# PREDICTING SCOUR
# IN WEAK ROCK
# OF THE OREGON COAST RANGE

**Final Report**

**SPR 382**

RESEARCH

*Oregon Department of Transportation*

# PREDICTING SCOUR
# IN WEAK ROCK
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**SPR 382**

by

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16. ABSTRACT

Recent experience in the Coast Range Province of Oregon demonstrates that weak sedimentary bedrock in stream channels can be vulnerable to scour. The presence of erodible rock adjacent to bridge foundations and abutments necessitates monitoring of the channel to preclude costly repairs, or in an extreme case undermining of the foundations and bridge collapse. Current design methods are not well suited for evaluating the potential for scour in weak rock, nor can the rate of scour be estimated. A design method for the latter would be useful for identifying the depth that the foundation should be socketed into the potentially scourable rock given the design life for the bridge. In an effort to relate the rate of scour in weak sedimentary rocks to the geological and geotechnical characteristics of the rock, as well as the hydraulic characteristics of the streams, a pilot study of eleven bridge sites was conducted. Geomechanical index tests were performed on bedrock specimens and the hydraulic properties of the stream channels were evaluated. A preliminary model has been proposed wherein the rate of degradation of the stream channel is related to the abrasive resistance of the bedrock and the hydraulic power of the stream. The proposed method can be used to obtain an approximate estimate of the degradation of unobstructed channels in weak sedimentary rock due to abrasion by bedload and flood events. The effects of local, or contraction, scour were not evaluated.

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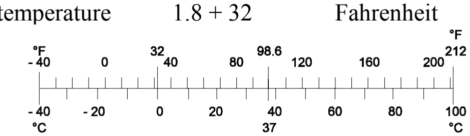
# SI* (MODERN METRIC) CONVERSION FACTORS

## APPROXIMATE CONVERSIONS TO SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | 25.4 | millimeters | mm |
| ft | feet | 0.305 | meters | m |
| yd | yards | 0.914 | meters | m |
| mi | miles | 1.61 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 645.2 | millimeters squared | $mm^2$ |
| $ft^2$ | square feet | 0.093 | meters squared | $m^2$ |
| $yd^2$ | square yards | 0.836 | meters squared | $m^2$ |
| ac | acres | 0.405 | hectares | ha |
| $mi^2$ | square miles | 2.59 | kilometers squared | $km^2$ |
| | | **VOLUME** | | |
| fl oz | fluid ounces | 29.57 | milliliters | mL |
| gal | gallons | 3.785 | liters | L |
| $ft^3$ | cubic feet | 0.028 | meters cubed | $m^3$ |
| $yd^3$ | cubic yards | 0.765 | meters cubed | $m^3$ |
| NOTE: Volumes greater than 1000 L shall be shown in $m^3$. | | | | |
| | | **MASS** | | |
| oz | ounces | 28.35 | grams | g |
| lb | pounds | 0.454 | kilograms | kg |
| T | short tons (2000 lb) | 0.907 | megagrams | Mg |
| | | **TEMPERATURE (exact)** | | |
| °F | Fahrenheit temperature | 5(F-32)/9 | Celsius temperature | °C |

## APPROXIMATE CONVERSIONS FROM SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | Millimeters | 0.039 | inches | in |
| m | Meters | 3.28 | feet | ft |
| m | Meters | 1.09 | yards | yd |
| km | Kilometers | 0.621 | miles | mi |
| | | **AREA** | | |
| $mm^2$ | Millimeters squared | 0.0016 | square inches | $in^2$ |
| $m^2$ | Meters squared | 10.764 | square feet | $ft^2$ |
| ha | Hectares | 2.47 | acres | ac |
| $km^2$ | Kilometers squared | 0.386 | square miles | $mi^2$ |
| | | **VOLUME** | | |
| mL | Milliliters | 0.034 | fluid ounces | fl oz |
| L | Liters | 0.264 | gallons | gal |
| $m^3$ | Meters cubed | 35.315 | cubic feet | $ft^3$ |
| $m^3$ | Meters cubed | 1.308 | cubic yards | $yd^3$ |
| | | **MASS** | | |
| g | Grams | 0.035 | ounces | oz |
| kg | Kilograms | 2.205 | pounds | lb |
| Mg | Megagrams | 1.102 | short tons (2000 lb) | T |
| | | **TEMPERATURE (exact)** | | |
| °C | Celsius temperature | 1.8 + 32 | Fahrenheit | °F |




* SI is the symbol for the International System of Measurement

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# DISCLAIMER

**PREDICTING SCOUR IN WEAK ROCK
OF THE OREGON COAST RANGE**

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# LIST OF SYMBOLS

| | |
|---|---|
| $I_d$ | Slake Durability Index |
| RQD | Rock Quality Designation |
| $K_h$ | Erodibility Index |
| β | Abrasion Number |
| $q_u$ | Unconfined Compressive Strength |
| ρ | Density of water |
| Ω | Integrated Stream Power (Average energy per unit area expended during a flood) |

# DEFINITIONS

**Abrasion Number (β)**: The abrasion resistance of rock specimens is evaluated using a modified version of the slake durability test (ASTM D4644), herein referred to as the "Continuous Abrasion" test. The percent weight loss of the rock specimen is plotted versus time (on a natural logarithmic scale) and the slope of the line between 120 minutes and 500 minutes is defined as the *Abrasion Number*.

**Average erosion**: In this study the degradation of stream channels over time is established using elevation data from two surveys performed several years or decades apart. Elevation data is generally obtained at 0.3 m to 0.5 m intervals across the channel. The amount or rate of erosion is not uniform across the channel, therefore a single erosion value that is representative of the entire perennially saturated width of the channel has been defined for use in the development of the empirical scour model. The *average erosion* that has occurred during the time interval between the two surveys is computed as the average of all the channel elevation changes measured in 0.3 m to 0.5 m wide sections of the channel.

**Stream power**: Power is defined as a rate of doing work or a rate of expending energy. The concept of a rate of energy dissipation per unit width of flow has been adopted in this study. Stream power is defined as:

$$P = \gamma q s_f L = \gamma q \Delta E \qquad (s_f L = \Delta E)$$

where $\gamma$ is the unit weight of water ($kN/m^3$), q is the unit discharge ($m^3/s\cdot m$), $s_f$ is the slope of the energy grade line, L is unit length, and $\Delta E$ is the energy loss per unit width of water (m) which is approximately related to the bed slope. The units for the rate of energy dissipation, or stream power, per unit width are $kW/m^2$.

**Integrated stream power (Ω)**: Daily discharge data can be readily converted to daily stream power given the channel geometry. In this investigation a cumulative stream power was computed as the hydraulic power that was expended during the time interval between the two baseline channel surveys. The cumulative stream power over the desired period is computed from the plot of daily stream power versus time. The *integrated stream power* (Ω) is the summation of the area under the daily power curve over the time period of interest. This is accomplished using a numerical integration technique to compute the cumulative, or integrated, stream power over the specified time interval.

# 1.0 INTRODUCTION

## 1.1 STATEMENT OF THE PROBLEM

Current practice for estimating maximum scour depths in stream channels utilizes analysis methods that are based on sand bed material. These methods are not directly applicable for scour analysis of weak, jointed and/or weathered bedrock, which is common in the Coast Range of Oregon. The lack of design methods for this type of material necessitates a potentially over-conservative approach to estimating scour depths. Primary consequences of the limitations posed by these design methods are two-fold: (1) costly and labor intensive monitoring of foundations at existing bridge sites where the rate of bedrock scour may not be sufficient to warrant continuous observation, and (2) on new projects (where economical spread footings may be appropriate), deep foundations and/or extensive rip-rap protection must be specified due to the uncertainty in the estimated depth of scour that may occur over the service life of the bridge.

At sites underlain by weak rock, foundation design has traditionally relied on deep foundations in order to obtain secure bearing beneath the potential zone of scour. This has been due to the conservative practice of applying methods of analysis for scour that are based on cohesionless soil bedload. These methods are not well suited for estimating scour due to abrasion in sedimentary rock formations such as shales, siltstones and sandstones. Recent Federal Highway Administration (FHWA) guidelines for scour require assessments and/or monitoring programs at scour-susceptible sites. The federal scour program requires evaluation of potential erosion from pier and contraction scour, and long-term aggradation/degradation around the footings of bridges spanning waterways. As a result of these evaluations, each structure will be classified according to the potential for critical scour. All scour critical structures will eventually require either permanent scour mitigation measures or continual observation in accordance with an approved scour monitoring program. Several state transportation departments have expressed concern that the uncertainty associated with estimating scour at weak rock sites could result in a rather arbitrary classification of these sites as scour prone as a conservative measure.

In the state of Oregon there are 5,408 bridges greater than 6 m in length that span waterways. These bridge sites must be evaluated for risks posed by scour. The Oregon Department of Transportation (ODOT) is charged with managing approximately 2,640 bridges, of which about 65% are over water. Figure 1.1 summarizes a survey of all the state bridges over water in Oregon. Of these bridges, 44% are pile supported and 16% are spread footings on non-erodible material. It is significant to note that 40% of the bridges are supported by spread footings on erodible material *(Bryson 1998)*. The remaining bridges are maintained by city, county, and other governmental organizations. In order to optimize the resources that are devoted to scour assessments and monitoring programs, a method of prioritizing the potentially hazardous bridge sites will be necessary.

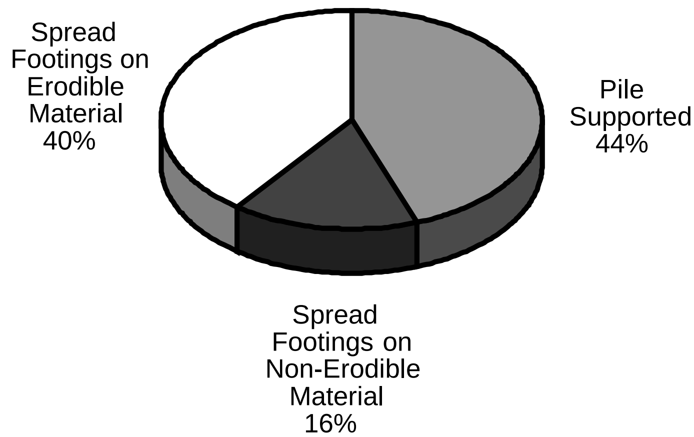


Figure 1.1: Summary of ODOT Bridge Foundations of Bridges over Water

A large percentage of ODOT bridges have spread footings on potentially erodible material. Many of these bridges are founded on weak rock that has been classified as erodible material. It should be noted that the rate of scour in most rock masses is much less than that observed in cohesionless soils, therefore the risk of catastrophic undermining of bridge foundations in rock and collapse of the structure is substantially smaller, provided that routine foundation inspections are made. Despite the lower risk of catastrophic failure, bridge footings on weak and jointed rock can, however, lead to chronic maintenance problems requiring close monitoring, channel modification, and/or footing protection.

## 1.2 OBJECTIVES AND SCOPE OF THE PROJECT

Many of the prevalent geologic units in the Coast Range Province of Oregon consist of weak, jointed and weathered sedimentary rock. Classification methods based on geomechanical rock properties demonstrate a range of behavior of these units that vary from weakly cemented soil to strong rock that may serve as a competent bearing material. Engineers with ODOT's Bridge Section have identified several sites in this region where the bedrock adjacent to bridge footings shows evidence of scour. The lack of guidelines for estimating the potential for significant scour over the service life of the bridges, combined with the federally mandated scour program presents a challenge for the engineering geologists, foundation engineers and hydraulics engineers charged with identifying potentially vulnerable bridges and prioritizing the bridges requiring scour monitoring and remedial measures.

This investigation represents a multi-disciplinary pilot project intended to combine geotechnical and hydraulic concepts in the development of a method for estimating scour in weak rock masses. The primary objectives of this investigation were to determine the significant factors affecting scour susceptibility of rock masses, determine geotechnical properties of the materials, apply standard of practice methods in hydraulic engineering, and to develop recommendations for evaluating the scour susceptibility of weak rock. Specific objectives include:

1. Perform an extensive review of the technical literature to establish the current state of knowledge concerning the erodibility of weak rock and the potential for scour under hydraulic conditions representative of natural streams.
2. Identify as many field sites as practicable so that the geomechanical and hydraulic characteristics represented in the collection are suitably varied.
3. Determine the historical rate of erosion at the selected sites.
4. Perform relevant geotechnical engineering index tests on specimens from the field sites in order to quantify the strength and abrasion resistance of the material.
5. Survey stream channels to compare the current geometry of the channels to the conditions that existed when the bridges were constructed. From these channel cross sections the extent and rate of channel degradation can be obtained.
6. Correlate the historical rate of erosion to selected geotechnical and hydraulic parameters, if possible.
7. Develop preliminary guidelines for classifying potentially scour susceptible rock and for estimating the rate of scour in weak rock.
8. Recommend areas where further study is warranted.

After an extensive review of office documents and field reconnaissance of numerous candidate sites, eleven bridge sites in the Oregon Coast Range were selected based on evidence of erosion, continuity of historical stream gauge information, site geology, and the nature of the bedrock exposure across the channel. Rock consisted of sedimentary lithologies varying from very soft siltstones to hard tuff. The research effort focused on relating the average rate of scour across a natural stream channel to the geomechanical properties of the rock and the hydraulic power of the water flowing over the rock. It should be noted that the effects of local scour and contraction scour were not investigated. The methods proposed herein are viewed as a point of departure for the development of more sophisticated analyses that account for critical factors such as local scour and contraction scour, both of which increase the stream power adjacent to bridge foundations. It is proposed that these phenomena could be accounted for in an approximate sense with the application of adjustment factors for local and contraction scour that have been applied by Smith *(1994)* to the rock erodibility method of Annandale *(1995)* as outlined in the following chapter.

## 1.3 RESEARCH PREMISE

In developing the scope of the investigation it was acknowledged that geologic, geotechnical and hydraulic factors must all be accounted for in the development of a method for evaluating scour in rock. In the formative stages of the project engineers at the ODOT and at Oregon State University (OSU) determined that the complexity of the rock scour phenomenon in natural channels precluded flume studies and numerical simulation. For this reason an empirical study based on measured changes in channel morphology and the hydraulic conditions that existed over the time interval of interest was conceived.

The empirical method has the inherent advantage of "accounting" for all of the variables influencing the rate of scour in rock stream channels. Interpreting the relative influence of the numerous variables is, however, not a straightforward process. Many of the key parameters for evaluation are listed in Table 2.2. The empirical approach is limited in that in order for the relative contributions of each of the variables to be assessed in a statistically significant manner many sites must be investigated. Given the constraints of this pilot project it was immediately apparent that the number of variables should be reduced. For this reason the study focussed on rock units in the Coast Range. Additionally, it was decided to select sites where the stream channel is straight, unobstructed, and does not show evidence for significant lateral migration over the period of interest. Sites that satisfied these requirements and several additional criteria (Section 3.1) were selected for investigation. At these sites the current channel geometry was compared to earlier channel surveys in order to evaluate the extent of scour that had occurred during the time interval between the surveys. The depth and rate of scour was then computed for each site. Concurrent efforts involved laboratory testing of rock specimens from the sites to obtain relevant geotechnical index properties of the rock as well as hydraulic studies of each site to ascertain the flow characteristics of the streams during the time intervals between the surveys. These parameters are summarized in Table 1.1.

**Table 1.1: Parameters Influencing the Rate of Scour in Rock**

| CONTRIBUTING VARIABLES | | |
|---|---|---|
| **GEOLOGIC** | **GEOTECHNICAL** | **HYDRAULIC** |
| Lithology | Rock density | Channel geometry |
| Frequency and character of discontinuities | Abrasion resistance | Year-round flow characteristics |
| Orientation of discontinuities | Slake durability | Energy gradient |
| Degree of weathering | Rock strength | Bedload characteristics |
| Degree of induration of the sedimentary rock | | Intensity and duration of flood events |

The development of a method for estimating scour in rock of the Oregon Coast Range involved the formulation of an empirically derived equation based on the measured scour rate, the geotechnical index properties of the bedrock, and the hydraulic characteristics of the streams. The basic scour data formed the basis for all of the general formulations evaluated in this study. It is acknowledged that the precision afforded by the various scour correlations that were attempted is limited by the uncertainties inherent in the stream survey data. This issue notwithstanding, it is proposed that a useful correlation can be established for estimating an approximate range of scour rates in selected sedimentary rocks in Oregon.

# 2.0 SCOUR OF WEAK ROCK

## 2.1 ROCK SCOUR

Scour can be defined as "the result of the erosive action of flowing water, excavating and carrying away loose material from the bed and banks of streams" *(Richardson, et. al. 1993)*. Previous investigators have classified short-term changes in streambed morphology as scour and fill phenomena, whereas long-term changes are referred to as degradation and aggradation processes *(e.g., Leopold et. al. 1964)*. Given the focus on bedrock, the terms scour and degradation have been used interchangeably in this report. It should be noted, however, that erosive processes in weak rock can be significant over both time intervals (i.e., one extreme flood event and/or decades of "average" flow conditions). The primary emphasis of this report is on the long-term changes in channel morphology that may take place over the service life of a bridge.

Field observations indicate that the potential for scour of a rock mass is a complex function of the geologic and geotechnical characteristics of the rock (e.g., lithology, the characteristics of discontinuities and rock mass quality, strength and abrasion resistance) as well as the hydraulic environment (e.g., boundary shear stresses, frequency and duration of flood events, bedload composition). Given the inherent differences in the character of uncemented soils and rock masses, the application of analytical and empirical methods for estimating scour in cohesionless sand beds is not appropriate for estimating scour depths in most rock. Although the relative influence of the geologic/geotechnical characteristics of the rock (hereafter referred to as *geomechanical* characteristics for the sake of brevity) and the hydraulic characteristics of the stream are not well understood, it is clear that scour can occur in any rock mass given sufficient time. The time interval of interest and the rate of scour are therefore important parameters in evaluating scour in rock. From the perspective of an engineer charged with the design of bridge foundations, the primary issue with respect to scour is the extent of channel degradation that may occur adjacent to footings over the service life of the bridge. A method for identifying geologic and hydraulic conditions leading to scour, and for estimating the rate of scour is clearly needed. Field evidence demonstrates that weak, jointed and weathered sedimentary rocks of the Oregon Coast Range, and other regions *(e.g., Lewis 1993)*, can be vulnerable to scour over time spans of concern to engineers.

A conceptual model for the relative contributions of hydraulic and geologic factors to scour of jointed rock masses has been proposed *(Akhmedov 1988)*. In this model three conditions, or modes of scour, have been identified. The occurrence of a specific mode of scour is primarily a function of the velocity and turbulence of water adjacent to the rock. These conditions are as follows:

1. The first mode involves removal of rock fragments due to hydraulic pressure gradients caused by turbulent flow. During this condition the characteristics of the discontinuities in

the rock mass have the greatest influence on the scour process. The pressure gradient created by turbulent flow must overcome the fragment's weight, interlocking between particles, and cohesive resistance along the joint in order to pull it out of the surrounding deposit. It should be noted that the abrasion resistance and strength properties of the rock are rather insignificant in this mode of scour. If this mode of scour persists long enough, then the increase in channel depth due to scour depth yields a larger flow area (this assumes a constant flow through a channel that is gradually enlarged due to scour).

2. As the flow area increases the flow velocity and consequentially, the bed-flow energy decreases. At this stage it is postulated that the turbulence and flow energy is still great enough to remove fragments, but now abrasive forces are relatively more important (i.e., the second mode of scour). Abrasive forces reduce the size of the fragment to a point where it is dislodged and removed.

3. Finally, once the flow energy is insufficient to remove the rock fragments scour is due purely to intensive abrasion by bedload (i.e., the third contributing mode of scour).

Relating these general flow conditions to those typically observed in the Oregon Coast Range streams investigated in this study, most streams would fall into the “third mode” category where bedrock scour is due predominately to abrasion. It does appear, however, that conditions at sites with very low rock mass quality and higher gradient streams (slope > 0.6 %) could also be represented by the second mode of scour during flood events. Qualitatively, this indicates that scour could be caused by both abrasion and turbulence-induced removal of rock fragments. It should be noted that these observations are confined to the vertical degradation of bedrock along straight, unobstructed stretches of streams, therefore lateral channel incision and sloughing of banks were not evaluated herein.

After an extensive review of the technical literature it is apparent that methods for estimating scour rates in natural channels incised in rock do not exist. It is therefore necessary to identify analogous situations for scour in rock masses. A relevant example of scour in rock is the flow of water through unlined spillways excavated in bedrock. During the evaluation of potential sites for dams, the foundation must be investigated for geologic properties such as the characteristics and orientation of discontinuities (i.e., joints, fractures, bedding planes). The quality of the rock mass adjacent to the proposed dam and appurtenant structures is a key design parameter as the foundations for these structures will be subjected to large hydraulic forces.

## 2.2 ANNANDALE’S PROCEDURE FOR EVALUATING SCOUR OF ROCK MASSES

The most applicable technique for evaluating the potential for scour in rock that has been proposed to date is an empirically based method for predicting the threshold at which scour will occur along unlined spillways *(Annandale 1995)*. In this landmark paper the geomechanical properties of the rock, the hydraulic characteristics of the channel, and the flow conditions are incorporated into a simple, straightforward method for evaluating the potential for scour in rock masses. The geomechanical properties of the rock mass are described by the Erodibility Index

($K_h$), first introduced by Kirsten *(1988)* for excavations in rock. The Erodibility Index is based on geomechnical parameters such as the Rock Quality Designation (RQD) proposed by Deere *(1963)*, the spacing and roughness of joints, and the unconfined compression strength of the rock, and it represents the relative resistance of the rock mass to degradation by hydraulic jacking and dislodging of particles. The hydraulic conditions are defined by a general expression for the rate of energy dissipation per unit discharge over a unit length of channel. The rate of energy dissipation per unit width of flow is expressed as:

$$\mathbf{P = \gamma q s_f L = \gamma q \Delta E} \qquad \textbf{(2-1)}$$

where $\gamma$ is the unit weight of water (kN/m$^3$), q is the unit discharge (m$^3$/s·m), $s_f$ is the slope of the energy grade line, L is unit length, and $\Delta E$ is the energy loss per unit width of water (m) which is approximately related to the bed slope. The units for the rate of energy dissipation, or stream power, per unit width are kW/m$^2$.

After compiling case study data for numerous unlined spillways, Annandale plotted the Erodibility Index versus the Rate of Energy Dissipation and noted cases where scour was observed in the rock at the base of the channels. This data is plotted in Figure 2.1 and a clear trend is evident in the conditions leading to scour. An empirically based boundary indicating a threshold for scour has been proposed. Given the erosion threshold only the Erodibility Index of the rock is required to establish the flow conditions necessary for the initiation of scour. The identification of threshold conditions at which scour will occur in rock is extremely useful as this method can be used as a screening tool for spillways excavated into rock.

The Colorado Department of Transportation (CDOT) has adopted this procedure for predicting scour depths in layered soil and rock profiles *(Smith 1994)*. Scour depths are estimated by determining if the scour threshold has been exceeded for the bed material, and if so, then evaluating the underlying strata until a scour resistant material has been reached. Erosion of each layer will occur sequentially as long as the rate of energy dissipation exceeds the Erodibility Threshold of the exposed material. If the resistant layer is deep then erosion will continue to a depth where the resulting rate of energy dissipation is less than the threshold due to changes in channel morphology.

It should be noted that the direct application of this empirical model for estimating rock scour in natural streams is complicated by several factors. First, the scour occurring along the base of a spillway represents "clear water" conditions, that is scour in the absence of bedload. Scour due to abrasion by bedload was not a consideration in the study. Additionally, the hydraulic conditions that are prevalent in the case studies most closely correspond to the first mode of scour described by Akhmedov *(1988)*. This implies that the channel is degraded by hydraulic jacking, dislodgment, and displacement of rock particles. The high rates of energy dissipation observed in steep spillways are not achieved in many lower gradient stream channels, therefore an extrapolation is required to lower energy levels. Thirdly, the duration of the peak discharge and the rate of scour are not addressed in the method.

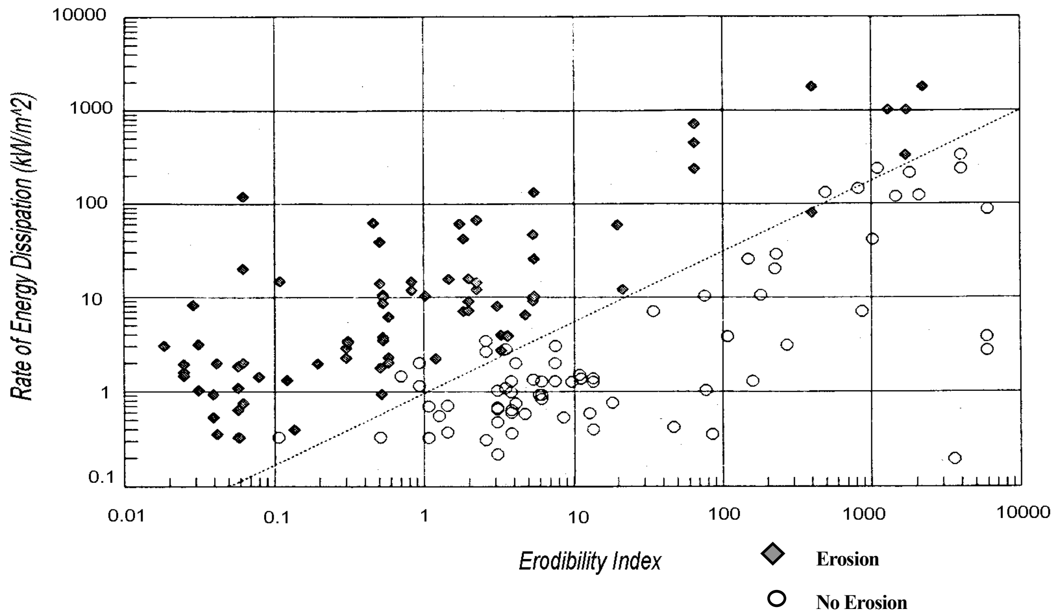


Figure 2.1: Erodibility of Rock and Complex Earth Materials *(Annandale 1995)*[1]

As applied by CDOT, it is assumed that if the erosion threshold for the exposed soil or rock is exceeded scour will occur to the base of the susceptible layer. The scour potential for the underlying unit is then evaluated, and this analysis proceeds until a scour resistant unit is encountered. The cumulative extent of the scour is expressed independently of time, therefore the duration and frequency of flood events is not included in the analysis. Based on this observation it may be suggested that some of the "no erosion" cases (Figure 2.1) representing short duration flows may possibly experience erosion if subjected to multiple floods and/or longer duration flood events having a similar rate of energy dissipation. This implies that the boundary line in Figure 2.1 may be unconservative if applied for natural streams (even if bedload effects are excluded).

The flow conditions in Oregon Coast Range streams vary from spillways in three important ways: (1) the existence of bedload; (2) the rate of energy dissipation is substantially lower than the range represented in Figure 2.1 due to the much more gentle bed slopes; and (3) flow is occurring perennially. These conditions are similar to the third mode of scour described by Akhmedov *(1988)*, when the stream power is too low for dislodgment and the process of abrasion presumably controls the rate of scour. The conditions in the streams evaluated herein were consistently below the scour threshold indicated in Figure 2.1, yet all of the study sites showed signs of bedrock erosion. This condition demonstrates the need for enhancing the scour model developed by Annandale to account for the effect of abrasion by the continuous movement of bedload over the rock. Pertinent characteristics of the bedload (e.g., largest particle size,

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[1] From personal communication with Mr. Annandale *(1997)*, the units for Rate of Energy Dissipation, P, are correctly represented by $kW/m^2$. From equation 2-1, the units for $\gamma$ are $kN/m^3$, for q $m^3/sec$, and $\Delta E$ 1/m. $\Delta E$ is the change in energy slope per unit width ($m/m^2$ or 1/m). When $\gamma$ and q are multiplied together, the units are kN/sec. Multiplying by the change in energy slope per unit width ($\Delta E$) $m/m^2$ yields $kN{\cdot}m/sec{\cdot}m^2$, or $kW/m^2$.

volume of bedload) that is moving at a given time will depend primarily on the stream discharge. If it is assumed that the abrasiveness of the bedload is due to the kinetic energy of the moving particles (factors such as particle angularity, hardness and density being equal), then the cumulative effect of the bedload on the rock can be attributed to the annual flow characteristics of the stream.

## 2.3 FLOW CHARACTERISTICS AND SCOUR IN ROCK

The influence of flow duration on the extent of scour in sand bed streams has been studied by Costa and O'Conner *(1995)*. The term "geomorphically effective floods" was applied to flood events that alter the stream channel and overbank areas. Based on investigations of floods in the northwest region of the United States, the importance of flood-flow duration was qualitatively evaluated. Whereas Annandale adopted the maximum flow, and therefore the maximum rate of energy dissipation, as the most important hydraulic variable in establishing a threshold for scour, Costa and O'Conner looked at the role of flood duration on the extent of channel degradation. The intensity and duration of the flood are primary hydraulic variables in the latter study.

A conceptual model for the influence of the intensity and duration of a flood on scour is illustrated in Figure 2.2. In this model the intensity of the flood is expressed as a stream power which is comparable to the rate of energy dissipation developed by Annandale *(1995)*. Flood "A" is a long term, low power flood that would cause insignificant scour. Similarly, flood "C" is a short duration, high power flood with relatively small scour potential. However, Flood "B" shows a high intensity, long duration flood that could potentially cause significant scour. It is interesting to note that the concept of a threshold for bedrock scour is indicated in Figure 2.2.

