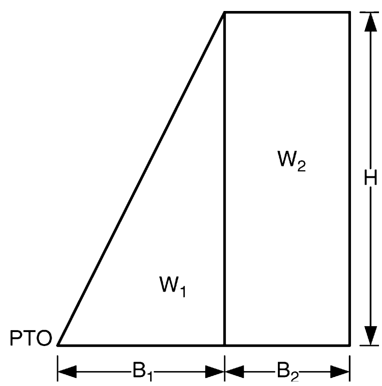


Fig. 6.11. Gravity wall dimensions used for calculations

conditions: sandy gravel, ϕ=36°, ϕ_w=0.8× ϕ=0.8×36=28.8°, α=90°, β=33.7° (1.5 horizontal:1 vertical), γ=17 kN/m^3 (1,735 kg/m^3), bearing capacity 240 kN/m^2.

$$K_a = \left(\frac{\sin(90-36)/\sin 90}{\sin(90+28.8)^{0.5} + \left[\sin(36+28.8)\sin(36-33.7)/\sin(90-33.7)\right]^{0.5}} \right)^2$$
$$= 0.499,$$

$$P_a = 0.5 \times 17 \times 6^2 \times 0.499 = 152.69 \text{ kN/m of wall},$$

$$P_{av} = 152.69 \sin 28.8 = 73.56 \text{ kN/m of wall},$$

$$P_{ah} = 152.69 \cos 28.8 = 133.80 \text{ kN/m of wall},$$

and

$$N = W_1 + W_2 + P_{av}.$$

W_1 and W_2 are calculated as

$$W_1 = 0.5 \times 6 \times 3 \times 17 = 153.0 \text{ kN/m of wall}$$

and

$$W_2 = 6 \times 1 \times 17 = 102.0 \text{ kN/m of wall},$$

and

$$N = W_1 + W_2 + P_{av} = 153.0 + 102.0 + 73.56 = 328.56 \text{ kN/m of wall}.$$

The ratio of the restoring moments to the overturning moment is

$$W_1 \times (2/3)\ B_1 + W_2\ (B_1 + B_2/2) + P_{av}\ (B_1 + B_2)/(P_{ah}H/3) = 153.0 \times (2/3) \times 3 + 102.0 \times (3+0.5) + 73.56 \times (3+1)\ /\ (133.8 \times 6/3) = 3.6,$$

and is therefore OK.
The ratio of the force resisting sliding to soil horizontal force is

$$(W_1 + W_2 + P_{av}) \tan\phi / P_{ah} = [(153.0 + 102.0 + 73.56) \tan 36]/133.8 = 1.8,$$

and is therefore OK.

The location of bearing pressure under the base of the wall measured from the toe is located at

$$[W_1 \times (2/3)\ B_1 + W_2\ (B_1 + B_2/2) + P_{av}\ (B_1 + B_2) - (P_{ah}H/3)]/(W_1 + W_2 + P_{av}) = X_r = \{[153.0 \times (2/3) \times 3] + [102.0 \times (3 + 0.5)] + [73.56 \times (3 + 1)] - (133.8 \times 6/3)\}/(153.0 + 102.0 + 73.56) = 2.10 \text{ m}$$

from the toe of the wall. This puts the center of pressure at 0.52, which is in the middle third of the base, so it is OK.

And lastly, to calculate the ratio of foundation-bearing capacity to the pressure under the wall we calculate the pressure under the toe (front), p_f, of the wall and the pressure under the rear of the wall, p_r, assuming the pressure distribution is linear and use the larger pressure to make a comparison with the allowable bearing capacity of the soil:

$$p_f = 6N/(B_1 + B_2)\ [0.667 - X_r / (B_1 + B_2)] = 6 \times 328.56/4 \times [0.667 - (2.1/4)] = 69.98\ \text{kN/m}^2$$

and

$$p_r = 6N/(B_1 + B_2)\ [X_r/(B_1 + B_2) - 0.333] = 6 \times 328.56/4 \times [(2.1/4) - 0.333] = 94.62\ \text{kN/m}^2$$

Therefore, the maximum pressure is under the rear of the wall and the ratio of the bearing capacity to the maximum bearing pressure under the wall is

$$240\ \text{kN/m}^2/94.62\ \text{kN/m}^2 = 2.5,$$

and is therefore OK.

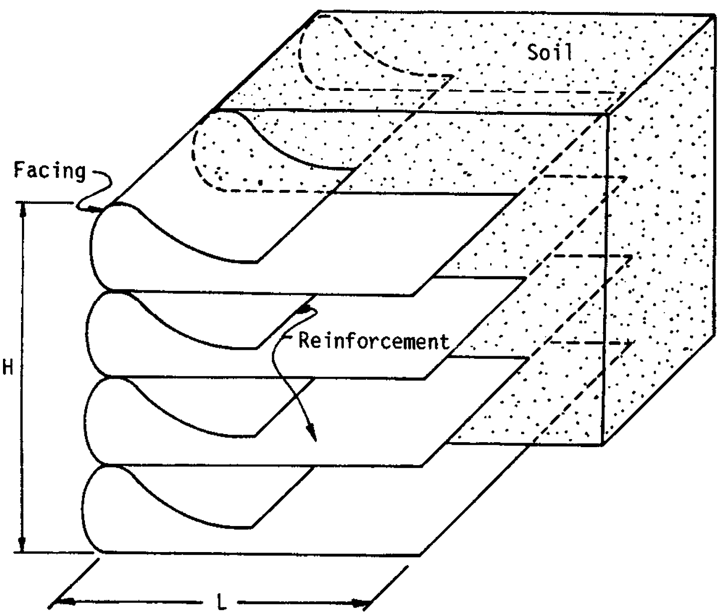


Fig. 6.12. Geotextile or chain-link fencing reinforced soil wall for height *H* and base *L*

6.4.8 Geotextile and Chain-Link Reinforced Walls

Mechanically stabilized earth structures are often a cost-efficient solution for retaining walls. A number of types exist. One that has particular appeal is soil reinforcement using flexible fabrics (geotextile) or fencing (chain link) to reinforce the earth. It has the advantages of (1) ease of transport of construction materials, (2) construction by unskilled labor, (3) limited heavy equipment required, (4) limited foundation preparation, (5) easy drainage of backfill, and (6) rapid construction. The wall facing is constructed by wrapping each geotextile sheet or fencing section around its overlying layer of backfill and reembedding the free end into the backfill (Fig. 6.12). The wrapped wall facing retains the soil immediately behind the wall face, and the embedded portion of the sheet transmits the lateral earth pressure loading. If geotextiles are used, a protective facing is required to protect the fabric from deterioration from ultraviolet light. If chain-link fencing is used, coating protection in acidic soils should be used.

7 Crossing Swamps and Wetspots

7.1 Buried Corduroy

One method of building roads across soft swamps is the use of corduroy construction as the foundation. A corduroy is a layer of brush, branches, or logs between a weak subgrade and the base course. This ensures that the integrity of the base course is maintained. The effect of the corduroy is to spread the load. Noncommercial trees or logs are laid down as a foundation to suspend the roadbed. They may be placed crosswise or lengthwise to provide a bridging effect. Usually the brush and limbs from the trees are placed beneath the corduroy as a mat. Sometimes whole trees with the tops on are used as corduroy. A brush mat can improve drainage by providing a drainage pathway for water infiltrating through the base course that overlays an impervious subgrade. Larcombe (1999) expresses the following relationship between subgrade shear strength, minimum required fill height to distribute the load, fill density, tire pressure, axle load, length of corduroy log, and diameter of corduroy log. A minimum factor of safety of 2.0 is suggested to account for dynamic loads.

Fill only (no log corduroy):

$$c = \frac{\mathrm{FOS} \times q}{5.14}\left[1 - \left(\frac{1}{1 + (R/z)^2}\right)^{3/2}\right] + \frac{\mathrm{FOS} \times Gz}{5.14}.$$

Fill over log corduroy:

$$c = \frac{\mathrm{FOS} \times L}{5.14\,lw}\left[1 - \left(\frac{1}{1 + (R/z)^2}\right)^{3/2}\right] + \frac{\mathrm{FOS} \times Gz}{5.14}.$$

FOS is the factor of safety, q is the tire pressure (in kilopascals), L is the axle load (in kilonewtons), l is the length of log corduroy (in meters), w is the diameter of the log corduroy (in meters), R is the effective load radius (in meters) expressed as $\frac{1}{2}\sqrt{\frac{2L}{\pi q}}$, G is the in-place fill density (in kilonewtons per cubic meter), z is the fill depth (in meters), and c is the subgrade shear strength (in kilopascals). Shear strength can be tested in the laboratory or estimated by using simple field tests (Table 7.1).

Example 1: Factor of safety of 2.0, soft subgrade with shear strength of 24 kPa, axle load of 80 kN (four tires at 20 kN), tire pressure of 580 kPa, and compacted fill density of 20 kN/m^3 (2,040 kg/m^3) Using trial and error for various fill depths, the minimum fill depth would be about 60 cm.

$$R = 0.5\times[(2 \times 80)/(3.1416 \times 580)]^{1/2} = 0.1482 \text{ m}$$

and

$$c = \frac{2 \times 580}{5.14} \times \left(1 - \left\{1/\left[1+(0.1482/0.6)^2\right]\right\}^{3/2}\right) + \frac{2 \times 20 \times 0.6}{5.14}$$
$$= 19.18+4.67 = 23.9 \text{ kPa},$$

and is therefore OK.

Example 2: If a corduroy made of logs 6-m wide with 10-cm log diameter was used with the other conditions in example 1, using trial and error, the minimum fill depth would be about 22 cm.

$$c = \frac{2 \times 80}{5.14 \times 6 \times 0.1} \times \left(1 - \left\{1/\left[1+(0.1482/0.22)^2\right]\right\}^{3/2}\right) + \frac{2 \times 20 \times 0.22}{5.14}$$
$$= 22.28+1.71 = 24 \text{ kPa}$$

and is therefore OK.

Table 7.1. Field test used to estimate soil shear strength

Description	Field test	Shear strength (kPa)
Very soft	Squeezes between fingers with fist closed	0–24
Soft	Easily molded by fingers	24–48
Firm	Molded by strong pressure of fingers	48–96
Stiff	Dented by strong pressure of fingers	96–144
Very stiff	Dented only slightly by finger pressure	144– 192
Hard	Dented only slightly by pencil point	>192

7.2 Surface Corduroy

For light, temporary passage across swamps, a surface corduroy can be used. The surface consists of crosspoles placed over longitudinal poles. They are fastened to each other by guard rails on both sides (Fig. 7.1).

7.3 Plank Roads

Another version of corduroy construction is the plank road. The plank road is made of short pieces that can be moved after temporary use. Planks are fastened end to end over underlying crosspoles.

7.4 Geotextiles

Synthetic nonwoven fabrics have been used successfully to provide a subgrade restraint over areas of low bearing pressure. Geotextile fabrics are made of polypropylene, are chemically inert, and thus will last indefinitely once buried. The fabric is placed over the native material and the embankment material is

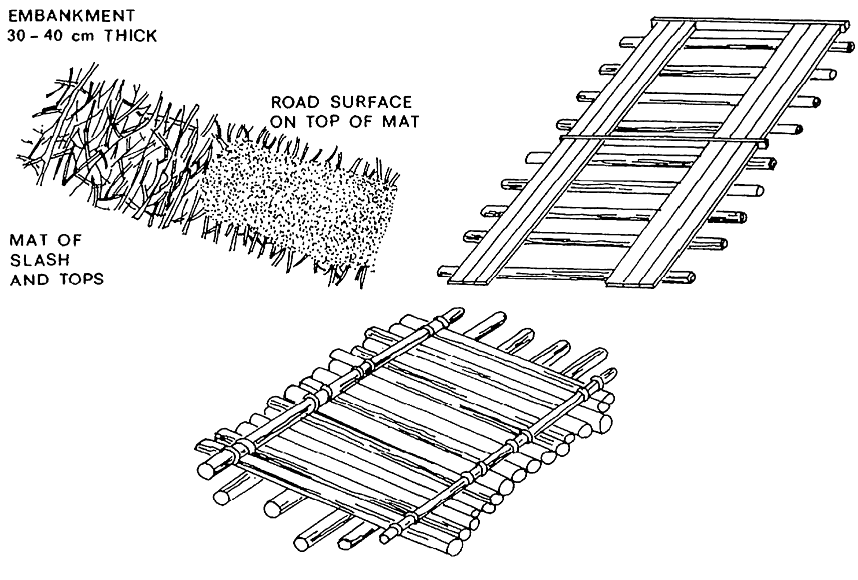


Fig. 7.1. Examples of corduroy and plank roads

built upon it. Occasionally, fabric has been placed over buried corduroy to cross wet holes. The relatively high cost of geotextiles (US $1–2 per square meter) has limited their introduction into forest roads in the tropics but in very soft soils they may be an alternative. In many cases, the use of geotextiles can reduce required aggregate depths by 30–40%.

Geotextiles perform three basic functions in stabilizing roads: separation, drainage, and reinforcement. Geotextiles provide a separation layer between the aggregate and the subgrade soil that prevents contamination of aggregate with fines. In addition to providing separation between the aggregate and the subgrade, the fabrics have high permeability, permitting drainage, and for very soft soils, they also provide reinforcement through the addition of tensile strength.

On soft soils where the subgrade is wet, the geotextile placed over it must be highly permeable to allow rapid drainage of water from the loaded subgrade soil up into the free draining aggregate base. Otherwise, under the rapid loading conditions from traffic, water pressures in the soil can fail the subgrade by soil liquefaction. Geotextiles provide this permeability as they keep fines from migrating upward into the aggregate.

