32 TFW-SH5-91-001

LITERATURE SEARCH
OF
EFFECTS OF TIMBER HARVEST TO DEEP-SEATED LANDSLIDES

Prepared By

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March,1992

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OF
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PREPARED BY

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MARCH, 1992

FOR

COOPERATIVE, MONITORING, EVALUATION AND RESEARCH STEERING
COMMITTEE
TIMBER-FISH-WILDLIFE AGREEMENT

ABSTRACT

Published literature concerning the effects of timber harvesting (road construction, logging, and burning) to deep-seated landslides is sparse. Some authors have provided descriptions of conditions affecting deep-seated landslides, most notably Sidle (1985) and Swanston and Swanson (1976), but few authors have collected field data for analysis that specifically adresses how timber harvesting affects deep-seated landslide stability. Research completed by Swanston, Lienkaemper, Mersereau and Levno (1988) is the only exception. These scientists evaluated, monitored, and analyzed the effects of road construction, logging, and slash burning to these large landforms in southwestern Oregon. Two other research projects by Pyles, Mills, and Saunders (1987) in western Oregon, and by Iverson and Major (1987) in northwestern California did not specifically look at the cause/effect relationship of timber harvesting to deep-seated landslides, but their collective work is important to understanding better the role of the ground water regime in these geomorphic features. Understanding the ground water regime in deep-seated landslides is considered by slope stability scientists as the most important factor in evaluating them.

In addition to the lack of documented research, two other research issues were found: 1) the research listed above were carried out in areas that were not modified by continental glaciation, a common geomorphic condition in Washington state; and, 2) no one has examined the relationship of timber harvesting to deep-seated landslides located on rock slopes, such as would be found in the Olympic, Cascade, and Okanogan Mountain Ranges of Washington. Because there is a lack of literature on this

topic, much work remains to be done to understand how timber harvesting effects deep-seated landslides in Washington.

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1.0.0 INTRODUCTION

1.1.0. Problem Definition

The effect on timber harvesting to deep-seated landslides was identified as an important topic of research by the Sediment-Hydrology and Mass-Wasting steering committee pursuant to the Timber-Fish-Wildlife Agreement. From the steering committee a statement was placed in the original work plan that the project objective was to "develop criteria for estimating the increase in the rate of existing deep-seated earthflows in response to forest harvesting" (CMER Work Plan, 1988). This report summarizes available literature pertaining to that topic.

1.2.0. Information Sources

I have used two main sources of information: 1) discussions with researchers and forest resource scientists knowledgeable in this topic; and, 2) United States Forest Service reference library, West Fornet. Colleagues in the Sediment-Hydrology and Mass Wasting steering committee have reviewed my reference list and provided additional literature sources.

1.2.1. Interviews

I have interviewed researchers, professional resource scientists, and managers knowledgeable in this topic and applied science. The objectives were to learn where other possible literature sources may be located, and to ask them for their insight to the topic. The researchers interviewed were Lee Benda, Pacific Watershed Institute, Thomas Dunne, University of Washington, and Jon Major, United States Geological Survey. Professional resource scientists were Mathew Brunengo, State of Washington Department of Natural Resources, Kenneth Neal, Geo-Engineers Inc., and Paul Kennard, Tulalip Tribe TFW Geologist. Resource managers I interviewed were Dennis Larson, Olympic National Forest, and Meredith Webster, Colville District Ranger.

Lee Benda gave me a summary of his work on the Hazel Landslide which he completed with Gerald Thorsen and Stephen Bernath. Thomas Dunne provided me with possible foreign literature referances. Jon Major reviewed my synopsis in this document of the paper on the Minor Creek landslide which he co-authored with R.M. Iverson. Matthew Brunengo, Kenneth Neal and Paul Kennard were instrumental in helping me not overlook possible grey literature sources (unpublished theses, agency internal documents, and consultant reports). Dennis Larson and Meredith Webster assisted me in finding pertinent resource management documentation.

1.2.2. Reference Library

Using the call-words of landslide, timber harvesting, slope stability, and geomorphology the staff at USDA United States Forest Service West Fornet retrieved a total of 76 papers. Out of this selection 47 papers were applicable to this study. In addition to these papers, another 5 documents were found through interviews. These papers are listed in the bibliography section.

1.3.0.Research History

In the 1970's the effect of timber harvesting on deep-seated landslides was first approached as a research topic. Megahan (1972) stated that erosional processes in steep forested lands, including deep-seated landslides, cannot be ignored and that resource scientists need to provide land managers with alternatives for mitigating activities (road construction, logging, and slash burning) and minimize sedimentation. Swanston (1970, 1974a and 1974b) gave definitions for soil creep, slumps and earthflows as types of slope mass movements that are deep-seated. Swanston and Swanson (1976) addressed the negligibility of tree root systems to the stability of deep-seated landslides, and they also described the reasons for increased slope movement due to roads:

> "Undercutting of toe slopes of earthflows and piling of rock and soil debris on slump blocks are common practices that increase slump-earthflow movement. Stability of such areas is also affected by modification of drainage systems, particularly where road drainage systems route additional water into the slump-earthflow areas."

Also in the 1970's, the qualifications of professionals who should evaluate deep-seated landslides in timber harvesting areas was first proposed. One paper written by Huffman (1977) addressed this issue. In his paper Huffman states that, because of their training, geologists are the best qualified due to the complex geologic conditions of deep-seated landslides and the difficulty in locating them:

> "Large ancient landslides are numerous on the north coastal slopes [of California]. Many of these occurred under the wet climatic conditions of the Pleistocene Epoch and are now mostly stabilized. Their landforms are seldom recognized or plotted on timber harvest maps. In some locations, the large-scale topographic benches that have been formed by ancient mass movements make convenient locations for road and skid trail constuction. However, stream-bank slumping, localized earthflow movement, and

> deep eroding gullies on the ancient slide terrains signal high or extremely high erosion hazards."

Historically, deep-seated landslides have not been very obvious until accelerated slope movement occurs. Usually slope modification on these landforms occur prior to any knowledge of slope instability. Man-made structures will consequently become damaged when slope acceleration increases. Some examples are of damaged structures in the British Isles where archaeological sites are located on or adjacent to deep-seated landslides (Johnson, 1987):

> "As Voight and Pariseau (1978) have aptly commented 'the larger the mass movement, usually the further back in time the event occurred, and in consequence, the more descriptive and less quantitative is our knowledge of the specifics of the event'."

These British archaeological case histories, however, do not provide insight into how the removal of timber influences the overall slope stability.

In the Yunnan province of the People's Republic of China there is a well established history of how timber harvesting has affected slope stability (Wieczorek, Wu, and Li, 1987). Timber was first removed from this rugged terrain during the Tang Dynasty (618-907 AD) and accelerated harvesting has occurred during the past 300-400 years to provide fuel and construction materials for the copper industry. Initially the landslide types were flows, but as drainages became deeply incised the slope failure mechanism became deep-seated. In this example deep-seated landslides are typical when the erosion process is in a mature stage.

2.0.0. Controlling Conditions

There is a large body of geotechnical engineering literature that explains landslide physical properties. However, very little of this literature addresses the effects of timber harvesting to deep-seated landslides in the Pacific Northwest. Literature pertinent to this topic has been written by a few geologists and hydrologists, most notable are Sidle (1985), and Swanston and Swanson (1976).

2.1.0. Natural Factors

Sidle classified into five process-related groups the following natural factors that influence the stability of forested hillsopes: geology/geomorphology, soil properties, hydrology, vegetation, and seismicity. The following is a summary of his paper pertinent to deep-seated landslides.

