AN ABSTRACT OF THE DISSERTATION OF

Elizabeth Myers Toman for the degree of Doctor of Philosophy in Forest Engineering and Civil Engineering presented August 3, 2007.

Title: Reducing Sediment Production from Forest Roads during Wet-Weather Use.

Abstract approved:

_____ _____

Arne E. Skaugset Marvin R. Pyles

Forest roads produce fine sediment with traffic during wet weather. If the forest road is connected to a stream it can be a source of turbidity and fine sediment that may be detrimental to aquatic organisms especially salmonids.

The goal of this work was to investigate turbid runoff during wet-weather use from the pavement of forest roads that were designed to reduce sediment production. This research explored the opportunity costs associated with upgrading forest roads for environmental performance, determined a method to design an unbound aggregate pavement to reduce sediment production, and tested alternatives for road pavements that were designed specifically to minimize turbid runoff during wet weather hauling.

The opportunity costs associated with restricted timber hauling and harvesting are potentially a resource that could be made available to improve aggregate road surfaces to minimize hauling restrictions during wet-weather. In this study the opportunity costs were 1.7 to 15 percent of the total net revenue for McDonald-Dunn Research Forest.

A method of design for the pavement structure for unbound aggregate roads was developed. This “reduced stress” design method designs against subgrade mixing by reducing stresses on the subgrade to allow for strain hardening of the subgrade. The method recommends depths of surface aggregate that are greater than traditional pavement design methods but is an appropriate design method to reduce sediment production from subgrade mixing.

Alternative designs of the pavement for unbound aggregate roads influenced the production of sediment, but results were not consistent; the pavement treatments produced different results across different research locations. The results suggest that fine sediment in surface runoff does not originate

from the subgrade but rather from the surface aggregate. Road managers that want to minimize the production of sediment from forest roads should be concerned with the unbound aggregate pavement rather than the subgrade. Managers should design the aggregate pavement with consideration to the availability of fine sediment in the aggregate and should design the pavement to resist rut formation.

Reducing Sediment Production from Forest Roads during Wet-Weather Use

by
Elizabeth Myers Toman

A DISSERTATION

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Doctor of Philosophy

Presented August 3, 2007
Commencement June 2008

Doctor of Philosophy dissertation of Elizabeth Myers Toman presented on August 3, 2007.

APPROVED:

_____

Co-Major Professor, representing Forest Engineering

_____

Co-Major Professor, representing Civil Engineering

_____

Head of the Department of Forest Engineering

_____

Head of the School of Civil and Construction Engineering

_____

Dean of the Graduate School

I understand that my dissertation will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my dissertation to any reader upon request.

_____

Elizabeth Myers Toman, Author

ACKNOWLEDGEMENTS

There were many people involved in this research and in the journey that brought me to this point. I know that if I tried to list them all I would miss someone. Rather than naming individuals I want to express my thanks and gratitude to all that have provided support, encouragement, advice, and kindness in the six years leading to this final goal. They are faculty, staff, and students at Oregon State University, and family and friends scattered everywhere. Although my name is the only one listed as author on the signature page, this research and dissertation were a community effort. Thank you.

I do want to acknowledge the efforts of two individuals, without whom I would never have begun or finished this journey. My advisor, Arne Skaugset, has become a close friend and someone I hope to work with for years to come. Arne's whistling through the hallways always made me smile and his advice and mentorship has helped me become a better individual. Thank you. My husband, Eric, whose support and enthusiasm helped me stretch farther than I ever could have imagined and achieve my greatest goals. I'm so grateful, Eric, that you will be by my side for the journeys to come as well. Thank you.

CONTRIBUTION OF AUTHORS

Dr. Arne E. Skaugset and Dr. Glen E. Murphy assisted in the data analysis and writing of Chapter 2.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

Figure Page

LIST OF FIGURES (Continued)

Figure Page

LIST OF FIGURES (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

REDUCING SEDIMENT PRODUCTION FROM FOREST ROADS DURING WET-WEATHER USE

CHAPTER 1: INTRODUCTION

Background

During the last decade many species and/or runs of anadromous salmonids have been listed as threatened or endangered in the Pacific Northwest as a part of the Endangered Species Act process (see NOAA 2004). Most salmon stocks throughout the Northwest are at a fraction of their historic levels with over fishing and, more recently, loss of freshwater habitat listed as the major causes of decline. Water quality and quantity contribute to critical habitat for salmonids and changes to either can alter fish productivity (Meehan 1991). The activities of forest management, especially timber harvesting, have been associated with impacts in stream temperature (Beschta *et al.* 1987), the supply of large woody debris (Bisson *et al.* 1987), dissolved oxygen concentration (Binkley and Brown 1993), streamflow (Chamberlin *et al.* 1991), fine and coarse sediment (Everest *et al.* 1987; Swanson and Dyrness 1975), and nutrient supply (Brown *et al.* 1973) and the subsequent reduction in populations of salmonids (Hicks *et al.* 1991).

Regulations that govern forest practices in some of the timber producing states in the western United States are increasingly restrictive in order to protect water quality and salmonids. The most recent changes to regulations in California (CDF&FP 2004), Washington (WSDNR 2006), and Oregon (ODF 2003) have come in the past five years after recommendations from boards of review. Monitoring efforts continue (Ice *et al.* 2004) and with further review state regulations may become even more restrictive.

An area of forest management that continues to be the focus of increasing environmental concern is forest roads. Research has shown that forest roads can be hydrologically connected to streams through road side ditches, stream crossings, and gullies (Toman 2004; Wemple *et al.* 1996). With this connectivity, forest roads have been hypothesized to permanently affect watershed hydrology by increasing peak flows (Jones and Grant 1996). Although other research suggests that roads may not increase peak flows (Beschta *et al.* 2000). Forest roads have been shown to be a source of accelerated erosion to streams including the occurrence of debris slides from roads (Swanston and Swanson 1976) as well as surface erosion from the road pavement (Bilby *et al.* 1989). While most erosion from slides will occur during large, infrequent winter storms, roads are also perceived to be a chronic source of fine

sediment from the pavement surface, drainage ditches, and cut-and-fill surfaces (Brown and Krygier 1971). Traffic use of forest roads can increase the production of fine sediment. One study reported that log truck traffic on forest roads during winter storms increased the yield of fine sediment during these storms by up to several orders of magnitude (Reid and Dunne 1984). For this reason, the subject of the production of fine sediment and delivery of turbid runoff to streams during wet-weather hauling has become an important and visible subject. Indeed, the recent changes to the forest practice rules of California, Washington, and Oregon have specifically addressed the subject of turbid runoff during wet-weather hauling.

The existing database of research regarding turbid runoff from wet-weather hauling is modest and what is available has become dated and does not accurately represent contemporary practices. More importantly, the existing research on turbid runoff consists of measuring sediment yield from unbound aggregate roads built from a standard design. In these studies, the roads were the result of a design method that was intended solely to support the traffic load of the trucks for the requisite number of axles. Once the designed road was in place the environmental performance of the road was evaluated. No research has been carried out on unbound aggregate roads designed with environmental performance as a primary constraint.

Research Objectives

The goal of this work was to investigate turbid runoff during wet-weather use from forest roads designed to reduce sediment production. The purpose of this research was to develop new knowledge that will allow forest land managers to make more informed decisions regarding the environmental performance of their roads. This research will first explore the opportunity costs associated with upgrading forest roads to reduce sediment production. Opportunity costs are defined as the total forgone value (including costs and predicted benefits) associated with an alternative action (Loomis and Walsh 1997). The opportunity costs associated with upgrading forest roads to reduce sediment production include the benefits of being able to haul on the road during wet weather. Is there financial impetus to construct and maintain roads to reduce sediment production? Next this research will determine one method to design a road to reduce sediment production with hauling during wet weather as well as for load support. Finally this research will test alternatives for road pavements that are constructed specifically to minimize turbid runoff during wet weather hauling and compare the monetary costs and environmental benefits of the alternatives for road design.

The primary practice advocated through existing forest practice rules to minimize fine sediment production from forest roads is to restrict hauling on unbound aggregate roads during wet-weather. This certainly restricts the flexibility of forest landowners who choose to harvest timber during

the wet season to maintain flexibility and access to seasonal markets. With cost and environmental performance data for alternative designs for forest roads, landowners can make the choice to pay for a more robust road design that will deliver environmental performance or lose the time available for hauling during wet weather. Knowledge of the cost of alternative designs and the environmental performance of the alternatives for unbound aggregate roads will help give forest landowners more flexibility in choosing a course of action for limiting the environmental effects of forest roads. This increased flexibility may help maintain the efficiency and competitiveness of the forest landowners.

References

Beschta, R. L., Bilby, R. E., Brown, G. W., Holtby, B. L., and Hofstra, T. D. (1987). "Stream Temperature and Aquatic Habitat: Fisheries and Forestry Interactions." Streamside Management: Forestry and Fishery Interactions, E. O. Salo and T. W. Cundy, eds., University of Washington, Seattle, 191-232.

Beschta, R. L., Pyles, M. R., Skaugset, A. E., and Surfleet, C. G. (2000). "Peakflow responses to forest practices in the western Cascades of Oregon, USA." *Journal of Hydrology*, 233, 102-120.

Bilby, R. E., Sullivan, K., and Duncan, S. H. (1989). "The generation and fate of road-surface sediment in forested watershed in southwestern Washington." *Forest Science*, 35(2), 453-468.

Binkley, D., and Brown, T. C. (1993). "Forest practices as nonpoint sources of pollution in North America." *Water Resources Bulletin*, 29(5), 729-740.

Bisson, P. A., Bilby, R. E., Bryant, C. A., Dolloff, C. A., Grette, G. B., House, R. A., Murphy, M. L., Koski, K. V., and Sedell, J. R. (1987). "Large woody debris in forested streams in the Pacific Northwest: past, present, and future." Streamside Management: Forestry and Fishery Interactions, E. O. Salo and T. W. Cundy, eds., University of Washington, Seattle, 143-190.

Brown, G. W., Gahler, A. R., and Marston, R. B. (1973). "Nutrient losses after clear-cut logging and slash burning in the Oregon Coast Range." *Water Resources Research*, 9, 1450-1453.

Brown, G. W., and Krygier, J. T. (1971). "Clear-cut logging and sediment production in the Oregon Coast Range." *Water Resources Research*, 7(5), 1189-1198.

CDF&FP. (2004). "California forest practice rules, title 14, California code of regulations, chapters 4, 4.5, and 10." The California Department of Forestry and Fire Protection, Resource Management, Sacramento, California.

Chamberlin, T. W., Harr, R. D., and Everest, F. H. (1991). "Timber Harvesting, Silviculture, and Watershed Processes." Influences of Forest and Rangeland Management on Salmonid Fishes and Their Habitats, W. R. Meehan, ed., American Fisheries Society Special Publication, 181-205.

Everest, F. H., Beschta, R. L., Scrivener, J. C., Koski, K. V., Sedell, J. R., and Cederholm, C. J. (1987). "Fine sediment and salmonid production: a paradox." Streamside Management: Forestry and Fishery Interactions, E. O. Salo and T. W. Cundy, eds., University of Washington, Seattle, 98-142.

Hicks, B. J., Hall, J. D., Bisson, P. A., and Sedell, J. R. (1991). "Responses of Salmonids to Habitat Changes." Influences of Forest and Rangeland Management on Salmonid Fishes and Their Habitats, W. R. Meehan, ed., American Fisheries Society Special Publication, 483-518.

Ice, G., Dent, L., Robben, J., Cafferata, P., Light, J., Sugden, B., and Cundy, T. W. (2004). "Programs assessing implementation and effectiveness of state Forest Practice Rules and BMPs in the west." *Water, Air, and Soil Pollution: Focus*, 4(1), 143-169.

Jones, J. A., and Grant, G. E. (1996). "Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon." *Water Resources Research*, 32(4), 959-974.

Loomis, J. B., and Walsh, R. G. (1997). *Recreation Economic Decisions Comparing Benefits and Costs*, Venture Publishing, Inc., State College, Pennsylvania.

Meehan, W. R. (1991). "Introduction and Overview." Influences of Forest and Rangeland Management on Salmonid Fishes and Their Habitats, W. R. Meehan, ed., American Fisheries Society Special Publication, 1-15.

NOAA. (2004). "Summary of Salmon and Steelhead Listings." National Oceanic and Atmospheric Administration, http://www.nwr.noaa.gov/ESA-Salmon-Listings/Index.cfm Accessed June 17, 2004.

ODF. (2003). "Forest Practice Administrative Rules and Forest Practices Act." Oregon Department of Forestry, Salem, Oregon.

Reid, L. M., and Dunne, T. (1984). "Sediment production from forest road surfaces." *Water Resources Research*, 20(11), 1753-1761.

Swanson, F. J., and Dyrness, C. T. (1975). "Impact of clear-cutting and road construction on soil erosion by landslides in the western Cascade Range, Oregon." *Geology*, 3(7), 393-396.

Swanston, D. N., and Swanson, F. J. (1976) "Timber harvesting, mass erosion, and steepland forest geomorphology in the Pacific Northwest." *Geomorphology and Engineering*, 199-221.

Toman, E. M. (2004). "Forest road hydrology: The influence of forest roads on stream flow at stream crossings," Master of Science Thesis, Oregon State University, Corvallis.

Wemple, B. C., Jones, J. A., and Grant, G. E. (1996). "Channel network extension by logging roads in two basins, western Cascades, Oregon." *Water Resources Bulletin*, 33(6), 1195-1207.

WSDNR. (2006). "Forest Practice Rules, Title 222 WAC." Washington State Department of Natural Resources, Olympia, Washington.

CHAPTER 2: AN ANALYSIS OF THE OPPORTUNITY COSTS WITH WET-WEATHER TIMBER HAULING

Elizabeth Myers Toman

Arne E. Skaugset

Glen E. Murphy

International Journal of Forest Engineering
Forest Products Society, Madison, Wisconsin
Volume 18, Issue 1, Pages 17-23

Introduction

Forest roads used to haul timber are most often surfaced with unbound aggregate. These low-volume roads produce fine sediment especially during wet-weather use (Bilby *et al.* 1989; Reid and Dunne 1984). Studies have shown that forest roads can be hydrologically connected via surface flow to the streams and that road runoff can enter the stream (Toman 2004; Wemple 1994). The potential for increased fine sediment and turbidity in fish-bearing streams has led to increased regulation in recent years in the western United States regarding timber harvesting and hauling activities during wet-weather. The *California Forest Practice Rules of 2004* (CDF&FP 2004) require that landowners submit winter period operating plans that address erosion and road use issues for timber operations during the winter period (October 15 through May 1). Also, hauling on forest roads during the winter period cannot occur when saturated soil conditions exist on the road, although no definition or standard of determination of when saturation exists is included in the rules (Chapter 4, Subchapters 4, 5, and 6, Article 12: 923.1, 943.1, 963.1 (j)). Forest landowners in California have taken these regulations seriously, and some have further restricted timber hauling during any period of precipitation. Regulations in California and other western states may become even more restrictive as technical panels review the current regulations and suggest changes.

These current changes in California's state regulations and potential changes in other western states mean that an increasing proportion of commercial forest land is taken out of production. In addition, the costs of carrying out intensive forest management activities, especially timber harvesting, are increased and the management flexibility of forest land managers and owners is decreased during the winter harvesting period. Thus, forest land managers, especially private industrial land managers, are increasingly put at a competitive disadvantage in domestic and international markets for solid wood as domestic costs grow.

A viable option for forest managers who wish to take advantage of winter log markets is to improve road surfaces and reduce the environmental problems that accompany wet-weather hauling. The objective of this analysis was to investigate the opportunity costs, or money available to improve the roads, associated with regulatory restrictions for timber hauling on a forest road during wet-weather.

Methods

In this analysis, the opportunity costs were taken as the difference between the cost for an all year operation and the cost for operations based on seasonal, wet-weather hauling restrictions. Three elements were necessary:

1. a land base over which to apply the analysis,

2. a harvest plan of sufficient detail that the sequential harvesting could be analyzed unit by unit, and
3. weather information of a form that allowed simulation of seasonal haul restrictions.

These elements were available for the McDonald-Dunn Research Forest located northwest of Corvallis, Oregon.

The McDonald-Dunn Research Forest is owned and managed by the College of Forestry at Oregon State University. The forest consists of roughly 4,550 hectares and is predominately managed for Douglas-fir (*Pseudotsuga menziesii*) in even-aged, two-storied, uneven-aged, and old-growth stands. A database is available for the forest that includes forest stand information by harvest unit. The McDonald-Dunn Research Forest is managed using a plan designed and periodically revised by the College of Forestry to provide "a management framework of policy and direction for forest staff" (Fletcher *et al.* 2005).

The forest management plan for the McDonald-Dunn Research Forest was recently reviewed and revised to evaluate possible silvicultural systems and harvesting systems, estimate production volume for each harvest unit, and determine harvesting scenarios for a future 10-year period. One such harvesting scenario is shown in Figure 2.1. Suggested 10-year scenarios from the forest management plan for the McDonald-Dunn Research Forest for the next two 10-year periods were chosen for this analysis and will be hereafter referred to as the 20-year harvest plan. The forest management plan for the McDonald-Dunn Research Forest and the existing forest database supplied this analysis with the silvicultural system (thin or clear cut), harvesting system (ground based or cable harvest system), estimated production volume, hillslope gradient, stand density, stand type, stand age and average tree diameter at breast height (DBH) for each harvest unit as well as the harvesting sequence.

Total daily precipitation for the area is available dating from 1889 to the present from the Hyslop Field Research Laboratory located approximately 4 miles northeast of Corvallis. The data from the Hyslop Lab are available as precipitation to the nearest 0.25 mm (0.01 in.) for each day. Annual blocks of daily precipitation data for the winter period from 1889 to 2003 were randomly applied to each year of the 20-year harvest plan.

The regulations in the *California Forest Practice Rules of 2004*, with regard to hauling and harvesting during the winter period were applied to the McDonald-Dunn Research Forest and the 20-year harvest plan. As previously mentioned, these regulations require that hauling shall not occur when saturated soil conditions exist on the road. They also require that tractor yarding and the use of tractors be done only when the soils are not saturated (Chapter 4, Subchapters 4, 5, and 6, Article 4: 914.7, 934.7, 954.7 Timber Operations, Winter Period [All Districts] (c) (1)). This includes ground-based

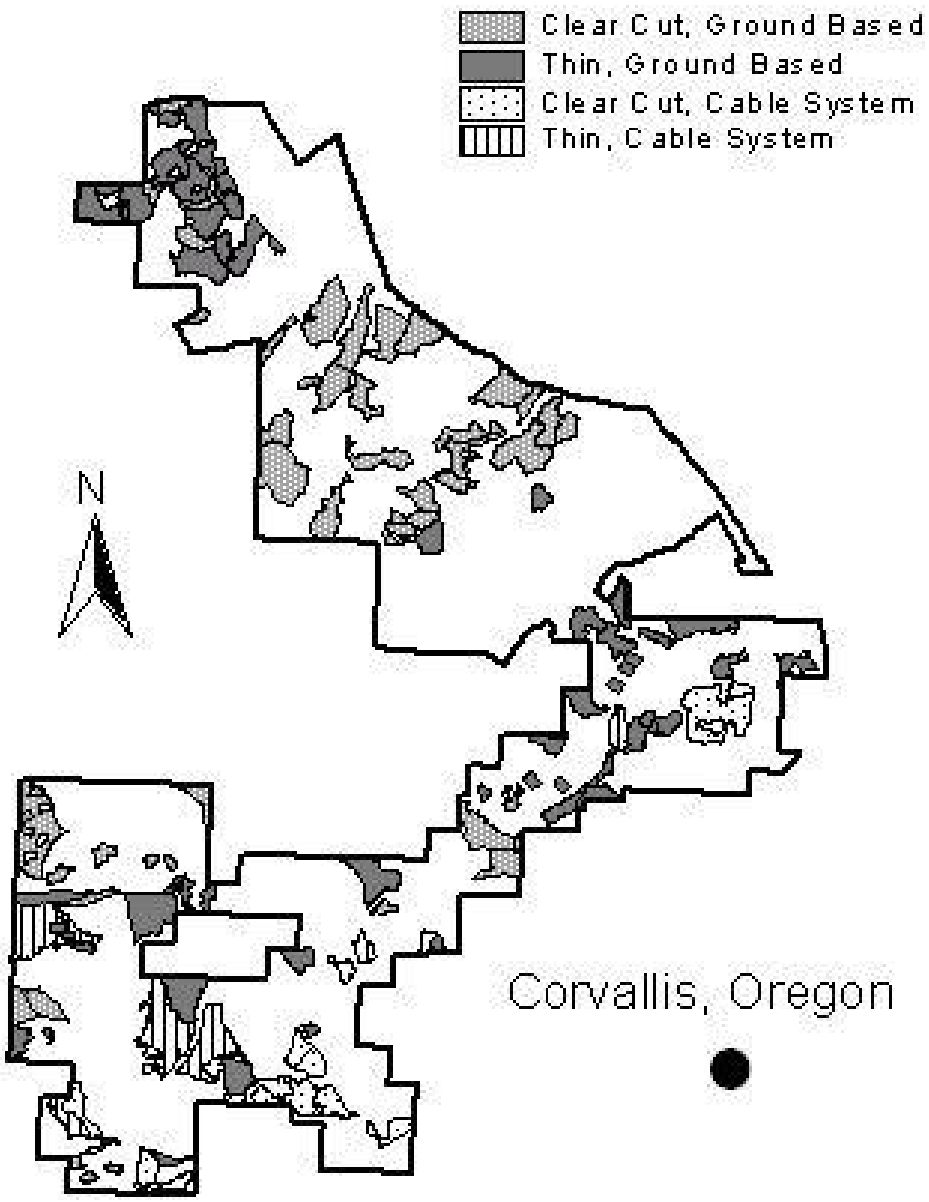


Figure 2.1 A map showing the McDonald-Dunn Research Forest and one possible harvesting scenario for a future 10-year period.

harvesting equipment and equipment that operate on the road surface such as loaders. As the rules do not define soil saturation or the precipitation levels that create this condition, a threshold precipitation value was required to represent saturated soil conditions for this analysis.

Operation managers apply the regulations of the *California Forest Practice Rules* on saturated soil conditions by monitoring precipitation. Personal communication with forest operation managers in California about harvesting and hauling during wet-weather in past years established that, while most managers did not gauge precipitation with equipment, there existed some precipitation continuum with a threshold cumulative precipitation value at which harvesting and hauling activities were suspended. Comparison of harvesting and hauling days in past years with precipitation records determined that a daily precipitation value of 5 mm (0.20 in.) agreed with operating practices to suspend timber harvesting and hauling activities for that day. Although the exact days that timber harvesting and hauling activities were suspended in this analysis may not have been the same days that were suspended in reality, the total annual number of suspended days were consistent with operating practices.

With the regulations in the *California Forest Practice Rules of 2004*, managers have some alternatives for their harvesting and hauling activities dependent upon their management objectives and equipment flexibility. The regulations decrease the number of days available during a year for harvesting and hauling timber when compared to a full year of operations without restrictions. Managers have the option of decreasing the annual timber production proportionally by the number of days that harvesting and hauling is suspended, or having timber production remain the same and increasing the machinery and operators or increasing the hours worked during non-suspended days. If managers chose to reduce timber production they have the additional option of moving the harvesting and hauling equipment to a different location that is not restricted (such as in contract use) or keeping the equipment inactive at location during suspended days.

For this analysis the estimated costs and revenue for the 20-year harvest plan without wet-weather restrictions were compared to three management scenarios for harvesting and hauling with wet-weather restrictions to determine the opportunity costs associated with wet-weather restrictions. The full year of harvesting and hauling without restrictions operated with 2,000 scheduled machine hours (SMH) for all harvesting equipment and 2,500 SMH for haul trucks (Brinker *et al.* 2002). Machine hours were scheduled for a Monday through Friday work week that did not include U.S. holidays. The analysis assumed that all harvesting operations were conducted on an independent contracting basis. Operator wages were calculated as hourly pay that included benefits. Log prices were kept constant over the harvest year. The volume of annual timber production was determined from the 20-year harvest plan for the McDonald-Dunn Research Forest.

Three management scenarios with wet-weather restrictions were evaluated:

1. Timber harvesting and hauling in the McDonald-Dunn Research Forest were suspended on days that precipitation exceeded 5 mm. Harvesting and hauling equipment were kept idle at location on these days. Consequently, SMH for all harvesting and hauling equipment were reduced based on the number of work days with precipitation that exceeded 5 mm and hence, annual timber production was reduced.
2. Timber harvesting and hauling in the McDonald-Dunn Research Forest were suspended on days that precipitation exceeded 5 mm. Production goals were met during hours that there were no wet-weather restrictions by the overtime use of existing equipment and labor or by bringing in additional equipment and labor.
3. Timber harvesting and hauling in the McDonald-Dunn Research Forest were suspended on days that precipitation exceeded 5 mm. All mobile equipment was used off-site on suspended days (no change in SMH); however, production within the McDonald-Dunn Research Forest was decreased.

Hourly costs of timber harvest activities were estimated for each scheduled unit based on production studies from the literature that were relevant to the characteristics of each harvest unit (Zhang *et al.* 2003). Hourly costs for timber hauling from the harvest units to a lumber mill located in Eugene, Oregon were based on new vehicle costs and were estimated using standard costing procedures. Hauling costs depended on the routes taken and road standards. Hauling routes taken and number of trips per day were optimized using Network2000® (Chung and Sessions 2000). Annual timber harvesting and hauling costs were discounted at an inflation free rate of 7 percent for future costs, and all costs were calculated in present net worth. Discounted costs for timber harvesting and hauling were subtracted from timber revenue to calculate net revenue for the forest in present net worth.

Results

Optimal Harvest Plan

The 20-year harvest plan for the McDonald-Dunn Research Forest included thinning and clear-cut operations with ground based and cable harvest systems determined by the average gradient of the hillslope in the harvest units. An average hillslope gradient of 35 percent in a harvest unit was used as the cut-off value between ground based and cable harvest systems. The 20-year harvest plan had an annual timber production of approximately 27,500 m^3 (4.1 million board feet [MMBF]). Of the total timber production from the forest for the 20-year harvest plan, 23 percent was harvested using a cable system and 77 percent harvested with a ground based system.

The McDonald-Dunn Research Forest consists of predominately Douglas-fir (*Pseudotsuga menziesii*) with a small grand fir (*Abies grandis*) component. The units in the 20-year harvest plan were managed for short-rotation and long-rotation, even-aged, Douglas-fir dominated plantations. For this study, only the harvest of Douglas-fir was considered. The average DBH of Douglas-fir was 30 cm (12 in.) within the thinning units and 51 cm (20 in.) within the clear-cut units. The average stand density was 667 trees per ha (270 trees per acre) in the thinning units and 334 trees per ha (135 trees per acre) within the clear-cut units.

Without reductions in timber production due to wet-weather restrictions the total production of the forest for the 20-year harvest plan was 550,990 m^3 (82.6 MMBF) with an average of 27,550 m^3 harvested each year. Of the 550,990 m^3 produced, 81 percent was harvested as clear cuts using both ground-based and cable harvesting systems and 19 percent was harvested as thinning using both harvesting systems (Table 2.1).

Harvesting and hauling costs and timber revenue were calculated for the McDonald-Dunn Research Forest for a full year operation without reductions due to wet-weather restrictions. Productivity costs ranged from \$13.36 to \$17.36 per m^3 for ground-based systems and \$26.22 to \$48.34 per m^3 for cable systems. The hauling costs were estimated to be \$54.86 per SMH. Discounted harvesting and hauling costs totaled \$7.9 million with \$6.2 million related to the harvesting operation (78 %) and \$1.7 million related to hauling (22 %). Labor costs were approximately 40 percent of the total harvesting and hauling costs and the remaining 60 percent were equipment costs. Total net revenue for the 20-year harvest plan for the McDonald-Dunn Research Forest was \$35.5 million in present net worth.

Table 2.1 Timber production for the 20-year harvest plan for the McDonald-Dunn Research Forest by year, silvicultural system, and harvest system.

	Timber Volume (m^3)*				
	Clear Cut		Thinning		
Year	Cable	Ground	Cable	Ground	Total
1	9600	11520	6960	0	28080
2	0	24400	2747	0	27147
3	22027	0	0	5067	27093
4	0	21413	4427	2187	28027
5	0	30933	0	0	30933
6	15040	6960	4560	1520	28080
7	0	21920	5013	2587	29520
8	0	21040	6747	0	27787
9	13573	8907	0	4347	26827
10	6960	13520	0	6800	27280
11	0	20240	0	7680	27920
12	0	19707	0	7547	27253
13	0	23520	0	3387	26907
14	0	27040	0	0	27040
15	3067	17440	0	6320	26827
16	0	25307	0	2160	27467
17	0	27040	0	0	27040
18	0	17120	0	10587	27707
19	20747	0	3947	1707	26400
20	0	17653	0	8000	25653
Total	91013	357013	34400	69893	550987
Percent of Total	17%	65%	6%	13%	

* 1 m^3 = 150 board feet

Wet-Weather Restrictions

The three management scenarios halted all timber harvesting and hauling in the forest on days when rainfall exceeded 5 mm. Over the 115-year record of precipitation from 1889 to 2003, halting timber harvesting activities when a daily rainfall reached or exceeded 5 mm resulted in an average annual reduction of 36.6 work days (27 % of eligible work days during the winter period of October 15 to May 1), or 293 work hours based on an 8-hour work day. Historical annual precipitation data was randomly applied to the 20-year harvest plan in 20 simulations. Over the 20 simulations, the average annual reduction of work hours was 294 hours with a standard deviation of 63 hours totaling an average of 5,878 hours lost over the 20-year period. Figure 2.2 shows the median, quartiles, and range of the annual reduction in work hours for each 20-year simulation with wet-weather restrictions as well as the historical average (dashed line).

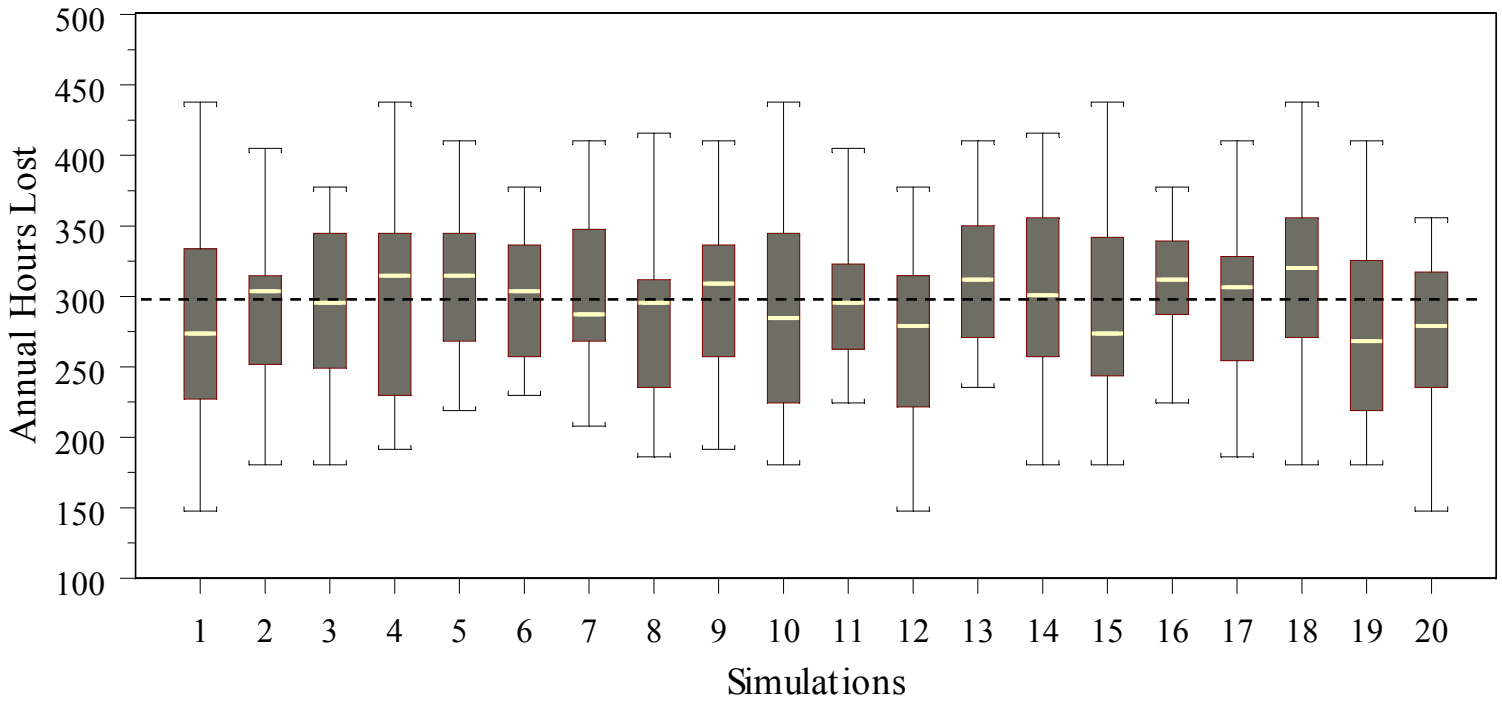


Figure 2.2 A whisker and box plot with the median (horizontal marker), first and third quartiles (boxes), and range of hours lost each year in the 20-year harvest plan over 20 simulations with daily rainfall restrictions at 5 mm. The historic average (1889 -2003) of annual hours lost is shown with the dashed line.

Costs of Wet-Weather Restrictions

The first management scenario considered a situation where harvesting and hauling equipment were not used on days when rainfall exceeded 5 mm and therefore there was no timber production on these days. The annual SMH for timber harvesting and hauling equipment were reduced by the hours lost to wet-weather restrictions. Although this decreased the annual operating costs, ownership costs remained the same and thus total machine costs per SMH were increased. Increases in timber harvesting and hauling costs per cubic meter over 20 simulations of the 20-year harvest plan ranged from 1.3 percent (simulation 12, year 8) to 7.1 percent (simulation 4, year 11) and averaged 3.5 percent. Approximately 73 percent of the increased harvesting and hauling costs were associated with the harvesting operations and 27 percent of the increased costs were associated with hauling timber from the harvest unit to the lumber mill. A histogram of increased costs per cubic meter over the 20 simulations is shown in Figure 2.3.

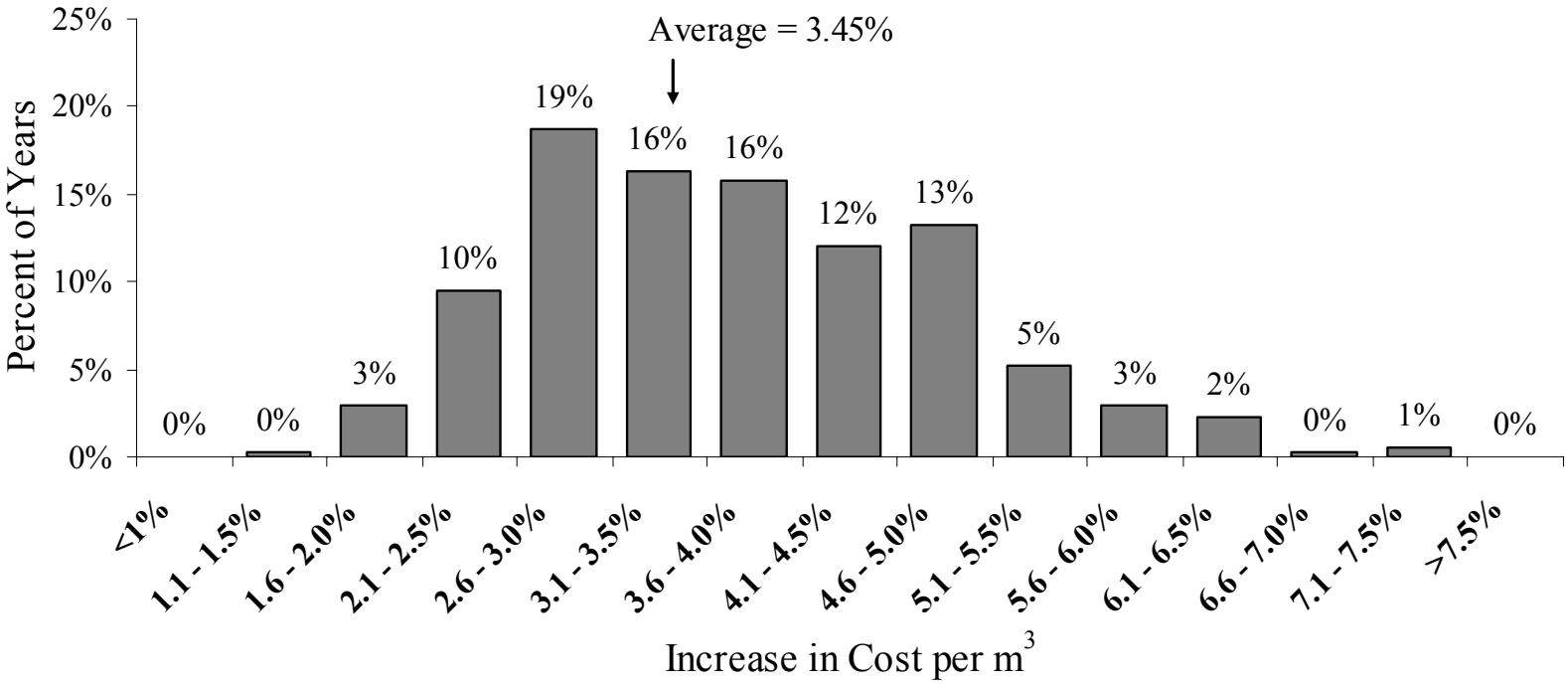


Figure 2.3 The annual increase in timber harvesting and hauling costs per cubic meter over 20 simulations of the 20-year harvest plan (400 total years).

The hours lost annually to wet-weather restrictions were also used to reduce the annual timber production. Over 20 simulations of the 20-year harvest plan, total timber production ranged from 465,330 m^3 (84 % of the total harvest, simulation 13) to 478,000 m^3 (87 % of the total harvest, simulation 12) and averaged 470,000 m^3 (85 % of the total harvest without wet-weather restrictions).

An increase in machine costs and a decrease in timber production produced an annual decrease in net revenue in comparison to the 20-year harvest plan without any wet-weather restrictions. Over 20 simulations of the 20-year harvest plan, this annual decrease in net revenue varied greatly. One year (simulation 20, year 16) had a 7.6 percent decrease in net revenue and another year (simulation 1, year 3) had a decrease of nearly a quarter of the annual net revenue (23.8 %). The decrease in annual net revenue averaged 15.4 percent over 20 simulations of the 20-year harvest plan (Figure 2.4). The total net revenue for the McDonald-Dunn forest over the 20-year harvest plan with this scenario ranged from $29.7 million to $30.6 million in present net worth and averaged $30.0 million.

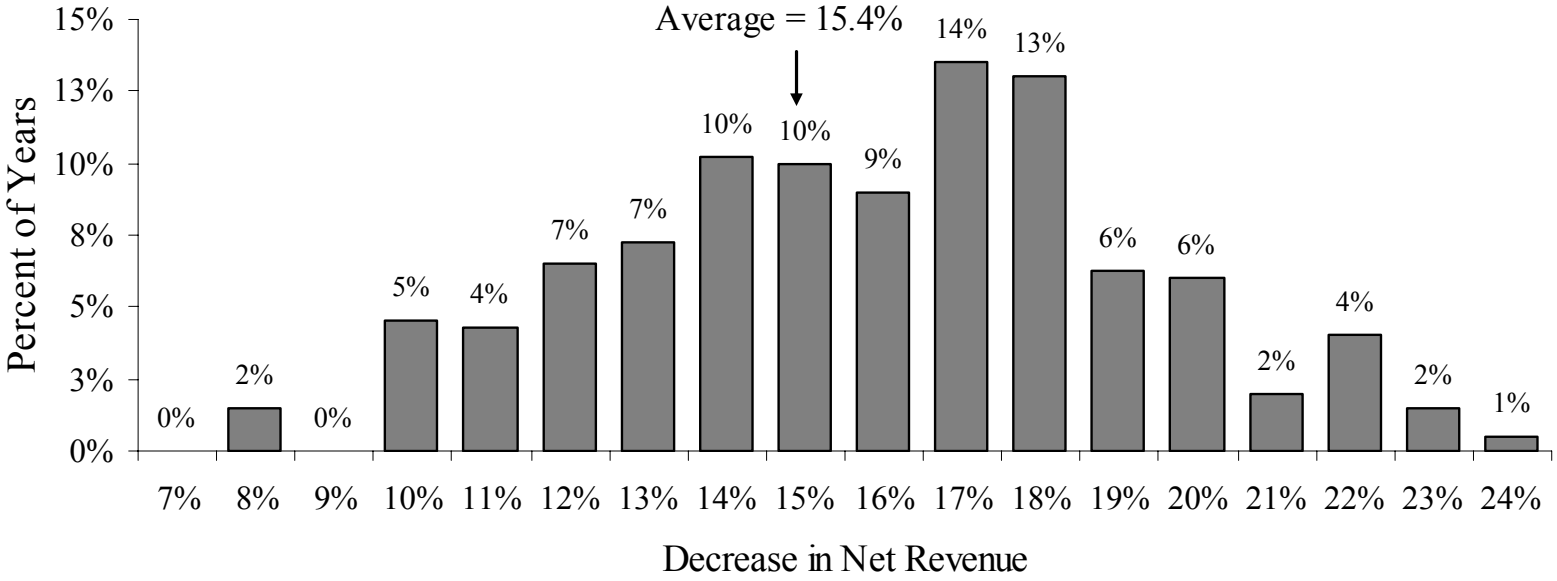


Figure 2.4 The annual decrease in net revenue over 20 simulations of the 20-year harvest plan (400 total years).

The second management scenario also halted harvesting and hauling with wet-weather restrictions. In this scenario, however, production goals were met during hours when there were no wet-weather restrictions. This was accomplished by using the available equipment and labor beyond the 8-hour work day (overtime). Only labor costs were affected because production and thus SMH for the equipment remained the same. Labor costs for work beyond the 8-hour work day were assumed to increase 50 percent (time and a half). Wet-weather halted harvesting and hauling, on average, 294 work hours a year over 20 simulations of the 20-year harvest plan. This is approximately 15 percent of the SMH for the harvesting equipment. Labor represented 40 percent of the total harvesting and hauling costs. Increasing 15 percent of the labor costs by 50 percent resulted in an average increase in total discounted harvesting and hauling costs of 3 percent over the 20-year harvest plan. In this scenario, total harvesting and hauling costs for the 20-year harvest plan for the McDonald-Dunn Research Forest totaled approximately $8.1 million.

Another approach to this second management scenario is to meet production goals during hours in which there were no wet-weather restrictions by bringing in additional equipment and labor. Additional move-in costs and contract administration costs are associated with this approach; however, the authors assume that these additional costs will be of a similar magnitude to the overtime approach.

Harvesting and hauling were again halted with wet-weather restrictions in the third management scenario. In this scenario the mobile harvesting and hauling equipment and labor were moved and used at a different location. An example of this situation is the contract use of equipment. Production from the McDonald-Dunn Research Forest decreased with wet-weather restrictions (similar to the first scenario), but harvesting and hauling costs remained the same. Over 20 simulations of the 20-year harvest plan, total timber production was between 465,330 m^3 and 478,000 m^3. Discounted harvesting and hauling costs totaled $7.9 million which resulted in a total net revenue of $28.7 to $29.7 million. With wet-weather restrictions, there was a decrease of $5.8 to $6.8 million in net revenue from the McDonald-Dunn Research Forest over the 20-year harvest plan with this scenario. Table 2.2 describes production, cost, and revenue results for the 20-year harvest plan for the McDonald-Dunn Research Forest without wet-weather restrictions and for the three management scenarios that include reductions due to wet-weather restrictions.

Table 2.2 The timber production, discounted costs, and revenue in present net worth for the 20-year harvest plan for the McDonald-Dunn Research Forest without wet-weather restrictions and for the three management scenarios that include reductions due to wet-weather restrictions (averaged over 20 simulations).

	Without Wet-Weather Restrictions	**Scenario**		
		1	**2**	**3**
Timber Production (thousand m^3)	551.0	470.0	551.0	470.0
Harvesting and Hauling Costs (million $)	7.9 ($14.34/$m^3$)	7.0 ($14.84/$m^3$)	8.1 ($14.77/$m^3$)	7.9 ($16.81/$m^3$)
Timber Revenue (million $)	43.4 ($78.75/$m^3$)	37.0 ($78.75/$m^3$)	43.4 ($78.75/$m^3$)	37.0 ($78.75/$m^3$)
Total Net Revenue (million $)	35.5 ($64.41/$m^3$)	30.0 ($63.91/$m^3$)	35.3 ($63.98/$m^3$)	29.1 ($61.94/$m^3$)
Decrease in Net Revenue with wet-weather restrictions (million $)	-	5.5 ($11.58/$m^3$)	0.2 ($0.43/$m^3$)	6.4 ($13.56/$m^3$)

Table 2.3 compares the differences between the average total net revenue for the 20-year harvest plan for the three scenarios in relation to production and harvesting and hauling costs and the total net revenue for the 20-year harvest plan for the McDonald-Dunn Research Forest. The $0.2 to 6.8 million decrease in total net revenue between the full-year operation and the three management scenarios that include restrictions for wet-weather hauling could be considered opportunity costs and used to upgrade the road surfaces to minimize sediment production and to allow for timber harvesting and hauling to occur during wet-weather.

Table 2.3 The relationship between harvesting and hauling costs, timber production, and average total net revenue for the 20-year harvest plan for each management scenario.