The successful use of geotextiles requires proper selection and installation. Geotextile performance depends heavily on proper selection of the pore size relative to the grain size distribution of the subgrade. Poor geotextile selection will result in clogged pores and trapped water in the subgrade, or pores that are too large and pass the fines into the aggregate.

Preparation affects job success. The four basic steps involved in placing geotextiles are subgrade preparation, geotextile placement, aggregate placement, and aggregate compaction. Fabric is rolled by workers onto the prepared subgrade. Usually the geotextile is laid in the direction of traffic, and geotextile panels are overlapped 0.5–1.0 m. Trucks then backdump aggregate onto the fabric. A tracked bulldozer then spreads the aggregate. Rubber-tired vehicles such as front-end loaders and graders have higher ground pressure and should be avoided on soft soils that may cause the fabric to crack or puncture. Vibratory compactors can be used, but only after reasonable compaction has been achieved by the bulldozer. At least 30 cm of aggregate cover is required to avoid problems with placement and operational performance. Mud waves may appear during aggregate placement over very soft subgrades. These are usually not a problem if they do not heave above the surface of the aggregate base.

If aggregate recycling is planned, then the use of woven geotextile is recommended. Woven geotextile is stronger than nonwoven geotextile; however, it is more expensive.

Stream Crossings 8

Streams can be crossed by installing various types of culverts, fords, and bridges. The choice of structure depends upon discharge, streambed characteristics, traffic, and local costs. Road approaches to streams must be carefully designed to prevent the road from being a point source for sediment entering the stream. Surface runoff from the road and ditches should be diverted from the road a minimum of 20 m before the stream crossing. If the approach to the stream is a descending grade, the approach should be surfaced with better-quality aggregate, if available, to reduce ruts channeling sediment into the stream. Bridge approaches should be designed, where possible, with at least a 2% ascending grade to the bridge decks.

8.1 Stream Flow

Of the factors affecting choice of structure, discharge is the most difficult to estimate. Rainfall in the tropics can be intense, exceeding 250 mm/h, with a mean flow of 15–30 $m^3/s/km^2$ on a 10–25-year return interval. This can be 10 times what would be expected in wet temperate areas and design charts must be used with care. Careful inspection of high-water marks may be the best guide. An estimate of the flow can be made using the Rational formula $Q=CI\,A/362$, where Q is the estimated flow (in cubic meters per second), C is a runoff coefficient that depends on watershed conditions, I is the rainfall intensity (in millimeters per hour), and A is the watershed area (in hectares). Values of C for forest on level ground range from 0.05 to 0.25, and for forest on steep slopes from 0.15 to 0.40. For agricultural areas, C varies from 0.20 to 0.60.
Example: I=200 mm/h, C=0.25, and A=100 ha (1 km^2),

$$Q = 0.25 \times 200 \times 100/362 = 13.8\ m^3/s.$$

If high-water marks are available, flow can be estimated using Manning's equation:

$$Q = (A/n)(A/P)^{2/3}\ (S^{1/2}),$$

where Q is the flow (in cubic meters per second), A is cross-sectional area (in square meters), P is the wetted perimeter (in meters), S is the channel slope (in meters per meter), and n is Manning's roughness coefficient. The wetted perimeter is the distance along the channel bottom and or sides that is under water within the area (A) of flow. The slope is measured in the actual stream channel upslope and downslope of the site. The area should be measured at a couple of representative cross sections along the flow channel. The roughness coefficient varies between 0.04 to 0.07 for natural channels. Roughness values generally increase as channel vegetation and debris increases, and as channel sinuosity increases. Smooth earth or rock channels can have lower roughness coefficients (0.02–0.03)

Example: A=20 m^2, P=14 m, S=0.02 m/m, and n=0.05,

$Q = (20/0.05) \times (20/14)^{2/3} \times (0.02)^{1/2} = 400 \times 1.27 \times 0.14 = 72$ m^3/s.

8.2 Culverts

Culverts made of concrete, metal (corrugated steel or aluminum), and plastic pipe are used as well as those made of masonry and wood. The type of material depends on cost and availability. Because of changing climatic conditions, debris and bedload in channels, changing land-use patterns, and uncertainties in hydrologic estimates, culvert size and capacity should be conservative, and should be oversized rather than undersized. To accommodate a given discharge a culvert with headwall and wingwalls will require a lower headwater depth than a mitered installation (Fig. 8.1). A culvert projecting from the fill will require the greatest headwater depth. Headwater depths must be considered during road design. Culvert capacities for concrete, metal, and plastic pipe are available from handbooks. Culvert exits should not be placed on fill slopes.

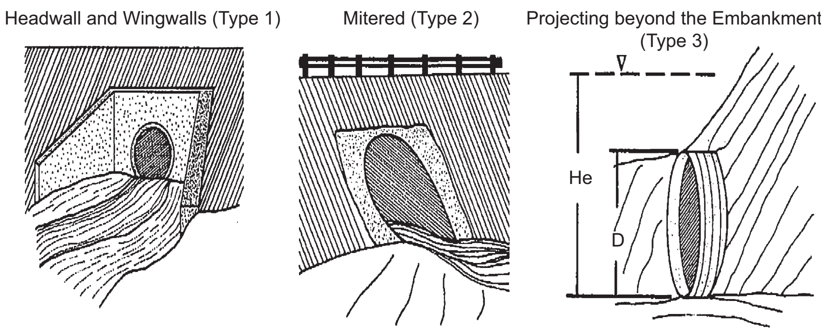


Fig. 8.1. Three types of inlet controls for culverts. (From Keller and Sherar 2003)

Use culverts long enough to extend to the toe of the slope or use headwall structures to retain the fill material and minimize the culvert length.

Ideally a culvert should be as wide as the natural channel to avoid channel constriction. Channel protection, riprap, overflow dips, headwalls, and trash racks can mitigate culvert problems, but none are as good as an adequately sized and well-placed culvert.

The major disadvantage of a culvert, compared with other stream crossing structures, is that a culvert requires more frequent maintenance for debris removal. Trash racks are options to reduce debris, and they can be installed either at the culvert inlet or upstream. Culverts with trash racks at the inlet run the risk of being blocked during a large rain event and therefore should be avoided if there are alternative locations. Access to trash racks is important for maintenance. One option to protect an important culvert is to provide an armored relief dip (Fig. 8.2). The armored relief dip is constructed in the road near the culvert. If the culvert becomes blocked or if the water discharge exceeds the design, water can enter an armored ditch line, flow across the road over an armored dip, and then be dissipated onto a riprap reinforced fill on the downslope side of the dip and filtered onto stable and vegetated ground. It is important to use a complete grade reversal within the length of the dip.

8.3 Low Water Crossings

When streams are shallow and currents are gentle, the streams can be crossed by means of low water crossings also known as drifts or fords. Drifts are low stone/concrete structures on the riverbed (Fig. 8.3). They are constructed a little above the hard riverbed and below the road level. Fords allow vehicles to pass through the water over their firm surface. They are cheap and solid solutions to be used in normally dry rivers which are periodically flooded. Smaller drifts are called splashes.

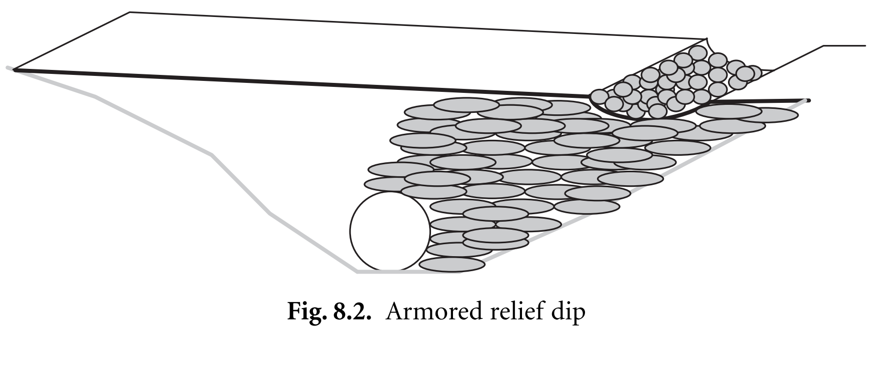


Fig. 8.2. Armored relief dip

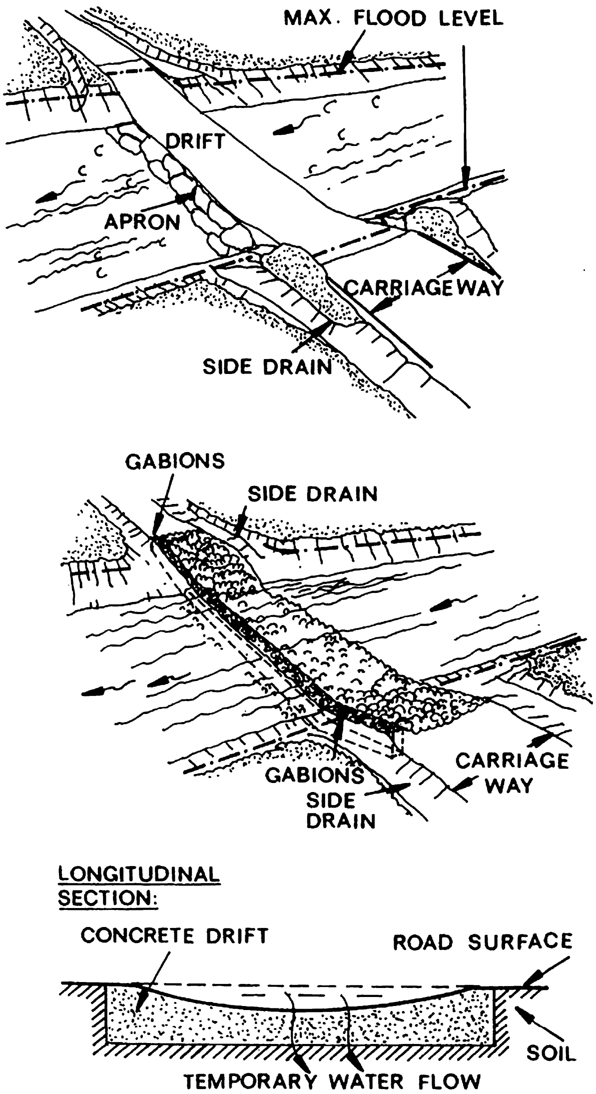


Fig. 8.3. Examples of drifts (fords)

Advantages of fords:

- Usually not susceptible to plugging by debris or vegetation the way a culvert may plug.
- Are typically less expensive than large culverts or bridges.
- Typically require less fill in the channel.

- Can accommodate larger flows.
- Fords with culverts can be used to pass low flow and keep vehicles out of the water, avoiding water-quality degradation.
- Are more flexible in design; an underestimate of water flow may still be accommodated.

Disadvantages of fords:

- Traffic may be delayed during periods of high water flow.
- Are restricted to gentle terrain; should not be placed in areas of high fills.
- Vehicles must cross at low speed.
- Fords with culverts must have maintenance similar to culvert maintenance.
- It may be difficult to provide fish passage.

When the water flow in the river is slow and the riverbed is firm enough to maintain a trafficable base under the water, the drift can be built of stones and gravel. Both upstream and downstream sides of the drift (or splash) are strengthened by stone aprons to prevent erosion. The riverbanks usually have to be excavated a little to allow smooth driving to and from the drift.

A stone-surfaced drift may be a suitable structure on a shallow sandy river where the fall is gentle. The riverbed can be strengthened by gabions, which are wire baskets filled with rocks or stones and bound together. These baskets are placed side by side on a trench dug along the downstream edge of the crossing. The top of the gabions must be completely level with the riverbed (Fig. 8.3). The approach to the ford should be surfaced with rock aggregate, or a concrete pad, to prevent water-quality degradation.

The trench for the gabions should be dug sufficiently deep. The crossfall of the riverbed should not exceed 3%. The stone layer of the drift should be at least 30-cm thick. In the middle of the stream, the top of the drift should be level with the stream bed. A stone "apron" is needed at the downstream side of the drift, just adjacent to the gabions.

A nonsurfaced drift can be used for low traffic. It consists of a porous dam which retains gravel with the help of rock-filled gabions. The size of these gabions is 1 m×1 m×2 m and trenches for them along the downstream side of the crossing must be dug 1.2m wide. A stone apron is placed on the downstream side of the gabions.

When the drift is used more regularly, the surface of the drift can be made of concrete (Fig. 8.3). A higher-elevated concrete drift should be built when the water flow in the river is strong. The "waterfall" on the downriver side of the drift locally increases the velocity of the water. The riverbed on the downstream side has to be protected against erosion by a stone apron. The apron must be of considerable strength and extend 3–4 m from the lower edge of the drift. Even with the concrete drift, the middle of the drift is lower than the sides of the riverbanks so that water flows over the drift.

Culvert drifts (vented fords, submersible bridges, and causeways) may be needed in small rivers having strong currents. The construction height of the culvert drift is higher than that of the usual concrete drift because it has to incorporate the culverts. Normally the water runs through the culverts. During floods, the water also runs over the concrete structure. In this way, large volumes of water can be managed and during low flows vehicles are not traveling in the stream bed (Fig. 8.4). Submersible bridges are bridges that are designed to be occasionally overtopped. They must be designed with erosion-resistance deck and approaches. Submersible bridges are ideal for fish passage.