2.1.1. Geology/geomorphology

> "Geologic factors predisposing certain terrain to soil mass movement include weak or soft rock composition, undesirable structure (e.g. discontinuities and folding), and unfavorable bedding sequences. Examples are: large earthflows associated with the Franciscan sedimentary assemblage of northern California; volcaniclastic rocks of the western side of the Cascade Range and the Columbia Gorge; rotational failures associated with weathered shales and siltstones of north-central Texas and the northern Oregon coast, and debris avalanches associated with competent sandstone and compact glacial till in the mountains of coastal Oregon and Alaska.
>
> "Weak rock types reflect the extent of weathering as well as the relative strength of the geologic material. In high rainfall areas, sedimentary and volcaniclastic rocks may weather into deep, clay-rich soils that are susceptible to deep-seated soil creep and earthflows.

Such soil mass movements are typical on slopes of the northern California Coast Range and the western side of the Cascade Range. Along the western side of the Cascade Range in Oregon, soil mass movements occur much more frequently in areas of predominantly altered volcaniclastic rocks (tuffs and breccias) at elevations below 2700 - 3000 feet than in areas comprised of unaltered lava flows (basalt and andesite) at high elevations (Dyrness, 1967, Swanson and Dyrness, 1975). Soil mass movement over a 25-year period in the unstable volcaniclastic terrain was 2.8 times higher for deforested areas compared to forested sites, indicating the stabilizing effect of vegetation on this weak rock.

"The influence of rock structures (bedding planes, folds, joints, faults, etc.) is an important factor in the stability of natural hillslopes. Downslope dipping planes between certain sedimentary and volcanic rocks of different competence or alteration, as well as joints and fractures oriented in the same direction, may likely impede vertical infiltration and root penetration, thus acting as potential failure planes. Horizontal or cross-dip bedding may provide natural buttresses that may actually increase the stability of slopes (Swanston, 1978). Fault zones often contain fractured, crushed, or partly metamorphosed rocks resulting from stress relief and intrusion of igneous or ultramafic rocks during geologic uplift. The inherent geologic weakness of these zones is further enhanced by deep percolation of water into the bedrock and subsequent chemical weathering of mantle material into clay-rich soil which is susceptible to slump-earthflow type of failures.

"...In areas where resistant flow rocks (for example, basalt) overlie incompetent, clay-rich volcaniclastic rocks, large-scale soil creep, earthflows and slumps can develop. Examples of such situations include soil creep and slump-earthflows along the Columbia Gorge in Oregon and Washington (Palmer, 1977), along the western side of the Cascade Range of southern Oregon (Swanson and Swanston, 1977), and along the eastern side of the Oregon Coast Range (Beaulieu, 1974, Swanston, 1978). Slumps and earthflows occurring in such terrain typically have steep headwall scarps (Swanson and James, 1975).

"...Slower processes, such as slumps and earthflows, initiate on slopes as gentle as 4-20 degrees. Soil creep has been measured on slopes as gentle as 1.3 degrees; however, certain sites may require gradients as steep as 25 degrees before measurable creep occurs (Burroughs et al., 1976)."

2.1.2. Soil properties

"...Smectites have been found to be major constituents in deep-seated mass soil movements, such as earthflows in the Cascade Range in Oregon (Paeth et al., 1971, Taskey, 1977). Earthflows in the Cascade Range and Coast Range of Oregon have been related to the presence of amorphous clays (Istok and Harward, 1982, Taskey et al., 1978). The instability of these amorphous clays was partially attributed to their high water-holding capacities. The water could presumably be released following disturbance, accounting for the fluid behavior of earthflows."

2.1.3. Hydrology

"Recharge of soil water is the result of water entering the soil and influenced by vegetation cover, cultural practices, and landscape shape, as well as soil physical properties affecting water movement...Cultural practices such as road building, logging, and burning can significantly reduce soil water recharge.

"Large, interconnected soil pores (that is, macropores, soil pipes) provide important passageways for transport of subsurface water in hillslope soil mantles. Although piping networks are believed to be somewhat interconnected over large areas, small breaks in this network would create potential sites of extensive positive pore-water pressure buildup as the surrounding soil would have a much lower permeability...Extensive but discontinuous piping networks have been found in earthflow landforms and are believed to accelerate movement by allowing excessive pore water pressures to build up. In such slow mass movements, it is conceivable that the size and extent of pipes, as well as their degree of interconnection, could change over short periods of time.

"Increased evapotranspiration may help to reduce the movement rate of deep-seated creep and earthflows. Conifers on slopes affected by these movement types will have beneficial effect, compared to other types of vegetation, by extending the period of low soil moisture, by drying the soil to a greater depth during low-rainfall seasons that would occur with shallow-rooted vegetation, and by delaying and extending the period during which recharge takes place.

"...Shallow-rapid soil mass movements generally respond to individual storm or snowmelt events, and deep-seated earthflows and soil creep are more influenced by seasonal rainfall. Movement of deep-seated failures is generally slow early in the wet season, while the soil mantle is recharging, and later becomes more responsive to rainfall inputs (Swanson and Swanston, 1977)."

2.1.4. Vegetation

> "...Swanson and Swanston (1977) suggest lateral root reinforcing across planes of weakness (for example, headwalls and tension cracks around earthflows) may also be important in providing stability to deeper soils prone to creep and earthflow movement."

2.1.5. Seismicity

> "...Deep-seated slumps and earthflows are generally initiated by stronger (and probably longer duration) seismic activity."

2.2.0. Forest Operations

In their 1976 paper, Swanston and Swanson give a discussion of how the impact of forest operations (roading and logging) effect slope stability. The following is a summary of their paper.

2.2.1. Roading

> "Engineering activities that involve excavation and fills frequently have dramatic impact on slump-earthflow activity. In the forest environment, there are numerous unpublished examples of accelerated or reactivated slump-earthflow movement after forest road construction. Undercutting of toe slopes of earthflows and piling of rock and soil debris on slump blocks are common practices that increase slump-earthflow movements. Stability of such areas is also affected by modification of drainage systems, particularly where road drainage systems route additional water into the slump-earthflow areas. These disturbances may increase movement rates from a few

millimeters per year to several tens of centimeters per year or more. Once such areas have been destabilized, they may continue to move at accelerated rates for several years."

2.2.2. Logging

"In massive, deep-seated failures, lateral and vertical anchoring of tree-root systems is negligible. However, hydrologic impacts appear to be important. Increased moisture availability due to reduced evapotranspiration will increase the volume of water not utilized by the vegetation. This water is therefore free to pass through the rooting zone to deeper levels of the earthflow. Although the hydrology of slump-earthflows has not yet been investigated, hydrology research on small watersheds suggests that this effect may be substantial...On poorly drained earthflows, the increased available moisture is likely to be stored in the subsoil for longer periods of time, possibly contributing to increased rate and duration of the wet season earthflow movement. It is not known whether possible clearcutting-related increases in peak discharge of surface and subsurface water influences earthflow movement."

3.0.0. Cultural Influences

Deep-seated landslides are influenced by cultural activities that include logging, slash burning, road construction and road usage. Most of the published literature pertaining to these activities and slope stability are for shallow landslide processes. Little work has been completed in this area for deep-seated landslides, although several authors allude to the belief that cause/effect relationships for deep-seated landslides are similar to those that apply to shallow features. The following is a summary from the literature dealing with the effects of logging, road construction and road usage on deep-seated landslide stability. No literature was found that addressed the effects of burning vegetation located on these large landforms.