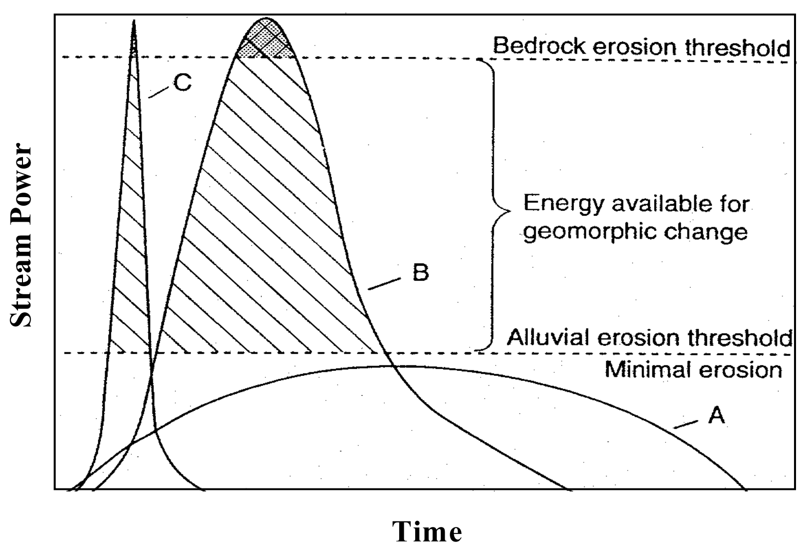


Figure 2.2: Conceptual Stream Power Graphs for Different Floods *(Costa and O'Conner 1995)*

Costa and O'Conner *(1995)* found that the geomorphic effectiveness of a flood is related to the cumulative stream power during a flood (i.e., the stream power integrated with respect to time). From this, an average energy per unit area expended during a flood ($\Omega$) is represented as:

$$\boldsymbol{\Omega = \int \gamma QS/wdt} \qquad \textbf{(2-2)}$$

Where; $\gamma$ is the unit weight of water, Q is the discharge, S is the energy grade, w is the water surface width, and t is time (dt is therefore the duration of the flood event).

It appears that by combining a scour threshold concept with a measure of cumulative flow through a channel, an improved method could be developed for evaluating both the potential for scour and, if scour is indicated, the rate of scour in rock. This concept forms the basis for the tasks undertaken in this investigation.

## 2.4 CURRENT DESIGN PROCEDURES

Current design procedures for predicting scour in soil bed materials are presented in Hydraulic Engineering Circular No. 18 (HEC 18) *(Richardson, et. al. 1993)*. These methods of analysis are based largely on laboratory flume studies of sand beds. Estimates can be made for local scour, contraction scour and degradation/aggradation in cohesionless materials using grain size, sediment transport and hydraulic properties such as flow and stream velocity. As of August 1999, a consensus on the scour resistance of various rock types had not been established and rational design methods were yet to be proposed. The issue of scour in highly resistant rock and spread footings on erodible rock is only briefly addressed in HEC 18. It is recommended that spread footings on highly resistant rock need only be laterally restrained with dowels embedded into the rock, while erodible rock requires evaluations by engineering geologists, supplemented with analysis of intact rock cores *(Richardson, et. al. 1993)*.

A memorandum issued by the Bridge Division of the FHWA *(Gordon 1991)* recommends that the scourability and rock quality of a specific unit should be assessed using the following geotechnical index parameters: (1) rock quality designation (RQD); (2) unconfined compressive strength of the material ($q_u$); (3) slake durability index; (4) sulfate soundness; and (5) the LA Abrasion test. The recommendations outlined in this FHWA memo represent the standard of practice at this time.

A telephone survey of 18 state transportation departments was conducted during this investigation to ascertain the design philosophy for scour in rock. Of the 18 offices contacted, 11 responses were obtained. The design methods are briefly outlined in Table 2.1. It is evident from the information gleaned in this cursory survey that there were no standard methods for evaluation of scour in weak (or "soft" rock as described by the respondents) as of late 1996.

**Table 2.1: Results of Telephone Survey of Selected State Transportation Departments**

| STATE | SCOUR MODEL | DESCRIPTION |
|---|---|---|
| Alaska | HEC-18 | Hard rock considered scour resistant; HEC-18 applied for soft rock. |
| Colorado | CDOT Model | Modification of Annandale's model. |
| Hawaii | HEC-18 | Hard rock considered scour resistant; HEC-18 applied for soft rock. |
| Idaho | CDOT Model, HEC-18 | Currently evaluating the CDOT model for fractured rock; HEC-18 used for other cases. |
| Illinois | None | Assume no scour in rock; key spread footings into rock 0.3 to 1.0 m depending on rock hardness. |
| Indiana | None | Assume no scour in rock; key spread footings into rock 0.3 to 0.6 m depending on rock hardness. |
| New Mexico | None | Assume no scour in bedrock. |
| North Carolina | Adjusted HEC-18 | Apply HEC-18 to estimate scour depth, then use adjustment factors for rock. |
| Oregon | In-house guidelines and HEC-18 | Assume scour in weak rock and key spread footings into rock; assume no scour in hard rock. |
| Virginia | Adjusted HEC-18 | Determine rock properties; scour potential based largely on past performance in similar rock units. |
| Wyoming | Adjusted HEC-18 | HEC-18 results are adjusted by geologists/geotechnical engineers. |

Field case studies have been used to enhance the general guidelines for evaluating scour in rock. Evidence of erosion and partially undermined footings existed in a study that included a bridge founded on the shale bedrock of the Canadaway Group in New York. The five tests recommended by Gordon *(1991)* were performed on the bedrock in overall agreement with the memorandum and some minor changes were recommended for unprotected footings on shale *(Avery and Hixon 1993)*. The geotechnical parameters given in the memorandum and the recommended changes suggested by Avery and Hixon are summarized in Table 2.2. These values represent an evaluation of the bedrock quality, which is important in locating and inspecting bridges and determining the susceptibility of scour. While this data provides valuable guidance for rock scour evaluations, there remains the need for a method that can be used to predict the depth to which scour will occur and the time required for this streambed degradation.

**Table 2.2: Summary of Existing Geotechnical Parameters for Evaluating Scour Potential**

| TEST | ASTM (1996) | FHWA MEMORANDUM (1991) | AVERY AND HIXON MODIFICATIONS (1993) |
|---|---|---|---|
| RQD *(Deere 1963)* | -- | > 50% | > 40% |
| Unconfined Compression ($q_u$) | D2938 | > 1724 kPa (250 psi) | > 1724 kPa (250 psi) |
| Slake Durability Index | D4644 | > 90 | >92 |
| Sulfate Soundness (Sodium)<br>(Magnesium) | C88 | > 12<br>> 18 | > 12<br>> 18 |
| LA Abrasion (Loss %) | C131 | < 40 | < 40 |

# 3.0 STREAM STUDY SITES

## 3.1 SITE SELECTION AND FIELD INVESTIGATIONS

The sites considered for this study are confined to the Coast Range Province of Western Oregon. This region was identified for two primary reasons: (1) the existence of scour-prone rock, and (2) for the purpose of limiting, somewhat, the variation in rock types that were investigated. Weak sedimentary rocks (e.g., mudstones to sandstones) are prevalent in this region. Although the rock types were limited, significant variation in the rock mass quality and geomechanical properties of the rocks at different sites were observed. These variations were considered very useful for highlighting the factors that are the most significant for rock scour.

For the purposes of this pilot study, criteria were established for selecting possible study sites. To study the rock scour in natural stream channels it was desirable to select sites that would allow for geotechnical and hydraulic variables to be isolated to see if the relative influence of the variables could be ascertained. The criteria for optimal study sites included:

1. Exposed bedrock over all or most of the channel. This would eliminate the effects of bedload armoring on scour in the rock and minimize the influence that a seasonally varying mantle of bedload would have on the comparisons of the stream cross sections.
2. Consistent lithology across the channel.
3. The cross section is made along a straight stretch of river that exhibits negligible evidence of meandering, thereby reducing the effects of lateral channel migration on the measured scour.
4. Cross section is isolated from the influence of natural and/or man-made obstructions (e.g., anomalous bedrock outcrops, abrupt constrictions in the channel, bridge piers or abutments). The measured scour depth is, therefore not affected by contraction scour or local scour.
5. The geometry of the channel and water depth (summer conditions) allows for the measurement of a longitudinal profile.
6. Rock samples should be obtained from the channel (as opposed to the stream banks, if practicable) therefore access should allow for drill rigs to reach the margins of the stream, or drilling should be possible from the bridge deck.
7. A stream gauge located in close proximity to the site.
8. Measured hydrologic data should be available for the time that elapsed between the first survey of the channel and the survey obtained for this study.

Approximately 50 candidate sites were initially identified from the files of ODOT and the Siuslaw National Forest. These sites are listed in Appendix A. A reconnaissance of each site was made and the primary study sites were selected on the basis of geology, availability of historical cross-sections and stream data, visible bedrock, and accessibility to the site. It became immediately evident that very few sites would satisfy all of the recommended criteria. The location of stream gauges relative to the bridge sites and the continuity of the hydrologic data were the most common deficiencies in securing useful sites. In many cases, however, gaps in the historical hydrologic data could be synthesized from data obtained at different stations on the same stream or in the same watershed. Eleven sites at which requisite data was available were selected as appropriate for the study.

The field investigation at each site consisted of drilling rock cores (rotary drill rig and/or hand operated drilling equipment) and surveying the stream channel geometry. The rock cores were taken to the geotechnical engineering laboratory at OSU for a variety of index properties tests (the data compilation is contained in Appendices B and C). The channel cross-sections made during this study were compared to historic cross-sections and used to create computer models for calculating the hydraulic variables. The cross sections were established by one of two methods: (1) "weight and line" depth profiling, herein referred to as "soundings" for brevity, and (2) transit and stadia rod surveys. The locations of the 11 sites are indicated in Figure 3.1. Background data at each site is provided in the following sections.

### 3.1.1 Nestucca River at Powder Creek Road

The Nestucca River site is located roughly 7 km east of Blaine near the intersection of Blaine Road and Powder Creek Road. The structure is a single span bridge crossing the Nestucca River. This site was selected, in part, because it was the focus of concurrent investigations by OSU researchers on predictive models for estimating flows in northern Oregon Coast Range streams *(Fluter 1997, Hadley 1997)*. These studies included a survey of the channel by "weight and line" sounding and the installation of a staff gauge. The soundings were taken in December 1995 on the downstream side of the bridge to allow for visibility of the weight as it was deflected downstream due to the strong current. In June 1997, the stream was resurveyed as a portion of this study using a fiberglass survey rod. The survey data reported herein was obtained by measuring the depth from the water surface to the bedrock and comparing the height of water with the staff gauge installed adjacent to the bridge in 1995.

The local bedrock geology primarily consists of undifferentiated, thin-bedded tuffaceous, volcaniclastic siltstone, clay siltstone, and sandstone ($T_{esu}$), with isolated outcrops of basaltic intrusive rocks ($T_i$) of late Eocene and middle Miocene ages *(Beaulieu 1973)*. The sedimentary strata are shallow dipping (generally less than 10 degrees). Geological mapping of the quadrangle by Beaulieu and others indentified basaltic intrusive rocks adjacent to the right abutment of the bridge and sedimentary rocks in proximity to the left abutment. Site specific observations made during this investigation indicate hard tuffaceous rocks on both sides of the channel. The bedrock at the study site was visible across the entire channel with little visible bedload during low-flow conditions. Additionally, geologic hazard mapping by Beaulieu and others identified stream bank erosion along this portion of the Nestucca River as potentially hazardous, yet not extreme *(1973)*. It should be noted however that this characterization was made for a regional hazard study, not a site-specific investigation.

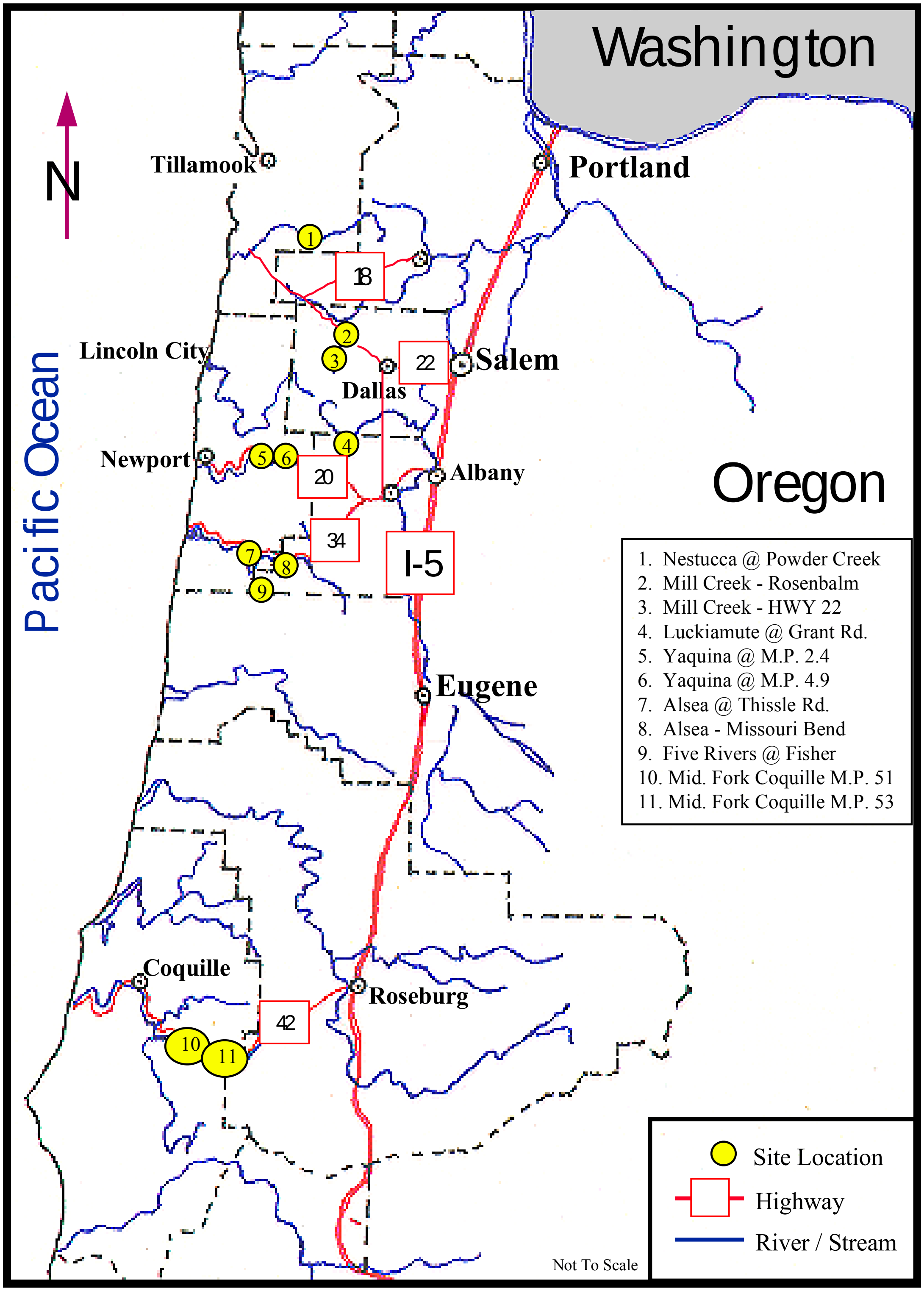


Figure 3.1: Site Locations

This site was drilled using portable coring equipment, thereby precluding the acquisition of site specific RQD data. The samples were obtained from the north side of the stream channel. The RQD and recovery values that are listed in this report were obtained from a geotechnical engineering report prepared for one of the Blaine Road bridges located near River Bend Road roughly 14 km downstream from the site (approximately 1.5 km east of the town of Beaver). Although this surrogate site is somewhat distant, the bedrock appears to be very similar to that at the Nestucca River - Powder Creek site.

During the two years that elapsed between the two surveys, this site experienced two 100-year flood events. Site specific stream gauge data was not available for the entire time interval of interest. The incomplete portion of the stream gauge data at this location was synthesized using a correlation with the average flow of the Wilson, Alsea, and Siletz Rivers with gauge data from USGS gauge 14303600 (Nestucca River near Beaver, Oregon). In order to provide a representative estimate of the flow at the site an adjustment was made to account for the difference in the drainage areas at this site versus the site of USGS gauge 14303600 using the method proposed by Harris and others *(1979)*.

In light of the geometry of the bridge abutments and the stream channel at this site, it is postulated that the channel degradation that occurred over the period of interest may have been intensified by contraction scour. Although it is difficult to assess the influence of this effect on the observed scour it is assumed that the relative contribution was minor.

### 3.1.2 Mill Creek at Rosenbalm Road

The Mill Creek - Rosenbalm Road site (Polk County bridge no. 53C068) is located off of Harmony Road approximately 1.5 km south of Highway 18 and roughly 6 km north of Highway 22 near Buell in Polk County. The bridge footings on the west side of Mill Creek were exposed with obvious signs of rock erosion and undermining as shown in Figure 3.2. The bridge at this site was replaced during the summer of 1997 by a single span structure.

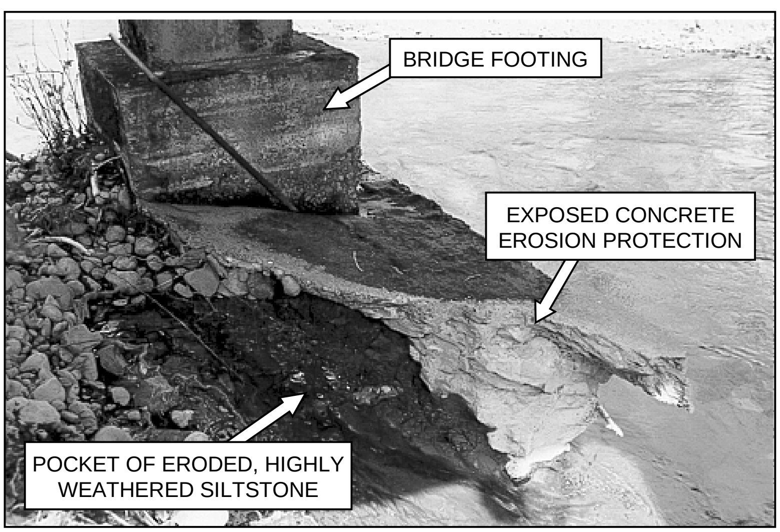


Figure 3.2: Evidence of Bedrock Erosion at Mill Creek - Rosenbalm

The bedrock geology consists of medium to dark gray, massive to faintly bedded, tuffaceous shale and siltstone, with locally interbedded medium gray to greenish gray sandstone *(Brownfield 1982).* These strata are marine sedimentary deposits which belong to the middle and upper Eocene Yamhill Formation ($T_y$). The orientation of bedding planes in the rock is variable in vicinity of the bridge with strikes and dips ranging from N35W/33 NE to N75E/15 N *(Brownfield 1982).* The bedrock at the bridge site is predominantly siltstone and this material was cored for laboratory testing.

The stream cross-sections were constructed with data obtained from soundings. Changes in channel morphology were assessed by comparing data obtained from the 1995 soundings with bridge inspection soundings from 1990.

Daily water flow information was obtained from USGS stream gauge 14193300 (Mill Creek near Willamina, OR). Recordings at this station were only obtained until 1973, therefore recent daily flow values were synthesized from a correlation with flows measured on the South Yamhill River. The flows were reduced to account for the different drainage areas by a method outlined in the USGS report "Magnitude and Frequency of Floods in Western Oregon" *(Harris et.al. 1979).*

This site was selected because of the obvious erosion and weak rock. Another bridge crossing Gooseneck Creek (a tributary of Mill Creek) also has visible erosion, however, due to the unusual flow conditions because of channel constrictions and repairs made to the bridge, this additional site was not selected for investigation.

### 3.1.3 Mill Creek at Highway 22

The Mill Creek - Highway 22 site (ODOT bridge no. 1756) is located approximately 6 km upstream (south along Harmony Road) of the Mill Creek - Rosenbalm Road site. The bridge is a triple span structure on Highway 22 crossing Mill Creek in Polk County. The bedrock at this site is very similar to the siltstone unit that is found at the Mill Creek - Rosenbalm Road site. The marine sedimentary rocks belong to the Eocene Yamhill Formation *(Brownfield 1982).* Geologic mapping of limited exposures along Mill *Creek (Brownfield 1982)* seems to indicate that site is located near the axis of an anticline that strikes to the northwest (roughly N35W to N40W). The bedrock adjacent to the bridge footings was observed to be shallow dipping. This site has two footings on the edges of the stream with undermining of one footing that is clearly visible (Figure 3.3). The erosion at this site is not as dramatic as that observed at the Rosenbalm Road site.

The site exhibits an armor layer on the downstream side of the bridge, however immediately upstream of the bridge the channel is predominantly bedrock with some bedload. The survey, which was made on the upstream side of the bridge, consisted of soundings and compared to cross-sections from plans created in 1983. The datum elevation used for the survey was established from the bridge plans.

The discharge data was obtained from the same stream gauge employed for the Rosenbalm site. The flow volumes were adjusted to account for drainage area and tributaries, and the resulting discharge is about one-third of that observed at the Rosenbalm site.

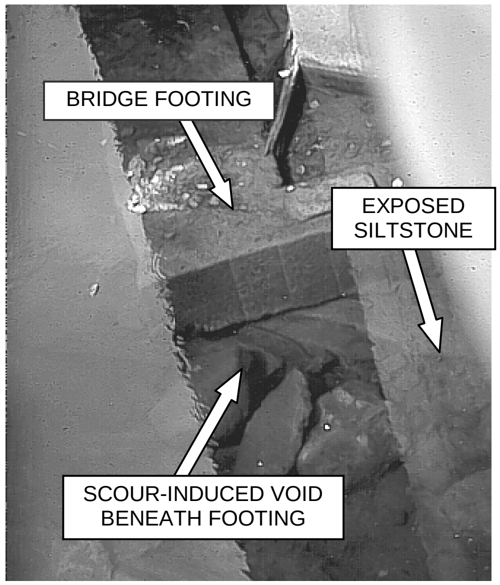


Figure 3.3: Evidence of Erosion under a Bridge Footing at Mill Creek - HWY 22

### 3.1.4 Luckiamute River at Grant Road

The Luckiamute River site (ODOT bridge no. 16693, Polk County bridge no. 1062) is located on Grant Road just east of the intersection with the Kings Valley Highway (OR 223), about 32 km northwest of Corvallis. The bridge is a single span structure crossing the Luckiamute River.

Regionally, the bedrock geology consists of massive bedded sandstone with thin interbeds of siltstone *(Baldwin 1947, Walker and MacLeod 1991)*. These strata belong to the Tyee Sandstone ($T_t$ or $T_{et}$), a marine deposit of the middle Eocene age. Early mapping by Baldwin *(1947)* noted that the Tyee sandstone in this area is generally characterized as medium grained, indurated, having slight to moderate calcareous content in the form of cement, and friable upon weathering. Sandstone samples were obtained at the site for geotechnical testing.

Soundings were performed and the profile compared to ODOT plans prepared in 1984. The available stream flow information was obtained at USGS gauge 14190000 (Luckiamute River near Pedee, Oregon). This gauge was operated until 1970, and discharge data from 1970 until 1996 was synthesized using gauge data obtained at two stations in the region, specifically, gauges at the Luckiamute River (at Suver) and the South Yamhill River (Gauge 14192500).

This site was drilled using portable rock coring equipment therefore RQD and percent recovery data is not available.

### 3.1.5 Yaquina River at Mile Post 2.4

The M.P. 2.4 bridge (ODOT bridge no. 1401A) spanning the Yaquina River is located on the Eddyville/Blodgett Highway roughly 4 km north of Eddyville, and about 40 km west of Corvallis. This bridge was affected by the February flood of 1996 as lateral migration of the stream scoured rock and fill material adjacent to the bridge abutment exposing the piles used in the foundation. The bridge is a two span structure with one footing placed in the middle of the stream. The channel is predominantly bedrock, however minor bedload was observed in the stream at the time of this investigation (summer, 1996). In addition a small bar is being formed downstream of the mid-channel pier.

The bedrock at this site consists of siltstone and fine sandstone of the Tyee Formation. Regionally, the Tyee Formation is characterized as rythmically bedded sandstone and sitlstone which forms beds 30 cm to 450 cm thick *(Schlicker, et. al. 1973).* In the vicinity of the site the bedding strikes roughly N35E to N45E and dips to the northwest between 5 and 15 degrees. Samples of siltstone were obtained by coring at this site.

The site geometry and geotechnical engineering data was obtained from ODOT and the historic cross sections are presented in the plans for the bridge prepared in 1976. The datum elevation used in the more recent survey of the channel was established from the 1976 plans, and the stream channel was surveyed by the sounding method. Complete daily stream values were obtained from USGS, stream gauge number 14306030 (Yaquina River near Chitwood Oregon).

### 3.1.6 Yaquina River at M.P. 4.9

As indicated by the milepost designations, this site (ODOT bridge no. 1402A) is located about 4 km upstream of the previous Yaquina River site on the Eddyville/Blodgett Highway. The bridge is a triple-span structure with in-channel piers, the lower portions of which are subjected to river currents during seasonal high water. The bedrock geology at this site is very similar to that observed at the Yaquina River - M.P. 2.4 site. Regional geologic maps *(Schlicker, et. al. 1973)* indicate that the bedrock is also Tyee Formation. Although the bedrock is similar, the material at this site is composed of more fine-grained sandstone with interbedded layers of weak siltstone.

The channel is predominantly bedrock, with some fine sand and fine-grained bedload observed during the field study in the summer of 1996. The soundings made during low-flow conditions encountered this material in the channel. An ODOT benchmark on one of the bridge bents was used as the datum for the recent channel survey.

Complete daily stream values from USGS, stream gauge number 14306030 (Yaquina River near Chitwood Oregon) were modified to account for the area of the drainage basin.

### 3.1.7 Alsea River at Thissel Road

The Thissel Road bridge (USFS Cannibal Mt. Bridge, no. 3430-0.1) that crosses the Alsea River is located approximately 10 km east of the town of Tidewater along Highway 34, adjacent to the confluence of Schoolhouse Creek. The three-span bridge is maintained by the U.S. Forest Service (Siuslaw National Forest District). This site is particularly valuable for this study because of the exposed bedrock in the channel and the proximity of a USGS stream gauge (USGS gauge 14306500, Alsea River near Tidewater). The site exhibits exposed bedrock across, and adjacent to, the stream channel. During high stage conditions, water flows around the piers creating some local scour effects.

The bedrock at this site consists of a moderately jointed, medium- to coarse-sandstone of the Tyee Formation. Regionally, the Tyee Formation is characterized as rythmically bedded sandstone and sitlstone which forms beds 30 cm to 450 cm thick *(Schlicker, et. al. 1973)*. In the vicinity of the site the bedding trends to the northwest and north and dips to the east and northeast at between 10 and 20 degrees. Samples of medium coarse sandstone were obtained by coring at this site.

High recovery rates and RQD values were obtained during the geotechnical exploration. The survey performed for this study consisted of soundings and the resulting profile was compared to the 1989 soundings performed during a bridge inspection by Siuslaw National Forest engineers. Given the location and continuous operation of the stream gauge no adjustments were made to the flow data.

### 3.1.8 Alsea River at Missouri Bend

The Alsea River-Missouri Bend site (USFS bridge no. 1418F) is located approximately 16 km upstream from the Alsea - Thissel site. This three-span bridge is located on Benner Creek Road immediately off of Highway 34. The bridge is maintained by the Siuslaw National Forest District. The bedrock is sandstone of the Tyee Formation. The footings for the bridge are located up the bank from the water and are subjected to flows only during unusually high flood events. The recovery rates and RQD values obtained by rock coring were very similar to the values obtained at the Alsea - Thissel site.

The survey performed during this study consisted of soundings and this data was compared to soundings performed during bridge inspection by Siuslaw National Forest engineers in 1978. The greater time interval between the stream surveys (as compared to the Alsea - Thissel site) is advantageous for this study due to the greater cumulative stream flow. Stream gauge data from the USGS station on the Alsea River near Tidewater was used in this study.

### 3.1.9 Five Rivers at Fisher

The Five Rivers site (ODOT bridge no. 901 B-1) is located on Primary Forest Route 32 roughly 10 km south of the Alsea - Thissel site. A single-span bridge across Five Rivers is located next to a covered bridge in Fisher, Oregon.

The bedrock at this site is sandstone of the Tyee Formation *(Schlicker, et. al. 1973)*. In the vicinity of the site the bedding trends to the northeast and dips to the northwest at between 15 and 25 degrees. Samples of fine- to medium-coarse sandstone were obtained by coring at this site. Qualitatively, the sandstone in outcrops at this site appeared to be harder than the Tyee sandstone at the Alsea sites. The geotechnical investigation consisted of wire-line rock coring with a rock recovery near 100% and RQD values between 75 to 100%.

The channel survey performed in this study was based on soundings and the resulting data was compared to ODOT plans prepare in 1973. The 23-year interval between the ODOT and OSU surveys represents the longest record of all the sites investigated herein.

The stream gauge data has been compiled from the USGS gauge number 14306400 (Five Rivers near Fisher, Oregon) and estimates based on local gauges. Gauge 14306400 was operated until September 1990. Since Five Rivers is a tributary of the Alsea, the Alsea near Tidewater gauge was correlated with the Fisher gauge and synthetic data was produced for the interval from October 1990 until October 1996.

### 3.1.10 Middle Fork of the Coquille River at Mile Post 51

The Middle Fork Coquille River – M.P. 51 site (ODOT bridge no. 16413) is located on Highway 42 (Coos Bay - Roseburg Highway) approximately 2.5 to 3 km west of the intersection with West Side Road, and about 6.5 km west of the town of Camas Valley. The bridge consists of the single-span structure crossing the Middle Fork Coquille.

Regionally, the bedrock geology consists of rhythmically bedded marine sandstone and siltstone. These strata have been broadly referred to by Ramp *(1972)* as a portion of the Eocene Umpqua Sedimentary Rocks ($T_{eu}$). More recently, the area has been mapped as thin- to thick-bedded Marine sandstone and siltstone ($T_{mss}$) *(Walker and MacLeod 1991)*, and as predominantly marine sandstone with siltstone of the White Tail Ridge Member of the Flournoy Formation *(Black and Priest 1993)*. In the vicinity of the site the units trend to the east-northeast and dip shallowly (5 to 15 degrees) to the north and northwest *(Black and Priest 1993)*. The rock core obtained at this site was classified as coarse sandstone.

The channel cross section was developed using sounding data and this data was compared to elevation data provided in ODOT plans prepared in 1981.

The bridge is located approximately 14 km upstream from USGS stream gauge 14326500 (Middle Fork Coquille River near Myrtle Point, Oregon). This gauge was only active until 1946, necessitating the development of a synthetic discharge record. This was achieved by utilizing recorded data from stations in or near the basin (South Umpqua and Rogue Rivers), and correlating the average with the available Middle Fork Coquille record. The flow was adjusted to account for the smaller drainage area using the ratio of drainage areas as outlined in the USGS report by Harris and others *(1979)*.