		Harvesting and Hauling Costs	
		No Change	Increase per m^3
Timber Production	No change	Without wet-weather restrictions $35,488,481	Scenario 2 $35,251,429
	Decrease	Scenario 3 $29,116,979	Scenario 1 $30,046,257

Discussion and Conclusions

Main Findings

With all management scenarios presented in this analysis, wet-weather restrictions decreased total net revenue for the McDonald-Dunn Research Forest. The magnitude of the decrease was dependent on the management objectives and equipment flexibility. The first management scenario did not have the flexibility to move equipment around during suspended days or have more equipment brought in on non-suspended days. This scenario may be representative of small land-owners. The opportunity costs associated with this type of management scenario were great, averaging 15.4 percent of the annual net revenue.

Management of the McDonald-Dunn Research Forest with the objective of meeting production goals and the flexibility of additional work hours or equipment, as in the second management scenario in this analysis, produced the smallest decrease in total net revenue at 1.7 percent. This management scenario would most likely represent the options available to a larger industrial land owner. Although a 1.7 percent decrease in total net revenue may not seem significant, at a large company it may represent a considerable dollar value and be worth investing as an opportunity cost.

Implications

The opportunity cost associated with restricted timber hauling and harvesting is potentially a resource that could be made available to improve aggregate road surfaces to minimize hauling restrictions during wet-weather. In this study the opportunity costs were 1.7 to 15.4 percent of the total net revenue for McDonald-Dunn Research Forest with 20 simulations of the 20-year harvest plan. Although 1.7 to 15.4 percent of the net revenue from the first year of harvesting may not be enough to improve all haul roads, over time improving the road surfaces may result in increases in production and net revenue.

The opportunity costs may be even greater in all scenarios. This analysis only considered labor working during the hours that equipment was in use. In actuality, some employees may be salaried and require pay regardless of the number of hours that they are unable to work due to wet-weather restrictions.

The opportunity costs will also vary with different regulations. Daily precipitation of 5 mm was assumed as the threshold value at which harvesting and hauling activities were suspended. This value was chosen to make the undefined regulations on the saturation of soil in the *California Forest Practice Rules* consistent with operational practices to facilitate this analysis. In areas with different regulations, harvesting and hauling activities may be suspended with more or less precipitation. Even within California the regulations may be interpreted differently. One land owner that the authors spoke with suspended all activities with any amount of precipitation. The more restrictive the regulations, the greater the opportunity costs could be.

Critical Points

A limitation of this analysis is that annual timber production was reduced in the first and third scenario and the value of the timber that was left standing was not considered. This timber has not been “lost.” An assumption made in this analysis was that it would be harvested at a future period when it

will not be worth as much and as such, the analysis did not include any future benefit from allowing unharvested timber to continue to grow.

This analysis did not consider the fluctuation of market log prices during the winter season; only an average log price for Douglas-fir from the McDonald-Dunn Research Forest during the dry season. Analysis of the past 10 years of saw log prices of Douglas-fir in real prices (adjusted for inflation using the Producer Price Index) from the region showed seasonal fluctuations. Saw logs were consistently priced highest in the fourth quarter after the wet season had begun and the demand for timber was still high.

Further Investigation

This analysis found that the opportunity costs associated with wet-weather restrictions can be significant depending on the management objectives and equipment flexibility. Further investigation is needed to determine how the opportunity costs can be best used to upgrade the road system for use during wet-weather. Future analysis and research should focus on determining what aspects of the road need to be upgraded to allow for wet-weather use and the costs associated with such upgrades. If the road can be upgraded, it will be useable in all weather.

As regulations for wet-weather hauling continue to become more restrictive, the log supply will continue to decrease and the demand and price for logs during the winter season will continue to increase. Forest land owners wishing to profit from the winter log market should consider the opportunity costs of upgrading their road surfaces for wet-weather hauling.

References

Bilby, R. E., Sullivan, K., and Duncan, S. H. (1989). "The generation and fate of road-surface sediment in forested watershed in southwestern Washington." *Forest Science*, 35(2), 453-468.

Brinker, R. W., Kinard, J., Rummer, B., and Lanford, B. (2002). "Machine Rates for Selected Harvesting Machines. Circular 296 (revised)." Alabama Agricultural Experiment Station, Auburn University, Auburn, Alabama.

CDF&FP. (2004). "California Forest Practice Rules, Title 14, California Code of Regulations, Chapters 4, 4.5, and 10." The California Department of Forestry and Fire Protection, Resource Management, Sacramento, California.

Chung, W., and Sessions, J. (2000). "Network 2000 Professional Version 1.0. A software program to optimize fixed and variable cost transportation problems." Corvallis, Oregon.

Fletcher, R., Johnson, B., Blanchard, G., Emmingham, B., Hayes, J., Johnson, D., Johnson, N., Lysne, D., Murphy, G., Newton, M., and Sessions, J. (2005). "McDonald-Dunn Forest Plan Revision." http://www.cof.ost.edu/cf/forests/mcdonald/plan/files/mcdunn_plan.pdf.

Reid, L. M., and Dunne, T. (1984). "Sediment production from forest road surfaces." *Water Resources Research*, 20(11), 1753-1761.

Toman, E. M. (2004). "Forest road hydrology: The influence of forest roads on stream flow at stream crossings," Master of Science Thesis, Oregon State University, Corvallis.

Wemple, B. C. (1994). "Hydrologic integration of forest roads with stream networks in two basins, Western Cascades, Oregon," Master of Science Thesis, Oregon State University, Corvallis, Oregon.

Zhang, X., Hartsough, B. R., and Fight, R. D. (2003). "STHARVEST: Small Timber Harvest Version 2.0.0. Software to estimate the cost of harvesting small timber."

CHAPTER 3: DESIGN OF THE UNBOUND AGGREGATE PAVEMENT TO REDUCE SEDIMENT PRODUCTION FROM SUBGRADE MIXING

Introduction

Roads paved with unbound aggregate are designed for the season and type of use. Forest roads that are used to haul logs are constructed to access a single harvest unit or for multiple-year use. Forest roads designed to be used for more than just summer use in the Pacific Northwest are constructed with an unbound aggregate pavement over a subgrade of native soil (Figure 3.1). The pavement structure may include a base course of a pit run or crushed, open-graded, large aggregate topped with a running course of well-graded, small aggregate (Kramer 2001).

The structure of forest roads varies by location because local soil and aggregate vary by location. There is variability inherent in the way forest roads are constructed because universal guidelines and/or quality control measures are not used. The American Association of State Highway and Transportation Officials (AASHTO) defines forest roads as "low-volume" roads designed for a maximum traffic level of 100,000 18-kip equivalent single axle loads (ESALs) over the lifetime of the road (AASHTO 1993). A recent AASHTO publication classified forest roads as "very low-volume local roads" within the functional subclass "rural resources recovery." The design for this classification considers the specific characteristics of: a rural location, a driving population that is mainly professional drivers with large vehicles, roads that are single-lane, and roads that are paved with unbound aggregate (AASHTO 2001).

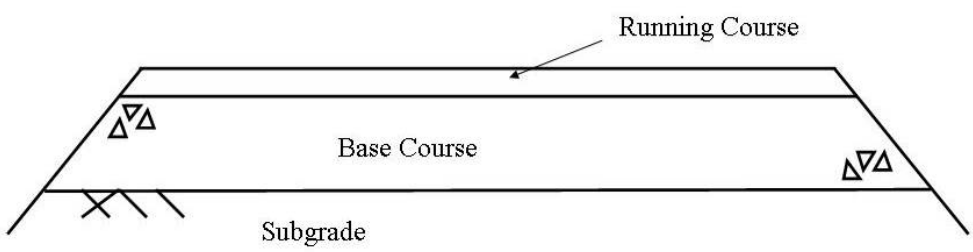


Figure 3.1 Forest road structure with subgrade, base course, and running course.

The current methods of design for roads with unbound aggregate pavement use empirical equations with user selected allowable depths for ruts, specified loads, and estimates of subgrade

strength. The most common methods are the American Association of State Highway and Transportation Officials (AASHTO) method and the United States Department of Agriculture, Forest Service (USFS) method (see AASHTO 1993; Bolander *et al.* 1995). Forest land owners typically do not evaluate the location of each road for site-specific design but use a "standard" road design for all locations. This design is based on the performance of existing roads and experience.

In the AASHTO and USFS design methods, an acceptable rut depth is selected for the end of the service life of the pavement. Then the thickness of unbound aggregate needed to achieve that rut depth given the subgrade strength and traffic is calculated. The AASHTO method is a ten-step process that requires trial values of aggregate thickness and allowable rut depth be selected. Then known values for traffic and subgrade strength are used to interpolate a final aggregate depth from nomographs. The USFS method is more straightforward and uses the equation:

$$RD = 0.1741\left(\frac{P_k^{0.4704} t_p^{0.5695} R^{0.2476}}{(\log t)^{2.002} C_1^{0.9335} C_2^{0.2848}}\right),$$

where RD is rut depth, P_k is the equivalent single-wheel load, t_p is the tire pressure, t is the thickness of the top layer, R is the repetitions of load or passes, C_1 is a strength value for the surfacing material, and C_2 is a strength value for the subgrade layer (Bolander *et al.* 1995).

The design methods use the resilient modulus (AASHTO) and California Bearing Ratio (USFS) of the subgrade as indices of subgrade strength. The test for resilient modulus (M_r) (test T 292-97, AASHTO 2004) is a standard test for base course and subgrades for flexible (i.e. hot-mix asphalt) pavements. This test is not appropriate for unbound aggregate pavements because confining stresses are used that are much higher than confining stresses for low volume roads. The results from resilient modulus tests are sensitive to test conditions, the tests have been shown to be not repeatable, and the test procedure was withdrawn from the most recent edition of the AASHTO test specifications. The California Bearing Ratio (CBR) (test T 193-99 (2003), AASHTO 2004) is a useful test that produces an index of subgrade strength but it does not incorporate changes in subgrade strength due to repeated loading.

The standard design methods for roads with unbound aggregate pavements (AASHTO and USFS) do not consider the environmental performance of the road. The methods result in a design depth of aggregate that is expected to yield a specified rut depth at the end of the service life of the road. The generation of fine sediment from the surface of these roads and the delivery of that sediment to streams is the environmental concern associated with aggregate surfaced roads. Fine sediment from aggregate surfaced roads increases the sediment load, and subsequently turbidity, in streams. Increased turbidity in streams is detrimental to fish and other aquatic biota and increases the cost to treat drinking water. The standard methods of design may result in a road that will fail environmentally, or produce and

deliver fine sediment to streams in unacceptable quantities, long before it reaches the end of its service life due to traffic.

Mills *et al.* (2003) reported the use of forest roads during wet weather increased turbidity in streams at locations where runoff from the road entered the stream. The amount of sediment produced from aggregate surfaced roads is related to the depth of the aggregate (Bilby *et al.* 1989; Mills *et al.* 2003), the quality of the aggregate (Foltz and Truebe 1995; Mills *et al.* 2003), and the texture of the subgrade (Luce and Black 1999).

Regulations for some states that produce timber in the western United States recently restricted the use of forest roads for log transportation during wet weather because of increased turbidity in streams. The California Forest Practice Rules of 2004 require that for timber operations during the winter period (October 15 through May 1), hauling on forest roads cannot occur when saturated soil conditions exist on the road (CDF&FP 2004). Regulations in California and other western timber-producing states may become even more restrictive as regulatory oversight committees review the current regulations and suggest changes. As such, the production of fine sediments from the road surface should be considered in the design process for low volume roads with unbound aggregate pavements.

Forest roads have been suggested to produce sediment that is available to run off the road through three processes. Fine sediment is available in the surface aggregate, especially for well-graded aggregate. Fine sediment is produced by the breakdown of the surface aggregate by traffic. Finally, fine sediment is available in the subgrade. Fine sediment from the subgrade is made available to runoff from the road surface when it is "pumped" into and through the aggregate surface with repeated loads from traffic (Koerner 1998). The origin of fine sediment in runoff from roads with unbound aggregate is difficult to determine, however a common assumption in the technical literature on roads with unbound aggregate is that the subgrade is a major source of fine sediment from these roads.

Traditional pavement engineering describes subgrade pumping as the ejection of sediment laden water through cracks in a pavement slab in response to dynamic loads due to traffic (Muench *et al.* 2003). The cause of subgrade pumping is water accumulation underneath the slab from a high water table or poor drainage creating high water pressures with traffic loads. Subgrade pumping is documented in flexible and rigid pavement and railroad ballast (Indraratna *et al.* 2006; Muench *et al.* 2003). In rigid pavements, pumping moves enough subgrade material to be a major cause of pavement failure (Huang 1993). Managers of unbound aggregate roads in the forestry environment have used the same term, "pumping," to describe a different process that also delivers subgrade material to the road surface.

The mechanism thought to cause subgrade pumping in forest roads is small, local bearing capacity failures at the aggregate/subgrade interface that forces the aggregate into the subgrade or conversely forces the subgrade material to move upward into the aggregate. This mechanism occurs when the subgrade approaches saturation, loses strength, and point loads at the contact between the aggregate and subgrade increase because of increased stresses due to traffic loads. The pavement structure becomes a matrix of subgrade and aggregate (Figure 3.2). As the matrix of subgrade and aggregate becomes thicker, the functional pavement becomes thinner, which causes progressively higher stresses at the now ill-defined subgrade/aggregate interface. Fines from the subgrade can reach the pavement surface in this manner and are available to be transported from the road.

To differentiate between traditional subgrade pumping and the mechanism that is occurring in unbound aggregate roads, subgrade pumping in terms of subgrade movement from small bearing capacity failures will be referred to as "subgrade mixing" from this point forward. Subgrade pumping in the traditional sense of ejection of sediment laden water through cracks in the pavement has not been documented to occur in unbound aggregate pavements.

A new design method for unbound aggregate pavements on low volume roads should support design loads but also reduce the generation of fine sediment from the road surface. Clean, high-quality aggregate, hypothetically, will reduce the production of fine sediment from the road surface because the high quality aggregate won't break down and clean aggregate will limit the availability of fines on the road surface. A design to reduce the production of fine sediment caused by subgrade mixing is more difficult. This design method should incorporate subgrade strength and traffic. Subgrade mixing is most likely to occur with saturated subgrades so the new method should also incorporate the behavior of the subgrade due to traffic during wet weather. There is little information available on the strength of subgrade soils during wet weather with loads due to log trucks.

Figure 3.2 Subgrade and surface aggregate matrix in an unbound aggregate pavement structure.

Considerations for a New Method for the Design of an Unbound Aggregate Pavement

One consideration for design of an unbound aggregate pavement that will reduce the production of sediment from the road surface is to reduce or eliminate subgrade mixing. Subgrade mixing can be reduced or eliminated if bearing capacity failures at the aggregate/subgrade interface are reduced or eliminated. This can accomplished by reducing the magnitude of the applied stresses at the surface of the subgrade to less than the subgrade strength. This method requires consideration of the strength of the subgrade, traffic, and the behavior of the subgrade under a pavement structure due to traffic.

Characterization of the Subgrade Soil

The first step in a new design method for unbound aggregate pavements is to characterize the subgrade. Characterization of the subgrade includes soil classification, plasticity index, and stress history. This information will allow an estimate of the strength of the subgrade.

Soil classification is based on the size of soil particles that are dominant in the soil. The Unified Soil Classification (USC) System (ASTM 1999) labels soils as gravel, sand, silt, or clay. A soil composed mostly of sand is stronger than one composed mostly of clay at the same moisture content. The plasticity index is used to classify soils and is important when fine-grained soils are classified (Das 2002). Soil strength is related to the plasticity of the soil.

Forest soils are often overconsolidated due to the annual wetting and drying cycle that desiccates the soil. Schoenmann and Pyles (1988) measured overconsolidation ratios of 15 to 30 for forest soils in the central Oregon Coast Range. Forest soils that are residual soils are differentially weathered and are anisotropic. A residual soil will have different strengths when stresses act in different directions. Subgrades for forest roads may be compacted, which will increase the bulk density of the soil and results in increased soil strength (Holtz and Kovacs 1981).

Characterization of the Loads

A second consideration in a new design method for unbound aggregate pavements is the nature of the load placed on the pavement at the subgrade. The design is based on the wheel load from a standard 80 kN (18 kip) axle. A differential element of soil at the subgrade/aggregate interface experiences increases in horizontal and vertical stresses as a result of the application of the load due to traffic (Figure 3.3).

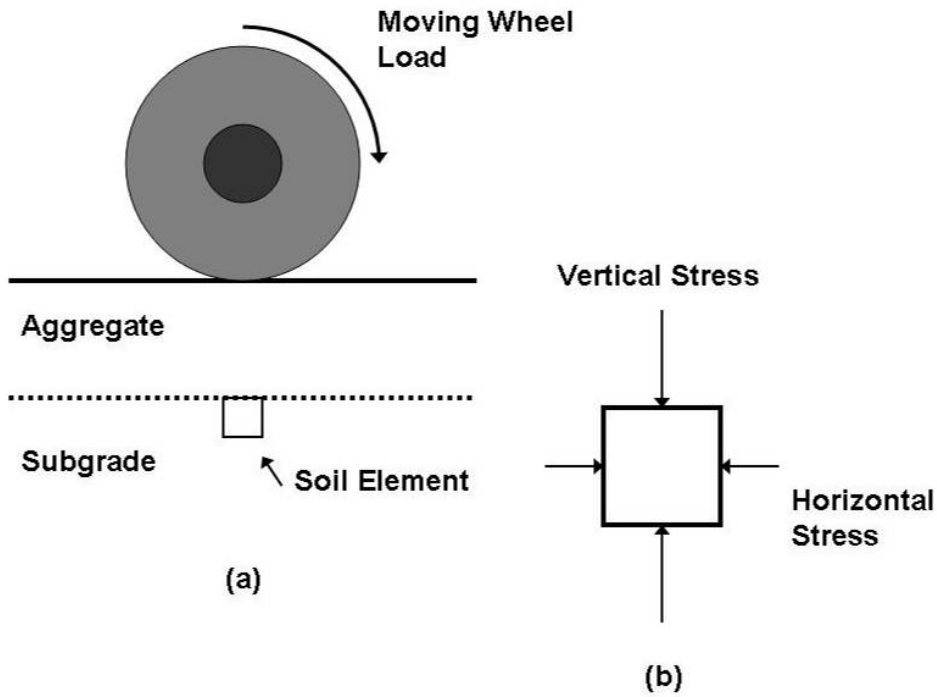


Figure 3.3 A differential element of the subgrade beneath a wheel load (a). The differential element is subjected to changes in vertical and horizontal stresses (b).

The load placed on the subgrade by the truck is affected by the weight of the load and the tire pressure. Stress imposed on the subgrade due to the passage of a log truck involves:

1. Rapid loading and unloading: The duration of a load cycle from a tire on a log truck going 15 km/hr (9.3 mile/hr) is approximately two seconds.
2. Cyclic loading: The road experiences thousands of load cycles during its life.
3. Drainage: The load cycle is rapid, which will produce undrained conditions in the subgrade during the application of the load. However, the time between vehicle passes is long. A heavily used road will experience 20 trucks a day. If the trucks are spaced evenly there is more than 20 minutes between truck passes, which should produce drained conditions in most subgrade soils between truck passes.
4. Low confining pressures: A pavement built with an aggregate with a unit weight of 19.6 kN/m^3 (125 pcf) that is 0.35 m (14 inches) deep results in a vertical confining stress on the differential

element at the aggregate/subgrade interface of 6.9 kPa (1.0 psi). Using a coefficient of lateral earth pressure, k_0, of 0.5 results in a horizontal confining stress of 3.5 kPa (0.5 psi).

5. Heavy loads: The load on a forest road from a loaded log truck is 160 kN (36 kip) per dual axle. If the tire pressure is 550 kPa (80 psi) and the aggregate depth is 0.35 m (14 inches) then the vertical stress on the subgrade due to the load is 104 kPa (15 psi) assuming a 2:1 vertical pressure distribution.
6. Principal stress rotation: The movement of the wheel load over the road causes the principal stresses on the differential soil element at the aggregate/subgrade interface to rotate (Figure 3.4). Brown (1996) reports that the pulse of stress generated when the wheel of a vehicle travels over a pavement consists of vertical and horizontal stress components with a double pulse of shear stress.
7. Load applied during saturated conditions: The worse case condition for the structural capacity of the road occurs during wet weather when the subgrade is saturated or near saturation. Hinshaw and Northrup (1991) measured moisture content of a subgrade under an aggregate surface in Idaho and found that the degree of saturation in subgrade soils varied from 55 percent in September to 97 percent in March and April. This study took place in a region with snowmelt hydrology, which will most likely have saturated subgrades during different times of the year than a region with rain-dominated hydrology.

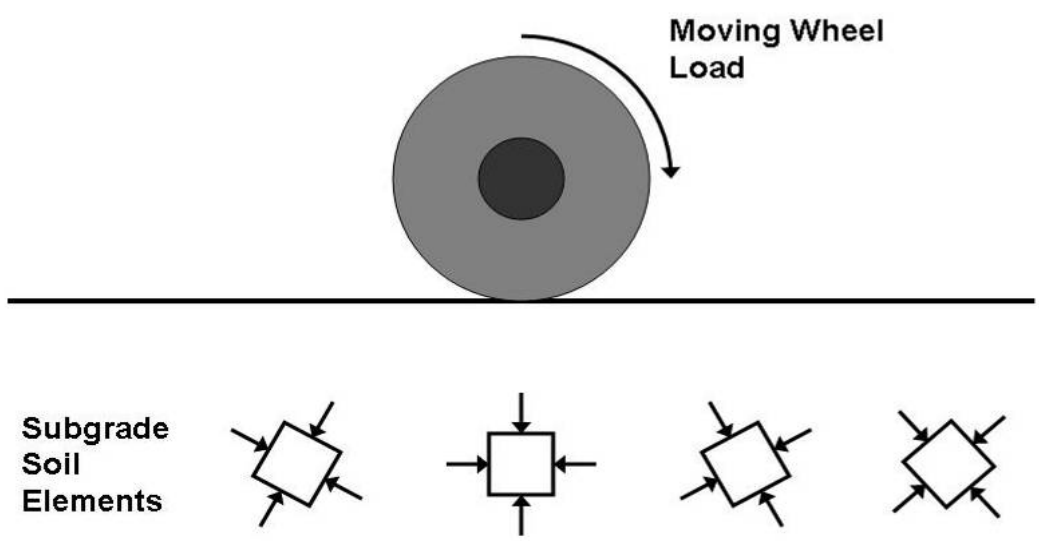


Figure 3.4 Principle stress rotation of a differential soil element in the subgrade with a moving wheel load.

Loads due to traffic occur at the pavement surface. The loads of concern for a low volume road design that designs against subgrade mixing occur at the subgrade surface. There are several methods to translate loads from the aggregate surface to the subgrade surface. These methods were developed for foundation design, however, they are reasonable approximations to translate traffic loads through an aggregate layer. The most basic method is the 2:1 slope method that defines the area of a zone of stress beneath a load, which increases with depth at a 2:1 slope (Bowles 1996). With this method, the pressure increase, Δq, at depth z is calculated as:

$$\Delta q = \frac{Q}{(B+z)(L+z)}$$

Where Q is the load, and B and L are the dimensions of the footing (Bowles 1996). An approximate stress distribution with the 2:1 method is shown in Figure 3.5 (recreated from Engineer Manual 1110-1-1904, USACE 1990).

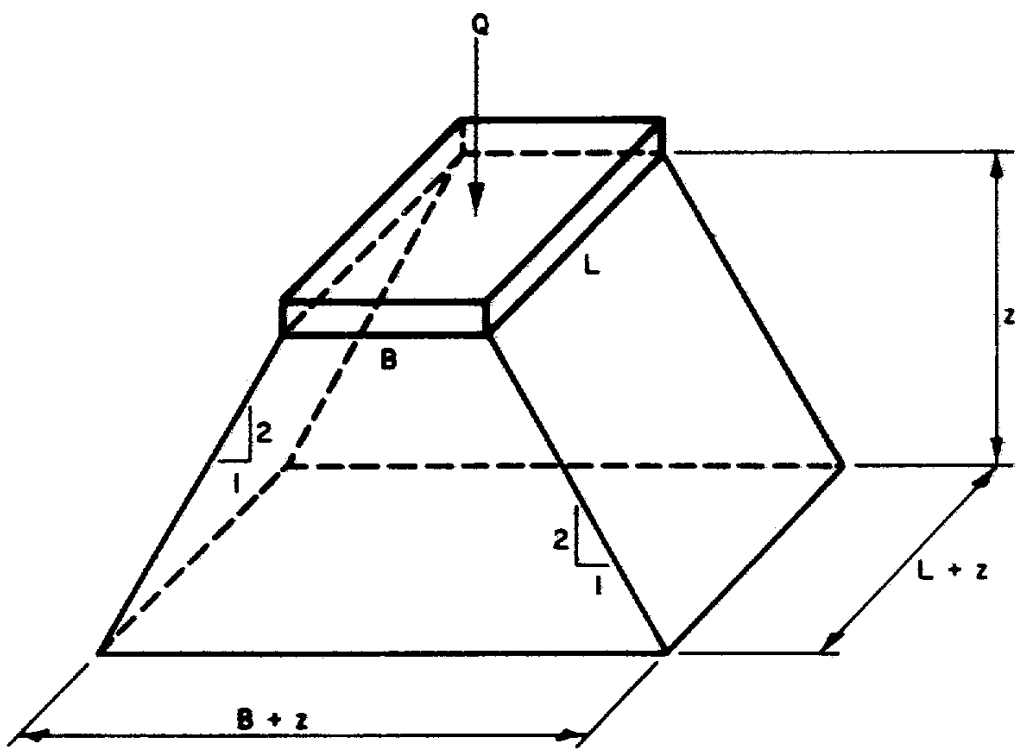


Figure 3.5 Approximate stress distribution for soil beneath a load by the 2:1 method. Recreated from USACE (1990).

The most common method used to calculate the stress in a soil at depth due to an applied surface load was developed by Boussinesq and is based on the Theory of Elasticity (Boussinesq 1885). The Boussinesq equation for stress (σ) at a point under the corner of a rectangular load is:

$$\sigma = \frac{q}{2\pi}\left(\tan^{-1}\frac{ab}{zC} + \frac{abz}{C}\left(\frac{1}{A^2} + \frac{1}{B^2}\right)\right),$$

$$A = a^2 + z^2,$$

$$B = b^2 + z^2,$$

$$C = \left(a^2 + b^2 + z^2\right)^{1/2}.$$

Where q is the contact pressure, a and b are the base and length of the pressure area, and z is the depth below the load of the point of load calculation (Taylor 1948; Terzaghi 1943). A graph of the coordinate system is shown in shown in Figure 3.6. To calculate stress at a depth (z) directly below the center of a rectangular load, superposition of the stresses is used.

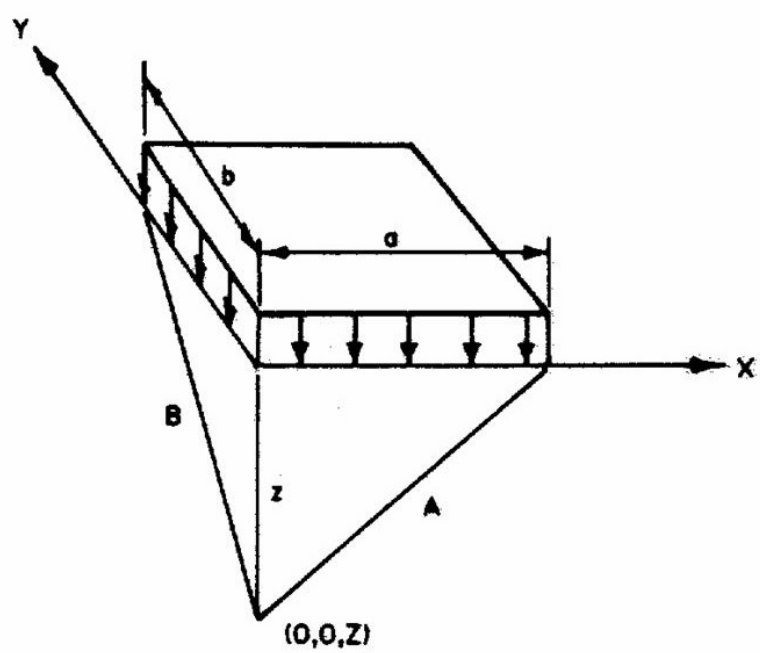


Figure 3.6 The coordinate system for the Boussinesq method (recreated from USACE 1990) for soil under a rectangular load with the Boussinesq method.

The limitations of this method arise from the assumption of elasticity for the layer; in other words that a constant linear relationship exists between stress and strain. Unbound aggregate is not elastic. Small loads may result in small strains in aggregate that are proportional to the applied stresses. Thus the Boussinesq method may be a reasonable estimate of stresses at the subgrade due to traffic loads at the aggregate surface.

Subgrade Behavior with Loading

The behavior of the subgrade due to the application of the load is an important consideration for a new design method for unbound aggregate pavements. In a review of existing design methods for unbound aggregate pavements, Yapp *et al.* (1991) concluded that the behavior of unbound aggregate roads is poorly understood. Laboratory and/or field trials are required to evaluate the behavior of subgrade soils. A standard soil test does not exist that simulates field conditions appropriately.

The repeated load triaxial test (RLTT) is a laboratory test that evaluates the effects of repeated loads. In this test, the confining stress in a triaxial cell is held constant and a deviator stress is pulsed. The pulse rate can simulate wheel loads. Triaxial tests with repeated loads are used to study, not only, traffic loads but also earthquake and wave loads. Triaxial tests with repeated loads are conducted as drained or undrained tests and researchers that investigate subgrade behavior use both methods (Konrad and Wagg 1993; Miller *et al.* 2000; Monismith *et al.* 1975; Puppala *et al.* 1999; Zergoun and Vaid 1994).

Soils have different behavior with repeated loads compared with a sustained monotonic load (Brown *et al.* 1975; Seed *et al.* 1955). Repeated loads on soil have vertical deformations that have permanent and resilient components (Figure 3.7).

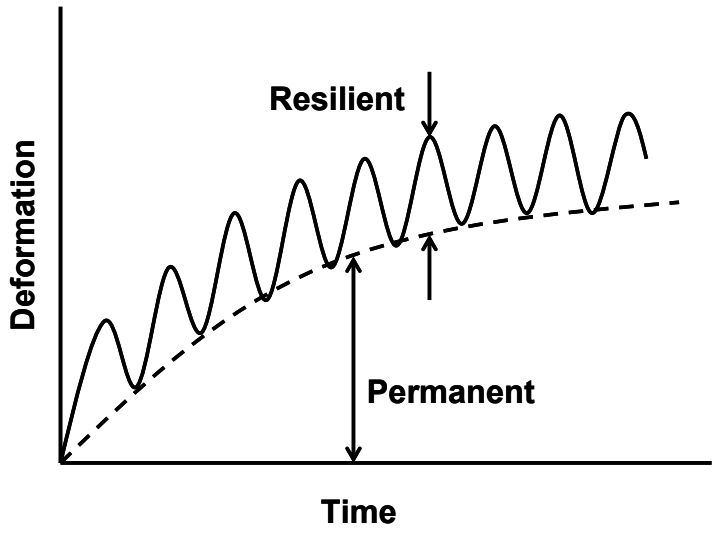


Figure 3.7 A conceptual model of the variation of deformation with repeated loads (after Brown *et al.* 1975).

Permanent strain in cohesive soils exhibits two patterns (Figure 3.8). In one pattern, the strain increases at an increasing rate with every load cycle until failure occurs (infinite strain at a given stress) (Figure 3.8 path 1). In the second pattern, the strain decreases at a decreasing rate with every load cycle until the strain reaches approaches a constant value (Figure 3.8 path 2). The first behavior is called strain softening and results in a failed subgrade. The latter behavior is called strain hardening and results in a stable subgrade. Larew and Leonards (1962) related the maximum permanent strain of a stable soil sample to a critical deviator stress that is repeated (threshold stress) above which the permanent (plastic) deformation of the soil increases rapidly with cyclic loading. France and Sangrey (1977) reported a critical level of repeated loads for dilative soils below which strain accumulation and volume change ceased. Nodes *et al.* (1997) reported a threshold value of deviator stress to a percent of monotonic undrained compressive strength, and depth of aggregate above the subgrade.

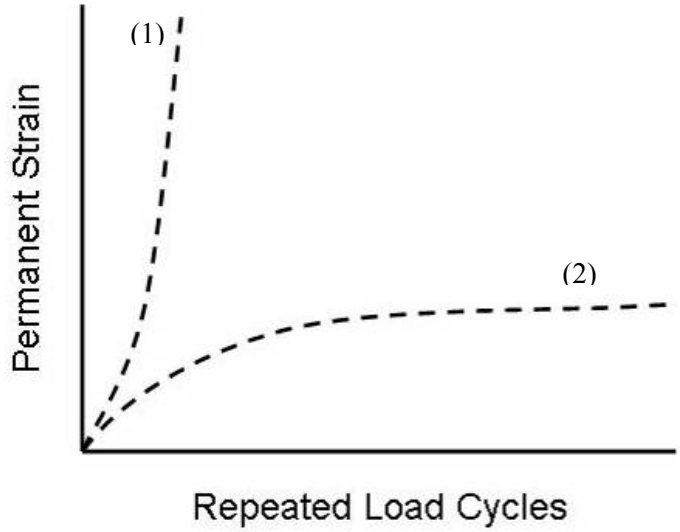


Figure 3.8 Two patterns of permanent strain accumulation with repeated loads.

The variable confining pressure (VCP) triaxial test is used to simulate the rotation of principal stresses that happens during the application of a wheel load more accurately. Results from VCP triaxial test are rare. To optimize the value of these results however, the results from VCP triaxial tests are compared with results from triaxial tests with constant confining pressure. Allen and Thomson (1974) compared the results from the two types of soil strength tests and found that soils were weaker (lower resilient moduli) when tested with VCP triaxial tests than those tested with constant confining pressure triaxial tests. Simonsen and Isacsson (2001) reported similar results with subgrade soils and conditions that simulated freezing and thawing. Although the VCP triaxial test describes traffic loading more accurately, little research using this method with subgrade soils and traffic loads for low-volume roads exists.

Repeated load testing is the best and most common way to test soil behavior due to traffic loads. Variables considered during repeated load tests for the strength of subgrade are: drainage, confining pressure, consolidation, saturation, and degree of compaction.

Drainage in a cohesive soil is important to the strength and strain behavior of the soil when it is subjected to repeated loads. Brown *et al.* (1977) reported that soil in undrained, repeated load tests developed more permanent strain than soil in drained, repeated load tests. This pattern of behavior diminished as the overconsolidation ratio increased (Brown *et al.* 1977). Butruille (1993) reported that in a drained soil sample three load pulses were required to reach 2.0 percent strain while in an

undrained soil sample 20 load applications were required to reach the same strain. A difference in the Butruille (1993) and Brown *et al.*(1977) studies is the low confining stresses used. Butruille (1993) tested samples under a confining stress of 4 kPa (0.6 psi) while Brown *et al.* (1977) tested at much higher confining stresses.

The confining pressure that subgrade soils are tested at is an important factor in their behavior. Fischer (2002) found dilative behavior for all soils tested with confining pressures below 22 kPa (3.25 psi) for forest soils from the Oregon Coast Range. This research combined with the work of Butruille (1993) shows the importance of confining stress to the behavior of subgrade soils during strength tests.

The overconsolidation of a soil is a factor in the behavior of subgrade soils. Using undrained repeated load triaxial tests, Brown *et al.* (1975) showed that the degree of overconsolidation of silty-clay soils influenced the amount of permanent strain deformation. Soils with higher overconsolidation ratios (OCRs) had greater strains at the same number of load cycles. Brown *et al.* (1975) also found that with single load triaxial tests the soils with OCRs of 4, 10, and 20 were dilative and the soil with an OCR of 2 was contractive.

The degree of initial saturation of a soil sample is important in the behavior of subgrade soils. Miller *et al.* (2000) found that the cyclic shear strength of subgrade soils under repeated loads decreased by as much as 80 percent as the initial degree of saturation increased from 90 to 100 percent. Hinshaw and Northrup (1991) reported that the California Bearing Ratio of subgrade soil decreased steadily with increasing saturation.

Compaction is the final factor in the behavior of subgrade soils. Schofield and Wroth (1968) hypothesized that the void ratio and confining pressure of a soil defined the behavior of the soil in relation to a critical state. Soils with low void ratios under low confining pressures, such as compacted subgrade soils, will dilate towards the critical state line (Figure 3.9).

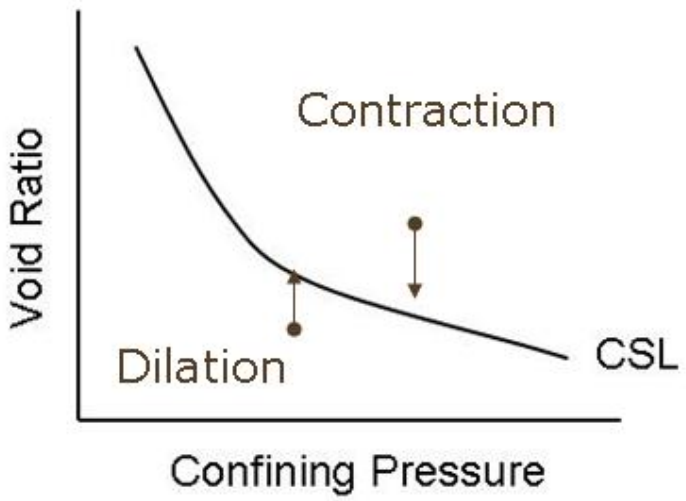


Figure 3.9 Soil behaviors in relation to the line of critical state. After Schofield and Wroth (1968).

The behavior of subgrade soils is important to understand to help predict the behavior of subgrades to simulated traffic over time Curve fitting models are used to predict the cumulative plastic strain with repeated applications of load. One curve fitting model developed by Li and Selig (1996) requires inputs of deviator stress, soil strength, and curve-fitting parameters related to the soil type. Although this type of model is easy to use to evaluate subgrade strength, it doesn't use variables that affect soil behavior such as the stress history and drainage.

From the original work of Larew and Leonards (1962), correlations were developed between threshold values of soil strength measured in the laboratory or the field and strain rate to failure. McCracken (1994) reported that a thicker layer of aggregate pavement increased the confining pressure at the surface of the subgrade and decreased the stress due to the applied load. For the subgrade soil from the Oregon Coast Range that was tested, an aggregate depth of 0.5 m (19.4 inches) would reach a permanent strain while the same subgrade soil with aggregate depths of 0.35 and 0.42 m (13.8 and 16.6 inches) would continue to strain with repeated loads until failure (McCracken 1994).

The behavior of subgrade soils in response to traffic was studied with triaxial strength tests that incorporate characteristics of the subgrade. Nodes *et al.* (1997) reported on a study where a forest soil from the Oregon Coast Range was compacted below the optimum water content, backpressure saturated, and subjected to the effective confining pressure of a subgrade with a 0.35 m layer of aggregate. Simulated traffic loads were applied for 2 second pulses with 2 minutes between each pulse for drainage to avoid the buildup of pore pressure. Permanent strain reached equilibrium with a repeated load that was 40 percent of the monotonic undrained strength. Soils tested with a repeated load that was

60 percent of the monotonic undrained strength continued to strain with load application until failure (Nodes *et al.* 1997). Frost *et al.* (2004) hypothesized that a threshold stress at which cumulative permanent deformation starts to increase significantly is between 50 and 100 percent of the undrained strength of the soil. They suggested that aggregate pavements be designed so that traffic loads on the subgrade do not exceed 50 percent of the undrained strength of the subgrade soil to allow strain hardening behavior.

A new design method for unbound aggregate pavement that reduces the generation of fine sediment should be based on the fundamentals of soil mechanics and knowledge of the strength and behavior of subgrade soil subjected to repeated loads in wet weather. A literature review of strength tests for subgrade soils indicates that many variables contribute to the strength and strain behavior of subgrade soils. There is no single study that incorporates all the characteristics of traffic loads but there are some consistent results with regard to subgrade behavior. Repeated and pulsed loads produce permanent and resilient strain and the subgrade can fail or strain soften, or stabilize or strain harden. Strain hardening is related to the monotonic shear strength of the soil. The load that can be applied as a pulsed load that will result in strain hardening and a stable, permanent deformation can be determined with a consolidated, undrained triaxial test that gives the monotonic undrained strength of the subgrade soil. The design method for unbound aggregate pavement for low-volume roads that reduces subgrade mixing should include strain hardening of the subgrade soil. A realistic value for a design stress at the subgrade/aggregate interface that would optimize strain hardening behavior is a design stress that is 50 percent of the monotonic strength of the subgrade soil.

Reduced Stress: A Method for the Design of Unbound Aggregate Pavement to Minimize Subgrade Mixing

A new method for the design of unbound aggregate pavement to minimize subgrade mixing was developed and designated the “reduced stress” method for pavement design. This method incorporates environmental performance of the aggregate pavement into the design by reducing the opportunity for subgrade mixing. This method reduces the stress on the subgrade due to wheel loading to approximately half of the monotonic soil strength of the subgrade in bearing capacity.

The first step in the design procedure is to determine the design load from traffic. The design load that acts on the pavement surface is translated through the layer of aggregate with the 2:1 slope and/or Boussinesq methods. The stress that acts on the subgrade depends on the depth of the surface aggregate.

The second step is to determine the strength of the subgrade soil. Monotonic shear strength can be determined in the laboratory with a triaxial test. The Mohr circle and Mohr-Coulomb failure

envelope describe stress on a soil approaching and at failure. In a Mohr circle diagram shear stress, τ, is graphed along the y-axis and the normal stress, σ, is graphed along the x-axis. The major and minor principal stresses, σ_1 and σ_3 respectively, are graphed on the x-axis as they represent the normal stresses that act on the soil when shear stress is not present. The Mohr-Coulomb failure envelope is defined by the friction angle, φ, and the cohesion intercept, c, of the soil. The difference between the total and effective Mohr circle and Mohr-Coulomb failure envelope is the value of the pore pressure, u, in the soil. Theoretically, shear strength at failure on the failure plane (τ_{ff}) corresponds to the shear stress at a point where the Mohr circle is tangent to the Mohr-Coulomb failure envelope for the soil sample (Scott 1963). In a laboratory it is possible to approximate this value as the undrained shear strength (C_u) and it is equal to the radius of the Mohr circle diagram (Figure 3.10). Undrained shear strength is an appropriate approximation for τ_{ff} because of the sampling disturbance that occurs in a laboratory setting. Determining soil strength by triaxial tests is impractical for a pavement design process for forest roads because it requires a soils laboratory, soil testing equipment, and many soil samples. However, undrained shear strength can be estimated with soil characteristics, aggregate characteristics, and assumptions about the water content of the subgrade.

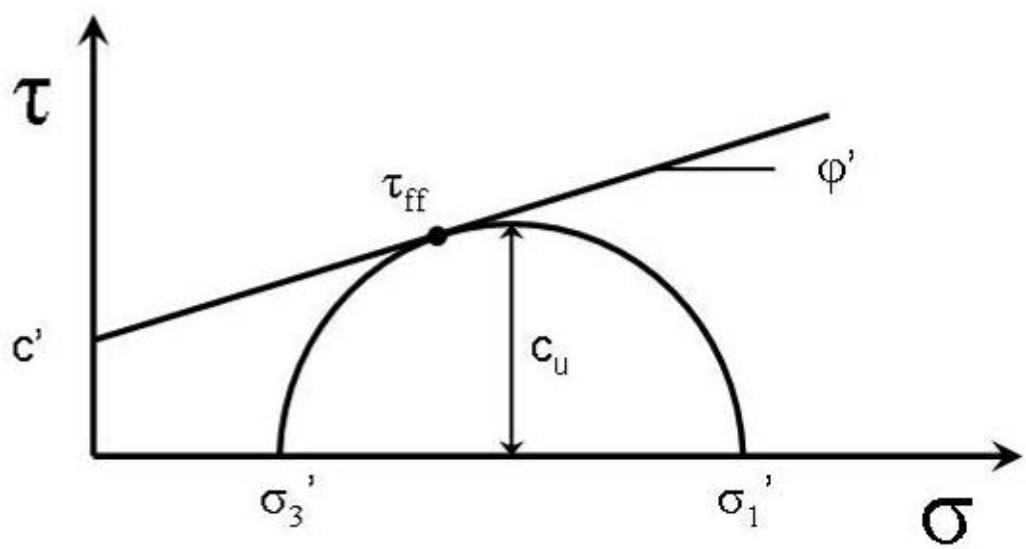


Figure 3.10 Mohr circle with a Mohr-Coulomb failure envelope.

The surface aggregate produces a confining pressure on the subgrade that is represented on Mohr's circle by the minor principle stress, σ_3. The effective minor principle stress, σ_3', is equal to the total minor principle stress, σ_3, at the end of consolidation in undrained triaxial testing as pore pressures are not present. The effective minor principle stress is calculated as:

$$\sigma_3' = K_o \gamma z$$

where K_o is the coefficient of lateral earth pressure at rest, γ is the aggregate unit weight, and z is the depth of the surface aggregate (Das 2002).

A p'-q diagram graphs the top points of the Mohr's circles and allows for a better visual description of the stress paths of the soil. In a p'-q diagram, p represents the average principle stress ($(\sigma_1 + \sigma_3)/2$) and q represents the radius of the Mohr circle ($\Delta\sigma/2$). The K_f failure line is calculated from the friction angle and cohesion intercept from the Mohr-Coulomb failure envelope with:

$$q_f = a + p_f \tan \psi,$$

where $\psi = \tan^{-1} (\sin \varphi)$ and $a = c' \cos \varphi$ (Holtz and Kovacs 1981). A p'-q diagram representing the horizontal pressure on the subgrade at the surface of the subgrade from the surface aggregate at the end of consolidation is shown in Figure 3.11.

