Bradley T. Piehl,[1] **Robert L. Beschta,** and **Marvin R. Pyles,**
Department of Forest Engineering, Oregon State University, Corvallis, Oregon 97331

Ditch-relief Culverts and Low-volume Forest Roads in the Oregon Coast Range[2]

Abstract

Drainage systems associated with gravel-surfaced roads often rely on culverts for moving water through the road prism and for minimizing onsite erosion. The purpose of this study was to determine the characteristics and functional capabilities of ditch relief culverts (DRC's) in the Coast Range of western Oregon. Five hundred and fifteen DRC's were evaluated to determine diameter and length, spacing, inlet conditions, skew angle, slope, and outlet erosion. Most DRC's (86%) were corrugated steel pipe. Pipe diameters were typically 38.1 or 45.7 cm (15 or 18 in.); average length was 10.7 m (35.1 ft.). Cross-sectional area of 74 percent of the inlets had been reduced by sediment deposition, pipe damage, cutbank sloughing, or organic debris; the inlet area of all DRC culverts averaged 81 percent of original. Spacing of DRC's varied by ownership category, with averages of 2.6 to 5.2 DRC's per km (4.2 to 8.4 per mi). Ditch erosion was minimal except with relatively long culvert spacing. Erosion at culvert outlets increased with culvert spacing.

Introduction

Low-volume roads (typically single-lane, gravel-surfaced roads with little traffic) are an essential component of managed forest lands throughout the western United States. Culverts provide the most common means for moving water across these roads and represent an important aspect of the overall design and operation of an effective forest road-drainage system. Road drainage not only influences road surface and ditch erosion, but in steep terrain it also can affect the occurrence of fillslope failures (Burroughs 1984). Direct costs associated with these failures include loss of use of the road and the expense of replacing the culvert and its associated fill. In addition, road failures represent an important management concern, because of their potential for directly impacting aquatic habitat and water quality of streams. Dyson *et al.* (1966) evaluated damages on U.S. Forest Service lands in the Pacific Northwest after major storms in December 1964 and January 1965. They concluded that failure of road-drainage facilities caused nearly all road damage and that plugged ditch-relief culverts contributed significantly to this problem.

More recently, Krag *et al.* (1986) completed a detailed analysis of thirty-one slope failures associated with logging roads on the Queen Charlotte Islands in Canada. Most of these road-associated failures were traced to problems of road drainage: the absence of ditches or ditches formed from road ballast, culverts that were spaced too far apart or poorly located, and culverts that were too small.

Forest roads typically intercept part of the subsurface flow moving down a slope and route it along a ditch until the water is diverted across the road. Surface runoff from insloped portions of the road adds more water to the ditch. In most cases, water diversion is accomplished with a ditch-relief culvert (DRC), also called a cross-drain culvert. The contributing area for DRC's is often small and poorly defined by surface topography.

Design of a DRC system (Figure 1) includes culvert spacing (uphill distance to the next culvert or grade break); ditch, inlet, and outlet geometry; and culvert diameter, slope, and skew angle. The basic objective is to provide stable drainage at lowest cost. This requires a tradeoff between initial installation cost and potential for future costs of road failure and environmental damage. However, economic costs of failure and environmental damage remain difficult to quantify.

In general, wider spacings result in more water flowing in the ditch, through the culvert, and discharging downslope. Greater amounts of water increase the potential for ditch and road-

[1]Currently with Riverside Technology, Ft. Collins, CO 80525.

[2]Paper 2198 of the Forest Research Laboratory, Oregon State University, Corvallis. This article is published with funds provided in part by the U.S. Geological Survey, Department of the Interior, as authorized by the Water Resources Research Act of 1984.

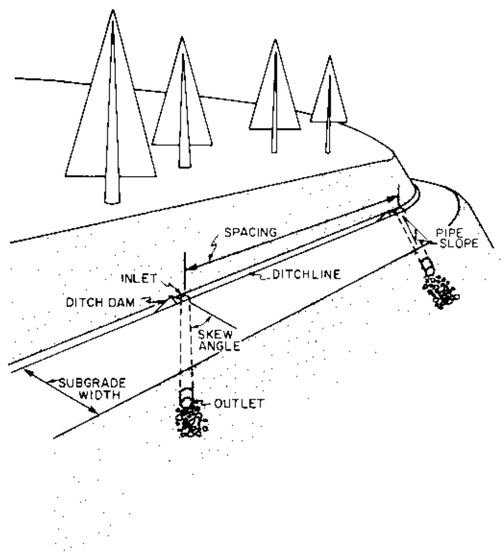

Figure 1. Ditch-relief culvert system.

surface erosion and for erosion of the fillslope or the natural slope below the culvert outlet. Any of this erosion could lead to complete road failure.