### 3.1.11 Middle Fork Coquille River at Mile Post 53

The Middle Fork Coquille River - M.P. 53 site (ODOT bridge no. 559B) is located immediately east of the intersection of Highway 42 and West Side Road, roughly 3 km upstream from the

M.P. 51 site. The bedrock at this site is similar to the rock exposed at the Middle Fork Coquille-M.P. 51, however the sedimentary rock consists of a harder fine-grained sandstone. This sandstone is also interbedded with layers of a darker mudstone. There is evidence of minor local scour in the rock around the edges of one of the bridge footings.

The site is similar to M.P. 51 except the discharge is lower due to the tributaries that reach the river between the two sites. The flow has been calculated using the same methods and adjusted to account for different drainage areas. The bedload consists of approximately 25 mm minus material on both sites with exposed bedrock visible in parts of the stream. The bridge footings at this site are affected by contraction effects during high flows.

### 3.1.12 Other sites

Numerous other sites were investigated during the study but the resulting data was not incorporated into this analysis. The rationale for omitting these sites included one or more of the following deficiencies: the lack of reliable stream gauge data; the stream gauge data could not be effectively synthesized; bedrock variations across the channel; or the existence of bedload of unknown thickness. These sites include bridges over Euchre Creek near Siletz; Deep Creek near Estacada; and Slick Rock Creek near Lincoln City. Difficulties in evaluating past cross-sections eliminated a candidate site along Mill Creek near Buell (Gooseneck Creek). Additionally, a bridge over the North Yamhill River (Oak Ridge Road approximately 3.5 km west of Yamhill) was not used because bedrock was exposed in only half of the channel, while the other half was covered by a layer of silty sand.

## 3.2 ACQUISITION AND INTERPRETATION OF SURVEY DATA

The primary focus of this report is on long-term elevation changes of stream channels in bedrock. The fundamental data for evaluating the scour process is therefore the channel survey data. The accuracy and the completeness of the survey data will directly influence subsequent interpretation of the scour phenomena. This is particularly relevant with respect to the original, or historic, surveys that are presented in file documents at ODOT and the Suislaw National Forest offices. An attempt was made during the selection process for the study sites to ascertain for each historic survey the following information: the survey method(s), river stage at the time of the survey, date of the survey, the location of the transect relative to the adjacent bridge, and most importantly, the datum or benchmark that was used during the development of the final cross-section. Although a benchmark could be established for all of the study sites, in several instances pertinent aspects of the prior surveys were not available. In each case the cross-sections were interpreted in terms of the confidence that could be placed on the survey data.

### 3.2.1 Stream Channel Cross Sections

Historic cross-sections for each of the 11 sites were obtained from bridge plans prepared by the organization responsible for maintenance of the specific bridge (i.e., ODOT or Siuslaw National Forest District). The cross-sections were established between 1940 and 1995 with a majority of the site surveys performed in the 1980's. It is apparent that the channel surveying techniques included both sounding techniques (from boats or existing bridges) and, to a lesser extent, the use of survey rods. When the stream velocity is low, there are only minor differences between rod readings and soundings. However, in higher velocity streams the sounding measurements are affected by water pushing the plumb weight from the vertical position and corrections must be made for this effect. It has been assumed herein that appropriate corrections were made to the original sounding data.

When comparing the original stream cross sections with subsequent surveys, two primary limitations are evident: (1) the surveys performed for this study are not taken at the exact position of the original, and (2) it is not possible to determine if a portion of the channel was covered with a thin layer of bedload at the time of the original survey. With respect to the first issue, it appears that the most recent surveys have been made within several feet of the original surveys. In these cases it may be assumed that any significant changes in the channel morphology would have roughly the same appearance at the two survey positions, allowing for a direct comparison of the transverse sections. Also, given the relatively gentle slope of the channel in the longitudinal direction, and the close spacing of the two survey lines, changes in channel elevation due to offset survey lines are negligible. With respect to the latter issue, the existence of bedload along portions of the traverse during one or both of the surveys could have a pronounced influence on the bedrock scour estimates. This could be due to relatively large changes in elevation associated with the scour and fill process observed in the bedload covered portions of the channels, and possibly to seasonal variations in the thickness of bedload over the bedrock. An effort was made to glean evidence of bedload during the previous surveys. Additionally, locations exhibiting anomalous scour depths at locations where bedload was noted in either the original survey or most recent survey were classified as zones of low confidence.

The cross-sections prepared during this study were based on sounding data at ten sites and survey rod readings at the remaining site. Corrections for the alignment of the measuring line were made at all sites. The recent sections were plotted with reference elevations provided by adjacent benchmarks, stream stage gauges, or a portion of the adjacent bridge. For the most part, the portions of the stream channels surveyed were clear of bedload at the time of the investigation. Locations of bedload were noted in fieldbooks and subsequent cross-sections.

Changes in the channel elevations evident by the original and most recent surveys were attributed to scour and fill processes. Overall, rather minor variations in the channel morphology and elevation were observed. This seems reasonable given the induration of the sedimentary rocks in the stream channels and the short time interval between the two surveys at most sites. Several localized pockets of significant scour were observed however. Again, these changes could have been caused by several of the following factors: the existence of isolated bedload in the original survey; the possible existence of an obstruction that may have been deposited by fluvial processes and later removed, thereby causing local scour effects; or by a permanent obstruction. Errors in survey technique or location have been ruled out at these locations due to the fact the pockets of scour are localized and the remainder of the channel profile appears to be credible.

### 3.2.2 Survey Uncertainty

A key premise of this investigation is that the change in elevation of the stream channels that occurred during the time interval between the two surveys can be quantified, albeit imprecisely, on the basis of the cross-sections. Because this data forms the basis for the proposed empirical scour model, it is necessary to evaluate sources of uncertainty associated with the survey data. This uncertainty reflects the combination of: (a) measurement error related to the precision of the sounding and rod surveying techniques; and (b) the accuracy involved in tying the cross sections to a common datum. The precision in the sounding measurements is assumed to be similar in both the original and most recent surveys. All of the measurements made during this study were made during low stream flow conditions, therefore the sounding data is judged to be of high quality. Possible measurement error is judged to be less than roughly ± 10 to 30 mm. This is consistent with the precision of standard Oregon Department of Transportation stream cross-section surveys of 30 mm *(Bryson 1999)*.

The uncertainty associated with establishing the common datum is difficult to assess at some sites. At locations where clearly defined benchmarks (e.g., USGS elevation markers, stream gauges, markers on the bridges) are located in close proximity to the survey line the uncertainty is small, perhaps ± 1 to 5 mm. At locations where well established benchmarks do not exist close to the channel, the elevation of a portion of the bridge was used as a control point (e.g., top of an abutment or wing wall, bottom of the bridge cord, top of a footing). This necessitated the use of as-built bridge plans to establish the location of the channel relative to the control point. In these instances the uncertainty is unknown, but an error of as much as 20 to 50 mm is judged to be reasonable. The erosion figures determined in this study should be evaluated in light of the precision of the measurements and the uncertainty inherent in the methods adopted herein.

A final point regarding the status of the local datum pertains to possible changes of coordinates over time. In several areas of Oregon the listed coordinates and elevations of numerous data have been modified following re-leveling surveys. Although this obviously does not affect the relative position of the stream channels to the bridges, it could result in errors when interpreting previous data from older as-built bridge plans. Periodic surveys along established transects can yield changes in elevation of as much as one meter *(Thommen 1999)*. This highlights the importance of site-specific surveying at study sites in order to eliminate the potential for gross errors in relating elevations from survey archives to contemporary survey data.

Once the change in channel elevation has been established a “rate of erosion” can be calculated. This rate can be computed as either the degradation of the channel as a function of time given the length of time between the two surveys, or as a function of the cumulative discharge that has flowed over the section during the time interval of interest. The latter concept appears to be more representative for two primary reasons: (1) the scour process is a function of the stream power and the corresponding volume of transported bedload that abrades the channel, and (2) long-term changes (i.e., scale of decades) in weather patterns result in cycles of prolonged above- or below-average stream flows and flood occurrence, thereby limiting the usefulness of a time-rate factor for scour. For example, the time interval between the two surveys at the Nestucca River site was only two years, however during that time the stream experienced two 100-year flood events. Scour observations made at sites like this would clearly skew empirical scour relationships if plotted only as a function of time.

It has been noted that scour in alluvial channels may not occur in proportion to discharge alone, but also on the volume of bedload that is transported through the section of stream *(Leopold et. al. 1964)*. This appears to be a valid assertion for channels in weak rock as well. While an important influence on the process of scour in rock, detailed characterization of the bedload as a function of discharge at each of the study sites was outside the scope of this project. Because the field investigations were made during the summer months, when low flows preclude significant movement of the large diameter bedload that is transported during the winter months, it was not possible to characterize the bedload for these conditions except in a very approximate manner.

In this study the rate of erosion has been defined as the vertical change in channel elevation divided by the cumulative stream power (stream power is defined in Sections 2.2, 2.3 and 5.2.1). Because the extent of the scour and the stream power both change across the channel, two methods of analysis were proposed for this study: (1) a unit-width concept, where the bedrock erosion (measured in individual 1 m wide, transverse "slices" of the stream) is divided by the stream power computed for that same slice, and (2) an averaging technique where the amount of erosion (measured across 0.3 m to 0.5 m wide slices) is averaged to yield a single value representative of the entire stream channel, and this erosion value is divided by the total stream power computed for the entire channel. The first technique more directly accounts for the influence of water depth and hydraulic power on the extent of the scour at a specific portion of the stream. This method also circumvents inherent limitations with the averaging technique, such as the changes in total stream power, wetted perimeter, and the relative scour potential across a stream channel during changes in stage. But from a practical perspective, the uncertainty associated with the cross sections in this study limits the applicability of a unit width method. Given the constraints on this pilot project, the second method was selected as an expedient technique that was suitable for the available data.

The effects of seasonal wetting and drying and other weathering processes were observed to significantly influence the amount of erosion along the stream channels. This effect was most pronounced in bedrock along the stream banks that were submerged during wet season and exposed during the dry months. Based on field observations at several sites, as the stream recedes, the recently exposed bedrock dries and the surface starts to crack and flake due to weathering processes. When winter storms result in high stage levels, the weakened, weathered rock is easily eroded. The amount of rock that is eroded in this fashion is dependent on the depth of the highly- to completely-weathered bedrock.

In this study an attempt was made to focus only on scour occurring in the portion of the channel that is submerged for all, or almost all, of the year; this would minimize the influence of lateral channel migration due to weathering and sloughing along the banks of the streams. Although the transverse channel sections extended from one terrace to the terrace on the opposite bank, the *average erosion* for each stream section was computed across the base of the channel only (i.e., the width of the stream at the low flow conditions observed during the summer surveys).

# 4.0 GEOTECHNICAL INVESTIGATION

A basic premise of this research is that the rate of scour of bedrock stream channel is a function of the hydraulic characteristics of the stream and the geomechanical characteristics of the rock mass. As previously discussed the process of scour in rock has been generalized as occurring in three distinct modes *(Akhmedov 1988)*. These modes are functions of the water velocity; they include: (1) removal of rock fragments by fluctuating hydraulic gradients, (2) the removal of rock fragments combined with abrasion of the rock by bedload, and (3) predominantly abrasion in lower velocity streams. It has also been noted that the hydraulic characteristics of the streams studied herein are most consistent with the abrasion mode of scour, with possible, short-term contributions from the removal/abrasion process. It is surmised that if the predominant mode of scour at the study sites is due to abrasion-induced erosion then the observed rates of scour should be related to the geotechnical characteristics of the rock (e.g., strength, durability, density), all hydraulic parameters being equal. The geotechnical investigation was therefore developed with an emphasis on the rock properties that most influence the scour resistance of the material.

## 4.1 GEOTECHNICAL SITE CHARACTERIZATION

The geotechnical characterization of the rock at each site consisted of in-situ characterization of the rock units, sampling, and subsequent laboratory tests on representative specimens of rock. Rock samples for the laboratory investigation were obtained either by triple barrel coring with a drill rig or sampling with a hand operated coring drill. At the outset of the investigation plans were made to obtain rock cores from the center of the stream channels by drilling from the bridge decks. Obtaining samples from the perennially submerged portion of the stream would circumvent issues associated with weathering profiles in the rock on exposed bars and along the riverbanks, thereby yielding the most representative samples. Complications associated with the drilling schedule and restricted access across the bridges precluded drilling from the bridge decks at most sites. In addition, resources were not available for requisite flagging crews for traffic control during the drilling operations. In light of these constraints attempts were made to locate the coring operations as closely as practicable to the stream channel.

At some sites drilling was possible along bars adjacent to the stream. At others, restricted access necessitated drilling at bridge approaches above and away from the channels. In order to obtain representative samples of rock at these latter sites, drilling was conducted on both sides of the channel and rock samples were obtained at the elevation of the stream bed, or from depths of three meters or greater (i.e., below the zone of highly weathered rock). Samples were collected, logged, and wrapped in cellophane to protect them from drying. Geologic and geotechnical characteristics of the rock were recorded. These properties include the following: visual characterization, percent recovery of the rock cores, joint locations and orientations, and RQD.

Limited access at several sites necessitated the use of portable hand operated coring equipment. A motorized hand coring drill provided by the Oregon Department of Mines was employed. The portable equipment was advantageous in that it allowed for the collection of samples directly from the streambed, and at a considerably lower cost than required for drill rigs. By sampling directly from the bedrock in the stream, weathering profiles from exposure to air are avoided. This hand coring method does have drawbacks. The hole can only be drilled to a depth of approximately 0.3 m before the rock samples are difficult to remove. In addition, the short length of the core barrel and the non-standard method of coring precluded the use of percent recovery and RQD parameters, and the sample is not the specified size or shape for some of the laboratory tests (i.e., unconfined compression tests). The samples that were collected with the hand operated core were judged, however, to be quite satisfactory for several of the index tests performed during the investigation.

## 4.2 LABORATORY TESTS

A variety of geotechnical laboratory tests were performed on the representative specimens in order to evaluate the strength and abrasion resistance of the rock. Tests included: LA Abrasion (ASTM C131), Unconfined Compression (ASTM D2938), Density (ASTM D2937), and Slake Durability (ASTM D4644). Pertinent references for these tests are contained in the reference section of this report. Also, a modification of the standard Slake Durability test was developed for this study and this test procedure is explained in Sections 4.3.1 and 4.3.2. In several cases the geotechnical index properties obtained on a rock specimen are plotted against the average erosion that was measured across the selected portion of the channel at the site. Trends in the data were evaluated and attempts were made where possible to establish simple single-parameter and/or multiple-parameter regressions from the data.

### 4.2.1 Slake Durability

A test for evaluating the wetting and drying effects on the slaking effects of clay bearing rock and siltstones has been devised *(Franklin and Chandra 1972)* and standardized by the ASTM (D4644). The standardized slake durability test consists of placing 500 g ± 50 g of oven dry material (10 pieces weighing about 50 g each) into a standard mesh cage (Figure 4.1), with water just below the axis of the rotating cage.

The cage is then rotated at 20 RPM for 10 minutes. The cage rotation maintains a tumbling action of the rock particles which are abraded due to continual impact with other rock particles and the cage itself. Weak rock fragments are progressively broken down until they pass through the wire mesh that makes up the cage. After one 20-minute rotation cycle, the cage and the contained portion of the specimen is removed from the apparatus and put into the oven for drying. After about 16 hours of drying, the cage and sample are weighed, then the process is repeated. The slake durability index ($I_d$) is defined as the ratio of the final weight of the specimen remaining in the cage after two cycles of cage rotation to the initial dry weight of the specimen *(Franklin and Chandra 1972)*.

The tumbling action of the rock particles during the test imparts an abrading action that is somewhat similar to that induced by the translation of bedload over rock at the base of the channel. Indeed, the slake-durability of the rocks tested in this investigation is a function of many of the same geotechnical properties that appear to control the abrasion resistance of the rocks in stream channels. As applied for the sedimentary rocks in this study a significant deficiency was noted in the current ASTM standard for the test. The process of wetting and oven drying the specimens dramatically accelerated the rate at which the particles abraded. Given the focus on rock that is either saturated year round, or which experiences only occasional, intermittent sub-aerial exposure and partial saturation, the extreme conditions imposed by the oven drying were judged to yield spurious results.

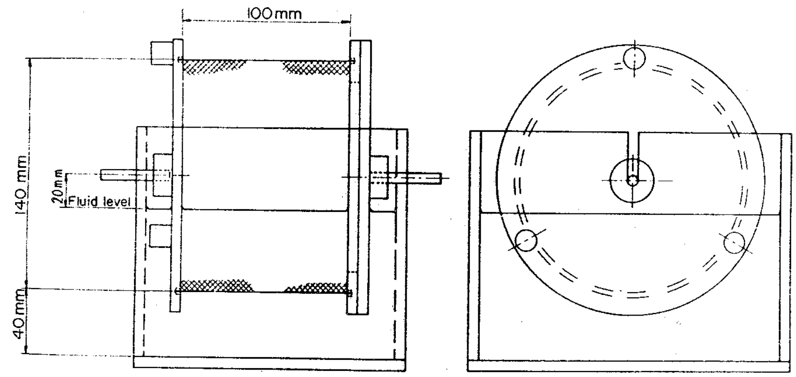


Figure 4.1: Standard Dimensions for Slake Durability Cage and Water Level

The influence of wetting and drying on sedimentary rocks has been investigated by several researchers *(e.g., Morgenstern and Eigenbrod 1974)*. Compressive strengths of continuously saturated rock specimens have been shown to be substantially greater than the strengths of rock specimens that have undergone several wetting and drying cycles. Furthermore, rocks that normally slake when subjected to wetting and drying cycles have been found to remain intact if maintained at their natural water content *(Morgenstern and Eigenbrod 1974)*. These conclusions support the observations made at several of the study sites that bedrock in the channel appears to be more scour resistant than rock along the banks that is exposed to seasonal wetting and drying. For example, at the Mill Creek - Rosenbalm site, bridge footings were located on rock within this wetting and drying zone. The footing was observed to be subjected to exposure and undermining due to bedrock erosion. The solution to this problem involved installing drilled shafts along the bank to a depth below the wetting and drying zone, and out of the stream channel. The bank adjacent to the drilled shafts was also protected with a rip-rap and shotcrete armor to reduce lateral stream migration in the highly erodible weathered rock along the bank

For the rock studied herein, the ASTM Slake Durability Test is more representative for materials that are exposed to cycles of wetting and drying. A modification to the ASTM standard has been developed which excludes the influence of the heating and drying on the durability of the rock samples. The procedure employed in this investigation involves the following steps:

1. Use a sample size of 500 g ± 50 g with rock particles between 12.5 to 25 mm in diameter, similar to the ASTM method. Store the sample in a saturated state up to the time of testing. Samples should be stored at a moisture content consistent with the field conditions, however

prolonged soaking could be detrimental to the sample because of softening effects. It has been recommended that any soaking of the specimen (if necessary) should be for less than 24 hours *(Morgenstern and Eigenbrod 1974).* If specimens are obtained from rock cores, then the selected portion of the core sample must be broken down into appropriate sized particles using a rock hammer.

2. Submerge the cage in water, remove the cage and dry off excess water with towels. Weigh the wet cage for a tare value.

3. Lightly dry off excess water from the rock particles and place them into the cage. Record the weight of the cage and the moist particles.

4. Fill the reservoir of the apparatus with water to the same levels as prescribed in ASTM for the slake durability test.

5. Engage the drive motor and allow the cage to rotate at 20 RPM for 30 minutes.

6. After 30 minutes turn the motor off and take the cage out of the water. Place at an angle to let the water inside the cage drain for 30 to 60 seconds. Remove the lid and lightly hand dry the cage using the same procedure as Step 2. Record the weight of the cage and the moist rock particles.

7. Repeat the procedure and subject the rock fragments to 30 minutes of rotation. Take weights of the cage and rock every 30 minutes for the first two hours then every hour up to a total duration of 8 to 9 hours.

8. Calculate the percent weight loss at the end of each 30-minute rotation cycle (equation 4-1) and prepare a plot of percent weight loss versus the total elapsed time of rotation.

$$\textbf{Percent Weight Loss} = (((W_R)_{t=0} - (W_R)_{t=x})/(W_R)_{t=0}) \times 100\% \qquad \textbf{(4-1)}$$

where; $(W_R)_{t=0}$ is the weight of the rock particles in the cage at the beginning of the test, and $(W_R)_{t=x}$ is the weight of the rock particles remaining in the cage at the end of a given rotation cycle (i.e., the total elapsed time since the beginning of the test).

The resulting percent weight loss is plotted versus time, as opposed to the straight comparison of final weight to initial weight as described in the ASTM standard. As an example, the percentage weight loss versus time for three sandstone specimens is plotted in Figure 4.2. Plotting the specimen weight versus time allows for trends in the abrasion resistance of different specimens to be observed. It should be noted that the term "slake durability" describes the behavior of rock or cohesive soil that has been subjected to wetting and drying cycles. The modified slake durability test performed in this study does not involve wetting and oven drying cycles, therefore the weight loss observed during the test is primarily due to the abrasion resistance of the material, not its slake characteristics. The term "*continuous abrasion*" test is used in this report to distinguish the behavior of the specimens tested herein to the behavior of similar rocks tested by the standard slake durability test.

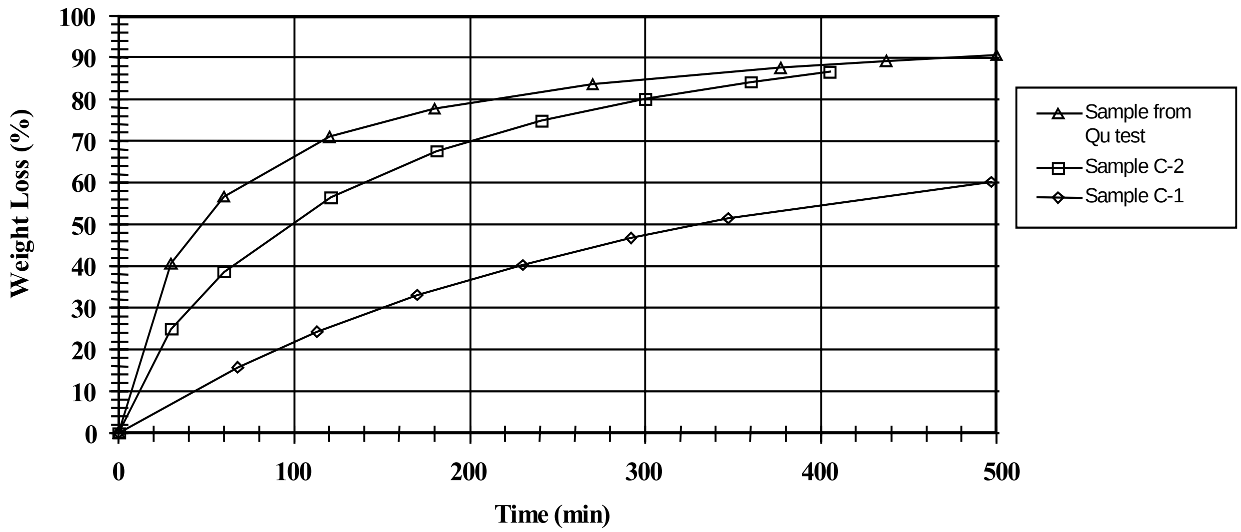


Figure 4.2: Continuous Slake/Abrasion Behavior of Three Tyee Sandstone Specimens from the Alsea-Thissel Site

### 4.2.2 Abrasion Resistance of Weak Sedimentary Rocks

The modified slake durability method proposed in this study has been used on samples of rock from all of the study sites in order to assess how the abrasion resistance of the material changes with time. The "long-term" or continuous abrasion resistance of the rock was also evaluated for each specimen.

The slake/abrasion behavior (i.e., weight loss) of the rock particles can be generalized as consisting of an initially high rate of weight loss which tapered off to a very small loss of material with time, as illustrated in Figure 4.2. The relatively high rate of weight loss at the outset of the test is due to the rapid abrasion of the angular edges of the particles. As the particles become sub-rounded to rounded, the abrasion resistance increases. Toward the end of the test the particles are commonly well rounded and very little weight loss is observed with additional rotation cycles. In general, the transition from a very steep curve of weight loss versus time to a more gradual, flat slope occurred after 120 to 200 minutes.

Continuous abrasion testing on multiple rock specimens from the same site demonstrated that although the initial portions of the continuous abrasion curves exhibited significant variations, the rate of weight loss with time became very similar during the latter portions of the tests (Figure 4.2). It was noted that after roughly 120 to 200 minutes of testing the weight loss curves for different specimens of the same rock were sub-parallel. The data in Figure 4.2 has been re-plotted in Figure 4.3 to demonstrate the variation of weight loss with time after 120 minutes. The data has been plotted in semi-log format and the slope of the line has been used as the basis for an index property called the *Abrasion Number* ($\beta$). The lines have the form:

$$\textbf{Weight Loss} = \beta \cdot \mathbf{Ln(T) + B} \qquad \textbf{(4-2)}$$

where β is the Abrasion Number, T is the elapsed time, and B is the y-intercept on the plot (i.e., the weight loss at t = 0). Given the non-linear behavior of the rock and the time interval of interest (t > 120 to 200 minutes), the y-intercepts on these plots are non-zero values. The B value represents the initial changes in weight loss, with higher values for rock particles that abrade quickly, and lower values for highly abrasion resistant materials whose edges do not chip easily (i.e., unweathered basalt).

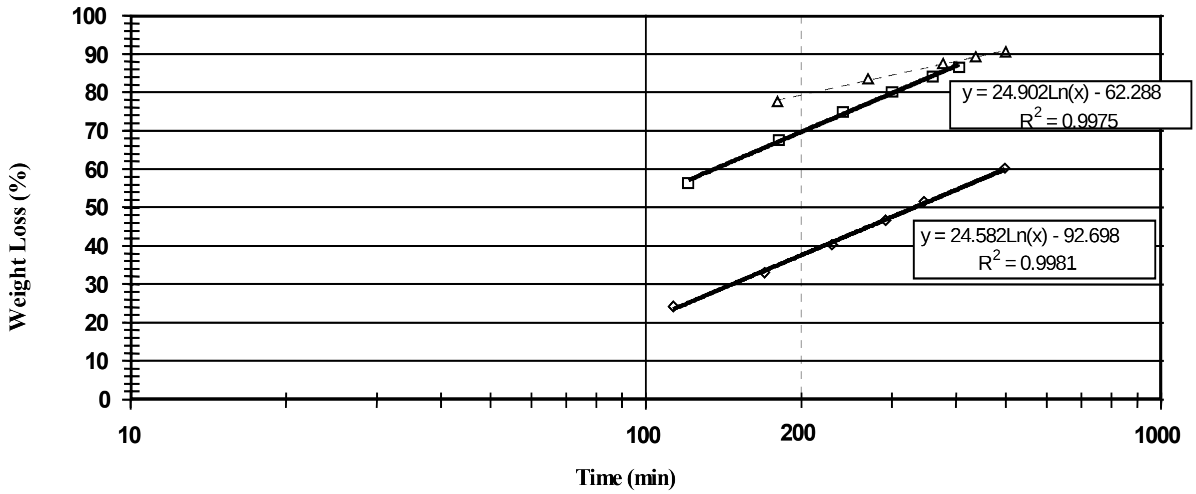


Figure 4.3: Semi-log Plot of Continuous Abrasion Behavior of Two Tyee Sandstone Specimens from the Alsea-Thissel Site

Continuous abrasion tests were performed on 31 rock samples. The Abrasion Numbers were found to vary between 3 and 30 with basalts and very hard rocks varying from 1 to 10, hard to weak sandstones from 10 to 20, and soft siltstones and shales, 20 to 30 or more. This test was found to be very useful for identifying erodible material that would not have been classified as such using data from other geotechnical tests. For example, the Tyee Sandstone exposed at the sites investigated herein is classified as weak rock. Field investigations demonstrated high core recovery and relatively high RQD values ranging from 70% to 100%. The compression strength of this material was comparable to the other sandstone units investigated. However, the β-value is between 20 and 25, indicating that the abrasion resistance of the sandstone is low and, thus, potentially susceptible to scour. This preliminary assessment demonstrates that although the rock would be classified as suitable for bridge foundations ($q_u \sim 40$ MPa), the material may be vulnerable to scour that could result in undermining of a footing.

The slake durability apparatus is not a common device in standard geotechnical laboratories and the data is not routinely used in practice. The limited availability of this equipment makes it difficult for most engineers to obtain slake durability data or the proposed Abrasion Number. It was deemed useful to relate the Abrasion Number to a standard rock property that is routinely obtained in practice. Several correlations between the Abrasion Number and other geotechnical engineering properties were evaluated; the most representative of these was based on the saturated density of the rock. A simple relationship between β and the saturated density of the rock cores has been developed (Figure 4.4). This plot demonstrates that the abrasion resistance of the rock increases with the saturated density of the material.