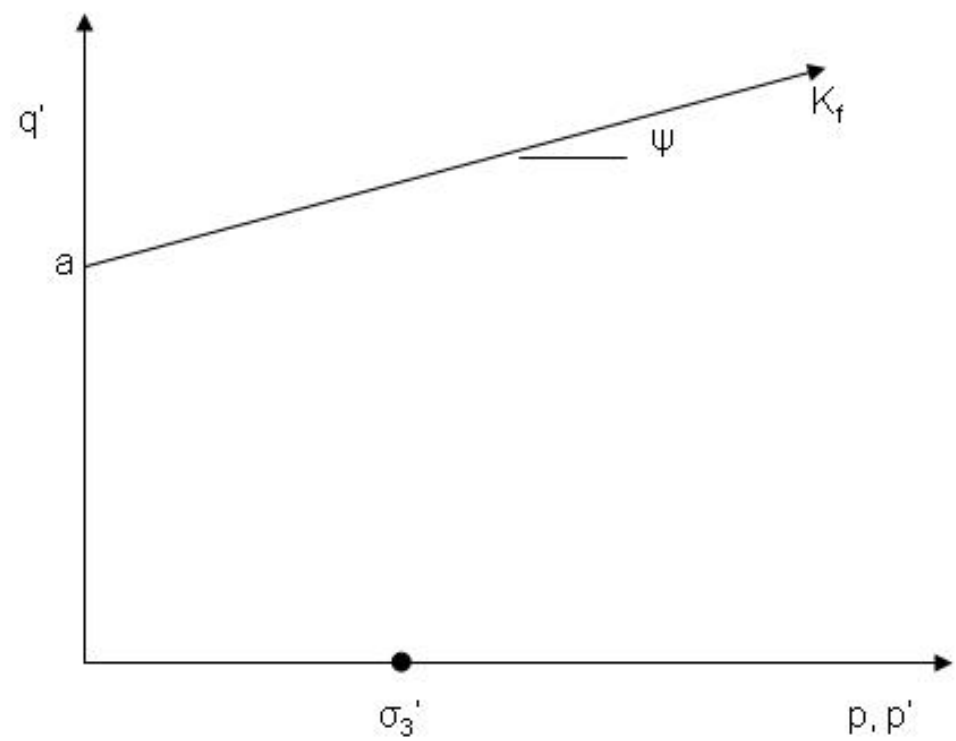


Figure 3.11 A p'-q diagram for a subgrade soil at the end of consolidation.

With vertical loading (from surface aggregate and traffic), the Mohr's circles representing the total and the effective stresses on the soil expand and the horizontal difference between the top points of the total and effective Mohr's circles is equal to the pore pressure of the soil. Total and effective Mohr's circles from the effective minor principle stress for a stress prior to failure are shown in Figure 3.12 on a p'-q diagram. The effective stress path is at an angle, θ, from vertical. The total stress path is at an angle approximately 45º from the horizontal. From geometry and the characteristics of a Mohr circle, θ can be calculated as:

$$\theta = \tan^{-1}\left(\frac{\frac{\Delta\sigma}{2} - \Delta u}{\frac{\Delta\sigma}{2}}\right).$$

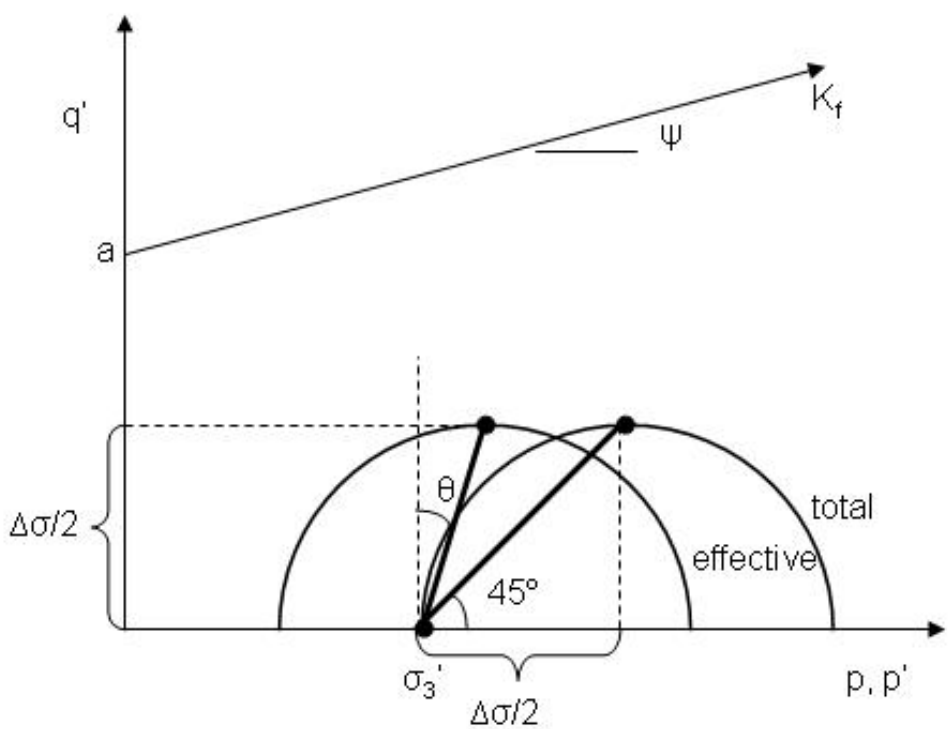


Figure 3.12 Total and effective Mohr's circles and stress paths prior to failure.

The reduced stress method assumes that the subgrade soil is completely saturated with the water table at the surface of the subgrade. This assumption is required to simplify calculations and is valid for representing subgrade soils during wet-weather use. Skempton's pore water pressure

parameter, A, is assumed to be a constant value. This assumption is appropriate for low confining pressures based on test results from published reports (Kliewer 1992; McCracken 1994). At complete saturation, Skempton's pore water pressure parameter is equal to the difference in pore water pressure divided by the difference in stress ($\Delta u/\Delta\sigma$). At complete saturation, θ simplifies to:

$$\theta = \tan^{-1}(1 - 2A).$$

Failure of the soil in shear occurs when the effective stress path meets the K_f line. The value of q' at this point is the undrained shear strength of the soil (Figure 3.13). From the geometry of the p'-q diagram, the undrained shear strength of the soil is defined as:

$$C_u = a + \frac{(\sigma_3' + a\tan\theta)\cos\theta}{\cos(\psi + \theta)}\sin\psi .$$

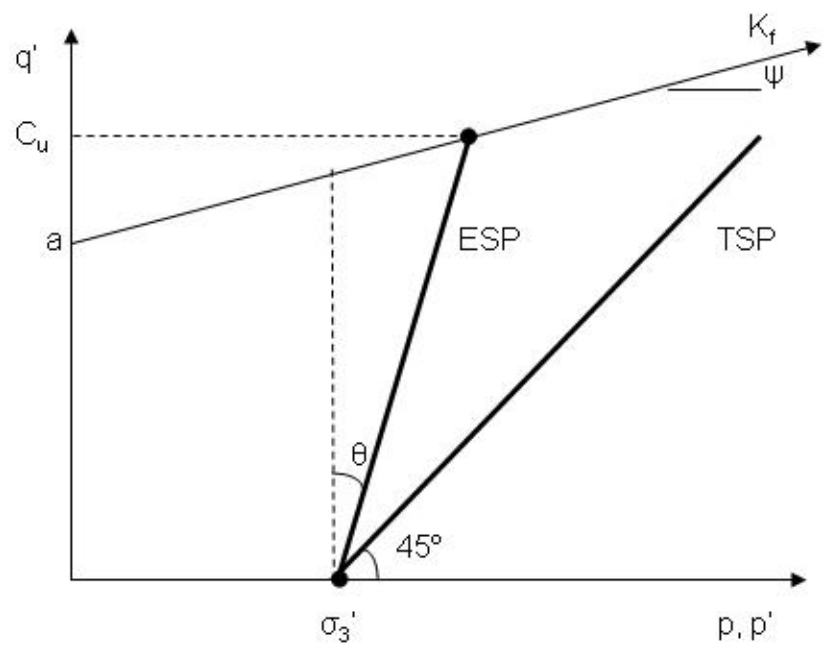


Figure 3.13 The effective stress path (ESP) and total stress path (TSP) of a soil to failure.

To solve for the undrained shear strength of the soil, the unit weight and depth of the surface aggregate and the effective friction angle, the cohesion intercept, and Skempton's pore water pressure parameter for the soil are required. The aggregate unit weight can be determined from simple laboratory

tests. The effective friction angle of the soil can be estimated using soil characteristics by means of the United States Navy method (USN 1971). This method relates the effective friction angle of the soil to soil type and dry unit weight of the soil. Soil type can be established in the field using ASTM standard tests for dry strength, dilatancy, and toughness (ASTM 2006). Dry unit weight is the weight of the solids in the soil per unit volume and it is related to how much the soil has been compacted. Dry unit weight can be determined by oven-drying and weighing soil samples of a known volume. The cohesion intercept and Skempton's pore water pressure parameter should be estimated from reported testing with similar soils.

In the reduced stress design method, 50 percent of the value for undrained shear strength is considered to be 50 percent of the monotonic shear strength for the soil. The goal of the reduced stress method is to reduce stresses at the surface of the subgrade to 50 percent of the monontonic shear strength of the soil in bearing capacity to allow for strain hardening. The bearing capacity of the subgrade is calculated as:

$$q_u = c' N_c + q N_q + \frac{1}{2} \gamma B N_\gamma ,$$

where 50 percent of C_u is substituted for cohesion, c', bearing capacity factors N_c=5.14, N_q=1.0, and N_γ=0 (in an undrained condition, φ' = 0), and the load, q, is calculated as the depth of the surface aggregate multiplied by the unit weight of the surface aggregate (Das 2002).

The calculations for stress on the subgrade and soil strength at the surface of the subgrade involve aggregate depth. These calculations can be solved simultaneously for aggregate depth such that the stress on the subgrade is equal to bearing capacity of the soil at 50 percent of monotonic shear strength. This calculation gives the depth of the surface aggregate to prevent bearing capacity failures at the subgrade and subsequent subgrade mixing.

Example of the Reduced Stress Method for Pavement Design

To determine the surface aggregate depth using the reduced stress method for pavement design, information on the traffic load, subgrade soil, and surface aggregate is required. The following analysis will go through the process of designing the depth of surface aggregate for a new forest road built west of Corvallis, Oregon.

The design load for this road has been identified as a standard 80 kN (18 kip) axle. The tires of the standard axle are assumed to have a tire pressure of 550 kPa (80 psi). A rectangular area of pressure of 725 cm^2 (113 in^2) with a length of 12 cm (4.7 in) and base of 61 cm (24 in) was determined from the load and tire pressure for the 2:1 slope and Boussinesq methods of pressure distribution.

In western Oregon, forest soils are cohesive and contain fine-grained material yet they are often classified as sands. Schroeder and Alto (1983) in a review of soil properties of the Oregon Coast range classified all the soil samples as SM (silty-sands) in the Unified Soil Classification System. Other studies in western Oregon have classified soil samples as fine-grained with both high and low plasticity (MH and ML) (Kliewer 1992; Smith 2001). Field and/or laboratory tests are required to determine the exact classification but for this analysis it is assumed that the subgrade soil has been classified as ML. The subgrade soil has been compacted and is determined to have a dry unit weight of approximately 14.1 kN/m^3 (90 pcf). A diagram from the US Navy recommends that the effective friction angle for this soil is 33º (USN 1971). The cohesion intercept is estimated to be 7 kPa (1 psi). This is an average of 57 values for c' for soils from the Oregon Coast Range as reported by Morgan (1995). The aggregate unit weight is 19.6 kN/m^3 (125 pcf). The confining pressure on the subgrade soil is equal to the aggregate unit weight multiplied by the aggregate depth and the coefficient of earth pressure at rest which was estimated at 0.5. Skempton's pore water pressure parameter, A, was estimated at 0.1. This value is typical of those reported by Kliewer (1992) and Fischer (2002) for soils tested with low confining pressures.

Stress on the subgrade soil from traffic loading using both the Boussinesq and 2:1 slope method and soil strength in bearing capacity using 50 percent of the undrained shear strength were calculated and graphed for varying depths of aggregate (Figure 3.14). The equations for stress on the subgrade were solved simultaneously with the soil strength equation to calculate aggregate depth. Using the Boussinesq method, stress from the traffic load was equal to soil strength at 0.56 m (22 in). Stress from the traffic load using the 2:1 slope method was also equal to soil strength at 0.56 m. This new method for pavement design for unbound aggregate roads suggests a surface aggregate depth equal to or greater than 0.56 m to prevent subgrade mixing for this specific example road west of Corvallis, Oregon.

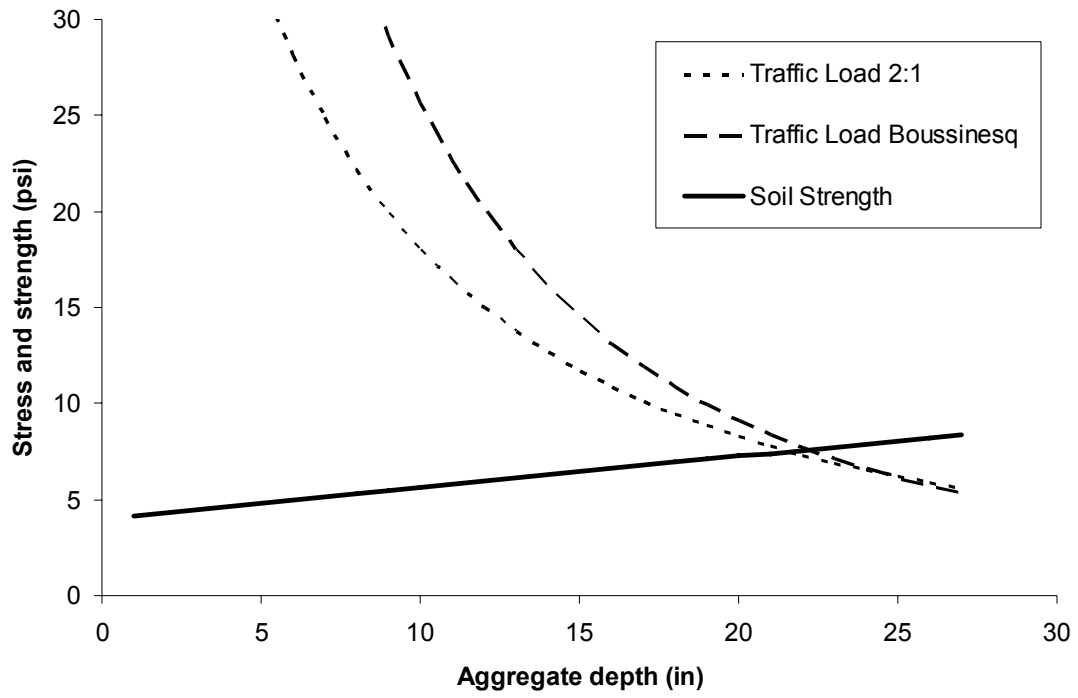


Figure 3.14 Soil strength and stress on the subgrade soil from traffic loading by surface aggregate depth.

Discussion

The design method presented for pavement depth for unbound aggregate roads is a simple yet appropriate design process that can be easily applied by road managers. Although based in soil mechanics and theory, it does not require a geotechnical engineer or specialized designer to implement. This method designs for environmental performance of the road in terms of subgrade mixing with repeated trafficking by reducing stresses on the subgrade such that bearing capacity failures are minimal. Like all design methods, this new method has strengths and weaknesses.

A strength of the new design method is that it is based on local conditions and can easily adapt to different locations. The existing subgrade determines the soil strength and subsequently the design aggregate depth. The same design process can be used at any location regardless of climate. A second strength is the ability to modify this design method for any traffic loading. The design vehicle can be a loaded log truck, off-highway log truck or even a passenger vehicle for roads used primarily for recreation. Finally, this design method is simple to use. It requires minimal data collection and the calculations are compatible for a spreadsheet format where the variables of subgrade soil type, effective

friction angle of the subgrade material, tire pressure, total load, and subgrade and aggregate unit weight are entered for a specific location and the aggregate depth is returned.

Although the new design method is based in soil theory, it still does not consider all aspects of soil behavior. The assumption that reducing traffic stresses to 50 percent of the monotonic strength of the subgrade will create a strain hardening condition of the subgrade is founded in laboratory studies that did not consider principle stress rotation. Traffic loading, with the rolling movement of a wheel load, does create this condition but there is a lack of scientific research to suggest how this will affect strain hardening with repeated loads. Another weakness of this pavement design method is that it only designs against subgrade mixing and does not prevent fines from being produced from the aggregate or prevent loss of existing fines. If these are areas of concern, then the pavement design should be focused on the quality and characteristics of the surface aggregate.

Some of the steps in this design process assume that the subgrade soil is cohesionless, however not all subgrade soils are. The presence of clay minerals may make a soil cohesive and even a small amount of clay minerals in a soil can markedly affect the engineering properties of that soil (Holtz and Kovacs 1981). A soil behaving as clay with inherent cohesion is likely to have higher shear strengths than that of a cohesionless soil so this design method is likely to give a lower, conservative estimate of soil strength with clay subgrade material. The US Navy method for determining an effective friction angle does not incorporate clay soil types and so the design method will have to be modified for cohesive subgrade soils to determine an appropriate effective friction angle. The generalizations and oversimplifications of this design method all err on the conservative side of pavement depth and although this may lead to an overestimation of the aggregate required, the new design will yield a pavement depth that prevents subgrade mixing and thus reduces the fine sediment produced from the forest road. The results of this design method may be an aggregate surface that is more deep than usual, but this is a design method that designs not just for load bearing but for environmental performance.

Conclusions

The design method presented is a valid design process for pavement depth for unbound aggregate roads with consideration to soil mechanics and emphasis on environmental performance. This method designs against subgrade mixing by reducing stresses on the subgrade to allow for strain hardening of the subgrade. The method requires simple field and/or laboratory tests on soil and aggregate characteristics and straightforward calculations to determine the depth of the aggregate surface. It is an appropriate design method for managers of forest roads that are concerned with the

environmental performance of the roads and in particular with the production and delivery of fine sediment from the road pavement to the streams.

References

AASHTO. (1993). "Chapter 4: Low volume road design." Guide for design of pavement structures, American Association of State Highway and Transportation Officials, Washington, District of Columbia.

AASHTO. (2001). *Guidelines for geometric design of very low-volume local roads (ADT≤400)*, American Association of State Highway and Transportation Officials, Washington, District of Columbia.

AASHTO. (2004). *Annual book of standards, standard specifications for transportation materials and methods of sampling and testing, 24th edition*, American Association of State Highway and Transportation Officials, Washington, District of Columbia.

Allen, J. J., and Thomson, M. R. (1974). "Resilient response of granular materials subjected to time dependent lateral stresses." *Transportation Research Record*, 510, 1-13.

ASTM. (1999). "ASTM D 2487, classification of soils for engineering purposes (unified soil classification system)." Annual book of ASTM standards, sec. 4, vol. 04.08, American Society for Testing and Materials, West Conshohoken, Pennsylvania.

ASTM. (2006). "ASTM D2488-06 Standard Practice for Description and Identification of Soils (Visual-Manual Procedure)." Annual Book of ASTM Standards, Sec. 4, Vol. 04.08, American Society for Testing and Materials, West Conshohoken, Pennsylvania.

Bilby, R. E., Sullivan, K., and Duncan, S. H. (1989). "The generation and fate of road-surface sediment in forested watershed in southwestern Washington." *Forest Science*, 35(2), 453-468.

Bolander, P., Marocco, D., and Kennedy, R. (1995). "Earth and aggregate surfacing design guide for low volume roads. Report no. FHWA-FLP-96-001." U. S. Department of Agriculture, Forest Service in cooperation with the U.S. Department of Transportation Federal Highway Administration, Washington, D.C.

Boussinesq, J. 1885. *Applications des Potentiels.* Gauthier-Villars, Paris.

Bowles, J. E. (1996). *Foundation analysis and design, fifth edition*, The McGraw-Hill Companies, Inc., New York, New York.

Brown, S. F. (1996). "Soil mechanics in pavement engineering. 36th Rankine lecture of the British Geotechnical Society." *Geotechnique*, 46(3), 383-426.

Brown, S. F., Andersen, K. H., and McElvaney, J. (1977). "The effect of drainage on cyclic loading of clay." *Proceedings, 9th International Conference of Soil Mechanics and Foundation Engineering, Tokyo*, 2, 195-200.

Brown, S. F., Lashine, A. K. F., and Hyde, A. F. L. (1975). "Repeated load triaxial testing of a silty clay." *Geotechnique*, 25(1), 95-114.

Butruille, F. R. (1993). "Repeated loading behavior of a compacted cohesive soil consolidated under low confining stress," Master of Science Engineering Report, Oregon State University, Corvallis, Oregon.

CDF&FP. (2004). "California forest practice rules, title 14, California code of regulations, chapters 4, 4.5, and 10." The California Department of Forestry and Fire Protection, Resource Management, Sacramento, California.

Das, B. M. (2002). *Principles of geotechnical engineering, fifth edition*, Brooks/Cole, Pacific Grove, California.

Fischer, G. S. (2002). "The influence of multi-stage triaxial testing on the behavior of Oregon coast range soil," Master of Science Engineering Report, Oregon State University, Corvallis, Oregon.

Foltz, R. B., and Truebe, M. A. (1995) "Effect of aggregate quality on sediment production from a forest road." *Transportation Research Board, Sixth International Conference on Low-Volume Roads*, Minneapolis, Minnesota, 49-57.

France, J. W., and Sangrey, D. A. (1977). "Effects of drainage in repeated loading of clays." *Journal of the Geotechnical Engineering Division, ASCE*, 103(GT7), 769-785.

Frost, M. W., Fleming, P. R., and Rogers, C. D. F. (2004). "Cyclic triaxial tests on clay subgrades for analytical pavement design." *Journal of Transportation Engineering*, 130(3), 378-386.

Hinshaw, R. F., and Northrup, J. L. (1991). "Predicting subgrade moisture under aggregate surfacing." *Fifth International Conference on Low-Volume Roads, Transportation Research Record 1291*, 2, 193-203.

Holtz, R. D., and Kovacs, W. D. (1981). *An introduction to geotechnical engineering*, Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

Huang, Y. H. (1993). *Pavement analysis and design*, Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

Indraratna, B., Shahin, M. A., Rujikiatkamjiorn, C., and Christie, D. (2006) "Stabilization of ballasted rail tracks and underlying soft formation soils with geosynthetic grids and drains." *Ground Modification and Seismic Mitigation (GSP 152)*, Shanghai, China, 20-20.

Kliewer, J. E. (1992). "Test procedures for low-confining stress, multi-stage triaxial testing of compacted cohesive soils," Master of Science Thesis, Oregon State University, Corvallis, Oregon.

Koerner, R. M. (1998). *Designing with geosynthetics*, Prentice Hall, Upper Saddle River, New Jersey.

Konrad, J.-M., and Wagg, B. T. (1993). "Undrained cyclic loading of anisotropically consolidated clayey silts." *Journal of Geotechnical Engineering*, 119(5), 929-947.

Kramer, B. W. (2001). *Forest road contracting, construction, and maintenance for small forest woodland owners*, Forest Research Laboratory, Oregon State University, Corvallis, Oregon.

Larew, H. G., and Leonards, G. A. (1962). "A strength criterion for repeated loads." *Proceedings, 41st Annual Meeting, Highway Research Board*, 529-556.

Li, D., and Selig, E. T. (1996). "Cumulative plastic deformations for fine-grained subgrade soils." *Journal of Geotechnical Engineering*, 122(12), 1006-1013.

Luce, C. H., and Black, T. A. (1999). "Sediment production from forest roads in western Oregon." *Water Resources Research*, 35(8), 2561-2570.

McCracken, M. J. (1994). "Drained behavior of a silt soil under repeated load triaxial testing," Master of Science Engineering Report, Oregon State University, Corvallis, Oregon.

Miller, G. A., Teh, S. Y., Li, D., and Zaman, M. M. (2000). "Cyclic shear strength of soft railroad subgrade." *Journal of Geotechnical and Geoenvironmental Engineering*, 162(2), 139-147.

Mills, K., Dent, L., and Robben, J. (2003). "Wet season road use monitoring project final report." Oregon Department of Forestry Forest Practices Monitoring Program Technical Report #17.

Monismith, C. L., Ogawa, N., and Freeme, C. R. (1975). "Permanent deformation characteristics of subgrade soils due to repeated loading." *Transportation Research Record*, 537, 1-17.

Morgan, D. J. (1995). "Strength Parameters and Triaxial Strength Testing of Soils of the Oregon Coast Range," Master of Science Engineering Report, Oregon State University, Corvallis, Oregon.

Muench, S. T., Mahoney, J. P., and Pierce, L. M. (2003). "Washington State Department of Transportation pavement guide interactive (m 46-03)." Olympia, Washington.

Nodes, J. E., Pyles, M. R., and Butruille, F. R. (1997) "Repeated-load test performance of a forest road subgrade soil at field stress levels." *UNB International Symposium on Thin Pavements, Surface Treatments, and Unbound Roads*.

Puppala, A. J., Mohammad, L. N., and Allen, A. (1999). "Permanent deformation characterization of subgrade soils from the RLT test." *Journal of Materials in Civil Engineering*, 11(4), 274-282.

Schoenemann, M. R., and Pyles, M. R. (1988). "Stress path considerations in multistage triaxial testing." Advanced triaxial testing of soil and rock, STP 977, Donaghe, Chaney, and Silver, eds., American Society for Testing and Materials (ASTM), West Conshohocken, PA, 732-739.

Schofield, A. N., and Wroth, C. P. (1968). *Critical state soil mechanics*, McGraw-Hill Publishing Company Limited, London.

Schroeder, W. L., and Alto, J. V. (1983). "Soil properties for slope stability analysis; Oregon and Washington coastal mountains." *Forest Science*, 29(4), 823-833.

Scott, R. F. (1963). *Principles of soil mechanics*, Addison-Wesley Publishing Company, Inc., Reading, Massachusetts.

Seed, H. B., Chan, C. K., and Monismith, C. L. (1955). "Effect of repeated loading on the strength and deformation of compacted clay." *Highway Research Board Proceedings*, 34, 541-558.

Simonsen, E., and Isacsson, U. (2001). "Soil behavior during freezing and thawing using variable and constant confining pressure triaxial tests." *Canadian Geotechnical Journal*, 38(4), 863-875.

Smith, R. S. (2001). "An investigation of the influence of root reinforcements on soil strength and the initiation of static liquefaction in forest soils," Master of Science Thesis, Oregon State University, Corvallis, Oregon.

Taylor, D. W. (1948). *Fundamentals of soil mechanics*, John Wiley and Sons, Inc., New York, New York.

Terzaghi, K. (1943). *Theoretical soil mechanics*, John Wiley and Sons, Inc., New York, New York.

USACE. (1990). "Engineering and Design, Settlement Analysis, Engineer Manual 1110-1-1904." Department of Army, U.S. Army Corps of Engineers, Washington, D.C.

USN. (1971). "Design manual: Soil mechanics, foundations, and earth structures. NAVFAC DM-7." United States Department of the Navy, Naval Facilities Engineering Command, Washington, District of Columbia.

Yapp, M. T., Steward, J., and Whitcomb, W. G. (1991). "Existing methods for the structural design of aggregate road surfaces on forest roads." *Fifth International Conference on Low-Volume Roads, Transportation Research Record 1291*, National Research Council, Volume 1, 41-57.

Zergoun, M., and Vaid, Y. P. (1994). "Effective stress response of clay to undrained cyclic loading." *Canadian Geotechnical Journal*, 31(5), 714-727.

CHAPTER 4: REDUCING SEDIMENT PRODUCTION FROM FOREST ROADS DURING WET-WEATHER HAULING

Introduction

Roads play a key role in forest management by allowing access to and transportation of resources. Forest roads in Pacific Northwest states are often constructed with a layer of unbound aggregate over a subgrade of native soil. Drainage is provided for the roads with features such as ditches, rolling dips, culverts, and bridges. Although forest roads are vital to forestry operations, they have environmental impacts.

The surface of a forest road is often compacted, by design, to improve the load bearing performance of the road. This decreases the permeability of the road surface, which causes surface runoff. Forest roads are built with soil and aggregate that contains fine sediment that can be eroded with road use. Traffic detaches fine sediment from the road surface and makes it available for transport. Forest roads may be connected hydrologically to streams through drainage features where road runoff enters the stream. Through the production and transport of fine sediment, wet weather use on forest roads can be a source of turbidity and fine sediment in streams. This fine sediment, in turn, may be detrimental to aquatic organisms especially salmonids.

Forest roads produce sediment from three different processes. Fine sediment is available in the surface aggregate at construction, especially for well-graded aggregate. Fine sediment is produced from the mechanical degradation of the surface aggregate under traffic loading (Foltz and Truebe 1995). Finally, fine sediment is available in the subgrade and is hypothesized to move through the aggregate layer with repeated loading during wet conditions (Koerner 1998). This process is termed “subgrade mixing” for this manuscript. No research has been conducted to ascertain the origin of fine sediment in road runoff; however it is commonly assumed that the subgrade is a major source.

Regulations that govern the use of forest roads during wet weather in the western United States have become increasingly restrictive to protect water quality. As a result, road managers are interested in ways to reduce the production of fine sediment from forest roads without significantly curtailing opportunities to haul logs. Current methods of design for unbound aggregate roads consider load support and do not consider the production of fine sediment. Road managers have made improvements to the road surface to reduce the production of fine sediment. These improvements include increased quality and/or quantity of surface aggregate, addition of chemical stabilizers, geosynthetic reinforcement, and reduced tire pressure of vehicles that traffic the road. While these changes to road design or use may reduce the production of fine sediment from roads, simply making these changes does not allow road managers to know the actual environmental benefits they achieved or to understand the tradeoffs with forgone productivity.

The goal of this research was to evaluate the environmental benefits, in terms of sediment production, of upgrading forest roads to reduce or eliminate subgrade mixing during wet weather hauling. The research project had three objectives: 1) to develop and test alternative designs for pavement structures for unbound aggregate roads that minimize the production of fine sediment from the road during use in wet weather. Emphasis was placed on designs that would minimize the production of fines from the subgrade as a source of sediment; 2) to investigate the role that aggregate quality plays in the generation of sediment from the road surface during use in wet weather; and 3) to compare the cost of the alternative designs for unbound aggregate pavement as installed with the savings in sediment from the road surface.

Background

Forest roads are described as non-point sources of pollution because they are a source of sediment in streams (Binkley and Brown 1993). Bilby (1985) found that the majority of sediment, 80 percent by weight, produced by the road were less than 0.004 mm in diameter. Fine sediment that enters the stream from a road may become suspended or be stored in the stream, thus could harm water quality and aquatic organisms. Fine sediment can clog the gills of aquatic organisms, reduce light available for photosynthesis, and interfere with the foraging success of aquatic organisms (Davies-Colley and Smith 2001; Gordon *et al.* 1994). Increased sediment in streams is particularly harmful to salmonids that are listed as endangered or threatened in the Pacific Northwest. In reviews of the effects of forest management on salmonid production, Furniss *et al.* (1991) and Everest *et al.*(1987) stated that increased sediment from forest roads can adversely affect all freshwater stages of salmonids. Fine sediment can impact salmonid habitat and survival and the emergence and growth of salmonid embryos and fry (Everest *et al.* 1987).

Regulations that govern forest practices in the timber producing states in the western United States are increasingly restrictive in order to protect water quality and salmonids. The most recent changes to regulations in California (CDF&FP 2004), Washington (WSDNR 2006), and Oregon (ODF 2003) have come in the past five years after recommendations from boards of review. Monitoring efforts continue (Ice *et al.* 2004) and with further review it is likely that state regulations will become even more restrictive. With the current increases in restrictions on log hauling in wet weather and the suggestion of further restrictions to come, it is important that the people who build and manage road systems understand the available options for alternative road designs that may minimize sediment production and the trade-offs and costs to install them.

Sediment Production from Forest Roads

The effect of forest roads on water quality depends on the amount of erosion and the degree of connectivity between the road and the stream (Novotny and Chesters 1989). The amount of erosion attributed to forest roads has been quantified by numerous studies (see Croke and Hairsine 2006; Fransen *et al.* 2001; Furniss *et al.* 1991). Early research focused on landscape effects of roads through road construction and mass movement of road material (Brown and Krygier 1971; Hoover 1952; Reinhart *et al.*1963), but recent studies have focused more directly on the contribution of surface erosion from the road prism (Bilby *et al.* 1989; Chappell *et al.* 2004; Luce and Black 2001).

The construction of forest roads results in soil disturbance. The effects of road construction on accelerated erosion is well documented by the paired watershed studies at Caspar Creek in northern California, H. J. Andrews Experimental Forest in the Oregon Cascades, and the Alsea Watershed Study in the Oregon Coast Range (Brown 1972; Burns 1972; Fredriksen 1970).

The contribution of road construction to accelerated erosion was quantified during the late 1960's and early 1970's at the Caspar Creek Paired Watershed Study in northern California. Roads were constructed and the timber was harvested in the South Fork of Caspar Creek 1960s. The North Fork Caspar Creek was left untreated as the control (Burns 1972). In the 1990s, the roles for the watersheds were reversed and roads were constructed and timber was harvested from the North Fork Caspar Creek while the South Fork Caspar Creek was the control watershed. Road construction and harvest was carried out using the California Forest Practice Rules (Lewis 1998). Immediately after road construction in the South Fork, Burns (1972) noted an increase in fine sediment and a decrease in salmonids. When the results from the 1960's and 1990's treatments were compared, Keppeler *et al.* (2000) reported that the suspended sediment load increased by 331 percent compared with the control watershed during the early study but increased only 89 percent in the later study. The difference in results was attributed to the use of best management practices (BMP's) for the placement and construction of new roads and harvesting methods (Lewis 1998).

To address the effects of harvesting with road construction and harvesting alone, researchers at the H.J. Andrews Experimental Forest studied three small watersheds. During the 1960s HJ1 was clearcut without roads, HJ2 was the control, and HJ3 was patch-cut (25% of basin area) with roads (6% of basin area) (Fredriksen 1970). Fredriksen (1970) found that during the first fall storm after road construction, sedimentation increased 250 times relative to the control. Grant and Wolff (1991) calculated a production of 21,000 t/km^2 of sediment from the roaded watershed compared to 800 t/km^2 from the control over a thirty-year period following the study. Forest management, including road building, increased the occurrence of landslides about five times relative to similar but forested areas (Swanson and Dyrness 1975). Overall, the greatest soil loss was associated with landslides and 90

percent of the eroded material originated from road fills suggesting that road failures were the source of a majority of the sedimentation (Grant and Wolff 1991).

The objectives of the Alsea Watershed Study were to compare the impact of two patterns of clearcutting on water yield, water quality, and fishery resources (Brown 1972). There were three study watersheds, Needle Branch was clear-cut, Deer Creek was 25 percent patch-cut, and Flynn Creek was the control (Brown and Krygier 1970). Roads were constructed on the treatment watersheds (Needle Branch and Deer Creek) a year before harvest. Annual sediment yield increased significantly after road construction in both the treatment watersheds and doubled in one (Brown and Krygier 1971). At the end of the study, Beschta (1978) concluded that landslides from the roads were the predominate source of accelerated erosion and hypothesized that the landslides were due to the decay of organic material buried in road fills during the construction of the roads.

Paired watershed studies outside of the northwestern United States describe accelerated erosion in conjunction with harvest activities that include the construction and use of roads. Reinhart *et al.* (1963) reported an increase in turbidity of 56,000 ppm in a clearcut with roads compared to a control watershed in West Virginia. Cornish (2001) reported an increase in turbidity associated with the construction and use of forest roads in watersheds in Australia. Anderson and Potts (1987) reported that suspended sediment increased 7.7 times in the first year after road construction in a watershed in Montana. Hoover (1952) reported an increase in turbidity of more than 6900 ppm in a logged and roaded area over an adjacent area that was left undisturbed in Coweeta, a research forest in North Carolina.

Rice *et al*. (1972), in a review on the erosional consequences of timber harvesting, reported that during timber harvest, “the severe disturbance caused by road construction is the most important source of sediment.” A similar review of research on the effects of timber harvest on water quality concluded that road construction increased suspended sediment in streams, but the amount of suspended sediment differed substantially by geographic location (Binkley and Brown 1993). Roads associated with different types of harvest systems also produce varied results. Jammer logging, which required a dense network of roads, increased sediment production 750 times over the natural rate while a neighboring skyline system that used existing roads only increased sediment production 1.6 times (Megahan and Kidd 1972).

Forest roads are prone to landslides because road construction creates locally over-steepened fill- and cutslopes and road drainage concentrates road runoff on hillslopes. Fransen *et al.* (2001) stated that road-related landslides contribute up to 3 orders of magnitude more sediment to streams than road surface erosion. Fredriksen (1970) measured sediment yield from three watersheds for ten-years. He reported that landslides were the major source of sediment in streams and landslide occurrence was

more frequent where logging roads intersected stream channels (Fredriksen 1970). Landslides from forest roads are bigger and travel farther than landslides from similar forested terrain. Swanston and Swanson (1976) found that erosion from landslides was 25 to 340 times greater in roaded areas compared with areas without roads. In a landslide inventory following a landslide producing storm in 1996, landslides associated with roads were, on average, four times larger than landslides that were not associated with roads (Robison *et al.* 1999). During one landslide producing storm in 1964, 90 percent of the volume of material moved by landslides originated from road fills (Grant and Wolff 1991).

Road drainage structures concentrate road runoff at discrete locations on the fill slope. Furniss *et al.* (1991) stated that road runoff and poor road location are landslide threats. Skaugset and Wemple (1999) reported that approximately half of the landslides that initiated from forest roads occurred at road drainage locations. Montgomery (1994) reported that roads influenced the distribution of erosion processes and asserted that they concentrated water into unstable hollows. Contemporary practices of road construction can reduce the risk of road related landslides. Sessions *et al.* (1987), found that forest managers are aware of the landslide hazards represented by roads and since the mid-1970s road construction and maintenance practices have improved and the subsequent risk of landslides was reduced.

While contemporary practices of road construction may reduce the amount of accelerated erosion from new roads, the environmental effects of existing or 'legacy' roads may cause the most concern at present (Skaugset *et al.* 2002). The road prism, which is the road running surface, fill slope, and cutslope with the adjoining ditch, is hypothesized to be a chronic source of erosion. Landslides are the dominant erosion process associated with forest roads (Beschta 1978; Mills 1997), however Furniss *et al.* (1991) argue that chronic surface erosion from the road prism is just as important as erosion from landslides because surface erosion contributes finer particles. Recently researchers have focused on surface erosion from the road prism. A summary of research projects that have focused on the production of surface erosion from the road prism is presented in Table 4.1.

The forest road is connected to the stream network through roadside ditches, gullies, and locations where the road crosses a stream (Wemple 1994). This connectivity allows surface runoff with suspended sediment to enter the stream. Measurement of the length of forest roads connected to streams on Oregon and Washington forest land ranged from 31 to 75 percent of the road system and depended on the location and age of the road network (Bilby *et al.* 1989; Reid and Dunne 1984; Skaugset and Allen 1998; Wemple *et al.* 1996).

Table 4.1 Review of research that has focused on the production of sediment from the road prism.

Study	Road location	Factors that contributed to sediment production from the road
Amann (2004)	Oregon Coast Range, USA	Cumulative runoff
Bilby *et al.* (1989)	Western Washington, USA	Traffic rate, depth and type of surface aggregate
Coker *et al.* (1993)	Queen Charlotte Forest, NZ	Traffic rate
Dent *et al.* (2003)	Western Oregon, USA	Traffic rate, depth of surface aggregate, length of road segment, percent of fines in the aggregate
Foltz and Truebe (1995; 2003)	Western Oregon, USA	Aggregate quality, percent of fines in the aggregate
Foltz *et al.* (1991), Foltz and Burroughs (1990)	Idaho, Montana, and Colorado, USA	Rutting, time since disturbance
Haupt (1959)	Idaho, USA	Road slope, length of road segment
Luce and Black (1999; 2001)	Oregon Coast Range, USA	Road slope, length of road segment, time since disturbance
MacDonald *et al.* (2001)	St John, US Virgin Islands	Total storm precipitation, precipitation intensity, storm runoff, traffic rate
Mills *et al.* (2003)	Western Oregon, USA	Three-day precipitation totals, aggregate size distribution, length of road segment
Packer (1967)	Idaho, USA	Aggregate size distribution, road slope, topographic position
Reid and Dunne (1984)	Western Washington, USA	Traffic rate
Wald (1975)	Western Washington, USA	Traffic rate, cumulative rainfall, road maintenance
Ziegler *et al.* (2000; 2001)	Northern Thailand	Traffic rate, time since disturbance, road maintenance

The volume of sediment produced from the road surface is highly variable. Precipitation characteristics, aggregate surfacing, road shape and attributes, road use and maintenance, and age of the road influence the amount of sediment generated from the road prism (Foltz and Truebe 1995; Luce and Black 1999; Luce and Black 2001; MacDonald *et al.* 2001; Reid and Dunne 1984). These characteristics vary across watersheds, regions and between storms.

An increase in the sediment content of runoff from the road prism is reported to be related to rainfall intensity (Dent *et al.* 2003; MacDonald *et al.* 2001), antecedent and storm precipitation (MacDonald *et al.* 2001; Mills *et al.* 2003), runoff volume (Amann 2004; MacDonald *et al.* 2001; Wald 1975), and rainfall and runoff erosivity (Egan 1999). In coastal Oregon, intense rainfall more than doubled the sediment content of runoff from the roads compared with less intense rainfall (Dent *et al.* 2003). This is most likely due to increased kinetic energy in the rain thus more energy is available to detach soil particles (Forman *et al.* 1993). In the US Virgin Islands, sediment production from a road surface was significantly correlated with total storm rainfall and rainfall intensity (MacDonald *et al.* 2001). Mills *et al.* (2003) found that significant increases in turbidity from road runoff were correlated with three-day precipitation totals between 3.8 and 7.6 cm (1.5 and 3.0 in). In Washington, Wald (1975) correlated cumulative rainfall to sediment volume in the runoff and attributed 53 percent of the variance in suspended sediment concentrations from a road to cumulative rainfall and truck traffic. Egan (1999) argued that the variables in the Universal Soil Loss Equation, which includes the rainfall erosivity index, R, are the most important to consider to minimize soil loss from a road prism.

The structure of the road is important to sediment production as well. Compaction of the road surface, depth and quality of surface aggregate, volume of fines in the surface aggregate, degree of vegetation on the road surface, and the texture of the subgrade all influence the production of sediment from the road surface. The running surface of the road is often compacted, by design, to improve the load bearing performance of the road surface. However, compaction results in a lower infiltration rate for the road surface than for the soils on the adjacent hillslopes. Ziegler and Giambelluca (1997) found that the saturated hydraulic conductivity of the road surfaces was approximately one order of magnitude lower than the saturated hydraulic conductivity for soil in nearby forests, agricultural fields, or roadside areas. They reported a significant portion of rain that fell on roads in Thailand did not infiltrate into the road surface during most storms due to lower saturated hydraulic conductivities (Ziegler and Giambelluca 1997). Marbet (2003) measured infiltration capacities of 2 to 9 mm/hr on road surfaces in western Oregon. With infiltration capacities of the surface of the road less than rainfall rates, roads produce more frequent surface runoff.

Forest roads built for all-weather use are constructed with a pavement of unbound aggregate over a subgrade of native soil (Kramer 2001). The depth, quality, and size distribution of the surface

aggregate influences the production of sediment from the roads. Bilby *et al.* (1989) reported that roads with a thicker aggregate layer produced less sediment. Dent *et al*. (2003) reported that turbidity values increased as surface aggregate became shallower. Foltz and Truebe (1995) reported that aggregate quality was important in the production of fine sediment from roads. Marginal quality aggregate produced 2.9 to 12.8 times more sediment than was produced from good-quality aggregate. Packer (1967) reported that the size distribution of aggregate played an important role in the production of sediment from road surfaces. Foltz and Truebe (2003) studied eighteen aggregates and concluded that the best predictor of sediment production was the percentage of the aggregate that had a diameter smaller than 0.6 mm. Mills *et al.* (2003) reported on the importance of the aggregate size distribution on the generation of fine sediment from forest roads. A significant increase in turbidity was observed for runoff from roads with surface aggregate where more than 7 percent of the aggregate had a diameter smaller than 0.075 mm (Mills *et al.* 2003).

The condition of the subgrade soil may also play a role in the production of fine sediment from forest roads. In a study of seventy-four plots along forest roads in the Oregon Coast Range, Luce and Black (1999) reported that roads constructed in coarse soils produced less sediment than roads constructed in fine soils. Elliot and Tysdal (1999), in a comparison of estimates from an erosion model with observed values of runoff and erosion from forest roads, suggested that soil type was a driving factor in sediment production from roads. Swift (1984a) reported more soil loss from roads constructed on a subgrade of clay loam (CL in the Unified Classification System (ASTM 1999)) than from roads constructed on a subgrade of sandy loam (SM in the Unified Classification System).

The running surface on a forest road is constructed with a slope to allow surface runoff to drain. The cross-section of a forest road can be insloped, to direct runoff to the inside of the road, outsloped to direct runoff to the outside of the road, or crowned to direct runoff in both directions away from the centerline (Kramer 2001). The insloped and crowned cross-sections require an inboard ditch and drainage features to remove runoff from the road to the downslope side of the road. The design cross section and the drainage features of the road affect the connectivity between the road and the stream.

The design and spacing of drainage structures on a forest road affects sediment production from the road. The distance between drainage structures such as ditch-relief culverts or rolling dips on a road with a ditch influences sediment production from the road (Dent *et al.* 2003; Elliot and Tysdal 1999; Haupt 1959; Luce and Black 1999; Mills *et al.* 2003). Longer segments of road allow for a greater volume of runoff to move fine sediment off the road.

An increased gradient of the road and the adjoining ditch increases the velocity of the runoff and thus the energy available to transport sediment (Haupt 1959; Packer 1967). Sediment production

from roads is directly correlated with road gradient (Egan 1999; Elliot and Tysdal 1999; Haupt 1959; Luce and Black 1999; MacDonald *et al.* 2001; Packer 1967). However, this relationship may not always be correct. A comparison of studies on erosion from forest roads in New Zealand showed that no relationships could be inferred regarding the effect of road gradient on sediment yield (Fransen *et al.* 2001).