Culvert plugging can lead to road-surface or gully erosion by water flowing on the road; catastrophic failure of fill or sidecast material; or water continuing down the ditch, to be diverted by the next DRC. Efficient inlet geometry, large culvert diameter and steep slope, and large skew angle are believed to increase hydraulic efficiency and reduce the occurrence of plugged culverts.

Arnold (1957) presented spacing guidelines developed in 1953 for U.S. Forest Service DRC's. These guidelines were based on his experience with road drainage structures in the Cascade Mountains of the Pacific Northwest. Control of ditch erosion was a major objective. Arnold's recommended spacing was a function of soil erodibility and road grade (Figure 2). Hillslope soils were categorized in ten erosion classes. Basic culvert spacing was adjusted by a rain-intensity factor based on the 25-year, 15-minute storm; higher rain intensity calls for closer spacing.

Baeder and Christner (1981) adjusted Arnold's spacing guidelines to provide closer spacings for most culverts in the Willamette National Forest in the Oregon Cascade Mountains by including slope position, aspect, and cutbank failure probability, but their revisions are not based on field data or a theoretical model.

This study was undertaken to determine the characteristics and functional capabilities of existing DRC's in the Oregon Coast Range and to determine the design provisions that appear to optimize performance. No ditch or outlet erosion and a clear inlet and culvert barrel were assumed to indicate optimum performance.

Study Area

The central Oregon Coast Range (in Lincoln, Benton, Lane, Douglas and Coos counties) is underlain by the relatively homogenous Tyee sandstone formation; soils therefore are of similar erodibility. Landforms are steep (up to 100% slope), with highly dissected hillslopes and sharply formed ridgelines. Annual precipitation (primarily rain) is high, ranging from about 180 cm (70.9 in.) near the coast to over 300 cm (118.2 in.) along the crest of the Coast Range. Nearly 80 percent occurs from October through March, when frontal storms often continue without interruption for several days. Daily rainfall amounts of 13 to 18 cm (5.1 to 7.1 in.) occur, on the average, about once every 10 years in the study area (Miller *et al.* 1973). Drainage densities are relatively high, averaging nearly 6.2 km of stream/km^2 (10.0 mi/mi^2) of watershed (G. S. Bush, unpublished data). Road densities on U.S. Forest Service lands average 1.6 km/km^2 (2.6 mi/mi^2), because the road system is not yet complete; road densities are generally greater for other ownerships.

Methods

Within the study area, three sections were randomly selected from each township. Within each section, all roads were divided into segments, where a segment represents the length of road between two intersections, or between an intersection and the end of the road. The segments were numbered and three of them were randomly chosen for examination. Culverts were selected by going to the nearest end of a selected road segment and examining the first six culverts encountered along that segment.

Since culverts were selected in sequence along a road segment, there is some opportunity