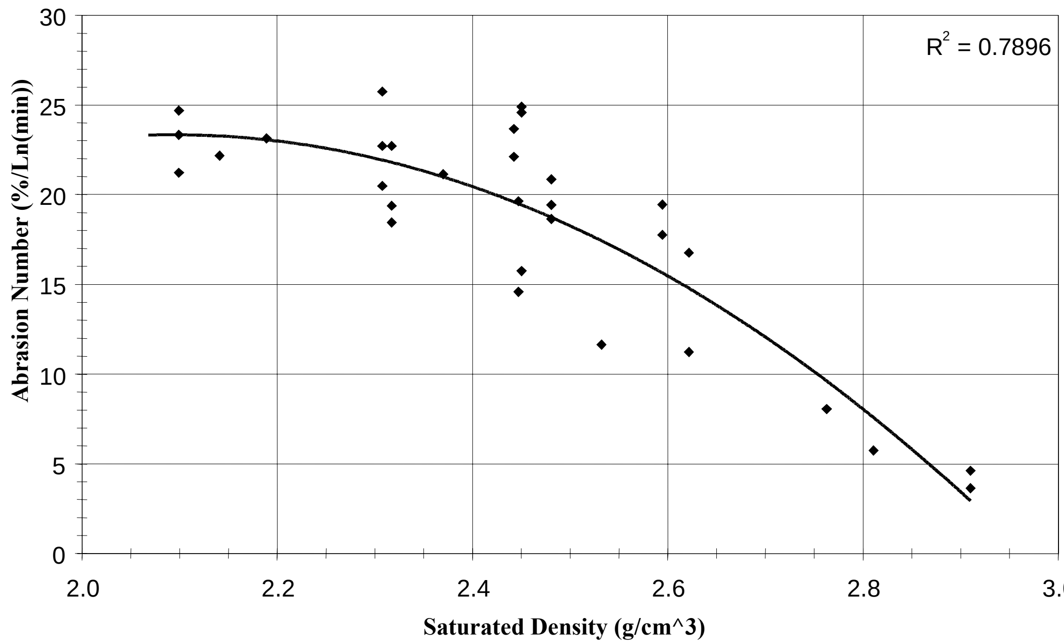


Figure 4.4: Relationship of Abrasion Number (β) and Saturated Bulk Density

The curve illustrated in Figure 4.4 can be represented by the formula:

$$\boldsymbol{\beta = -30.51\rho^2 + 127.65\rho - 110.19} \qquad \textbf{(4-3)}$$

It should be noted that the proposed relationship between saturated density and Abrasion Number is applicable only for weak sedimentary rocks similar to the materials that were tested herein. The relationship is considered useful for estimating the Abrasion Numbers of Coast Range sedimentary rocks having densities between roughly 2.1 and 2.9 g/cm$^3$.

## 4.2.3 Unconfined Compression Strength

Unconfined compression strength ($q_u$) is a useful index parameter for describing the strength of rock specimens that are free of discontinuities. For the sedimentary rocks tested in this study the unconfined compressive strength can be indirectly related to particle cementation and the density of the rock, both parameters that influence the abrasion resistance of the material. The unconfined compression test consists of axially loading an intact sample from a rock core to failure. The compressive strength is defined as the maximum axial compressive stress at failure. The test is widely used in foundation practice, however, it does not account for the influence of discontinuities (e.g., bedding planes, joints, fractures) on the strength of the rock mass.

Given the routine use of the unconfined compression strength in practice, a relationship between the $q_u$ and the Abrasion Number was evaluated. The results from ten compression tests are plotted against the Abrasion Numbers for the same material (Figure 4.5). Based on this comparison it is apparent that abrasion resistance (as defined by the Abrasion Number) is weakly correlated with the unconfined compression strength. This suggests that $q_u$ may not be a particularly useful parameter for estimating the scour resistance of weak sedimentary rock. This observation should be tempered by the fact that the data set provided is very small. Notwithstanding the small data set, the range of Abrasion Numbers for rock specimens exhibiting unconfined strengths between 35 to 45 is substantial.

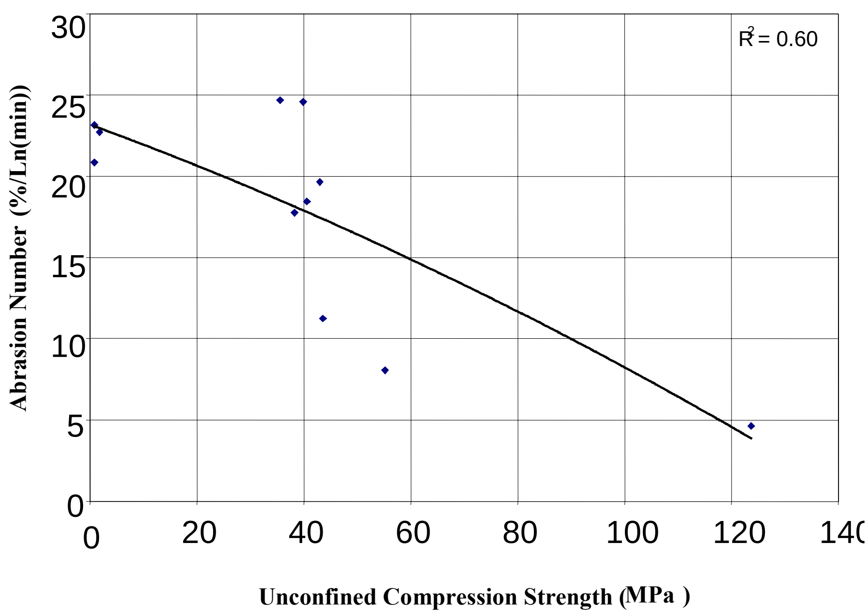


Figure 4.5: Abrasion Number (β) versus Unconfined Compression Strength

## 4.2.4 Density

The bulk density of rock has been used in numerous empirical correlations with other engineering properties. The ease with which this parameter can be obtained from rock cores or grab samples is advantageous for use in practice. The density of the sedimentary rocks in this study is primarily a function of the specific gravity of the grains, porosity, and cementation. The abrasion resistance of rock has been demonstrated to vary linearly with density *(Goodman 1989)*.

Bulk densities of saturated specimens were measured for all the rock samples. The density values ranged from 2.0 to 3.0 g/cm$^3$ (125 to 190 pcf). As shown in Figure 4.4, the saturated density relates quite well to the Abrasion Number.

## 4.2.5 LA Abrasion Test

The LA Abrasion test (ASTM C131) was developed to determine the durability of gravel or crushed rock for use in concrete and asphalt concrete for paved road applications. The procedure includes taking a representative sample of an aggregate or gravel with a known gradation (about 5 to 10 kg per gradation size), placing the sample into a large steel drum along with 10 steel balls of a specified size, and rotating the drum for 500 revolutions. The impact of the steel balls and the specimen during the rotation of the drum crushes and abrades the aggregate. The degree to which the aggregate has been crushed is evaluated in terms of the change in the gradation of the sample during the test. The rock is deemed acceptable for use in construction if the gradation has not changed beyond a certain percent.

The LA Abrasion Test is difficult to perform on core samples of weak sedimentary rock for the following reasons:

1. The sample is cylindrical and it must be pulverized with a hammer or small crusher before insertion into the drum.
2. In order to satisfy the weight requirement specified in the test standard the length of core sample that is needed is excessive. Numerous boreholes would be required to obtain the requisite quantity of rock.
3. The oven drying that is specified would alter the engineering properties of the rocks evaluated in this study. It was demonstrated in this study that drying reduces the crushing strength of the rock and results in a very brittle material. This effect along with the size of the 10 steel balls results in the almost complete pulverization of the specimens. A modified version of the test was evaluated wherein only 4 steel balls were used and the effect was the same on all of the rock samples tested. The samples of different rock performed uniformly poorly, as expected. The method was therefore abandoned as an effective screening tool for the weak sedimentary rocks tested in the study.

While the LA Abrasion Test is worthwhile for assessing the durability and hardness of competent rock and gravel, it is not recommended for use with the type and grade of rocks tested herein.

## 4.3 DISCUSSION OF GEOTECHNICAL RESULTS

### 4.3.1 Wetting and Drying Effects

Of the geotechnical index tests performed for this study, the modified ASTM Slake Durability test (i.e., the Continuous Abrasion Test) appears to provide a very useful material property for evaluating the abrasion resistance of weak sedimentary rocks. The test procedure most closely mimics the action of bedload striking rock in a stream channel, and it demonstrates the increase in abrasion resistance with time as angular particle edges are smoothed and rounded. As discussed in Section 4.3.1, the oven drying that is required in the standard Slake Durability Test has a negative effect on the engineering properties of the sedimentary rocks that were studied. The test results for rock from the Mill Creek - Hwy. 22 site (Figure 4.6), demonstrate the significant difference in the material behavior with and without the drying cycle. The specimen tested in accordance with ASTM D4644 was completely degraded after 20 minutes of testing. For the sake of comparison, this corresponds to an Abrasion Number of 1.0. The Continuous Abrasion tests performed on three specimens from the site resulted in a uniform behavior that was markedly different from degradation behavior resulting from the ASTM D4644 procedure. The behavior of the specimens during the Continuous Abrasion tests is assumed to be more useful as a diagnostic tool for scour evaluations.

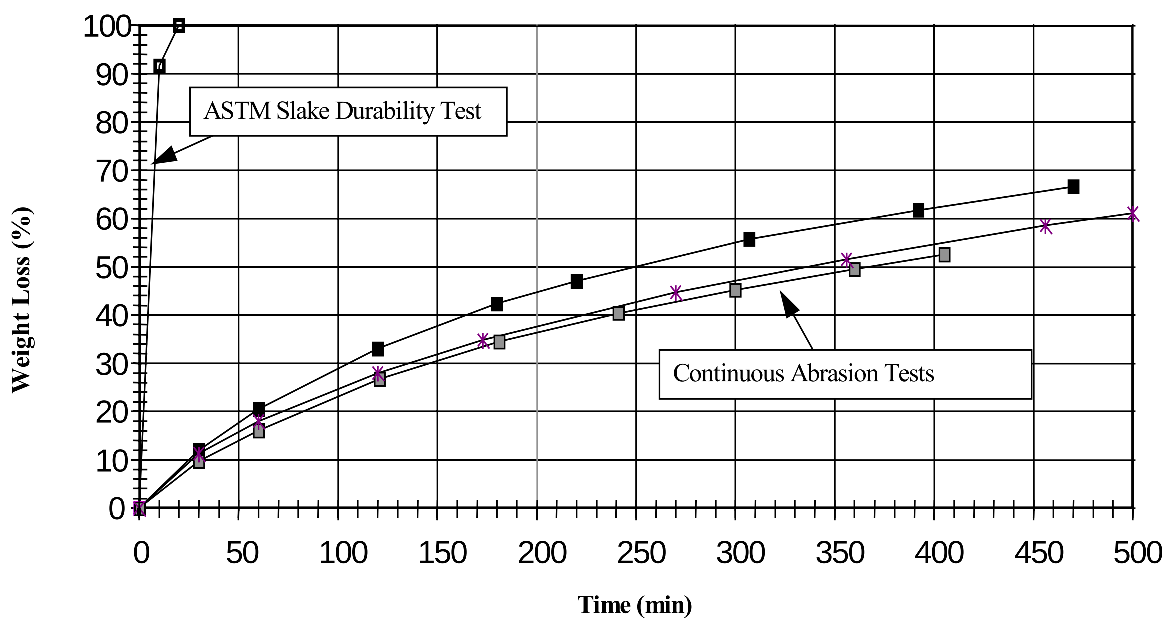


Figure 4.6: Comparison of Slake and Abrasion Test for Siltstone Specimens from the Mill Creek-HWY 22 Site

# 5.0 HYDRAULIC INVESTIGATION

The vulnerability of a stream channel to scour reflects both the abrasion resistance of the streambed and the flow characteristics of the stream. While the geotechnical investigation focused on the resistance of the rock to abrasive forces, a concurrent portion of this study was undertaken to characterize the hydraulic characteristics and discharge patterns of the streams. These hydraulic factors directly influence the magnitude of the forces acting on the rock at the base of the channel (e.g., turbulence-induced uplift, impact forces of bedload on the bedrock, continuous abrasion by bedload). In general the hydraulic factors can be thought of as imposing the demand on the bedrock, while the geotechnical parameters describe the capacity of the rock to resist the erosive forces. Both the geotechnical and the hydraulic parameters are requisite input for engineering evaluations of scour.

In addition to the channel surveys the hydraulic investigations at the study sites included: (1) acquisition and synthesis of daily stream gauge data, (2) computer modeling using the Corps of Engineers HEC-RAS water surface profile program *(USACE 1997)*, and (3) the development of annual flow and stream power curves. As previously outlined in Section 1.2, the rate of scour being evaluated in this study is based on the channel erosion as a function of cumulative stream power. All geotechnical parameters being equal, the rate of erosion is a function of the volume and velocity of the bedload that translates over the bed, as well as the water velocity and turbulence adjacent to the bed. As an approximation it is assumed that these factors can be related to the intensity and duration of the discharge, or to the cumulative stream power. A primary objective of the hydraulic investigation was the development of time histories of stream power that span the time interval of interest (i.e. from the date of the first channel cross-section to the date of the most recent survey). This effort is described in the following sections.

## 5.1 ACQUISITION AND SYNTHESIS OF DISCHARGE DATA

Stream gauge data was obtained from the United States Geological Survey via the Internet *(USGS 1997)*. In several cases, available gauge data was supplemented with synthetic data developed from relationships with streams in or adjacent to the same drainage basin. The adjustments that were made to the USGS discharge data and the method of synthesizing data is described in the following section.

### 5.1.1 Adjusting and Synthesizing Daily Flow Values

Adjustments to the recorded flow data were required for sites located far enough away from the gauge station to yield a significant change in the drainage area. The adjustments for drainage area were made based on the procedures outlined in the USGS/ODOT report "Magnitude and Frequency of Floods in Western Oregon" *(Harris, et. al. 1979)*. The criteria proposed by Harris and others for estimating design flow or peak discharge are based on the relative area of the drainage basin contributing to the flow at the site of interest (the "ungauged" location) and the area of the basin at the reference gauge (the “gauged” location). When the difference in the drainage areas is less than 5%, the flow data obtained at the reference gauge is used without adjustment. If the difference in drainage areas is between 5 and 25%, the flow adjustment is made with the following simple relationship:

$$\mathbf{Q_u = Q_g * (A_u/A_g)^a} \quad \textbf{(5-1)}$$

Where; $Q_u$ is the ungauged discharge, $Q_g$ is the gauged discharge, $A_u$ is the ungauged drainage area, $A_g$ is the gauged drainage area, and $a$ is a drainage area exponent from the regression equations in the USGS/ODOT report.

When the drainage areas differ by more than 25%, the report recommends using regression equations that are based on precipitation intensity, forest cover, areas of lakes, and drainage area. This method can be used to estimate flows for the 2, 5, 10, 25, 50, and 100-year events *(Harris, et. al. 1979)*.

The historic record of discharge at most of the sites contained gaps. The lack of a complete record of daily flow data for the time intervals of interest necessitated the synthesis of this data. Several methods were attempted in order to create correlation equations for daily stream flows at the local gauge and other gauges having complete daily stream flow records. This was achieved by comparing the available stream record at the site of interest with the records at reference gauges located in the same drainage basin or an adjacent basin. Once the correlation equations were established, then data from the continuously monitored reference site(s) could be adjusted to yield the flow at the site of interest. In order of highest to lowest data quality and reliability, the methods included: (a) comparison of the local gauge data with a near-by gauge on the same stream during a period when both gauges were operating concurrently; (b) comparison of the local gauge to two or more gauges located within the basin; and (c) comparison of the local gauge to two or more gauges located within the basin or in an adjoining basin. The site-specific flow data was plotted against the nearby stream data and a linear regression was established.

An example of the technique is provided in Figure 5.1 for correlation between the Five Rivers - Fisher gauge and Alsea River - Tidewater gauge. In this case stream gauge data measured at the Fisher site are simply plotted against the gauge data obtained on the same days at the Alsea River - Tidewater site. A linear relationship was found to exist for the flow conditions at the two sites. Given the relationship between the flows at these two sites the flow at one site can be estimated based on gauge data from the other. This flow estimation technique is very useful as gaps in data due to the loss of operation of an important stream gauge can be synthesized from existing data at near-by stations with continuous stream records.

The quality of the stream gauge correlations was evaluated using simple statistical procedures. For the simple linear regressions performed herein, the coefficient of determination ($r^2$), defined as the square of the coefficient of correlation, was used to evaluate the strength of the correlation between the two data sets. A $r^2$ value of 0.70 was selected as minimum acceptable value. If the $r^2$ value was less than 0.70 (if the scatter in the gauge data was too great) then records from other streams were evaluated. In most cases the formulas relating the flow at one gauge to another yielded $r^2$ values greater than 0.87. The minimum $r^2$ value of 0.70 was exceeded in every case.

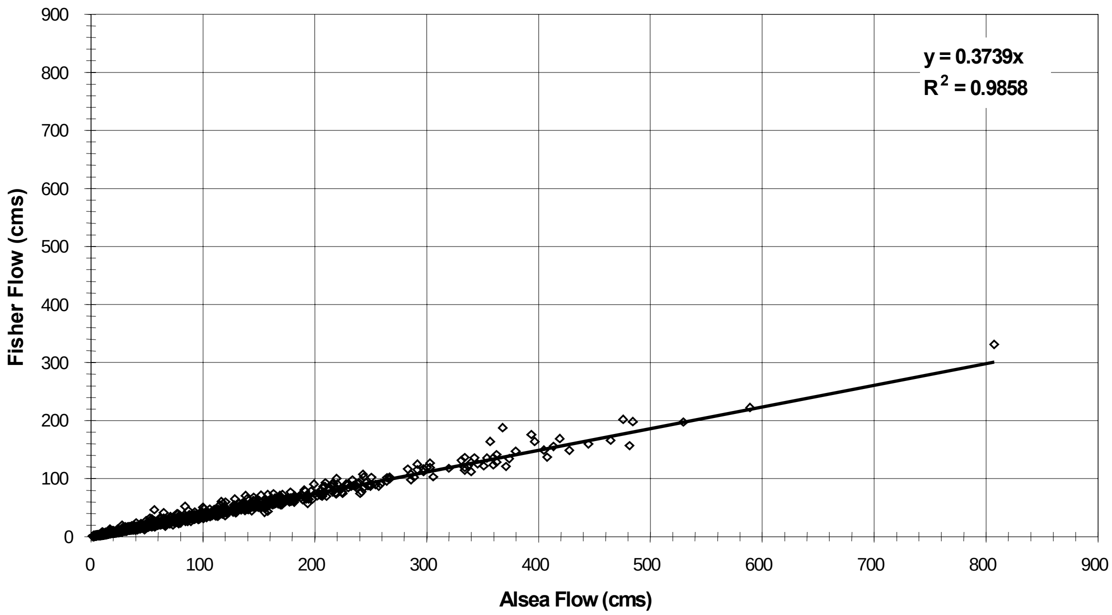


Figure 5.1: Regression of Alsea River-Tidewater and Five Rivers-Fisher Daily Flows

## 5.2 EVALUATION OF HYDRAULIC VARIABLES

The primary hydraulic variables that were evaluated in this study included flow volume, stream power, shear, and velocity. The variables were calculated using the Army Corps of Engineers HEC-RAS version 2.0 water surface profile analysis program *(USACE 1997)*. The stream model was based on the channel cross-sections surveyed for this study and longitudinal profiles constructed with elevation data from USGS 7.5-minute quadrangle maps. Limited resources and safety concerns precluded extensive longitudinal surveys of the larger rivers. At each site a 60 m long section of the river was modeled using HEC-RAS. The channel was modeled using the cross section adjacent to the bridge. This cross section was used as a “template,” thereby establishing a uniform channel extending 30 m upstream and downstream of the bridge.

In addition to the channel cross section, the slope of the channel or the slope of the water surface is required to initiate HEC-RAS computations. The slopes of the channels were obtained from one or more of the following: (1) a site specific survey performed in this study, (2) a site specific survey performed by ODOT, or (3) estimates made from USGS topographic maps. Although smaller streams could easily be surveyed for longitudinal bed profiles, difficulty in surveying the slopes of larger rivers made this approximation necessary. Although potentially significant differences were observed in the slopes obtained from these three sources (explained in more detail in Section 5.2.1), the slopes provided by the 7.5-minute quadrangle maps were used in all cases for consistency.

The study assumed that the slope of the stream is equal to the energy gradient of the stream. This is a common assumption, although at times erroneous in the following cases: (a) non-uniform, subcritical flow where the energy slope is larger than the bed slope, and (b) non-uniform supercritical flow where the energy grade is less than the bed slope *(Annandale 1995)*. After the cross-sections were entered at the appropriate elevations, Manning's roughness coefficient *(n)* was estimated for the channel and the overbank sections, and different flows ranging from the lowest observed value to the highest observed value were modeled. Hydraulic variables such as stream power, shear, velocity, and Froude number were computed for each stream section. These variables were plotted against the representative flow and simple equations describing the relationships between the specific parameters were developed.

An example of the relationship between the flow data and the computed stream power is shown in Figure 5.2. It should be noted that the stream power is computed for the entire width of the stream and a unit length of channel. A high correlation ($r^2 > 0.95$) between the discharge and the stream power was observed in all cases. The equation of the best fit allowed for the conversion of daily stream flow data (Figure 5.3) to daily stream power (Figure 5.4). The daily velocity and daily shear values could also be computed. Given these daily flow values, sediment transport and scour potential can be evaluated. The proposed technique for estimating the rate of scour based on geotechncial and hydraulic parameters is explained in detail in Chapter 6.

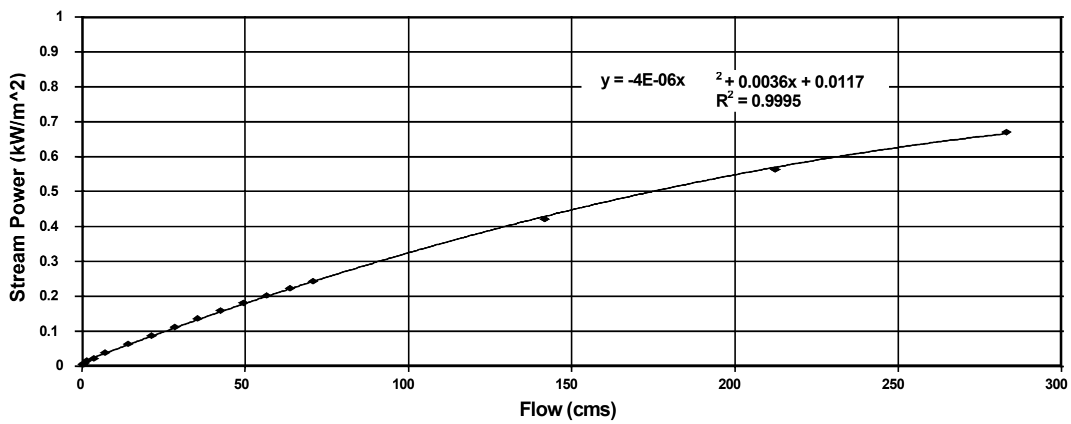


Figure 5.2: Relationship between Daily Flow and Stream Power at the Five Rivers-Fisher Site

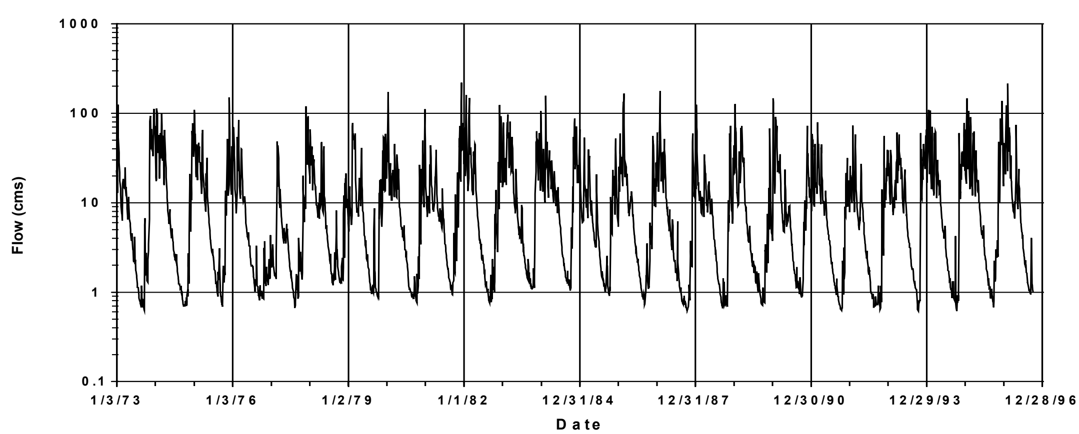


Figure 5.3: History of Daily Flow at the Five Rivers-Fisher Site

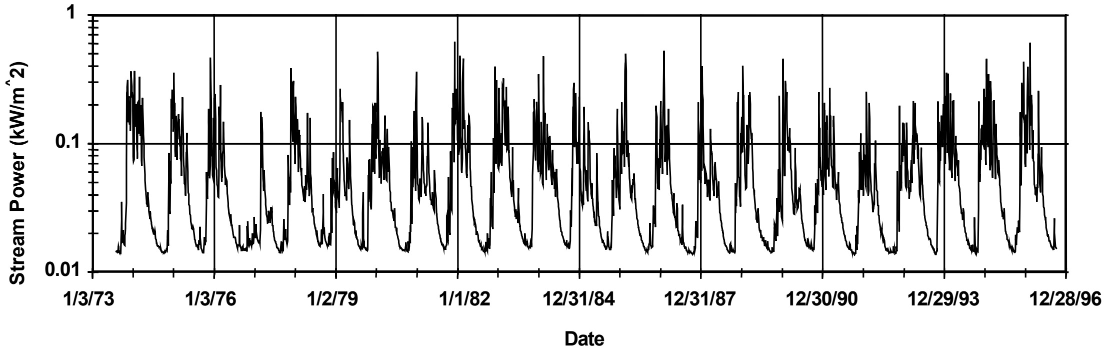


Figure 5.4: History of Daily Stream Power at the Five Rivers-Fisher Site

### 5.2.1 Effect of Slope on Stream Power

As illustrated in Figures 5.2 to 5.4, the stream power is computed directly from the daily flow data. The stream power is computed as:

$$\mathbf{P = \gamma q s_f L} \qquad \mathbf{(5\text{-}2)}$$

where P is the unit stream power, $\gamma$ is the unit weight of water, q is the unit discharge, $s_f$ is the energy gradient and L is unit length of the channel in the direction of flow *(Annandale 1995)*. Since it is assumed that $s_f$ is equal to the slope of the bed ($s_o$), a substitution of variables in equation 5-2 yields:

$$\mathbf{P = \gamma q s_o L} \qquad \mathbf{(5\text{-}3)}$$

It is evident from equation 5-3 that the channel slope is an important variable in determining the stream power.

At sites where survey data obtained by OSU and/or ODOT was compared to the slopes estimated from the USGS quad maps, significant differences in the channel slope were observed, as previously mentioned. For example, the influence of the bed slopes obtained by three independent methods on the computed stream power at the Luckiamute River site is shown in Figure 5.5. It was determined that very small variations in the slope can have a pronounced affect on the computed stream power values. For example, the difference in the ODOT- and USGS-based stream power curves shown in Figure 5.5 results from an elevation difference of only 2.75 mm in 1 meter. The sensitivity of the computed stream power to the bed slope necessitates the use of field survey data and/or appropriate judgment by knowledgeable engineers.

The influence of the slope on the computed stream power is compounded at high flows, where the potential for scour is the greatest. In this case the slope provided by the 7.5-minute quadrangle sheet is the greatest of the three methods evaluated. For most of the sites included in this study, the slopes obtained from the USGS maps were greater than those obtained by field methods. This trend would not be expected at all sites. Local variations in the channel elevation are smoothed out on the quadrangle maps. The slopes derived from these maps could therefore be either greater or smaller than the actual slope at the section of interest due to the characteristics of the channel perhaps as far as 100 m upstream and downstream. Field surveys along the stream channels were not performed at all of the study sites, therefore the potential existed for incompatible slopes based on different procedures. In order to minimize the potential for this systematic error, the 7.5-minute quadrangle sheets were used at all of the sites.

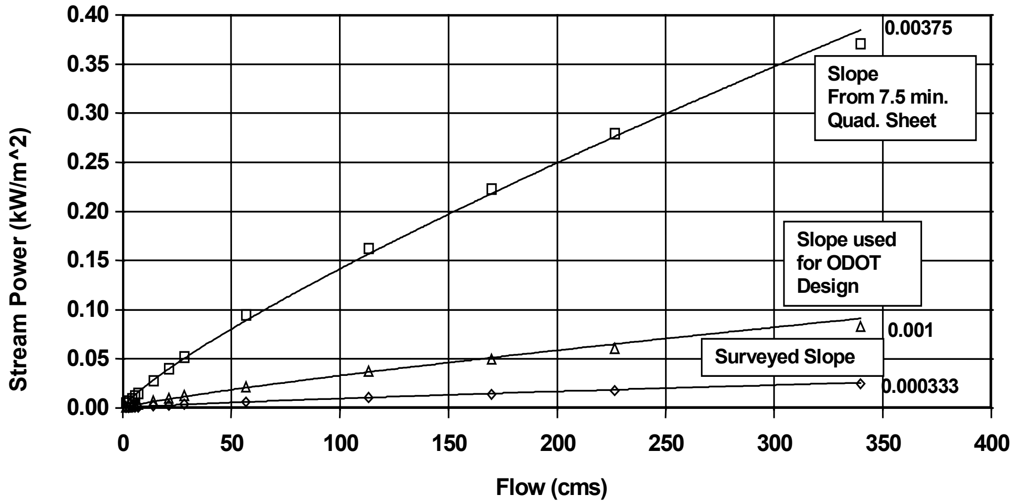


Figure 5.5: Effect of Bed Slope on the Computed Stream Power (Luckiamute River Site)

## 5.3 DISCUSSION OF THE HYDRAULIC STUDY

One of the primary objectives of this study was the possible development of a practice-oriented method for evaluating scour potential. Toward this goal, simple, straightforward methods have been proposed for obtaining pertinent geotechnical and hydraulic parameters. In order to avoid cumbersome, time consuming data manipulations the following approximations are suggested for the hydraulic evaluations:

1. Relatively straight channels can be modeled by applying the reference (i.e., near-bridge) cross section at the upstream and downstream boundaries of the HEC-RAS model.

2. Only the most current cross-sections are used to model the stream. The influence of long-term changes in the channel on the computed hydraulic parameters is therefore not addressed.

3. A consistent method for obtaining the bed slope is recommended. The 7.5-minute USGS quadrangle maps have been used as the basis for the procedures developed herein.

4. For rather shallow sloping channels the bed slope can be assumed to be equivalent to the energy gradient.

The adequacy of the cross section approximation was evaluated at a site where upstream and downstream cross sections were obtained in addition to the section adjacent to the bridge. A comparison of the computed hydraulic parameters was made between the model using the three independent cross sections and the model based on the single cross section as a "template" for the upstream and downstream boundaries. The Mill Creek - Rosenbalm site, which happens to be one of the smaller streams, was modeled. The same channel slope was used in both models. The results were not significantly different, thereby supporting the use of the single cross section at three points in the model. It should be noted that this comparison was performed for a natural channel that is relatively straight. Additionally, the geometry of the single span bridge at this site does not contribute to any pier or contraction scour effects. If the stream exhibits significant curvature over the length of the channel being modeled, or pier and contraction scour effects are anticipated, the proposed simplification is clearly not appropriate and multiple cross sections should be used in the numerical model.