8.4 Permanent Bridges

A bridge may be needed to lead the road over a ravine or creek where large volumes of water run temporarily, and where drifts cannot be used. The bridge must be elevated sufficiently high above maximum flood level, and be sufficiently

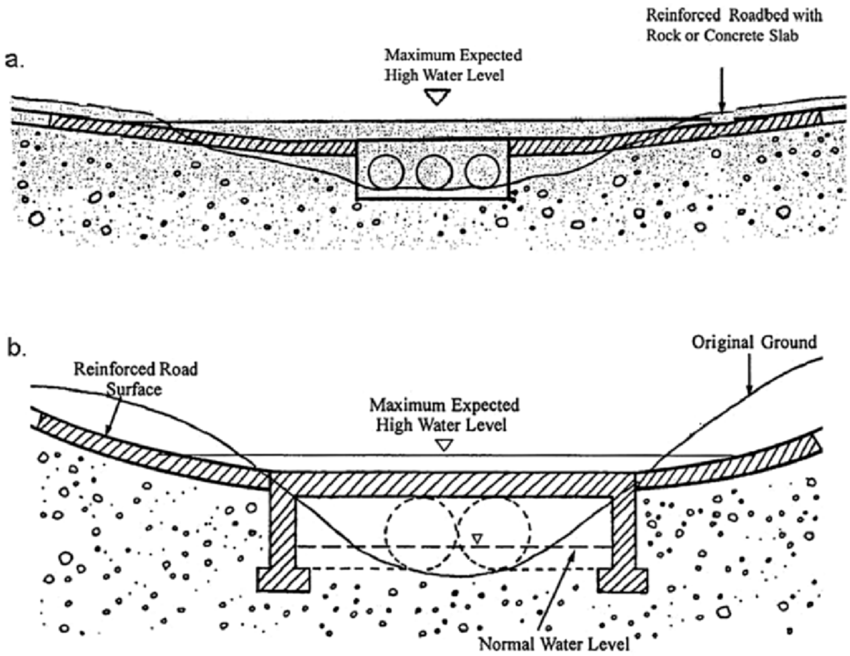


Fig. 8.4. Examples of fords with culverts and open box (From Keller and Sherar 2003)

strong to carry the expected traffic. For these reasons, the construction costs of a bridge are rather high. In view of these high costs, calculations are always needed to decide whether the road could be alternatively located to avoid bridge building. When there is no better alternative to a bridge, the (technically and economically) most suitable construction must be determined. In areas without danger of termites, wooden bridges may be safe for 10 years if built correctly, and may stay in service even longer when inspected and repaired regularly. Wooden bridges are most suitable for narrow streams with steep and rocky banks. Frequently, bridges are constructed of steel, prefabricated wooden or concrete units, or glued and laminated (glulam) units.

Specialized engineering skills are required to ensure sufficient load-bearing capacity. The safety factor for wooden bridges is calculated according to the strength of timber and local conditions. Special attention and precautions are needed to build safe bridges for loaded timber trucks with a total weight of 10–20 t, and in some regions up to 50 t or more.

Small bridges can be built by experienced workers if workers are given design graphs or design tables showing correct structures for bridges of different spans. Basic components of wooden bridges are shown in the Fig. 8.5. A pile abutment is shown on the left bank, and a crib abutment on the right one. In order to prevent debris clinging to the piers, a V-shaped deflection device should be built upstream of the piers, but is not shown in the illustration. A simple timber-stringer bridge can be constructed of two sill logs (head logs) anchored on each bank of the stream, and two or more stringers lying on the logs (Fig. 8.6).

8.4.1 Bridge Location

Bridge locations often control the road location. Small changes in bridge location can sometimes greatly affect costs, so bridges should be located to provide

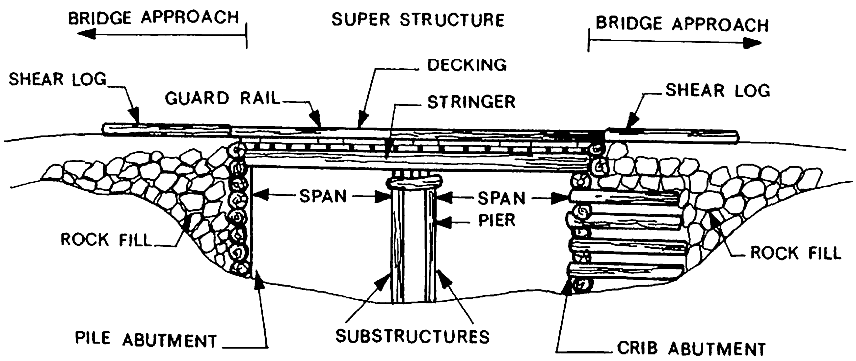


Fig. 8.5. Log stringer bridge

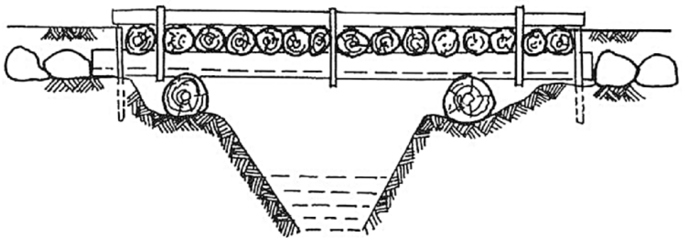


Fig. 8.6. Log stringer bridge on simple log sills (From Kantola and Harstella 1988)

the greatest design flexibility. Bridges should be located where the stream channel is narrow, straight, and uniform. Cross the stream perpendicular to the channel to minimize the bridge span, and to minimize earthwork in the stream. This will result in the lowest bridge cost and minimize stream impacts. If a horizontal curve is required on a one-lane bridge approach, make sure there is an adequate horizontal tangent distance from the curve point to prevent vehicle off-tracking onto the bridge deck. Where possible, the crossing should have solid bridge abutment foundations.

Consider natural channel adjustments and possible channel location changes over the design life of the structure. Channels that are sinuous, have meanders, or have broad flood plains may change location after a major storm event. Avoid narrowing the width of the natural stream channel. Design bridge approaches such that the bottom of the stringers is at least 0.5 m and preferably 2 m above high water to pass storm flow and debris, unless the bridge has been specifically designed to be occasionally submerged. Avoid placing abutments in the active stream channel. Where necessary, place in-channel abutments in a direction parallel to the flow. Place foundations on non-scour-susceptible material, or below the maximum expected depth of scour. Prevent foundation or channel scour with the use of locally available heavy riprap, gabion baskets, or concrete reinforcement.

8.4.2 Abutments

The bridge abutments support the bridge structure and determine the length of span needed. Setting back the abutment increases the span so there is a tradeoff between the cost of constructing a vertical or sloping abutment and using shorter, smaller stringers, or using the natural ground slope and using longer stringers. Abutments should not interfere with the active channel. In situations where this cannot be avoided, abutment protection will be required.

If the ground of the banks is too soft to support the bridge on a single sill log, the load-bearing area on the bank must be increased (Fig. 8.7). Mud sills under the sill logs should have a diameter of more than 25 cm and a length of more than 1.5 m. The mud sills should be made of debarked, seasoned wood. To ensure longer working life, the sapwood from the upper side and underside should be trimmed away. The sill logs should rest evenly on the mud sills.

Instead of mud sills, concrete pads can be used. At both ends of the stringers, a girder log or girder stones are needed to hold the stringers firmly in place. Foundation logs can be placed under the mud sills to make an even firmer foundation. They should be longer and much thicker than the sill logs. If there is risk of undermining by erosion, the foundation logs should be lashed together with steel wire.

To improve stability, notches should be made on top of the sill logs, mud sills, and foundation logs where they contact overlying logs. A multiple sill log abutment

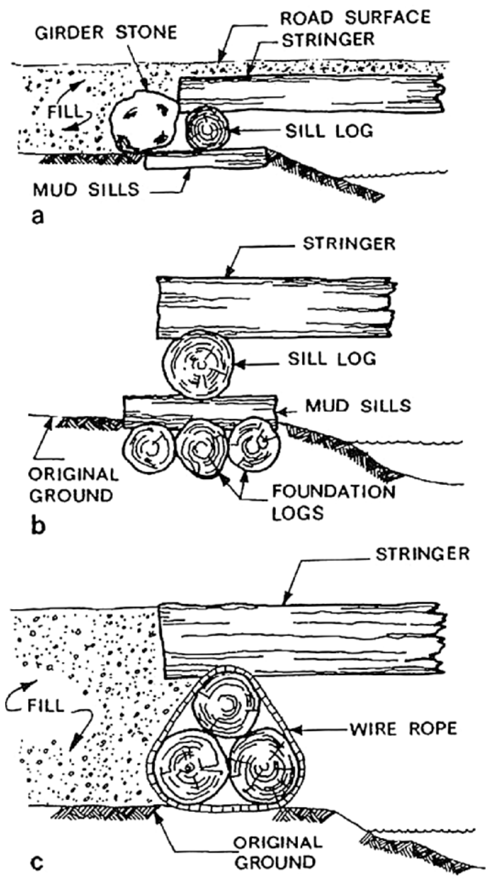


Fig. 8.7. Alternative sill constructions. **a** Mud sill. **b** Mud sill with foundation logs. **c** Multiple log sill. (From Kantola and Harstella 1988)

is needed when a single sill log is not high enough for the bridge level. To create more height, three or more logs are lashed together with wire rope on each end and at the middle (Fig. 8.7). The top log acts as the sill log. To meet the stringers at an exact height, the top log may be flattened accordingly.

If the multiple-sill abutment does not provide sufficient height, different kinds of log cribs can be built. A simple log crib is built from face logs placed parallel to the stream bed, and tieback logs (wing logs) positioned perpendicular to them. Figure 8.8 shows an open-end log crib made of face logs, wing logs, and tieback logs. Wing logs are visible from the outside, follow the gradient of the sideslopes, and contain the fill inside of the cribbing. Tieback logs anchor the middle section of the crib, and are held in place by friction.

8.4.3 Stringers

The size of and number of stringers should be determined from structural timber handbooks. The diameter of the stringers depends upon the unsupported length of the span, the number of axles, axle spacing, timber characteristics,

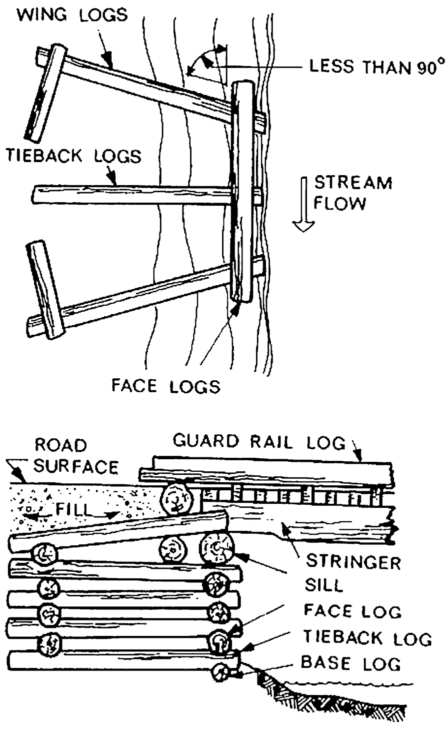


Fig. 8.8. Log crib abutment

and type of decking. The strength capacity of a stringer is a function of the third power of the diameter and its strength (maximum allowable bending stress at outer fiber). Bending stress properties are related to oven-dry specific gravity and many tropical timbers have high specific gravities. As an illustration, timber bridges for heavy loads constructed with a single span of 9–12 m and round-wood stringers might require a mid-diameter of around 75 cm. If the clear span is 15–20 m, a mid-diameter of 90–100 cm is required (Kantola and Harstella 1988). The intended useful life of the bridge is an important factor in selecting bridge stringers. Log stringers deteriorate over time. Choosing oversize stringers extends bridge life.

A common single-span, log stringer bridge for a single vehicle uses four stringers from local materials with a rough sawn, wood plank deck. It is important to identify the most critical vehicle that will use the bridge. To illustrate the importance of matching the bridge design to the vehicle use, stringer dimensions for different spans are shown in Table 8.1 for a 35-t truck, a 50-t truck, and a 48-t bulldozer. Table 8.1 includes log stringers for two maximum bending stresses, 10,000 and 8,000 kPa.

From Table 8.1, the bulldozer would be the critical vehicle for the shorter spans. Transport of the bulldozer by a lowboy with suitable axle spacing would permit use of smaller stringers. Table 8.1 also illustrates the difficulty with posting bridge load limits. A 50-t load limit designed for timber trucks would not adequately protect the bridge from a 48-t bulldozer. This is because at shorter spans, the wheel loads from the timber trucks are not concentrated on the bridge deck, while the shorter track base of the bulldozer concentrates the load. At longer spans, the differences diminish, and at very long spans (more than 30 m), it may be better for the bulldozer to be offloaded from a lowboy and to walk itself across the bridge.

The diameter of stringers should be taken under bark at midspan, and under sapwood if the bridge is to be used for longer periods. Stringers should

Table 8.1. Stringer diameters (cm) for a 35-t five-axle truck, a 50-t five-axle truck, and a 48-t bulldozer for 10–20-m spans for maximum stresses of 10,000 and 8,000 kPa. Overall truck axle spacing is 11.6 m front axle to middle of trailer tandem axles, 6.1 m center to center of tandem axles with a weight distribution of 10,45, and 45%. Bulldozer track load is distributed over 3.1 m. The timber deck is rough lumber planking

	35-t truck	50-t truck	48-t bulldozer	35-t truck	50-t truck	48-t bulldozer
	10,000 kPa	10,000 kPa	10,000 kPa	8,000 kPa	8,000 kPa	8,000 kPa
10-m span	54	59	64	59	64	69
15-m span	72	77	79	79	84	89
20-m span	89	97	97	100	107	107

be alternated large end to small end with shims placed as necessary. If all small ends are grouped together, then instead of using the midspan diameter, the diameter at two thirds of the stringer length toward the small end should be used in stringer selection. If four stringers of adequate size cannot be found, a greater number of smaller-diameter stringers can be used.

Stringers should be debarked, mortised, and anchored by wooden poles in the ground. They should extend at least 0.5 m beyond the sill logs on the banks. When small bridges are built for temporary use and have a long span, the stringers may need additional support. One possibility is to provide intermediate support by substructures. In times of flood, these substructures may trap debris from the water and thus destroy the bridge. Other possibilities include use of a temporary support which is later removed, or to design the bridge with larger stringers. Piers between the abutments are needed when the length of a bridge is too long or too expensive for a single span. They may be pile piers, post-bent piers, log crib piers, or concrete piers.