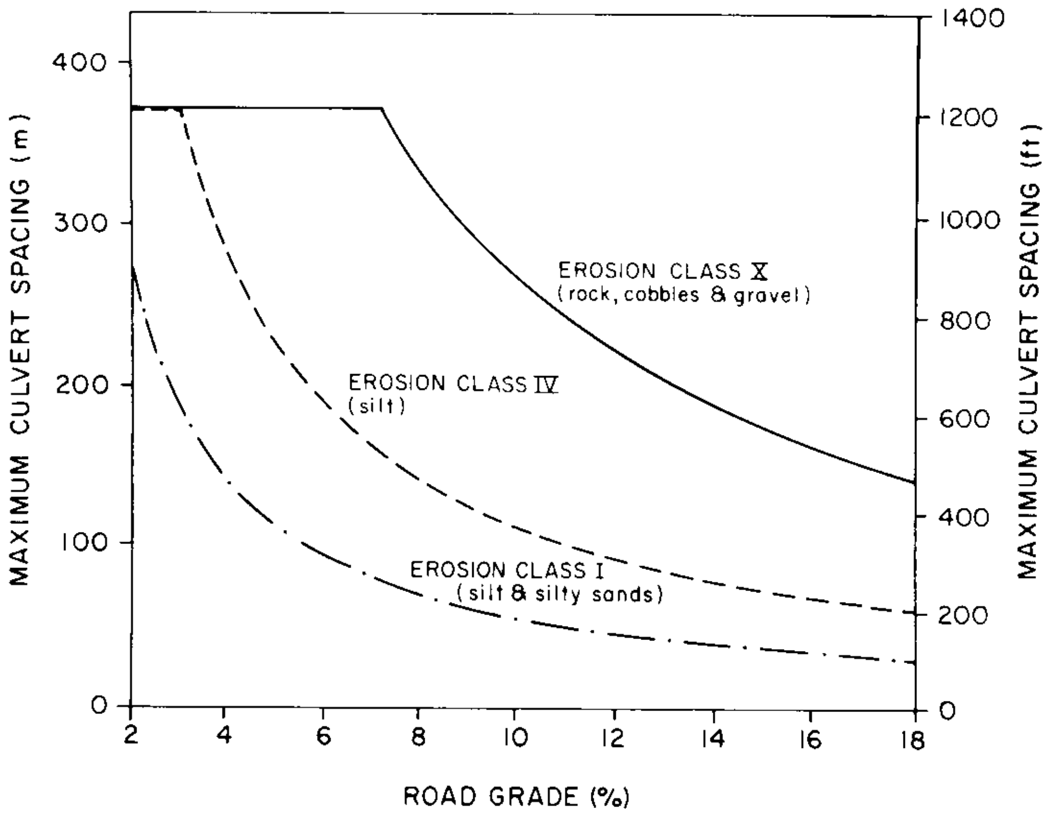

Figure 2. Sample guideline for culvert spacing (adapted from Arnold, 1957). The most erodable soils are in erosion class I; the least erodable, in erosion class X.

for non-independence in the data. However, adjacent DCR's were often separated by topographic ridges, the crest of a vertical curve, or stream crossing culverts (stream crossing culverts were excluded from this analysis). Thus the potential dependency may be relatively small. Furthermore, the basic design of DRC's is for independent operation. Dependence between adjacent DRC's will only occur if an up-grade culvert fails, and by-passes water and sediment down to the next DRC culvert.

During the summers of 1984 and 1985, DRC's were characterized by diameter and length, spacing, inlet condition, skew angle, slope, and outlet erosion. Outlet erosion was determined by visually projecting surface contours across any erosion below the pipe outlet and calculating the volume of eroded soil. Five hundred and fifteen DRC's were evaluated, although some variables could not be measured at all culverts.

Results and Discussion

The DRC's evaluated in this study were on 1- to 1.5-lane roads. Over 50 percent of the DRC's were near ridgetops, reflecting the practice of building roads near ridges to minimize direct impacts to riparian zones, reduce risk of mass failure from mid-slope roads, and provide access for harvesting systems that can remove felled timber efficiently and with minimal onsite impacts. Gravel road surfaces associated with these culverts averaged 4.1 ± 0.8 m (13.5 ± 2.6 ft.) wide (mean ± standard deviation); road subgrades averaged 6.6 ± 1.4 m (21.7 ± 4.6 ft.) wide. Fifty-five percent of the DRC's were made of corrugated steel; 31 percent, of corrugated steel with asphalt; 11 percent, of aluminum; and 3 percent, of concrete. Most (90%) had projecting entrances. Culvert lengths averaged 10.7 ± 2.6 m (35.1 ± 8.5 ft.); diameters and cross-sectional areas are given in Table 1.

TABLE 1. Dimensions of ditch relief culverts in the central Oregon Coast Range (n = 515).

Diameter (cm)	Cross-sectional area (m^2)	% of culverts
30.5 (12 in.)	0.07 (0.79 ft^2)	1
38.1 (15 in.)	0.11 (1.23 ft^2)	36
45.7 (18 in.)	0.16 (1.77 ft^2)	62
70.0 (24 in.)	0.29 (3.14 ft^2)	1

Culvert Spacing

Average number of DRC's per mile on U.S. Forest Service roads was 38 to 98 percent greater than for other ownerships (Table 2). Actual spacings in our study area exceeded Arnold's guidelines (Figure 2) by an average of 70 percent (Table 2). Ditch erosion generally was not a problem with the forest roads sampled, except where spacing distances were exceptionally large. Long ditchlines between DRC's, which were frequently found on state and private roads, diverted ditchwater into small streams at crossings, or onto slopes at switchbacks or topographic "saddles."