It has been assumed in the modeling that there are no major changes in the morphology of the channel. At sites that have experienced significant lateral migration of the channel or degradation of the bed during the time interval between the initial and most recent surveys, the change in the channel should be accounted for in the HEC-RAS modeling.

# 6.0 DEVELOPMENT OF AN EMPIRICAL MODEL FOR ESTIMATING LONG-TERM SCOUR AT WEAK ROCK SITES

With the geotechnical and hydraulic information from each study site, the final task of this pilot study was to develop a simple, straightforward method for evaluating the potential for scour of weak rocks which are similar to the sedimentary units of the Oregon Coast Range. The extent of the scour observed by comparing multiple cross sections at each site was to be related to site specific geotechnical and hydraulic properties. Single- or multiple-parameter regressions were to be performed in an attempt to develop an empirical procedure for estimating scour rates in bedrock. The limited data set precluded rigorous regression and statistical analyses.

Despite the rather limited data set (i.e., 11 sites), the intermediate- to long-term scour at the study sites was related to the geotechnical and hydraulic parameters that were judged to govern the scour process. After reviewing numerous possible combinations of these parameters the most promising variables appeared to be: (a) the Abrasion Number, which reflects the abrasion resistance of the rock, and (b) the power of the stream which can be related to the hydraulic turbulence and uplift forces on rock particles, as well as the particle sizes and volume of bedload that translates over the bedrock. The stream power was computed as the cumulative, or integrated, hydraulic power that was expended during the time interval between the reference channel surveys. The resulting procedure for estimating scour accounts, albeit simply, for the scour resistance of the rock and the hydraulic parameters contributing to the scour process.

Because the proposed procedure is based on a very limited data set, inevitable uncertainties in the survey data must also be considered when interpreting the rates of scour computed in this study. Deriving the scour resistance on an abrasion parameter implicitly assumes that all of the channel degradation at the study sites was due to bedload abrading the rock bed. Based on general rules of thumb and semi-quantitative scour methods, it appears that the predominant mode of scour at the study sites is abrasion by bedload. While this generalization may be appropriate for the continuously submerged portions of the channels, it is not considered valid for the stream banks and portions of the channel exposed to seasonal wetting and drying and other weathering phenomena. In addition, discharge data and stream profiles at several of the sites indicate that flow velocities may have been high enough to induce jacking and dislodging of rock particles during extreme flood events. These limitations considered, the empirical procedure should be viewed as a preliminary screening tool that can supplement existing guidelines for evaluating scour in rock, and a point of departure for more comprehensive studies of the scour phenomena.

## 6.1 COMPARISON OF CROSS SECTIONS

As the basis for the rate of scour estimation the average erosion value obtained from the cross section is the most important variable in this study. The recent cross-sections were plotted against the initial cross sections, and the average change in elevation across the width of the channel was used to determine the amount of erosion. The average erosion was calculated using two different methods. The first method was to find the area of the displaced material between the two sections, then divide it by the width of the stream considered. The resulting value has units of length and can be considered an approximate average scour depth. The second method was to take average depths across the width of the stream using elevation data spaced every 30 cm to 60 cm. The channel width used for both methods was the distance across the submerged channel at the time of the field surveys, which was during the summer months. The conditions that existed at this time correlate approximately to the low flow condition for the stream. The saturated width is important due to accelerated weathering effects in the wetting and drying zone.

Several of the sites exhibited localized conditions that affected the average scour across the channel. For instance, at the Mill Creek - Rosenbalm Road site, there was an isolated 1 m drop in channel elevation near the middle of the stream over the seven-year period between the two surveys. This localized scour is clearly significant, however when this elevation change is averaged with data from the rest of the channel the average loss in elevation does not appear to be as severe. In another example, when comparing cross-sections from 1940 for Mill Creek – Hwy. 20 the section shows a flat riverbed and the footing buried into what was termed “soapstone”. This bridge was re-sectioned in 1980 for a project that involved widening the bridge. When the 1980 cross-section was compared to the 1940 cross-section, the “soapstone” (now called shale) was no longer present. Upon observation, there is no evidence to confirm that the footing was buried into the shale, therefore the section from 1980 was used.

Finally, the Nestucca River - Powder Creek site is the only site that was not re-measured with soundings. In December 1995 this site was sounded during high flow, and the water level was compared to a staff gauge located at this bridge. In June 1997, the cross-section was obtained by measuring the depth from the water surface (assumed to be level) to the bedrock using a fiberglass elevation rod. The water surface was then measured in relation to the staff gauge. After normalizing the cross-sections to a constant water surface, the depths could be compared.

## 6.2 INFLUENCE OF BEDLOAD ON ROCK SCOUR

Abrasion of bedrock in stream channels by translating bedload is clearly a primary influence on the rate of scour. The role of bedload on the scour process poses two distinct challenges for scour models such as the empirical model proposed herein: (1) estimating abrasive forces on bedrock due to the bedload, and (2) potential errors in the scour estimates due to thin bedload deposits overlying the bedrock. With respect to the former, it is postulated that the bedrock is subjected to abrasive forces from the impact of individual bedload particles. The abrasive forces exerted on the bedrock by the bedload is a function of the bedload characteristics (e.g., density, angularity, particle size, bedload volume) as well as the hydraulic conditions (e.g., water velocity and boundary shear stresses near the bed, depth, channel gradient). Clearly, many of these variables change in response to storms, seasonal flows, position in the channel, and other factors. The cumulative effect of the bedload can be viewed simply as related to the total number of particle impacts per unit area.

As noted, abrasive forces are a function of the size, shape, velocity and orientation of motion of a particle prior to impact. The translational velocity of the particle is related to boundary water velocity, and this can be estimated using empirical relationships. Calculation of the impact force requires that the mass of the particle be known. If, for the sake of illustration, bedload of uniform particle size and weight is considered, then the boundary water velocities can be associated with the threshold of particle movement, and translation can be specified. Water velocities below the threshold value would be insufficient to move the bedload and no scour due to abrasion would result. As the water velocity exceeded the threshold for particle translation, the water velocity (or stream power) could be used as a surrogate for particle velocity, thus facilitating the use of flow intensity and duration to approximate the cumulative impact forces.

The calculation of cumulative impact forces leading to scour is complicated by the existence of non-uniform bedload. The maximum particle size that is moving at any time is related to the boundary water velocity. In addition, the volume of particles that are translating at a point in time depends on the flow velocity and the rate of sediment transport into the stream. If equivalent bedload particle size distributions are assumed for each stream given equivalent boundary water velocities, then a simplified measure of the impact forces could be established. The cumulative effect of the abrasive impact forces could be approximated if the threshold water velocity for each grain size is accounted for, and the velocity of the particles can be estimated. Calibration of the model could be provided by bedload sampling during different flow conditions. It is surmised that incorporating a methodology such as this would enhance the empirical scour prediction model. This technique could be useful in assessing the relative influence of perennially moving sand size bedload or intermittently moving cobbles on the rate of scour in weak rock. Most importantly, this may also lead to the identification of a threshold stream power at which the rock is prone to scour.

In general, very little bedload was observed along the transverse stream sections investigated in this study. This includes stationary bedload deposited during periods of greater flow velocity, but also translating bedload, judged to be relatively minor during the low flow conditions. Despite the minor amount of bedload observed at the survey sections during the summer months when most the stream surveys were made, it is acknowledged that bedload is continually moving across the stream bed, thereby contributing to continuous abrasion of the bed. Additionally, the existence of gravelly point bar deposits along all of the streams demonstrates that the bedload in these streams is composed of coarse-grained particles during high flow conditions.

Extensive sampling of bedload during different stream flow conditions was not possible during this study. To estimate, in a very general sense, the characteristics of the bedload at the study sites, sediment samples were obtained from point bar deposits near the study sites. The point bar samples were obtained from similar portions of respective point bars, therefore it may be assumed that the gradations reflect similar depositional environments. These bedload samples were collected for comparative studies of gradation. The results of these gradation analyses support an overly simple, yet implicit assumption in the empirical scour estimation procedure that the particle size distribution of the bedload is roughly similar at all sites. This bedload evaluation is clearly simplistic and it is recommended that more rigorous bedload studies be made in order to refine the abrasion model.

## 6.3 DEVELOPMENT OF THE EMPIRICAL SCOUR MODEL

The fundamental parameters used in this study to model the scour process are average channel erosion, a newly defined Abrasion Number (β), and the cumulative stream power consistent with the investigations by Annandale *(1995)* and Costa and O'Conner *(1995)*. The cumulative stream power was computed using daily stream flow data and the channel geometry in HEC-RAS modeling studies. The resulting history of stream power as a function of time is integrated to obtain a cumulative stream power over the time interval of interest. To obtain a scour prediction, the practitioner would convert an average annual hydrograph from flow volume or stage to power, integrate the stream power for the one year interval then multiply this value by the design life of the bridge.

The stream power computed using HEC-RAS is derived for a unit length of channel and the entire width of the stream. The width of the stream is a function of the channel geometry and the discharge, therefore it is not a constant value. Although the stream width that is used in the computation of stream power varies with discharge, the width of the channel across which the rate of scour is determined is constant. As previously discussed, only the portion of the channel that remains saturated year round was considered in estimating the rate of scour. This was specified to avoid the effects of weathering on the observed channel erosion. This saturated portion of the channel was assumed to correspond to low flow conditions at the time of the field surveys (the mid- to late-summer months). It is recognized that lower flow conditions are likely to have existed intermittently in the past.

Also, the stream power used in the study reflects one "global" value for the unit length of channel considered. A more representative technique would yield stream power values for specific portions, or perhaps "unit widths", of the channel. This measure would more accurately reflect the stream power and bedload transport at specific portions of the channel, yielding improved estimates for the abrasive forces acting on the rock. It is not possible to obtain the stream power per unit width using the HEC-RAS model employed, therefore the "global" stream power per unit length of channel was used as a surrogate.

The geotechnical and hydraulic parameters that are pertinent to this project are summarized in Table 6.1. This data formed the basis for the empirical scour prediction models evaluated herein. Initial studies focused on the use of a commercially available statistical package to identify the variables with the highest significance. The statistics program was used to discover the significant variables through stepwise linear regression analysis. Given the limited data set this regression analysis was performed with the goal of identifying useful trends in the data. The average erosion was specified as the dependent variable and a relationship was examined using only the Abrasion Number (β) and the Integrated Stream Power (Ω). The method of obtaining average erosion that resulted in the best relationship was the method of averaging depths over the width of the stream. Statistically, eleven sites is a small population, therefore the multivariate linear regression output of a linear model was disregarded.

Table 6.1: Variables Used in the Statistical Study

| SITE | DATES OF OBSERVATION | FIELD DATA | GEOTECHNICAL LABORATORY DATA | | | | HYDRAULIC DATA COMPUTED FROM DAILY STREAM FLOW RECORDS | | |
|---|---|---|---|---|---|---|---|---|---|
| | | Average Amount of Erosion (mm) | Density, ρ (g/cm$^3$) | Slake per ASTM (%) | Abrasion Number, β | Unconfined Compression, $q_u$ (MPa) | Integrated Stream Power, Ω (kN/mm) | Average Power (kW/m$^2$) | Average Flow (m$^3$/s) |
| **Mill Creek** | | | | | | | | | |
| HWY22 | 9/18/80 to 10/13/96 | 57.2 | 2.10 | 0.0 | 23.1 | 0.9 | 5170 | 0.01 | 50.7 |
| Rosenbalm | 4/4/90 to 4/18/97 | 96.5 | 2.17 | 0.3 | 24.8 | 0.9 | 5038 | 0.02 | 83.3 |
| **Yaquina River** | | | | | | | | | |
| M.P. 2.4 | 7/27/76 to 10/13/96 | 57.6 | 2.31 | 3.2 | 23.0 | 1.8 | 4021 | 0.01 | 40.3 |
| M.P. 4.9 | 7/27/96 to 10/13/96 | 0.0 | 2.32 | 73.6 | 20.2 | 43.0 | 1070 | 0.00 | 34.7 |
| **Alsea River** | | | | | | | | | |
| Missouri Bend | 12/11/78 to 10/15/96 | 170.9 | 2.44 | 95.0 | 22.9 | 39.9 | 10915 | 0.02 | 241.2 |
| Thissel Rd. | 9/1/87 to 10/18/96 | 181.2 | 2.45 | 73.6 | 21.9 | 43.6 | 9856 | 0.03 | 400.8 |
| **Five Rivers** | | | | | | | | | |
| Fisher | 8/1/73 to 10/1/96 | 362.6 | 2.45 | 96.5 | 16.3 | 35.6 | 44922 | 0.06 | 146.6 |
| **Nestucca River** | | | | | | | | | |
| Powder Creek | 12/12/95 to 6/26/97 | 171.9 | 2.81 | 99.8 | 5.1 | N/A | 808 | 0.02 | 345.9 |
| **Middle Fork Coquille** | | | | | | | | | |
| M.P. 51 | 11/2/81 to 10/14/96 | 79.8 | 2.59 | 72.2 | 18.6 | 40.7 | 8033 | 0.02 | 40.2 |
| M.P. 53 | 11/2/81 to 10/14/96 | 114.0 | 2.62 | 97.9 | 14.0 | 38.3 | 12027 | 0.02 | 26.1 |
| **Luckiamute River** | | | | | | | | | |
| Grant Rd. | 6/20/84 to 9/12/97 | 134.6 | 2.37 | N/A | 21.6 | N/A | 5440 | 0.01 | 84.2 |

The variables β and Ω were individually plotted against average erosion in Figure 6.1. The weak trends in the data are due primarily to limitations imposed by the single parameter nature of the relationships (i.e., the average erosion is a function of both parameters). From Figure 6.1 it is evident that there are distinguishable, yet weak, trends of average erosion with each independent variable. However, only one variable is compared with average erosion. The goal is therefore to demonstrate the necessity of a two parameter, hydraulic and geotechnical model.

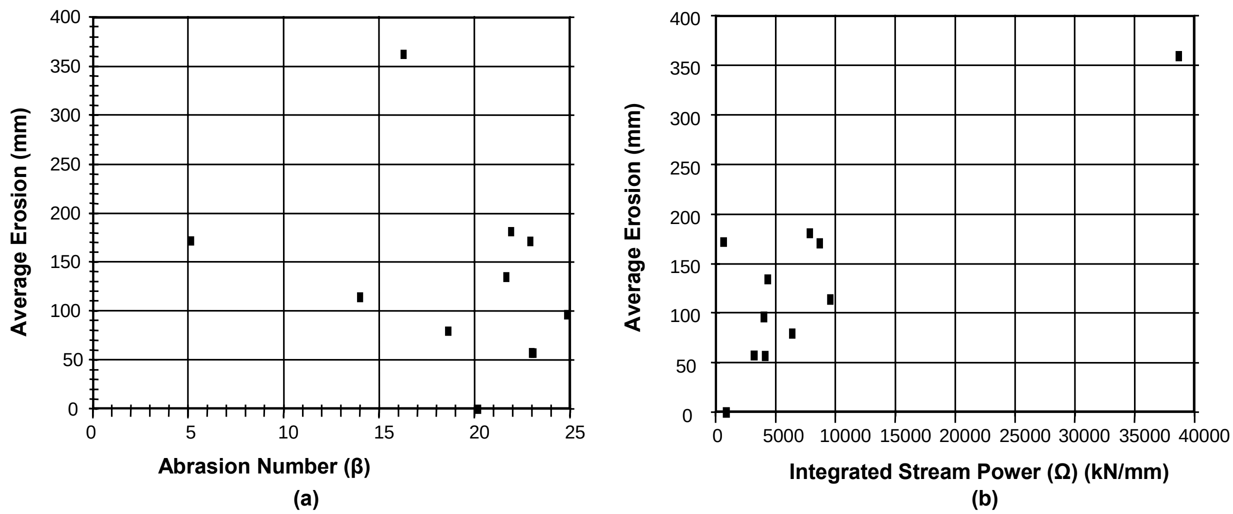


Figure 6.1: Plots of (a) Average Erosion versus β and (b) Average Erosion versus Integrated Stream Power

As previously discussed, the primary variables in this analysis are the abrasion resistance and the stream power. A simple scour model that that is based on these parameters is provided in Figure 6.2. An attempt has been made to combine the primary geotechnical and hydraulic parameters into a single figure that can be used as a preliminary screening tool for scour investigations. In this figure the average erosion observed at the study sites is plotted against Integrated Stream Power, and the influence of the Abrasion Number is indicated with contour lines. The data plotted in Figure 6.2 is listed in Table 6.1. A trend in the data is apparent, although the limited data set and inherent scatter precludes any more than the generation of approximate contour lines based on informed judgement. It is interesting to note that the anomalous point plotted with an average erosion of roughly 170 mm and a stream power of less than 1000 kN/mm corresponds to the Nestucca River site. Recall that this site was subjected to two 100-year flood events in only two years and it is surmised that hydraulic jacking and dislodgement of rock particles, as well as contraction effects contributed to the scour at this site.

In Figure 6.2, the dashed contour line for the β = 10 contour represents a best estimate using judgement. It is noted that the contours do not originate at the origin, or zero stream power, indicating that this relationship is not linear. It can be stated that as the rock becomes weaker (i.e., β gets larger), less stream power is required to abrade or scour the rock. However, the low abrasion resistance of the rock may still be sufficient to withstand the minor abrasion caused by the translation of relatively fine particle bedload. As a conceptual example, consider two different streams with different bedrock and the Integrated Stream Power equal to 5000 kN/mm. The first site has weak sandstone (β~20) and the other has a harder sandstone (β~15). On the basis of the relationships presented in the chart, the average erosion at the first site is about 55 mm and no scour is indicated for the second site. The contours have been constructed to demonstrate a threshold stream power below which scour will not occur in the weak rock. This threshold is estimated on this figure as the intersection of the contours with the X-axis.

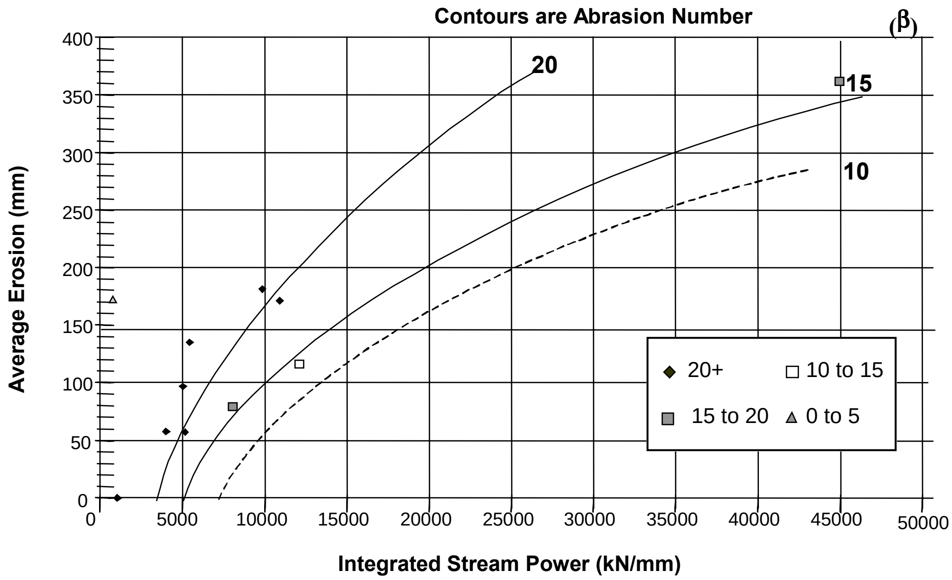


Figure 6.2: Average Erosion versus Integrated Stream Power (Ω) and Abrasion Number (β)

The small population of data plotted in Figure 6.2 precluded rigorous statistical analysis. Additionally, a clear gap in the data exists between Integrated Stream Power values of 15,000 and 45,000 kN/mm. The contours in this range were established based on engineering judgment. This estimation leads to some uncertainty; it is anticipated that the inclusion of additional data will enhance the relationships illustrated in Figure 6.2. It is recommended that this figure, combined with Figure 4.4 (Saturated Density versus β), be used to supplement existing methods for evaluating scour in rock. The primary advantage of this procedure is that the rate of scour can be estimated as a function of stream power, not just time. This allows for estimates of scour depths given discharge data based on probabilistic hydraulic studies.

## 6.4 DISCUSSION

The goal of this pilot study was to determine the primary variables that govern the process of erosion and scour of weak sedimentary rock. A preliminary relationship for estimating long-term scour rates has been developed in chart form. Although the chart is based on a relatively small database the trends that are proposed are considered useful for the purposes of initial screening and basic investigations of scour at existing bridge sites.

Several useful trends in the susceptibility of weak rock to channel erosion have been identified. Important relationships between various geotechnical and hydraulic variables and the rate of scour were identified in this research. It appears that the scour process in rock is governed by particle dislodging and removal in high power streams, and continuous abrasion in low power streams. Given this qualitative assessment there should be an approximate boundary where scour due to dislodgment and scour due to abrasion contribute equally to the scour process. The predominant mechanism for dislodgment is high stream power combined with a highly jointed rock mass. At this stage the abrasive resistance of the rock is not the most significant geotechnical parameter. Conversely, at low stream power abrasion is the predominant process leading to bedrock scour.

In addition to the continuous abrasion of rock caused by long-duration average flow conditions, the influence of high intensity floods of short- to moderate-duration should be evaluated. For example, the Nestucca River site was studied over a period that included two 100-year floods. This is significant because the characteristic, average annual stream power value is much lower than that computed during this period of anomalously high flow. On the basis of Annandale's *(1995)* procedure, the Erodibility Index for the tuff at the Nestucca River site is relatively low when compared to the siltstone and sandstone at other sites. However, the uncharacteristically high stream power associated with the floods in 1995, 1996 and 1997 could have caused dislodgment of fragments along with abrasion, increasing the scour depths despite the high Abrasion Number for the rock.

The parameter "integrated stream power" is computed based on a model of the stream cross-sections. As the basis for the stream power computation, the model should be validated for various flow conditions. One method for confirming the stream power computed by the HEC-RAS model is to calibrate the stream elevations with known gauge information. Optimally, this requires a stream gauge at every site that would record daily height and velocity measurements. A true validation of the model would require that a series of flow conditions are estimated numerically, and followed by field measurements at river stages that correspond to the modeled conditions for a direct comparison of the predicted and actual hydraulic parameters. This type of validation was not performed during the investigation.

The primary geomechanical parameter, the Abrasion Number relies on representative specimens of rock from the site. It is recommended that multiple specimens from different borings at each site be tested using the proposed Continuous Abrasion Test procedure. The evaluation of numerous samples would be helpful for identifying potential zones of weaker, less scour-resistant rock. In addition, site characterization should focus on the weakest rock that the stream flows over, therefore if relatively weak rock is observed in the stream channel, this material should be sampled for subsequent laboratory testing. Finally, the rock samples used for laboratory tests should not be obtained from the upper portions of riverbanks or terraces (unless bridge abutment issues warrant) due to weathering and seasonal wetting and drying conditions that are not representative of the conditions in the channel. The use of weathered material in the slake durability and/or continuous abrasion test would lead to erroneous $\beta$-values which would overestimate scour depths.

## 6.5 PROPOSED DESIGN APPLICATIONS

The proposed method for evaluating scour in weak rock is clearly in a formative stage of development. This procedure is proposed as a preliminary screening tool, consistent with the objectives of the investigation. As a screening tool the method can be used to supplement existing guidelines for assessing the susceptibility of weak sedimentary rock to scour. The method has been formulated in a simple, straightforward manner that facilitates a first-order estimate of long-term scour given easily determined geotechnical parameters (e.g., $\beta$ or $\rho$) and the stream flow characteristics anticipated over the design life of the bridge. The following list outlines procedures for estimating the rate of scour in weak, sedimentary rock. A design example of this procedure is outlined in Appendix D of this report.

1. Perform a thorough geologic and geotechnical investigation of the potential bridge site with drilling to identify the rock type(s), the characteristics of discontinuities in the rock mass, RQD, recovery, etc. Coring with a drill rig is preferred over hand coring so that the RQD and percent recovery can be readily obtained. The drilling should extend at least 4.6 m into the bedrock to insure proper identification of layering or weathered zones, consistent with current FHWA guidelines for foundation investigations in rock *(FHWA 1984)*. Drilling on both sides of the channel is recommended to insure representative characterization of the local bedrock.

2. Perform the following laboratory tests on representative specimens of the rock. The unconfined compression test is a standard test for establishing the allowable bearing pressure of footings, and it has been proposed as a diagnostic parameter for scour evaluations. The Continuous Abrasion Test has been demonstrated to provide useful data for scour assessments. Additionally, the density and slake behavior of the rock are potentially useful parameters.

3. Establish the daily flow data for the site based on recorded or synthesized flow data.

4. Perform a standard hydraulic investigation of the river channel. As a minimum this includes preparation of channel cross-sections and numerical modeling with a computer programs such as HEC-RAS. Calculate the channel stream power for various flows starting with the lowest observed flow up past the highest flow on record. The computed values of stream power are plotted against the stream flow and a regression analysis performed to establish a representative correlation. For the flow conditions evaluated in this study simple equations based on power or quadratic relationships were sufficient. Correlation coefficients can be obtained using standard spreadsheet software. The resulting correlation equation is used to convert daily flow values into daily power values.

5. Apply correction factors to the stream power values to account for local scour and contraction scour effects, as outlined by Smith *(1994)*. These corrections should be applied with great caution, however, as these effects were not evaluated in the development of the empirical method proposed herein.

6. Compute the cumulative stream power over the desired period from the plot of daily stream power versus time. The cumulative stream power ($\Omega$) is the summation of the area under the daily power curve. In practice, the cumulative stream power represents the summation of the daily stream power over the design life of the bridge. The design life will reflect the importance of the bridge and this may be 25 to 50 years. The record of available stream flow data at the site of interest may be considerably shorter than this length of time. Therefore, the

"average annual cumulative stream power" may be computed based on available flow data, and this value multiplied by the design life of the bridge to yield the appropriate cumulative stream power for use in the proposed design chart. This approximation would fail to account for long-term cycles (decade scale) in rainfall patterns, however, in light of the uncertainties associated with this preliminary model this is considered a minor factor.

7. Finally, once the Integrated Stream Power (Ω) and Abrasion Number (β) have been determined, establish the average depth of erosion by using the chart. An appropriate factor of safety should be applied to the resulting scour depth. As an example, if the Integrated Stream Power is 17,500 kN/mm and the Abrasion Number is 16, then the average erosion, as shown in Figure 6.3, is roughly 200 mm.

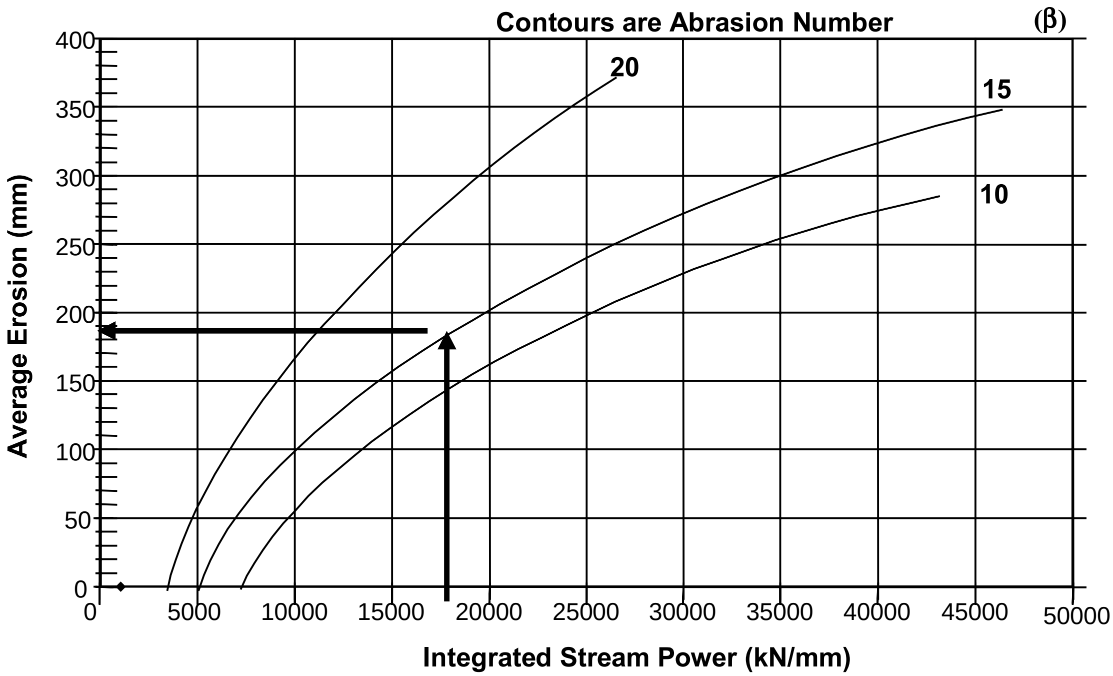


Figure 6.3: Design Example for Estimating Average Erosion

## 6.6 EVALUATION OF EXISTING STRUCTURES

This preliminary procedure can be used to supplement existing methods for evaluating the current safety of bridge foundations on weak rock:

1. A thorough bridge investigation is recommended. This includes visual inspection of all piers and footings, photographs and cross-sections or soundings of the stream channel. Compare this information to previous inspection reports and cross-sections.

2. Obtain geologic and geotechnical data on the type of bedrock, and the geotechnical parameters that were used in design. If this data is not available, then refer to Step 1 of the proposed design applications.

3. Obtain core samples of the saturated bedrock, and insure that the cores remain at the in situ water content during transport and storage.

4. Characterize the flow conditions at the site using recorded or synthesized stream gauge data.

5. Using the flow data, calculate daily stream power and the cumulative stream power corresponding to the time interval of interest.

6. Given the cumulative stream power and the Abrasion Number for the bedrock, refer to Figure 6.2 for the estimate of the long-term scour in the stream channel.