3.1.0. Logging

In the Pacific Northwest many of the most productive forests grow on marginally stable slopes where timber harvests and road construction increase the likelihood of erosion (Amaranthus, Rice, Barr, and Ziemer, 1985). Burroughs (1985) cites Robert Meurisse, who wrote an internal US Forest Service report where he states:

> "...unstable soils are common in Region 6 [Oregon and Washington]. About 11% (2,712,000 acres) of the region has soils that are moderately unstable or unstable. They have important implications for the development of forest resources. Some of the most unstable areas are presently being developed or will be within the next 10 years. Unstable soils are the most productive in the region...Some have as high as 100 thousand board feet/acre. These soils are widely distributed throughout the region, but are dominantly on the western Cascades and Coast Range. Some of the most extensive acreages are in watersheds with high value anadromous fisheries, in municipal supply watershed upstream from reservoirs and in areas of high visual resource quality."

3.2.0. Road Construction and Road Usage

For shallow landslide features, road construction and usage have a major effect. For example, Fredriksen (1970) made the observation that few slides occurred adjacent to roads in the H.J. Andrews Experimental Forest in Oregon, but they were an important sediment source:

> "...these slides accounted for 93% of the soil lost in the area. The lesser importance of landslides at clearcut and green timber sites is indicated by a much smaller volume of soil lost."

In another example, Swanston and Swanson (1976) describe the reasons for an increase of landslide movement in response to road construction:

> "Undercutting of toe slopes of earthflows and piling of rock and soil debris on slump blocks are common practices that increase slump-earthflow movement. Stability of such areas is also affected by modification of drainage systems, particularly where road drainage systems route additional water into the slump-earthflow areas."

For a deep-seated landslide, where the slide mass is several tens to hundreds of acres in size and is several tens of feet deep, a logging road (usually a few tens of feet wide from cutslope top to fillslope toe) will not have much influence to the stability of the slope. For example, Mills (1984) found from his observations in his study:

> "the effect of a road on overall slope stability was fairly small because of the insignificant change in overall slope geometry."

The effect of loading to a landslide mass as a result of log truck traffic is dependent on the relative size of the log trucks and the landslide. A deep-seated landslide that is half a square mile in area and several tens of feet deep will not be greatly influenced by log truck traffic. A large hillslope mass weighs much more than a loaded log truck, and the additional driving force created by the truck traffic will be insignificant.

Rerouting of water along roadways may severely impact the stability of deep-seated landslides. However, little documentation on this topic is found in the published literature although a fair amount of research has been published on the effects on shallow landslide features. It makes intuitive sense that if the surface runoff is concentrated on a roadway, it could be discharged at a critical point or several points along a deep-seated landslide resulting in accelerated slope movement, but research is clearly needed to verify such hypotheses.

4.0.0. Completed Work - Case Histories

In addition to the three case histories presented in this paper, other researchers have also performed similar work (Harvey, 1978; Hicks, 1982; Benda, Thorsen, and Bernath, 1988), although not to the same detail as in the case histories. Harvey's work in the Van Duzen River drainage in northern California describes the surface morphology, movement, and sediment production of deep-seated landslides. Indirect evidence in this study suggests that a change in the vegetative cover may have increased the rate of earthflow movement. Hicks found that deep-seated landslides in the western Cascades of Oregon probably moved during glacial or interglacial periods of the late Pleistocene. He also found some evidence of road-related slope instability from a deep-seated landslide. Unfortunately this work was performed many years after road construction was completed and the evidence was not clear. Benda and others studied the Hazel landslide on the North Fork of the Stillaguamish River in western Washington. They performed an aerial photography analysis of this area with photographs from 1942 through 1987, examining the timing of timber cutting with the precipitation record and slope movement. A field check was completed to confirm these data. From this study they concluded that there is a relationship between timber harvesting, increase recharge of the ground-water, and increase slope movement.

The following three case histories of Lookout Creek earthflow, Minor Creek landslide, and the Baker Creek earthflow, are given here to illustrate the state of knowledge regarding deep-seated landslides. The described slides are located in Oregon and California; no similar research work has been carried out in Washington.

The studies at Lookout Creek and Minor Creek did not specifically examine the cause/effect relationship of timber harvesting (road construction, logging, and slash burning) to deep-seated landslide stability; but the research gave thorough explanations of how the ground-water regime influences the landslide mass, and in particular the basal shear zone. The ground-water regime in a deep-seated landslide is thought to be the most critical factor in determining the stability of these large landforms.

The Baker Creek earthflow case history is the only published research I found that specifically addresses the effects on timber harvesting to deep-seated landslides. The best explanation for the lack of research of this topic is the long time period required for such a study. To properly evaluate, monitor, and analyze the effects of timber harvesting on a deep-seated landslide requires upwards of ten years of field data collection (approximately three years of data collection per stage for pre-harvest, harvest, and post-harvest stages). Also, to convince forest managers to build roads, log, and burn slash on large, potentially unstable slopes is not an easy task. It is obvious that the research in this topic is sparse.

4.1.0. LOOKOUT CREEK EARTHFLOW, OREGON

4.1.1. Problem Definition

The Lookout Creek earthflow is located in the western Cascade Mountains of Oregon. Mills (1984) completed a study of this deep-seated landslide for his M.S. degree at Oregon State University. Since then Pyles, Mills, and Saunders (1987) have continued this work to determine if the slide mass moves in response to changes in the ground-water regime.

4.1.2. Location and Geology

This earthflow is located along the north bank of Lookout Creek in the H.J. Andrews Experimental Forest. It is situated near the lower east margin of an area about 1.5 mi^2 (3.9 km^2) in size. The underlying bedrock types in the Lookout Creek drainage are extrusive igneous and volcaniclastic rocks of Oligocene to Miocene age; discontinuous glacial deposits probably of Wisconsin age are exposed along Lookout Creek downstream of the earthflow (Swanson and James, 1975). A poorly-sorted gravel deposit located in the scarp of another earthflow a few thousand feet west of the Lookout Creek earthflow may be a glacial till. The age of this deposit is unknown. The Lookout Creek earthflow has not been dated, but similar features nearby have wood fragments radiocarbon dated at 35,000 years B.P., and they are overlain by Mazama ash deposits which suggest an age of at least 6,700 years B.P.

4.1.3. Earthflow Materials

An exploratory borehole was drilled in 1983 on the earthflow. The bottom of the hole was 151 ft (46 m) deep. No bedrock was encountered and the soils were sandy silt, silty sands, gravelly silty sands, bouldery silty sand, cobbles and boulders. Fine-grained materials were plastic or had a low plasticity. At a depth of 120 ft (36.6 m), near the present elevation of Lookout Creek, a layer of rounded gravel and small cobbles were collected. This material was interpreted to be of alluvial origin. The authors didn't provide an interpretation of the origin of the overlying soil units. At a depth of about 78 ft (24 m) a wood fragment was recovered during drilling and has been radiocarbon dated as older than 40,000 years B.P.

4.1.4. Slope Movement Data and Evaluation Methods

Slope movement has been interpreted in part by evaluating tree growth on the Lookout Creek earthflow. At several locations along the west side of the earthflow the trunks of standing trees have been split by either shear or tension cracks in the earthflow. Swanson and Swanston (1977) determined this movement to be at least 80 years old by examining the scar tissue in the trees.