Inlet Condition

The relative importance of sediment plugging, pipe damage, cutbank sloughing, organic debris blockage, or combinations of these factors was evaluated by expressing existing cross-sectional area of the culvert inlet as a percent of original area (Figure 3). Average cross-sectional area for all DRC inlets was 81 percent of original; averages ranged from 73 percent for private lands to 85 percent for state lands.

Inlet areas had been reduced in 74 percent of the DRC's. Sediment deposition, occurring at 24 percent of the installations, was the main cause. Physical damage or denting, the second most frequent cause, occurred at 17 percent of the installations. Where sediment deposition or denting occurred separately, each reduced the cross-sectional area of DRC inlets to an average of approximately 80 percent of original area. Another 7 percent of the culverts were reduced by combined effects of sediment and denting; average cross-sectional area for these pipes was only 61 percent of the original. Thus, inlets of nearly half (48%) of the DRC's were reduced by sediment, denting, or both. Cutbank slumpage severe enough to affect entrance conditions was

TABLE 2. Ditch-relief culverts in the central Oregon Coast Range: owners, spacing, and outlet erosion volumes.

Owner	Sampled road sections n	Sampled road sections %	Ditch relief culverts n	Ditch relief culverts %	Culverts/km[a]	Relative Culvert spacing[b]	Outlet erosion volume (m^3)[a,c]
USDA Forest Service	52	52.5	326	63.3	5.1 [2.2]	1.3 [0.8]	0.6 [1.8]
USDI Bureau of Land Management	27	27.3	118	22.9	3.5 [1.2]	2.1 [1.7]	0.6 [1.8]
State	10	10.1	37	7.2	3.7 [1.7]	2.4 [1.7]	1.4 [2.8]
Private	10	10.1	34	6.6	2.6 [1.6]	2.7 [2.0]	1.3 [3.6]
Average	—	—	—	—	4.4 [2.1]	1.7 [1.3]	0.7 [2.1]
Total	99	100.0	515	—	—	—	—

[a]Mean [standard deviation]

[b]Mean [standard deviation] culvert spacing relative to Arnold's (1957) guidelines, i.e., observed spacing/Arnold's spacing. For example, a mean value of 1.7 indicates that the observed spacing was 70 percent greater than indicated by Arnold's guidelines.

[c]Two outlet erosion volumes (i.e., landslides comprising 841 and 127 m^3) were not utilized in calculating the "outlet erosion volume" mean and standard deviation (see text.)