Other attributes of forest roads influence the sediment yield from the road. Packer (1967) reported that the topographic position of the road (upper, middle, or lower portion of a hillside) and the aspect (north or south-facing slopes) played a minor role in the production of sediment from a forest road. The condition of the surface of the road contributes to sediment production. Burroughs *et al.* (1984) reported that a road with ruts in the wheel paths produced twice as much sediment as a graded road without ruts. Foltz and Burroughs (1990) reported that forest roads that maintained their shape and did not rut did not significantly lose sediment. Beschta (1978) reported a reduction in surface erosion with revegetation of the road surface. The condition of the inboard ditch influences sediment transport because the vegetation in the ditch acts as a roughness element and reduces the velocity of the water in the ditch, which may cause some sediment to settle out of suspension. Luce and Black (1999) reported that removing vegetation from the ditch and cutslope increased sediment production by a factor of 7.4. However, Fransen *et al.* (2001) again asserted that no clear relationship could be made regarding the condition of the running surface of the road and ditch on sediment yield from the road for studies in New Zealand.

The production of sediment from a forest road is also influenced by time. Luce and Black (2001) reported that sediment yield from forest roads the first year after they were disturbed was a function of the transport capacity of the road (the length and gradient of the road segment). As the surface of the roads became armored over time, they produced less and less sediment (Luce and Black 2001). Zieger *et al.* (2000) reported that a layer of disturbed soil on a road made out of native soil in Thailand washed off the road quickly, but the underlying soil was resistant to erosion. Studies from Idaho, Montana, and Colorado emphasize the importance of time to reduce erosion from the surface of roads (Foltz and Burroughs 1990; Foltz *et al.* 1991). Foltz and Burroughs (1990) suggested that decreased sediment production over time after a disturbance was not a result of the formation of an armor layer on the road surface but a decreased supply of sediment available for transport.

Road maintenance and the use of a forest road by traffic also create disturbance on the road surface that influences sediment production from the road. Routine maintenance of the ditch and shaping the road surface by grading does not allow revegetation of these surfaces. Maintenance activities detach soil particles and make them available for transport (Croke and Hairsine 2006). Fahey and Coker (1989) suggest that grading the road surface be minimized to avoid exacerbating sediment

production. Traffic affects forest roads similarly. Ziegler *et al.* (2001) reported that traffic disturbed the road surface, and generated loose material that was subsequently eroded. Bilby *et al.* (1989) reported that the amount of sediment produced from a road segment on an hourly basis was related to rate of traffic. Many other studies have stressed the importance of traffic to sediment production (Coker *et al.* 1993; Dent *et al.* 2003; Fransen *et al.* 2001; Furniss *et al.* 1991; MacDonald *et al.* 2001; Wald 1975; Ziegler *et al.* 2000). In the Pacific Northwest, Reid and Dunne (1984) found that a road segment that was used by more than four loaded trucks per day generated 130 times the sediment of an abandoned road.

Fine sediment in road runoff originates from the road prism and an understanding regarding which part of the road produces the most sediment remains elusive. Koerner (1998) argues that sediment from the subgrade moves upward through the aggregate. Fines are also available in the material used as an aggregate pavement (Dent *et al.* 2003; Foltz and Truebe 2003; Mills *et al.* 2003; Packer 1967). Bilby *et al.* (1989) and Foltz and Truebe (1995) report that fines are produced from the breakdown of the surface aggregate. Sediment also comes from the ditch, cutslope and fillslope of the road (Burroughs and King 1989; Carr and Ballard 1980; Elliot and Tysdal 1999; Fahey and Coker 1989; Hafley 1975; Megahan *et al.* 2001; Swift 1984b). Elliot and Tysdal (1999) stressed that erosion from the cutslope is small compared with erosion from the road surface. Fahey and Coker (1989) measured sediment from plots on the road surface and on the cutslope and determined that the primary source of sediment in road runoff was from the cutbank, ditch, and fill slope rather than the road surface. Burroughs and King (1989) reported that of the total sediment produced from the road prism, 60 percent was from the fill slopes, 25 percent from the road surface, and 15 percent from the cutslope and ditch. Research has shown that sediment production from ditches, cutslopes and fill slopes can be reduced by mulch, grass seed, and natural regeneration (Carr and Ballard 1980; Megahan *et al.* 2001; Swift 1984b).

Improvements to the Road Pavement

The most common methods of design for unbound aggregate roads are the American Association of State Highway and Transportation Officials (AASHTO) method and the United States Department of Agriculture, Forest Service (USFS) method (see AASHTO 1993; Bolander *et al.* 1995). A full discussion of these methods is given in chapter 3; however it is important to note that the standard methods of design do not consider the production of sediment from aggregate surfaced roads as a design constraint. Rather, they design for a specified load failure evidenced by rut depth. The reduced stress method of design for unbound aggregate pavement presented in chapter 3 was developed to have minimal mixing of subgrade fines up into the aggregate surface and the subsequent generation

of fine sediment by the road surface. The design constraint for this method is to reduce stresses at the subgrade/aggregate interface and allow strain hardening to occur in the subgrade.

Changes in the design of the unbound aggregate pavement have been researched to improve the environmental and load-bearing performance of the road. Most of these studies measure the performance of the pavement by rut formation and depth. The performance of the road pavement can be improved by an altered depth or type of surface aggregate (Kochenderfer and Helvey 1987; Swift 1984a), addition of chemical stabilizers (Burroughs *et al.* 1984; Monlux and Mitchell 2006; Rushing *et al.* 2006), use of geosynthetics in the pavement structure (Army Corps of Engineers 1981; Bender and Barenberg 1978; Fannin 2001; Giroud and Noiray 1981; Mohney and Steward 1982), and reduced tire pressure on vehicles that traffic the road (Foltz 1995; Powell and Brunette 1991).

Unbound aggregate as a part of the structure of the road pavement reduces the production of sediment from forest roads over a surface of soil. Large differences in sediment yield were reported when the erosion loss from roads composed of native soil were compared with roads with a pavement that included unbound aggregate (Barrett and Conroy 2002; Burroughs *et al.* 1984; Day 1996; Kochenderfer and Helvey 1987). The aggregate used to surface roads may not need to be very deep to reduce erosion. Burroughs *et al.* (1984) reported that the sediment yield from a road segment was reduced by a factor of 4.3 for 10 cm of crushed aggregate surface compared to an unsurfaced road. Kochenderfer and Helvey (1987) reported that a road with 2.5 cm gravel surface reduced sediment production by 67 to 84 percent. Swift (1984a) reported greater reductions in sediment yield with increased depth of aggregate from bare soil up to 20 cm of aggregate, the greatest depth of aggregate studied. The decrease in sediment production that results from surfacing roads with aggregate is seen by improvements in water quality in the stream. Barrett and Conroy (2002) opine that the total sediment load in streams can be reduced by 50 percent by surfacing roads that are hydrologically connected to the stream system with unbound aggregate. An aggregate surface on a forest road also increases the strength of the road and its load bearing performance. Day (1996) reported that a gravel surface on the soil subgrade that was allowed to work into the subgrade increased the undrained strength of the subgrade.

The quality and size distribution of the surface aggregate also affects the environmental performance of the road. Swift (1984a) reported more soil loss from roads surfaced with crushed gneiss, where all particles had a diameter less than 3.8 cm, compared to roads surfaced with large, clean rock with an average diameter of 7.5 cm. Foltz and Truebe (2003) reported that the parent material of the surface aggregate affects the breakdown of large material and the production of fine sediment.

Sediment production from forest roads occurs during dry months in the form of dust from wind and traffic. The generation of fine sediment as dust is a loss of aggregate and subsequent deterioration

of the road surface. Chemical stabilizers bind fines together in the aggregate, retain moisture and are used to suppress dust from forest roads. Sanders *et al.* (1997) reported that lignosulfonate and chloride-based compounds reduced sediment loss from unbound aggregate roads by 55 to 66 percent. Chemical stabilizers are used for dust abatement during dry summer months. Little is known regarding their effectiveness to reduce sediment production from forest roads in wet weather. Orts *et al.* (2007) reported that an application of polyacrylamide copolymers reduced sediment runoff by 60 to 85 percent during simulated rainfall on a road cut. Burroughs *et al.* (1984) reported that sediment produced from the surface of forest roads with simulated rain was reduced by a factor of 3.2 for roads surfaced with dust oil and 28.7 for roads with a bituminous surfacing compared with an unsurfaced road. The environmental benefits gained from the use of dust suppressants in terms of reduced production of sediment may be offset by other potential environmental impacts from their use. Some chemicals used for dust abatement are able to leach from the soil with precipitation (Wu *et al.* 2007).

Geosynthetics are synthetic materials that are used in different applications to improve the performance of forest roads. Geosynthetics are used to strengthen unbound aggregate roads. They are used to separate pavement layers, reinforce the subgrade/aggregate pavement structure, and facilitate drainage (Bender and Barenberg 1978; Fannin 2001). The performance of a road strengthened with a geosynthetic is quantified by the development of ruts, deformation of the subgrade, and strain in the geosynthetic. The most common geosynthetic used in road applications is the geotextile but geocells are used to strengthen unbound aggregate roads, especially roads with weak subgrade soils.

Geotextiles are fabrics manufactured from plastics; the most common is polypropylene. Fibers are produced from the polymers through a process of spinning and melting. The type of fiber controls properties such as linear density, tensile strength, strain at breaking load, shrinkage, and creep (Van Santvoort 1994). Fibers are woven, knitted, matted, thermally-bonded, or chemically-bonded together to produce the geotextile fabric (Ingold and Miller 1988). Different types of geotextiles have different flexibility, permeability (opening size), thickness, and weight.

Geotextiles are placed between the subgrade and aggregate in unbound aggregate roads. They are used to reinforce the subgrade soil, separate the subgrade and aggregate, and drain water in plane flow from the road. Geotextiles have high tensile strength, which is useful to reinforce soils that have high compressive strength but low tensile strength. Geotextiles are flexible, which allows geotextiles to transmit a portion of their perpendicular loads along the length of the geotextile. Thus a geotextile is able to distribute vertical wheel loads over a larger area of the subgrade. Giroud and Noiray (1981) hypothesized that geotextiles can improve the bearing capacity of an unbound aggregate road by 1) distributing a greater load in the aggregate layer; 2) increasing the bearing capacity factor due to confinement of the subgrade leading to plastic rather than elastic deformation and 3) developing a

tensioned-membrane effect in the deformed geotextile when large ruts form. The improved performance of an unbound aggregate road that results from the use of a geotextile can be modeled (Giroud and Noiray 1981; Henry 1999; Milligan *et al.* 1989a; Milligan *et al.* 1989b). However, Mohney and Steward (1982) measured no strains in geotextiles placed in logging roads and suggested that the geotextile did not contribute to reinforcement of the subgrade.

A geotextile used to separate the subgrade and aggregate prevents the fine soil from the subgrade from entering the voids of the aggregate. It also keeps the aggregate from being pushed down into the soil. These actions reduce the strength of the pavement structure of the road (Koerner 1998). The geotextile also acts as a filter in an unbound aggregate road, which allows water to pass through the geotextile without passing sediment. Geotextiles have a range of hydraulic conductivities based on the manufacturing process and are designed for slow or rapid water transfer. The design of pavement structures with a geotextile must be made with particle size in mind. Geotextile openings should be small enough that fine soil particles will not pass through. Narejo (2003) reported that a geotextile must have an apparent opening size (O_{95}) of less than the 85 percent size of soil particles (D_{85}) to perform satisfactorily as a barrier to soil movement.

Geotextiles improve the performance of unbound aggregate roads regardless of the source of stabilization (reinforcement, separation, or drainage). In studies on traffic, geotextiles in unbound aggregate roads improved the strength of the road (Delmas *et al.* 1986; Potter and Currer 1981; Ramalho-Ortigao and Palmeira 1982; Webster and Alford 1978). A geotextile placed over a weak subgrade in Singapore significantly reduced rut development of an unbound aggregate road (Leong *et al.* 2000). Fannin and Sigurdsson (1996) tested sections of roads with different geotextiles and found less rut depth with thicker aggregate depth over the geotextile.

Problems encountered with geotextiles are creep, temperature and sunlight deterioration, clogged pores, and age (Ingold and Miller 1988). Creep and clogged pores can be avoided with proper design and knowledge of the soil and load conditions of the application. High temperatures and direct exposure to sunlight accelerate degradation but, again, these can be addressed in the design process. Geotextiles in road applications have only been studied for the past 30 years and while current research indicates a long life with proper use and care, further study is needed to determine the long-term effects of aging on geotextiles.

Geocells, or confinement cells, are a three dimensional geosynthetic in a honeycomb structure. The cells are filled with sand, soil, aggregate, concrete, or any combination of these and compacted to form a pavement structure with high flexural strength. Under load, the system generates high confining stresses (Flynn 1996). The confining stresses improve the shear strength of the system and increase the bearing capacity of the subgrade. Geocells are manufactured in a wide range of sizes with depths from

75 to 200 mm and diameters up to 500 mm. The increased strength provided by the geocell structure is proportional to cell depth (Koerner 1998; Visser and Hall 2003).

Geocells are a recent development in geosynthetics. The US Army Corps of Engineers first experimented with sand-filled plastic pipes standing on their ends in the early 1980's (Army Corps of Engineers 1981). The Army Corps, in conjunction with Presto Products Company, developed the geocell structure in 1985 as a means of allowing military vehicles to drive over sand. Roads reinforced with geocells were later built for military vehicles during the Persian Gulf War (Flynn 1996).

For unpaved roads, geocells improve road performance. According to Presto Products Company their product, *Geoweb,* can extend the life of a pavement from four to six years to 50 to 60 years (Presto Products Company 2003). The improved performance is attributed to the confinement of aggregate giving lateral support to the pavement layer and transmitting vertical forces through this layer rather than to the supporting subgrade. Tandem-axle trucks with 230 kN loads were tested on a road with a geocell over a subgrade road and on the subgrade alone and found only slight ruts on the geocell road after 10,000 passes compared to deep ruts after 10 passes on the subgrade road (Koerner 1998). An additional advantage of geocells in unpaved roads is that less aggregate is needed. Presto Products Company reports that pavement thickness may be reduced by 50 percent for the same structural strength of the road when using their product (Presto Products Company 2003).

The performance of unbound aggregate roads may be improved by altering traffic factors. Reduced tire pressure of vehicles that traffic the road showed improvements to the road pavement. Douglas *et al.* (2000) and Douglas (1997a; 1997b; 1999) reported that reduced tire pressures did not affect strains at the subgrade soil and only influenced the surface aggregate. Lower tire pressures distribute the load of the vehicle over a larger area and reduce loads at a single point. Powell and Brunette (1991) suggested that low tire pressure did not break down surface aggregate as quickly and thus reduced the production of fine sediment from breakdown of aggregate. Moore *et al.* (1995) reported that reduced tire pressure on vehicles from 620 to 345 kPa (90 to 50 psi) reduced sediment from the road an average of 80 percent over a three year period. Foltz (1995) reported that reduced tire pressures resulted in reduced ruts in the road surface and reduced production of fine sediment.

Improvements to road pavement and changes in traffic may reduce the environmental impacts of the road, however, all improvements cost money. Takallou *et al.* (1987) evaluated the life cycle costs of alternatives for surfacing for forest roads and reported that chemical stabilization was the least expensive alternative while crushed aggregate and geosynthetics were cost prohibitive in some circumstances. Sanders *et al.* (1997) reported that the cost in lost aggregate for an untreated road was more expensive than chemical treatments to prevent erosion. Chapter 2 of this dissertation describes the

opportunity costs available to improve the forest road as a consequence of regulatory restrictions for wet weather use.

Methods

The goal of this research was to evaluate the environmental benefits, in terms of reduced sediment production, of alternative designs for pavements structures for unbound aggregate roads used during wet weather. Three alternative designs for the pavement structure, including one developed by the author specifically to address subgrade mixing during wet weather hauling, were developed to reduce production of sediment during wet weather hauling. The alternative pavement designs, along with a standard design (control) were installed at locations in California and Oregon. Sediment production was estimated from all pavement treatments during truck traffic while simulated rainfall was applied and compared to the controls. Tests were conducted on the quality of the surface aggregate. The costs of the alternative pavements were compared with the estimated reduction in sediment from the road surface.

Research Locations

This research was replicated on three road segments that were located near Arcata, California; Manzanita, Oregon; and Molalla, Oregon. The roads were owned, constructed, and maintained by cooperators in this research project that agreed to build the roads to our specifications, however, the cooperators were allowed to use their "normal" construction and quality control practices. The roads were newly constructed and built for timber extraction. A segment of road that was 91 m (300 ft) long and had a consistent gradient was the experimental road segment for this study. The experimental road segments were constructed with an outsloped cross-section and an inboard ditch to allow intercepted subsurface flow from the hillslope to bypass the experimental road segments (Figure 4.1). Table 4.2 summarizes the characteristics of each experimental road segment. Figures 4.2, 4.3, and 4.4 show the road segments during or immediately after construction.

The first experimental road segment was located on forest land owned and managed by Green Diamond Resource Company in northern California. It was located approximately 5.3 km (3.3 miles) northeast of Trinidad, California. The average precipitation for this area is 1500 mm (58 in) a year, and occurs predominately as rainfall between October and April. A weather station maintained by the U.S. Department of Commerce, National Oceanic and Atmospheric Administration (NOAA) located nearby recorded 2439 mm (96 in) during October 1, 2005 to May 1, 2006 when the research activities took place (weather station ID: WEDC1). The road was constructed in September 2005 to extract timber

during January through April 2006. The experimental road segment had a consistent gradient of 8 percent and was located at approximately 412 m (1350 ft) above sea level.

The second experimental road segment was located on forest land owned by a private landowner but the road was administered by the Oregon Department of Forestry (ODF) as an easement. The property was located approximately 24 km (15 miles) northeast of Manzanita, Oregon. The average precipitation for this area is 2500 mm (99 in) a year and occurs predominately as rainfall between October and April. A weather station maintained by NOAA located nearby recorded 2646 mm (104 in) between October 1, 2006 and May 1, 2007 when the research activities took place (weather station ID: SFKO3). A forest road was constructed in September 2006 to extract timber during December 2006 through April 2007. The experimental road segment had a consistent gradient of 8 percent and was located at approximately 190 m (625 ft) above sea level.

The third experimental road segment was located on forest land owned and managed by Port Blakely Companies. This property was located approximately 11 km (7 miles) south of Molalla, Oregon. The average precipitation for this area is 1420 mm (56 in) a year and occurs predominately as rainfall between October and April. A weather station maintained by NOAA located nearby recorded 1017 mm (40 in) between October 1, 2006 and May 1, 2007 when the research activities took place (weather station ID: C1855). A forest road was constructed along an existing railroad grade in August 2006 to extract timber during April and May 2007. The experimental road segment had a consistent gradient of 6 percent and was located at approximately 335 m (1100 ft) above sea level.

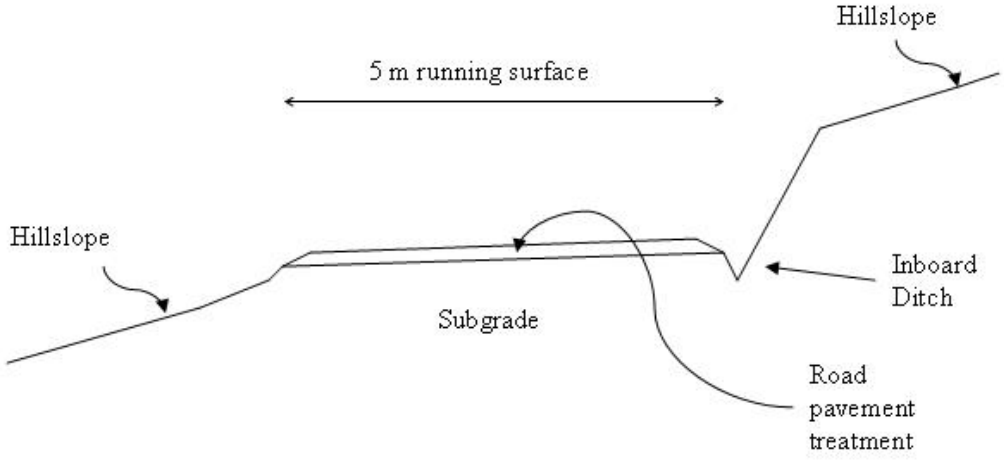


Figure 4.1 Cross section of an experimental road segment.

Table 4.2 Characteristics of the experimental road segments.

Nearest Town	Name	Precipitation during winter of research (mm)	Elevation above sea level (m)	Average road gradient (%)
Arcata, California	Crannell	2439	412	8
Manzanita, Oregon	South Burma	2646	190	8
Molalla, Oregon	Molalla	1017	335	6

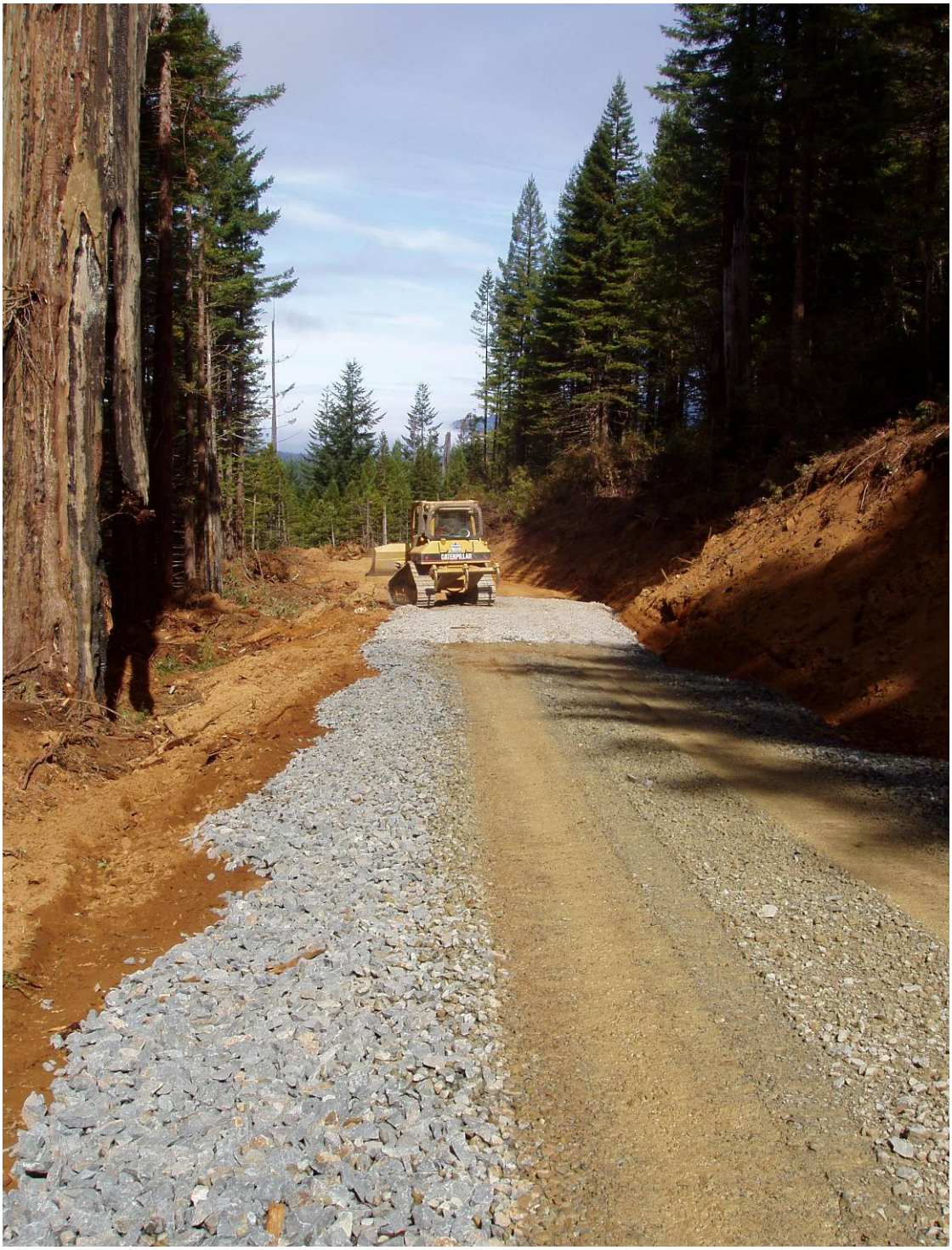


Figure 4.2 Experimental road, "Crannell," located outside of Arcata, California during construction, September 2005.

Figure 4.3 Experimental road, "South Burma," located northeast of Manzanita, Oregon after construction, September 2006.

Figure 4.4 Experimental road, "Molalla," located outside of Molalla, Oregon after construction, August 2006.

Experimental Design

Experimental sections of road were constructed and tested to meet three objectives: 1) to develop and test alternative designs for pavement structures of unbound aggregate to reduce the generation of fine sediment from the road during log hauling in wet weather with emphasis placed on reduction of fines from the subgrade as a source of sediment; 2) to investigate the role that aggregate quality plays in the generation of sediment from the road surface during log hauling in wet weather; and 3) to compare the cost of the alternative designs for unbound aggregate pavement as installed with the reduction in sediment from the road surface.

A standard (control) design for a pavement structure with unbound aggregate roads was required to compare the alternative designs to. A standard design of 20 cm (8 in) of open-graded, aggregate as a base layer and a cap of 3 to 5 cm (1 to 2 in) of well-graded, crushed aggregate with a diameter up to 3.8 cm (1.5 in) was chosen as a result of discussions with industrial forest land managers throughout the Pacific Northwest (Figure 4.5). This design was the control and was standardized across all of the experimental road segments. Two sections of the control treatment were constructed at each experimental road segment.

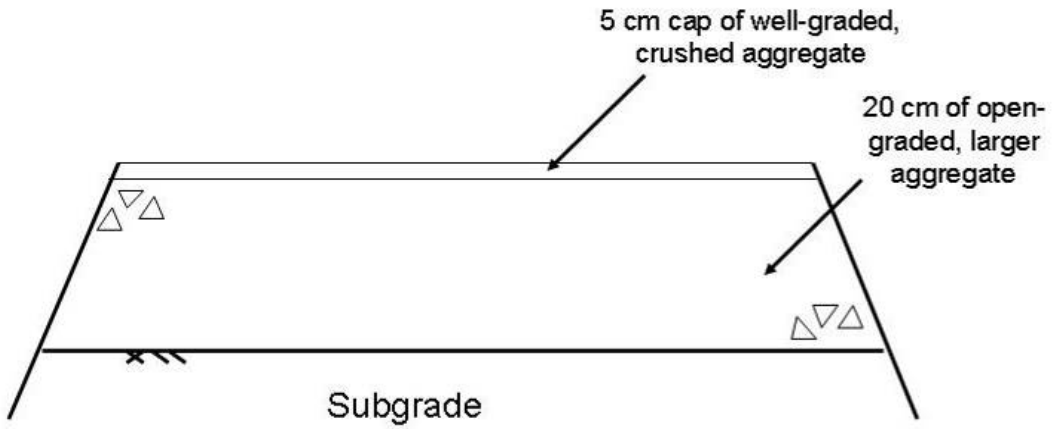


Figure 4.5 Design of the control treatment.

Research objective 1: To develop and test alternative designs for pavement structures for unbound aggregate roads that reduce the generation of fine sediment from the road surface during log hauling in wet weather with emphasis placed on reduction of fines from the subgrade as a source of sediment.

Three alternative designs for pavements structures for unbound aggregate were developed to reduce the production of sediment from the road surface with emphasis placed on reduction of subgrade mixing. The sediment produced from the alternative designs for pavement structures were compared with the sediment produced from the control design. The statistical design was a repeated control block design with two sections of the control design and three treatment sections, or sections with the alternative designs, at each experimental road segment.

The subgrade as a source of fine sediment brought to the road surface can be contained by separating the subgrade from the aggregate layer with a geotextile or by reducing loads due to traffic on the subgrade/aggregate interface (Koerner 1998). One treatment or one of the alternative designs for the pavement structure was the same design as the control but a geotextile was placed between the subgrade and aggregate to maintain separation of these materials (Figure 4.6). The geotextile is hypothesized to be a barrier to fine sediment movement from the subgrade into the aggregate by the action of the traffic loads. This treatment was labeled “geotextile.” A second treatment or a second alternative design for the pavement structure was similar to the control but had a greater depth of base aggregate (Figure 4.7). The depth of base aggregate was calculated to eliminate bearing capacity failures at the subgrade/aggregate interface and that depth was calculated using the reduced stress method presented in Chapter 3. This treatment reduces loads at the subgrade/aggregate interface from traffic to less than 50 percent of the monotonic shear strength of the subgrade soil through the increased the depth of aggregate. This treatment was labeled “more rock.” The third treatment or the third alternative design for the pavement structure was a geocell pavement structure that consisted of a geotextile over the subgrade, a geocell layer backfilled with well-graded aggregate with a maximum diameter of 4 cm, and a top layer of 13 cm of the same aggregate (Figure 4.8). The geocell structure was designed to reduce pressure at the subgrade/aggregate interface and separate the subgrade and aggregate to prevent mixing of the subgrade. The technical overview and design calculations for the geocell structure are presented in Appendix A. This treatment was labeled “geocell.”

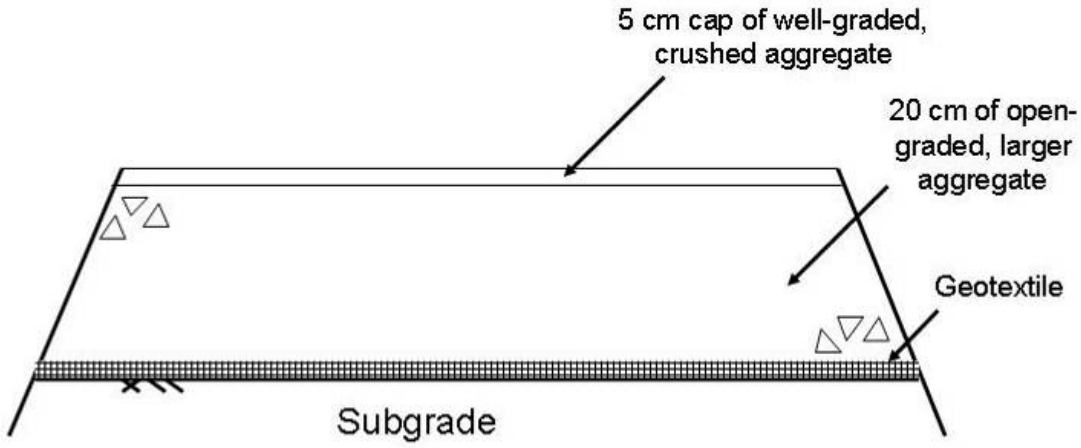


Figure 4.6 Design of the geotextile treatment.

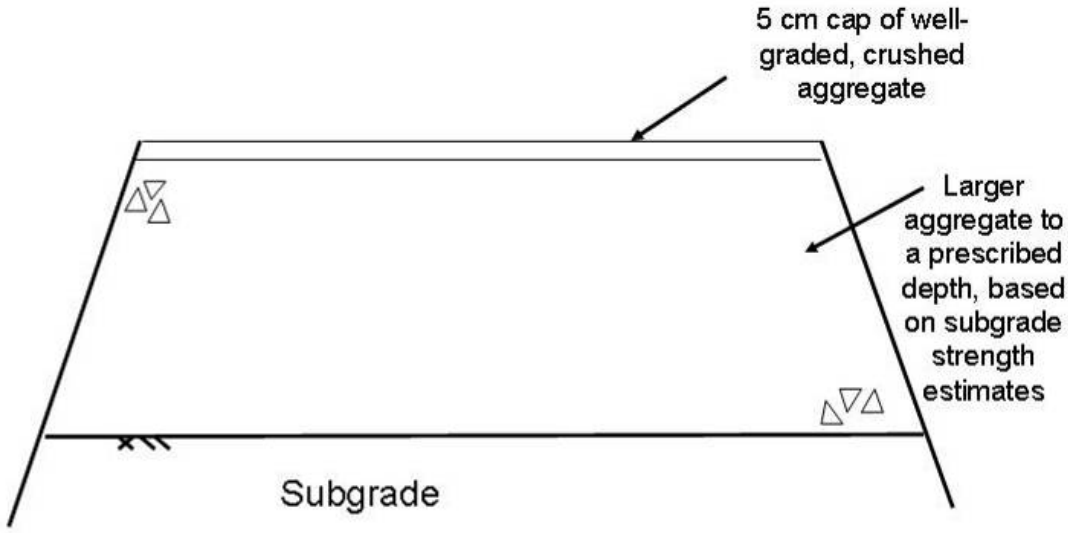


Figure 4.7 Design of the more rock treatment.

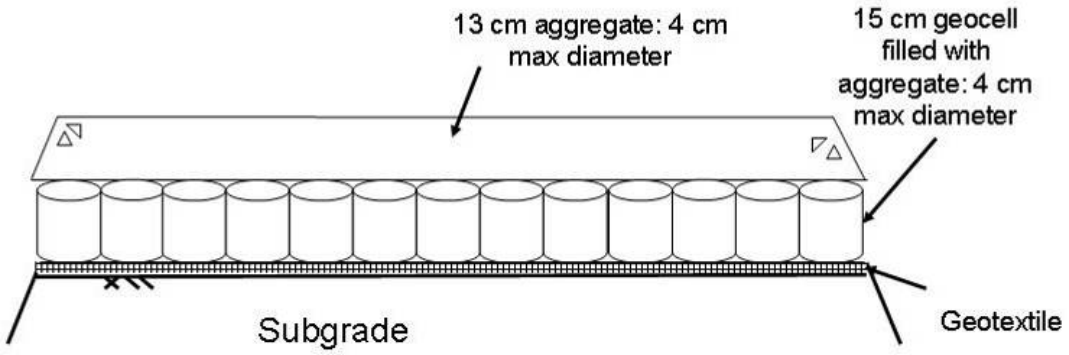


Figure 4.8 Design of the geocell treatment.

The two control and three treatment sections were assigned randomly to neighboring 18 m sections of the experimental road segment at each study location. The geocell material was not available when the Crannell road was constructed so a second geotextile treatment was installed in place of the geocell treatment. The contractor that built the South Burma road began construction and rocking on two treatment sections before approval from the Oregon Department of Forestry, so these sections were changed to control treatments to account for this mistake. The Molalla road used only one smaller size of aggregate (max diameter 3.8 cm) for entire depth of the aggregate because of the source of rock for this road. Table 4.3 shows the assignment of treatments to sections of the experimental road segments in order of decreasing elevation. The road grade was adverse for the Crannell and Molalla roads so the loaded truck traffic traveled from sections E to A and the grade was favorable for the South Burma road so the loaded trucks traveled from A to E.

Table 4.3 Randomized assignment of treatments to sections of the experimental road segment at each study location.

	Treatment Sections				
	A	**B**	**C**	**D**	**E**
Crannell	Control	Geocell (Geotextile)	Geotextile	Control	More Rock
South Burma	Geocell	Geotextile	More Rock	Control	Control
Molalla	Control	Geotextile	Geocell	Control	More Rock

The treatments were separated by waterbars constructed from conveyor belts and these structures were also used to facilitate the collection of surface runoff from each treatment (Figure 4.9). The wood beam with the conveyer belt material attached was buried in the road so that 5 to 10 cm of the conveyer belt stuck out of the road pavement. The waterbars were put in place during road

construction at the Molalla site and after road construction at the Crannell and South Burma site with an excavator and/or a small tractor. The waterbars were placed at a 60 degree angle to the road in the direction of surface flow to direct surface runoff toward the ISCO water samplers and also for greater traveling comfort for traffic using the road. Upon completing the first replication at Crannell, it was clear that the waterbars provided a discontinuity in the surface aggregate and facilitated infiltration of the surface runoff into the aggregate and underneath the waterbar. Subsequently, the waterbars for the South Burma and Molalla experimental road segments were constructed with a geomembrane "bib" that was attached to the wood beam and extended approximately 1 m upslope of the waterbar and underneath the aggregate (Figure 4.10). The geomembrane was an impermeable, flexible, sheet of plastic 2 mm thick. The geomembrane intercepted surface runoff that infiltrated the surface aggregate at the waterbars and directed it off the road.

Figure 4.9 Picture of a rubber waterbar with geomembrane bib during the installation process.

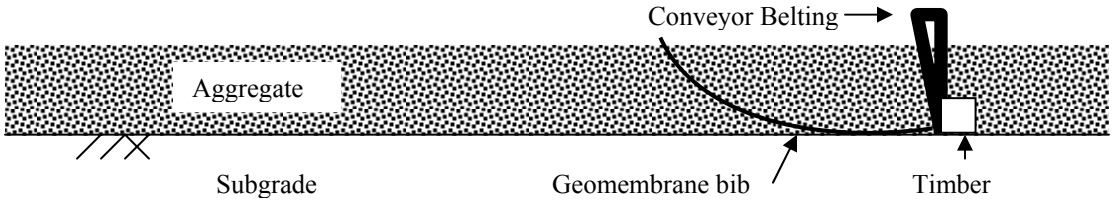


Figure 4.10 Schematic of a rubber waterbar installed in an unbound aggregate pavement with a geomembrane bib.

The experimental road segments were constructed to be hauled on over one winter. Data collection was scheduled to sample changes in sediment generation as a function of time and cumulative traffic. Data collection consisted of applying simulated rainfall to the segment of experimental road while loaded log trucks traversed the road. Runoff generated as a result of the simulated rainfall during log hauling was collected from each treatment. Ideally, runoff data was collected at the beginning, middle, and end of hauling to allow for repeated measures in the statistical analysis. Because of difficulties in coordination and logistics between the landowners, contractors, and researchers, ideal data collection was not always possible. Data collection took place February 15-17, 2006 after 145 loaded truck passes and April 6-7, 2006 after 276 loaded truck passes at the Crannell road. Data collection took place January 24, 2007 after 852 loaded truck passes, February 22, 2007 after 1177 loaded truck passes, and March 20-21, 2007 after 1435 loaded truck passes at the South Burma road. Data collection took place April 25, 2007, May 2, 2007, and again May 10, 2007 after a total of 203 loaded truck passes at the Molalla road.

Surface runoff on the road was sampled with ISCO automatic water samplers (Teledyne Technologies). The intake for the ISCOs was placed such that a sample of surface runoff running down the road could be collected. The ISCOs collected 200 mL samples at 5 minute intervals (4 minute interval for Crannell) for a period of time before the trucks passed until such time after the truck passed that the surface runoff cleared to a background condition. Water samples were stored in airtight, polypropylene bottles at 4 ºC until they were analyzed.

A sprinkler system was used to provide the simulated rainfall. The sprinkler system consisted of Rain Bird 3500 Series Rotor sprinkler heads spaced 4.5 m apart along the length of the experimental road segment. The # 0.75 nozzle size was used with the sprinkler heads to provide a sprinkling radius of 4.5 m and a precipitation rate of 11.7 mm/hr. The flow rate at each of the 21 sprinkler heads was approximately 2.0 L/sec (0.54 GPM). The sprinkler heads were connected to a 45 m section (11 sprinkler heads) and a 41 m section (10 sprinkler heads) of garden hose with a 19 mm diameter. The

water supply was provided by water trucks with a pump for the sprinkler system. The garden hose was connected to the pump with fire hose. Three tipping bucket rain gauges measured total precipitation on the road surface at the Crannell road. These were placed out of the way of traffic and the raingauge orifice was too high above the road surface to capture much of the simulated rainfall. The tipping-bucket rain gauges were replaced with small, wedge rain gauges at the South Burma and Molalla roads. Fifteen wedge rain gauges were placed down the center of the road between the wheel tracks (Figure 4.11). The wedge rain gauges were kept upright by connecting them to rectangular blocks of polypropylene outdoor carpet with Velcro® fabric hook and loop fasteners. The carpet eliminated raindrop splash. Figure 4.12 shows the layout of the data collection equipment that includes waterbars and the ISCO's on pavement treatments A through E at each experimental road segment.

The precipitation rate for the sprinkler system was chosen to simulate a sub-annular rain event in the Pacific Northwest that would produce runoff on the road surface. Although a sub-annular event varies in intensity and duration for the three experimental locations, one representative rate was required as the sprinkler system was not easily adjusted and calibrated for different precipitation rates. Intensity-duration curves for precipitation in the central Oregon Coast Range were used as a reference (Figure 4.13). The intensity-duration curves were average values from a network of 13 rain gauges in the region (Goard 2003). The average annual precipitation for the area covered by the rain gauges was between 2,032 and 4,318 mm. The average precipitation intensity for a 2-hour event at the 2-year return interval using this reference was 13 mm/hr. Sprinkling experiments were estimated to last approximately 2-hours and so the precipitation rate of 11.7 mm/hr given by the # 0.75 nozzle adequately simulated a sub-annual rain event for the area covered by the rain gauges. Precipitation rates for the Crannell and South Burma research locations should be similar to those given by the rain gauge network in the central Oregon Coast Range. Precipitation rates for the Molalla location are likely less than those of the central Oregon Coast Range as the average annual precipitation is much lower.

Figure 4.11 Wedge gauges measured precipitation down the center of the experimental roads.

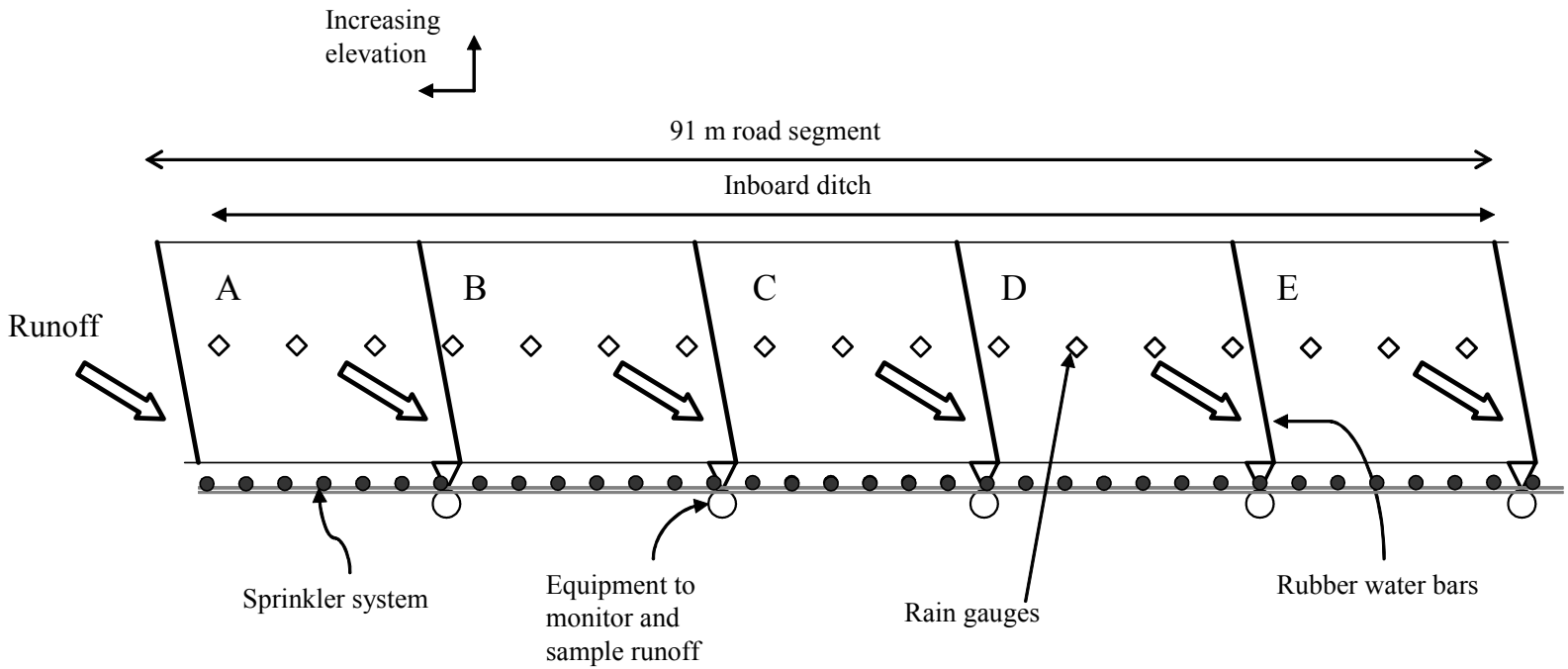


Figure 4.12 Experimental setup at each experimental road segment.

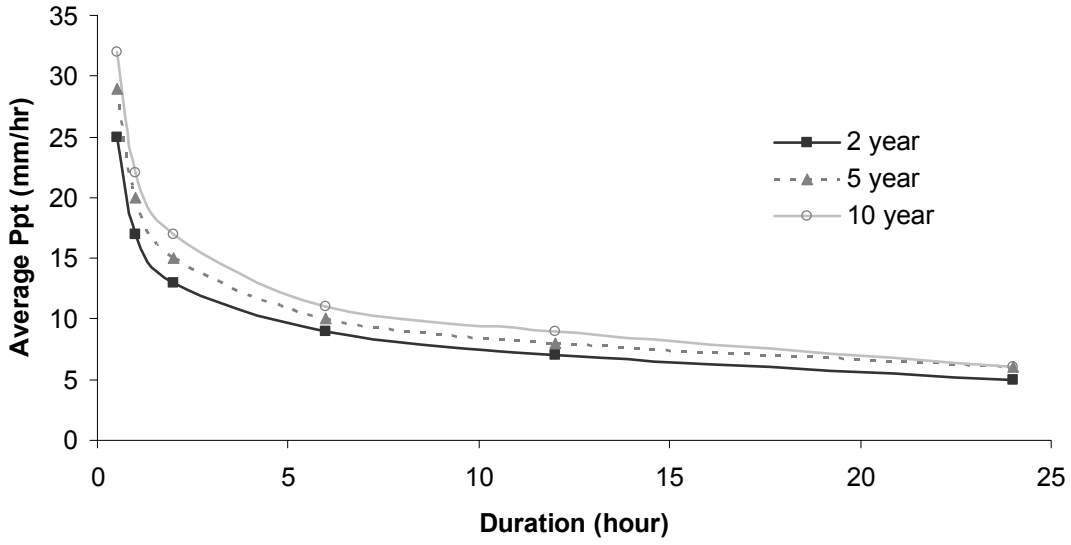


Figure 4.13 Intensity-duration curves for 2, 5, and 10-year return interval precipitation events in the Oregon Coast Range near Corvallis, Oregon.