Recent movement has been monitored since 1975. Initially the monitoring was completed by using stake arrays installed across shear and tension cracks at the boundary of the active area and across tension cracks within it. Originally these stake arrays were surveyed twice a year, but in 1977 this was changed to about every three weeks to determine the amount and distribution of annual movement. In 1977 recording extensiometers were installed across the shear crack along the west side of the active area and across a tension crack within it to continuously monitor movement. By monitoring the data over several years Swanson and Swanston (1977) found that the slope movement was related to seasonal weather conditions and not to individual storm events.

In the mid-1970's three inclinometer casings were installed 17 to 25 ft (5.2 to 7.6 m) deep in the earthflow. Although the authors felt that the inclinometer casings didn't penetrate the shear zone at the base of the earthflow, the resulting data indicated a movement pattern which is not surficial creep. Four piezometers were installed in the earthflow beginning in 1976. The first three were placed so that their tips were 10 to 15 ft (3.0 to 4.6 m) below the ground surface, in an attempt to use piezometer and extensiometer data for correlation and to help explain the timing of earthflow movement. The fourth piezometer was placed to a depth of 145 ft (44.2 m) which is well below the shear zone (21.5 ft (6.6 m) below the surface). Data from this piezometer showed that the piezometric surface is generally about 32 ft (9.8 m) below the ground surface, far below the level indicated by the other three piezometers. This indicated ground-water perched in the earth flow, possibly on the shear zone. Their hypothesis was that partial drainage of water is occurring through the shear zone. The relationship of partial drainage to slope movement was thought to be critical in understanding accelerated slope movement of this deep-seated landslide.

The infinite slope method was used in evaluating the factor of safety for this earthflow. The authors assumed ground-water seepage through the slide mass was parallel to the slope and that soil cohesion was equal to zero. Using back-analysis and the assumption that the factor of safety was 1.0 or less, the authors evaluated the stability of the shear zone and the effects of ground water on the shear zone. Since the phreatic surface varied through the year in response to seasonal weather changes, the infinite slope equation reflected these changes. Assuming cohesionless soil, this equation is:

$$F.S. = [d\gamma - (d - d_w)\gamma_w]\tan\phi' / d\gamma \tan\beta$$

where:

$F.S.$ = factor of safety

ϕ' = effective friction angle (degrees)

β = failure surface, phreatic surface, and ground surface angle (degrees)

γ = total unit weight of soil (pcf or kN/m^3)

γ_w = unit weight of water (pcf or kN/m^3)

d = depth to the failure surface (ft or m)

d_w = depth to the phreatic surface (ft or m)

To determine accurately the pore-water pressures in the shear zone the authors used the Terzaghi theory of one-dimensional consolidation (Taylor, 1948). If their hypothesis of partial drainage of the shear zone is correct, then the pore-water pressure computed for the shear zone when the earthflow begins to move (factor of safety = 1.0) should be the same for each year. The value of pore-water pressure that initiates movement can be termed the threshold pore-water pressure. The Terzaghi theory of consolidation relates non-equilibrium pore-water pressure (u), time (t), vertical position within a soil layer (z), and soil permeability and compressibility by the differential equation:

$$\partial u/\partial t = c_v(\partial^2 u/\partial z^2)$$

where: c_v = coefficient of consolidation (includes effect of compressibility and permeability).

The authors assumed that the boundary pore-water pressures above the shear zone are those indicated by the daily piezometer record within the earthflow mass. The nature of the lower shear zone boundary, however, was problematic. The authors presented two possibilities: the lower boundary is impermeable or the lower boundary is permeable.

Another problem was their inability to recover shear zone soil samples for consolidation testing. Rather, they collected soil samples from the toe of the earthflow near the elevation of the shear zone. Since layer thickness (earthflow mass thickness), boundary condition (number of permeable surfaces), and coefficient of consolidation all control the rate at which pore-water pressures propagate into the shear zone, the authors had another problem because these parameters are impossible to determine exactly. Therefore, they used the borehole and piezometric data to provide an estimate of shear zone thickness and boundary condition. They also relied on the laboratory consolidation testing to get an estimate for a range of values for the coefficient of consolidation. Using these data they then tested a range of coefficients of consolidation by using the time factor equation (Taylor, 1948):

$$T = c_v t/H^2$$

where: t = time

H = drainage path (layer thickness/number of permeable boundaries).

4.1.5. Results

Data collected relative to when the Lookout Creek earthflow moved lead the authors to hypothesize that the shear zone material is behaving in a partially-drained manner when the earthflow becomes unstable. Their analyses, using the infinite slope equation and the theory of one-dimension consolidation, indicated how the ground-water regime affects movement of the earthflow. They found that the ability of the earthflow to drain rapidly to a base level will produce only modest increases in movement. This indicates that a large increase in movement resulting from timber harvesting on the earthflow is unlikely. They also argued that an exact estimate of the potential for increased movement cannot be made without detailed data on regional ground-water flow and the harvesting related changes in evapotranspiration. Their approach to evaluating earthflow movement can be used for other deep-seated landslides *if* sufficient field data can be collected.

4.2.0. MINOR CREEK LANDSLIDE, NORTHWESTERN CALIFORNIA

4.2.1. Problem Definition

Few studies have focused on spatially variable, transient ground-water flow and how it affects the motion of persistent deep-seated landslides. Many researchers have found complex relationships between rainfall and intermittent movements of active landslides. Minor Creek landslide in northwestern California is one example. This landslide moves significant distances each rainy season; however, the timing, duration, and speed of movement do not correlate directly with the timing and amount of rainfall. Iverson (1984, 1985, 1986) approached this problem by collecting detailed rainfall, ground-water, and movement data for analysis that used simple, physically based theories. From this analysis Iverson and Major (1987) were able to infer that persistent downward hydraulic gradients, unsaturated ground-water storage, propagation and attenuation of rainfall-induced pore pressure waves, and near-surface ground-water circulation can influence landslide motion significantly.

4.2.2. Location and Geology

Minor Creek landslide covers about 25 ac (10 ha) in the Redwood Creek drainage basin of northwestern California. The authors classified this deep-seated landslide as a compound, complex, earthflow according to Varnes' (1978) classification system. From aerial photographs they dated the landslide as at least 50 years old; it is probably much older. The landslide head is located near a topographic divide, and its toe adjoins the channel of Minor Creek, a perennial tributary of Redwood Creek. Within the Redwood Creek basin the bedrock consists largely of accreted Franciscan terrane composed of fractured sedimentary and metamorphosed rocks.

4.2.3. Earthflow Materials

Soil physical characteristics were determined from field inspection and laboratory tests of cores and cuttings collected from about 50 boreholes drilled in 1982. Twelve cores were collected at depths between 9.8 to 16.4 ft (3 to 5 m). Average weight distributions of grain sizes were 22% clay, 16% silt, 40% sand, and 22% gravel. The soil classifies as a SC, clayey sand with gravel, using the Unified Soil Classification System. Iverson and Major classified the soil as a poorly-sorted, dense, low plasticity, gravelly clayey sand, but do not define their soil classification system. During drilling there were few distinct textural changes with depth, except where drilling met refusal on rock. They suspected that the rock materials may have been boulders suspended in the soil, and may not have reflected stratigraphic boundaries.

4.2.4. Slope Movement Evaluation Methods

The hydrology, slope movement, and deformation was monitored with a variety of methods beginning in 1973; intensive monitoring occurred between 1982 and 1985. Iverson and Major found that the landslide accelerates smoothly sometime between November and March, and then maintains a relatively steady pace that is 10 to 100 times faster than its slow summer creep rate of 0.04 to 0.16 in (1 to 4 mm) per month. Rapid movement generally persists into May or June, when the lanslide smoothly decelerates to its very slow summer rate. There is, however, no consistent relationship of timing, duration, and speed of movement with the timing and amount of rainfall.