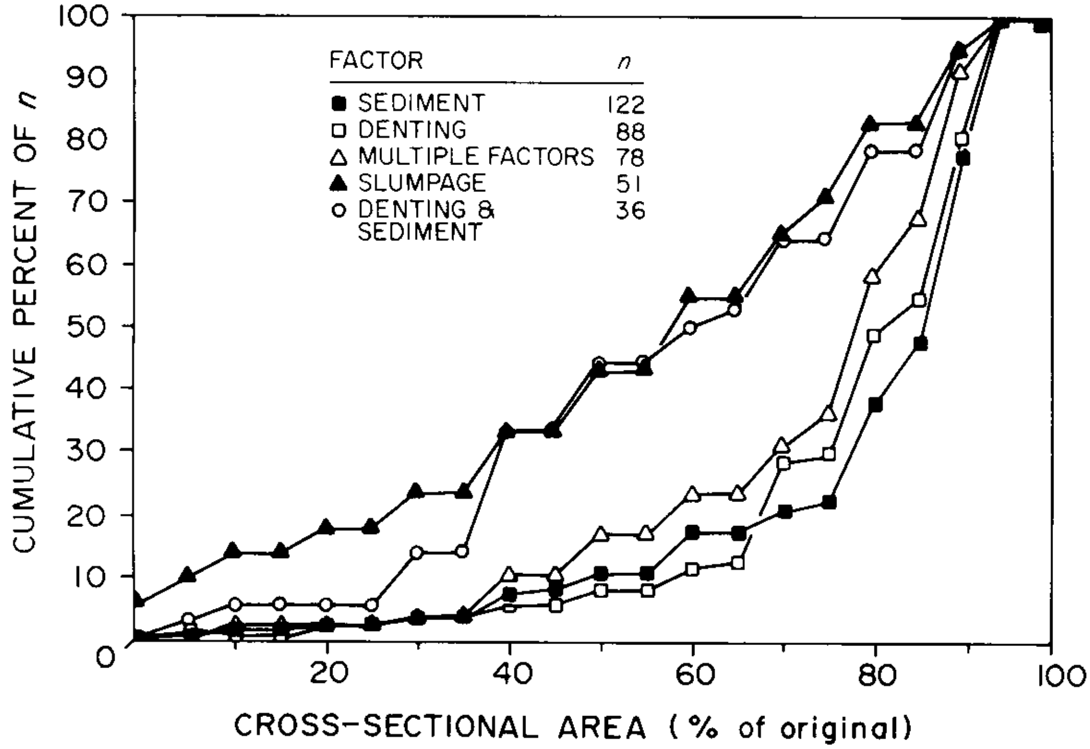

Figure 3. Factors affecting reduction in cross-sectional area of ditch-relief-culvert inlets.

relatively infrequent (10% of all DRC's) but reduced inlet cross-sectional area to an average of 56 percent of the original. Only 1 percent of the DRC's were plugged by organic debris. Multiple factors affected inlet cross-sectional area in another 15 percent; area of these inlets averaged 74 percent of original area.

The only aspects of inlet condition that might be influenced by between-culvert dependence is plugging of an inlet with sediment or organic debris. Since by-passing of water, sediment or organic debris from one pipe to the next would require nearly complete plugging of the first pipe, which was not found, dependence is unlikely and the evaluated inlet characteristics should provide a reasonable representation of inlet conditions for the population of DRC's in the central Oregon Coast Range.

Skew Angle

Garland (1983) suggested that ditch relief culverts be installed with approximately 30° of skew (Figure 1); skew angles in this study averaged 15° (Figure 4A). Greater skew angles should help pass water, sediment and debris through culvert inlets. As skew angle decreases, water flowing along the ditch and any transported material must turn more sharply to enter the pipe; as a result, water velocity is reduced and sediment, organic debris, or both may be deposited. However, reductions in cross-section area at DRC inlets by sediment and debris accumulation were not significantly correlated with skew angle ($P > 0.10$).

Culvert Slope

The slope of DRC's generally should be at least 3 percent to maintain high water velocity and prevent deposition of sediment (Rothwell 1978); over 90 percent of the DRC's met this criterion. Culverts also should be inclined 2 percent more than the road grade (Rothwell 1978); only 40 percent of the DRC's in this study satisfied this criterion. Average slope of DRC's was 6 percent (Figure 4B); average road slope was 7 percent. Sediment deposition at DRC inlets was less at

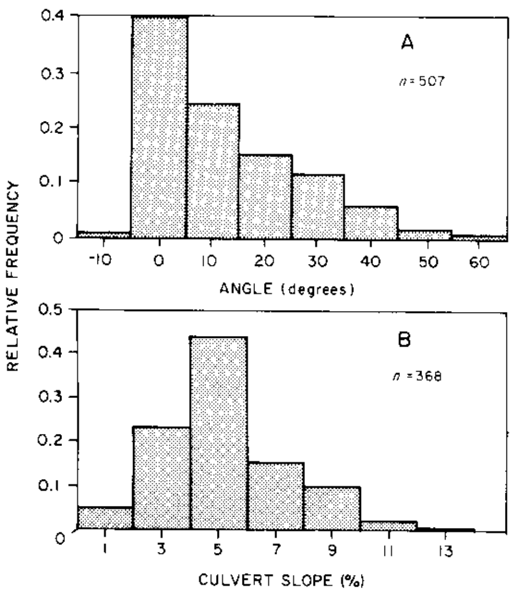

Figure 4. Distribution of (A) skew angles, and (B) slopes for ditch-relief culverts.

steeper pipe slopes. Unexpectedly, these steeper pipes also had a higher percentage of dented inlets and an increased occurrence of cutbank slumpage.