Log trucks drove over the experimental sections of road when they came to the harvest unit (unloaded) and then left the harvest unit (loaded). The number of trips of loaded log trucks were counted until logging in the harvest unit was completed. Each land-owner (Green Diamond Resources, Oregon Department of Forestry, Port Blakely Companies) kept track of the number of loads with weigh station tickets. Most of the log trucks were conventional 5-axle single-trailer trucks (Federal Highway Administration vehicle class 9). Occasionally, short log trucks or 7-axle double-trailer trucks were used (vehicle class 13). Every vehicle had a maximum gross weight of 36,000 kg (80,000 lb). Only the number of trips of loaded trucks was counted and the number of trips was not stratified by the type of truck.

The samples of surface runoff were analyzed for turbidity and suspended sediment concentration (SSC). Turbidity was measured in nephelometric units (NTUs) with a Hach turbidimeter. When turbidity values were too high for the turbidimeter to measure, the samples were diluted using standard methods and turbidity was back-calculated. Turbidity was measured for every sample of surface runoff. SSC was measured using standard methods described in appendix B. Organics were not separated, thus SSC includes organic and inorganic components. SSC analysis was expensive and time-consuming and it was apparent after the initial sampling experiments at Crannell, which resulted in 801 samples, that SSC could not be analyzed for all samples. Analysis of the initial samples of surface

runoff from Crannell showed that a large number of samples were not necessary to capture the necessary information. Fewer runoff samples were collected at South Burma and Molalla (343 and 314 runoff samples respectively). SSC was analyzed for all runoff samples from South Burma and Molalla.

SSC and turbidity were analyzed for 233 of the runoff samples from Crannell and relationships between turbidity and SSC were determined for each pavement treatment at this location (Figure 4.14). For all five treatments, the relationships between turbidity and SSC were linear and positive. Relationships between turbidity and SSC were strong while turbidity values were below 25,000 NTU but variability increased with increasing values of NTU. The primary interest of this research was in the values of SSC during truck passes, especially peak values of SSC. As such, all of the runoff samples with turbidity values above 25,000 NTU and all of the samples during and immediately after a truck pass were analyzed for SSC as well as every 10th sample with turbidity values below this threshold. This resulted in an additional 367 samples analyzed for SSC. For the remaining 201 samples, only turbidity was measured and SSC for these samples was estimated using the regression equations produced for each treatment. Regression equations used to estimate SSC for each pavement treatment at Crannell were:

Control 1: SSC = 0.5854 (Turbidity) + 573.9

Geotextile 1: SSC = 1.022 (Turbidity) – 3305

Geotextile 2: SSC = 0.5985 (Turbidity) + 28.96

Control 2: SSC = 0.5802 (Turbidity) + 2324

More Rock: SSC = 0.6116 (Turbidity) + 431.6

The standard deviation for the estimated values versus the measured values of SSC for all of the relationships was 6159 mg/L (Figure 4.15).

Statistical analysis to compare sediment production across research locations and pavement treatments used only peak SSC values which were all measured values. The estimated SSC values from Crannell were only used in visual analysis of sediment production with time.

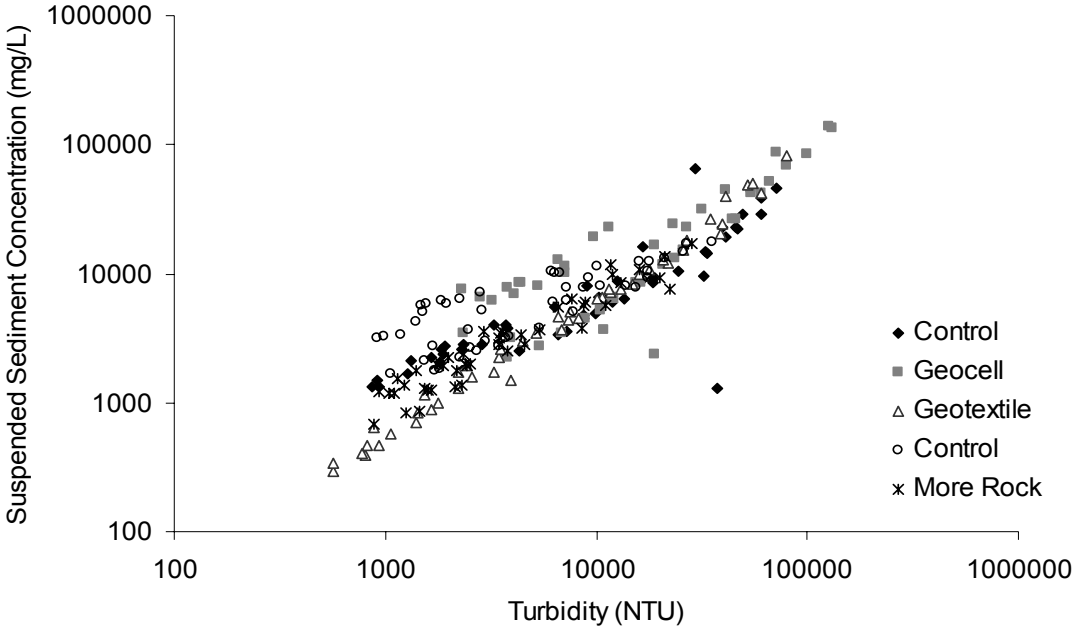


Figure 4.14 Turbidity and SSC measured from 233 runoff samples from the five pavement treatments at Crannell.

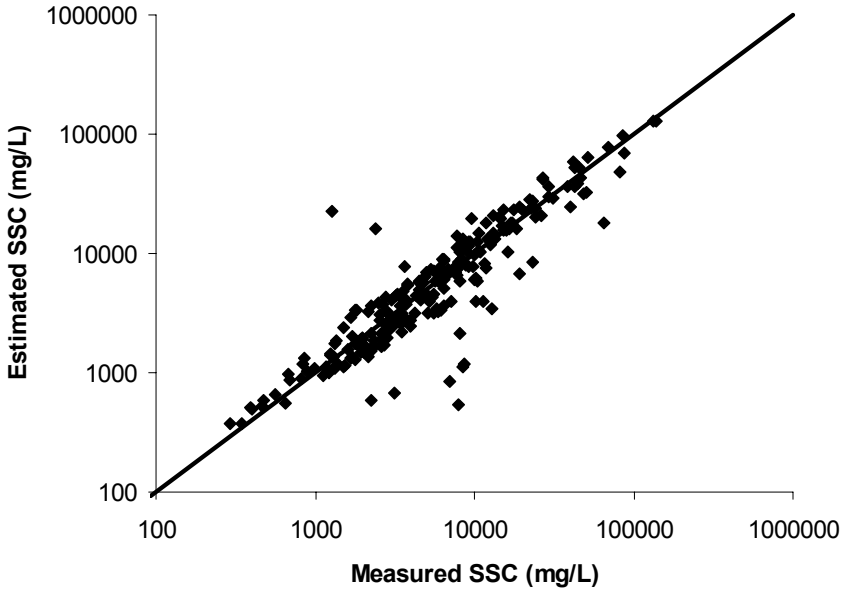


Figure 4.15 Estimated SSC from regression relationships against measured SSC with a 1:1 line.

Graphs of SSC over time for each pavement treatment were produced and matched with the number of traffic loads. SSC peaked after each truck pass and returned to pre-pass level within 12 to 20 minutes. The peak SSC values for each pavement treatment were treated as an individual estimate of sediment production. The peak SSC values were averaged for days that data collection took place. The average peak sediment production from each pavement treatment were considered repeated measures and were used to compare total sediment production with a repeated control, block design (RCBD), 2-way analysis of variance (ANOVA). Further statistical analysis was conducted to compare the alternative treatments to the control treatments where warranted.

An autopsy of the pavement treatments was conducted by digging trenches through the approximate center of each of the pavement treatments. Surveys of the road cross-sections were made after hauling was completed on each of the experimental road segments to determine the condition of the road surface and subgrade. A backhoe with a shovel or small tractor with a blade dug a trench across each of the pavement treatments. A visual inspection of the condition of the aggregate pavement and the subgrade was made and pavement depth above the subgrade was measured at each edge of the road, in the wheel tracks, and down the center line. Data from the trenches were used to determine rut depth and qualitative results of the pavement for each treatment.

Research objective 2: To investigate the role that aggregate quality plays in the generation of sediment from the road surface during log hauling in wet weather.

The pavement treatments used aggregate that was available locally and it varied by location. To investigate the quality of the aggregate, laboratory tests were conducted on samples of aggregate from each research location. At least 30 kg of aggregate sample were taken from each location while the surface aggregate was being placed. The particle size distribution for all sampled aggregate was determined with sieve analysis. The sieves used had decreasing opening sizes of 25.0, 19.0, 12.5, 9.5, 4.75, 2.36, 1.18, 0.600, 0.300, 0.150, and 0.075 mm. The durability and resistance to abrasion of the aggregate were determined with Micro-Deval tests (AASHTO 2000). This test measured abrasion loss of the aggregate in the presence of water and an abrasive charge (steel balls). A sample of the aggregate in the 9.5 to 19.0 mm size range was placed in a jar mill with water and steel balls. The jar was revolved at 100 rpm for 2 hours. The total aggregate loss was expressed as a percent by mass of the material passing the 1.18 mm sieve of the original material after rotations. Because the Mico-Deval method measures aggregate loss with the presence of water, it is reasonable to assume that it more appropriately describes the conditions on a forest road with wet-weather use than other standard tests for aggregate quality.

The experimental design allowed for statistical analysis using 2-way ANOVA with the local aggregate quality and subgrade conditions treated as a block effect. The presence of two control treatments at each location provided additional degrees of freedom to investigate experimental error within each block or research location using a block-by-treatment interaction term. The ANOVA table for the statistical analysis of sediment production from pavement treatments is shown in Table 4.4.

Table 4.4 Two-way ANOVA table with 3 research locations and 5 treatments at each location.

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F-Statistic	P-Value
Model	$B_{ss}+T_{ss}+I_{ss}$	11	$(B_{ss}+T_{ss})/11$	F_{Model}	P_{Model}
Block	B_{ss}	2	$B_{ss}/2$	F_{Block}	P_{Block}
Treatments	T_{ss}	3	$T_{ss}/3$	$F_{Treatment}$	$P_{Treatment}$
Interactions	I_{ss}	6	$I_{ss}/6$	$F_{Interaction}$	$P_{Interaction}$
Residual	R_{ss}	3	$(\text{Standard Deviation})^2$		
Total	$B_{ss}+T_{ss}+I_{ss}+R_{ss}$	14			

Research objective 3: to compare the cost of the alternative designs for unbound aggregate pavement as installed with the savings in sediment from the road surface.

The alternative designs for pavement structures required using additional materials over that required for the control design. The additional costs of these materials were calculated for each treatment and compared to the difference in sediment production from the control design. The expectation was to give road managers an estimate of the increased costs of upgrading forest roads and the benefits in terms of sediment production they gain from the upgrades.

Results

Crannell

At Crannell, field identification procedures classified the subgrade as an ML in the Unified Soil Classification system (ASTM 1999) with slight dry strength, slow dilatancy, and no toughness. The calculations for the reduced stress design method for the ‘more rock’ treatment for a soil classified as ML are presented in Chapter 3. The reduced stress method as presented in Chapter 3 is correct, however, when the method was used to calculate the aggregate depth for the ‘more rock’ treatment it

had an error. This error led to the calculation of a base aggregate depth of 0.41 m rather than the 0.56 presented in Chapter 3 for a soil classified as ML. The 'more rock' treatment was constructed before the error in the reduced stress method was discovered and so the 'more rock' treatment had a base aggregate depth of 0.41 m. This value is twice the aggregate used for the control treatments. The geotextile used in the two geotextile treatments was a woven fabric with a weight of 136 g/m^2 (4 oz/yd^2).

Soil samples from the prepared subgrade were taken in August 2005 before the pavement treatments were constructed and in January 2006 from the road cutslope and fill slope with a soil core slide hammer. The samples were taken back to the laboratory and weighed and oven-dried. Gravimetric water content ranged from 26 percent (an August sample) to 48 percent (a January sample). Bulk densities ranged from 1.03 to 1.29 g/cm^3 and averaged 1.17 g/cm^3.

Samples of the surface aggregate were taken while the pavement for the experimental road segment was being placed. The aggregate used for the base was open-graded with a diameter up to 8 cm (3 inch) and had very little fine material. This material was too large for sieve analysis with the available equipment. The aggregate used for the running course was crushed aggregate with 34 percent passing the 4.75 mm sieve and 0.4 percent passing the 0.075 mm sieve. A graph of the particle size distribution for the cap aggregate is shown in Figure 4.16. The aggregate retained on the 16.0, 12.5, and 9.5 mm sieves was oven-dried and a 1500 g sample that consisted of these sizes was tested for durability with Micro-Deval testing. The aggregate weighed 1096 g after testing resulting in a Micro-Deval abrasion loss of 26.9 percent. A study of 72 aggregates in 8 southern states found Micro-Deval abrasion losses ranged from 2.8 percent from an Alabama gravel to 39.9 percent from a Florida limestone (Cooley *et al.* 2002). The National Cooperative Highway Research Program (NCHRP) project 4-19 recommends a maximum Micro-Deval abrasion loss of 18 percent for aggregate used in hot-mix asphalt applications (Kandhal and Parker 1998). There are currently no published results or guidelines for Micro-Deval abrasion loss values for aggregate used in unbound aggregate roads.

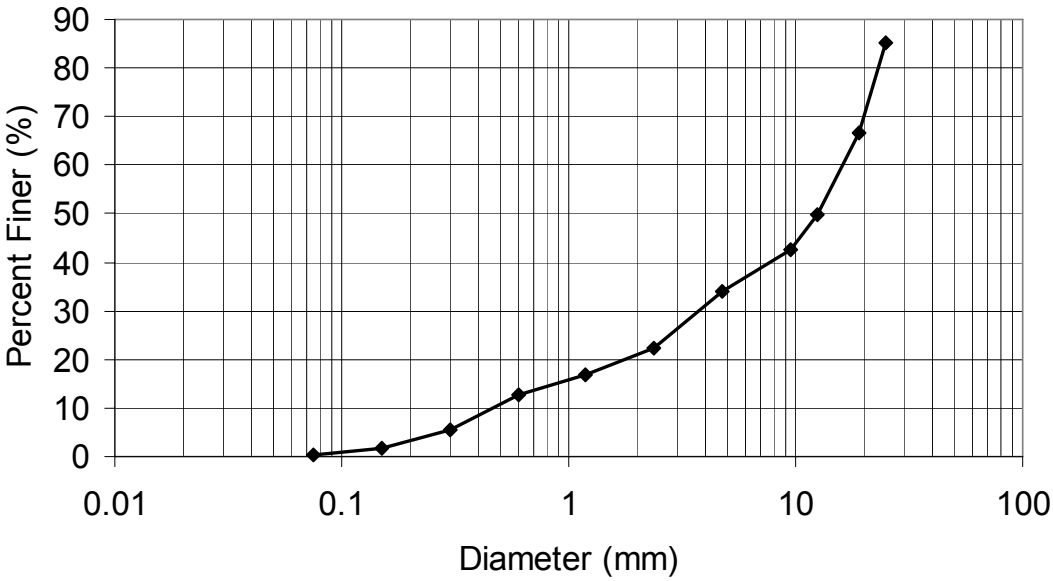


Figure 4.16 Distribution of particle sizes for the cap aggregate from Crannell.

The pavement treatments at Crannell were constructed in August, 2005. The unbound aggregate pavement was not compacted with compaction equipment. A water truck drove over the pavement to wet the surface aggregate and aid compaction. A small tractor with track tires and a blade drove over the surface and graded the cross-section of the road. The surface material was expected to compact with time and traffic.

Hauling the right-of-way logs took place on the road before the pavement layer was constructed and included 58 loads. Hauling on the completed road began in February 2006. Data collection took place on February 15 to 17, 2006 after 87 additional loads. Four loaded trucks drove over the road during sampling on February 15, three on February 16, and four on February 17. Data collection took place again on April 6 and 7, 2006 after 276 loads. Five and six loaded truck passed on the 6th and 7th, respectively, which resulted in runoff samples for 22 truck passes for Crannell. Log hauling on the road ended shortly after data collection occurred in April with 292 total loads. One trench was dug and five survey transects were made across each pavement treatment on July 25, 2006. The trenches were dug through the pavement layer and into the subgrade with a small excavator.

Simulated rainfall was applied at Crannell using an 11 m^3 (3000 gal) water truck to supply the water for the sprinkler system. The simulated rainfall was sufficient to produce runoff. With the open-graded aggregate for the base layer, much of the precipitation infiltrated into and percolated through the

aggregate and ran off the road at the surface of the subgrade. Surface runoff was produced mainly in the wheel tracks where it ran down the road to the water bars. When runoff left the wheel tracks it would infiltrate into the aggregate pavement and did not make it across the road. The waterbars created puddles of runoff at the bottom of each pavement treatment where the intakes for the ISCOs were placed (Figure 4.17).

Figure 4.17 Intake tube and strainer of an ISCO sampler in a waterbar puddle.

The ISCOs sampled runoff at 4 minute intervals through the periods of data collection. There were times at each pavement treatment when runoff puddles were not deep enough to provide a runoff sample or when the intake strainers were moved out of the puddles by passing vehicles and a runoff sample was not captured. These situations created gaps in the runoff data.

Truck passes were clearly identifiable in graphs of SSC and turbidity over time. A peak value of SSC and turbidity occurred immediately after a truck passed and then SSC and turbidity returned to pre-pass values within 20 minutes. A graph of SSC versus time for the five treatments during two passes of a loaded truck is shown in Figure 4.18. The two geotextile treatments and the first control treatment had consistently higher values of SSC with truck passes than the second control and the 'more rock' treatment. Peak values of SSC from each pavement treatment were identified for each truck pass. These peak values of SSC from all truck passes were summed for each pavement treatment. The total number of truck passes, the sum of peak SSC values from all truck passes, the average peak SSC per truck pass, and rank in sediment production for each pavement treatment is shown in Table 4.5. In order of greatest sediment production with truck passes the treatments ranked: 1) Geotextile 1, 2) Geotextile 2, 3) Control 1, 4) Control 2, and 5) 'more rock.' The means of the peak values of SSC from the treatments were significantly different after accounting for differences in truck passes ($p<0.0001$ from an ANOVA test). Sediment production from the geotextile treatments was significantly different than sediment production from the control treatments after accounting for differences in truck passes ($p<0.001$ from an ANOVA test). Sediment production from the more rock treatments was not significantly different than sediment production from the control treatments after accounting for differences in truck passes.

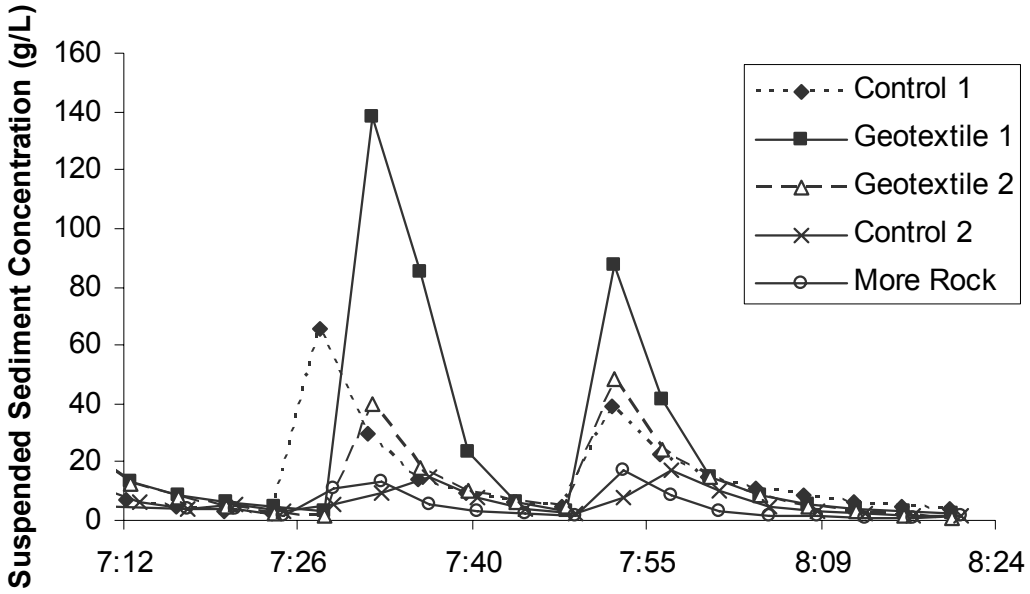


Figure 4.18 Suspended sediment concentration with time for the five treatment plots during the April 7, 2006 sampling period.

Table 4.5 Number of truck passes, sum of peak SSC values, average peak SSC per truck pass, and the rank in sediment production for each pavement treatment at Crannell.

Pavement Treatment	Truck Passes Captured	Sum of all peak SSC values (mg/L)	Average peak SSC per truck pass (mg/L)	Sediment Production Rank
Control 1	20	748,919	37,446	**3**
Geotextile 1	20	1,208,651	60,433	**1**
Geotextile 2	21	795,152	37,864	**2**
Control 2	21	321,785	15,323	**4**
More Rock	17	224,198	13,188	**5**

A trench was dug across each pavement treatment through the surface aggregate to the subgrade in July 2006 after log hauling was completed on the road. The condition of the subgrade was inspected visually and the depth of aggregate above subgrade was measured.

Ruts developed in the wheel paths with time and cumulative traffic. Deep ruts (greater than 2 cm deep) developed in the geotextile treatments and in the first control treatment. These are the same treatments that produced the highest values of SSC. When log hauling ended on the road, ruts in the wheel paths of these treatments were as deep as 10 cm (4 in). Overall, the pavement treatments that held their shape produced lower values of SSC than the pavement treatments that developed ruts.

The geotextile treatments were particularly prone to rut formation. This is possibly due to the failure of the open graded rock on top of the geotextile. Because there was little fine material available in the base aggregate, the aggregate was not able to lock together into a stable structure. Also, the geotextile prevented the aggregate from being pushed into the subgrade to be locked in place.

As ruts developed, more runoff was directed down the road in the wheel paths. The pavement treatments that did not develop ruts efficiently directed surface runoff off the road and little runoff collected at the water bars. The total sediment production from the pavement treatments was not measured because the pavement treatments, especially the second control and the 'more rock' treatment, did not deliver surface runoff to a single location.

Although the subgrade was outsloped, the surface aggregate developed a crowned cross-section with traffic. Upon further inspection at the end of hauling it was clear that the aggregate depth varied across each pavement treatment and the fill slope side of the road had a greater depth of aggregate. One of the geotextile treatments had an aggregate depth of 13 cm (5 in) on the hillslope side of the road and 27 cm (11 in) on the fill slope side (Figure 4.19). Final grading or construction of the aggregate pavement was not carried out for an outsloped cross-section and this created the differences in aggregate depth across the pavement treatments.

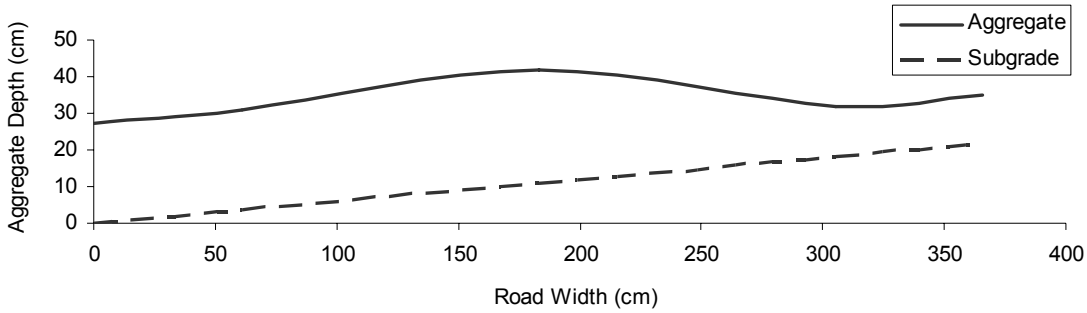


Figure 4.19 Sketch of a trench dug across the first geotextile treatment that shows the depth of aggregate above the subgrade. The fill slope side of the road is on the left and the hillslope side of the road is on the right.

The difference in aggregate depth across the treatments may have affected rutting, however, ruts developed in both wheel paths. It is hypothesized that the second control treatment had more aggregate than called for to transition to the neighboring treatment that had twice the base aggregate. A trench dug across this treatment showed aggregate depths similar to the first control treatment, however, the trench was located closer to the geotextile treatment (upslope) than the additional aggregate treatment.

Trenches dug across the treatments revealed a clear boundary at all treatments between the aggregate and the subgrade (Figure 4.20). There was no evidence of subgrade movement into the aggregate as a result of the traffic. Suspended sediment measured in the road runoff had to originate from fines in the aggregate and not from the subgrade.

(Photograph: M.R. Pyles)

Figure 4.20 A trench across a geotextile treatment that shows a cross-section with significant rut formation and differences in aggregate depth. The hillslope side of the road is on the left and the fill slope side is on the right.

South Burma

The subgrade at South Burma was field identified as an ML in the Unified Soil Classification system (ASTM 1999). The calculations for the reduced stress pavement design method for the 'more rock' treatment were the same as for Crannell (subgrade also classified as ML) and resulted in a base aggregate depth of 0.41 m. The geotextile used in the geotextile treatment and the geocell treatment was woven with a weight of 136 g/m^2 (4 oz/yd^2).

Soil samples from the prepared subgrade were taken in February, 2007 from the cutslope and fill slope of the road with a soil core slide hammer. The samples were taken back to the laboratory, weighed, and oven-dried. Gravimetric water content ranged from 41 to 47 percent. Bulk densities ranged from 1.16 to 1.34 g/cm^3 and averaged 1.25 g/cm^3.

Samples of the surface aggregate were taken while the pavement for the experimental road segment was being placed. The aggregate used for the base was open-graded with a diameter up to 8 cm (3 inch) and very little fine material. This material was too large for sieve analysis. The aggregate used for the running course was crushed aggregate with 45 percent passing the 4.75 mm sieve and 1.3 percent passing the 0.075 mm sieve. A graph of the particle size distribution for the cap aggregate is shown in Figure 4.21. The aggregate retained on the 16.0, 12.5, and 9.5 mm sieves was oven-dried and a 1500 g sample that consisted of these sizes was tested for durability with Micro-Deval testing. The aggregate weighed 1309 g after testing, which resulted in a Micro-Deval abrasion loss of 12.7 percent.

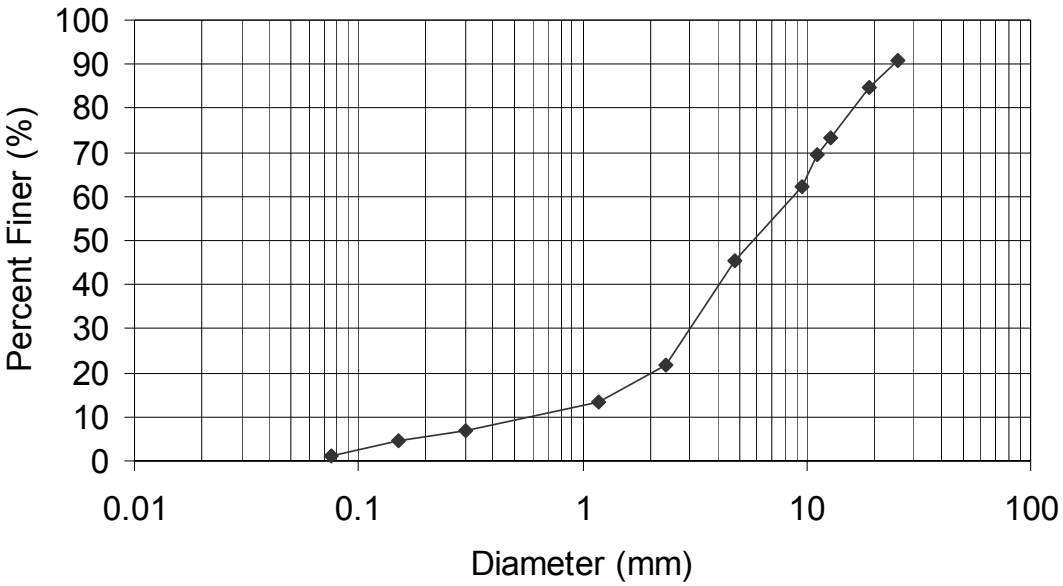


Figure 4.21 Distribution of particle sizes for the cap aggregate from South Burma.

The pavement treatments on the experimental road segment at South Burma were constructed in September 2006. Dump trucks applied aggregate to the prepared subgrade and a small tractor with a blade spread the aggregate across the road. The geocell structures were stretched out across a geotextile that was laid out on top of the subgrade. Dump trucks backed to the geocell structure and back-spread into the geocell structure while reversing (Figure 4.22). When the geocell structures were completely filled, the dump trucks applied the additional 13 cm of surface aggregate and a small tractor with a blade spread the aggregate over the entire width of the road. A roller-compactor and grader were used to compact and shape the surface aggregate for all pavement treatments.

Figure 4.22 Dump truck filling the geocell structure by method of back spread at the South Burma.

Hauling of right-of-way logs took place on the road before the pavement layer was constructed. Hauling on the completed road began in October 2006. Data collection took place on January 24, 2007 after 852 loads. Two loaded trucks drove over the road during sampling on January 24th. Data collection took place again on February 22, 2007 after an additional 325 loads and three loaded trucks passed. Two of the loaded trucked passed within 5 minutes of each other and the

individual effects of each load could not be separated. They were counted as one pass for consideration of sediment production. Final data collection took place on March 20 and 21, 2007 after an additional 258 loads for a cumulative total of 1435 loads. Data for the passage of two loads was measured on each of these days which resulted in runoff samples for a total of eight truck passes for South Burma. Data collection on March 21, 2007 included logging equipment traversing the experimental road segment. A stroke-boom delimber took approximately four minutes to travel over the experimental road segment and was followed closely by a loaded log truck (Figure 4.23). Later that day a loader took approximately 3 minutes to travel over the road segment.

The stroke-boom delimber traveled slowly out of the harvest unit and created a traffic queue. Within seven minutes of the stroke-boom delimber leaving the experimental road segment two loaded trucks and one empty truck passed over the road. In aggregate, this traffic created high values of peak SSC. Sampling intervals of runoff at the pavement treatments were set at 5 minutes and so the effects of the individual vehicles were not able to be separated. Hydrographs of SSC for the pavement treatments over the time that the stroke-boom delimber and subsequent trucks passed depicted a sharp rising limb with two high values and a sharp descending limb (Figure 4.24). The peak SSC values from this traffic were 63 (geocell treatment) to 530 (geotextile treatment) percent greater than peak values of SSC from a loaded truck that passed 25 minutes after the stroke-boom delimber. Data from the trafficking of the stroke-boom delimber and subsequent trucks were not used in the statistical analysis of the comparison of sediment production from pavement treatments.

A 4 m^3 (1000 gal) water truck was used to supply the water for the sprinkler system at South Burma. The truck provided approximately 40 minutes of continuous precipitation. The truck was filled three times during the first day and twice on the subsequent days. Fifteen wedge gauges placed along the centerline of the road (3 in each pavement treatment) measured a maximum of 3.6, 2.5, 2.4, and 2.4 cm of simulated rainfall delivered at approximately 1.2 cm/hr from the sprinkler system during the four days of data collection.

The simulated rainfall delivered by the sprinkler system was sufficient to produce runoff. Much of the precipitation infiltrated into and percolated through the aggregate and drained off the road at the surface of the subgrade. Surface runoff was produced mainly in the wheel tracks where it ran down the road to the water bars. ISCO intakes were placed in puddles of runoff in front of the waterbars and in rutted areas along the experimental road section.

The ISCOs sampled runoff at 5 minute intervals through the periods of data collection. There were times at each pavement treatment when the puddles of runoff were not sufficient to provide an adequate sample or when the intake of the ISCOs were moved out of the puddles by passing vehicles and a sample of runoff was not collected. These situations created gaps in the runoff data.

Figure 4.23 A stroke-boom delimber traveling on the experimental road segment at South Burma.

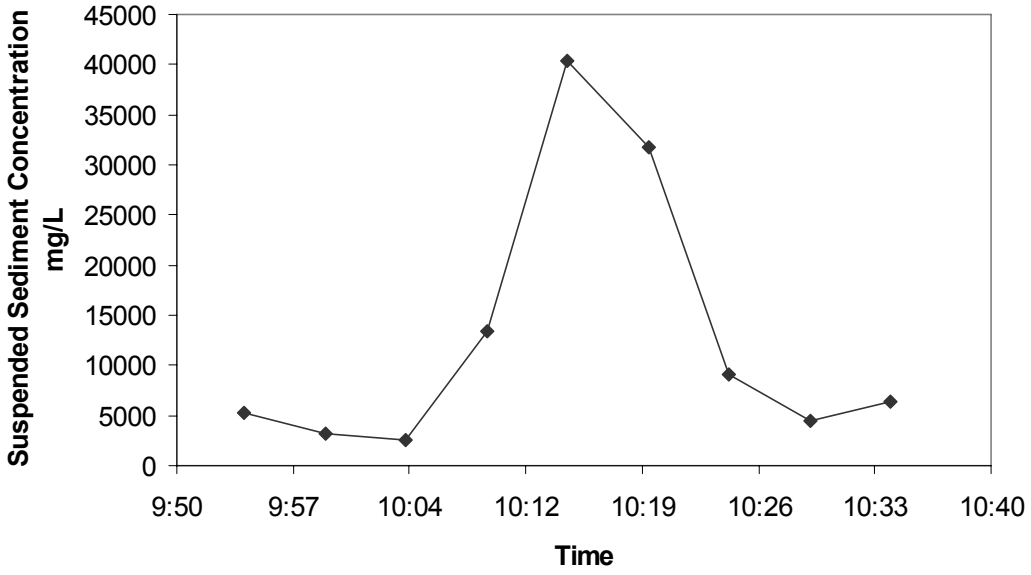


Figure 4.24 Graph of suspended sediment concentration over time with the stroke-boom delimber and subsequent log trucks for the 'more rock' treatment at South Burma.

The peak values of SSC from each pavement treatment were identified for each truck pass. The number of truck passes sampled, sum of peak SSC values from all sampled truck passes, average peak SSC per truck pass, and rank of sediment production for each pavement treatment is shown in Table 4.6. The geocell and geotextile pavement treatments each had missing data for one truck pass. The geotextile pavement treatment consistently produced the most sediment with truck passes. This treatment, on average, produced almost double the sediment than the 'more rock' treatment and close to three times the sediment produced from the other pavement treatments. In order of greatest sediment production per truck passes the treatments ranked: 1) Geotextile, 2) More Rock, 3) Control 1, 4) Geocell, and 5) Control 2. The averages of the peak values of SSC from the treatments were significantly different after accounting for differences in truck passes ($p<0.01$ from an ANOVA test). Sediment production from the geotextile treatment was significantly different than sediment production from the control treatments after accounting for differences in truck passes ($p<0.01$ from an ANOVA test). Sediment production from the 'geocell' and 'more rock' treatments were not significantly different than sediment production from the controls after accounting for differences in truck passes.

Table 4.6 Number of truck passes sampled, sum of all peak SSC values, average peak SSC per truck pass, and the rank in sediment production for each pavement treatment at South Burma.

Pavement Treatment	Truck Passes Captured	Sum of all peak SSC values (mg/L)	Average peak SSC per truck pass (mg/L)	Sediment Production Rank
Geocell	7	45,678	6,525	**4**
Geotextile	7	133,691	19,099	**1**
More Rock	8	80,942	10,118	**2**
Control 1	8	54,165	6,771	**3**
Control 2	8	44,471	5,559	**5**

Ruts developed in the wheel paths of all pavement treatments with time and traffic. Similar to Crannell, substantial ruts developed in the geotextile treatment (Figure 4.25). The Oregon Department of Forestry contract administer for the road was surprised at the depth of ruts for the geotextile treatment and hypothesized that the ruts developed on a “soft spot” in the subgrade. The researchers observed that surface aggregate built up on the outside edges of the geotextile pavement treatment and hypothesized that the aggregate moved out from under the wheel loading across the geotextile boundary.

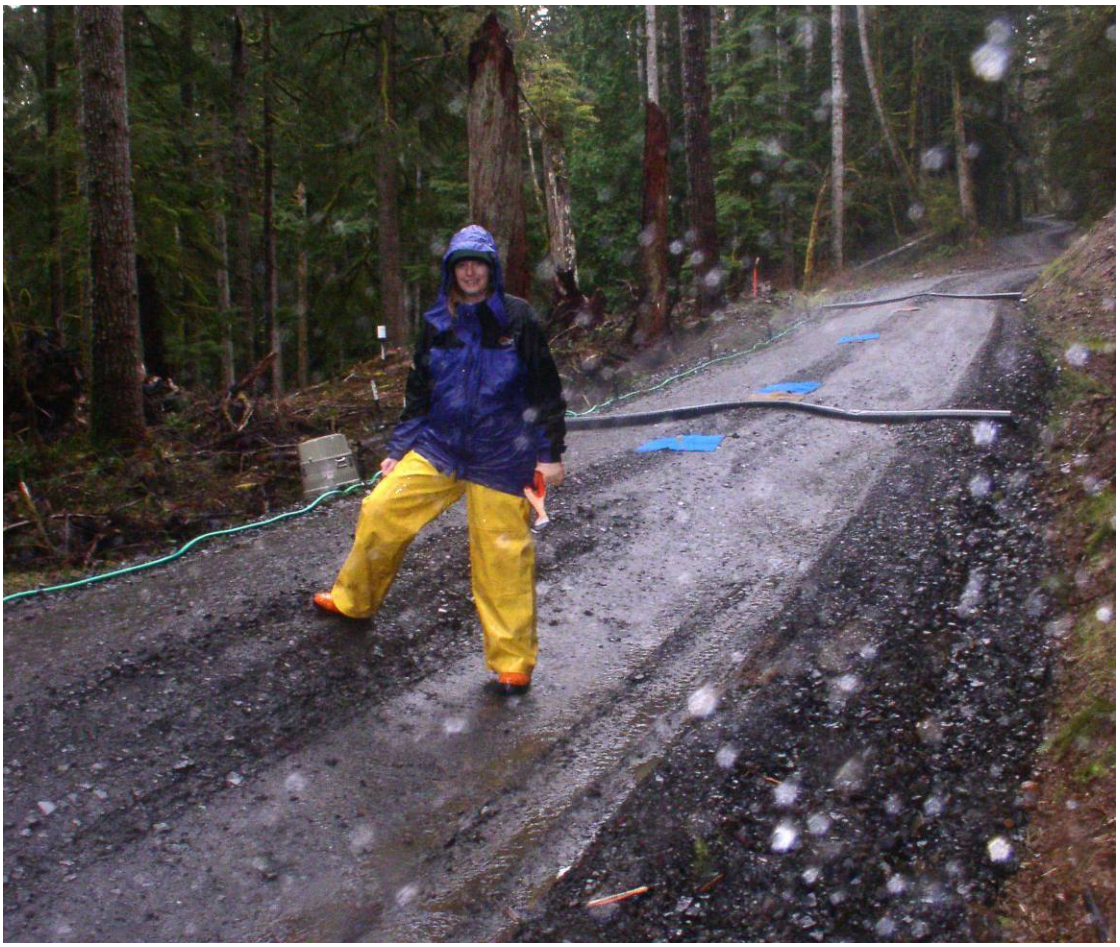


Figure 4.25 Deep ruts developed in the geotextile treatment at South Burma.

Molalla

The subgrade at Molalla was field identified as an ML in the Unified Soil Classification system (ASTM 1999). The calculations for the reduced stress pavement design method for the 'more rock' treatment were the same as for Crannell and South Burma and resulted in a base aggregate depth of 0.41 m for the 'more rock" treatment. The geotextile used in the geotextile treatment and the geocell treatment was woven with a weight of 136 g/m^2 (4 oz/yd^2).

Soil samples were taken in August 2006 before construction of the pavement treatments with a soil core slide hammer. The prepared subgrade was too dry and hard for the slide hammer to penetrate and so soil cores were taken from the forest adjacent to the experimental road segment at approximately 15 and 20 cm below the ground surface. The samples were taken back to the laboratory and weighed

and oven-dried. Gravimetric water content averaged 22 percent. Bulk densities ranged from 0.99 to 1.09 g/cm^3 and averaged 1.04 g/cm^3.

Samples of the surface aggregate were taken while the pavement for the experimental road segment was being placed. The aggregate used for the base and the running course was crushed aggregate with 34 percent passing the 4.75 mm sieve and 0.8 percent passing the 0.075 mm sieve. A graph of the particle size distribution for the cap aggregate is shown in Figure 4.26. The aggregate retained on the 16.0, 12.5, and 9.5 mm sieves was oven-dried and a 1500 g sample that consisted of these sizes was tested for durability with Micro-Deval testing. The aggregate weighed 1213 g after testing resulting in a Micro-Deval abrasion loss of 19.1 percent.

The pavement treatments on the experimental road segment at Molalla were constructed in August 2006. Dump trucks applied aggregate to the prepared subgrade. The geocell treatment required additional equipment. Dump trucks created piles of aggregate on the edge of the road right-of-way. The geocell structures were stretched out across a geotextile that was laid out on top of the subgrade. The geocell was back-filled with an excavator using aggregate from the piles (Figure 4.27). When the geocell structures were completely filled, the dump trucks drove over them to apply the additional 13 cm of surface aggregate and a grader spread the aggregate over the entire road width. A roller-compactor and grader were used to compact and shape the surface aggregate for all pavement treatments.

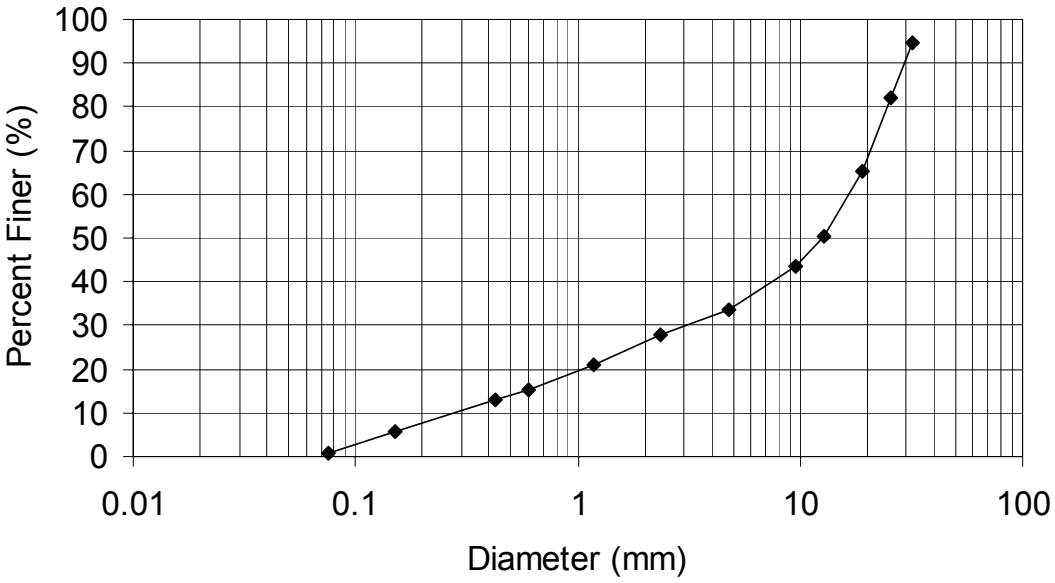


Figure 4.26 Distribution of particle sizes for the aggregate from Molalla.

Figure 4.27 Excavator filling the geocell structure at Molalla.

Hauling of right-of-way logs took place on the road before the pavement layer was constructed. Hauling on the completed road began in April 2007. Data collection took place on April 25, 2007 and three loaded trucks drove over the road during sampling on this day. Data collection took place again on May 1, 2007. Three loaded trucks again drove over the road during data collection on this day. The final data collection took place on May 10, 2007 after a total of 203 loaded truck passes over the experimental road section. Data was collected for three loaded truck passes on this day. This

resulted in runoff samples for 9 truck passes at Molalla. One trench was dug and five survey transects were made across each pavement treatment on July 13, 2007. The trench was dug with the back heel of a yoder (yarding loader) through the pavement layer and into the top of the subgrade.

Substantial ruts developed in the wheel tracks along the entire experimental segment of road at Molalla. These ruts developed before the first application of simulated rainfall after approximately 30 loads. The land owner believed the rutting developed because of a saturated subgrade. The ruts and the condition of the surface required that loaded trucks (traveling uphill) be 'snapped' out of the spur road with a skidder (Figure 4.28). Although road maintenance was not part of the experimental design, the road was re-shaped with additional rock to be operable. An additional 30 m^3 (40 yd^3) of aggregate was placed on the experimental road segment of the spur road after the first application of simulated rainfall and then compacted and re-shaped. The maintenance resulted in additional depth of surface aggregate to the road and, at some locations, the waterbars were buried. Before the second and third applications of simulated rainfall, the waterbars were dug out to prevent the contamination of runoff from one pavement treatment to the next. The maintenance activities disturbed some of the geocell material in the geocell pavement treatment. An edge of the geocell material was pulled up out of the surface aggregate. This only occurred in one place in the center of the road and did not appear to affect the geocell structure for the rest of the pavement treatment.