In the summer of 1982, 60 open standpipe piezometers were installed in boreholes throughout most of the landslide length. Four additional piezometers were installed in the slide toe in the summer of 1983. Three electrical piezometers were installed in the landslide's basal shear zone. These electrical piezometers, however, began to yield spurious data within a few months of their installation, probably owing to deformation and leakage of the protective housings. Data collected during the time when both the electrical and non-electrical piezometers were functioning allowed the authors to compare their responses. From these data they concluded that high-frequency head fluctuations, which could be missed in the weekly well readings, do not occur within the basal shear zone.

Iverson and Major found that, despite marked differences in the amount and distribution or rainfall, the seasonal responses of water levels in most piezometers were remarkably consistent from year to year. Differing responses were, however, measured at different points in the landslide. These spatial diffences reflect spatial variations in ground-water responses. Data recorded in hydrographs show that hydraulic heads tend to be higher in shallow piezometers (< 9.8 ft (3 m) deep) than in intermediate (9.8 to 19.7 ft (3 to 6 m) deep) or deep piezometers (> 19.7 ft (6m) deep). From this they concluded that a downward component of the hydraulic gradient persists year-long throughout most of the landslide, and that deep portions of the ground-water flow field are continuously recharged by percolation from above. After a seasonal high level is reached, it tends to be quite persistent and is affected relatively little by superposed short-term fluctuations. Also, virtually all wet season water levels in shallow wells are less than 3.3 ft (1 m) below the ground surface, and many are within inches (decimeters) of the surface. From this they inferred that the deep-seated landslide is almost completely saturated during most of the rainy season. Although soil deformation may alter the hydraulic head distribution, they observed no head fluctuations were clearly caused by landslide movement. They assume, therefore, that the soil deforms with constant volume and that deformation effects may be neglected.

Assuming steady, gravity driven, Darcian potential flow in a saturated, homogeneous, isotropic, porous slope, the authors performed an analysis of the deep-seated landslide hydrogeology. First they constructed a flow net which was constrained by the mean slope of of the water table and by the wet-season piezometric data. No basal or lateral flow boundaries were imposed. The flow net showed that, on average, wet-season ground-water flow is driven by a total head gradient of magnitude 0.6 to 0.7, which includes a strong downward component. This downward component reflects widespread infiltration and recharge, and it affects the balance of forces that controls landslide motion.

Second, they used numerical models to evaluate the complicated hydrogeologic effects of the hummocky landslide surface. They concluded from these models that ground water circulates in the slide mass in two cell patterns. At the hillslope scale, the ground-water circulation is controlled by the recharge near the top of the slope and discharge near the base. At the local scale, the circulation results from hydraulic gradients caused by the surficial hummocks and is most conspicuous where large scale recharge and discharge do not overwhelm the local flow. Both local recharge and discharge are concentrated in the concavities that separate hummocks, with discharge focused near the bases of steep sections of the slope. Local ground-water circulation can extend to considerable depths throughout much of the hillslope, regardless of the lower, impermeable boundary depth.

Using a model of transient, vertical ground-water flow, the authors evaluated the time-dependent head fluctuations using the linear diffusion equation. They concluded from this analysis that:

1) the heads in shallow piezometers reflect the influence of every storm;
2) heads in intermediate-depth piezometers are less sensitive to individual storms, but respond to rainfall on a month-to-month basis;and,
3) in deep piezometers the heads reflect little other than seasonal or longer-term rainfall cycles.

During this analysis they were able to determine a hydraulic diffusivity of the order of $10^{-6}m^2/s$ ($1.07 \times 10^{-4}ft^2/s$). Using this they determined wave speed, length, and phase lag associated with different pore-pressure wave frequencies. Their calculations show that all pore-pressure waves attenuate almost completely before they have traveled more than half a wavelength into the soil. The calculated phase lags at the depth of 90% wave attenuation range from 2.5 days for weekly-cycle waves, to 130 days for annual-cycle waves. Ground-water reponses at the landslide base are thus predicted to lag a few weeks to a few months behind the rainfall cycle. This prediction corresponded well with their field data.

Temporal and spatial variations in ground-water flow influence the effective stress distribution and motion of Minor Creek landslide in several ways. Times of high ground-water head at the base of the landslide correspond well with times of rapid landslide motion. From their field data, Iverson and Major were able to define a threshold for rapid movement measured as mean water depth of 7.4 ft (2.25 m) below the surface. If there is sufficiently great ground-water storage in the unsaturated zone, the slide mass will move early in the wet season even if antecedent rainfall is low. Spatial variations in the ground-water flow field produce seepage forces that are spatially also variable. The authors' analysis showed that a horizontal seepage direction maximizes instability. From their model and qualitative field observations they found that emergent seepage can occur locally at the base of steep hummock faces on the landslide. They also inferred that the stress field near the base of hummock faces favors instability, because high shear stresses and low normal stresses are commonly focused near such points. When rapid motion and deformation of the landslide occur, they observed ground breakage and surficial failures that commonly begin near the bases of steep sections of the landslide.

Iverson and Major speculated that the long-term behavior of unstable ground is related to hummocky microtopography, which in turn may lead to local failures that create new hummocks. This process, they inferred continues until the mean slope is flattened appreciably or a cataclysmic failure occurs. Such a failure mechanism might explain the widely divergent movement rates observed on morphologically similar landslides in northwestern California.

4.2.5. Results

From field observations and inferences from physically based theory, Iverson and Major reached the following conclusions about the relationship between ground-water flow and seasonal landslide movement:

1. The basal shear zone of Minor Creek landslide is virtually always saturated, and nearly the entire depth of the landslide is saturated during the winter wet season when landslide movement occurs.

2. The mean hydraulic gradient is directed mostly downward, even though the ground water flow field varies considerably in time and space. They are therefore skeptical of analyses that employ few data and make "standard" assumptions (such as slope-parallel flow) about how ground water affects slope stability.

3. Hydraulic conductivity and diffusivity of 1.64×10^{-7} ft/s and 3.28×10^{-6} ft/s (5×10^{-8} m/s and 1×10^{-6} m/s) were measured. These variables are within the range anticipated for the landslide's poorly-sorted, clay-rich soil.

4. Transient ground-water pore pressure responds to rainfall by an increasing attenuation with depth and lag behind the rainfall. Responses that occur early in the wet season can be influenced strongly by antecedent water storage in the unsaturated zone. However, responses that occur later in

the wet season are directly related to pore pressure transmission that accompanies saturated ground-water flow.

5. Ground-water head distribution is the critical factor at incipient motion. The delicate balance between seasonal changes of the ground-water flow field and seasonal landslide movement indicates that if the slope angle, thickness, strength, or hydrology of the landslide were changed even slightly, a significant departure from the current landside behavior could result.

6. Iverson and Major infer that local ground-water circulation can perturb the over-all stress state and pattern of motion at Minor Creek landslide.

The major implication of this study to forest practices is the relationship of how the ground-water regime in a slide mass changes in response to management activities such as timber harvesting, road construction and maintenance. A deep-seated landslide may be stable prior to road construction and timber harvesting; but, because the ground-water regime could change in response to these activities the landslide may become more unstable. It is also possible that the landslide stability decreases because road maintenance, or lack of road maintenance, alters significantly the ground-water regime.