## 6.7 RECOMMENDATIONS FOR FURTHER RESEARCH

At the outset of this project there were no design methods or rational guidelines for estimating the rate of bedrock scour in natural streams. Engineers representing several state transportation departments have indicated that key issues for foundation design include: (a) at proposed bridge sites, establishing appropriate depths for spread footings in weak rock; and (b) evaluating the potential for scour around existing footings. This pilot project was conducted to identify geotechnical and hydraulic parameters that govern the scour process in weak sedimentary rock. It was also anticipated that the framework for a practice-oriented design procedure could be developed to assist engineers with scour risk studies for bridge foundations.

The process of scour in rock involves numerous geologic, geotechnical and hydraulic phenomena, many of which are very difficult to replicate in the laboratory. In light of the significant limitations that would be associated with flume studies an empirical approach for evaluating scour in rock masses was pursued in this investigation. The empirical method has the inherent advantage of "accounting" for all of the variables influencing the rate of scour in rock stream channels. Interpreting the relative influence of the numerous variables is, however, not a straightforward process. In many cases approximations have been made in order to allow for the formulation of a straightforward procedure for estimating the rate of scour in rock. Given the embryonic stages of development of rock scour models these approximations are viewed as appropriate and necessary for the identification of the primary variables governing the scour process.

Requisite information for a complete scour investigation demands significant effort in the review of engineering files, completion of field investigations and laboratory tests, compilation of hydraulic data, hydraulics modeling of stream channels, and data synthesis. Given the available resources and the corresponding scope of this investigation, the field investigations were limited to 11 bridge sites. It must be acknowledged that the limited data set precludes the development of a robust design procedure for scour in rock. The primary contribution of the investigation is the development of a multi-disciplinary framework from which further work may proceed. The project team has endeavored to highlight the strengths and limitations of the proposed empirical model throughout this report. Finally, recommendations are provided for future work on this topic. The suggested research issues are arranged as recommendations for enhancing the method proposed herein, and those that are more general in nature.

### 6.7.1 Recommendations Pertinent to the Proposed Rock Scour Model

1. To improve the statistical significance of the proposed model, data from more sites should be collected. This could be facilitated by incorporating data from files of additional agencies (e.g. state transportation departments, U.S. Geological Survey, U.S. Forest Service Districts, U.S. Army Corps of Engineers, etc.).

2. Difficulties in establishing a common datum for the "before" and "after" surveys results in potential errors in scour estimates. These errors may be due to the use of as-built bridge plans, poorly located benchmarks, or distant stations locating benchmarks when establishing the common datum. A low-cost, long term solution may be to establish several sites at which precise surveys are performed, with plans to re-survey the sites in the future. Sonic methods now exist that would significantly reduce survey error. This does not necessarily solve problems associated with localized pockets of bedload overlying the bedrock channel, but allows for precise readings that cannot be achieved with soundings and rod surveying.

3. The geologic characteristics of the rock mass should be thoroughly evaluated at study sites. The role of plucking and removal of rock along discontinuities (e.g., bedding planes, joints, fractures) warrants further investigation. The orientation of the discontinuities relative to the stream channel may prove to be a significant factor in rock scour rates. Quantifying the relative contribution of scour by abrasion and by plucking is viewed as very worthwhile.

4. The abrasion resistance of many more specimens should be evaluated by means of the continuous abrasion test proposed herein. This testing should focus on additional specimens of sedimentary rock from the Oregon Coast Range, as well as a variety of other rock types. This work would demonstrate the applicability of the Abrasion Number proposed in this study.

5. In order to evaluate the contribution of bedload to the abrasion process an investigation of the sediment transport during different flow conditions is needed. The concept of threshold conditions for particle movement (e.g., Shield's relationships) should be incorporated into the evaluation to determine the length of time that bedload is moving and contributing to erosion. Numerical models could be calibrated on a site-specific basis by means of bedload sampling at different times of the year, and the development of site-specific relationships between stream flow and the particle size distribution of moving bedload. A method of accounting for the particles that are translating over the rock as a function of the stream flow would likely enhance the proposed model. This would be particularly true for streams where abrasion is a primary agent in the rock scour process.

6. The stream power concept should be modified so that the power is computed for individual channel widths as opposed to a "global" value for the entire stream. This measure would more accurately reflect the stream power and bedload transport at specific portions of the channel, yielding more representative estimates for the abrasive forces acting on the rock.

7. The proposed method should be modified for applications involving contraction and local scour effects. Complementary studies could involve an evaluation of established adjustment factors for stream power at bridge contractions and at bridge piers.

### 6.7.2 General Recommendations for Future Research

1. Recent studies of scour in cohesive soils have focused on flume studies. Fundamental data on the process of scour of these materials due to clear water flow has been obtained. Similar studies of weak rock may be fruitful avenues for continued research. Laboratory tests have the advantage of controlled conditions that allow the investigator to evaluate the influence of individual parameters on the scour process. Potential disadvantages include the acquisition of bedrock samples, limitations associated with replicating representative bed shear stresses in flumes, and the length of time that might be required for significant erosion. Evaluating the effect of coarse grain bedload on the scour process is also very difficult to model in the flume.

2. A comprehensive program of channel profiling near existing bridge footings and piers is highly recommended. A proposed program of channel surveying would provide the basic data for empirical models of rock scour. This would require a long-term commitment by stakeholders to: (1) archive the data in an easily retrievable manner, (2) perform periodic surveys at the same sites, (3) insure that requisite hydraulic data is compiled for the duration of the project, and (4) optimally that the data would be available for on-going scour investigations by affiliated organizations.

3. It is recommended that a quantitative procedure be developed for determining when the scour process is govern by jacking and dislodgement, dislodgement and abrasion, or abrasion only. Given the broad range of characteristics of discontinuities in rock masses fruitful avenues for continued research may focus on flume studies and in situ monitoring.

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# APPENDICES

# APPENDIX A

# SITES CONSIDERED FOR STUDY

| SITE | BR # | COUNTY | HYD FILE | HISTORICAL X-SECT | STREAM GAGE | CORE SAMPLE | OTHER |
|---|---|---|---|---|---|---|---|
| Fall River Bridge | | | | N/A | Y | | |
| Wiley Creek Bridge | 43C38 | Linn | 22-53 | N/A | Y | | |
| Gates Bridge | 02523 | Linn | | 1940 | Y | 1992 | Hard Rock |
| Eagle Creek | 06561A | | | | | | |
| Rhinehart Lane | 61C20 | Union | | | Y | | |
| W Fork Salt Creek | 10050A | Polk | 27-35 | 1985 | N | | |
| W Fork Salt Creek | 10051A | Polk | 27-35 | 1985 | N | | |
| *N Yamhill River* | *06610A* | *Yamhill* | *36-11* | *1980* | *Y* | | |
| Elk Creek | 16688 | Jackson | 15-54 | 1984 | Y | | |
| Myrtle Creek | 16763 | Coos | 06-34 | 1984 | N | | |
| Trout Creek | 16961 | Jefferson | 16-13 | 1988 | Y | | |
| Steel Creek | 16756 | Coos | 06-36 | 1984 | N | | |
| **Fisher Br (Five Rivers)** | **12050A** | **Lincoln** | **21-12** | **1973** | **Y** | | |
| Grub Cr. | | Clatsop | 04-31 | 1986 | N | | |
| Fishawk Creek | | Clatsop | 04-30 | 1985 | | | Basalt |
| **Mid. Fork Coquille (2)** | | **Douglas** | **10-43** | **1982** | | | |
| Olalla Creek | | Douglas | 10-71 | 1949? | | 1993 | Mudstone |
| Oak-Knoll-Neil Cr. | | Jackson | 15-69 | | | | |
| *Slick Rock Creek* | | *Lincoln* | *21-23* | *1983* | | | |
| *Euchre Cr.* | | *Lincoln* | *21-32* | | | | |
| Roots Cr. | | Lincoln | 21-33 | | | | |
| Skunk Cr. | | Lincoln | 21-34 | | | | |
| Canyon Cr. | | Linn | 22-54 | | | | |
| N. Fork Silver Cr. | | Marion | 24-64 | | | | |
| Soap Cr. | | Polk | 27-21 | 1980 | | | |
| Zig-Zag | 01472 | Clackamas | 03-58 | | | | |
| Fishawk Crk. Br. | 03103A | Clatsop | 04-30 | 1985 | | 1985 | Shale |
| Carberry (Indian Cr.) | 16842 | Jackson | 15-62 | | | | |
| Gate Cr. Bridge | 01324A | Lane | 20-67 | 1985 | | | |
| Calapooya Cr. | 07563A | Douglas | 10-67 | | | | |
| W. Fork Salt Creek | 10051A | Polk | 27-35 | 1985 | N | 1985 | Shale/Sand stone |
| **Mill Creek (mp 4.71)** | **1756A** | **Polk** | **27-23** | **1980** | **N** | | **Shale** |
| **Mill Creek - Rosen.** | | **Polk** | | **1990** | **N** | **1995** | **Sandy Shale** |
| **Yaquina R. Bridges** | **MP 4.93** | **Lincoln** | **21-20** | **1976** | **Y** | **1974** | **Sandy -** |
| | **MP 2.40** | **Lincoln** | **21-20** | **1976** | **Y** | | **Shale** |
| Spout Creek | | Siuslaw | | | | | |
| Nestucca Limestone | | Siuslaw | | | | | |
| Niagra Creek | | Siuslaw | | | | | |
| Big Elk Creek | | Siuslaw | | | | | |

| SITE | BR # | COUNTY | HYD FILE | HISTORICAL X-SECT | STREAM GAGE | CORE SAMPLE | OTHER |
|---|---|---|---|---|---|---|---|
| **Nestucca River** | | **Siuslaw** | | **Data from Oregon State University** | | | |
| Little Nestucca | | Siuslaw | | | | | |
| Sugarloaf | | Siuslaw | | | | | |
| **Missouri Bend** | | **Siuslaw** | | **1978** | **N** | | **Sandstone** |
| Digger Mountain | | Siuslaw | | | | | |
| **Cannibal Mountain** | | **Siuslaw** | | **1987** | **Y** | | **Sandstone** |
| Alsea Rapids | | Siuslaw | | | | | Sandstone |
| Upper Fall Creek | | Siuslaw | | | | | Sandstone |
| Green River | | Siuslaw | | | | | Sandstone |
| Lobster Creek | | Siuslaw | | | | | Sandstone |

**Boldface indicates selected sites**
*Italics indicates rock samples only*

# APPENDIX B

# DATA SHEETS FOR ALL SITES IN THE STUDY

# SITE LOCATION

**SITE CROSS SECTIONS**
**AND DATES OF STUDY PERIOD**

## Location Information

Site Name

| | |
|---|---|
| Site Location | *Legal Site Location Description* |
| Quadrangle Sheet Name (USGS) | *Oregon 7 1/2 Minute Quadrangle Maps* |

County

## Geomechanical Information

Material Designation
Coring Method
Strike and dip of bedding
Recovery/RQD
Density
Unconfined Compressive Strength
ASTM Slake Durability
Abrasion Number

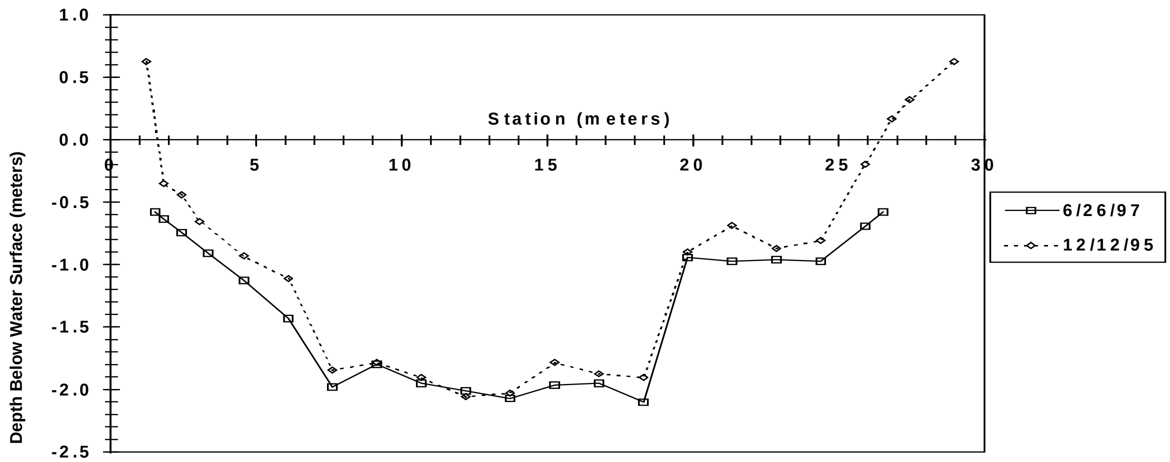
## Hydraulic Information

USGS Stream Gage Name
USGS Stream Gage Number

| | |
|---|---|
| Approximate River Bearing | *In the flow direction* |
| Synthesized Data | *Time period that data was synthesized.* |
| Average Flow | |
| Average Velocity | *Averaged over* |
| Average Power | *the duration of the study* |

Integrated Stream Power
Cross-Section Method
Previous Cross-Section

# NESTUCCA RIVER @ POWDER CREEK




## Location Information

| | |
|---|---|
| Site Name | Nestucca River at Powder Creek |
| Site Location | NE1/4,SW1/4,Sec. 3,T4S,R8W,W.M. |
| Quadrangle Sheet Name (USGS) | Blaine Quadrangle |
| County | Tillamook |

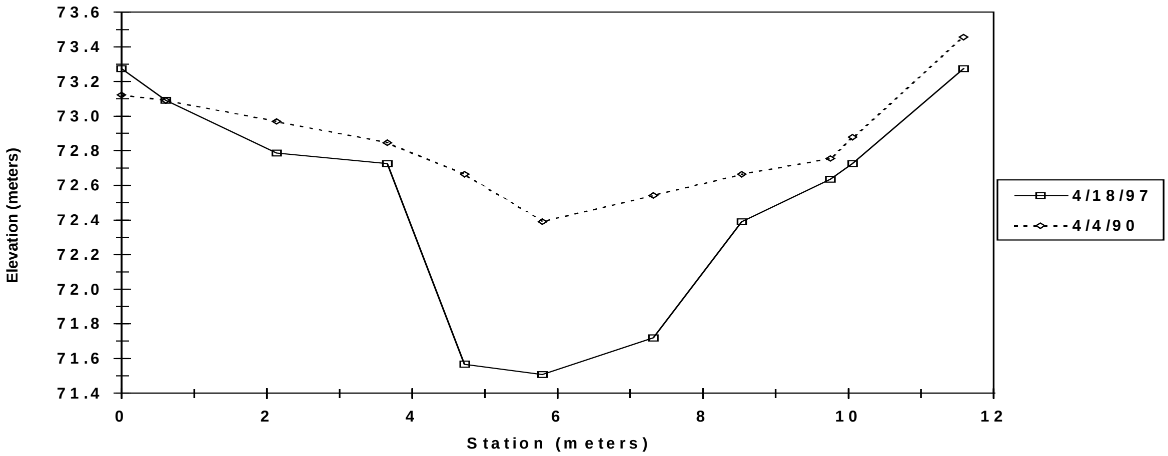
## Geotechnical Information

| | |
|---|---|
| Material Designation | Tuff |
| Coring Method | Hand Core |
| Strike and Dip of Bedding | No data available |
| RQD | 70 |
| Density | 2.81 g/cm (175.4 pcf) |
| Unconfined Compressive Strength | 12.7 MPa (1837 psi) |
| ASTM Slake Durability | 99.8% |
| Continuous Slake Number | 5.1 |

## Hydraulic Information

| | |
|---|---|
| USGS Stream Gage Name | Nestucca River near Beaver, Oregon |
| USGS Stream Gage Number | 14303600 |
| Approximate River Bearing | N20W to N25W |
| Synthesized Data | 1995-1997 |
| Average Flow | 345.9 cms (1221.4 cfs) |
| Average Velocity | 0.83 m/s (2.72 ft/s) |
| Average Power | 0.016 kW/m$^2$ (1.10 lb/ft-sec) |
| Integrated Stream Power | 5440.3 kN/mm (4315 lb/ft) |
| Cross-Section Method | Depth Measurement with Survey Rod |
| Previous Cross-Section | Oregon Department of Transportation |

# MILL CREEK @ ROSENBALM ROAD




**Location Information**

| | |
|---|---|
| Site Name | Mill Creek @ Rosenbalm Rd. |
| Site Location | NW1/4,NW1/4,Sec. 9,T6S,R6W,W.M. |
| Quadrangle Sheet Name (USGS) | Sheridan Quadrangle |
| County | Polk |

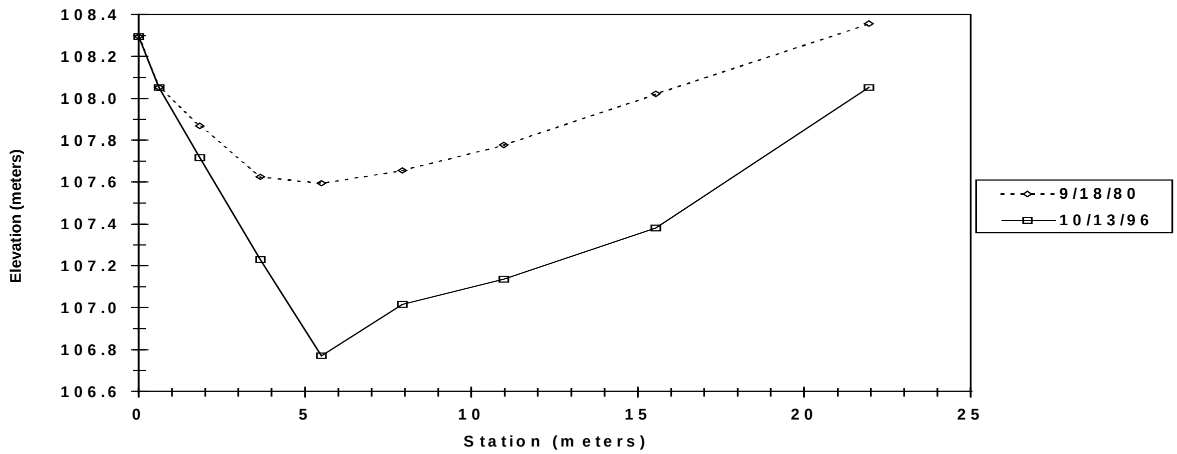
**Geotechnical Information**

| | |
|---|---|
| Material Designation | Siltstone |
| Coring Method | Wire-Line and Hand Core |
| Strike and Dip of Bedding | Two adjacent outcrops yield N35W/33NE and N75E/15N |
| Recovery/RQD | 97% / 81% |
| Density | 2.17 g/cm (135.1 pcf) |
| Unconfined Compressive Strength | 0.9 MPa (126.2 psi) |
| ASTM Slake Durability | 0.3% |
| Continuous Slake Number | 24.8 |

**Hydraulic Information**

| | |
|---|---|
| USGS Stream Gage Name | Mill Creek near Willamina, Oregon |
| USGS Stream Gage Number | 14193300 |
| Approximate River Bearing | S80W to N85W |
| Synthesized Data | 1990-1996 |
| Average Flow | 83.3 cms (294.3 cfs) |
| Average Velocity | 1.0 m/s (3.3 ft/s) |
| Average Power | 0.023 kW/m$^2$ (1.55 lb/ft-sec) |
| Integrated Stream Power | 5038.0 kN/mm (3996 lb/ft) |
| Cross-Section Method | Soundings |
| Previous Cross-Section | Oregon Department of Transportation |

# MILL CREEK @ HIGHWAY 22




**Location Information**

| | |
|---|---|
| Site Name | Mill Creek @ HWY 22 |
| Site Location | NE1/4,SE1/4,Sec. 28,T6S,R6W,W.M. |
| Quadrangle Sheet Name (USGS) | Sheridan Quadrangle |
| County | Polk |

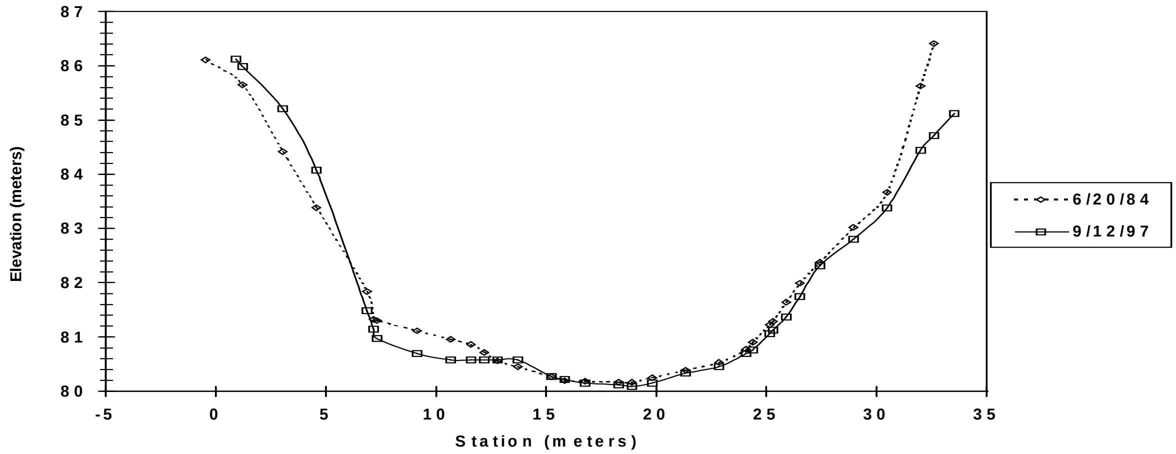
**Geotechnical Information**

| | |
|---|---|
| Material Designation | Siltstone |
| Coring Method | Wire-Line |
| Strike and Dip of Bedding | N35W to N40W/shallow dip (near axis of anticline) |
| Recovery/RQD | 98% /93 % |
| Density | 2.10 g/cm (131.0 pcf) |
| Unconfined Compressive Strength | 0.9 MPa (126.2 psi) |
| ASTM Slake Durability | 0.0% |
| Continuous Slake Number | 23.1 |

**Hydraulic Information**

| | |
|---|---|
| USGS Stream Gage Name | Mill Creek near Willamina, Oregon |
| USGS Stream Gage Number | 14193300 |
| Approximate River Bearing | N75E to N85E |
| Synthesized Data | 1980-1996 |
| Average Flow | 50.7 cms (178.9 cfs) |
| Average Velocity | 0.70 m/s (2.3 ft/s) |
| Average Power | 0.010 kW/m$^2$ (0.70 lb/ft-sec) |
| Integrated Stream Power | 5170.2 kN/mm (4101 lb/ft) |
| Cross-Section Method | Soundings |
| Previous Cross-Section | Oregon Department of Transportation |

# LUCKIAMUTE RIVER @ GRANT RD.




**Location Information**

| | |
|---|---|
| Site Name | Luckiamute River @ Grant Rd. |
| Site Location | NW1/4,NW1/4,Sec. 9,T10S,R6W,W.M. |
| Quadrangle Sheet Name (USGS) | Kings Valley Quadrangle |
| County | Polk |

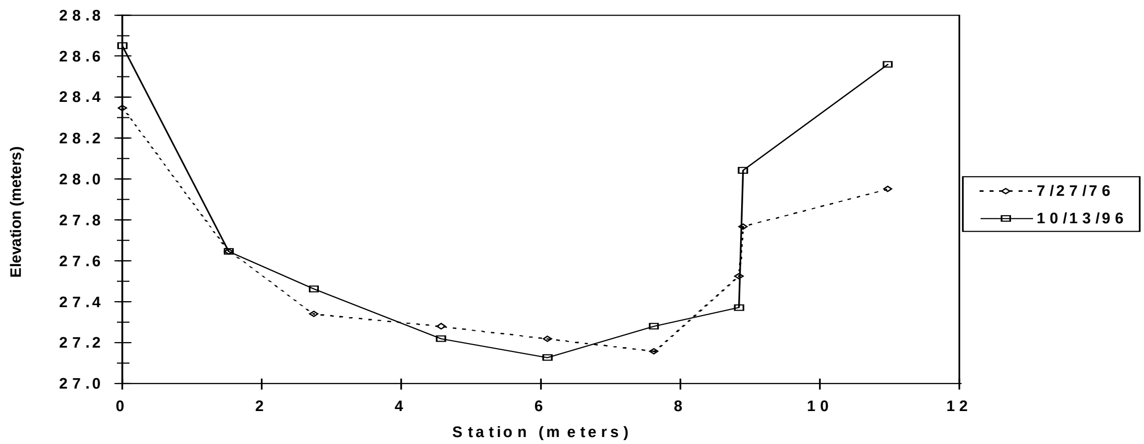
**Geotechnical Information**

| | |
|---|---|
| Material Designation | Sandstone (Tyee) |
| Coring Method | Hand Core |
| Strike and Dip of Bedding | No data available |
| Recovery/RQD | N/A |
| Density | 2.37 g/cm (147.9 pcf) |
| Unconfined Compressive Strength | N/A |
| ASTM Slake Durability | N/A |
| Continuous Slake Number | 21.6 |

**Hydraulic Information**

| | |
|---|---|
| USGS Stream Gage Name | Luckiamute River near Pedee, Oregon |
| USGS Stream Gage Number | 14190000 |
| Approximate River Bearing | N5W to N15W |
| Synthesized Data | 1984-1997 |
| Average Flow | 84.2 cms (297.3 cfs) |
| Average Velocity | 0.32 m/s (1.07 ft/s) |
| Average Power | 0.013 kW/m$^2$ (.89 lb/ft-sec) |
| Integrated Stream Power | 5440.3 kN/mm (4315 lb/ft) |
| Cross-Section Method | Soundings |
| Previous Cross-Section | Oregon Department of Transportation |

# YAQUINA RIVER @ M.P. 2.4




**Location Information**

| | |
|---|---|
| Site Name | Yaquina M.P. 2.4 |
| Site Location | SE1/4,SW1/4,Sec. 35,T10S,R9W,W.M. |
| Quadrangle Sheet Name (USGS) | Eddyville Quadrangle |
| County | Lincoln |

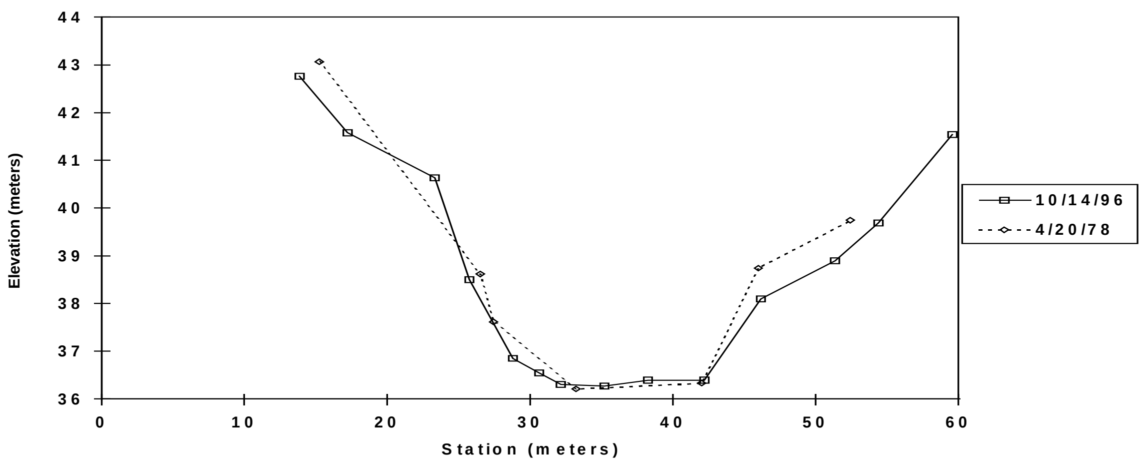
**Geotechnical Information**

| | |
|---|---|
| Material Designation | Siltstone |
| Coring Method | Wire-Line |
| Strike and Dip of Bedding | N35E to N45E/5 to 15 NW |
| Recovery/RQD | 96% / 80% |
| Density | 2.31 g/cm (144.0 pcf) |
| Unconfined Compressive Strength | 1.8 MPa (256.7 psi) |
| ASTM Slake Durability | 3.2% |
| Continuous Slake Number | 23.0 |

**Hydraulic Information**

| | |
|---|---|
| USGS Stream Gage Name | Yaquina River near Chitwood, Oregon |
| USGS Stream Gage Number | 14306030 |
| Approximate River Bearing | S40E to S45E |
| Synthesized Data | 1991-1996 |
| Average Flow | 40.3 cms (142.2 cfs) |
| Average Velocity | 0.46 m/s (1.5 ft/s) |
| Average Power | 0.005 kW/m$^2$ (0.36 lb/ft-sec) |
| Integrated Stream Power | 4021.4 kN/mm (3190 lb/ft) |
| Cross-Section Method | Soundings |
| Previous Cross-Section | Oregon Department of Transportation |

# YAQUINA RIVER @ M.P. 4.9




**Location Information**

| | |
|---|---|
| Site Name | Yaquina M.P. 4.9 |
| Site Location | SE1/4,SW1/4,Sec. 36,T10S,R9W,W.M. |
| Quadrangle Sheet Name (USGS) | Eddyville Quadrangle |
| County | Lincoln |

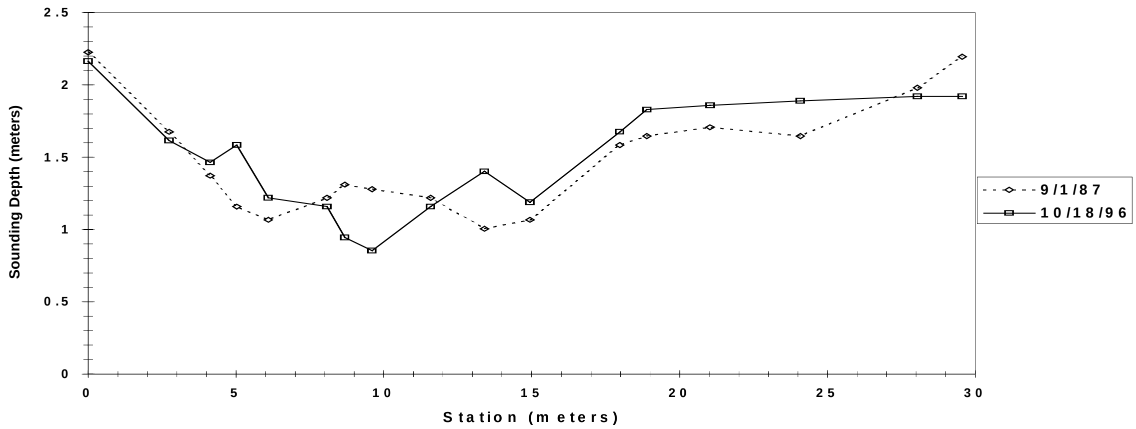
**Geotechnical Information**

| | |
|---|---|
| Material Designation | Fine Sandstone |
| Coring Method | Wire-Line |
| Strike and Dip of Bedding | No data available |
| Recovery/RQD | 87% / 75% |
| Density | 2.32 g/cm (144.6 pcf) |
| Unconfined Compressive Strength | 43.0 MPa (6234 psi) |
| ASTM Slake Durability | 73.6% |
| Continuous Slake Number | 20.2 |