8.4.4 Decking

The decking of a stringer bridge rests on the stringers, provides the running surface for vehicles, and distributes the load over the stringers. The decking may be made of debarked logs 10–20 cm or thicker, which are flat on top (also a little flat on the bottom where they rest on the stringers).

The deck logs may be placed perpendicularly, transversely, or diagonally in relation to the stringers. When they are laid 1–2 cm apart, soil and dirt are allowed to drop between the logs, greatly improving the life of the bridge by improving ventilation. Planks can be laid over the decking to serve as tracks. To offer safe passage over the bridge, guard rail logs (curbs) are fastened on the sides of the deck. When secured to the stringers, they reinforce the load-carrying structure.

Where stringers cover the entire width of the road, sometimes laterite or aggregate surfacing is used rather than decking to distribute the wheel loads and to provide the running surface. The small voids between the stringers are filled with branches or small poles. The advantage of the using surfacing rather than decking is ease of construction and cost. The disadvantages include the additional dead weight of the bridge, shorter bridge life due to prolonged moisture contact, and the difficulty for truck operators to follow the transition from road to bridge to check driving conditions, particularly at night. To illustrate the additional stringer size to accommodate the surfacing, the three previous cases from Table 8.1 are repeated in Table 8.2 with a 45-cm compacted laterite surface. The use of the laterite surfacing added 14–18% to the required stringer diameters.

Table 8.2. Stringer diameters (cm) for a 35-t five-axle truck, a 50-t five-axle truck, and a 48-t bulldozer for 10–20 m spans for maximum stresses of 10,000 and 8,000 kPa. Overall truck axle spacing is 11.6 m front axle to middle of rear trailer tandem axle, 6.1 m center to center of tandem axles with a weight distribution of 10,45, and 45%. Bulldozer track load is distributed over 3.1 m. The bridge deck is 45 cm of compacted laterite

	35-t truck	50-t truck	48-t bulldozer	35-t truck	50-t truck	48-t bulldozer
	10,000 kPa	10,000 kPa	10,000 kPa	8,000 kPa	8,000 kPa	8,000 kPa
10-m span	64	69	72	69	74	77
15-m span	86	89	92	94	100	100
20-m span	107	112	112	117	122	122

8.5 Portable Bridges

In some situations portable bridges are a useful stream-crossing alternative. Portable bridges have the advantages of reducing construction time, are reusable, and eliminate access to property after harvesting has been completed. Portable bridges can be made from a variety of materials. Laminated wood structures are often used. Most are designed as single-span structures, 10–15 m in overall length, and consist of several panels. Installation is usually by excavator but a crawler tractor could be used to winch the panels into place. Sometimes the deck panels are placed directly onto the stream banks. However, placing a sill log under each end prevents differential settlement of the deck panels. Installation takes less than a day and removal can be done in about half a day. A wear surface is usually not required. As with any bridge, the bridge capacity must be appropriate for the intended use. Portable bridges have been used for both log-truck haul and for skidding along major skid trails. Portable bridges for skid trails are installed by a grapple skidder or by winching the panels into place with a skidder or crawler tractor. When using a grapple skidder, the grapple skidder picks up the panel, backs the panel into place across the stream, and then lowers the panel directly on the stream bank.

Forest Road Maintenance 9

The purpose of road maintenance is to protect the road structure, permit safe travel, maintain truck transport productivity, and minimize the adverse impacts to water quality, fish habitat, wildlife habitat, and other natural resources that may be caused by the presence of the road system. Lack of road maintenance increases truck maintenance costs, reduces truck speed, reduces safety, increases sediment, may cause mass soil movement, and, in the extreme, renders the road unusable.

The objectives of road maintenance are to maintain roads and structures to the intended design standards, to maintain a fully functional drainage system, to minimize soil disturbance during maintenance activities, to minimize impacts to water quality, aquatic habitat, and wildlife habitat, to combine professional-level expertise and operator experience in the formation of on-the-ground decisions, and to provide a protocol for identifying and responding to immediate maintenance needs.

The appropriate maintenance cycle depends on the level of traffic, season of use, grade, alignment, and surfacing type. The maintenance level of the road is measured by visual inspection of the drainage system and road surface, and road roughness measurements. The key factor to road performance is maintenance of the drainage system. This consists of maintaining and restoring the road crown and surface, ditch, and culvert cleaning (Fig. 9.1). Other road maintenance activities include clearing brush on the right of way to improve sight distance, applying dust abatement, and resurfacing.

The basis for the development of a road maintenance plan is a thorough understanding of the road system, its characteristics and needs. This is accomplished by establishing and maintaining an inventory of the road system. The inventory provides the information necessary for identifying and prioritizing required maintenance. In addition, the inventory will also provide the basis for development of road improvement plans. At a minimum, the inventory will categorize roads, identify drainage structures, rate their condition, identify and assess potential slope stability problems, and maintain information related to the condition of the road.

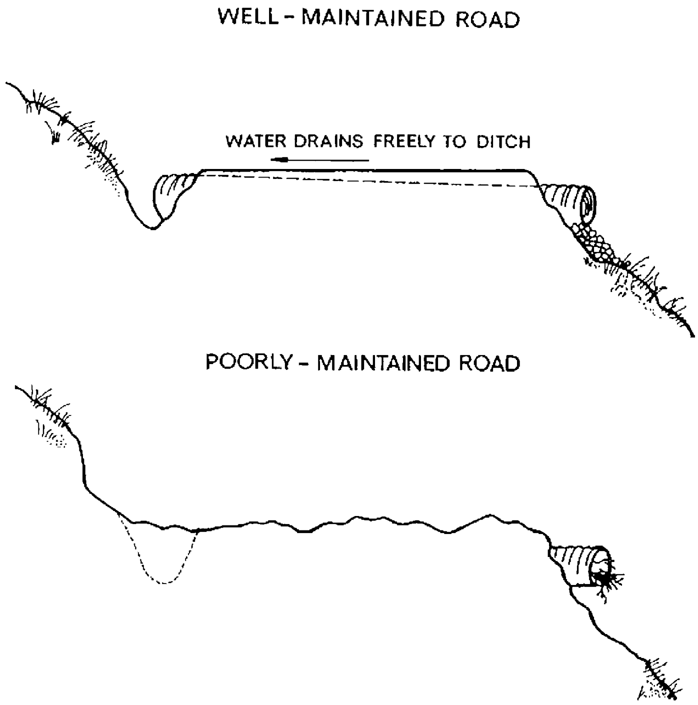


Fig. 9.1. Examples of some important differences between well-maintained and poorly maintained roads

Roads should be inspected on a seasonal basis or more frequently as the level of road use varies or local conditions warrant. The inspection will assess the condition of the road, identify any maintenance activity that is required, and provide information necessary to update the inventory. Particular attention should be paid to culvert inlets and outlets, ditches, road surface drainage, and cut slope and fill slope stability. The inspection should take place early enough so that any work identified can be completed prior to the start of wet season rains. Roads should be inspected regularly during periods of heavy hauling in order to detect signs of initial damage. Standing water or ruts indicate that the strength of the road is deteriorating and that immediate attention is needed. Often a small amount of maintenance at the right time can save large expenditures in road repairs later.

9.1 Ditch and Culvert Maintenance

The most important type of maintenance for culverts is prompt removal of any material that restricts water flow. Remove woody debris, leaves, mud, and gravel from within the culvert and from the inlet and outlet. It is especially important to remove large debris because it can greatly reduce water flow by itself. Reduced water flow will trap additional material. Hand cleaning of culverts is best because it reduces the possibility of structural damage. At a minimum, the culverts should be inspected just before each rainy season. Inspection and cleaning during wet weather can be effective in preventing more serious problems. Inspecting ditches during periods of high rainfall is a good time to determine if ditches need cleaning to improve their capacity or if ditches are carrying too much water. It is also a good time to prioritize the location of new lateral drainage structures. Ditches that show signs of erosion or down cutting will need additional cross drains or need to be armored with riprap to prevent further erosion. Marked culvert locations can substantially improve the efficiency of inspection activities, as well as help to reduce damage from heavy equipment.

Certain preventive measures can be used to reduce culvert problems and the need for cleaning and other maintenance. For example, drainages and ditches that supply water to culverts should be cleaned free of floatable debris for no less than 10 m above the inlet and preferably 30–60 m above it. Another approach is to install some type of rack or grate at the inlet to catch material before it becomes wedged within the culvert. The rack will require regular cleaning, but this work is easier that cleaning the culvert itself. In addition to regular cleaning, the area near each end of the culvert must be maintained. Scouring of soil at the culvert inlet or outlet can become increasingly worse.

In steep terrain, slumps and slides sometimes occur on cut and fill slopes, blocking ditches and other drainages. Clean these promptly, especially during wet weather. Transport the slide material to a location where it will not create additional erosion problems. Frequent grading or “pulling” of ditches is usually unnecessary, and can cause excessive erosion. When pulling a ditch, avoid pulling the material across the road surface. This can lead to contamination of the surfacing material and increased erosion, particularly during the onset of the wet season. Material pulled from the ditch can be windrowed on the inside road shoulder and transported away for proper disposal.

9.2 Restoring Camber

Roadways lose camber through improper grading practices, loss of material, settlement, poor construction, or inadequate drainage. In the tropics, if a road loses camber it will no longer be able to provide effective drainage, leading to ruts, mudholes, and ultimately structural failure. In order to restore camber, the road must be reshaped. The best procedure to reshape the road involves scarifying the surface, adding material either imported or extracted from the road edges, mixing and shaping the surface to form the camber, and compacting at the optimum moisture content. Blading should never be done without good moisture in the material: material should be moist, but not saturated. Grading should begin at the edge of the road and work inward. The windrowed material is positioned at the center of the road and then spread back evenly across the cut surface. This procedure is repeated on each side of the roadway. It is important that the grader does not make a final pass down the center of the road with the blade down and horizontal as this will remove the camber.

On steep grades, grader operators need to be careful to not increase superelevation around curves where loaded trucks are hauling uphill as this will reduce gradeability of the vehicle. On horizontal curves, grader operators need to maintain the transition superelevation between a horizontal curve and the tangent section to prevent sideslipping of the vehicle.

9.3 Washboarding

Washboarding or the creation of parallel ridges more or less at right angles to the road axis is a phenomenon well known in tropical forests, whether they have laterite or gravel surfaces. The height of the corrugations increases with the number of vehicle passages and the corrugations harden. Washboards are caused by a combination of factors, including insufficient fines in the surface layer, dryness, and tire interaction with the road. Hard acceleration and hard braking can lead to washboarding. When a vehicle tire loses a firm grip on the road and either spins or skids, a slight amount of surface material is displaced. With repetition, the surface material will align into a washboard pattern. Light vehicles with small wheels and light suspensions and empty trucks and trailers are the greatest contributors. Washboarding usually appears where you would expect repeated hard acceleration or braking, such as at intersections or sharp curves. Vehicle passage over washboards increases vehicle maintenance cost, reduces vehicle speeds, reducing productivity, and can lead to loss of vehicle control. Reduction of speed and reduced tire inflation pressure can reduce washboard occurrence. If washboards occur, experience shows that the best solution is to suppress the corrugations before they become too troublesome. To do this, maintenance consists of lightly reshaping the surface to restore the camber of the road. Simply blading over washboards with a motorgrader – skimming off the ridges and filling the depressions – is almost useless. The best way to eliminate washboarding is to cut all of the material loose to a depth of 2.5 cm or more below the bottom of the washboard area, then work the material to mix in the fines brought up from below, finally reworking the material back to the proper shape and camber.

Use of a commercially available attachment of rotating scarifying teeth attached to the moldboard of the grader blade produces excellent results, mixing the fines back into the surface gravel. A replaceable bit-type cutting edge on a front-mounted dozer blade can also be used to cut material loose and mix it. Use of a conventional scarifier works too, but only if you can avoid going too deep, bringing up dirt and large rocks from the subgrade, and contaminating the gravel. A drag can also be used. The drag is an economical device, often locally shop-made, which is pulled behind an agricultural tractor. Drags have been constructed from salvaged rail and weighted with concrete or from grader blades attached to wooden beams and weighted with ballast.

When placing new material on a washboarded area, always cut and rework the area before adding the new material. Otherwise, the washboard pattern in the original surface will reflect up to the new surface and you will have the same problem you started with – sometimes in as little as just a few weeks.

Treating gravel with calcium chloride or magnesium chloride is also an option. These commercially available products are not binders, but aid in keeping gravel in place by drawing moisture from the air. The key to success with these products is using them on gravel that already has proper gradation and good natural binding characteristics. These chloride compounds will work to keep the surface slightly damp and the gravel tightly bound.

9.4 Wheel Ruts

On a single-lane road, the wheels of vehicles often use the same track. This repeated passage compacts the track more than the adjacent running surface and provides a path for water to follow which becomes a channel running along the axis of the road. Road maintenance for this problem again consists of restoring the camber to the road. Shallow rutting which does not penetrate through the improved surface layer is considered normal deterioration. It is easily observed prior to blading and can be corrected by routine blading and reshaping. Significant damage affects both the improved surface layer and the subgrade. It is usually detected during the first cutting pass of road reshaping. Rutted surface roads requiring more than two cutting passes of a grader at the same location probably will require a bulldozer or loaders and trucks to repair them.