4.3.0. BAKER CREEK EARTHFLOW, SOUTHWESTERN OREGON

4.3.1. Problem Definition

The Baker Creek earthflow was selected by Swanston et al. (1988) for study since it met the following criteria: it is a deep-seated landslide, an extensive logging road system provides access for drilling and monitoring, and clearcut timber harvesting was scheduled far enough in advance to provide adequate monitoring time prior to harvest.

4.3.2. Location and Geology

Baker Creek is approximately 41.6 mi (67 km) southeast of Coos Bay in the Klamath Mountains of southwestern Oregon. Sedimentary bedrock in the Baker Creek drainage is highly susceptible to chemical decomposition and erosion by mass-wasting processes. These sandstones and siltones belong to the Otter Point Formation of late Jurassic to early Cretaceous age. Outcrops are few due to the nearly continuous colluvial mantle, deep residual soil, and saprolite produced by mass movement and weathering processes. Soil depth is variable in this watershed ranging between less than 3.9 in (0.1 m) on the ridge tops to more than 32.8 ft (10 m) within earthflows and on middle to lower slopes undergoing creep.

4.3.3. Earthflow Materials

In the Baker Creek watershed soils are mostly stony loams (gravelly sands) and stony-clay loams (clayey sands with gravel) of the Etelka and Whobrey Series. These soils are typically deep and have variable soil conductivities. They are derived from the underlying sedimentary bedrock and are developed in colluvium and residuum. Underlying these soil units are saprolites (clay-rich, decomposed bedrock) rich in silt-sized particles and montmorillonite clay with depths ranging between 9.8 to 16.4 ft (3 to 5 m). Where the saprolites are in contact with the unweathered bedrock they commonly display alternating thin layers of slightly altered and deeply decomposed and leached parent materials. These decomposed and leached zones are usually associated with subsurface water movement and constitute potential zones of weakness along which failures can develop.

4.3.4. Slope Movement Evaluation Methods

Four inclinometer access tubes were installed within and adjacent to the Baker Creek earthflow. This earthflow was located within the boundaries of a planned timber sale. At the start of this study in 1974 the logging boundaries had been marked, but the timber was not scheduled for harvest for another 2 to 3 years. This gave the authors time to measure and characterize prelogging rates of creep and earthflow activity. One tube was installed above the earthflow headwall and outside of the planned harvest area. A second tube was placed midslope and within the planned cutting unit; this second tube was located approximately 1970 ft (600 m) downslope from the first tube and within the active earthflow zone. The third tube was installed within the toe of the earthflow, also within the cutting unit; this tube was approximately 400 ft (120 m) downslope from the second tube. The last tube was positioned east of the second tube and outside of the harvest unit. The bottom ends of the inclinometer tubes were installed into stable bedrock; this allowed the authors to collect slope deformation data in a three-dimensional coordinate system.

Monitoring of inclination and water level changes inside the tubes took place over a ten-year period during the autumn and spring. Pre-harvest monitoring occurred between 1974 and 1976; harvest monitoring occurred during 1976; and, post-harvesting occurred over 1977 through 1984.

Water levels fluctuated within a narrow range between the ground surface and a depth of 4.9 ft (1.5 m) at all four sites. By the end of the winter rainy period the water levels tended to be near the surface. The authors interpreted this to be the result of ground-water flowing in from one or more of the water-bearing horizons located in the saprolite (decomposed bedrock), and not a reflection of year-round saturated conditions within the entire soil profile.

The inclination of access tubes was measured at 19.4 in (0.5 m) intervals during each survey. Subsequent surveys provided the necessary data for vertical profile plots, showing distance and direction of movement between successive surveys through the depth of the hole. Variability in direction and distance of movement between successive surveys at each depth interval was occasionally large. Small, random displacements laterally and upslope are largely a response to differential movement of the inclinometer tube within the drilled hole. To construct the vertical profile of movement and compare profile changes over time, cumulative position vector coordinates were projected into a single plane with an azimuth appproximating the dominant movement direction. This plane was designated the "plane of maximum movement" (PMM). An approximate PMM was graphically determined for each hole from the general direction of a plot of surface movement over the total period of monitoring. Once the profiles were plotted in the plane of maximum movement, displacement configuration with depth and the location of shear zones or accelerated deformation were defined. Annual and seasonal displacement and rates of movement at the surface were obtained by calculation and graphic scaling from the profiles. Displacement and rates were then compared with annual and seasonal precipitation and with cumulative departures from mean precipitation to determine relations that might exist between movement and prevailing climate conditions.

4.3.5. Results

Earlier work by Swanston (1981) provided descriptions of three types of vertical soil movement profiles indicative of accelerated soil movement: a shear strain profile, an extesion-flow profile, and a block-gliding profile. Inclinometer access tubes 1 and 4 (located outside of the earthflow boundary) exhibited creep (shear strain profile) characteristics. Access tubes 2 and 3 (located within the active zone of the earthflow) exhibited finite failure (block-gliding profile) characteristics, with uniform movement occurring above a shear zone. For the second tube the shear zone was from 10.5 to 12.1 ft (3.2 to 3.7 m) deep. Total displacement for this tube at the surface exceeded 2.7 in (68 mm) over the 10 years from 1974 to 1984 with 70% of the total cumulative movement (1.6 in or 41 mm) occurring during the two years from winter 1977 to winter 1979 (after timber harvest). For the third tube the shear zone was from 17 to 18 ft (5.2 to 5.6 m) deep. Substantially less displacement of the third tube occurred than that recorded for the second tube: total displacement was about 0.7 in (16.5 mm) at the surface over the 10 years. Of this displacement, 75% (0.5 in or 12 mm) resulted from a surge during summer, fall, and early winter of 1978.

Effects of precipitation were determined at each site. Earlier work suggested that both displacement amount and movement rate are sensitive to seasonal and annual precipitation. Linear regression of both displacement and rate against seasonal and annual rainfall for each access tube was completed. They found that there were no significant correlations between these variables, and they concluded that soil movement was progressing independently of short-term precipitation (seasonal and annual) and that soil movement might have been responding to long-term variations in soil-water content in the soil. From 1978 to 1980 they found a substantial increase in displacement in access tubes 2 and 3, despite below-average rainfall. Their interpretation was that the soil was responding to destabilizing forces that had accelerated earthflow activity independently of precipitation.

Accelerated movement appeared to be directly related to harvest activities occurring in the upper portion of the Baker Creek earthflow. The earthflow was clearcut by felling and yarding in the fall and winter of 1976. During the winter of 1977 an increase in displacement rate was measured at access tube 2 located in the lower half of the earthflow. The same displacement was measured in access tube 3, located at the earthflow toe, by the summer of 1978. East of the earthflow, at access tube 4, a slight displacement was measured in the summer of 1978. Continued displacement was measured at tube 2 through the summer of 1979 after which the displacement rate returned to prelogging levels. Accelerated movement in the earthflow toe continued for only a single season, and by the spring of 1979, displacement rates had returned to prelogging levels. The authors' interpretation was that the short time span of acceleration was probably the result of generally dry conditions and the small size of the blocks involved in the displacement. This result, they believed, was a rapid redistribution and balancing of stresses in the earthflow mass.

The authors caution that, although the combined operations of timber felling and yarding were strongly implicated as the cause of the increased activity, it is not possible to use this evidence to specifiy the actual mechanism of destabilization. The movement was unlikely the direct result of loss of anchoring and reinforcing effects of roots. This conclusion is based on three facts: first, root strength loss occurs several years after harvest; second, coniferous root systems in a deep-seated landslide have no direct effect at a shear zone which is located many feet deeper than the roots; and third, root systems occupy only a small proportion of the slide mass. They concluded that the dominant effect of timber removal is probably the immediate elimination of interception and evapotranspiration from the site, which resulted in a change in the slope hydrology. Also, surface water may be concentrated into channels formed by yarding, and into other depressions such as tension cracks and sag-ponds.