**Hydraulic Information**

| | |
|---|---|
| USGS Stream Gage Name | Yaquina River near Chitwood, Oregon |
| USGS Stream Gage Number | 14306030 |
| Approximate River Bearing | N40W to N45W |
| Synthesized Data | 1991-1996 |
| Average Flow | 34.7 cms (122.4 cfs) |
| Average Velocity | 0.36 m/s (1.17 ft/s) |
| Average Power | 0.001 kW/$m^2$ (0.10 lb/ft-sec) |
| Integrated Stream Power | 1070.2 kN/mm (848.9 lb/ft) |
| Cross-Section Method | Soundings |
| Previous Cross-Section | Oregon Department of Transportation |

# ALSEA RIVER AT THISSEL RD.




**Location Information**

| | |
|---|---|
| Site Name | Alsea at Thissel Rd. |
| Site Location | NE1/4,NW1/4,Sec. 6,T14S,R9W,W.M. |
| Quadrangle Sheet Name (USGS) | Hellion Rapids Quadrangle |
| County | Lincoln |

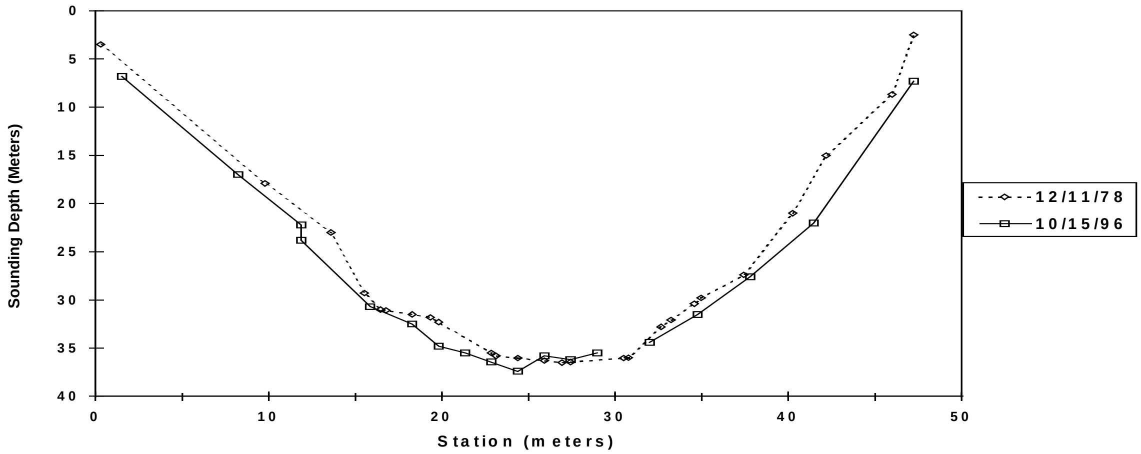
**Geotechnical Information**

| | |
|---|---|
| Material Designation | Sandstone (Tyee) |
| Coring Method | Wire-Line |
| Strike and Dip of Bedding | NW strike/dip 10 to 20E to NE |
| Recovery/RQD | 96% / 77% |
| Density | 2.45 g/cm (152.9 pcf) |
| Unconfined Compressive Strength | 43.6 MPa (6322 psi) |
| ASTM Slake Durability | 73.6% |
| Continuous Slake Number | 21.9 |

**Hydraulic Information**

| | |
|---|---|
| USGS Stream Gage Name | Alsea River near Tidewater |
| USGS Stream Gage Number | 14306500 |
| Approximate River Bearing | N50W to N55W |
| Synthesized Data | No |
| Average Flow | 40.1 cms (1415.6 cfs) |
| Average Velocity | 1.10 m/s (3.62 ft/s) |
| Average Power | 0.032 kW/m$^2$ (2.16 lb/ft-sec) |
| Integrated Stream Power | 9856 kN/mm (7817.8 lb/ft) |
| Cross-Section Method | Soundings |
| Previous Cross-Section | Siuslaw National Forest |

# ALSEA RIVER AT MISSOURI BEND




## Location Information

| | |
|---|---|
| Site Name | Alsea at Missouri Bend |
| Site Location | NE1/4,SW1/4,Sec. 13,T14S,R9W,W.M. |
| Quadrangle Sheet Name (USGS) | Digger Mountain Quadrangle |
| County | Benton |

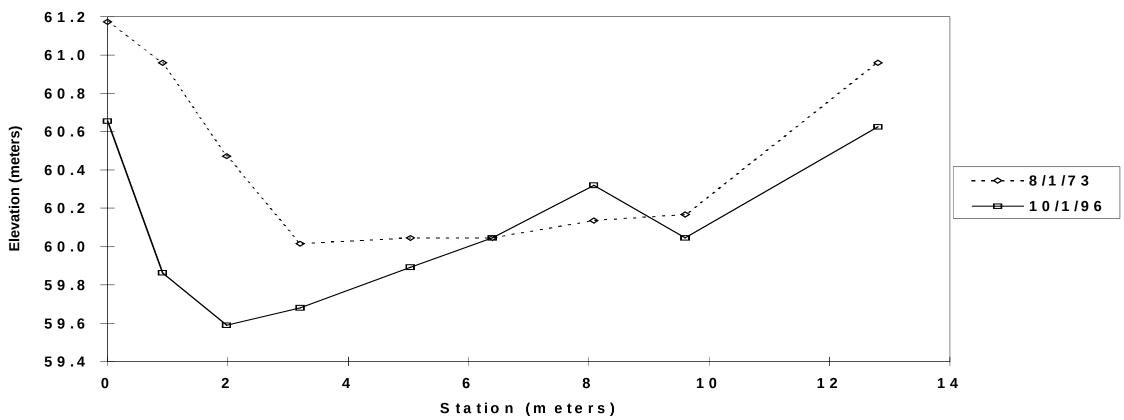
## Geotechnical Information

| | |
|---|---|
| Material Designation | Sandstone (Tyee) |
| Coring Method | Wire-Line |
| Strike and Dip of Bedding | No data available |
| Recovery/RQD | 96% / 68% |
| Density | 2.44 g/cm (152.4 pcf) |
| Unconfined Compressive Strength | 39.9 MPa (5783.7 psi) |
| ASTM Slake Durability | 95.0% |
| Continuous Slake Number | 22.9 |

## Hydraulic Information

| | |
|---|---|
| USGS Stream Gage Name | Alsea River near Tidewater |
| USGS Stream Gage Number | 14306500 |
| Approximate River Bearing | N0W to N5W |
| Synthesized Data | No |
| Average Flow | 241.2 cms (851.8) cfs |
| Average Velocity | 0.84 m/s (2.77 ft/s) |
| Average Power | 0.016 kN/mm (2.16 lb/ft-sec) |
| Integrated Stream Power | 10915.7 kN/mm (8658.3 lb/ft) |
| Cross-Section Method | Soundings |
| Previous Cross-Section | Siuslaw National Forest |

# FIVE RIVERS NEAR FISHER




**Location Information**

| | |
|---|---|
| Site Name | Five Rivers near Fisher, Oregon |
| Site Location | NW1/4,SE1/4,Sec. 1,T15S,R10W,W.M. |
| Quadrangle Sheet Name (USGS) | Five Rivers Quadrangle |
| County | Lincoln |

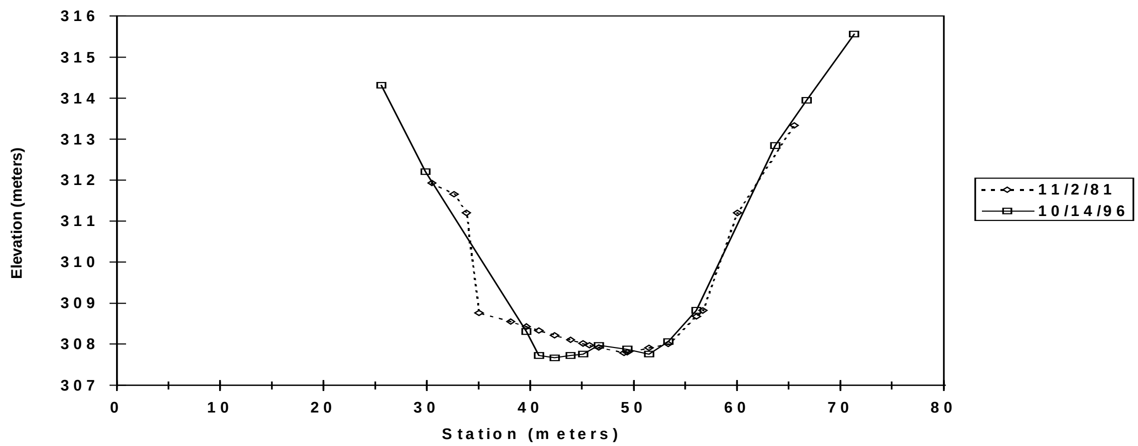
**Geotechnical Information**

| | |
|---|---|
| Material Designation | Sandstone (Tyee) |
| Coring Method | Wire-Line |
| Strike and Dip of Bedding | NE strike/15 to 25 NW dip |
| Recovery/RQD | 95% / 82% |
| Density | 2.45 g/cm (152.7 pcf) |
| Unconfined Compressive Strength | 35.6 MPa (5159.7 psi) |
| ASTM Slake Durability | 96.5% |
| Continuous Slake Number | 16.3 |

**Hydraulic Information**

| | |
|---|---|
| USGS Stream Gage Name | Fiver Rivers near Fisher, Oregon |
| USGS Stream Gage Number | 14306400 |
| Approximate River Bearing | N55W to N65W |
| Synthesized Data | 1990 - 1996 |
| Average Flow | 146.6 cms (517.6 fps) |
| Average Velocity | 1.39 m/s (4.56 ft/s) |
| Average Power | 0.061 kW/m$^2$ (4.20 lb/ft-sec) |
| Integrated Stream Power | 44921.7 kN/mm (35631.8 lb/ft) |
| Cross-Section Method | Soundings |
| Previous Cross-Section | Oregon Department of Transportation |

# MIDDLE FORK COQUILLE RIVER @ M.P. 51




**Location Information**

| | |
|---|---|
| Site Name | M.F.C. 51 |
| Site Location | SW1/4,SW1/4,Sec. 36,T29S,R9W,W.M. |
| Quadrangle Sheet Name (USGS) | Camas Valley Quadrangle |
| County | Douglas |

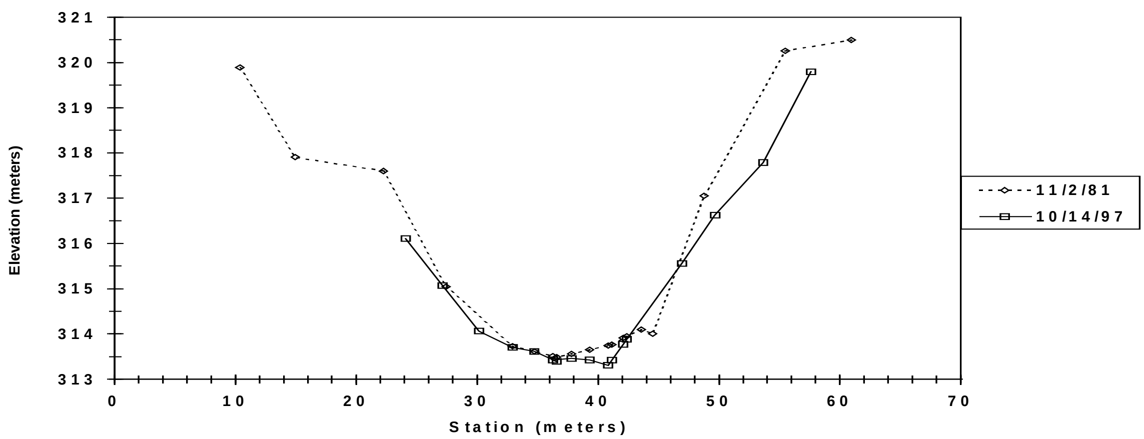
**Geotechnical Information**

| | |
|---|---|
| Material Designation | Coarse Sandstone |
| Coring Method | Wire-Line |
| Strike and Dip of Bedding | E-NE strike/dipping 5 to 15 N and NW |
| Recovery/RQD | 100% / 98% |
| Density | 2.59 g/cm (161.9 pcf) |
| Unconfined Compressive Strength | 40.7 MPa (5895.9 psi) |
| ASTM Slake Durability | 72.2% |
| Continuous Slake Number | 18.6 |

**Hydraulic Information**

| | |
|---|---|
| USGS Stream Gage Name | Mid. Fork Coquille River near Myrtle Point |
| USGS Stream Gage Number | 14326500 |
| Approximate River Bearing | N75W |
| Synthesized Data | 1981-1996 |
| Average Flow | 40.2 cms (142.0 cfs) |
| Average Velocity | 0.73 m/s (2.4 ft/s) |
| Average Power | 0.017 kW/m$^2$ (1.13 lb/ft-sec) |
| Integrated Stream Power | 8032.9 kN/mm (6371.7 lb/ft) |
| Cross-Section Method | Soundings |
| Previous Cross-Section | Oregon Department of Transportation |

# MIDDLE FORK COQUILLE RIVER @ M.P. 53




**Location Information**

| | |
|---|---|
| Site Name | M.F.C. 53 |
| Site Location | SE1/4,NE1/4,Sec. 36,T29S,R9W,W.M. |
| Quadrangle Sheet Name (USGS) | Camas Valley Quadrangle |
| County | Douglas |

**Geotechnical Information**

| | |
|---|---|
| Material Designation | Sandstone |
| Coring Method | Wire-Line |
| Strike and Dip of Bedding | No data available |
| Recovery/RQD | 81% / 72% |
| Density | 2.62 g/cm (163.6 pcf) |
| Unconfined Compressive Strength | 38.3 MPa (5558 psi) |
| ASTM Slake Durability | 97.9% |
| Continuous Slake Number | 14.0 |

**Hydraulic Information**

| | |
|---|---|
| USGS Stream Gage Name | Mid. Fork Coquille River near Myrtle Point |
| USGS Stream Gage Number | 14326500 |
| Approximate River Bearing | S30E |
| Synthesized Data | 1981-1996 |
| Average Flow | 26.1 cms (92.1 cfs) |
| Average Velocity | 0.68 m/s (2.2 ft/s) |
| Average Power | 0.022 kW/m$^2$ (1.53 lb/ft-sec) |
| Integrated Stream Power | 12027.3 kN/mm (9540 lb/ft) |
| Cross-Section Method | Soundings |
| Previous Cross-Section | Oregon Department of Transportation |

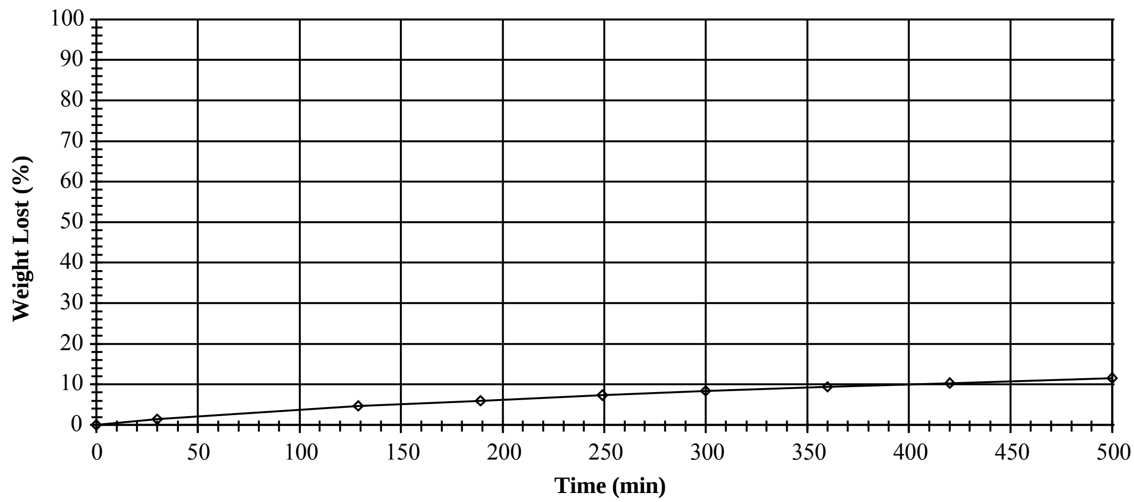
# APPENDIX C

# LABORATORY RESULTS

# NESTUCCA RIVER @ POWDER CREEK

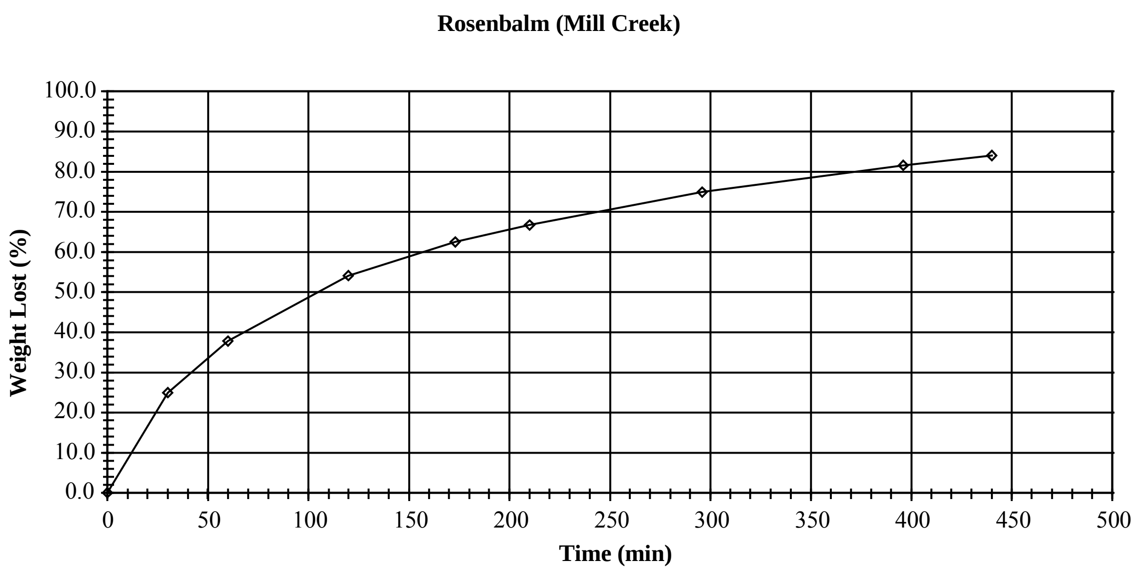
LA Abrasion Test Not Performed for Nestucca River @ Powder Creek

**Continuous Slake Test for Nestucca River @ Powder Creek**

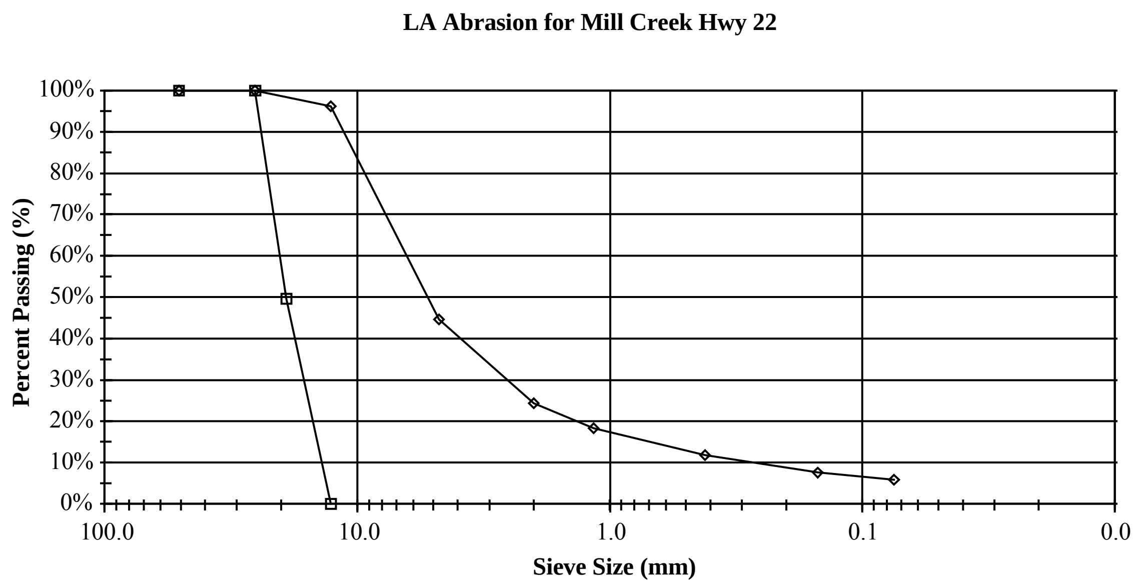


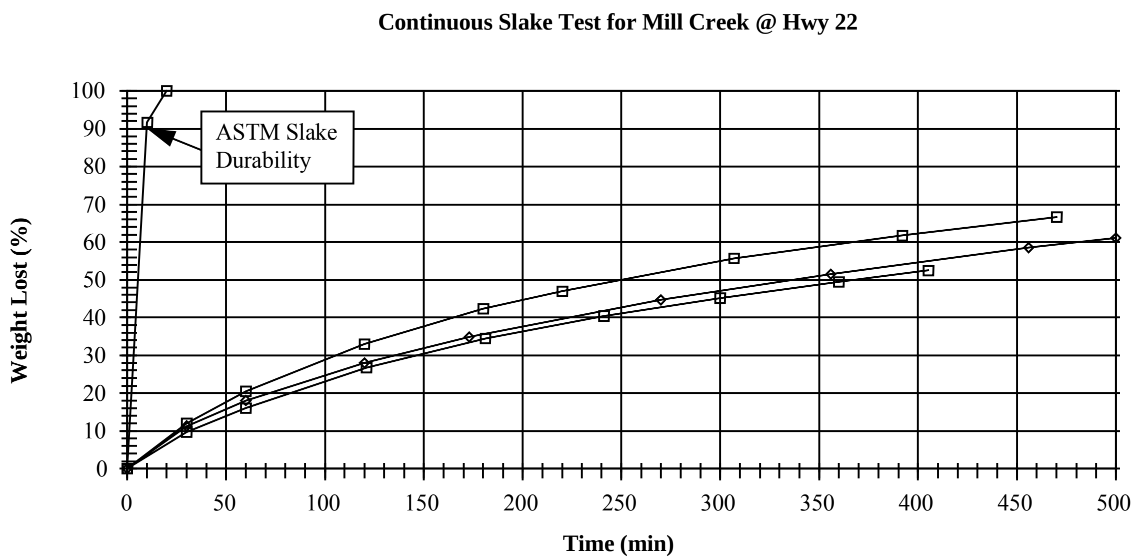
# MILL CREEK @ ROSENBALM ROAD

LA Abrasion Test Not Performed for Mill Creek @ Rosenbalm Road



# MILL CREEK @ HIGHWAY 22

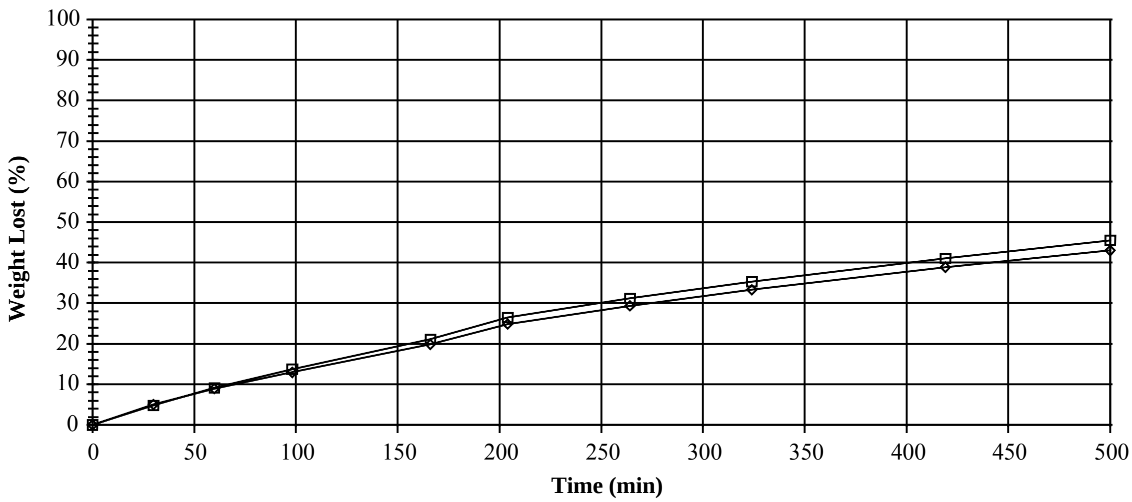


## LUCKIAMUTE RIVER @ GRANT ROAD

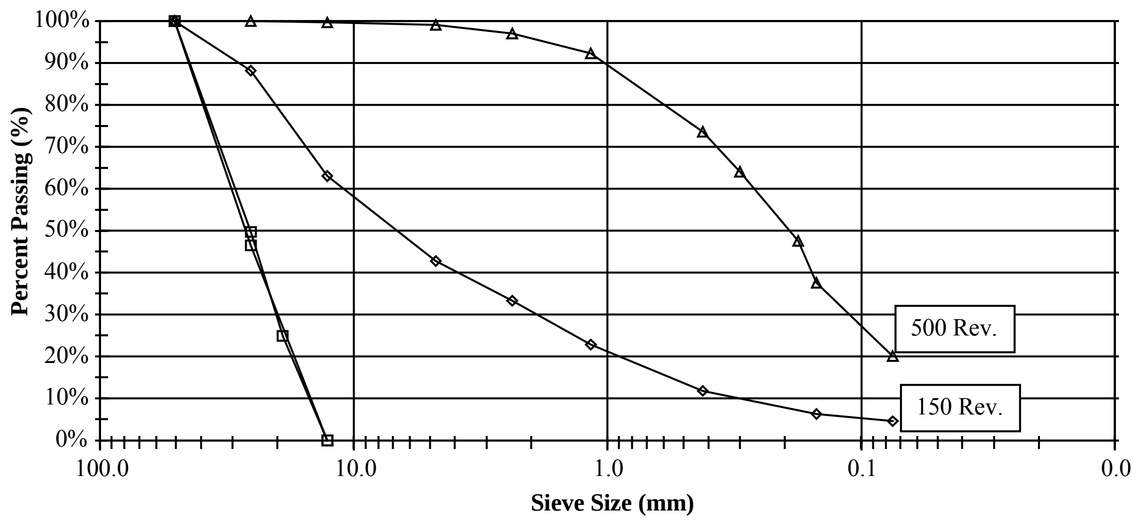
LA Abrasion Test Not Performed for Luckiamute @ Grant Rd.