9.5 Mudholes

Mudholes occur primarily as the result of poor drainage. Untreated mudholes can destroy the roadway. The holes should be drained and allowed to dry and then filled with material of comparable composition and hardness to those of the surface layers of the roadway around them in order to reestablish as uniform a surface as possible. Mudholes should not be filled when wet, nor should stones or hard pieces of laterite be thrown in the hole. If this is done, the water which stays in the hole continues to weaken the surrounding road and any hard rocks are just pushed into the softer surrounding material. Sometimes a trench must be cut from the soft spot and back-filled with coarse gravel to allow the collected water to drain in order to stabilize the wetspot.

9.6 Dust Abatement

Many areas in the tropics have one or more dry seasons per year. During the dry season, traffic-associated road dust on major roads can cause serious traffic safety problems as well as lead to conditions promoting road roughness. Dust consists of the fine particles that are necessary to bind the road surface together. When fines are lost from a gravel surface, the stone and sand-sized material that remain loose on the surface lead to washboards, reduced skid resistance, and reduced truck gradeability. Loose gravel will also contribute to whip-off of aggregate. Thus dust is both a safety issue and a road cost issue. It is possible to lose 1 cm of road surface annually on a high-traffic aggregate surface. On a 5-m-wide road this amounts to 50 m^3/km annually, which can be a substantial cost if the fine materials must be replaced and the road regraded.

Water applications have been commonly used to reduce dust. Chemical additives are another alternative. Calcium chloride, magnesium chloride, lignum sulfate, and soybean oil are common additives. The chloride additives pull moisture from the air to maintain damp road surfaces. The effects can last an entire dry season. Additives are expensive, but their costs need to be evaluated against road surfacing savings, vehicle safety, and perhaps increased vehicle productivity owing to improved visibility. A final alternative is to provide dust masks for workers.

Equipment must also be protected from dust. Air filters need to be monitored and changed regularly.

9.7 Cut and Fill Slopes

The key to maintaining cut and fill slopes, including sidecast materials, is to regularly observe them and note when and how changes to these features occur. Often, small slope failures can be symptoms of larger slope stability issues. Left untreated, these unstable features can fail suddenly and develop into debris flows and landslides that can cause considerable downslope damage.

When changes to cut or fill slopes are noticed or suspected, consultation with geotechnical specialists can help ensure that the real problem is identified and the proper solution is formulated. Proper corrective measures can then be planned and implemented.

Typical cut slope problems include raveling, erosion, or slumping, each of which can lead to blocked ditches or contaminated surfacing. These areas frequently require more frequent ditch cleaning and maintenance. Long-term solutions might be to flatten the cut slope, revegetate areas of bare soil, widen the ditch so it cannot be blocked as easily, or build a retaining structure to contain or prevent slope movement. Often loading the toe of a small cut-bank slump with heavy riprap can provide sufficient support to stabilize it.

Local slides and slumps in the roadbed or shoulder often occur where material was placed or pushed over groundwater springs, where the road crosses steep draws, where organic material such as stumps, logs, or other organic material has been buried, or where material has been sidecast onto steep slopes. Instability in fill slopes and sidecast materials often shows up on the surface or outer shoulder of the road as tension cracks and small scarps along the boundary of the unstable material. Some settling of recently placed sidecast can be expected, but if movement persists and scarps continue to develop, appropriate action needs to be taken before the slope fails. These actions may include drainage (additional culverts and ditches), retaining structures, or the excavation and removal of unsuitable or excess materials. Any materials that have been excavated must be properly placed in a waste-disposal area. In steep terrain, cracks in older roads are likely evidence of a potential landslide. If improved drainage does not stop movement immediately, pullback may be required very quickly to prevent damage.

9.8 Gullies

Gullies are a specific form of severe erosion typically caused by concentrated water flow on erosive soils. Gullies can form if road drainage has concentrated downstream water flow, or if upstream land use has changed. Gullies can have major environmental impacts, including removing land from production, lowering the water table, as well as being a major source of sediment. Once formed, gullies grow with time and continue downcutting until resistant materials are reached. They also expand laterally as they deepen. Stabilization of gullies requires removing the source of water flowing down the gully and building small dams in the gully to dissipate the energy. Typical gully stabilization structures are constructed with rock, gabions, logs, brush, bamboo, or vegetation structures. The spacing of structures depends on the slope of the channel and the height of the structure. An energy dissipater may also be needed at the outlet. If a gully starts to form, gully protection should be installed as soon as possible.

9.9 Bridges

The primary causes of bridge wear in the tropics are water, decay, and mechanical damage. Bridge inspections should be done by qualified engineers. If scour is detected along the bridge supports, installing riprap or alternatively gabions (wire-mesh baskets filled with rocks) will protect the footings.

The anticipated life of bridge stringers is dependent upon species, depth of sapwood, circulation of air, and conditions favoring fungi at the site. Inspections should include chopping into rotten outer wood until sound wood is reached. Rotten wood is less damaging if it is near the ends of the stringers compared with the middle of the stringers which are subject to the greatest stress.

Since stringer strength is a function of the cube of the diameter, a 1% decrease in sound stringer diameter will have a larger corresponding decrease in stringer strength. The reduction in bridge loading capacity will even be greater than the reduction in stringer strength since part of the bridge loading capacity is used to support the weight of the bridge structure. Bridges with heavy laterite surfacing will have larger deductions in bridge capacity following a reduction in sound stringer diameter than a bridge with a wood decking.

As an example, if the weight of the bridge structure (stringers plus decking) takes 40% of the bridge capacity of an 80-cm log stringer bridge and the stringers are each found to have 1-cm decay around the entire stringer at the middle of the span, then the stringer has $(78/80)^3$ = 92.7% of its original capacity and the remaining design live-load capacity is $(1.0\times0.927–0.4)/0.6=0.878$ or about 88% of its original design live-load capacity. The actual loss in capacity is overestimated as the weight of the bridge structure will probably have decreased over time as the stringers and deck have dried, but it illustrates the sensitivity of bridge capacity to stringer decay.

If the capacity reduction of the bridge from stringer decay becomes too large to be acceptable, the options are to (1) reduce load size, (2) shorten the span by using a bent or intermediate support, (3) add large log curbs and a cross beam (Fig. 9.2) to provide additional support, or (4) rebuild the bridge. The addition of a crossbeam will reduce bridge clearance at high water.

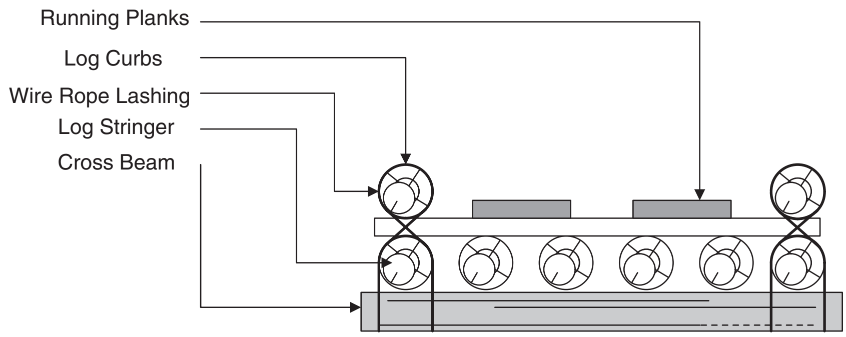


Fig. 9.2. Example of cross beam and log curb to reinforce a log stringer bridge

9.10 Control of Truck Transport

A lot of damage to compacted earth roadways in the tropics can be avoided if truck transport is halted during and shortly after heavy rains. Permitting the road surface to drain and to be exposed to the sun for even 1 h can substantially reduce road damage. Even in the tropics, there are normally a sufficient number of dry days, or dry parts of days, such that forest transport can maintain a fairly regular production.

9.11 Supervision and Control of Maintenance

Regardless of the maintenance methods employed, the knowledge, skills, and abilities of the supervisors, equipment operators, and other workers are crucial to the successful maintenance of the road system. They need knowledge of good road maintenance practices and the ability to apply them in the proper situations. They also need the ability to recognize unusual conditions that may require the use of specialized equipment or the advice of technical specialists.

Maintenance work should always be carried out by workers permanently engaged in this occupation. Continuous maintenance by a small crew to clean culvert entrances, unplug ditches, repair mudholes, and remove objects from the roadway is always more economical than intermittent work carried out by a larger crew. Each crew should be assigned to a specified road. Typical hand tools include a wheelbarrow, shovel, pick, axe, and machete. Maintenance work requiring mechanized equipment is given to a team responsible for the whole road system. Schematic books with examples of proper final shapes for road sections should be provided to all maintenance crews.

9.12 Maintenance Frequency

To protect the road infrastructure and reduce vehicle operating cost, periodic maintenance is necessary. The frequency of this maintenance is a function of season of use, level of use, location, and road surface materials. A road that has been planned and designed to accommodate a large volume of traffic will require more frequent maintenance. A road that is designed for occasional use will require less frequent maintenance. To reduce the maintenance load, roads that are seldom or occasionally used become good candidates for road closure between periods of use. In mountainous areas, roads located on ridge tops will require less frequent maintenance owing to fewer drainage structures, smaller cut banks, and usually a higher degree of slope stability. Roads located in valley bottoms require more frequent maintenance owing to the greater number of drainage structures and their proximity to larger streams. Roads located on sidehills require the greatest maintenance frequency. Cut banks are higher and more prone to raveling, cut and fill slope stability issues are more frequent, and there are generally a large number of drainage structures.

Regular and timely maintenance helps to ensure that the road system remains fully functional. Conversely, poorly timed maintenance can create problems that might have greater consequences than not maintaining a road. As examples, cleaning ditches during wet weather can cause excessive sedimentation, and grading a road during heavy rain can lead to contamination of the surfacing material. On the other hand, cleaning culvert inlets and minor blockages of ditches during rain events can prevent much serious damage. It is important that any maintenance activity be conducted at a time when the weather conditions allow for a minimal amount of soil disturbance and sediment movement. It is essential to maintain the integrity of the road surface and subgrade while conducting maintenance activities.

Two types of surface maintenance are defined: periodic maintenance to reduce road roughness and surface replacement. Periodic maintenance to reduce road roughness involves removal of ruts, washboards, potholes, and spot gravelling. Surface replacement involves replacing the surface course before it is no longer able to function and vehicle wear has reached the base course. The World Bank (2004) has developed a model to define technical relationships for modeling road surface deterioration and to estimate user costs. The latest model is Highway Development and Management Version 4 (HDM-4). In order to plan the most efficient maintenance schedule it is necessary to understand the relationship between traffic and road roughness, rut depth, and loose material and the vehicle operating cost as a function of road conditions. An example from Kenya provides an illustration of these technical relationships (Table 9.1).

Table 9.1. Vehicle operating cost (*VOC*) equations from a study in Kenya. Adapted from Faiz and Staffini, 1979

Road surface and vehicle type	VOC estimation equation	Maximum T^a	Number of observations	Upper-bound limit on VOC (US $ equivalent)
Laterite[b]				
Light-goods vehicle	$VOC=213.32+0.0094T^2$	100	19	310
Single-unit truck	$VOC=392.44+0.0216T^2$	100	19	610
Medium truck-trailer	$VOC=692.98+0.0422T^2$	80	19	1,020
Heavy truck-trailer	$VOC=861.93+0.0557T^2$	80	19	1,225
Sand–clay[c]				
Light-goods vehicle	$VOC=207.02+12.87T-0.2496T^2$	30	17	370
Single-unit truck	$VOC=385.96+18.56T-0.2660T^2$	30	17	710
Medium truck-trailer	$VOC=676.29+34.73T-04365T^2$	30	17	1,350
Heavy truck-trailer	$VOC=833.83+51.40T-0.7947T^2$	30	17	1,675
Track				
Light-goods vehicle	$VOC=206.86+21.51T-0.8051T^2+0.003T^4$	30	17	370
Single-unit truck	$VOC=384.54+31.04T-1.0593T^2+0.004T^4$	30	17	710
Medium truck-trailer	$VOC=675.07+58.37T-1.9396T^2+0.008T^4$	30	17	1,350
Heavy truck-trailer	$VOC=831.15+86.49T-3.0527T^2+0.012T^4$	30	17	1,675

VOC is in units of US dollars per 1,000 km
[a] *T* is the cumulative traffic volume between gradings in both directions (in units of 1,000 vehicles)
[b] Applies to gravel roads with at least 2 cm of laterite surface
[c] Applies to earth roads and gravel roads with less than 2 cm of laterite surface

The following are road deterioration relationships.
Lateritic gravels roads:

$$R = 3250 + 84T - 1.62T^2 + 0.016T^3$$

$$RD = 11 + 0.23T - 0.0037T^2 + 0.000073T^3$$

$$LD = 1.5 - 14e^{-0.23T}$$

$$GL_a = 0.94\frac{T_a^2}{T_a^2 + 50}(4.2 + 0.092T_a + 3.5R_1^2 + 1.88VC)$$

Sand–clay earth roads:

$R = 3250 + 785T$

$\text{RD} = 14 + 1.2T$

$\text{LD} = 1.5 + 14e^{-0.23T}$; under dry grading with $\text{LD} \geq 10.0$ mm

$\text{LD} = 1.0$; under wet grading

Tracks:

$R = 3250 + 1255T$

$\text{RD} = 14 + 1.2T$

$\text{LD} = 1.5 + 14e^{-0.23T}$; with $\text{LD} \geq 10.0$ mm

R is the mean roughness (in millimeters per kilometer), RD is the rut depth (in millimeters), LD is the depth of loose material (in millimeters), T is the cumulative traffic volume in both directions since the last grading (thousands of vehicles), GL_a is the annual gravel loss (in millimeters), T_a is the annual traffic volume in both directions (thousands of vehicles), R_1 is the annual rainfall measured (in meters), and VC is the rise and fall, vertical curvature (in percent).

For the study in Kenya, the frequency of grading that minimized the sum of vehicle operating costs and maintenance cost varied as a function of traffic. The grading frequency was lowest on graveled roads and highest on dirt tracks (Table 9.2).