Figure 4.28 Skidder assisted adverse hauling on experimental road segment at Molalla.

A skidder assisted the loaded trucks through the experimental road segment during the first and second applications of simulated rainfall. The skidder created tire tracks that collected runoff and created a runoff pathway down each wheel track (Figure 4.29). The skidder also bent down the waterbars allowing runoff to pass over the waterbars to the next pavement treatment. Where this occurred, ditch-out channels were dug from the ruts off the edge of the road surface immediately below the waterbar to prevent contamination of runoff from one pavement treatment to the next.

Figure 4.29 Runoff puddles in skidder tracks along the experimental road segment.

A 6 m^3 (1600 gal) water truck was used to supply the water for the sprinkler system at Molalla. This truck provided approximately 80 minutes of continuous simulated rainfall. The truck was filled twice on each day of data collection. The ruts were deep enough for the first day of simulated rainfall that trucks would 'high center' or scrape the road surface between the wheel tracks so wedge rain gauges for the first day of simulated rainfall were placed on the edge of the road on the same side as the sprinkler system. For the other days of simulated rainfall the fifteen wedge rain gauges were placed down the centerline of the experimental road segment (3 in each pavement treatment). The wedge rain gauges collected a maximum of 2.5, 2.3, and 3.8 cm at an intensity of approximately 1.2 cm/hr from the sprinkler system for the three days of simulated rainfall.

The simulated rainfall was sufficient to produce runoff. Once again, the simulated rainfall infiltrated and percolated through the aggregate and was observed to daylight the pavement structure at the edge of the road at the aggregate/subgrade interface. The intakes for the ISCOs were placed in puddles created in front of the waterbars. The ISCOs sampled runoff at 5 minute intervals through the periods of data collection. There were times at each pavement treatment when runoff puddles were not deep enough to provide a runoff sample or when the intake strainers were moved out of the puddles by passing vehicles and a runoff sample was not collected. These situations created gaps in the runoff data.

The experimental road segment was used as a landing to load logs between the second and third periods of data collection. Organic debris in the form of bark, branches, chunks, and chips remained on the road surface on the three pavement treatments that were lowest on the road. The organic debris acted as mulch during the third period when simulated rainfall was applied, however, the debris did not prevent surface runoff from occurring.

The peak values of SSC from each pavement treatment were identified for each truck pass. The number of truck passes sampled, sum of peak SSC values from all sampled truck passes, average peak SSC per truck pass, and rank of sediment production for each pavement treatment is shown in Table 4.7. Data were missing for one truck pass for the geocell and the second control and for two truck passes for the geotextile treatment. In order of greatest sediment production per truck passes, the treatments ranked: 1) Control 1, 2) Geotextile, 3) Geocell, 4) Control 2, and 5) More Rock. This is the same as the order of the treatments along the experimental road segment from highest elevation to lowest. Unlike Crannell and South Burma, there was no significant difference between the means of the peak values of SSC between the treatments after accounting for differences in truck passes ($p>0.1$ from an ANOVA test). Sediment production from the geotextile, geocell, and ‘more rock’ treatments were not significantly different than sediment production from the controls after accounting for differences in truck passes. The pavement treatments at Molalla did not significantly affect the production of sediment.

Table 4.7 Number of truck passes, sum of all peak SSC values, average peak SSC per truck pass, and the rank in sediment production for each pavement treatment at Molalla.

Pavement Treatment	Truck Passes Captured	Sum of all peak SSC values (mg/L)	Average peak SSC per truck pass (mg/L)	Sediment Production Rank
Control 1	9	994,990	110,554	**1**
Geotextile	7	584,712	83,530	**2**
Geocell	8	618,676	77,335	**3**
Control 2	8	603,806	75,476	**4**
More Rock	9	615,866	68,430	**5**

A trench was dug across each pavement treatment through the surface aggregate to the surface of the subgrade in July 2007 after hauling was completed on the road. The condition of the subgrade was visually inspected and the depth of aggregate above subgrade was measured. Trenches in the two control treatments revealed a boundary between the surface aggregate and the subgrade material with 3 to 5 cm of contamination of the layers. Trenches in the geocell and 'more rock' treatments revealed a clear boundary between the surface aggregate and the subgrade material with zero to 1 cm contamination of the layers. Although there were ruts in the wheel paths of the surface aggregate, there was no evidence of rutting in the subgrade at the control, geocell, and more rock treatments. The depth of aggregate to subgrade across the treatments averaged 31 cm for the first control, 29 cm for the second control, 27 cm for the geocell, and 34 cm for the more rock treatment. The aggregate depth for the control and geocell treatments was greater than prescribed and likely due to the additional aggregate that was added after the original rutting. The average aggregate depth across the more rock treatment was 12 cm less than required.

A trench dug through the geotextile treatment exposed a subgrade and geotextile failure. There were ruts in the subgrade and subgrade material was forced upward between wheel ruts. The geotextile had pulled out from the edges of the road and was also pushed upward in the center. There was significant contamination of the aggregate and subgrade material in the wheel paths. The depth of aggregate to subgrade material varied from 30 cm in the right wheel rut to 14 cm just right of the centerline.

Comparison of All Research Locations

The soil type of the subgrade for all three roads was an ML but there were differences in dry bulk densities. The bulk density of the subgrade ranged from 0.99 g/cm^3 at Molalla to 1.34 g/cm^3 at

South Burma. Differences in bulk density may be due to the location and depth below the ground surface that the soil cores were taken. The soil samples at Molalla were taken from the adjacent forest soil, 15 cm below the ground surface and the soil samples at South Burma were taken from the base of a 2 m cutslope.

The aggregate used for the running course at all of the experimental road segments (and the base course at Molalla) had similar distributions of particles sizes but varied in quality as measured by Micro-Deval abrasion loss. Pavement engineering defines fine aggregate as the percent of aggregate by mass that passes the 4.75 mm sieve and is retained on the 0.075 mm sieve and mineral filler as the percent of aggregate by mass that passes the 0.075 mm sieve. The aggregate from South Burma had the greatest quantity of fine aggregate (44.1% by mass) and mineral filler (1.3 % by mass), while the aggregate from Crannell had the greatest Micro-Deval abrasion loss (26.9 %, Table 4.8). These results suggest that the aggregate from South Burma had more fines in the surface aggregate to transport from the road surface while the aggregate from Crannell was more likely to breakdown and produce fine sediment with traffic. However, these results only pertain to the 5 cm cap of running surface at Crannell and South Burma but to the entire aggregate depth at Molalla. Crannell and South Burma had larger aggregate with fewer fines for the remainder of the aggregate depth. Thus, Molalla had more total fines in the complete depth of the aggregate.

Table 4.8 Micro-Deval abrasion loss, percent fine aggregate, and percent mineral filler for the aggregate at all research locations.

	Micro-Deval Abrasion Loss	Fine Aggregate (percent by mass passing the 4.75 mm sieve and retained on the 0.075 mm sieve)	Mineral Filler or Fine Sediment (percent by mass passing the 0.075 mm sieve)
Crannell	26.9 %	33.5 %	0.4 %
South Burma	12.7 %	44.1 %	1.3 %
Molalla	19.1 %	32.9 %	0.8 %

The particle size distributions for Crannell and Molalla were similar, especially in the gravel sizes (above 4.75 mm diameter, Figure 4.30). The aggregate from Crannell met the grading requirements of the Oregon Department of Transportation (ODOT) for dense-graded aggregate used in a base course with a nominal maximum size of 37.5 mm. ODOT requires that 40 to 60 percent of the material passing the 6.3 mm sieve pass the 2.00 mm sieve. The aggregate from Molalla almost met the ODOT requirements for dense-graded aggregate but had more material from the 6.3 mm sieve (70 %)

passing the 2.00 mm sieve than prescribed by ODOT. The aggregate from South Burma almost met the requirements for dense-graded aggregate used in a base course with a nominal maximum size of 25.0 mm. This aggregate had less material from the 6.3 mm sieve (38 %) passing the 2.00 sieve than prescribed by ODOT.

Although sample collection during simulated rainfall for all three experimental road segments occurred only during one wet season, the amount of loaded log trucks that traversed the experimental road segments varied greatly. The number of loaded trucks at Crannell and Molalla were 292 and 203 respectively, which are similar. The number of loaded trucks at South Burma was nearly five times greater with 1,435. Sample collection during simulated rainfall at South Burma did not even begin until after 852 loads. Ruts did form on the South Burma road, especially in the geotextile treatment, however after 1,435 loads the road was still operable. The road at Molalla was inoperable after only 30 loads and it required immediate maintenance.

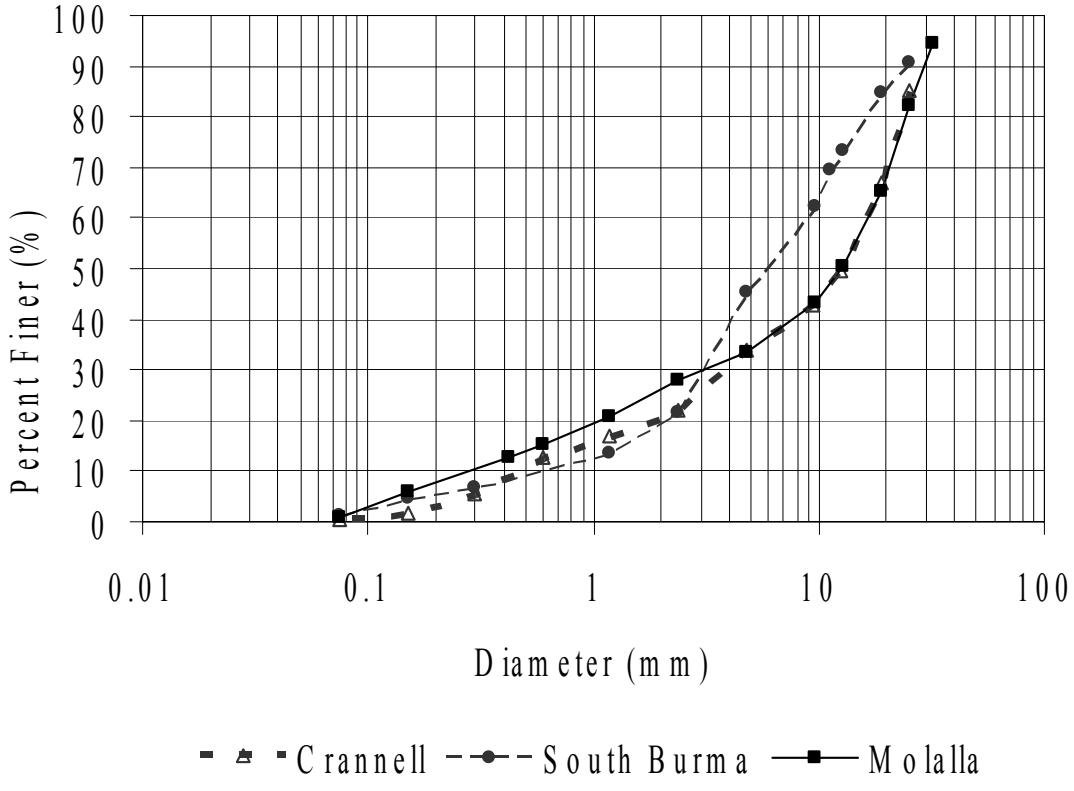


Figure 4.30 Distribution of particle sizes for the aggregate from all research locations.

Sediment production from each pavement treatment did not always increase with time and traffic. The average SSC with a truck pass did increase at all but the second control at Crannell between the first and second sample collection during simulated rainfall. At South Burma, average SSC values with passage of a truck pass between the first and second days of data collection decreased between the second and third day of sample collection for all pavement treatments. Average SSC with a truck pass did not consistently increase or decrease between days of sample collection for each pavement treatment at Molalla (Table 4.9).

Table 4.9 Average SSC (mg/L) per truck pass for each pavement treatment for each period of data collection at each research location.

		Period of Data Collection		
		1	2	3
Crannell				
	Control 1	26,410	46,475	
	Geotextile 1	39,335	86,219	
	Geotextile 2	14,482	59,121	
	Control 2	15,378	15,273	
	More Rock	10,065	15,374	
South Burma				
	Control 1	5,671	7,778	4,393
	Control 2	2,188	3,711	10,592
	More Rock	5,723	27,122	3,813
	Geotextile	27,970	36,384	10,342
	Geocell	2,768	13,363	4,472
Molalla				
	Control 1	65,455	94,924	171,285
	Geotextile	97,552	39,576	173,328
	Geocell	138,535	38,187	42,233
	Control 2	157,120	65,135	31,387
	More Rock	60,645	112,818	31,826

The different periods when sample collection occurred were considered repeated measures on the same experimental unit (single pavement treatment at a research location). Statistically, repeated measures gives more detailed information at a lower level but does not provide replication for inference about the treatment effects. An average SSC value per truck pass for each pavement treatment over all days of sample collection was calculated. An analysis of variance test for a randomized complete block design with two controls was used to test the difference in sediment production between pavement

treatments after accounting for research location (block). There was no significant difference in sediment production, in terms of average SSC per pass of a loaded truck, between treatments after accounting for research location (p-value = 0.22). This suggests that the alternative pavement treatments did not affect sediment production compared with the control from all of the experimental road segments. There was also no evidence that differences in treatments changed from one research location to another (p-value for interaction = 0.78). There was a significant difference in sediment production, in terms of average SSC per pass of a loaded truck, between research locations (p-value <0.01), which indicates a block effect. This indicates that sediment production was dependent on the differences between research locations. The ANOVA table from this analysis is shown in Table 4.10. Because there was not a geocell treatment at Crannell, the treatment effects are unbalanced. Also, the missing geocell treatment meant that the degrees of freedom associated with the interaction term decreased by one and the degrees of freedom associated with the residuals increased by one (Table 4.4).

While there was no treatment effect, there was a block effect as the average value for SSC per pass of a loaded truck for each pavement treatment varied by research location. South Burma, on average, produced the least amount of sediment per pass of a loaded truck and Molalla, on average, produced the greatest amount of sediment. Average values of sediment production from pavement treatments at Crannell were between values for Molalla and South Burma. The controls at Molalla produced a sediment concentration that was 17 times more than the controls at South Burma. The sediment concentrations at Molalla were 5.6 times greater for the 'more rock' treatment, 4.2 times greater for the geotextile treatment, and 10.6 times greater for the geocell treatment than for the same treatments at South Burma (Table 4.11). When average sediment concentration from all research locations are considered, the geotextile treatments had the greatest suspended sediment concentrations, followed by the controls. The 'more rock' and geocell treatments had average suspended sediment concentrations that were 27 and 7 percent less, respectively than the controls.

Table 4.10 Analysis of variance table for the average suspended sediment concentration per pass of a loaded for all research locations.

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F-Statistic	P-Value
Between Groups	1.80E+10	10	8.59E+09	39.98	0.9954
Treatments	1.49E+09	3	4.97E+08	2.31	0.2177
Block	1.60E+10	2	7.99E+09	37.18	0.0026
Interactions	5.23E+08	5	1.05E+08	0.49	0.7750
Within Groups	8.59E+08	4	2.15E+08		
Total	1.88E+10	14			

Estimated standard deviation = 14,656 mg/L

Table 4.11 Average values of SSC (mg/L) per pass of a loaded truck for each pavement treatment at all research locations.

	Crannell	South Burma	Molalla
Control	25,833	5,722	97,551
More Rock	13,402	12,219	68,430
Geotextile	44,273	24,899	103,485
Geocell		6,868	72,985

The costs of the materials used in each pavement treatment were calculated and compared to the average suspended sediment concentration from each pavement treatment. The costs of aggregate are difficult to estimate because landowners use their own quarries as sources of aggregate and hauling costs vary by hauling distance. Oregon Department of Transportation reported costs for construction materials for 94 projects that were bid on during 2006 (ODOT 2007). The bid prices for crushed aggregate were averaged for each quarter and ranged from $16.05 to $22.87 per metric ton. The average bid price for crushed aggregate for the 94 projects was $17.51 per metric ton. This price was used to estimate the costs for the smaller or cap aggregate used in the pavement treatments. Crushed aggregate requires more processing than pit-run aggregate so the larger, pit-run aggregate used as base aggregate in the pavement treatments was discounted. A review of bids for new construction of forest roads estimates a difference of $1.00 per metric ton between crushed and pit-run aggregate so the pit-run aggregate was estimated to cost $16.51 per metric ton. Aggregate density was estimated to be 1600 kg/m^3 (100 lb/ft^3) and this value was used to convert the volume of aggregate needed for the pavement treatments to a unit of mass for cost analysis. Costs for the pavement treatments were estimated per station (30.5 m) for forest road with a width of 4.6 m. The geotextile used in the geotextile and geocell pavement treatments was a woven geotextile purchased in bulk, 3.6 m wide rolls by the land owners. An online geosynthetic distributor, Specialty Construction Supply, charges $0.77 per m^2 for a similar geotextile sold in bulk. The total price for the geotextile was $106.67 per station. The geocell structures used in the geocell pavement treatment were ordered from Geo Products, LLC based in Houston, Texas. The geocell structures were 15 cm deep, EnviroGrid® EGA20 in 9.8 m^2 panels with 35 cells per m^2. The specifications provided by the manufacturer for the geocell structures are shown in Appendix C. The geocell structures cost $9.26 per m^2 and included shipping charges. Total costs per station for each of the pavement treatments are shown in Table 4.12. The geocell treatment at $2,488.75 per station was the most expensive and cost more than 2.5 times the control ($947.44/station), the least expensive treatment. The geotextile treatment cost slightly more, $1054.11 per station, than the control. The 'more rock' treatment, at $1696.32 per station, cost approximately 80 percent more than the control.

Over all research locations and days of sample collection, the geotextile treatment produced the most sediment expressed in terms of an average suspended sediment concentration. The geotextile treatments produced, on average, 34 percent more sediment expressed as suspended sediment concentration than the controls. The 'more rock' and geocell treatments produced less sediment expressed as an average suspended sediment concentration than the controls. The geocell treatments produced, on average, 7 percent less and the 'more rock' treatments produced, on average, 27 percent less sediment expressed as suspended sediment than the controls. The extra cost of the geotextile over the controls did not provide any savings in sediment production. The geocell treatments provided a slight decrease in sediment production over the controls. However these treatments were the most expensive and could be cost prohibitive. The more rock treatments cost nearly 80 percent more than the controls but provided, on average, a 27 percent decrease in sediment production (Table 4.12).

Table 4.12 Total cost per station and the average savings in sediment production over the control treatments for each pavement treatment.

Treatment	$/Station	Average sediment production over control
Control	$ 947.44	-
Geotextile	$ 1054.11	-34 %
Geocell	$ 2488.75	7 %
More Rock	$ 1696.32	27 %

Discussion

Production of Fine Sediment

A key finding of this research is that subgrade mixing did not occur. The trenches dug across the pavement treatments at Crannell and Molalla revealed a clear boundary between the subgrade and the aggregate in all but one pavement treatment. A matrix of aggregate and subgrade was not formed. Subgrade did not move up into the aggregate and was not available to runoff at the road surface. It is commonly assumed that subgrade mixing is if not the primary source then a major source of the fine sediment produced from forest roads and delivered to streams. A focus of this research project was to improve the forest road by reducing subgrade mixing. The design method presented in chapter 3 was developed specifically to produce an unbound aggregate pavement structure that significantly reduces the opportunity for subgrade soils to move into the aggregate pavement. The other pavement treatments

tested were chosen to reduce the opportunity for subgrade mixing into the aggregate pavement. Although these results were not expected, they provide insight into the processes that are responsible for the production of fine sediment from the surfaces of forest roads and suggest that there is room for the current thinking to be challenged.

If the subgrade soils were not a source of the sediment produced by the road surface, then the suspended sediment that was produced by the road had to originate from fines that were in the surface aggregate. This source of fine sediment was placed on the road with the surface aggregate or was a product of the breakdown of the surface aggregate by traffic. If the fine sediment produced by the road surface was solely from the surface aggregate placed on the road, this suggests that the solution of the problem of the production of fine sediment from forest roads during log hauling during wet weather is more complex than originally anticipated. Fines are required in surface aggregate for adequate compaction, stabilization, and for a smooth running surface. But this research indicates that this material is also the primary material available for transport from the road.

There were not great differences between the particle size distributions for the surface aggregate for the three research locations (Figure 4.30), but there were large differences in the suspended sediment concentrations produced by the roads at the different research locations. Specifically, pavement treatments at the Molalla research location produced 2 to 17 times more sediment than the same treatments at the other two locations, yet the source aggregate from the Molalla research location had a particle distribution very similar to that from Crannell. One reason for the differences in sediment production may be the differences in the depth of the surface aggregate for the pavement structure. Molalla had a smaller aggregate (Figure 4.30) for the entire depth of the pavement while the other research locations used the smaller aggregate (Figure 4.30) for only the top 5 cm of the pavement treatments as the running surface. While Molalla had less fines in the aggregate (material passing the 4.75 mm sieve) than the other research locations had in the top 5 cm of pavement (33 % compared to 34 and 44 % at Crannell and South Burma), Molalla had much more of this same material in the remaining depth of pavement compared to the other research locations. The running surface may provide fine materials for the entire depth of aggregate pavement for the purpose of stabilizing the aggregate and allowing for greater compaction through the settling of fines through the pavement structure (Kramer 2001). If fine material is already available in the base aggregate and it is not necessary for fines in the cap material to settle into the base aggregate or if fine sediment through the entire depth of aggregate pavement is easily transported, then more fine sediment may be available to surface runoff.

Design for bound aggregate pavements considers material that passes the 4.75 mm sieve to be fine aggregate and material that passes the 0.075 mm sieve to be mineral filler. The Unified Soil

Classification System considers material that passes the 4.75 mm sieve and is retained on the 0.075 mm sieve to be sand and material that passes the 0.075 mm sieve to be fines or silt and clay. Any size of sediment can transported from the road surface if there is enough energy available in the runoff. There is no definitive particle size for fine material that is the most important for environmental concerns regarding forest roads and water quality. Bilby (1985) stated that very fine sediment or material less than 0.004 mm produced from forest roads was the most detrimental to stream health. This size of material can not be measured with sieve analysis and must be determined through hydrometer analysis. The amount of material in particles sizes less than 0.075 mm was not determined for the aggregate used in this research project. However, the proportion of particles that passed the 0.075 mm sieve was small for the aggregate used for all of the research locations and it ranged from 0.4 (Crannell) to 1.3 (South Burma) percent. Thus, the percent of material less than 0.004 mm was quite small. Foltz and Truebe (2003) argue that the most important particle size in surface aggregate for the production of fines is the percent passing the 0.6 mm sieve. Their study found that sediment production from forest roads increased as the percentage of fines passing the 0.6 mm sieve in the surface aggregate increased. In particular, roads that contain aggregate with greater than 14 percent that passed the 0.6 mm sieve had much higher rates of sediment production (Foltz and Truebe 2003). Table 4.13 shows a comparison of the proportion of the surface aggregate that passed the 0.6 mm sieve from all of the research locations in this study. Molalla, which had the highest values of sediment production and the only value greater than 14 percent, had the greatest percent volume of aggregate that passed the 0.6 mm sieve. The results from this study appear to support the statement presented by Foltz and Truebe (2003).

Table 4.13 Comparison of aggregate passing the 0.6 mm sieve at each research location.

Research location	Percent aggregate passing the 0.6 mm sieve
Crannell	12.6
Molalla	15.2
South Burma	9.0*

*The 0.6mm sieve was not used on the South Burma aggregate. This value was interpolated from the aggregate passing the 1.18 and 0.3 mm sieves.

A large volume of fine materials in the surface aggregate with the presence of surface runoff is not enough to increase sediment production from a forest road. This research saw that sediment production from the experimental roads increased with traffic use and that suspended sediment levels would return to background 12 to 20 minutes after a vehicle pass. Traffic use creates a disturbance on the surface of the unbound aggregate road and allows particles present in the surface aggregate to detach. Particles may then be suspended in runoff and be transported from the road surface. Graphs of sediment production in time with traffic from this research are similar to one presented by Reid and Dunne (1984). This supports the idea that sediment production from forest roads increases with traffic use and that a used forest road will produce more sediment than an unused one.

Integrity of the Unbound Aggregate Pavement

Another key observation from this research is that suspended sediment concentrations were greater from pavement treatments that developed ruts than from those that held their shape in cross-section. The geotextile treatments and the first control at Crannell and the geotextile treatment at South Burma all developed significant ruts with traffic. These treatments also produced more sediment than the other treatments at the same locations. The entire length of the experimental road segment at Molalla developed ruts. Ruts create a flow pathway for surface runoff. Luce and Black (1999) stated that "rutting captures water that would otherwise be ditchflow." A channelized flow pathway for runoff collects a greater volume of runoff, which in turn provides more kinetic energy to detach and transport sediment particles from the road surface. Research on unsurfaced roads showed that roads with ruts produced 2 to 4 times more sediment compared to similar roads without ruts (Burroughs *et al.* 1984; Foltz 1995; Foltz and Burroughs 1990). Current design methods for unbound aggregate pavements design for a specified rut depth. To minimize sediment production from forest roads, a design rut depth should be reduced if not eliminated. Road managers that wish to reduce the production of sediment from roads should design and maintain the roads to maintain the integrity of the cross-section.

Observation of the trenches installed in the pavement treatments at the completion of research at Crannell and Molalla, showed that the ruts only developed in the surface aggregate in all but one treatment. The ruts in the surface aggregate were not 'mirrored' into the subgrade. This result is different than published results and some current thinking where the belief is that ruts form in the subgrade and, more specifically, that ruts form because of a weak subgrade. The ruts at Crannell and Molalla, in all but one treatment, were completely contained in the surface aggregate, which suggests that the strength of the subgrade was not a factor in the failure of the aggregate pavement. The ruts in the aggregate may be the result of inadequate compaction of the surface aggregate, insufficient fines in the aggregate to stabilize the pavement structure, too many fines to create an aggregate matrix, or an

inadequate depth of aggregate to support the traffic loads. The geotextile may have contributed to rut formation because this material was a barrier between the aggregate and the subgrade that allowed the aggregate to fail at the aggregate/geotextile interface rather than protrude into the subgrade where failure would be resisted. This research project was not designed to determine the cause of rut formation in the surface aggregate. However, it is interesting to note the consistent formation of ruts in the geotextile treatments and the absence of ruts in the 'more rock' treatment at Crannell and South Burma.

Characteristics of Forest Roads for Sediment Production

The important characteristics for sediment production from the experimental road segments were fines in the surface aggregate, the integrity of the unbound aggregate pavement, traffic, and surface runoff. Previous studies have shown that levels of traffic are proportional to sediment production (Reid and Dunne 1984) and that the roughness of pavement and the development of ruts increases with time and traffic (Douglas and McCormack 1997). If these were the most important factors in the production of sediment from forest roads then the pavement treatments at South Burma should have produced the most sediment because the pavement treatments at this location experienced five times the traffic as the pavement treatments at the other two research locations. However, the pavement treatments at South Burma produced less sediment than the same pavement treatments at Crannell and Molalla.

Although South Burma experienced a lot of traffic, only the geotextile treatment developed ruts. The geotextile treatment at South Burma developed significant ruts and was the treatment that produced the most sediment at that research location. What was different about the treatments at South Burma that gave the pavement structure greater integrity than at Crannell and Molalla? The aggregate used in the surface course had more fines and mineral filler than the aggregate used in the surface course at Crannell and Molalla (Table 4.8). This same aggregate had a lower volume of material that passed the 0.6 mm sieve than the other two research locations (Table 4.13). The aggregate at South Burma was less resistant to loss from abrasion than the aggregate at Crannell and Molalla (Table 4.8). This research was not designed to determine the reasons for the differences between research locations, however administration of the construction of the pavement treatments at South Burma was better controlled and sufficient compaction techniques were included in the construction of the road, and the aggregate used in the surface course at this location had an adequate volume of fine sediment to compact and stabilize the aggregate pavement. Because the construction of the pavement treatments at Crannell did not include dedicated compaction techniques and because the depth of the surface aggregate was not controlled, pavement treatments at this research location developed ruts and produced more sediment than the same pavement treatments at South Burma. Pavement treatments at

Molalla developed significant ruts and produced more sediment than the pavement treatments at the other two research locations because of the high volume of fine material throughout the entire aggregate pavement. The volume of fine sediment did not allow for adequate compaction and provided fine material available for transport. The pavement treatments at Molalla did not have the base course of larger, open-graded aggregate that provided structural support at the other two research locations. Thus, the key to the construction forest roads that minimize the generation of fine sediment during wet weather hauling has as much to do with the administration of and quality of construction of the road as it does with design methods and construction materials.

Other Considerations for Forest Road Design

The experimental road segments studied in this research were new roads that were constructed to be hauled on the first winter season after construction. The roads were spur roads that were intended to be used for one-season to access a specific harvest unit and consequently were designed for a short design life. The days when samples were collected were over one winter season of log truck traffic at each location. Luce and Black (2001) argue that time is an important factor in the production of sediment from forest roads. They suggest that sediment production decreases with time and age of the road as the ditch becomes armored and the fines are washed from the surface of the road (Luce and Black 2001). As the experimental roads in this research were built only for short-term use, the season of use was the most important for research on the production of sediment from the roads. The roads may have produced less sediment if hauling had taken place years after construction, but this research project addressed current road building and hauling practices. Of particular importance to meet regulations is the time period of use and in current practice that is typically shortly after a road is built or rehabilitated.

The analysis of sediment production in this research only included SSC with a loaded truck pass. Other types of vehicles use the road including passenger vehicles and heavy logging equipment. Although it was not included in the statistical analysis, SSC was monitored through passes of passenger vehicles and a stroke-boom delimber as well as passes of the empty log trucks as they came into the harvest units. Values of peak SSC with a vehicle pass differed by type of vehicle and it appeared that sediment production increased with vehicle weight. Graphs of SSC over time with some of the passes of passenger vehicles did not illustrate any increase in SSC over background levels. This may be a function of the sampling increments. A passenger vehicle could have passed over the experimental road segment immediately following an automated sample and increased SSC but values could have decreased back to background levels before the next automated sample five minutes later. Peak SSC with a vehicle pass were greatest from the stroke-boom delimber, although these samples also included

sediment produced from the two loaded and one empty log truck that passed over the experimental road segment within seven minutes after the stroke-boom delimber. All loaded trucks in the first and second sampling periods at Molalla were assisted over the experimental road segment by a skidder. This may have increased the sediment produced from each of the treatments at this location. However, average values of SSC with a loaded truck pass from the third sampling period when the skidder was not assisting, were higher in some of the pavement treatments than from the first and/or second sampling period from the same pavement treatments. This suggests that if the skidder had any effect on the production of sediment from the pavement treatments it was minimal compared to the effects from the loaded log truck.

The geotextiles used in the geotextile and geocell pavement treatments were provided by the landowners. While all geotextiles were woven with similar unit weights there may have been some slight differences between the geotextiles used at the different research locations. Mohney and Steward (1982) suggest that a geotextile used in an unbound aggregate road pavement does little in terms of tensile reinforcing, especially in a road without ruts. A geotextile used between the subgrade and surface aggregate would not improve the strength of the subgrade but would only function for separation between the pavement and subgrade layers (Mohney and Steward 1982). If this is the case, slight differences in the weight and type of geotextile would not change the function of the geotextile. If subgrade mixing is not a factor in the production of sediment from forest roads then the geotextile does nothing to improve the design of the forest road.

Conclusions

Alternative designs for road pavement produced varied amounts of sediment holding other variables including road slope, length, precipitation intensity and duration, and traffic rate constant. Although the design of the pavement influenced the production of sediment, results were not consistent; the pavement treatments produced different results across different research locations. The results suggest that, for new roads used over one wet season, fine sediment in surface runoff does not originate from the subgrade but rather from the surface aggregate. Post-mortem analysis of the experimental forest roads supported this theory as a clear boundary between the subgrade and surface aggregate was identified in all but one pavement treatment. Pavement integrity was found to be more influential to the production of sediment than pavement design. Pavement treatments that developed substantial ruts produced more sediment than those treatments that held their shape in cross-section. Post-mortem analysis determined that rutting only occurred in the surface aggregate in all but one pavement treatment and was not realized at the subgrade.

References

AASHTO. (1993). "Chapter 4: Low Volume Road Design." Guide for Design of Pavement Structures, American Association of State Highway and Transportation Officials, Washington, District of Columbia.

AASHTO. (2000). "TP58-00 Standard Test Method for Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus." American Association of State Highway and Transportation Officials, Washington D.C.

Amann, J. R. (2004). "Sediment production from forest roads in the upper Oak Creek watershed of the Oregon Coast Range," M.S. Thesis, Oregon State University, Corvallis, Oregon.

Anderson, B., and Potts, D. F. (1987). "Suspended sediment and turbidity following road construction and logging in western Montana." *Water Resources Bulletin*, 23(4), 681-690.

Army Corps of Engineers. (1981). "WES Developing Sand-Grid Confinement System." *Army Research, Development and Acquisition*, 22(4), 7.

ASTM. (1999). "ASTM D 2487, Classification of Soils for Engineering Purposes (Unified Soil Classification System)." Annual Book of ASTM Standards, Sec. 4, Vol. 04.08, American Society for Testing and Materials, West Conshohoken, Pennsylvania.

Barrett, J. C., and Conroy, W. J. (2002) "Improved Practices for Controlling both Point and Nonpoint Sources of Sediment Erosion from Industrial Forest Roads." *Total Maximum Daily Load (TMDL) Environmental Regulations: Proceedings of the March 11-13, 2002 Conference*, Fort Worth, Texas, USA.

Bender, D. A., and Barenberg, E. J. (1978). "Design and Behavior of Soil-Fabric-Aggregate Systems." *Transportation Research Record*, 671, 64-75.

Beschta, R. L. (1978). "Long-term patterns of sediment production following road construction and logging in the Oregon Coast Range." *Water Resources Research*, 14(6), 1011-1016.

Bilby, R. E. (1985). "Contributions of road surface sediment to a Western Washington stream." *Forest Science*, 31(4), 827-838.

Bilby, R. E., Sullivan, K., and Duncan, S. H. (1989). "The generation and fate of road-surface sediment in forested watershed in southwestern Washington." *Forest Science*, 35(2), 453-468.

Binkley, D., and Brown, T. C. (1993). "Forest practices as nonpoint sources of pollution in North America." *Water Resources Bulletin*, 29(5), 729-740.

Bolander, P., Marocco, D., and Kennedy, R. (1995). "Earth and aggregate surfacing design guide for low volume roads. Report no. FHWA-FLP-96-001." U. S. Department of Agriculture, Forest Service in cooperation with the U.S. Department of Transportation Federal Highway Administration, Washington, D.C.

Brown, G. W. (1972). "The Alsea Watershed Study." *Pacific Logging Congress, Loggers Handbook*, Vol. XXXII, 1-6.

Brown, G. W., and Krygier, J. T. (1970). "Effects of clear-cutting on stream temperature." *Water Resources Research*, 6(4), 1133-1139.

Brown, G. W., and Krygier, J. T. (1971). "Clear-cut logging and sediment production in the Oregon Coast Range." *Water Resources Research*, 7(5), 1189-1198.

Burns, J. W. (1972). "Some effects of logging and associated road construction on northern California streams." *Transactions of the American Fisheries Society*, 101(1), 1-17.

Burroughs, E. R., Jr., Watts, F. J., and Haber, D. F. (1984) "Surfacing to reduce erosion of forest roads built in granitic soils." *Symposium on effects of land use on erosion and slope stability*, Honolulu, Hawaii, 255-264.

Burroughs, E. R., and King, J. G. (1989). "Reduction of Soil Erosion on Forest Roads. General Technical Report INT-264." U. S. Department of Agriculture, Forest Service, Intermountain Research Station, Odgen, Utah.

Carr, W. W., and Ballard, T. M. (1980). "Hydroseeding forest roadsides in British Columbia for erosion control." *Journal of Soil and Water Conservation*, 35(1), 33-35.

CDF&FP. (2004). "California Forest Practice Rules, Title 14, California Code of Regulations, Chapters 4, 4.5, and 10." The California Department of Forestry and Fire Protection, Resource Management, Sacramento, California.

Chappell, N. A., Douglas, I., Hanapi, J. M., and Tych, W. (2004). "Sources of suspended sediment within a tropical catchment recovering from selective logging." *Hydrological Processes*, 18(4), 685-701.

Coker, R. J., Fahey, B. D., and Payne, J. J. (1993). "Fine Sediment Production from Truck Traffic, Queen Charlotte Forest, Marlborough Sounds, New Zealand." *Journal of Hydrology (New Zealand)*, 31(1), 56-64.

Cooley, A. L., Huner, M. S., and James, R. H. (2002). "Micro-Deval Testing of Aggregates in the Southeast, NCAT Report 02-09." National Center for Asphalt Technology, Auburn, Alabama.

Cornish, P. M. (2001). "The effects of roading, harvesting and and forest regeneration on streamwater turbidity levels in a moist eucalypt forest." *Forest Ecology and Management*, 152, 293-312.

Croke, J. C., and Hairsine, P. B. (2006). "Sediment delivery in managed forests: a review." *Environmental Reviews*, 14(1), 59-87.

Davies-Colley, R. J., and Smith, D. G. (2001). "Turbidity, Suspended Sediment, and Water Clarity: A Review." *Journal of the American Water Resources Association*, 37(5), 1085-1101.

Day, R. W. (1996). "Effect of Gravel on Pumping Behavior of Compacted Soil." *Journal of Geotechnical Engineering*, 122(10), 863-866.

Delmas, P., Matichard, Y., Gourc, J. P., and Riondy, G. (1986) "Unsurfaced roads reinforced by geotextiles -- a seven year experiment." *3rd International Conference on Geotextiles*, Vienna, Austria, 1015-1019.

Dent, E. F., Mills, K. A., and Robben, J. (2003) "Turbidity Off of Forest Roads in Oregon." *Total Maximum Daily Load (TMDL) Environmental Regulations–II*, Albuquerque, New Mexico USA, 191-197.

Douglas, R. A. (1997a). "Heavy load, low tire pressure rutting of unbound granular pavements." *Journal of Transportation Engineering*, 123(5), 357-363.

Douglas, R. A. (1997b). "Unbound roads trafficked by heavily loaded tyres with low inflation pressure." *Proceedings of the Instituation of Civil Engineers, Transportation*, 123(8), 163-173.

Douglas, R. A. (1999). "Delivery, the transportation of raw natural resource products from roadside to mill." New Zealand School of Forestry, University of Canterbury, Christchurch, New Zealand.

Douglas, R. A., and McCormack, R. (1997) "Pavement management applied to forest roads, Paper No. 975031." *ASAE Annual International Meeting*, Minneapolis, Minnesota.

Douglas, R. A., Woodward, W. D. H., and Woodside, A. R. (2000). "Road contact stresses and forces under tires with low inflation pressure." *Canadian Journal of Civil Engineering*, 27, 1248-1258.

Egan, A. F. (1999). "Forest roads: where soil and water don't mix." *Journal of Forestry*, 97(8), 18-21.

Elliot, W. J., and Tysdal, L. M. (1999). "Understanding and reducing erosion from insloping roads." *Journal of Forestry*, 97(8), 30-34.

Everest, F. H., Beschta, R. L., Scrivener, J. C., Koski, K. V., Sedell, J. R., and Cederholm, C. J. (1987). "Fine sediment and salmonid production: a paradox." Streamside Management: Forestry and

Fishery Interactions, E. O. Salo and T. W. Cundy, eds., University of Washington, Seattle, 98-142.

Fahey, B. D., and Coker, R. J. (1989). "Forest road erosion in the granite terrain of southwest Nelson, New Zealand." *Journal of Hydrology (New Zealand)*, 28(2), 123-141.

Fannin, J. (2001) "Basic Geosynthetics: A Guide to Best Practices in Forest Engineering." *Proceedings of the International Mountain Logging and 11th Pacific Northwest Skyline Symposium*, Seattle, Washington.

Fannin, R. J., and Sigurdsson, O. (1996). "Field Observations on Stabilization of Unpaved Roads With Geosynthetics." *Journal of Geotechnical Engineering*, 122(7), 544-553.

Flynn, L. (1996). "Geosynthetic spins 'web' of success." *Roads and Bridges*, 34(3), 46-47.

Foltz, R. B. (1995). "Sediment Reduction from the Use of Lowered Tire Pressures." Central tire inflation systems: managing the vehicle to surface. SP-1061, Society of Automotive Engineers, Warrendale, Pennsylvania, 47-52.

Foltz, R. B., and Burroughs, E. R., Jr. (1990) "Sediment production from forest roads with wheel ruts." *Proceedings of the Symposium on Watershed Planning and Analysis in Action*, Durango, Colorado, 266-275.

Foltz, R. B., Rauch, K. S., and Burroughs, E. R., Jr. (1991) "Hydraulic Roughness and Sediment Yield in Wheel Ruts on Forest Roads." *Proceedings of the National Conference on Hydraulic Engineering*, Nashville, Tennessee, 1108-1113.

Foltz, R. B., and Truebe, M. A. (1995) "Effect of aggregate quality on sediment production from a forest road." *Transportation Research Board, Sixth International Conference on Low-Volume Roads*, Minneapolis, Minnesota, 49-57.

Foltz, R. B., and Truebe, M. A. (2003) "Locally available aggregate and sediment production." *Eighth International Conference on Low-Volume Roads*, Reno, Nevada, 185-193.

Forman, R. T. T., Sperling, D., Bissonette, J. A., Clevenger, A. P., Cutshall, C. D., Dale, V. H., Fahrig, L., France, R., Goldman, C. R., Heanue, K., Jones, J. A., Swanson, F. J., Turrentine, T., and Winter, T. C. (1993). *Road Ecology Science and Solutions*, Island Press, Washington, D.C.

Fransen, P. J. B., Phillips, C. J., and Fahey, B. D. (2001). "Forest road erosion in New Zealand: overview." *Earth Surface Processes and Landforms*, 26, 165-174.

Fredriksen, R. L. (1970). "Erosion and sedimentation following road construction and timber harvest on unstable soils in three western Oregon watersheds." *Research Paper PNW-104*, USDA Forest Service. Pacific Northwest Forest and Range Experiment Station.

Furniss, M. J., Roelofs, T. D., and Yee, C. S. (1991). "Road construction and maintenance." Influences of Forest and Rangeland Management, W. R. Meehan, ed., American Fisheries Society, Bethesda, Maryland.

Giroud, J. P., and Noiray, L. (1981). "Geotextile-reinforced unpaved road design." *Journal of Geotechnical Engineering*, 107(9), 1233-1254.

Goard, D. L. (2003). "Characterizing the Spatial Distribution of Short Duration, High Intensity Rainfall in the Central Oregon Coast Range," Master of Science Thesis, Oregon State University, Corvallis.

Gordon, N. D., McMahon, T. A., and Finlayson, B. L. (1994). "Chapter 7: Patterns of shifting sand stream." Stream Hydrology: An Introduction for Ecologists., John Wiley and Sons, Chichester, 288-345.

Grant, G. E., and Wolff, A. L. (1991). "Long-term patterns of sediment transport after timber harvest, western Cascade Mountains, Oregon, USA." Sediment and Stream Water Quality in a Changing Environment: Trends and Explanation, IAHS Publ., Gentbrugge, Belgium, 31-40.

Hafley, W. L. (1975). "Rural Road Systems as a Source of Sediment Pollution -- A Case Study." Watershed Managment. Proceedings of A Symposium conducted by the Irrigation and Drainage Division of the American Society of Civil Engineers, Logan, Utah, ASCE, 393-405.

Haupt, H. F. (1959). "Road and Slope Characteristics Affecting Sediment Movement from Logging Roads." *Journal of Forestry*, 57(4), 329-332.

Henry, K. S. (1999). "Geotextile Reinforcement of Low-Bearing-Capacity Soils, Comparison of Two Design Methods Applicable to Thawing Soils, Special Report 99-7." US Army Corps of Engineers.

Hoover, M. D. (1952). "Water and Timber Management." *Journal of Soil and Water Conservation*, 7(2), 75-78.

Ice, G., Dent, L., Robben, J., Cafferata, P., Light, J., Sugden, B., and Cundy, T. W. (2004). "Programs assessing implementation and effectiveness of state Forest Practice Rules and BMPs in the west." *Water, Air, and Soil Pollution: Focus*, 4(1), 143-169.

Ingold, T. S., and Miller, K. S. (1988). *Geotextiles Handbook*, Thomas Telford, London.

Kandhal, P. S., and Parker, F. (1998). "Aggregate Tests Related to Asphalt Concrete Performance in Pavements. National Cooperative Highway Research Program Report 405." National Cooperative Highway Research Program, National Academy Press, Washington, D.C.

Keppeler, E., Lewis, J., and Lisle, T. (2000). "Effects of Forest Management on Streamflow, Sediment Yield, and Erosion, Caspar Creek Experimental Watersheds." USDA Forest Service, Pacific Southwest Research Station, Arcata, CA.

Kochenderfer, J. N., and Helvey, J. D. (1987). "Using gravel to reduce soil losses from minimum-standard forest roads." *Journal of Soil and Water Conservation*, 42(1), 46-50.

Koerner, R. M. (1998). *Designing with Geosynthetics*, Prentice Hall, Upper Saddle River, New Jersey.

Kramer, B. W. (2001). *Forest Road Contracting, Construction, and Maintenance for Small Forest Woodland Owners*, Forest Research Laboratory, Oregon State University, Corvallis, Oregon.

Leong, K. W., Tan, S. A., Chew, S. H., Karunaratne, G. P., Chia, W. Y., and Thein, P. (2000). "Anchored and Pre-tensioned Geosynthetics in Unpaved Roads." *Geotechnical Special Publication, From GeoDenver 2000 Congress, "Advances in Geoenvironmental Systems Using Geosynthetics."*(103), 383-397.