**Continuous Slake Test for Luckiamute @ Grant Rd.**

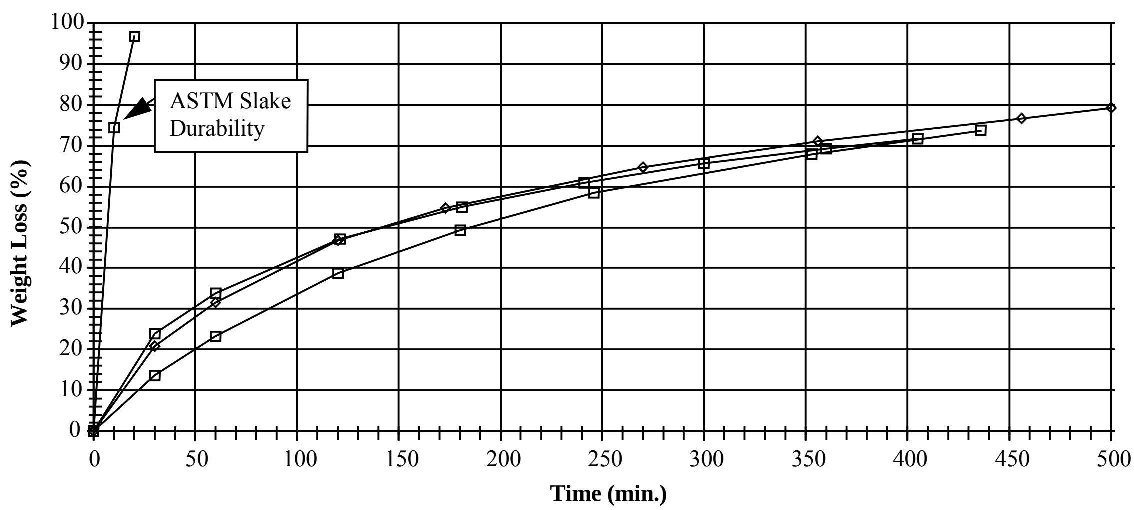


# YAQUINA RIVER @ M.P. 2.4

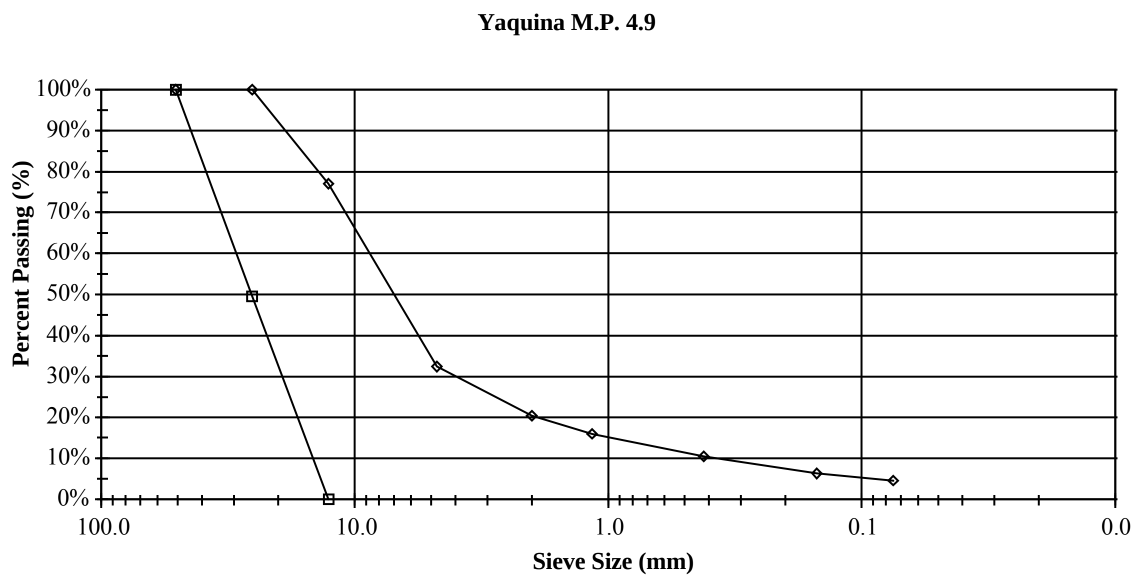
**LA Abrasion for Yaquina M.P. 2.4**

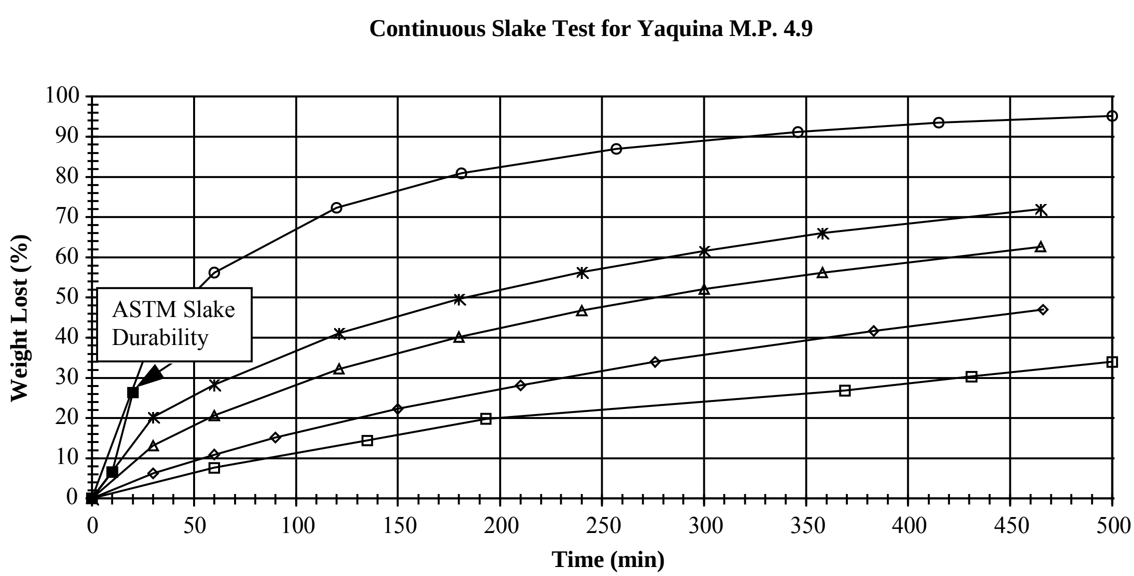



**Continous Slake Test for Yaquina M.P. 2.4**

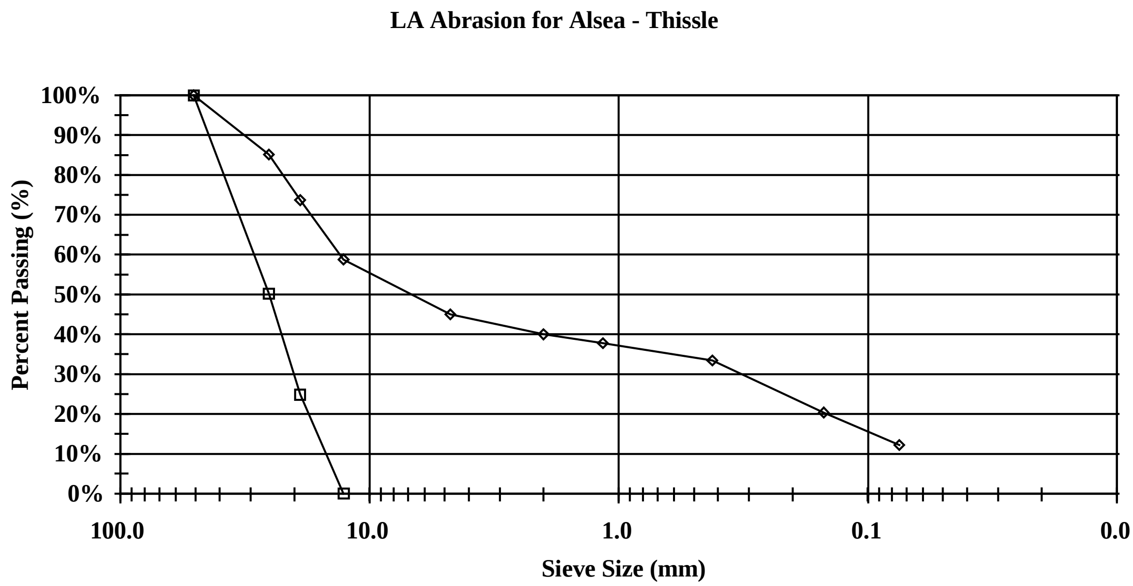


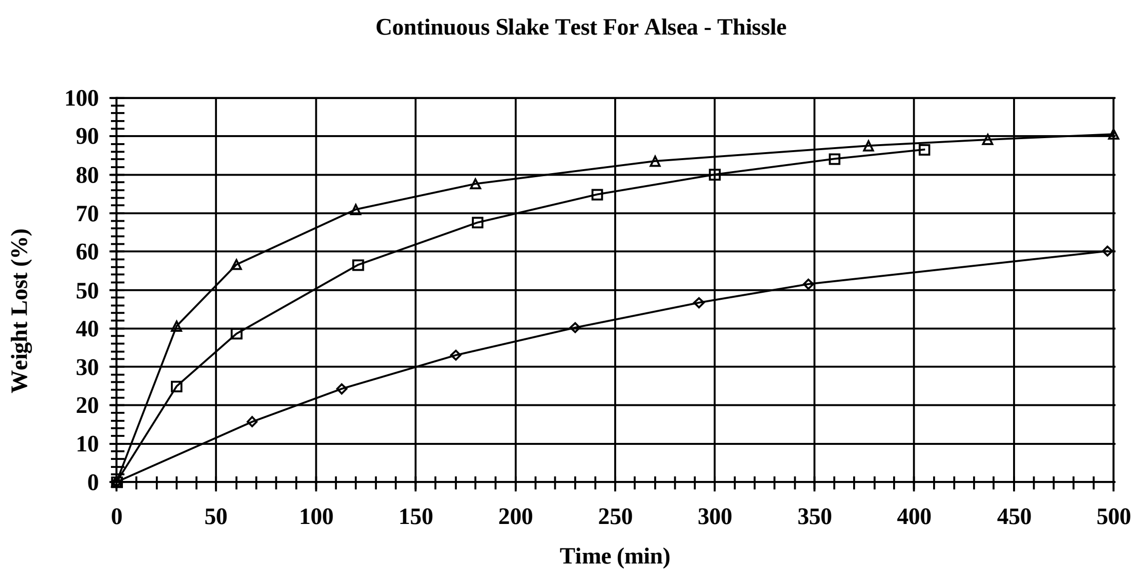
# YAQUINA RIVER @ M.P. 4.9



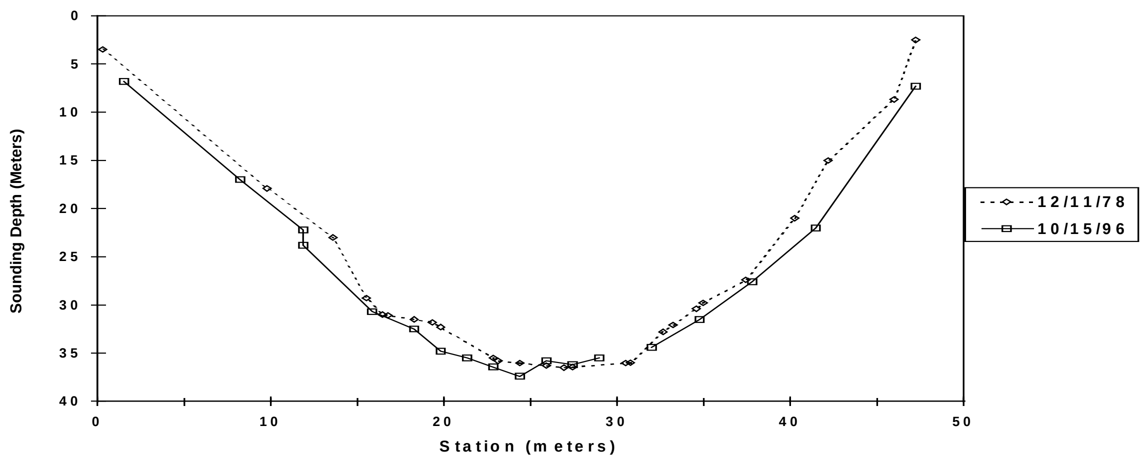



## ALSEA RIVER – THISSEL ROAD



# ALSEA RIVER AT MISSOURI BEND




## Location Information

| | |
|---|---|
| Site Name | Alsea at Missouri Bend |
| Site Location | NE1/4,SW1/4,Sec. 13,T14S,R9W,W.M. |
| Quadrangle Sheet Name (USGS) | Digger Mountain Quadrangle |
| County | Benton |

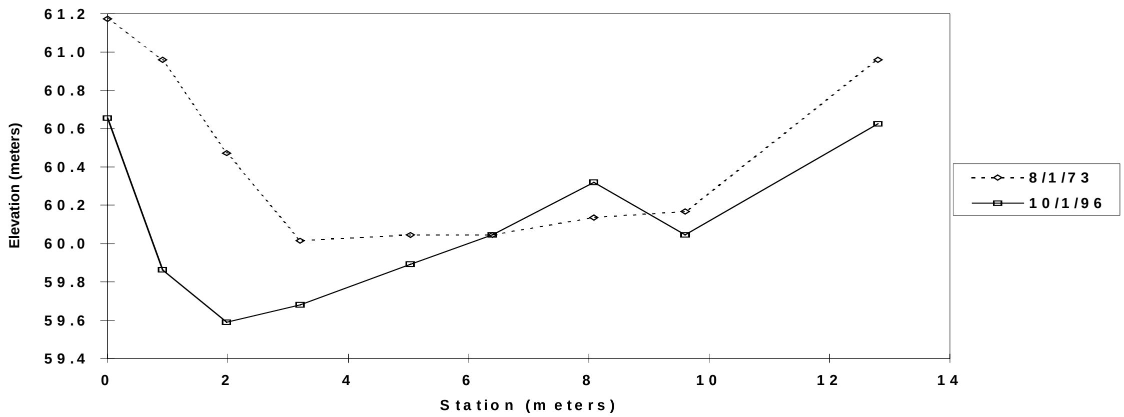
## Geotechnical Information

| | |
|---|---|
| Material Designation | Sandstone (Tyee) |
| Coring Method | Wire-Line |
| Strike and Dip of Bedding | No data available |
| Recovery/RQD | 96% / 68% |
| Density | 2.44 g/cm (152.4 pcf) |
| Unconfined Compressive Strength | 39.9 MPa (5783.7 psi) |
| ASTM Slake Durability | 95.0% |
| Continuous Slake Number | 22.9 |

## Hydraulic Information

| | |
|---|---|
| USGS Stream Gage Name | Alsea River near Tidewater |
| USGS Stream Gage Number | 14306500 |
| Approximate River Bearing | N0W to N5W |
| Synthesized Data | No |
| Average Flow | 241.2 cms (851.8) cfs |
| Average Velocity | 0.84 m/s (2.77 ft/s) |
| Average Power | 0.016 kN/mm (2.16 lb/ft-sec) |
| Integrated Stream Power | 10915.7 kN/mm (8658.3 lb/ft) |
| Cross-Section Method | Soundings |
| Previous Cross-Section | Siuslaw National Forest |

# FIVE RIVERS NEAR FISHER




**Location Information**

| | |
|---|---|
| Site Name | Five Rivers near Fisher, Oregon |
| Site Location | NW1/4,SE1/4,Sec. 1,T15S,R10W,W.M. |
| Quadrangle Sheet Name (USGS) | Five Rivers Quadrangle |
| County | Lincoln |

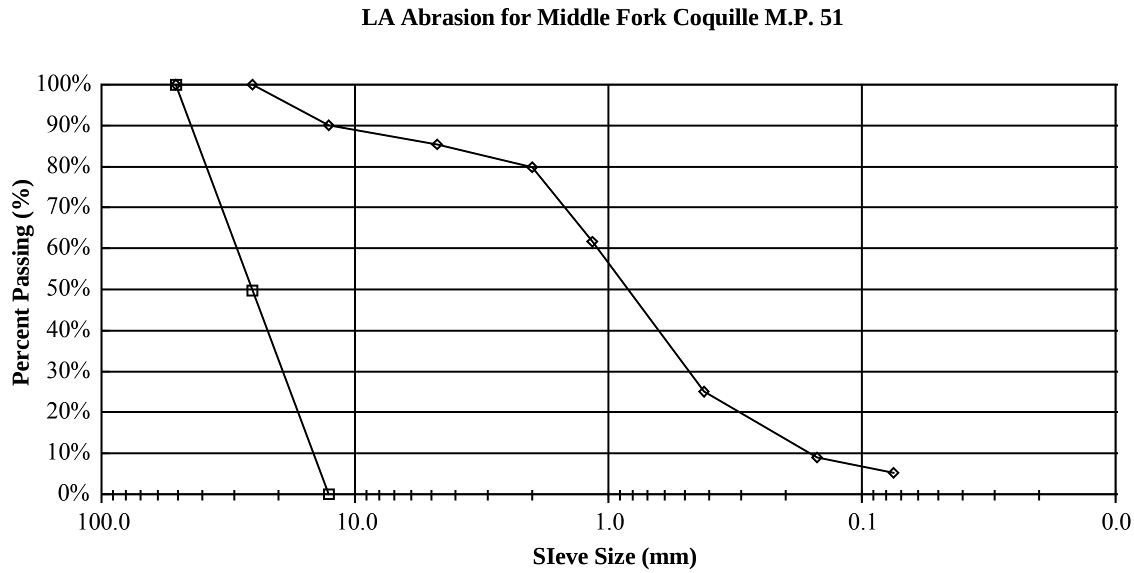
**Geotechnical Information**

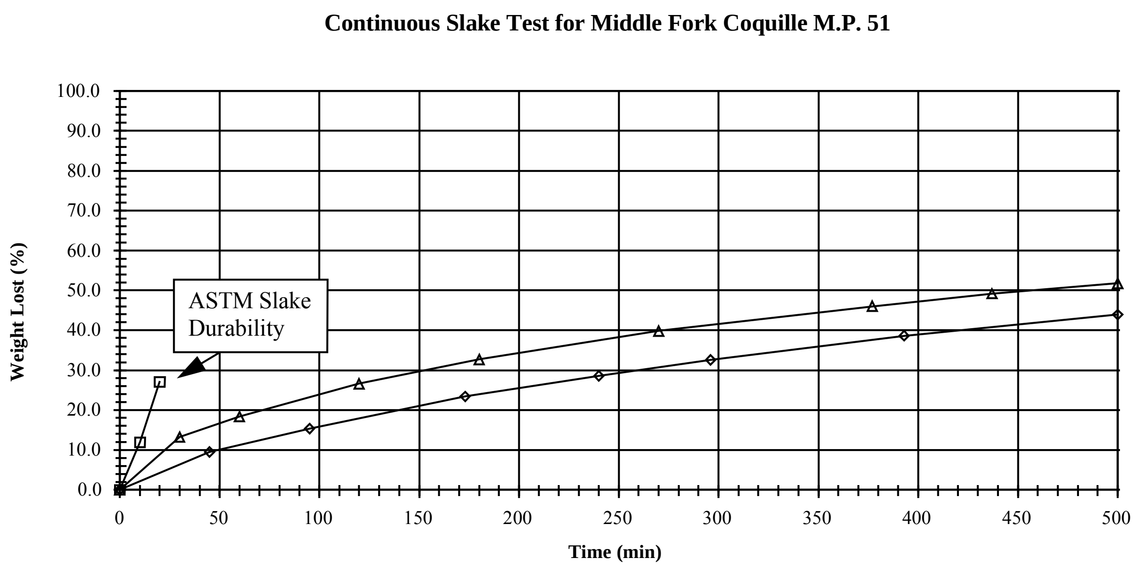
| | |
|---|---|
| Material Designation | Sandstone (Tyee) |
| Coring Method | Wire-Line |
| Strike and Dip of Bedding | NE strike/15 to 25 NW dip |
| Recovery/RQD | 95% / 82% |
| Density | 2.45 g/cm (152.7 pcf) |
| Unconfined Compressive Strength | 35.6 MPa (5159.7 psi) |
| ASTM Slake Durability | 96.5% |
| Continuous Slake Number | 16.3 |

**Hydraulic Information**

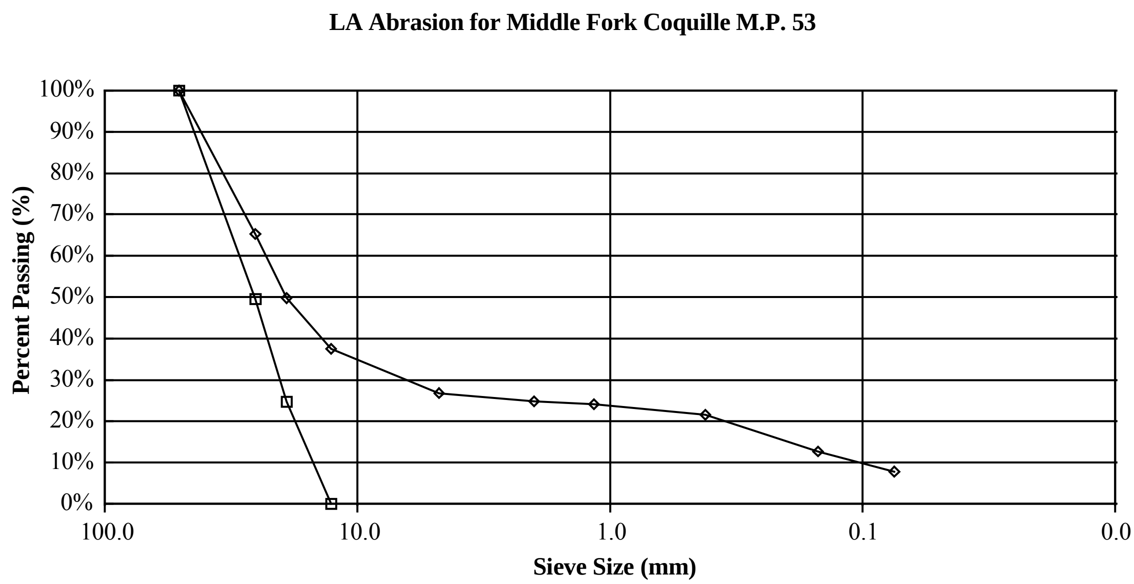
| | |
|---|---|
| USGS Stream Gage Name | Fiver Rivers near Fisher, Oregon |
| USGS Stream Gage Number | 14306400 |
| Approximate River Bearing | N55W to N65W |
| Synthesized Data | 1990 - 1996 |
| Average Flow | 146.6 cms (517.6 fps) |
| Average Velocity | 1.39 m/s (4.56 ft/s) |
| Average Power | 0.061 kW/m$^2$ (4.20 lb/ft-sec) |
| Integrated Stream Power | 44921.7 kN/mm (35631.8 lb/ft) |
| Cross-Section Method | Soundings |
| Previous Cross-Section | Oregon Department of Transportation |

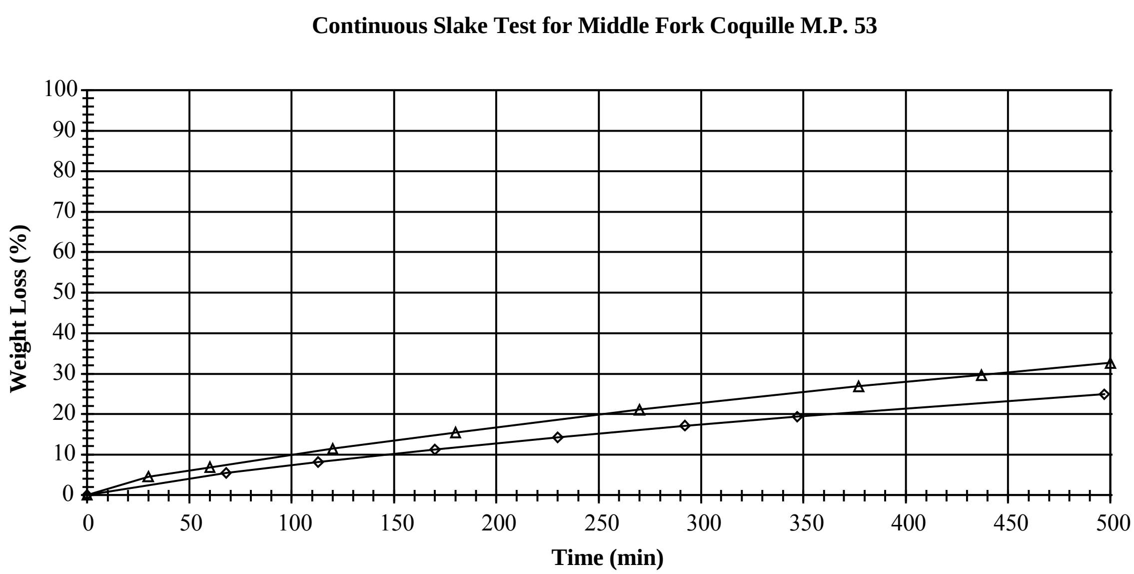
# MIDDLE FORK COQUILLE RIVER @ M.P. 51



# MIDDLE FORK COQUILLE RIVER @ M.P. 53



# APPENDIX D

# SAMPLE PROBLEM

## SAMPLE PROBLEM

For the sake of illustration an example problem is outlined in this appendix. The design application involves a simple channel geometry, and the geotechnical and hydraulic parameters that have been specified are representative of conditions in the Oregon Coast Range. A hypothetical bridge has been assigned a 25-year design life. The proposed scour model will be applied to estimate how much degradation will occur in the bedrock channel over the 25-year time period.

### a) Problem Statement

Estimate the amount of channel scour that will occur over 25 years for a channel given the following parameters (all measurements are given in English units):

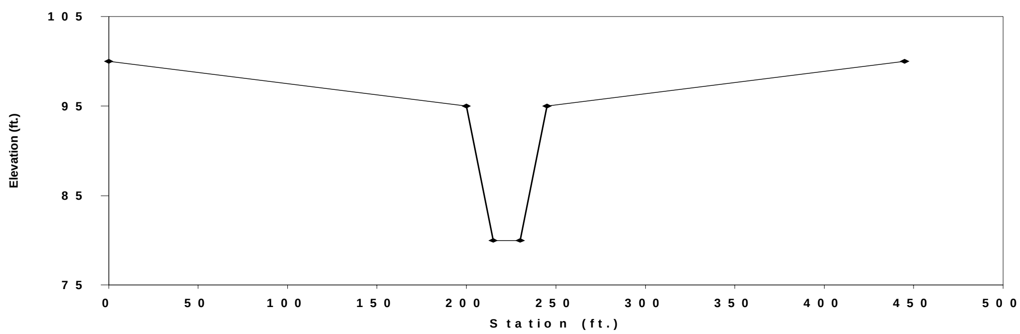



Figure D-1: Cross section of the Stream Channel

| | |
|---|---|
| Channel slope | 0.002 |
| Channel geometry | Relatively straight channel longitudinally |
| Manning's Rougnness parameter (n) | 0.045 |
| Bedrock | Weak Sandstone |
| Abrasion Number ($\beta$) | 20 |
| Available flow record | 25 years |

### b) Establish the Time History of Stream Power.

Model the river channel using the HEC-RAS water surface profile analysis, or similar, program. The channel geometry provided in Figure D-1 can be used as a template for sections upstream and downstream of the bridge site. Establish the relationship between stream flow and stream power, as shown in Figure D-2. On the basis of the computed relationship between daily flow and stream power convert the daily stream flow data to corresponding stream power values and plot the time history of stream power (Figure D-3).

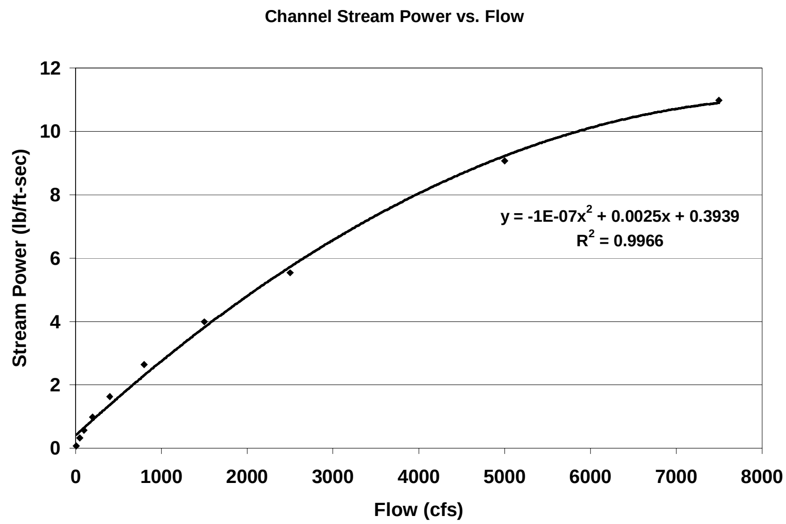



Figure D-2: Relationship between Measured Flow and Computed Stream Power

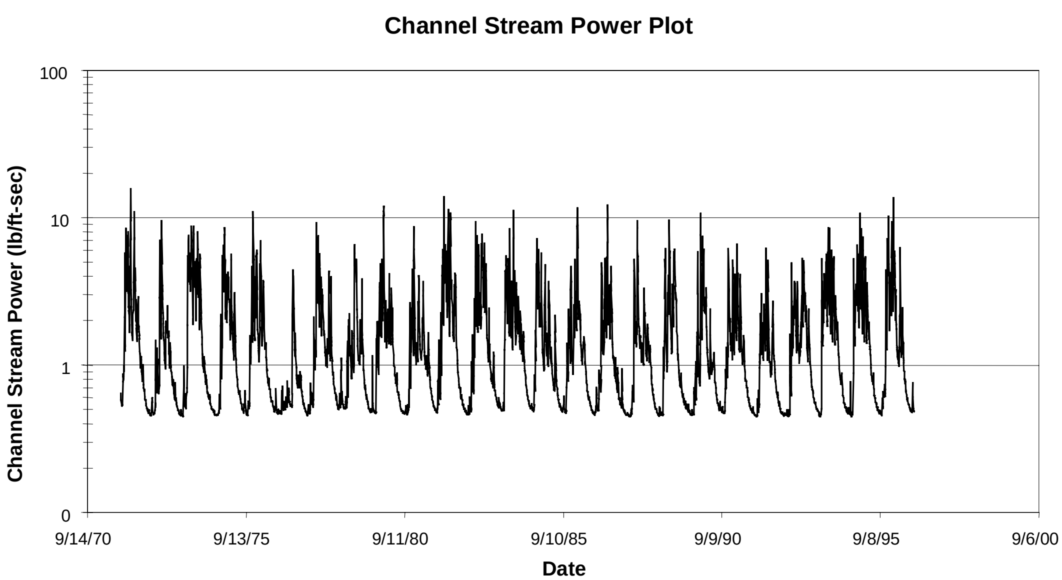



Figure D-3: Time History of Daily Stream Power

## c) Calculate the Cumulative Stream Power

The cumulative stream power that is expended by the stream over a 25 year period can be calculated by several means: (1) on the basis of the 25 year record of daily stream flow data, (2) if a full 25 year record is not available, then the recorded data can be "extrapolated" by multiplying the cumulative stream power for the available record by the quotient of the desired time interval to the duration of the recorded stream flow data, or (3) by establishing a mean or mean plus one standard deviation annual stream power and multiplying this value by the number of years required. Care should be used when using very short stream flow records to insure that the discharge during the period of record is representative of mean long-term conditions.

Given that a full 25-year time history of data is available for this example the first method will be used. The stream power data is easily manipulated using commercially available spreadsheet software and a simple numerical integration technique (e.g., Simpson's Rule, Trapezoidal Rule) is used to compute the cumulative, or integrated, stream power over the period of interest. The integrated stream power (Ω) for this example is 14,799 (lb/ft-sec)*day. Using the metric conversion [1 (lb/ft-sec)*day = 1.26 kN/mm] yields 18,647 kN/mm.

### d) Estimate the Scour Depth in the Weak Sandstone

Given the Abrasion Number (β = 20) and the Integrated Stream Power (Ω = 18,647 kN/mm), the approximate depth of scour anticipated over the 25-year period can be estimated from Figure 6.3. The average erosion over the width of the channel is estimated to be 290 mm. This is a scour rate of roughly 11.6 mm/yr.

As previously noted, this problem could also be solved using the product of *average annual stream power * 25 years* since the annual stream power trends are relatively constant.

| | |
|---|---|
| Average Channel Stream Power | = 1.6 lb/ft-sec |
| Time of Interest | = 25 years (9,125 days) |
| Integrated Stream Power (Ω) | = 1.6*9125 = 14,600 (lb/ft-sec)*days |
| Metric Conversion | = 14,600*1.26 = 18,396 kN/mm |
| Average Erosion | = 290 mm (from Figure 6.3) |

It is recommended that a factor of safety be applied to this scour estimate. In light of the limited database available for the development of this procedure, a factor of safety of 2 to 3 appears to be warranted Accordingly, the corresponding scour depth to be considered in the design and/or evaluation process ranges from approximately 600 to 900 mm.