Outlet Condition

Outlet erosion volume (volume of soil removed by erosion of roadfill, hillslope, or both) was estimated at each culvert outlet; measurable outlet erosion was associated with 38 percent of the DRC's. In two cases, large landslides below the culvert outlets resulted in erosion volumes (841 and 127 m^3) that comprised 72 percent of the total outlet erosion for all culverts. Because landslides occur by a different mechanism than surface erosion by water evident for the remainder of the culverts, these two values were not included in this analysis. Landslides are an important problem associated with forest roads, but any analysis would require a much larger data set than the two slides we observed. Outlet erosion volumes of the remaining culverts (Table 2) averaged 0.73 m^3 (0.96 yd^3).

Outlet erosion volumes increased with increased spacing, averaging 3.4 m^3 (4.4 yd^3) per culvert where spacing exceeded Arnold's (1957) guidelines by more than 100 percent, but only 1.2 m^3 (1.6 yd^3) where spacing exceeded those guidelines by less than 100 percent. The observed spacing of culverts on U.S. Forest Service lands exceeded Arnold's guidelines by an average of 30 percent. In contrast, spacing distances on private lands averaged 170 percent greater than Arnold recommended (Table 2).

Fillslopes were rated qualitatively and placed into one of three categories: "stable," "eroding intermittently," and "eroding actively." Sixty percent of the fillslopes fell in the first class, 28 percent in the second, and 12 percent in the third. The proportion of culverts associated with intermittently and actively eroding roadfills increased as spacing, expressed as a percentage of Arnold's (1957) guidelines, increased (Figure 5).

Conclusions

A consistent procedure for DRC spacing on low-volume forest roads has not been used in the central Oregon Coast Range, and spacings typically exceed those identified by Arnold (1957). Widely spaced DRC's would tend to carry more water during major rainfall events, and the potential for erosion is increased, as indicated by greater erosion volumes associated with larger spacings. Where outlet erosion is significant, reducing DRC spacing should decrease outlet erosion. With continued outlet erosion, roadfills on steep slopes may ultimately be undermined and fail. Field observations indicated that ditch erosion was not a problem between most DRC's.

Large landslides were found below the culvert outlets for two of the 515 DRC's evaluated. Although some aspect of road drainage may have been associated with these slides, neither the physical evidence nor statistical inference from such a small sample size could be used to confirm this.

Our use of Arnold's (1957) spacing guidelines is not meant to imply that his spacings are necessarily the "standard" to be used for DRC spacing in western Oregon. We chose them as a basis for comparison because they have existed for 30 years and provide guidelines on a site-specific basis. To our knowledge they have not been systematically evaluated. Furthermore, the guidelines are based on several important variables that might logically be expected to affect DRC spacing, i.e., erosion classes based on soil characteristics, ditchline gradient, and precipitation intensity. The development of new or