Lewis, J. (1998). "Evaluating the impacts of logging activities on erosion and suspended sediment transport in the Caspar Creek watersheds." *PSW-GTR-168*, USDA Forest Service.

Luce, C. H., and Black, T. A. (1999). "Sediment production from forest roads in western Oregon." *Water Resources Research*, 35(8), 2561-2570.

Luce, C. H., and Black, T. A. (2001). "Spatial and Temporal Patterns in Erosion for Forest Roads." Influence of Urban and Forest Land Uses on the Hydrologic-Geomorphic Responses of Watersheds, M. W. Wigmosta and S. J. Burges, eds., Water Resources Monographs, American Geophysical Union, Washington, D.C., 165-178.

MacDonald, L. H., Sampson, R. W., and Anderson, D. M. (2001). "Runoff and road erosion at the plot and road segment scales, St. John, U.S. Virgin Islands." *Earth Surface Processes and Landforms*, 26, 251-272.

Marbet, C. E. (2003). "Hydrology of five forest roads in the Oregon Coast Range," Master of Science Thesis, Oregon State University, Corvallis.

Megahan, W. F., and Kidd, W. J. (1972). "Effects of logging and logging roads on erosion and sediment deposition from steep terrain." *Journal of Forestry*, 70, 136-141.

Megahan, W. F., Wilson, M., and Monsen, S. B. (2001). "Sediment production from granitic cutslopes on forest roads in Idaho, USA." *Earth Surface Processes and Landforms*, 26(2), 153-163.

Milligan, G. W. E., Jewell, R. A., Houlsby, G. T., and Burd, H. J. (1989a). "A new approach to the design of unpaved roads - Part I." *Ground Engineering*, 22(3), 25-29.

Milligan, G. W. E., Jewell, R. A., Houlsby, G. T., and Burd, H. J. (1989b). "A new approach to the design of unpaved roads - Part II." *Ground Engineering*, 22(8), 37-42.

Mills, K. (1997). "Forest Roads, Drainage, and Sediment Delivery in the Kilchis River Watershed." Oregon Department of Forestry, Tillamook Bay National Estuary Project, Garibaldi, Oregon.

Mills, K., Dent, L., and Robben, J. (2003). "Wet season road use monitoring project final report." Oregon Department of Forestry Forest Practices Monitoring Program Technical Report #17.

Mohney, J. W., and Steward, J. E. (1982) "Construction and Evaluation of Roads over Low Strength Soils Using Nonwoven Geotextiles." *19th Annual Engineering Geology and Soils Engineering Symposium*, Pocatello, Idaho, 161-180.

Monlux, S., and Mitchell, M. (2006) "Chloride Stabilization of Unpaved Road Aggregate Surfacing." *The 29th Council on Forest Engineering Conference*, Coeur d'Alene, Idaho, 149-156.

Montgomery, D. R. (1994). "Road surface drainage, channel initiation, and slope instability." *Water Resources Research*, 30(6), 1925-1932.

Moore, T., Foltz, R. B., and Cronenwett, L. (1995). "Central Tire Inflation (CTI) Reduces Sediment up to 84% - A Method to Help Meet New Water Quality Standards and Guidelines." San Dimas Technology and Development Center, San Dimas, California.

Narejo, D. B. (2003). "Opening size recommendations for separation geotextiles used in pavements." *Geotextiles and Geomembranes*, 21(2003), 257-264.

Novotny, V., and Chesters, G. (1989). "Delivery of sediment and pollutants from nonpoint sources: A water quality perspective." *Journal of Soil and Water Conservation*, 44, 568-576.

ODF. (2003). "Forest Practice Administrative Rules and Forest Practices Act." Oregon Department of Forestry, Salem, Oregon.

ODOT. (2007). "Oregon Highway Construction Cost Trends." Oregon Department of Transportation .Accessed June 6, 2007. http://www.oregon.gov/ODOT/HWY/ESTIMATING/cost_trends.shtml.

Orts, W. J., Roa-Espinosa, A., Sojka, R. E., Glenn, G. M., Imam, S. H., Erlacher, K., and Pedersen, J. S. (2007). "Use of Synthetic Polymers and Biopolymers for Soil Stabilization in Agricultural, Construction, and Military Applications." *Journal of Materials in Civil Engineering*, 19(1), 58-66.

Packer, P. E. (1967). "Criteria for Designing and Locating Logging Roads to Control Sediment." *Forest Science*, 13(1), 2-18.

Potter, J. F., and Currer, E. W. H. (1981). "The effect of a fabric membrane on the structural behavior of a grandular road pavement. Lab Report 996." Transport and Road Research Laboratory, Crowthorne, England.

Powell, B., and Brunette, B. (1991). "Reduced Tire Inflation Pressure -- A Solution for Marginal-Quality Road Construction Rock in Southeast Alaska." *Transportation Research Record*, 1291(1), 329-334.

Presto Products Company. (2003). "Geoweb system specifications and product features.http://www.prestogeo.com/Solutions/Geoweb_specifications.html (November, 2003)."

Ramalho-Ortigao, J. A., and Palmeira, E. M. (1982) "Geotextile performance at an access road on soft ground near Rio de Janeiro." *2nd International Conference on Geotextiles*, Las Vegas, USA, 353-358.

Reid, L. M., and Dunne, T. (1984). "Sediment production from forest road surfaces." *Water Resources Research*, 20(11), 1753-1761.

Reinhart, K. G., Eschner, A. R., and Trimble, G. R. (1963). "Effect on Streamflow of Four Forest Practices in the Mountains of West Virginia, USFS Research Paper, NE-1." U. S. Department of Agriculture, Forest Service, Upper Darby, Pennsylvania.

Rice, R. M., Rothacher, J. S., and Megahan, W. F. (1972) "Erosional consequences of timber harvesting: An appraisal." *National Symposium on Watersheds in Transition*.

Robison, E. G., Mills, K., Paul, J., Dent, L., and Skaugset, A. E. (1999). "Oregon Department of Forestry storm impacts and landslides of 1996: Final report."

Rushing, J. F., Harrison, A., Tingle, J. S., Mason, Q., and McCaffrey, T. (2006). "Evaluation of Dust Palliatives for Unpaved Roads in Arid Climates." *Journal of Performance of Constructed Facilities*, 20(3), 281-286.

Sanders, T. G., Addo, J. Q., Ariniello, A., and Heiden, W. F. (1997). "Relative Effectiveness of Road Dust Suppressants." *Journal of Transportation Engineering*, 123(5), 393-397.

Sessions, J., Balcom, J. C., and Boston, K. (1987). "Road location and construction practices: effects on landslide frequency and size in the Oregon Coast Range." *Western Journal of Applied Forestry*, 2(4), 119-124.

Skaugset, A. E., and Allen, M. M. (1998). "Forest road sediment and drainage monitoring project report for private and state lands in Western Oregon." Oregon Department of Forestry, Salem, Oregon.

Skaugset, A. E., Reeves, G. H., and Keim, R. F. (2002). "Landslides, Surface Erosion, and Forest Operations in the Oregon Coast Range." Forest and Stream Management in the Oregon Coast Range, S. D. Hobbs, J. P. Hayes, R. L. Johnson, G. H. Reeves, T. A. Spies, J. C. Tappeiner, and G. E. Wells, eds., Oregon State University Press, 213-241.

Skaugset, A. E., and Wemple, B. C. (1999) "The response of forest roads on steep, landslide-prone terrain in western Oregon to the February 1996 storm." *Proceedings of the International Mountain Logging and 10th Pacific Northwest Skyline Symposium, March 28-April 1, 1999*, Corvallis, OR, USA, 193-203.

Swanson, F. J., and Dyrness, C. T. (1975). "Impact of clear-cutting and road construction on soil erosion by landslides in the western Cascade Range, Oregon." *Geology*, 3(7), 393-396.

Swanston, D. N., and Swanson, F. J. (1976) "Timber harvesting, mass erosion, and steepland forest geomorphology in the Pacific Northwest." *Geomorphology and Engineering*, 199-221.

Swift, L. W. (1984a). "Gravel and Grass Surfacing Reduces Soil Loss From Mountain Roads." *Forest Science*, 30(3), 657-670.

Swift, L. W. (1984b). "Soil Losses from Roadbeds and Cut and Fill Slopes in the Southern Appalachian Mountains." *Southern Journal of Applied Forestry*, 8(4), 209-215.

Takallou, M. B., Layton, R. D., and Hicks, R. G. (1987). "Evaluation of Alternate Surfacings for Forest Roads." *Transportation Research Record*, 1106(2), 10-22.

Van Santvoort, G. P. T. M. (1994). "Geotextiles and Geomembranes in Civil Engineering, Revised Edition." A.A. Balkema, Rotterdam.

Visser, A. T., and Hall, S. (2003). "Innovative and Cost-Effective Solutions for Roads in Rural Areas and Difficult Terrain." *Transportation Research Record*, 1819(1), 169-173.

Wald, A. R. (1975). "The impact of Truck Traffic and Road Maintenance on Suspended-Sediment Yield from a 14' Standard Forest Road," Master of Science, University of Washington, Seattle.

Webster, S. L., and Alford, S. J. (1978). "Investigation of construction concepts for pavements across soft grounds, Tech. Rep. S-78-6." US Army Corps of Engineers, Vicksburg, Mississippi.

Wemple, B. C. (1994). "Hydrologic integration of forest roads with stream networks in two basins, Western Cascades, Oregon," Master of Science Thesis, Oregon State University, Corvallis, Oregon.

Wemple, B. C., Jones, J. A., and Grant, G. E. (1996). "Channel network extension by logging roads in two basins, western Cascades, Oregon." *Water Resources Bulletin*, 33(6), 1195-1207.

WSDNR. (2006). "Forest Practice Rules, Title 222 WAC." Washington State Department of Natural Resources, Olympia, Washington.

Wu, C., Zhou, B., and Li, Z.-J. (2007). "Test of Chlorides Mixed with CaO, MgO, and Sodium Silicate for Dust Control and Soil Stabilization." *Journal of Materials in Civil Engineering*, 19(1), 10-13.

Ziegler, A. D., and Giambelluca, T. W. (1997). "Importance of rural roads as source areas for runoff in mountainous areas of northern Thailand." *Journal of Hydrology*, 196, 204-229.

Ziegler, A. D., Sutherland, R. A., and Giambelluca, T. W. (2000). "Runoff generation and sediment production on unpaved roads, footpaths and agricultural land surfaces in Northern Thailand." *Earth Surface Processes and Landforms*, 25(2000), 519-534.

Ziegler, A. D., Sutherland, R. A., and Giambelluca, T. W. (2001). "Interstorm surface preparation and sediment detachment by vehicle traffic on unpaved mountain roads." *Earth Surface Processes and Landforms*, 26, 235-250.

REDUCING SEDIMENT PRODUCTION FROM FOREST ROADS DURING WET-WEATHER USE

CHAPTER 5: CONCLUSIONS

General Conclusions

The goal of this work was to investigate turbid runoff during wet-weather use from the pavement of forest roads that were designed for environmental performance. This research explored the opportunity costs associated with upgrading forest roads for environmental performance, determined how to design an unbound aggregate pavement to minimize sediment production as well as for load support, and tested alternatives for road pavements that are designed specifically to minimize turbid runoff during wet weather hauling and compared the monetary costs and environmental benefits of the alternatives for road pavements.

Turbid runoff from forest roads during wet-weather use will continue to be an issue that drives public policy and forest management. As concerns over water quality from forested watersheds increase, regulations governing harvesting practices will become more restrictive. Opportunity costs are the costs associated with an alternative action that could result in benefits that outweigh, or at least offset the costs. The opportunity cost associated with restricted timber hauling and harvesting is potentially a resource that could be made available to improve aggregate road surfaces to minimize hauling restrictions during wet-weather. In this study the opportunity costs were 1.7 to 15 percent of the total net revenue for McDonald-Dunn Research Forest. Although 1.7 to 15 percent of the net revenue from the first year of harvesting may not be enough to improve all haul roads, over time improving the road surfaces may result in increases in production and net revenue.

Turbid runoff from forest roads during wet-weather use is a function of the design of the forest road pavement. Fine sediment available to runoff is thought to be produced from subgrade mixing. Current design methods do not consider sediment loss from the road but rather design solely for load support. The reduced stress design method presented in chapter 3 is a valid design process for pavement depth for unbound aggregate roads with consideration to soil mechanics and emphasis on reducing sediment production. This method designs against subgrade mixing by reducing stresses on the subgrade to allow for strain hardening of the subgrade. The method requires simple field and/or laboratory tests on soil and aggregate characteristics and straightforward calculations to determine the depth of the surface aggregate. It is an appropriate design method for managers of forest roads that are

concerned with the environmental performance of the roads and in particular with the production and delivery of fine sediment from subgrade mixing.

Turbid runoff from forest roads during wet-weather use is affected by the design of the forest road pavement. Alternative designs for road pavement produced varied amounts of sediment holding other variables including road slope, length, precipitation intensity and duration, and traffic rate constant. Although the design of the pavement influenced the production of sediment, results were not consistent; the pavement treatments produced different results across different research locations. The results suggest that fine sediment in surface runoff does not originate from the subgrade but rather from the surface aggregate. Post-mortem analysis of the experimental forest roads supported this theory as a clear boundary between the subgrade and surface aggregate was identified in all but one pavement treatment. Pavement integrity was found to be more influential to the production of sediment than pavement design. Pavement treatments that developed substantial ruts produced more sediment than those treatments that held their shape in cross-section. Post-mortem analysis determined that rutting only occurred in the surface aggregate in all but one treatment and was not realized at the subgrade.

Road managers that want to minimize the production of sediment from forest roads should be concerned with the unbound aggregate pavement rather than the subgrade. Managers should design the aggregate pavement with consideration to the availability of fine sediment in the aggregate and should design the pavement to resist rutting.

Future Work

This research found that the surface aggregate is the most important factor for sediment production from forest roads. Additional research is necessary to determine how the availability of fines in the aggregate influences sediment production. Fine sediment is needed for adequate compaction, stabilization, and for a smooth running surface but this research shows that this material is also available for transport from the road. Is there a threshold value of fine sediment existing in the aggregate as laid that will provide the positive attributes without any of the negative? Would a pavement constructed with “clean” aggregate with no fines produce sediment with wet-weather use? Another important aspect in this discussion is the origin of the fine sediment that is measured in runoff. Is it from the aggregate source or from the breakdown of the surface aggregate with traffic use? An idea for future research would be to construct forest road segments with surface aggregate with varying volumes of fine sediment and measure sediment production with traffic use in wet weather. Another study could construct side by side road segments with the same particle size distributions for the surface

aggregate but vary the quality of the aggregate and again measure sediment production from each segment with traffic use in wet weather.

If fine sediment available to runoff is detached from the surface aggregate then future work is necessary to determine how these fines can be stabilized in the unbound aggregate pavement. Much work has been done with chemical stabilizers for dust abatement but the majority has only been studied in dry weather when air quality and/or wind erosion is important. Orts et al. (2007) studied the effects of chemical stabilizers with wet weather on cutslopes and found a reduction in sediment runoff by 60-85 percent during simulated heavy rains, however, this study only considered cutslopes, areas with no traffic use. There is currently no research on the effect of chemical stabilizers on unbound aggregate roads with traffic and wet-weather in terms of sediment production. Most chemical stabilizers bind dust to make it immobile. Would binding work with saturated conditions? Would chemical stabilizers used in wet-weather also be available to runoff and create and additional environmental concerns? An idea for future research would be to treat sections of a forest road with different environmentally sensitive stabilizers such as calcium chloride, lignin sulfonate, vegetable oil, and acrylic copolymers and measure sediment production from each treatment with traffic use during wet weather.

The production of fine sediment from forest roads will continue to be an area of concern. This research shows that current thinking on the methods of sediment production is not necessarily correct and that more research is required to understand the processes that produce fine sediment and the methods to reduce this environmental impact of forest roads.

References

Orts, W. J., Roa-Espinosa, A., Sojka, R. E., Glenn, G. M., Imam, S. H., Erlacher, K., and Pedersen, J. S. (2007). "Use of Synthetic Polymers and Biopolymers for Soil Stabilization in Agricultural, Construction, and Military Applications." *Journal of Materials in Civil Engineering*, 19(1), 58-66.

BIBLIOGRAPHY

AASHTO. (1993). "Chapter 4: Low Volume Road Design." Guide for Design of Pavement Structures, American Association of State Highway and Transportation Officials, Washington, District of Columbia.

AASHTO. (2000). "TP58-00 Standard Test Method for Resistance of Coarse Aggregate to Degradation by Abrasion in the Micro-Deval Apparatus." American Association of State Highway and Transportation Officials, Washington D.C.

AASHTO. (2001). *Guidelines for Geometric Design of Very Low-Volume Local Roads (ADT≤400)*, American Association of State Highway and Transportation Officials, Washington, District of Columbia.

AASHTO. (2004). *Annual Book of Standards, Standard specifications for transportation materials and methods of sampling and testing, 24th edition*, American Association of State Highway and Transportation Officials, Washington, District of Columbia.

Allen, J. J., and Thomson, M. R. (1974). "Resilient response of granular materials subjected to time dependent lateral stresses." *Transportation Research Record*, 510, 1-13.

Amann, J. R. (2004). "Sediment production from forest roads in the upper Oak Creek watershed of the Oregon Coast Range," M.S. Thesis, Oregon State University, Corvallis, Oregon.

Anderson, B., and Potts, D. F. (1987). "Suspended sediment and turbidity following road construction and logging in western Montana." *Water Resources Bulletin*, 23(4), 681-690.

Army Corps of Engineers. (1981). "WES Developing Sand-Grid Confinement System." *Army Research, Development and Acquisition*, 22(4), 7.

ASTM. (1999). "ASTM D 2487, Classification of Soils for Engineering Purposes (Unified Soil Classification System)." Annual Book of ASTM Standards, Sec. 4, Vol. 04.08, American Society for Testing and Materials, West Conshohoken, Pennsylvania.

ASTM. (2006). "ASTM D2488-06 Standard Practice for Description and Identification of Soils (Visual-Manual Procedure)." Annual Book of ASTM Standards, Sec. 4, Vol. 04.08, American Society for Testing and Materials, West Conshohoken, Pennsylvania.

Barrett, J. C., and Conroy, W. J. (2002) "Improved Practices for Controlling both Point and Nonpoint Sources of Sediment Erosion from Industrial Forest Roads." *Total Maximum Daily Load (TMDL) Environmental Regulations: Proceedings of the March 11-13, 2002 Conference*, Fort Worth, Texas, USA.

Bender, D. A., and Barenberg, E. J. (1978). "Design and Behavior of Soil-Fabric-Aggregate Systems." *Transportation Research Record*, 671, 64-75.

Beschta, R. L. (1978). "Long-term patterns of sediment production following road construction and logging in the Oregon Coast Range." *Water Resources Research*, 14(6), 1011-1016.

Beschta, R. L., Bilby, R. E., Brown, G. W., Holtby, B. L., and Hofstra, T. D. (1987). "Stream Temperature and Aquatic Habitat: Fisheries and Forestry Interactions." Streamside Management: Forestry and Fishery Interactions, E. O. Salo and T. W. Cundy, eds., University of Washington, Seattle, 191-232.

Beschta, R. L., Pyles, M. R., Skaugset, A. E., and Surfleet, C. G. (2000). "Peakflow responses to forest practices in the western Cascades of Oregon, USA." *Journal of Hydrology*, 233, 102-120.

Bilby, R. E. (1985). "Contributions of road surface sediment to a Western Washington stream." *Forest Science*, 31(4), 827-838.

Bilby, R. E., Sullivan, K., and Duncan, S. H. (1989). "The generation and fate of road-surface sediment in forested watershed in southwestern Washington." *Forest Science*, 35(2), 453-468.

Binkley, D., and Brown, T. C. (1993). "Forest practices as nonpoint sources of pollution in North America." *Water Resources Bulletin*, 29(5), 729-740.

Bisson, P. A., Bilby, R. E., Bryant, C. A., Dolloff, C. A., Grette, G. B., House, R. A., Murphy, M. L., Koski, K. V., and Sedell, J. R. (1987). "Large woody debris in forested streams in the Pacific Northwest: past, present, and future." Streamside Management: Forestry and Fishery Interactions, E. O. Salo and T. W. Cundy, eds., University of Washington, Seattle, 143-190.

Bolander, P., Marocco, D., and Kennedy, R. (1995). "Earth and aggregate surfacing design guide for low volume roads. Report no. FHWA-FLP-96-001." U. S. Department of Agriculture, Forest Service in cooperation with the U.S. Department of Transportation Federal Highway Administration, Washington, D.C.

Boussinesq, J. 1885. *Applications des Potentiels.* Gauthier-Villars, Paris.

Bowles, J. E. (1996). *Foundation Analysis and Design, fifth edition*, The McGraw-Hill Companies, Inc., New York, New York.

Brinker, R. W., Kinard, J., Rummer, B., and Lanford, B. (2002). "Machine Rates for Selected Harvesting Machines. Circular 296 (revised)." Alabama Agricultural Experiment Station, Auburn University, Auburn, Alabama.

Brown, G. W. (1972). "The Alsea Watershed Study." *Pacific Logging Congress, Loggers Handbook*, Vol. XXXII, 1-6.

Brown, G. W., Gahler, A. R., and Marston, R. B. (1973). "Nutrient losses after clear-cut logging and slash burning in the Oregon Coast Range." *Water Resources Research*, 9, 1450-1453.

Brown, G. W., and Krygier, J. T. (1970). "Effects of clear-cutting on stream temperature." *Water Resources Research*, 6(4), 1133-1139.

Brown, G. W., and Krygier, J. T. (1971). "Clear-cut logging and sediment production in the Oregon Coast Range." *Water Resources Research*, 7(5), 1189-1198.

Brown, S. F. (1996). "Soil mechanics in pavement engineering. 36th Rankine Lecture of the British Geotechnical Society." *Geotechnique*, 46(3), 383-426.

Brown, S. F., Andersen, K. H., and McElvaney, J. (1977). "The effect of drainage on cyclic loading of clay." *Proceedings, 9th International Conference of Soil Mechanics and Foundation Engineering, Tokyo*, 2, 195-200.

Brown, S. F., Lashine, A. K. F., and Hyde, A. F. L. (1975). "Repeated Load triaxial testing of a silty clay." *Geotechnique*, 25(1), 95-114.

Burns, J. W. (1972). "Some effects of logging and associated road construction on northern California streams." *Transactions of the American Fisheries Society*, 101(1), 1-17.

Burroughs, E. R., Jr., Watts, F. J., and Haber, D. F. (1984) "Surfacing to reduce erosion of forest roads built in granitic soils." *Symposium on effects of land use on erosion and slope stability*, Honolulu, Hawaii, 255-264.

Burroughs, E. R., and King, J. G. (1989). "Reduction of Soil Erosion on Forest Roads. General Technical Report INT-264." U. S. Department of Agriculture, Forest Service, Intermountain Research Station, Odgen, Utah.

Butruille, F. R. (1993). "Repeated loading behavior of a compacted cohesive soil consolidated under low confining stress," Master of Science Engineering Report, Oregon State University, Corvallis, Oregon.

Carr, W. W., and Ballard, T. M. (1980). "Hydroseeding forest roadsides in British Columbia for erosion control." *Journal of Soil and Water Conservation*, 35(1), 33-35.

CDF&FP. (2004). "California Forest Practice Rules, Title 14, California Code of Regulations, Chapters 4, 4.5, and 10." The California Department of Forestry and Fire Protection, Resource Management, Sacramento, California.

Chamberlin, T. W., Harr, R. D., and Everest, F. H. (1991). "Timber Harvesting, Silviculture, and Watershed Processes." Influences of Forest and Rangeland Management on Salmonid Fishes and Their Habitats, W. R. Meehan, ed., American Fisheries Society Special Publication, 181-205.

Chappell, N. A., Douglas, I., Hanapi, J. M., and Tych, W. (2004). "Sources of suspended sediment within a tropical catchment recovering from selective logging." *Hydrological Processes*, 18(4), 685-701.

Chung, W., and Sessions, J. (2000). "Network 2000 Professional Version 1.0. A software program to optimize fixed and variable cost transportation problems." Corvallis, Oregon.

Coker, R. J., Fahey, B. D., and Payne, J. J. (1993). "Fine Sediment Production from Truck Traffic, Queen Charlotte Forest, Marlborough Sounds, New Zealand." *Journal of Hydrology (New Zealand)*, 31(1), 56-64.

Cooley, A. L., Huner, M. S., and James, R. H. (2002). "Micro-Deval Testing of Aggregates in the Southeast, NCAT Report 02-09." National Center for Asphalt Technology, Auburn, Alabama.

Cornish, P. M. (2001). "The effects of roading, harvesting and and forest regeneration on streamwater turbidity levels in a moist eucalypt forest." *Forest Ecology and Management*, 152, 293-312.

Croke, J. C., and Hairsine, P. B. (2006). "Sediment delivery in managed forests: a review." *Environmental Reviews*, 14(1), 59-87.

Das, B. M. (2002). *Principles of Geotechnical Engineering, Fifth edition*, Brooks/Cole, Pacific Grove, California.

Davies-Colley, R. J., and Smith, D. G. (2001). "Turbidity, Suspended Sediment, and Water Clarity: A Review." *Journal of the American Water Resources Association*, 37(5), 1085-1101.

Day, R. W. (1996). "Effect of Gravel on Pumping Behavior of Compacted Soil." *Journal of Geotechnical Engineering*, 122(10), 863-866.

Delmas, P., Matichard, Y., Gourc, J. P., and Riondy, G. (1986) "Unsurfaced roads reinforced by geotextiles -- a seven years experiment." *3rd International Conference on Geotextiles*, Vienna, Austria, 1015-1019.

Dent, E. F., Mills, K. A., and Robben, J. (2003) "Turbidity Off of Forest Roads in Oregon." *Total Maximum Daily Load (TMDL) Environmental Regulations–II*, Albuquerque, New Mexico USA, 191-197.

Douglas, R. A. (1997a). "Heavy load, low tire pressure rutting of unbound granular pavements." *Journal of Transportation Engineering*, 123(5), 357-363.

Douglas, R. A. (1997b). "Unbound roads trafficked by heavily loaded tyres with low inflation pressure." *Proceedings of the Instituation of Civil Engineers, Transportation*, 123(8), 163-173.

Douglas, R. A. (1999). "Delivery, the transportation of raw natural resource products from roadside to mill." New Zealand School of Forestry, University of Canterbury, Christchurch, New Zealand.

Douglas, R. A., and McCormack, R. (1997) "Pavement management applied to forest roads, Paper No. 975031." *ASAE Annual International Meeting*, Minneapolis, Minnesota.

Douglas, R. A., Woodward, W. D. H., and Woodside, A. R. (2000). "Road contact stresses and forces under tires with low inflation pressure." *Canadian Journal of Civil Engineering*, 27, 1248-1258.

Egan, A. F. (1999). "Forest roads: where soil and water don't mix." *Journal of Forestry*, 97(8), 18-21.

Elliot, W. J., and Tysdal, L. M. (1999). "Understanding and reducing erosion from insloping roads." *Journal of Forestry*, 97(8), 30-34.

Everest, F. H., Beschta, R. L., Scrivener, J. C., Koski, K. V., Sedell, J. R., and Cederholm, C. J. (1987). "Fine sediment and salmonid production: a paradox." Streamside Management: Forestry and Fishery Interactions, E. O. Salo and T. W. Cundy, eds., University of Washington, Seattle, 98-142.

Fahey, B. D., and Coker, R. J. (1989). "Forest road erosion in the granite terrain of southwest Nelson, New Zealand." *Journal of Hydrology (New Zealand)*, 28(2), 123-141.

Fannin, J. (2001) "Basic Geosynthetics: A Guide to Best Practices in Forest Engineering." *Proceedings of the International Mountain Logging and 11th Pacific Northwest Skyline Symposium*, Seattle, Washington.

Fannin, R. J., and Sigurdsson, O. (1996). "Field Observations on Stabilization of Unpaved Roads With Geosynthetics." *Journal of Geotechnical Engineering*, 122(7), 544-553.

Fischer, G. S. (2002). "The influence of multi-stage triaxial testing on the behavior of Oregon Coast Range soil," Master of Science Engineering Report, Oregon State University, Corvallis, Oregon.

Fletcher, R., Johnson, B., Blanchard, G., Emmingham, B., Hayes, J., Johnson, D., Johnson, N., Lysne, D., Murphy, G., Newton, M., and Sessions, J. (2005). "McDonald-Dunn Forest Plan Revision." http://www.cof.ost.edu/cf/forests/mcdonald/plan/files/mcdunn_plan.pdf.

Flynn, L. (1996). "Geosynthetic spins 'web' of success." *Roads and Bridges*, 34(3), 46-47.

Foltz, R. B. (1995). "Sediment Reduction from the Use of Lowered Tire Pressures." Central tire inflation systems: managing the vehicle to surface. SP-1061, Society of Automotive Engineers, Warrendale, Pennsylvania, 47-52.

Foltz, R. B., and Burroughs, E. R., Jr. (1990) "Sediment production from forest roads with wheel ruts." *Proceedings of the Symposium on Watershed Planning and Analysis in Action*, Durango, Colorado, 266-275.

Foltz, R. B., Rauch, K. S., and Burroughs, E. R., Jr. (1991) "Hydraulic Roughness and Sediment Yield in Wheel Ruts on Forest Roads." *Proceedings of the National Conference on Hydraulic Engineering*, Nashville, Tennessee, 1108-1113.

Foltz, R. B., and Truebe, M. A. (1995) "Effect of aggregate quality on sediment production from a forest road." *Transportation Research Board, Sixth International Conference on Low-Volume Roads*, Minneapolis, Minnesota, 49-57.

Foltz, R. B., and Truebe, M. A. (2003) "Locally available aggregate and sediment production." *Eighth International Conference on Low-Volume Roads*, Reno, Nevada, 185-193.

Forman, R. T. T., Sperling, D., Bissonette, J. A., Clevenger, A. P., Cutshall, C. D., Dale, V. H., Fahrig, L., France, R., Goldman, C. R., Heanue, K., Jones, J. A., Swanson, F. J., Turrentine, T., and Winter, T. C. (1993). *Road Ecology Science and Solutions*, Island Press, Washington, D.C.

France, J. W., and Sangrey, D. A. (1977). "Effects of drainage in repeated loading of clays." *Journal of the Geotechnical Engineering Division, ASCE*, 103(GT7), 769-785.

Fransen, P. J. B., Phillips, C. J., and Fahey, B. D. (2001). "Forest road erosion in New Zealand: overview." *Earth Surface Processes and Landforms*, 26, 165-174.

Fredriksen, R. L. (1970). "Erosion and sedimentation following road construction and timber harvest on unstable soils in three western Oregon watersheds." *Research Paper PNW-104*, USDA Forest Service. Pacific Northwest Forest and Range Experiment Station.

Frost, M. W., Fleming, P. R., and Rogers, C. D. F. (2004). "Cyclic triaxial tests on clay subgrades for analytical pavement design." *Journal of Transportation Engineering*, 130(3), 378-386.

Furniss, M. J., Roelofs, T. D., and Yee, C. S. (1991). "Road construction and maintenance." Influences of Forest and Rangeland Management, W. R. Meehan, ed., American Fisheries Society, Bethesda, Maryland.

Giroud, J. P., and Noiray, L. (1981). "Geotextile-reinforced unpaved road design." *Journal of Geotechnical Engineering*, 107(9), 1233-1254.

Goard, D. L. (2003). "Characterizing the Spatial Distribution of Short Duration, High Intensity Rainfall in the Central Oregon Coast Range," Master of Science Thesis, Oregon State University, Corvallis.

Gordon, N. D., McMahon, T. A., and Finlayson, B. L. (1994). "Chapter 7: Patterns of shifting sand stream." Stream Hydrology: An Introduction for Ecologists., John Wiley and Sons, Chichester, 288-345.

Grant, G. E., and Wolff, A. L. (1991). "Long-term patterns of sediment transport after timber harvest, western Cascade Mountains, Oregon, USA." Sediment and Stream Water Quality in a Changing Environment: Trends and Explanation, IAHS Publ., Gentbrugge, Belgium, 31-40.

Hafley, W. L. (1975). "Rural Road Systems as a Source of Sediment Pollution -- A Case Study." Watershed Managment. Proceedings of A Symposium conducted by the Irrigation and Drainage Division of the American Society of Civil Engineers, Logan, Utah, ASCE, 393-405.

Haupt, H. F. (1959). "Road and Slope Characteristics Affecting Sediment Movement from Logging Roads." *Journal of Forestry*, 57(4), 329-332.

Henry, K. S. (1999). "Geotextile Reinforcement of Low-Bearing-Capacity Soils, Comparison of Two Design Methods Applicable to Thawing Soils, Special Report 99-7." US Army Corps of Engineers.

Hicks, B. J., Hall, J. D., Bisson, P. A., and Sedell, J. R. (1991). "Responses of Salmonids to Habitat Changes." Influences of Forest and Rangeland Management on Salmonid Fishes and Their Habitats, W. R. Meehan, ed., American Fisheries Society Special Publication, 483-518.

Hinshaw, R. F., and Northrup, J. L. (1991). "Predicting Subgrade Moisture Under Aggregate Surfacing." *Fifth International Conference on Low-Volume Roads, Transportation Research Record 1291*, 2, 193-203.

Holtz, R. D., and Kovacs, W. D. (1981). *An Introduction to Geotechnical Engineering*, Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

Hoover, M. D. (1952). "Water and Timber Management." *Journal of Soil and Water Conservation*, 7(2), 75-78.

Huang, Y. H. (1993). *Pavement analysis and design*, Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

Ice, G., Dent, L., Robben, J., Cafferata, P., Light, J., Sugden, B., and Cundy, T. W. (2004). "Programs assessing implementation and effectiveness of state Forest Practice Rules and BMPs in the west." *Water, Air, and Soil Pollution: Focus*, 4(1), 143-169.

Indraratna, B., Shahin, M. A., Rujikiatkamjiorn, C., and Christie, D. (2006) "Stabilization of Ballasted Rail Tracks and Underlying Soft Formation Soils with Geosynthetic Grids and Drains." *Ground Modification and Seismic Mitigation (GSP 152)*, Shanghai, China, 20-20.

Ingold, T. S., and Miller, K. S. (1988). *Geotextiles Handbook*, Thomas Telford, London.

Jones, J. A., and Grant, G. E. (1996). "Peak flow responses to clear-cutting and roads in small and large basins, western Cascades, Oregon." *Water Resources Research*, 32(4), 959-974.

Jurgenson, L. (1934). "The Application of Theories of Elasticity and Plasticity to Foundation Problems." *Journal of the Boston Society of Civil Engineers*, 148-183.

Kandhal, P. S., and Parker, F. (1998). "Aggregate Tests Related to Asphalt Concrete Performance in Pavements. National Cooperative Highway Research Program Report 405." National Cooperative Highway Research Program, National Academy Press, Washington, D.C.

Keppeler, E., Lewis, J., and Lisle, T. (2000). "Effects of Forest Management on Streamflow, Sediment Yield, and Erosion, Caspar Creek Experimental Watersheds." USDA Forest Service, Pacific Southwest Research Station, Arcata, CA.

Kliewer, J. E. (1992). "Test procedures for low-confining stress, multi-stage triaxial testing of compacted cohesive soils," Master of Science Thesis, Oregon State University, Corvallis, Oregon.

Kochenderfer, J. N., and Helvey, J. D. (1987). "Using gravel to reduce soil losses from minimum-standard forest roads." *Journal of Soil and Water Conservation*, 42(1), 46-50.

Koerner, R. M. (1998). *Designing with Geosynthetics*, Prentice Hall, Upper Saddle River, New Jersey.

Konrad, J.-M., and Wagg, B. T. (1993). "Undrained cyclic loading of anisotropically consolidated clayey silts." *Journal of Geotechnical Engineering*, 119(5), 929-947.

Kramer, B. W. (2001). *Forest Road Contracting, Construction, and Maintenance for Small Forest Woodland Owners*, Forest Research Laboratory, Oregon State University, Corvallis, Oregon.

Larew, H. G., and Leonards, G. A. (1962). "A strength criterion for repeated loads." *Proceedings, 41st Annual Meeting, Highway Research Board*, 529-556.

Leong, K. W., Tan, S. A., Chew, S. H., Karunaratne, G. P., Chia, W. Y., and Thein, P. (2000). "Anchored and Pre-tensioned Geosynthetics in Unpaved Roads." *Geotechnical Special Publication, From GeoDenver 2000 Congress, "Advances in Geoenvironmental Systems Using Geosynthetics."*(103), 383-397.

Lewis, J. (1998). "Evaluating the impacts of logging activities on erosion and suspended sediment transport in the Caspar Creek watersheds." *PSW-GTR-168*, USDA Forest Service.

Li, D., and Selig, E. T. (1996). "Cumulative plastic deformations for fine-grained subgrade soils." *Journal of Geotechnical Engineering*, 122(12), 1006-1013.

Loomis, J. B., and Walsh, R. G. (1997). *Recreation Economic Decisions Comparing Benefits and Costs*, Venture Publishing, Inc., State College, Pennsylvania.

Luce, C. H., and Black, T. A. (1999). "Sediment production from forest roads in western Oregon." *Water Resources Research*, 35(8), 2561-2570.

Luce, C. H., and Black, T. A. (2001). "Spatial and Temporal Patterns in Erosion for Forest Roads." Influence of Urban and Forest Land Uses on the Hydrologic-Geomorphic Responses of Watersheds, M. W. Wigmosta and S. J. Burges, eds., Water Resources Monographs, American Geophysical Union, Washington, D.C., 165-178.

MacDonald, L. H., Sampson, R. W., and Anderson, D. M. (2001). "Runoff and road erosion at the plot and road segment scales, St. John, U.S. Virgin Islands." *Earth Surface Processes and Landforms*, 26, 251-272.

Marbet, C. E. (2003). "Hydrology of five forest roads in the Oregon Coast Range," Master of Science, Oregon State University, Corvallis.

McCracken, M. J. (1994). "Drained behavior of a silt soil under repeated load triaxial testing," Master of Science Engineering Report, Oregon State University, Corvallis, Oregon.

Meehan, W. R. (1991). "Introduction and Overview." Influences of Forest and Rangeland Management on Salmonid Fishes and Their Habitats, W. R. Meehan, ed., American Fisheries Society Special Publication, 1-15.

Megahan, W. F., and Kidd, W. J. (1972). "Effects of logging and logging roads on erosion and sediment deposition from steep terrain." *Journal of Forestry*, 70, 136-141.

Megahan, W. F., Wilson, M., and Monsen, S. B. (2001). "Sediment production from granitic cutslopes on forest roads in Idaho, USA." *Earth Surface Processes and Landforms*, 26(2), 153-163.

Miller, G. A., Teh, S. Y., Li, D., and Zaman, M. M. (2000). "Cyclic Shear Strength of Soft Railroad Subgrade." *Journal of Geotechnical and Geoenvironmental Engineering*, 162(2), 139-147.

Milligan, G. W. E., Jewell, R. A., Houlsby, G. T., and Burd, H. J. (1989a). "A new approach to the design of unpaved roads - Part I." *Ground Engineering*, 22(3), 25-29.

Milligan, G. W. E., Jewell, R. A., Houlsby, G. T., and Burd, H. J. (1989b). "A new approach to the design of unpaved roads - Part II." *Ground Engineering*, 22(8), 37-42.

Mills, K. (1997). "Forest Roads, Drainage, and Sediment Delivery in the Kilchis River Watershed." Oregon Department of Forestry, Tillamook Bay National Estuary Project, Garibaldi, Oregon.

Mills, K., Dent, L., and Robben, J. (2003). "Wet season road use monitoring project final report." Oregon Department of Forestry Forest Practices Monitoring Program Technical Report #17.

Mohney, J. W., and Steward, J. E. (1982) "Construction and Evaluation of Roads over Low Strength Soils Using Nonwoven Geotextiles." *19th Annual Engineering Geology and Soils Engineering Symposium*, Pocatello, Idaho, 161-180.

Monismith, C. L., Ogawa, N., and Freeme, C. R. (1975). "Permanent deformation characteristics of subgrade soils due to repeated loading." *Transportation Research Record*, 537, 1-17.

Monlux, S., and Mitchell, M. (2006) "Chloride Stabilization of Unpaved Road Aggregate Surfacing." *The 29th Council on Forest Engineering Conference*, Coeur d'Alene, Idaho, 149-156.

Montgomery, D. R. (1994). "Road surface drainage, channel initiation, and slope instability." *Water Resources Research*, 30(6), 1925-1932.

Moore, T., Foltz, R. B., and Cronenwett, L. (1995). "Central Tire Inflation (CTI) Reduces Sediment up to 84% - A Method to Help Meet New Water Quality Standards and Guidelines." San Dimas Technology and Development Center, San Dimas, California.

Morgan, D. J. (1995). "Strength Parameters and Triaxial Strength Testing of Soils of the Oregon Coast Range," Master of Science Engineering Report, Oregon State University, Corvallis, Oregon.

Muench, S. T., Mahoney, J. P., and Pierce, L. M. (2003). "Washington State Department of Transportation Pavement Guide Interactive (M 46-03)." Olympia, Washington.

Narejo, D. B. (2003). "Opening size recommendations for separation geotextiles used in pavements." *Geotextiles and Geomembranes*, 21(2003), 257-264.

NOAA. (2004). "Summary of Salmon and Steelhead Listings." Dep. of Commerce, National Oceanic and Atmospheric Administration. http://www.nwr.noaa.gov/ESA-Salmon-Listings/Index.cfm Accessed June 17, 2004.

Nodes, J. E., Pyles, M. R., and Butruille, F. R. (1997) "Repeated-load test performance of a forest road subgrade soil at field stress levels." *UNB International Symposium on Thin Pavements, Surface Treatments, and Unbound Roads*.

Novotny, V., and Chesters, G. (1989). "Delivery of sediment and pollutants from nonpoint sources: A water quality perspective." *Journal of Soil and Water Conservation*, 44, 568-576.

ODF. (2003). "Forest Practice Administrative Rules and Forest Practices Act." Oregon Department of Forestry, Salem, Oregon.

Oregon Department of Transportation. (2007). "Oregon Highway Construction Cost Trends." Accessed June 6, 2007. http://www.oregon.gov/ODOT/HWY/ESTIMATING/cost_trends.shtml.

Orts, W. J., Roa-Espinosa, A., Sojka, R. E., Glenn, G. M., Imam, S. H., Erlacher, K., and Pedersen, J. S. (2007). "Use of Synthetic Polymers and Biopolymers for Soil Stabilization in Agricultural, Construction, and Military Applications." *Journal of Materials in Civil Engineering*, 19(1), 58-66.

Packer, P. E. (1967). "Criteria for Designing and Locating Logging Roads to Control Sediment." *Forest Science*, 13(1), 2-18.

Potter, J. F., and Currer, E. W. H. (1981). "The effect of a fabric membrane on the structural behavior of a grandular road pavement. Lab Report 996." Transport and Road Research Laboratory, Crowthorne, England.

Powell, B., and Brunette, B. (1991). "Reduced Tire Inflation Pressure -- A Solution for Marginal-Quality Road Construction Rock in Southeast Alaska." *Transportation Research Record*, 1291(1), 329-334.

Presto Products Company. (2003). "Geoweb system specifications and product features.http://www.prestogeo.com/Solutions/Geoweb_specifications.html (November, 2003)."

Puppala, A. J., Mohammad, L. N., and Allen, A. (1999). "Permanent deformation characterization of subgrade soils from the RLT test." *Journal of Materials in Civil Engineering*, 11(4), 274-282.

Ramalho-Ortigao, J. A., and Palmeira, E. M. (1982) "Geotextile performance at an access road on soft ground near Rio de Janeiro." *2nd International Conference on Geotextiles*, Las Vegas, USA, 353-358.

Reid, L. M., and Dunne, T. (1984). "Sediment production from forest road surfaces." *Water Resources Research*, 20(11), 1753-1761.

Reinhart, K. G., Eschner, A. R., and Trimble, G. R. (1963). "Effect on Streamflow of Four Forest Practices in the Mountains of West Virginia, USFS Research Paper, NE-1." U. S. Department of Agriculture, Forest Service, Upper Darby, Pennsylvania.

Rice, R. M., Rothacher, J. S., and Megahan, W. F. (1972) "Erosional consequences of timber harvesting: An appraisal." *National Symposium on Watersheds in Transition*.

Robison, E. G., Mills, K., Paul, J., Dent, L., and Skaugset, A. E. (1999). "Oregon Department of Forestry storm impacts and landslides of 1996: Final report."

Rushing, J. F., Harrison, A., Tingle, J. S., Mason, Q., and McCaffrey, T. (2006). "Evaluation of Dust Palliatives for Unpaved Roads in Arid Climates." *Journal of Performance of Constructed Facilities*, 20(3), 281-286.

Sanders, T. G., Addo, J. Q., Ariniello, A., and Heiden, W. F. (1997). "Relative Effectiveness of Road Dust Suppressants." *Journal of Transportation Engineering*, 123(5), 393-397.

Schoenemann, M. R., and Pyles, M. R. (1988). "Stress path considerations in multistage triaxial testing." Advanced Triaxial Testing of Soil and Rock, STP 977, Donaghe, Chaney, and Silver, eds., American Society for Testing and Materials (ASTM), West Conshohocken, PA, 732-739.

Schofield, A. N., and Wroth, C. P. (1968). *Critical State Soil Mechanics*, McGraw-Hill Publishing Company Limited, London.

Schroeder, W. L., and Alto, J. V. (1983). "Soil Properties for Slope Stability Analysis; Oregon and Washington Coastal Mountains." *Forest Science*, 29(4), 823-833.

Scott, R. F. (1963). *Principles of Soil Mechanics*, Addison-Wesley Publishing Company, Inc., Reading, Massachusetts.

Seed, H. B., Chan, C. K., and Monismith, C. L. (1955). "Effect of repeated loading on the strength and deformation of compacted clay." *Highway Research Board Proceedings*, 34, 541-558.