Swanston and co-workers found this deep-seated landslide had accelerated slope movement in a two year period in response to timber harvesting. Different portions of this earthflow moved during this time frame. By the end of three years after harvesting the slope movements had returned to prelogging levels.

5.0.0. CURRENT AND FUTURE WORK

The erosion-hazard assessment program (under the direct of the Sediment-Hydrology and Mass-Wasting technical steering committee) includes several research projects pertinent to the subject of deep-seated landslides and timber harvesting. These projects are: the effects of timber harvesting on deep-seated landslides, hazard zonation, and site hazard methods (road related). Currently the projects are in various stages and future work will evolve over time. A short discription of the status of these projects and how they are related to one another is provided below.

5.1.0 Current Work

5.1.1. Geomorphological Watershed Analyis

A research group lead by Tom Dunne and Dave Montgomery, from the University of Washington, is involved in the development of a geomorphological analysis in watersheds. Three components constitute this analysis: shallow sediment sources, deep-seated mass failures, and the assessment of channel conditions and responses. Deep-seated landslides, the second component, may be studied to provide:

1. A method for systematic prediction of potential sites of deep-seated mass failures in a watershed.

2. A method for predicting the alteration of stability as a result of changes in hydrology due to natural weather fluctuations or to management.

3. Guidelines for field studies to provide appropriate data to make predictions for areas that have been flagged as potentially unstable.

5.1.2. Hazard Zonation

The hazard zonation project under the direction of Matthew Brunengo, from the Washington Department of Natural Resources, is in the field inventoring stage. Various methods for evaluating slope stability hazards, including deep-seated landslides, are being field-tested for applicability in forest practices.

5.1.3. Site Hazard Methods

Many existing road systems cross landslides, including deep-seated landslides. Consequently, the number of successful road management decisions pertaining to slope instability (a potential hazard) are dependent upon the skill level of forest geotechnical engineering specialists providing data for these decisions (Koler and Neal, 1989). Therefore the site hazard methods, the third part of the erosion hazard assessment program, is an important component of the study of deep-seated landslides.

At the present time this project is at a development stage. Scientists and engineers of Golder and Associates, have completed the interviewing of geotechnical engineering specialists with work experience on forest roads. The purpose of the interviewing was to learn what current methods are being used in evaluating unstable slopes at a site-specific scale. Concurrent with the interviews, Golder and Associates' staff have put together a process for assessing potential or existing road failures (hazards). Included within this process will be a hazard/risk method for assigning values relative to slope stability, to help geotechnical specialists provide managers with accurate data for decision-making for protecting resources (at risk).

There is an overlap between these three projects. Their relationship with one another can be explained by their application to four levels of forest resource management: 1) basin-wide planning (e.g. cumulative effects analysis); 2) activity planning (e.g. timber sale environmental assessment); 3) corridor planning (e.g. road, power transmission line, and small hydro-power penstock); and 4) design application (geotechnical engineering road design, rock quarry and gravel pit design, fish ladder design, and so on). Products from the geomorphological watershed analysis will provide a method for performing basin-wide planning. Products of the hazard zonation project will provide a process for the first three levels, basin-wide planning through corridor planning. Results from the site-hazard project will give field technicians and professionals a process to evaluate slope stability in corridor planning and design applications. All four levels are integral parts of the analysis of slope stability, including that of deep-seated landslides.

5.2.0 Future Work

From the available literature we have the following generalizations:

1) Deep-seated landslides generally have accelerated mass movement in response to seasonal precipitation, storm events don't usually increase slope movement;

2) If ground water is retained through the drier months, accelerated movement of deep-seated landslides can occur early in the wet season;

3) Piezometric levels flunctuate among areas that are undergoing different stresses; and,

4.) Vegetation cover in one case (Swanston and others, 1988) was not significant except for the first two years after timber harvesting; however, disturbance of the vegetation can change the ground-water regime resulting in a decrease of the slope stability (Iverson and Major, 1987).

New and remaining questions are:

1) Are deep-seated landslide areas unsuitable for timber harvesting?

2) What are the differences between deep-seated landslides located in different geologic materials (e.g. slump-earthflows in glacial materials in comparison to those in volcaniclastic materials)?

3) Will various management activities (logging, slash burning, road construction and road use) have different

consequences in deep-seated landslides composed of different geologic materials?

4) Will these activities also affect slope hydrology? Will the change affect the slope stability? Is this change consistent between deep-seated landslides composed of different geologic materials?

5) Can the change in slope hydrology of deep-seated landslides be mitigated? What are the various options?

5.2.1. Future Application of Case-History Methods

Much work has been directed toward understanding the mechanics and hydrology of deep-seated landslides. Pyles and others showed, through the use of the one-dimensional consolidation test, how pore-water pressure can be evaluated within the landslide shear zone. Iverson and Major presented a method using piezometers for evaluating the ground-water regime in a deep-seated landslide. They showed how the hydrology of an entire slide mass (regional scale) can be evaluated and compared with the microtopological (local scale) hydrology. By using these methods, in future site-specific studies of deep-seated landslides, we can acquire more data and hopefully increase our knowledge of the mechanics and hydrology of these large landforms.

The work completed by Swanston and others on the Baker Creek earthflow presents a good procedure for evaluating the effects of timber harvesting on deep-seated landslides. Installing instruments on and adjacent to a slide mass well before timber harvesting will enable a researcher to measure the landslide ground-water flow regime in an "undisturbed" state. Continuing this monitoring during and after timber harvest provides a record of changes in the ground-water flow regime and slope stability. Obviously, field data collection occurs over a period as long as a decade, depending upon when monitoring starts and timber harvesting ends. Because of the long time period involved, it may be difficult to staff and finance such a project.

This kind of site-specific work should be started in Washington for several reasons. First, the work of the University of Washington researchers (see section 5.1.1.) will hopefully provide a method to predict the location and stability of deep-seated landslides within a watershed. This method, however, will not be suitable for road construction design or timber harvest layout applications. Second, although the three projects described here were carried out in geologic materials similar to those found in Washington, few studies have been sited in glacial or volcaniclastic materials typical of many deep-seated landslides in this state. Third, with the advent of more non-clearcut harvesting techniques, we need a better understanding of how the ground-water regime and slope stability of a deep-seated landslide change in response to non-traditional harvesting methods.

5.3.0. Potential Project Areas

There have been several operational projects completed to provide specific answers pertaining to proposed timber harvests and for road construction. Descriptions of these projects are located in the gray literature, written by the geotechnical engineering staff of the Mt. Baker Snoqualmie, Olympic, and Gifford Pinchot National Forests, the Washington Department of Natural Resources (Divisions of Engineering, Forest Practices, and Geology and Earth

Resources), and others. Using this information as a starting point, we can make a laundry list of potential study areas which are different from those described in the case history section of this paper. I have divided this list into categories based on geomorphology and geologic materials.

5.3.1. Alpine Glaciation

On the west side of the Olympic Peninsula are several river valleys with thick deposits left by alpine glacial processes. Many geotechnical engineering projects dealing with road construction and slope stability have been completed on these lands for the Olympic National Forest (Koler and Neal, 1989). Slump-earthflows studied in these projects are located along the East and West Forks of the Humptulips River. To the north, staffs of the Washington Department of Natural Resources, local Native American tribes, and the University of Washington have been evaluating slope stability in the Hoh River drainage system.