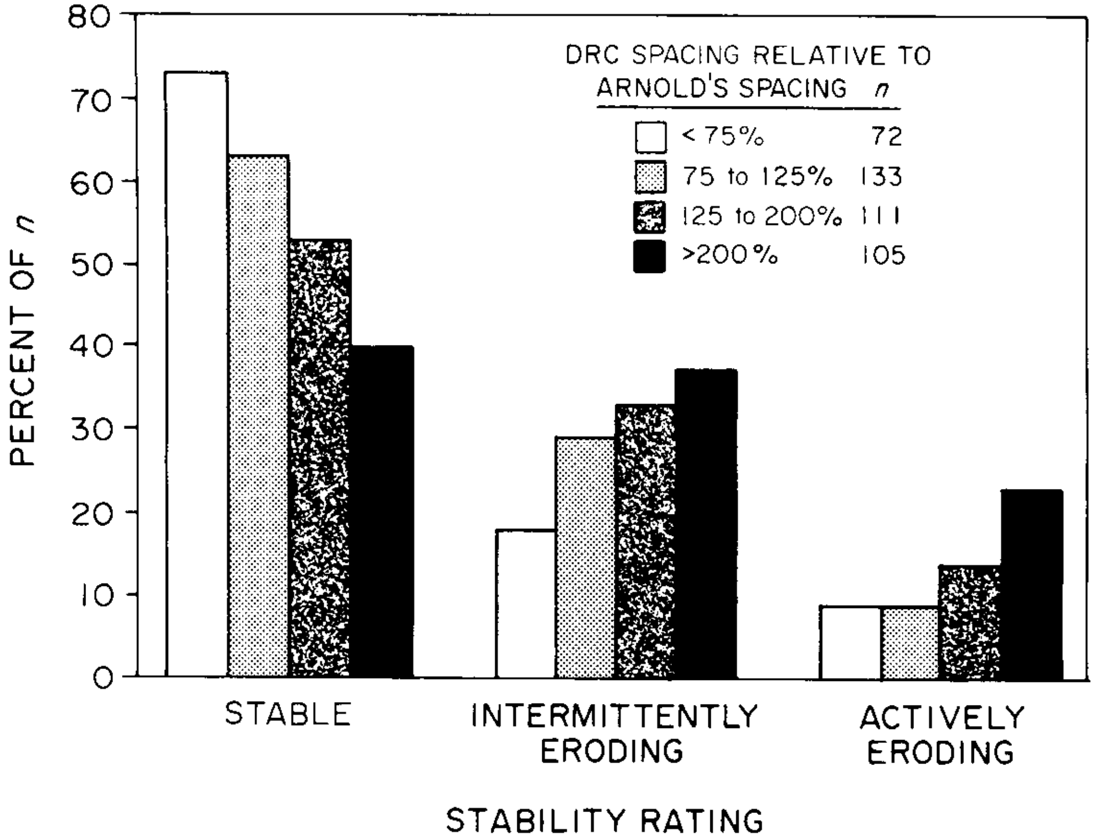

Figure 5. Stability rating of fill slopes of ditch-relief culverts (DRC), in comparison with Arnold's (1957) spacing guidelines.

revised spacing guidelines was beyond the scope of this study.

Little culvert plugging by organic debris was found which may indicate that existing maintenance programs are keeping inlets acceptably free of woody debris. Road maintenance (i.e., grading of road surfaces and cleaning ditches or inlets with equipment) and vehicle travel can damage inlets and reduce cross-sectional area. The relatively high percentage of inlets with reduced cross-sectional area indicates that improved maintenance procedures, quality control, or inlet design may be needed to prevent continued damage and denting. Whether this reduction is considered in original sizing and design of culverts is not known.

This study provides an initial evaluation of ditch-relief culverts within a relatively limited geographic area of coastal Oregon. Our ability to extrapolate these results or compare them with results from other areas and ownerships is limited. The scientific literature is noticeably deficient in research on road drainage structures in mountainous terrain. Given the thousands of miles of low-volume roads in Oregon alone, this regrettable lack of knowledge may severely limit the ability of forest landowners to manage transportation systems efficiently and to reduce storm-related road damage.

Literature Cited

Arnold, J. 1957. Chapter XIII. Engineering aspects of forest soils. *In* An introduction to forest soils of the Douglas-fir region of the Pacific Northwest. Western Forestry and Conservation Assoc., Portland, Oregon. Pp. 1-15.

Baeder, L., and J. Christner. 1981. Revision of the guide for spacing relief culverts for the Willamette National Forest. USDA For. Serv. Pac. Northwest Reg., Willamette Natl. For., Eugene, Oregon.

Burroughs, E. R. 1984. Survey of slope stability problems on forest lands in the west. *In* Proceedings of a workshop on slope stability; problems and solutions in forest management. USDA For. Serv. Gen. Tech. Rep. PNW-180. Pp. 6-16.

Dyson, E. L., J. R. Risher, H. E. Graham, T. B. Glazebrook, L. W. Murphy, and J. S. Rothacher. 1966. Part II: A report of the Region 6 storm damage evaluation committee (Storms of December 1964 and January 1965). USDA For. Serv. Pac. Northwest Reg., Portland, Oregon.

Received 25 June 1987
Accepted for publication 7 January 1988

Garland, J. J. 1983. Designing woodland roads. Oreg. State Univ. Ext. Serv. Ext. Circ. 1137, Oregon State University, Corvallis.

Krag, R. K., E. A. Sauder, and G. V. Wellburn. 1986. A forest engineering analysis of landslides in logged areas on the Queen Charlotte Islands, British Columbia. Forest Engineering Institute of Canada, Land Management Report Number 43. 138 pp.

Miller, J. F., R. H. Frederick, and R. J. Tracey. 1973. NOAA Atlas 2: Precipitation—frequency atlas of the western United States. Volume X—Oregon. U.S. Dept. Comm., Natl. Oceanic Atmos. Admin., Natl. Weather Serv.

Rothwell, R. L. 1978. Watershed management guidelines for logging road construction in Alberta. Environ. Can., For. Serv., North. For. Res. Cent., Edmonton, Alberta. Inf. Rep. NOR-X-208.