Sessions, J., Balcom, J. C., and Boston, K. (1987). "Road location and construction practices: effects on landslide frequency and size in the Oregon Coast Range." *Western Journal of Applied Forestry*, 2(4), 119-124.

Simonsen, E., and Isacsson, U. (2001). "Soil behavior during freezing and thawing using variable and constant confining pressure triaxial tests." *Canadian Geotechnical Journal*, 38(4), 863-875.

Skaugset, A. E., and Allen, M. M. (1998). "Forest road sediment and drainage monitoring project report for private and state lands in Western Oregon." Oregon Department of Forestry, Salem, Oregon.

Skaugset, A. E., Reeves, G. H., and Keim, R. F. (2002). "Landslides, Surface Erosion, and Forest Operations in the Oregon Coast Range." Forest and Stream Management in the Oregon Coast Range, S. D. Hobbs, J. P. Hayes, R. L. Johnson, G. H. Reeves, T. A. Spies, J. C. Tappeiner, and G. E. Wells, eds., Oregon State University Press, 213-241.

Skaugset, A. E., and Wemple, B. C. (1999) "The response of forest roads on steep, landslide-prone terrain in western Oregon to the February 1996 storm." *Proceedings of the International Mountain Logging and 10th Pacific Northwest Skyline Symposium, March 28-April 1, 1999*, Corvallis, OR, USA, 193-203.

Smith, R. S. (2001). "An investigation of the influence of root reinforcements on soil strength and the initiation of static liquefaction in forest soils," Master of Science Thesis, Oregon State University, Corvallis, Oregon.

Swanson, F. J., and Dyrness, C. T. (1975). "Impact of clear-cutting and road construction on soil erosion by landslides in the western Cascade Range, Oregon." *Geology*, 3(7), 393-396.

Swanston, D. N., and Swanson, F. J. (1976) "Timber harvesting, mass erosion, and steepland forest geomorphology in the Pacific Northwest." *Geomorphology and Engineering*, 199-221.

Swift, L. W. (1984a). "Gravel and Grass Surfacing Reduces Soil Loss From Mountain Roads." *Forest Science*, 30(3), 657-670.

Swift, L. W. (1984b). "Soil Losses from Roadbeds and Cut and Fill Slopes in the Southern Appalachian Mountains." *Southern Journal of Applied Forestry*, 8(4), 209-215.

Takallou, M. B., Layton, R. D., and Hicks, R. G. (1987). "Evaluation of Alternate Surfacings for Forest Roads." *Transportation Research Record*, 1106(2), 10-22.

Taylor, D. W. (1948). *Fundamentals of Soil Mechanics*, John Wiley and Sons, Inc., New York, New York.

Terzaghi, K. (1943). *Theoretical Soil Mechanics*, John Wiley and Sons, Inc., New York, New York.

Toman, E. M. (2004). "Forest road hydrology: The influence of forest roads on stream flow at stream crossings," Master of Science Thesis, Oregon State University, Corvallis.

USACE. (1990). "Engineering and Design, Settlement Analysis, Engineer Manual 1110-1-1904." Department of Army, U.S. Army Corps of Engineers, Washington, D.C.

USN. (1971). "Design Manual: Soil Mechanics, Foundations, and Earth Structures. NAVFAC DM-7." United States Department of the Navy, Naval Facilities Engineering Command, Washington, District of Columbia.

Van Santvoort, G. P. T. M. (1994). "Geotextiles and Geomembranes in Civil Engineering, Revised Edition." A.A. Balkema, Rotterdam.

Visser, A. T., and Hall, S. (2003). "Innovative and Cost-Effective Solutions for Roads in Rural Areas and Difficult Terrain." *Transportation Research Record*, 1819(1), 169-173.

Wald, A. R. (1975). "The impact of Truck Traffic and Road Maintenance on Suspended-Sediment Yield from a 14' Standard Forest Road," Master of Science, University of Washington, Seattle.

Webster, S. L., and Alford, S. J. (1978). "Investigation of construction concepts for pavements across soft grounds, Tech. Rep. S-78-6." US Army Corps of Engineers, Vicksburg, Mississippi.

Wemple, B. C. (1994). "Hydrologic integration of forest roads with stream networks in two basins, Western Cascades, Oregon," Master of Science, Oregon State University, Corvallis, Oregon.

Wemple, B. C., Jones, J. A., and Grant, G. E. (1996). "Channel network extension by logging roads in two basins, western Cascades, Oregon." *Water Resources Bulletin*, 33(6), 1195-1207.

WSDNR. (2006). "Forest Practice Rules, Title 222 WAC." Washington State Department of Natural Resources, Olympia, Washington.

Wu, C., Zhou, B., and Li, Z.-J. (2007). "Test of Chlorides Mixed with CaO, MgO, and Sodium Silicate for Dust Control and Soil Stabilization." *Journal of Materials in Civil Engineering*, 19(1), 10-13.

Yapp, M. T., Steward, J., and Whitcomb, W. G. (1991). "Existing Methods for the Structural Design of Aggregate Road Surfaces on Forest Roads." *Fifth International Conference on Low-Volume Roads, Transportation Research Record 1291*, National Research Council, Volume 1, 41-57.

Zergoun, M., and Vaid, Y. P. (1994). "Effective stress response of clay to undrained cyclic loading." *Canadian Geotechnical Journal*, 31(5), 714-727.

Zhang, X., Hartsough, B. R., and Fight, R. D. (2003). "STHARVEST: Small Timber Harvest Version 2.0.0. Software to estimate the cost of harvesting small timber."

Ziegler, A. D., and Giambelluca, T. W. (1997). "Importance of rural roads as source areas for runoff in mountainous areas of northern Thailand." *Journal of Hydrology*, 196, 204-229.

Ziegler, A. D., Sutherland, R. A., and Giambelluca, T. W. (2000). "Runoff generation and sediment production on unpaved roads, footpaths and agricultural land surfaces in Northern Thailand." *Earth Surface Processes and Landforms*, 25(2000), 519-534.

Ziegler, A. D., Sutherland, R. A., and Giambelluca, T. W. (2001). "Interstorm surface preparation and sediment detachment by vehicle traffic on unpaved mountain roads." *Earth Surface Processes and Landforms*, 26, 235-250.

APPENDICES

Appendix A: Presto Products Company Technical Overview and Design Calculations for Geocell Structure

Design Parameters - Granular Pavements

The following information and input parameters are required for design of the Geoweb load support system for granular pavements.

Wheel Load

The design wheel load is the heaviest single or dual wheel load that the granular pavement will be required to support over the proposed life of the structure.

Tire Pressure

The tire pressure is the tire inflation pressure of the design wheel load and is approximately equal to the ground contact pressure. An input value is required for determination of the effective contact radius of the design wheel load.

Bearing Capacity Coefficient

Bearing capacity coefficients are mathematically or empirically derived coefficients used within standard equations for determination of the bearing capacity of a soil. For unpaved roads over soft cohesive soils, the US Forest Service and others have developed bearing capacity coefficients for determination of the bearing capacity of soils subjected to dynamic loading wherein punching (local) shear failure is more prevalent than general shear failure. The US Forest Service developed the following bearing coefficients for unpaved haul roads for two broad ranges of traffic loading.

$N_c = 2.8$	High traffic with little rutting (i.e. > 1000, < 10000)
$N_c = 3.3$	Low traffic with significant rutting (i.e. < 1000)

Depth to Top of Geoweb section

The depth of placement of the Geoweb layer influences the distribution of stresses through the system and has a significant effect on the design. Since vertical stresses are higher near the surface, optimum performance and maximum thickness reduction are obtained by placing the Geoweb as close to the surface as possible. However, in order to protect the top of the Geoweb cell walls, a 25 mm - 50 mm (1 in - 2 in) aggregate wearing surface is typically recommended.

Subgrade Strength

There are several laboratory and field test methods available to determine the strength of subgrade soils for design purposes. The calculations require soil strength to be expressed in terms of shear strength or cohesion. Shear strength can be determined in the field by the vane shear test or in the laboratory by the shear box or triaxial compression tests. Soil strength is also commonly determined by the Standard Penetration Test and the California Bearing Ratio (CBR) test. For cohesive soils, shear strength of a soil can be estimated from the standard penetration resistance (N) or the California Bearing Ratio (CBR). In the absence of field or laboratory test data, the strength of the subgrade soil can be estimated by it's consistency (see the Field Identification section of Table 4). When estimating a soil's strength by it's consistency, the soil sample should be taken from a test pit which is deep enough to ensure it's properties have not been affected by changing surface conditions (e.g. rain water, hot dry weather, etc.).

Brief descriptions of the most common test methods for determining the strength of subgrade soils are given below.

California Bearing Ratio (CBR) Test

The California Bearing Ratio test is an index test used to determine the relative strength of a soil compared to a standard high-quality crushed stone material. The test specimen is prepared by compacting a sample of the soil, in multiple lifts, into a 6 inch diameter cylinder, applying a surcharge in the form of circular plates to approximate the confining stress of the final pavement on the soil and soaking the entire sample for a period of 4 days. The test consists of loading the soil sample with a 3 square inch (1935 square mm) circular piston, through holes in the surcharge plates, at a rate of 0.10 inch (2.54 mm)/minute up to a maximum of 0.5 inches (13 mm). The CBR value is the ratio of the unit load at 0.10 inch (2.54 mm) or 0.20 inch (5.04 mm) to that of the standard crushed stone material at the same depth of penetration (whichever is higher). The unit loads are given in Table 2.

Table 2 Unit Loads for Standard Crushed Stone Material

0.1 inch penetration	1000 psi
0.2 inch penetration	1500 psi
0.3 inch penetration	1900 psi
0.4 inch penetration	2300 psi
0.5 inch penetration	2600 psi

Standard Penetration Test

The standard penetration test provides an indication of the density, and the angle of internal friction of cohesionless soils and the shear strength of cohesive soils. The tests consists of driving a split spoon sampler, equipped with a cutting shoe and attached to the end of a drill rod, into a soil by dropping a 140 lb (63.6 kg) hammer a distance of 30 inches (0.76 m). A split spoon sampler is a thick-walled steel tube, split lengthwise, used to obtain undisturbed samples of soil from drill holes. The number of blows required for each 6 inches (150 mm) of penetration of the split spoon sampler is recorded. The standard penetration resistance is the sum of the blows for the second and third increments of 6 inches (150 mm) and is termed N in blows/ft (blows/300 mm).

Shear Strength Tests

The shear strength of a soil is the stress at which the soil fails in shear. It can be calculated by dividing the shear force at which a soil fails by the cross-sectional area of shear or, if the cohesion and angle of internal friction are known, by the general Coulomb equation.

$$s = c + \sigma \tan \phi$$

where c is the soil's cohesion (i.e. interparticle attraction) expressed in terms of force per unit area

σ is the overburden or surcharge pressure in terms of force per unit area

ϕ is the soil's angle of internal friction (i.e. resistance to interparticle slip) in degrees

Granular soils do not have cohesion and therefore shear strength is governed by overburden pressure that explains why granular pavement surface materials are inherently unstable. Undrained cohesive soils (e.g. soft and saturated clays) do not have internal friction and therefore shear strength is governed by cohesion that can vary with moisture content. Drained cohesive soils can have both cohesion and internal friction.

The shear strength of granular soils can be measured in a laboratory by the shear box test. Cohesion and the angle of internal friction of cohesive soils can be measured in a laboratory for drained and undrained conditions by triaxial compression tests. In the field, shear strength can be measured by the field vane shear test. Refer to a textbook on soil mechanics or geotechnical engineering for more information about the shear strength of soils and test methods.

Angle of Internal Friction - Geoweb Infill Material

The angle of internal friction of a cohesionless granular soil can be determined by measuring the maximum shear stress at failure over a range of normal stresses (i.e. confining pressures) and plotting the results on a graph. The angle formed by the best-fit straight line through the origin and the horizontal axis is a close approximation of the angle of internal friction. See Figure 5. For compacted granular materials, the angle of internal friction is typically within a range of 30° to 40°. The higher the quality of the granular material (e.g. angularity, gradation, hardness, etc.) the higher the angle of internal friction.

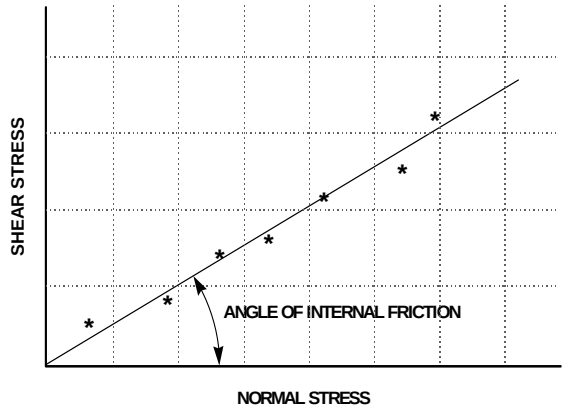


Figure 5 Angle of Internal Friction

Geoweb Cell Wall/Infill Friction Angle Ratio

The Geoweb cell wall/infill material friction angle ratio is the ratio of angle of shearing resistance between the infill material and the Geoweb cell wall over the peak friction angle of the infill soil in-isolation. It will vary depending upon the gradation and particle angularity of the infill material and the roughness of the cell wall or the size and spacing of perforations in the cell wall.

Shear box tests have been carried out to determine angles of shearing resistance between standard Geoweb cell wall treatments and typical granular materials. The results were expressed in terms of peak friction angle ratios (or Geoweb Cell Wall/Infill Friction Angle Ratio), where Peak Friction Angle Ratio is defined as the angle of shearing resistance between the granular infill and the Geoweb cell wall divided by the peak friction angle of the infill material in-isolation. Geoweb Cell Wall/Infill Friction Ratios for standard cell wall treatments and typical compacted granular materials are given in Table 3. The values presented in Table 3 are used to develop the relationships in Table 1 and base thickness in Table 5.

Table 3 Recommended Peak Friction Angle Ratio

Granular Infill Material	Cell Wall Type	$r = \delta/\phi$
Coarse Sand / Gravel	Smooth	0.71
	Textured	0.88
	Textured - Perforated	0.90
#40 Silica Sand	Smooth	0.78
	Textured	0.90
	Textured - Perforated	0.90
Crushed Stone	Smooth	0.72
	Textured	0.72
	Textured - Perforated	0.83

Design Calculations Granular Pavements

Illustrated here are the design procedures and calculations for determining aggregate thickness requirements for granular-surfaced pavements (e.g. access, utility and haul roads) both with and without the Geoweb cellular confinement system. Empirically derived bearing capacity coefficients are first used to determine the maximum allowable stress on a subgrade with either known or estimated shear strength. The maximum allowable stress is that stress which would cause local punching / shear failure of the subgrade under sustained loading conditions. Since granular pavement loads are transient, the effective strength of the soil is typically higher than it would be under static loading. Therefore, the maximum allowable stress is the limiting stress for design purposes. Boussinesq theory is then used to determine the required depth of granular cover beneath the design wheel load to ensure that the maximum allowable stress is not exceeded. The calculations outlined herein are intended for low volume roads where minor deformations are tolerable or for design of pavement subbase layers over soft soils. They are not intended for design of flexible pavement structures with paved surfaces. The calculations are only valid for granular pavement design over cohesive subgrade soils with CBR values less than 5.

Variable Names

c_u	Subgrade shear strength
N_c	Bearing capacity coefficient - based on design traffic - see below
P	Design wheel load
p	Contact pressure
r	Geoweb cell wall/Infill peak friction angle ratio
δ	Angle of shear resistance between the granular infill and Geoweb cell wall
ϕ	Angle of internal friction of the Geoweb infill material
z_t	Depth from surface to top of Geoweb cell walls
z_b	Depth from surface to bottom of Geoweb cell walls

Calculations

Determine the subgrade shear strength. Refer to Table 4 if the subgrade strength is reported in terms of Standard Penetration Resistance, CBR or by Field Identification.

Determine the maximum allowable stress on the subgrade, q_a

$$q_a = N_c c_u$$

where N_C = 2.8 (High Traffic, Low Rutting - from U.S. Forest Service guidelines)

N_C = 3.3 Low Traffic, High Rutting - from U.S. Forest Service guidelines)

Determine the required thickness of granular pavement, z_U, without the Geoweb cellular confinement system using the following equation (Boussinesq equation for estimating vertical stress at a given depth below a circular load re-written to calculate the depth of cover above a given vertical stress, q_a).

$$z_U = \frac{R}{\sqrt{\frac{1}{\left(1 - \frac{q_a}{p}\right)^{2/3}} - 1}}$$

where R = Radius of loaded area (i.e. effective radius of single or dual tires)

$$R = \sqrt{\frac{P}{p\pi}}$$

Determine the required thickness of granular pavement, z_G, with the Geoweb cellular confinement system.

Table 4 Correlation of Subgrade Soil Strength Parameters for Cohesive (Fine-Grained) Soils

California Bearing Ratio CBR (%)	**Undrained Shear Strength** c_u kPa (psi)	**Standard Penetration Resistance** SPT (blows/ft)	**Field Identification**
< 0.4	< 11.7 (1.7)	< 2	Very soft (extruded between fingers when squeezed)
0.4 - 0.8	11.7 - 24.1 (1.7) - (3.5)	2 - 4	Soft (molded by light finger pressure)
0.8 - 1.6	24.1 - 47.6 (3.5) - (6.9)	4 - 8	Medium (molded by strong finger pressure)
1.6 - 3.2	47.6 - 95.8 (6.9) - (13.9)	8 - 15	Stiff (readily indented by thumb but penetrated with great effort)
3.2 - 6.4	95.8 - 191 (13.9) - (27.7)	15 - 30	Very stiff (readily indented by thumbnail)
> 6.4	> 191 (27.7)	> 30	Hard (indented with difficulty by thumbnail)

The total required thickness of granular pavement with the Geoweb cellular confinement system is a function of the Geoweb cell depth, the depth of placement below the applied load, the wheel load and tire pressure and the infill material properties. Surface stress (i.e. wheel load contact pressure) is distributed both vertically and horizontally through the Geoweb cellular structure. Horizontal stresses, in turn, are converted into vertical resisting stresses along the cell walls thus reducing the total vertical stress directly beneath the center of the loaded area. The total resisting stress provided by the Geoweb cell structure is calculated and added to the maximum allowable stress on the subgrade for determination of the total required thickness of granular pavement with the Geoweb cellular confinement system.

The first step is to select the Geoweb section placement depth, z_t within the granular pavement structure. Since vertical stresses are higher near the surface, optimum performance and maximum thickness reduction are obtained by placing the Geoweb as close to the surface as possible. However, to protect the top of the Geoweb cell walls, a 25 mm to 50 mm (1 in to 2 in) aggregate wearing surface is typically recommended.

After selecting a trial depth of placement, calculate the vertical stress, σ_{vt}, at the top of the Geoweb section using the following equation.

$$\sigma_{vt} = p\left[1 - \left(\frac{1}{1 + \left(\frac{R}{z_t}\right)^2}\right)^{3/2}\right]$$

Next, calculate the vertical stress, σ_{vb}, at the bottom of the Geoweb section. The bottom depth, z_b, is the top depth, z_t, plus the thickness (or depth) of the Geoweb section.

$$\sigma_{vb} = p\left[1 - \left(\frac{1}{1 + \left(\frac{R}{z_b}\right)^2}\right)^{3/2}\right]$$

Calculate the horizontal stress at the top, σ_{ht}, and bottom, σ_{hb}, of the Geoweb section using the following equations.

$$\sigma_h = K_a \sigma_v$$

where K_a is the coefficient of active earth pressure.

$$K_a = \tan^2\left(45 - \phi/2\right)$$

Horizontal stress at the top of the Geoweb section, σ_{ht}

$$\sigma_{ht} = K_a \sigma_{vt}$$

Horizontal stress at the bottom of the Geoweb section, σ_{hb}.

$$\sigma_{hb} = K_a \sigma_{vb}$$

The average horizontal stress on the Geoweb cell walls is then determined as follows.

$$\sigma_{avge} = \frac{\left(\sigma_{ht} + \sigma_{hb}\right)}{2}$$

Next, calculate the reduction in stress, σ_r, directly beneath the center of the loaded area due to stress transfer to the Geoweb cell walls using the following equation.

$$\sigma_r = 2\left(\frac{H}{D}\right)\sigma_{avge}\tan\delta$$

where H = Geoweb cell depth in mm (in)

D = Effective Geoweb cell diameter = 190 mm (7.5 in)

δ = Angle of shearing resistance between granular infill material and Geoweb cell walls.

$\delta = r\phi$ (obtain test data or estimate r from Table 3)

Determine the design allowable stress, q_G, on the subgrade with the Geoweb cellular confinement system using the following equation.

$$q_G = q_a + \sigma_r$$

Determine the total required thickness of granular pavement, z_G, with the Geoweb cellular confinement system.

$$z_G = \frac{R}{\sqrt{\frac{1}{\left(1 - \frac{q_G}{p}\right)^{2/3}} - 1}}$$

If the total required thickness is greater than the surface thickness (i.e. depth to the top of the Geoweb section); in addition, the depth of the Geoweb section, a subbase layer is required. The thickness of the subbase layer must be equal to the total required thickness minus the surface thickness and the Geoweb section depth.

Using the equations presented herein, Table 5 gives base/subbase thickness requirements vs. cell wall type for the Geoweb load support system, under the following load condition:

- 203 mm (8 in) depth of Geoweb section,
- crushed stone infill,
- 38 degree friction angle,
- 690 kPa (100 psi) tire pressure,
- 25 mm (1 in) depth of cover over the Geoweb section,
- 2.8 bearing capacity coefficient.

Table 5 Total Thickness of Coarse Sand / Gravel Base Including Geoweb Section

Subgrade CBR	Wheel Load		Smooth r = 0.71		Textured r = 0.88		Textured - Perforated r = 0.90		Unconfined Stone	
%	kN	(lbf)	mm	(in)	mm	(in)	mm	(in)	mm	(in)
0.2	**27**	**(6,000)**	277	(10.9)	241	(9.5)	236	(9.3)	876	(34.5)
	53	**(12,000)**	366	(14.4)	315	(12.4)	310	(12.2)	1240	(48.8)
	111	**(25,000)**	490	(19.3)	419	(16.5)	411	(16.2)	1788	(70.4)
	222	**(50,000)**	655	(25.8)	556	(21.9)	546	(21.5)	2527	(99.5)
0.5	**27**	**(6,000)**	251	(9.9)	221	(8.7)	218	(8.6)	546	(21.5)
	53	**(12,000)**	335	(13.2)	292	(11.5)	287	(11.3)	772	(30.4)
	111	**(25,000)**	450	(17.7)	389	(15.3)	384	(15.1)	1113	(43.8)
	222	**(50,000)**	605	(23.8)	518	(20.4)	511	(20.1)	1575	(62.0)
1.0	**27**	**(6,000)**	218	(8.6)	203	(8.0)	203	(8.0)	376	(14.8)
	53	**(12,000)**	292	(11.5)	257	(10.1)	254	(10.0)	531	(20.9)
	111	**(25,000)**	396	(15.6)	345	(13.6)	340	(13.4)	767	(30.2)
	222	**(50,000)**	536	(21.1)	465	(18.3)	457	(18.0)	1085	(42.7)
2.0	**27**	**(6,000)**	203	(8.0)	203	(8.0)	203	(8.0)	251	(9.9)
	53	**(12,000)**	231	(9.1)	206	(8.1)	203	(8.0)	353	(13.9)
	111	**(25,000)**	315	(12.4)	279	(11.0)	274	(10.8)	536	(21.1)
	222	**(50,000)**	429	(16.9)	376	(14.8)	368	(14.5)	721	(28.4)

NOTE: The above wheel load values are from either single or dual wheels. For axle loads multiply by 2. **This table is based on theoretical methodologies outlined herein. Values are for comparative purposes only and are not a substitute for project specific design.**

THE GEOWEB® LOAD SUPPORT SYSTEM TECHNICAL OVERVIEW

Available Tools & Services

Presto Geosystems and its authorized distributors offer assistance to anyone interested in evaluating, designing, building or purchasing a Geoweb load support system. You may access these services by calling 800-548-3424 or 920-738-1118. In addition to working directly with you, the following information has been specifically developed and available for your use with the **Geoweb Load Support System**.

General Overview	Product data, basic engineering concepts and theory for general application of the Geoweb system.
Application Overview	How the system works, specific to the application area.
Case Histories	Specific project information on the design, construction and performance of the Geoweb system for all application areas.
SPECMaker™ Specification Development Tool	A software tool available to develop complete material and construction specifications specific both to the application area and to details controlling the specific project.
Design Package	
System Component Guideline	A set of tables relating system components to application areas.
Request for Project Evaluation	An application-specific project checklist to ensure all relevant data is collected for detailed engineering design of the Geoweb system.
Material Specification	An inclusive specification for most variations of the Geoweb material, anchoring materials, tendons, etc. See SPECMaker™ Tool.
CSI Format Specifications	Comprehensive guide specification & product description of the Geoweb cellular confinement system in the standard CSI format.
Construction Specifications	Available through SPECMaker™ Tool.
AutoCAD® Drawings	Drawings in DWG format and paper copy providing all the engineering details needed for plans with the Geoweb system.
Technical Overview	An application-specific, in-depth discourse centered on the theory and application of theory to solving problems with the Geoweb system.
Construction Package	
Installation Guideline	An illustrated, application-specific, guideline for installation of the Geoweb system.
Other Resources	
Videos	***Advancing Geotechnology*** ***Construction Techniques – Load, Slope & Channel*** ***Construction Techniques – Earth Retention*** Available in Multiple Languages
Technical Resources Library CD	All of the above and more. Requires Microsoft® Internet Explorer 4.0 and Windows® 95 minimum.
Project Evaluation Service	Available through authorized distributors and representatives for all applications of the Geoweb cellular confinement system.

Disclaimer

This document has been prepared for the benefit of customers interested in the Presto Geoweb Cellular Confinement System. It was reviewed carefully prior to publication. Presto Products Company assumes no liability and makes no guarantee or warranty as to its accuracy or completeness. Final determination of the suitability of any information or material for the use contemplated, or for its manner of use, is the sole responsibility of the user.

References

1. Bathurst, Richard J. and Jarrett, Peter M., *Large-Scale Model Tests of Geocomposite Mattresses over Peat Subgrades*, Transportation Research Record 1188, 1988
2. Christopher, Barry R. and Holtz, Robert D., *Geotextile Engineering Manual*, Course Text, Prepared for Federal Highway Administration, National Highway Institute, Washington, D.C. under Contract DTFH61-80-C-00094
3. Guido, Vito A. and Sotirakis, N. Chirstou, *Bearing Capacity and Settlement Characteristics of Geoweb-Reinforced Earth Slabs*, "Special Topics in Foundations", ASCE 1988 Spring Meeting, Nashville, TN, May 9-11, 1988
4. Jamnejad, G, Kazerani, G., Harvey, R.C. and Clarke, J.D., *Polymer Grid Cell Reinforcement in Pavement Construction*. Proceedings, 2nd International Conference on Bearing Capacity of Roads and Airfields, Plymouth, U.K., Sept. 1986, pp. 537-546
5. Kazerani, G. and Jamnejad, G., *Polymer Grid Cell Reinforcement in Construction of Pavement Structures*, Proceedings, Geosynthetics '87 Conference, New Orleans, LA, Feb. 1987
6. Koerner, Robert M., Designing with Geosynthetics, Prentice-Hall, 1986
7. Mitchell, J. K., Kao, T. C. and Kavazanjian, E., *Analysis of Grid Cell Reinforced Pavement Bases*, Report GL-79-8. Geotechnical Laboratory, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, July 1979
8. Rea, C. and Mitchell, K., *Sand Reinforcement Using Paper Grid Cells*, Proceedings, Symposium on Earth Reinforcement, ASCE Annual Convention, Pittsburgh, PA, April 27, 1978, pp. 644-663
9. Steward, J. E., Williamson, R. and Mohney, J., *Guidelines for Use of Fabrics in Construction and Maintenance of Low Volume Roads*, U.S. Forest Service, Portland, OR, June 1977
10. Webster, S. L., *Investigation of Beach Sand Trafficability Enhancement Using Sand-Grid Confinement and Membrane Reinforcement Concepts*, Report GL-79-20 (1). U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, Nov. 1979
11. Webster, S. L. and Alford, S. J., *Investigation of Construction Concepts for Pavements Across Soft Ground*, Report S-78-6. Geotechnical Laboratory, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, July 1978
12. Webster, S. L. and Watkins, J. E., *Investigation of Construction Techniques for Tactical Approach Roads Across Soft Ground*, Report S-77-1. Soils and Pavements Laboratory, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, Feb. 1977
13. Yoder, E.J. and Witczak, M.W, Principles of Pavement Design, Second Edition, John Wiley & Sons, Inc., 1975

Appendix B: Laboratory Procedures for Determining Suspended Sediment Concentration

LABORATORY PROCEDURES FOR DETERMINING SUSPENDED SEDIMENT CONCENTRATION

Oregon State University
Department of Forest Engineering

Revision Dates:
1/5/07

Table of Contents

Materials:

Sample bottles

Washed bottles with DI (deionized) water for blanks

Vacuum filtration manifold with Buchner funnels

Vacuum pressure hose/rubber stopper/glass tube assembly for carboy and vacuum line

Vacuum pump

Large carboy for filtrate

Desiccator cabinet and jar of desiccant

Liqui-Nox soap

Forceps/tweezers

1.5 µm glass fiber filter paper (Whatman 934-AH) sized to fit Buchner funnels – **ALWAYS** HANDLE GLASS FIBER FILTER PAPERS WITH FORCEPS/TWEEZERS

Oven at 105° C

Baking pans and aluminum foil

Analytical balance accurate to 0.0001 gram for weighing filters

Macro balance able to handle load of one sample bottle filled with sediment and water

Preparing Filters

1. Always handle filters with forceps. (A fingerprint weighs approximately 0.0001 gm. This adds a 10% error for a sample that contains 0.0010g of sediment.)
2. Write the filter ID number on one side of filter with ultra-fine Sharpie. Underline the numbers as necessary to avoid confusion if read upside down. (Example: 6 and 9 can be confused when not underlined).
3. Put filters in oven for 24 hours at 105 degrees C.
4. After 24 hours put filters in desiccator for about 10 minutes to allow for cooling. Do not remove filters from desiccant cabinet until you are ready to weigh them since they will absorb moisture from the air and alter the actual filter weight.
5. Weigh filter on analytical balance using forceps to handle filter.
6. Record filter ID number and oven dry weight on filter record sheet. If a filter is contaminated or punctured, discard that filter and check it as a “discarded” on filter record sheet.
7. When preparing filters ahead of time put filters in Ziploc baggies for storage.

Turbidity

1. Check sample log for the earliest logged samples. Get those samples/bins from cooler to process. If Toman samples refer to ‘Toman SSC flow chart’ otherwise

refer to 'SSC Flow chart'.

2. Organize samples in numerical order and record sample ID on SSC data sheets. Make sure to circle which site samples are from and record run number at the top of data sheet.
3. For **Oak Creek** samples log ID into log book, shake bottle to re-suspend sediment and pour aliquot into scintillation vial with corresponding label from logbook. Initial SSC data sheet to indicate samples have been split.
4. For **Toman** samples look for sample ID. If there is no ID go to logbook and assign ID and record on bottle.
5. Set up turbidimeter by running Gelex secondary standards to verify accuracy of calibration.
6. Record Gelex standards value on Turbidimeter calibration checklist.
7. Shake ISCO sample bottle several times to re-suspend sediment in solution.
8. Pour an aliquot of sample into clean sample vial provided in the turbidimeter kit.
9. Clean sample vial with Kim-wipe, apply silicone with soft cloth and align vial in turbidimeter – diamond orientated towards the front aligned with the dash on unit. (It is very important to always use the diamond as your vial orientation reference when lining it up in the unit. This allows for consistent measurements between samples.)
10. Pour contents of sample vial into dish pan or other waste bucket and rinse sample vial 3 times with DI water. Waste water can be disposed of as needed.
11. Update SSC data sheet with initials to indicate you were the one to run turbidity.
12. Update Sample Log sheet with date and initials indicating turbidity has been run.
13. Check turbidity box on bin label indicating that turbidity has been run.

Weighing Sample Bottles

1. After turbidities have been run weigh each sample bottle on the macro balance.
2. Tare balance and make sure the balance is level by examining level bubble. If it is not in the black circle (which indicates balance) adjust dials on balance legs/feet until bubble rests in that black circle.
3. Check to see the last time the balance calibration was checked. It should be done once a week. Check calibration if necessary and record standard weights on log sheet.
4. Remove cap from sample bottle and weigh. Record weight on SSC data sheet. Repeat for all samples being processed.
5. Initial and date SSC data sheet to indicate bottles weighed.
6. Check 'weights' on bin label indicating that weights have been taken.

Filtration Process

1. Take oven dry filters from storage or desiccator and record oven dry weights on SSC data sheet along with filter number. Update SSC data sheet with initials to indicate you were the one to transfer OD weights of filter.

2. Line up samples in order on data sheet and in numerical order with filter numbers assigned in previous step.
3. Seat filters with numbered side down on the vacuum filter cup. Wet filters with DI water. This will create a seal and prevent floating of the filter paper during sample filtration.
4. Line up bottles in front of filter apparatus with corresponding filter in cup.
5. Turn on the vacuum making sure that at least two (2) lines of the manifold are open/on. Check for holes in filters - if there is a hole, the air will make a whistling sound. If so, replace filter with another number, update oven dry weight and record new filter number on SSC data sheet.
6. Pour sample into the funnel **slowly**, taking care that suction is continuously maintained. (If the water has too much sediment, just filter what you can on the first filter and filter the remainder with another filter and combine the sediment weights.)
7. Rinse sample bottle with DI water and filter cup sides with DI water to ensure all sediment has been removed from bottle and now resides on the filter. **Watch the carboy to make sure it isn't too full to pull water through the lines; empty the carboy as needed.**
8. Turn off the vacuum and carefully remove filter. Place filters on foil lined baking pan or cookie sheet and heat in oven at 105^0C for 24 hours.
9. Clean funnels with DI water and Kimwipes between samples and after use.
10. Filter at least one (1) blank filter paper per run using only DI water. Note: filter from blanks will typically lose weight; this represents loss of filter fibers during filtration.
11. Record spills, errors, or notes in the comment column of the data form. It is important to record any observations or suspicions that may explain unusual results.
12. Indicate on oven log the pan label, when the filters were placed in the oven and when they can come out. Also update the whiteboard drawing to indicate where in the oven the pans were placed.
13. Remove pan from oven and place filters in desiccant cabinet to cool for at least 10 minutes before weighing. Do not remove filters from desiccant cabinet until you are ready to weigh them since they will absorb moisture from the air.
14. Tare analytical balance and make sure the balance is level by examining level bubble. If it is not in the black circle (which indicates balance) adjust dials on balance legs/feet until bubble rests in that black circle.
15. Check to see the last time the balance calibration was checked. It should be done once a week. Check calibration if necessary and record standard weights on log sheet.
16. Weigh each filter and record the weight on SSC data sheet. Record initials on SSC data sheet indicating you were the one to weigh filters.
17. Update Sample Log sheet with date and initials indicating filtration has been done.

18. Check ‘filtered’ and ‘to be washed’ boxes on bin label indicating that samples have been filtered and bottles need to be washed.
19. Initial and date SSC data sheet to indicate samples have been filtered.

Washing bottles

1. Collect bottles to be washed near sink. LEAVE ALL LABELS ON BOTTLES!!
2. Fill sink or wash bin with water and Liqui-Nox soap. Rinse bottles and caps three times in soapy water and use scrub brush to clean inside bottles.
3. Rinse bottles and caps three times in tap water.
4. Rinse bottles and caps three times in DI water.
5. Place in bins to air dry.

Weighing Empty Bottles

1. Once bottles have dried completely weigh (without caps) on macro balance and record weights on SSC data sheet.
2. Initial SSC data sheet to indicate complete.
3. Check ‘Clean bottle weights’ on bin label indicating that weights have been taken.
4. Remove labels from bottles.

Notes:

- The samples should be processed in approximately the same order in which they arrive at the lab. This limits the amount of evaporation from the bottles, reduces fading of the labels, and generally keeps the processing as parallel to the sampling as possible.

- Dry the desiccant at 200 C for two hours or until blue. Keep the desiccant cabinet door closed as much as possible and the transfer desiccant quickly. Periodically grease the door seal with silicon lubricant.

Adapted from:

Method 2540D in: Clesceri, L.S., A.E. Greenberg and A.D. Eaton, eds. 1998. Standard Methods for the Examination of Water and Wastewater. 20th ed. American Public Health Association, Washington, DC.

USFS Redwood Sciences Lab Sediment Lab Manual. Laboratory Procedures for Determining Suspended Sediment Concentration. 13p. Arcata, California. http://www.fs.fed.us/psw/topics/water/tts/manuals/sedlab_manual.doc

Appendix: Computation of Suspended Sediment Concentration

Equations for computation of suspended sediment concentration:

SSC (mg/L) = (Mass of sediment x 1000000)/ Actual volume of sample (ml)

Mass of sediment (g) = Mass of sediment and filter (g) – mass of oven-dried filter (g)

Calculated volume (g) = Mass of bottle and sample (g) - mass of bottle (g)

Actual mass of water in sample (ml) = (calculated volume (g) - mass of sediment (g)) x (1ml/g)

Mass of sediment/particle density (2.65 g) converted to ml = (mass of sediment (g) / 2.65 g) x (1 ml/g)

Actual volume of sample (ml) = Actual mass of water in sample (ml) + Mass of sediment converted to ml

Note:
Assumption: density of water is 1gm/ml therefore 1 gm of water has a volume of 1 ml
Assumption: Particle density = 1 cc of soil = 2.65 g

Appendix: Photos of vacuum filtration manifold

Figure 1. Vacuum filtration manifold with 8-55mm Buchner funnels.

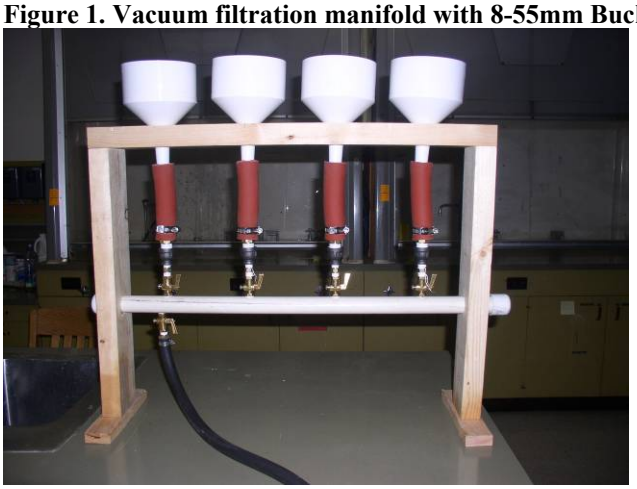
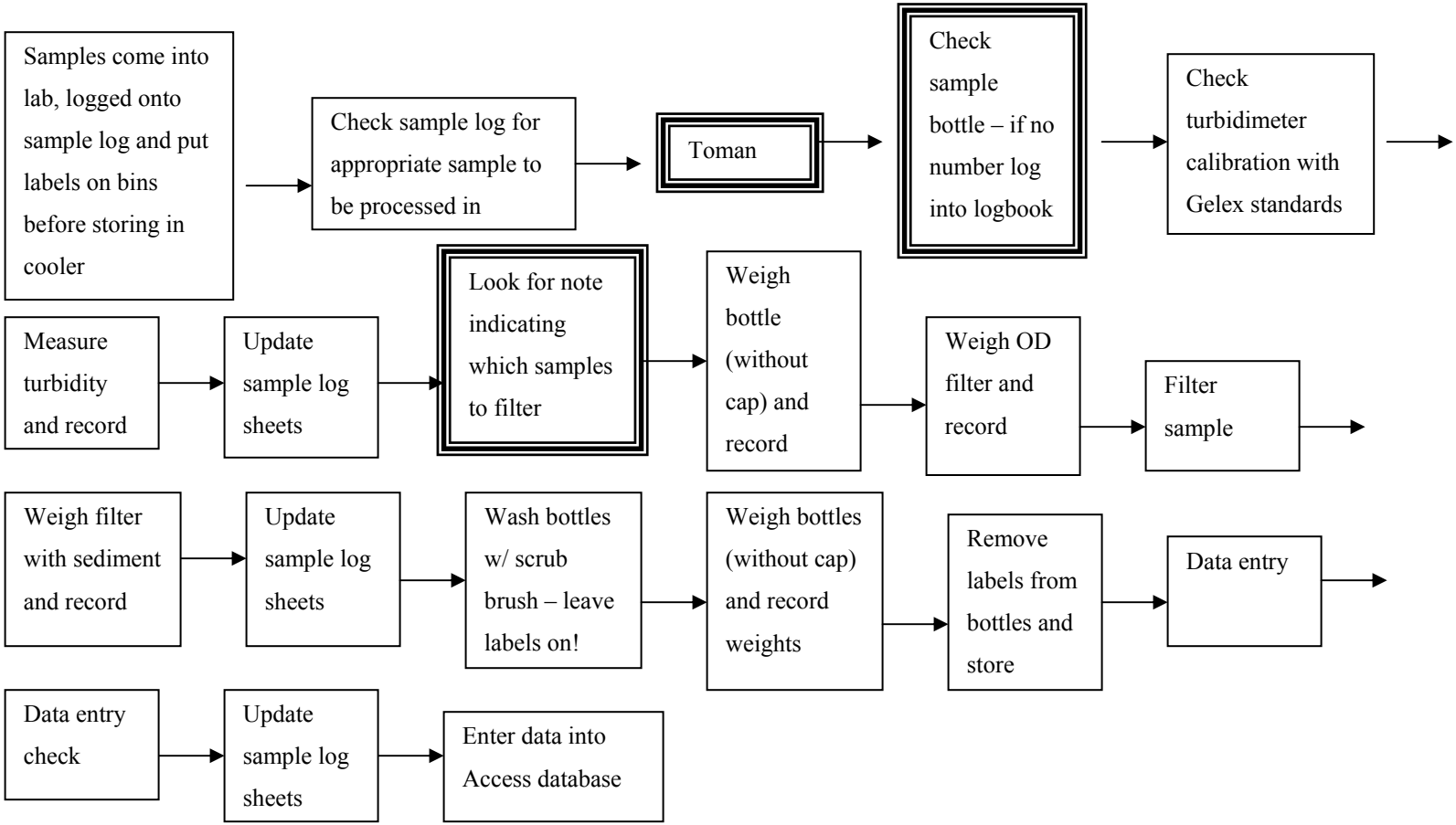


Figure 2. Vacuum filtration manifold with 4-110mm Buchner funnels.

SSC Flow Chart – TOMAN



Appendix C: EnviroGrid EGA20 specifications

EnviroGrid®

EnviroGrid® Adjustable (EGA) Series is designed to provide more flexibility in section size than regular EnviroGrid®. Section and cell size will change as each section is expanded to the required dimension. Section length can be increased or decreased by adding or subtracting cells at no additional charge.

EGA Series Nomenclature
(XA) Nominal Panel Length in feet (20, 30, and 40)
(P) If Perforated
EGAXAYP – NC (number of cells long)
(Y) Cell Depth in Inches (3, 4, 6, and 8)

EGA20

Example EGA204P - 29

EGA Standard sections are manufactured from 58 strips of HDPE, resulting in a section length of 29 cells and 10 cells wide. Each strip is the appropriate width and 142 inches (3.6m) in length. Weld spacing is 14.0 in ± .12 in (355 ± 3mm). Cell density is 35 cells per meter squared. Cell walls are smooth and if perforations are required 11% ± 2% of the cell wall is removed.

MATERIAL PROPERTIES	TEST METHOD	UNIT	TEST VALUE
Minimum Polymer Density	ASTM D 1505	g/cm^3 (lb/ft^3)	0.940 (58.7)
Environmental Stress Crack Resistance	ASTM D 1693	hrs	3400
Carbon Black Content	ASTM D 1603	% by weight	1.5% minimum
Nominal Sheet Thickness	ASTM D 5199	mm (mils)	1.25 (50)±5%

PHYSICAL PROPERTIES	UNIT	TYPICAL VALUE			
Nominal-Expanded Cell Size (width x length)	mm (in)	259 (10.2) x 224 (8.8)			
Nominal-Expanded Cell Area	cm^2 (in^2)	289 (44.8)			
Nominal-Expanded Section (width x length)	m (ft)	2.56 (8.4) x 6.52 (21.4)			
Nominal-Expanded Section Area (width x length)	M^2 (ft^2)	16.7 (180)			
Cell Depth	mm (in)	75 (3.0)	100 (4.0)	150 (6.0)	200 (8.0)
Seam Peel Strength[1]	N (lbs)	1065 (240)	1420 (320)	2130 (480)	2840 (640)
Flexural Strength	--	15 layers of a 102mm (4.0 in) perforated material shall be tested for flexural strength (simply supported beam) per ASTM D 790 modified. Minimum value Flexural Stiffness (EI) of 40,000 (lb-in^2), cross-head speed 0.5, in/min, EI = PL3/48fc			
Section Weight	Kg(lbs)	19.5(43)	25.9(57)	39(86)	51.7(114)
Sections per Pallet	--	60	50	30	25
Seam Hang Strength	--	A 102mm (4.0in) weld joint supporting a load of 72.5 kg (160 lbs) for 30 days minimum or a 102mm (4.0in) weld joint supporting a load of 72.5 kg (160 lbs) for 7 days minimum while undergoing temperature change from 23°C (74°F) to 54°C (130°F) on a 1 hour cycle.			

[1] *Seam Peel Strength per U.S. Army Corps of Engineers Technical Report GL-86-19, Appendix A*

[2] *Licensed from the United States Army under Patent No. 4,797,026.*

GEO PRODUCTS, LLC
8615 Golden Spike Lane ❖ Houston, TX 77086
Phone: (281) 820-5493 ❖ Fax: (281) 820-5499
www.geoproducts.org

10/12/04