5.3.2. Continental Glaciation

Several deep-seated landslides have been evaluated in continental glacial materials of western Washington by the geotechnical engineering staffs of the Mt. Baker-Snoqualmie and Olympic National Forests. In nearly all of the cases the physical properties of the glacial materials were measured and mapped in the field prior to geotechnical drilling. Many soil samples were collected and tested in the U.S.F.S. materials laboratory, and there are many data on file. Unfortunately, the projects were short and few data were collected over a five year or longer time. Examples are the Grey Wolf landslide on the northeast side of the Olympic Peninsula, and the Deforest Creek landslide in the Deer Creek drainage in the foothills of the North Cascade Range.

On lands bordering the Cascades and the Puget Lowland, several slump-earthflow areas have been evaluated through interdisciplinary-team studies. The most comprehensive study was completed on the Hazel slide on the North Fork of the Stillaquamish River (Benda, Thorsen, and Bernath, 1988), where a time-series analysis of slope movement, logging and rainfall was performed. This work, however, did not include the determination of the physical strength properties of the slide materials.

5.3.3. Rock slope failure

The geotechnical engineering staffs at the three national forests in western Washington have been involved, over the past 20 years, with the evaluation of deep-seated landslides in rock. This work has typically been site-specific, and related to road structure design. The most recent project in this category, in which field mapping and geotechnical drilling occurred, was on the Prairie Creek landslide in the Olympic National Forest. Preliminary results from this on-going project indicate that this slide mass failed along a shear zone over 50 ft (15 m) below the surface. Rock and soil mass failure resulted when a road ditchline became blocked and water was concentrated on the slide during a large storm. Antecedent moisture in the slide mass probably contributed to the deep-seated movement.

6.0.0. GLOSSARY

6.1.0. Creep

Creep has come to mean different things among earth scientists, and it seems best to avoid the term or to use it in a well-defined manner. As used here, creep is considered to have a meaning similar to that used in mechanics of materials; that is, creep is simply deformation that continues under constant stress. Some of the creep deformation may be recoverable over a period of time upon release of the stress, but generally most of it is not. Creep movement is quasi-viscous, occurring under shear stresses sufficient to produce permanent deformation but too small to produce discrete shear failure (Swanston, 1974b). Mobilization of the soil mass is primarily by deformation at grain boundaries and with clay mineral structures. Both interstitial and adsorbed water appear to contribute to creep movement by opening the structure within and between mineral grains, thereby reducing friction within the soil mass. This permits a "remoulding" of the clay fraction, transforming it into a slurry, which then lubricates the remaining soil mass. In local areas where shear stresses are great enough, discrete failure may occur, resulting in development of slump-earthflow due to progressive failure of the mantle materials (Swanston and Swanson, 1976).

There is disagreement as to whether creep in rock and soil should be restricted to those movements that are distributed through a mass rater than along a defined fracture. Authorities are about equally divided on this point, but, in keeping with the use of the term in engineering mechanics, the acceptance of this restriction is no favored. Creep movements can occur in many kinds of topples, slides, spreads, and flows, and the term creep need not be restricted to slow, spatially contiguous deformation. Therefore, spatially continuous deformations are classified as various types of flow in rock, debris, and earth (Varnes, 1978).

6.2.0. Earth Flows

Frequently there is some confusion with the term earth flow. Many earth scientists equate the word earthflow with landslide, as I have done in this paper. However, there is also the term earth flow which is commonly used by engineering geologists and civil engineers. The following description of earth flow is taken from Varnes (1978).

Subaerial flows in fine-grained materials such as sand, silt, or clay are classified as earth flows. Flows that have a coarse-grained texture are classified as debris flows. Both types of flows are generally shallow although some are deeper than one or two meters (yards). Earth and debris flows, however, are not considered by most earth scientists to be "deep-seated landslides" because the rheology of flows is different from the rheology of creep and slump-earthflows.

In his paper classifying landslide types, Varnes uses some of the Soviet work which describes earth flows as

> "...a classification of mud flows based on a.) the nature of the water and solid material supply; b.) the structural-rheological model, that is whether the transporting medium is largely water in the free state or is a single viscoplastic mass of water and fine particles; c.) the composition of the mud flow mass, that is, whether it consists of mud made up of water and particles less than 0.04 in (1mm) in size or of mud plus gravel, rubble, boulders, and rock fragments; and d.) the force of the mud flow as defined by volume, rate of discharge, and observed erosive and destructive power. In the Soviet literature mud flows include not only what are here classified as debris flows but also heavily laden flows of water-transported sediment.

Varnes also describes how the conditions of an earth flow can change its rheology, and therefore fall within the category "deep-seated landslides" use in my paper.

> "The somewhat drier and slower earth flows in plastic earth are common in many parts of the world wherever there is a combination of clay or weathered clay-bearing rocks, moderate slopes, and adequate moisture."

6.3.0. Slump-earthflow

Slumps and earthflows begin initially as rotational failures usually triggered by soil saturation and rapid increases in pore water pressure in the immediate area of failure. Slumping involves the downward and backward rotation of a soil block or group of blocks with small, lateral displacement. The main scarp is a steep headwall and is generally bare and concave toward the toe. The toe is hummocky or broken by individual slump blocks and, if an earthflow is involved, may be lobate in shape. Earthflows frequently incorporate much larger masses of soil which move downslope through a combination of flowage and slumping. The main scarp is usually circular or spoon-shaped with a steep headwall and narrow oriface through which the soil flow issued. The toe is characteristically hummocky and lobate in form (Swanston, 1974b).

Simple slumping takes place as a rotational movement of a block of earth over a broadly concave slip surface and involves very little breakup of the moving material. Where the moving material slips downslope and is broken up and transported either by a flowage mechanism or by gliding displacement of a series of blocks, the movement is termed slow earthflow. The combined term slump-earthflow is used because many deep-seated mass movements in the Pacific Northwest have slump characteristics in the headwall area and develop earthflow features downslope.

In the Pacific Northwest, these features may range in area from less than 1 acre to more than several square miles. The zone of failure occurs at depths of a few yards to several tens of yards below the surface. Commonly, there is a slump basin with a headwall scarp at the top of the failure area. Lower ends of earthflows typically run into stream channels. Transfer of earthflow debris to stream channels may take place by shallow, small scale debris avalanching or by gullying and surface erosion, depending on soil and vegetation conditions. Therefore, the general instability set up by an active slump-earthflow initiates erosion activity by a variety of other processes. Because earthflows are slow moving, deep-seated, poorly drained features, individual storm events probably have much less influence on their movement than on the occurrence of debris avalanches and torrents. Where planes of slump-earthflow failure are more than several yards deep, weight of vegetation and vertical root-anchoring effects are negligible (Swanston and Swanson, 1976).

7.0.0 ACKNOWLEDGEMENTS

I wish to thank several colleagues who gave the time to give a critical review of this paper. Three reviewers were especially comprehensive in their comments: Matthew Brunengo, Daniel Miller, and Jon Major. Other reviewers who gave suggestions were Dennis Harr, Dennis Larson, Neal Birli, Mary Raines, and Paul Kennard.

8.0.0. BIBLIOGRAPHY

The following list provides the literature that I reviewed that was pertinent to this study. A total of 76 papers were read, of which 52 were within the framework of this research. Many of the papers listed here are not discussed in the text; this is simply due to the fact that many of these papers overlap in content. In those cases I cited the most recent paper.

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