Many road roughness measurement systems have been developed to help road maintenance managers determine when road maintenance is necessary. Methods range from subjective ratings from individuals or panels to devices that measure the longitudinal and lateral road profile. The international roughness index (IRI) has become a standard index in many countries for measuring surface roughness along the longitudinal profile. The IRI is an index that is derived from "driving" a model car over the simulated road profile. The simulated road profile could have been obtained by a number of methods ranging from use of a detailed survey of the road using advanced surveying instruments to driving a specially equipped vehicle over the road. The IRI has been correlated with vehicle operating costs and normal driving speed. Some industrial forestry companies have equipped one or more of their log-transport trucks with response devices to provide real-time road roughness measurements to guide daily scheduling of road maintenance crews.

Table 9.2. Economically optimal frequency of gradings per year for the study in Kenya as a function of surface type and average daily traffic *(ADT)* measured in vehicles per day (*VPD*). From Faiz and Staffini, 1979

Road and surface type	ADT (VPD)	Without compaction[a]	With compaction[b]	Total
Gravel road (laterite)	10	1	0	1
	30	1	0	1
	50	1	0	1
	70	1	1	2
	90	1–2	1	2–3
	120	1	2	3
	150	1–2	2	3–4
	200	2	3	5
	250	3	3	6
Earth road (sand-clay)	10	1	0	1
	30	2	2	4
	50	4	3	7
	70	6	4	10
	90	7	5	12
	120	10	7	17
Track (earth)	5	1	0	1
	10	2	0	2
	30	4	1	5

[a]Unit cost of grading is US $80 per kilometer
[b]Unit cost of grading with compaction is US $400 per kilometer

Road Equipment and Machinery 10

10.1 Considerations in Selection

The essential machines and equipment for construction and maintenance work on forest roads are generally powerful, expensive, and usually operated under very difficult conditions. Equipment selection should consider:

- Choice of the right size for the conditions
- Maintenance requirements
- Ease of dismantling
- Operation by semiskilled personnel
- Strength and resistance of parts to wear
- Availability of parts
- Availability of technical support

Select the appropriate size and power configuration for the job to be done. Selecting equipment that is too large requires more room to maneuver and creates the possibility for the operator to easily overbuild the road. Selecting too small a piece of equipment forgoes construction choices such as the ability to rip or hammer rather than to blast in rocky terrain. Since tropical forest operations are often isolated, it is better to standardize equipment makes and models to the extent possible to minimize spare parts, maintenance tools, and skill requirements of maintenance personnel. Eventually, usable equipment parts can also be salvaged from retired machines. A major concern can be availability of parts, particularly for imported parts. This aspect should be investigated carefully prior to machine selection. A good idea is to visit neighboring operations to see what has worked and what has not. All road construction and maintenance equipment should be equipped for high-humidity, high-temperature operation, both mechanically and ergonomically.

Table 10.1. Characteristics of road construction equipment

Criteria	Bulldozer	Front-end loader	Hydraulic backhoe	Dump trucks or scrapers	Farm tractors
Excavation mode (level of control of excavated materials)	Digs and pushes; adequate control (depends on blade type)	Minor digging of soft material; lifts and carries; good control	Digs, swings, and deposits; excellent control; can avoid mixing materials	Scrapers can load themselves: "top down" subgrade excavation; used for long-distance material movement; excellent control	Minor digging and carrying; good control because it handles small quantities
Operating distance for materials movement	120 m; pushing downhill	100 m on good traction surfaces	20 m (limited to swing distance)	1 km, scrapers; 3 km, trucks must be loaded	35 m (approximately)
Suitability for fill construction	Adequate	Good	Limited to smaller fills	Good for larger fills	Not suitable
Clearing and grubbing (capacity to handle logs and debris)	Good	Adequate	Excellent	Not suitable	Handles small material only
Ability to install drainage features	Adequate	Digging limited to soft materials	Excellent	Not suitable	Adequate for small tasks only
Operating cost per hour	Moderate, depends on machine size	Relatively low	Moderate to high, but productivity excellent	Scraper very high, loader and trucks very high	Low
Special limitations or advantages	Widely available; can match size to job; can do all required with good operator	Cannot dig hard material; may be traction limited	Good for roads on steep hillsides; can do all required except spread rock for rock surfacing	Limited to moving material long distances; can haul rock, riprap, etc.	Very dependent on site conditions and operator skill

10.2 Types of Equipment

The minimum pieces of equipment required for road construction and maintenance are (1) 125–190-kW bulldozer, (2) a road grader, although for a small operation a towed grader is adequate, (3) a 30–45-kW four-wheel drive agricultural tractor with scoop bucket for towing a rubber-tired roller, grader, or drag, (4) a mobile workshop, and (5) two dump trucks. Costly machines such as self-propelling graders, scrapers, tracked or rubber-tired front-end loaders are suitable for larger operations which require the work of several bulldozers. For work in steeper terrain, a 100–150-kW hydraulic excavator is recommended. An excavator at the larger end would be recommended if substantial ripping or hammering is anticipated. Characteristics of road construction equipment are shown in Table 10.1, with the exception of graders and compactors.

11 Environmental Protection

A number of relatively inexpensive actions, if done in a consistent and disciplined manner, will protect the quality of the tropical forest environment. Actions that contribute to environmental protection connected with design, road construction, bridge construction, and road maintenance follow.

11.1 Design

- Use competent engineers to conduct roadline surveys and design roads.
- Design roads for the required use. Identify those roads that should have restricted access during the wet season and integrate those plans with the harvest operating plans.
- Minimize the total length of roads required to meet management objectives. The total cost of road construction plus harvesting costs is often flat with respect to road density, so road density can often be reduced at little overall cost, particularly on gentle terrain.
- Fit the road as closely as possible to the terrain.
- Reduce the total area disturbed by opening the minimum clearing limits necessary and by not using excessive road widths, particularly in steep terrain.
- Avoid locating roads on wet soils, unstable slopes, or steep sideslopes.
- Avoid steep grades through soils which erode easily.
- Minimize earthwork by minimizing cutting and filling. Plan to end-haul where necessary, and use proper blasting techniques.
- Keep road grades as low as possible but roll grades as necessary to keep water moving so that sediment does not deposit in ditches.
- Use adequately spaced cross drains to keep water velocity down.
- Make sure culverts are installed, not only at certain distances, but also where they are actually needed.

- In steeper terrain, stake cut and fill limits to control earthwork during construction.
- Design road crossings to streams to divert road surface runoff and ditch flow before the road reaches the stream so that the road does not become a point source for sediment entering the stream. Harden road approaches to streams.
- Incorporate landing design, when possible, into the road design to ensure proper drainage so surface water from skid trails and landings does not flow onto the road.
- Consider periodic canopy bridges over roads for wildlife in areas that are safe from erosion and do not need drying after rainfall.

11.2 Construction

- Use competent engineers to supervise road construction.
- Use appropriate size and power configuration of equipment. Too large a piece of equipment can overbuild the road. Too small a piece of equipment may require alternative building techniques, i.e., blasting versus ripping.
- Use only adequately trained, skilled, and experienced machine operators for road construction in sensitive and difficult terrain.
- Where large trees *not* designated for harvest are in the right of way, consider if small changes in alignment could avoid them.
- Earthwork should take place during relatively dry weather.
- Where sidecasting soil with tractors and shovels will cause siltation of watercourses, haul away excavated material for disposal at a safe location.
- Stabilize cuts and fills with retaining walls or some other suitable method, where there is danger of slippage into watercourses.
- Build proper ditches and culverts.
- Provide suitable drainage while the road is under construction and allow the road to stabilize before permitting heavy traffic. Construct the road at least 1-year prior to its first wet-season heavy-traffic use.
- Deposit cut material in stable locations above high-water levels and avoid depositing any materials or debris in streams.
- Keep machine activity in stream beds to an absolute minimum. Choose temporary stream crossings where they create a minimum of soil disturbance. Cross streams only at right angles.
- Where practical, seed cut banks and fill slopes with grass or alternative cover to reduce erosion and improve appearance. Give preference to native vegetation.

- Construct ditches on all roads to handle maximum flows expected.
- Use proper blasting techniques, particularly soft blasting to minimize disturbance.
- Avoid blasting excessive rock into watercourses.
- Use excavators to construct roads in steep terrain.
- When possible, surface roads with stronger, more durable material to reduce sedimentation.
- If available, use rock in selected locations (ditches, culvert outlets, and fords) to protect against erosion.

11.3 Bridges and Culverts

- Construct bridges and culverts to handle the maximum water flows expected, with special attention to areas of heavy rainfall.
- Design bridges and culverts to allow free passage of fish.
- Consider the use of temporary or portable bridges where access to forest areas is to be limited after harvesting.
- Orient bridges and culverts with the natural stream channels, with a minimum of disturbance of stream banks and bottoms. Arch culverts may be necessary to accomplish this goal.
- Incorporate in culvert design an entrance pool and discharge exit that eliminates bank erosion.
- Stabilize bridge and culvert backfills to prevent erosion.
- Consider fords as alternatives to culverts in crossing perennial streams carrying high loads of sediments or the combined use of a ford and culvert where torrents are to be crossed, with a culvert for the normal runoff and a ford for high floods.
- Use armored relief ditches in critical locations where blockage of a culvert could cause serious road and downslope impacts.
- During bridge construction, ensure that oils, chemicals, excess concrete, or other waste materials do not enter the stream or river.
- Allow treated material (piling) to dry prior to use in bridge construction.
- Burn or remove debris accumulated at a bridge construction site.

11.4 Road Maintenance

- Grade main and spur roads to remove berms and crown roads to prevent ponding. Where applicable, use berms to prevent erosion of fill areas.
- Clean out roads and ditches at landings or logging sites immediately after logging. Give special attention to damaged culverts and culvert openings.
- Identify bridges, culverts, and ditches that are potential problem areas, maintain them regularly, and check them frequently during periods of heavy rainfall.
- Deposit material removed from ditches during maintenance in a safe location away from streams.
- Appropriately close and retire roads not needed for continuous use to prevent erosion and to prevent access by wildlife poachers.

Concluding Comments 12

Forest roads are an essential component of forest management. Well-planned, well-constructed, and well-maintained roads provide for efficient forest operations while minimizing environmental impacts. In Chap. 1, we introduced the argument that the reason for improperly designed, constructed, and maintained roads is not so much a shortage of funds, lack of modern and suitable road building equipment, or working methods, but too little awareness of the negative impacts of poorly designed, planned, and constructed road systems on the entire forest ecosystem. That best management practices, if followed, will markedly reduce and control the negative environmental impacts of road construction and maintenance. To a large degree this is true. A number of relatively inexpensive actions, if done in a consistent and disciplined manner, will contribute to the protection of the quality of the tropical forest environment. But the tropics do offer some substantial challenges owing to high-intensity rainfall, swamps, scarce surfacing materials, and low timber harvest yields compared with other forest areas. It can be argued that road engineers in the tropics must deliver more performance with fewer resources than road engineers in other forest regions. New road building and operating technologies, including geosynthetics, variable tire inflation, aggregate recycling, and portable bridges, increase options for road design and operations for the special challenges in tropical regions.

Appendix: Forest Road Measurements in the Tropics

A variety of analog and digital tools are available for road and landscape measurements in forested road environments. Tropical forested climates in developing countries, however, pose unique challenges to collecting field measurements. Climate conditions are often humid and may be subject to short or long periods of intense rain. Humidity and exposure to rainy conditions may damage sensitive optical equipment and periods of intense rain may shorten the number of daylight hours in which measurements can be efficiently collected. Vegetation may greatly reduce lines of sight on the ground. As a result, brushing may be needed and can require significant amounts of time. When lines of sight are limited, the ability to take measurements over long distances is also typically reduced and more, shorter-distance measurements will be required in comparison with traverses in open landscapes. Additional measurements will require more frequent moving and repositioning of equipment. For optically based devices, leveling of the instrument at every new position is usually required and requires operator time. Regardless of the type of measurement device, the opportunity for measurement errors or blunders increases as the number of movements and equipment setups increase.

An additional challenge in tropical areas is access to electrical power. Many forms of modern digital equipment require that power be available in order to operate. The power may be supplied by an internal or removable battery that will provide enough electrical current for equipment to operate over a short period. Many equipment manufactures provide internal and external batteries that are designed to operate for a typical work day (8 h) before expiring or requiring a recharge. In the case of rechargeable batteries, access to electrical current will be necessary in order to recharge the battery. In some cases in which access to electrical current is limited and the voltage of the battery is relatively low, it is possible to use a solar-powered device to recharge a battery. Digital equipment that use an internal (nonremovable) battery may pose additional constraints on measurement activities as exchanging of batteries is difficult or not possible.

A.1
Analog Location Measurement Tools

Analog forest measurement tools are still in prevalent use throughout the world owing to their ability to operate in almost any setting and also for their nonreliance on power sources. Analog devices for measuring directions (azimuths or bearings) or angles between objects include the hand compass, staff compass, transit, and theodolite. The hand compass and staff compass are both capable of establishing a direction between objects and rely on the Earth's magnetic field for measurements. Although the hand compass is accurate to about 2°, the staff compass can likely determine direction to about 1° when used properly but is considerably more expensive (about US $450 for a quality staff compass compared with US $75 for a hand compass). Both the hand compass and the staff compass will measure the magnetic azimuth or bearing of a direction unless the user adjusts the compass dial to account for magnetic variation. Magnetic variation is the angular distance at any location on the Earth between true north and the orientation of the Earth's magnetic field. Magnetic variation can range from 0° to well over 20° in tropical areas. In addition, these manual compasses will be subject to local attraction. Local attraction occurs when a compass needle is directed toward or away from an object that interferes with the magnetic field. Local attraction can be caused by a mineral deposit, a vehicle, or a mechanical pencil in a nearby shirt pocket. The risk of recording directions influenced by local attraction can be minimized by taking fore azimuths and back azimuths and comparing the two measurements. After accounting for a 180° difference, the measurements should be approximately equal. If not, local attraction may be occurring.

Transits and theodolites are predecessors of the modern-day digital total station (discussed later) and rely on the user establishing a starting azimuth or bearing through an initial back sight. Directions between subsequent objects can be derived by forming a continuous traverse such that all objects are connected to each other through a series of back sights and fore sights. The angular resolution of a typical transit is approximately 20–30′, while some theodolites have resolutions as fine as 0.1′. Theodolites can be thought of as a high-precision transit and have evolved into digital measurement equipment. Both transits and theodolites require mounting on a fixed tripod or other firm surface that can be leveled and operator skill. A transit costs about US $1,200, while an optical theodolite would cost about US $1,600.

Analog measurement equipment for measuring gradients or elevation differences include a clinometer, an Abney level (Fig. A.1), a transit, a theodolite, a dumpy level, an automatic level, and a hand level. The clinomoter is a small handheld device (it may also be mounted on a staff or other surface) and

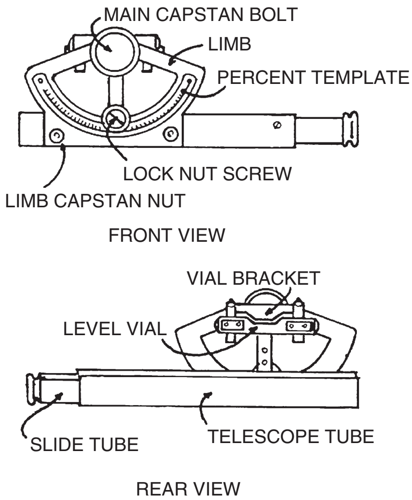


Fig. A.1. The Abney level (From Waldbridge 1990)

provides a convenient method of measuring gradients from the user's eye to any object. Typical angular resolution of a clinometer is about 1–2° and the purchase price would be about US $100. The Abney level, similarly to the clinometer, is a handheld instrument, but is capable of greater precision in measuring angles, with resolutions reaching 10′ and has a slightly higher purchase price of about US $130. Transits and theodolites are also capable of measuring gradients with a precision of 1′ and 0.1′, respectively. The automatic level is used to determine elevation differences between objects and requires mounting on a tripod. The process of using an automatic level to determine elevation difference is known as differential leveling. Although an operator can start from a known or an assumed elevation benchmark, it is the elevation differences between features that determine their height relationships to one another. The automatic level requires two people to operate it efficiently; one person uses the level instrument to sight on a level rod, while the other person holds the rod vertically. Level rods contain graduated readings of typically 0.01 m on them – these markings determine the precision at which the automatic level can determine elevation differences. A hand level can be used in a similar manner to an automatic level but typically is attached at a fixed height to a staff. The hand-level operator reads elevations from a level rod placed on an object; differences between the fixed height of the hand level and level rod determine elevations.

Analog approaches for measuring distances include measurement tapes and pacing. Coiled steel tapes may provide the most reliable method of measuring distances without digital tools. These tapes are sometimes referred to as engineer's or surveyor's tapes and are also available in fiberglass. Metric steel tapes come in size increments of 15, 30, or 50 m and are typically graduated in meters and decimeters, occasionally in millimeters. Using an engineer's tape typically involves two people and team coordination to ensure that the ends of the tape are positioned precisely between or over objects (with assistance from plumb bobs) from which distances are desired. The tape must be held level and straight to capture accurate distances, and it is relatively easy to snap or break a tape should a kink develop. Steel tapes are subject to rust and should be wiped clean following use. String boxes are a low-cost method for measuring distance by measuring the length of string that passes around a measuring wheel. The string is tied to a bush and the slope distance is displayed on the counter on the device as the person walks. They can be used to for a variety of tasks, including curve layout. It is a simple, rugged tool that will allow individuals to measure distance by themselves. Pacing is a less reliable than taping for measuring distances but offers the advantage of convenience. A person's average pace length can be estimated by establishing a measurement course through topography that is similar to that in which measurements are to be taken. The person walks the course several times using a pace that is relaxed and can be maintained through an entire day. The total length walked is divided by the total number of paces to derive an average distance per pace. This average can then be used to approximate distance measurements in the field.

A.2 Digital Location Measurement Tools

There are many types of digital measurement tools that are available for road operations in forested environments. These tools range from handheld devices such as digital range finders, to aerial-based platforms such as LiDAR, to space-based systems that are capable of taking imagery of the Earth's surface. Choosing the appropriate digital tool for road-related measurements will involve many considerations, including cost, time constraints, accuracy requirements, topography, and access to power sources. Digital measurement tools are capable of great time savings in taking and recording measurements; many digital measurement tools are capable of automatically saving measurements to a personal digital device or data collector. This capability removes the need for transferring measurements from a field notebook to a computer following data collection, a process that has a high likelihood of introducing errors. Conversely, digital measurement tools are often fragile and require a high level of expertise to operate comfortably. Should a device stop working in the field or in the air if it is based on an aerial platform, owing to power loss, damage, or other reason, measurement work must often cease unless a backup device exists or the difficulty can be resolved. In addition, should a digital instrument that is recording measurement data stop functioning, there is also the question of whether collected data can be retrieved from the device. Nonetheless, technological advancements continue to result in the development of digital tools and techniques for forest measurements, leading to greater economy, reliability, and performance for consumers.

Digital range finders have become a widely used tool in forest measurement applications. Most digital range finders operate by emitting a laser pulse from a handheld device and measuring the amount of time it takes the pulse to return. The elapsed time is then used with the speed of light to determine a distance. Some range finders use sound waves rather than light pulses. Many digital range finders do not require a reflective surface for the emitted laser but a reflective tape may help in areas that are densely forested. Range finders are capable of distance measurements within several millimeters of actual distances but there are considerable performance issues between types. In addition, many range finders are also capable of deriving slope distances, vertical angles, tree heights, and distances between two objects that are within visible range. Some range finders can work in tandem with a data collector to automatically download measurements to a database. Digital compasses have also been developed to provide a directional measurement device for use in tandem with digital range finders. The advantage of such a combined system would be that users could measure both directions and distances between objects through traverses. Digital compass technology, however, appears to not be reliable for directional measurements but improvements will likely occur in the near future.

Global Positioning System (GPS) measurement applications have been a source of frustration for those wishing to apply this technology for forest operations but there is recent evidence that some GPS receivers are capable of reliably collecting measurements under canopy in certain conditions. The limiting factor for GPS applications in forestry has been that lines of sight between GPS receivers on the ground and space-based satellite systems are often limited by canopy conditions, topographic barriers, or some combination thereof. A GPS receiver calculates a position by being able to receive signals from at least four satellites, with more satellites leading to better data collection opportunities. The GPS receiver can use information included in the signals to calculate the range (distance) between the receiver and each satellite it communicates with. These ranges are used to estimate a position through trilateration.

Satellite signal quality and reliability for measurement determination is reliant on satellite availability and the geometry of the available satellites in relation to the GPS receiver. Potential satellite signal quality can be estimated as a position dilution of precision (PDOP) statistic. Mission planning software for GPS is used to calculate an expected PDOP value for a field site and can identify preferred times for collecting data. Larger values of PDOP infer diminished satellite geometry and measurement reliability.

Potential sources of variability and error for GPS measurements include atmospheric interference of satellite signals, timing errors between satellites and the GPS receiver, the rotation of the Earth, and orbital satellite patterns. A portion of these errors, in some cases considerable, can be estimated and removed through the process of differential correction. Differential correction involves having a fixed GPS base station at a known location that continuously compares GPS-derived positions to its known position. GPS base stations are located using very accurate and precise measurements. The difference between the known location and the GPS-derived locations is a correction factor that can also be applied to other GPS receivers that are collecting measurements nearby.

Another way in which to reduce errors is to collect multiple measurements at single locations. Given the number of potential errors, a coordinate determination based on the average of multiple measurements should be more statistically reliable than that based on one measurement.

In addition to the difficulty in receiving satellite signals in forested mountainous terrain, there was only one satellite system available to users worldwide until recently. The primary satellite system for GPS measurements is the NAVSTAR (Navigation Satellite Tracking and Ranging) system operated by the US Department of Defense. NAVSTAR became available in the early 1980s and has 24 operational satellites with satellite signals freely and continuously available to GPS users worldwide. NAVSTAR satellite signals were intentionally scrambled, under a procedure known as selective availability, in this system until 2001 and could lead to measurement errors of 100 m or more. Since 2001, selective availability has been removed and several new satellite syztems have become operational. There is no guarantee however, that selective availability will remain off in the future.

In addition to NAVSTAR, there are now space-based augmentation systems (SBAS) that are capable of providing conventional real-time differential corrections to GPS receivers as they collect data. Conventional real-time differential uses the more accessible coarse/acquisition (C/A) satellite signals rather than phase code signals. Although phase code signals possess greater potential for accurate GPS measurements, continuous and uninterrupted satellite signals are necessary, a condition that is not always available under forest canopy. SBAS derives measurement correction factors for several potential GPS error sources, including atmospheric interference of signals, time sequences for satellite signal range (distance) estimates, and satellite orbital patterns. The primary SBAS for many users is the US Federal Aviation Administration's Wide Area Augmentation System (WAAS), which has three operational satellites as of 2006 and more satellites are expected in the near future. A single WAAS satellite signal is required for a GPS receiver to apply real-time correction factors but reception from additional WAAS satellite signals is preferred as they provide a backup should reception from one satellite become unavailable. There are also other SBAS, including the European Geostationary Navigation Overlay System (EGNOS) and the Japanese MTSAT satellite-based augmentation system (MSAS). Some GPS can operate with all SBAS.

Other GPS systems include GLONASS (Global Navigation Satellite System), which was developed by the Russian military. GLONASS was made fully operational with 24 satellites in 1996 but has been subject to irregularity in the number of operational satellites. A system under the guidance of the European Space Agency called Galileo is expected to be operational in 2008.

GPS receivers can be partitioned by measurement accuracy and price into three broad grades or categories: survey, mapping, and consumer. Measurement accuracy can be thought of as the difference between a GPS-collected measurement and the true location of the GPS receiver when it collects a measurement. The most accurate and expensive GPS receivers are called survey grade and can estimate positions within 1 cm of true location when used properly. Survey-grade GPS receivers are full-featured and allow users to differentially correct collected data and to work with various satellite systems. Beyond the relatively high cost of survey-grade GPS receivers (typically greater than US $10,000), operator proficiency is required with hardware and software applications. The use of survey-grade GPS receivers in forested landscapes is ill-advised owing to the delicate nature of the equipment and a requirement for continuous adequate satellite reception in order to derive measurements efficiently. Beyond these concerns, the accuracies of survey-grade GPS receivers, even if achievable, are probably greater than those required for most forest road operations.

Mapping-grade or resource-grade GPS receivers represent the second category of the three GPS receiver categories and can be purchased for between US $2,000 and US $10,000 depending on the features and the manufacturer. These types of GPS receivers are also sometimes called GIS-grade GPS receivers. Many mapping-grade GPS receivers come with software for differential correction. Manufacturer estimates of positional accuracy are 2–5 m depending on the receiver and the application for mapping-grade GPS receivers. These estimates often reflect best-case data collection scenarios and may not be possible in forested environments, but several studies have been reported. Positional accuracies between 12.3 and 25.6 m during leaf-on conditions and between 3.8 and 8.8 m during leaf-off conditions have been reported in a mixed-hardwood forest during selective availability. Some studies have examined several mapping-grade receivers under dense hardwood canopy and determined average positional errors of 4.0 m. Positional errors have been reported between 0.5 and 5.6 m that were influenced by basal area density and data collection times in Sitka spruce (*Picea sitchensis*). A nondifferentially corrected mapping-grade GPS receiver below a partial hardwood forest canopy was used and reported accuracies of 20–30 m. Other studies have tested a variety of mapping-grade

GPS receivers and configurations and reported accuracies between 2.4 and 4.5 m under forest canopy with at least 70% obstruction of the sky in deciduous and red-pine forests.

Consumer-grade GPS receivers are the least accurate and most affordable of the GPS grades, with many receivers in this category costing between US $100 and US $500. Although the price range is attractive for most budgets, there are several disadvantages that must be considered. Consumer-grade GPS receivers usually do not allow operators to set minimum thresholds for satellite signal quality before measurements can be calculated and stored digitally. The majority of consumer-grade GPS receivers do not allow a minimum PDOP level to be set as a quality control for data collection and do not include mission planning software. Some consumer-grade GPS receivers do not enable users to conduct point averaging to determine a single position. In addition, while most consumer-grade GPS receivers afford users the ability to store measurements individually, the common storage limit of 500 points for receivers in the several hundred dollar range makes point averaging impractical. Differential correction capabilities are limited in consumer-grade GPS receivers and must be accessed through third-party software.

Consumer-grade GPS receiver accuracy in forested settings has been reported in previous studies. One study investigated the positional accuracies and reliability of six consumer-grade GPS receivers within several different forest types and reported measurement accuracies within 10 m of true position under dense conifer canopy and within 5 m under partial canopy depending on the type of consumer-grade GPS receiver. Average accuracies of consumer-grade GPS receivers between 6.5 and 7.1 m under dense primarily hardwood canopies have been reported. Although the typical average accuracies reported by these studies (5–10 m) may be acceptable for some forestry applications, the limitations of consumer-grade GPS receivers must be considered. These limitations include the ability to set minimum satellite quality standards, whether point averaging is possible, and access to differential correction procedures.

A digital total station is capable of highly accurate and precise measurements of forested features to less than 1 cm from actual locations. Measurement capabilities include distances and angles in both horizontal and vertical dimensions, with horizontal angles being the least reliable of the possible measurements. The total station still has few equals for reliable measurements in the forest but requires a clear line of sight to a reflective surface for distance measurements. The total station is similar to a handheld laser range finder in that a beam of light is emitted from the instrument, reflects off of a target, and is sensed by a receiving lens. Distances are computed through the amount of time that elapses during the light beam's travel. A reflective prism composed of mirrors and/or glass is often users to provide a reflective target. Some digital total stations can operate without the use of a reflective target but questions remain as to the accuracy of such measurements. Digital total stations can be purchased for approximately US $6,000–12,000 for manually operated instruments. Robotic total stations are available for approximately US $30,000. Robotic total stations allow for remote control of targeting and measurement operations and require only one operator (a typical total station crew will involve an instrument operator and someone to position and move the rod upon which the prism is placed). Consequently, robotic total stations can greatly increase the efficiency of measurements when only one operator is available.

Considerable care must be taken when using a total station to ensure that the instrument is level, that its starting position is known or at an assumed location, and that accurate measurement and recording of instrument and prism heights is made. The instrument and prism heights must also be involved in any calculations that involve gradients or elevations. Proper total station use typically requires an investment of time beyond that required by handheld range finders and handheld GPS receivers. In comparison, these other tools are somewhat forgiving and user-friendly, while proper total station use requires that operators be well versed in instrument use and data collection, transfer, and data processing routines. Despite these concerns, a total station remains perhaps the most reliable instrument for gathering accurate and precise measurement data in forested settings.

Measurements related to forest road operations can also be captured through remote-sensing techniques from aerial-based or space-based platforms. Georeferenced color aerial photography can now be collected at resolutions finer than 1 m. Aerial platforms for this purpose combine an inertial guidance system with a digital camera system and can provide georeferenced imagery within several hours of a flight.

LiDAR systems can be operated from both aerial platforms and ground-based locations. The aerial platform combines a laser emitting–receiving scanning unit, a differential GPS receiver on the ground and on the aerial platform, and an inertial guidance unit to measure various terrain characteristics. Individual tree attributes, forest structure, and detailed topographic measurements can all be derived from lidar data. One of the most promising products for road operations is the ability of lidar to support the creation of detailed (1-m resolution) digital terrain models. Digital terrain models at this resolution could provide valuable information in road design and planning activities.

Space-based remote-sensing platforms include Landsat Thematic Mapper (TM), IKONOS-2, and SPOT (Système Pour l'Observation de la Terre). Landsat TM represents a system of satellites with the ability to image wide swaths (185 km) of the Earth's surface in a single orbital pass. Landsat-1 was the first satellite in a series and was launched in 1972. The most recent, Landsat7, was launched in 1999 and can capture imagery in 15-m panchromatic resolution and 30-m multispectral resolution. IKONOS-2 is a single satellite and is capable of 1-m resolution for panchromatic imagery and 4-m resolution in multispectral imagery. IKONOS is highly maneuverable and can be redirected to image specific objects on the Earth's surface. SPOT was initiated by the French government in 1978 but also had assistance from Sweden and Belgium. SPOT-5 is the latest realization of this effort and captures a 120-km swath of the Earth and is capable of 2.5-m panchromatic resolution and 10-m multispectral resolution. Although the orbits of the SPOT satellites have regular patterns, the optical system can be directed toward features of interest.

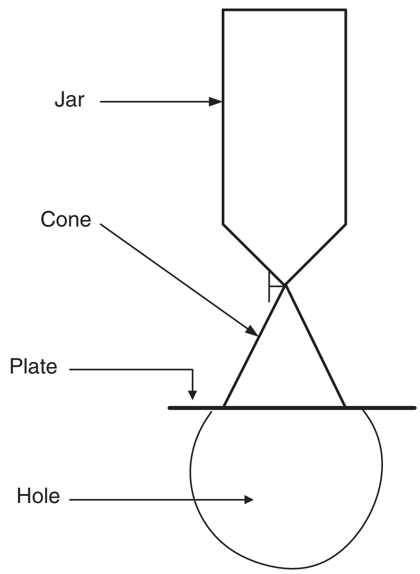
A.3 Soil Measurement Tools

Several inexpensive tools are available to measure various aspects of soil strength. The sand cone (Fig. A.2) allows the user to determine the wet and dry unit weight of the soil. A hole is dug in the road subgrade and the soil is collected and weighed to determine the wet unit weight, or it can be dried to determine the dry unit weight. The volume of the hole is determined by measuring the change in weight of the sand-cone device. It is a low-cost reliable method used to determine wet and dry unit weights for road subgrades.

The Clegg hammer (Fig. A.3) consists of a tube with a weight that is allowed to freefall inside the tube. The weight contains an accelerometer that resides at the base of the handle with a triaxial cable that connects the handle to a digital readout device. The weight is lifted to the top of the tube and allowed to freefall, with the accelerometer recording the maximum deceleration rate. Typically, the value after the fourth drop is recorded as the measure of soil strength.

Dynamic and static cone penetrometers measure the resistance that occurs from driving a cone into the soil with a fixed forced from a dropping weight or by applying a steady force manually. The resistance measured is displayed on a digital device or a circular dial. Care must be used to keep the device vertical and to not use a jerking motion when applying force to the penetrometer. Correlations between the dynamic cone penetrometer and the California bearing ratio and other strength values have been developed for cohesive and noncohesive soils.

Fig. A.2. The sand cone



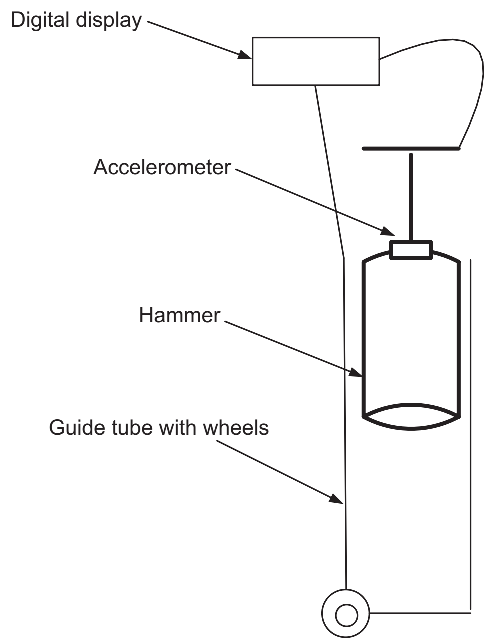


Fig. A.3. The Clegg hammer

References

Burch D (2000) Estimating excavation. Craftsman Book Company, Carlsbad

Byrne J, Nelson R, Googins P (1960) Logging road handbook: the effect of road design on hauling costs. USDA Forest Service agricultural handbook 183. USDA Forest Service, Washington

Caterpillar (2003) Caterpillar performance handbook CD-ROM, 33rd edn. Caterpillar, Peoria

Dykstra D (1996) FAO model code of forest harvesting practice. FAO, Rome

Faiz A, Staffini E (1979) Engineering economics of the maintenance of earth and gravel roads. Transportation record 702, Transportation Research Board, pp 260–268

FAO (1964) Road construction in the tropics. Unasylva 17:(2–3)

FAO (1977) Planning forest roads and harvesting. FAO forestry paper 2. FAO, Rome

FAO (1999a) Code of practice for forest harvesting in Asia-Pacific. RAP publication 1999/12. FAO and Asia-Pacific Forestry Commission. http://www.fao.org/docrep/004/ac142e/ac142e00.htm

FAO (1999b) Environmentally sound road construction in mountainous terrain. FAO forest harvesting case-study 10. FAO, Rome

FAO (2005) Regional code of practice for reduced-impact forest harvesting in tropical moist forests of west and central Africa. FAO, Rome

Garland J (1983) Road construction on forest properties. Oregon State University extension circular 1135. Oregon State University, Corvallis

Heinrich R (1975) Problems of forest road construction in tropical high forests. Technical Report of FAO/Austria training course on forest roads and harvesting in mountainous forests. FAO, Rome

Kantola M, Harstella P (1988) Handbook on appropriate technology for forestry operations in developing countries. Part 2. Wood transport and road construction. Forestry training programme publication no 19. National Board of Vocational Education of the Government of Finland, Helsinki

Karlsson LS, de Veen JJ (1981) Guide to the training of supervisors for labour-based road construction and maintenance. ILO, Geneva

Keller G, Sherar J (2003) Low-volume road engineering. USAID, Washington

Larcombe, G (1999) Forest roading manual. LIRO Forestry Solutions, Rotorua

Sedlak O (1982) Types of roads and road network under difficult mountainous conditions and its relation to operation of cable systems. ECE/FAO/ILO joint committee on forest working techniques and training of forest workers/IUFRO, division III. Norwegian Forest Research Institute, Oslo

Sessions J (1992) Cost control in forest harvesting and road construction. FAO forestry paper 99. FAO, Rome

USDA Forest Service (1966) Transportation engineering handbook. Region 6. USDA Forest Service, Portland

Walbridge TA Jr (1990). The direct location of forest roads. Virginia Polytechnic Institute and State University, Blacksburg

Walbridge TA Jr (1991). The paper location of forest roads. Virginia Polytechnic Institute and State University, Blacksburg

World Bank (2004) Highway development and management (HDM-4). World Bank, Washington

Zaremba W (1976) Logging reference manual. Volume 3. Logging roads. Bulletin 52. Department of Forestry, Pretoria

Further Reading

Akay AE, Sessions J (2004). Forest operations: roading and transport operations. In: Burley J, Evans J, Youngquist JA (eds) Encyclopedia of forest sciences. Elsevier, Oxford, pp 259–269

Al-Amoudi O, Asi I, Wahhab H, Khan Z (2002). Clegg hammer-California-bearing ratio correlations. J Mater Civ Eng 14(6):512–523

Allal A, Edmonds G (1977) Manual on the planning of labour-intensive road construction. ILO, Geneva

Amini F (2003) Potential applications of dynamic and static cone pentrometer in MDOT pavement design and construction. MS-DOT-RD-03-162. Jackson State University Department of Civil Engineering

Antola A (1979) Techniques in forest road construction. Research notes 39. Department of Logging and Utilization of Forest Products. University of Helsinki (in Finnish)

Balcom J (1988). Construction costs for forest roads. Research bulletin 64. Forest Research Laboratory, Oregon State University, Corvallis

Brown C, Sessions J (1999) Variable tire pressures for tropical forests? A synthesis of concepts and applications. J Trop For Sci 11(2):380–400

Cornell J, Mills K (eds) (1999) Forest road management guidebook. Maintenance and repairs to protect fish habitat and water quality. Oregon Department of Forestry, Oregon State University, Corvallis

de Veen JJ (1980) The rural access roads programme, 3rd impression. ILO, Geneva

Douglas R (1999). Forest roads/resource access roads, delivery. The transportation of raw natural resource products for roadside to mill. University of New Brunswick

FAO (1979) Mountain forest roads and harvesting. FAO forestry paper 14. FAO, Rome

Gray D, Leiser A (1982) Biotechnical slope protection and erosion control. Van Nostrand Reinhold, New York

Hindson J (1983) Earth roads. Intermediate Technology Publications, London

Holmes D (1982) Manual for roads and transportation, vol 2. British Columbia Institute of Technology, Burnaby

ILO (1981) Guide to tools and equipment for labour-based road construction. ILO, Geneva

Khedr S, Kraft D, Jenkins J (1985) Automated cone penetrometer: a nondestructive field test for subgrade evaluation. Transportation Research record N1022, analysis and testing of granular bases and subbases. Transportation Research Board, Washington, pp 108–115

Kramer B (1993) A road design process for low volume recreation and resource development roads. Oregon State University Bookstore, Corvallis

Kramer B (1994) Forest road surveying field handbook. Oregon State University Book Store, Corvallis

Megahan WF (1976) Tables of geometry for low-standard roads for watershed management considerations, slope staking and end areas. USDA Forest Service general technical teport INT-32. USDA Forest Service, Ogden

Mitchell K, Villet W (1987) Reinforcement of earth slopes and embankments. National Cooperative Highway Research Report 290. Transportation Research Board

Nagy MM, Trebett JT, Wellburn GV (1980) Log bridge construction handbook. Forest Engineering Research Institute of Canada, Vancouver-Pointe Blaire

Sedlak O (1985) Forest road planning location and construction techniques in steep terrain. FAO forestry paper 14, revision 1. FAO, Rome

Sedlak O (1986) General principles of forest road net; general introduction to forest road construction methods; costs and production in forest road construction; maintenance of forest roads. FAO/Finland training course on appropriate wood harvesting operations. Mutare, Zimbabwe, 9–26 June 1986. FAO: AWHO/86/LP/12-15

Sedlak O (1996). Forest harvesting and environment in Austria. In: Forest codes of practice. Contributing to environmentally sound forest operations. FAO forestry paper 133. FAO, Rome

Sessions J (1986) Cost control in logging and road construction. FAO.FO: AWHO/86/LP5. FAO, Rome

Sessions J, Heinrich R (1993) Forest roads in the tropics. In: Pancel L (ed). Tropical forestry handbook. Springer, Berlin Heidelberg New York, pp 1269–1324

Sessions J, Boston K, Thoreson R, Mills K (2006) Optimal policies for managing aggregate resources on temporary roads. West J Appl For 21:207–216

Steward J, Williamson R, J Mohney J. Guidelines for use of fabrics in construction and maintenance of low-volume roads. Report no FHWA-TS-78-205. US Department of Transportation.

USDA Forest Service (1996) Earth and aggregate surfacing design guide for low volume roads. Publication EM-7170-16, USDA Forest Service

USDA Forest Service (2004) Portable bridges as a best management practice in forest management. Report NA-TP-04-04, USDA Forest Service, Morgantown

Yeap Y, Sessions J (1989) Optimizing spacing and standards of logging roads on uniform terrain. J Trop For Sci 1:215–228

Index