582

Erosion and Sediment Transport in Pacific Rim Steeplands. I.A.H.S. Publ. No. 132 (Christchurch, 1981)

Creep and earthflow erosion from undisturbed and management impacted slopes in the Coast and Cascade Ranges of the Pacific Northwest, U.S.A.

Douglas N. Swanston, USDA Forest Service, Forestry Sciences Laboratory, Box 909, Juneau, Alaska 99802

Abstract. Soil creep, slumping, and earthflows are major processes of natural slope erosion and sediment transport on slopes underlain by deeply weathered parent material in the Cascade and Coast Ranges of Oregon, Washington, and northern California, USA. Creep movement is quasi-viscous, occurring under shear stresses too small to produce discrete failure. The soil mass is primarily mobilised by breakdown of included clay structures. Remolding transforms the clay fraction into a slurry which lubricates the remaining soil mass. Where shear stresses are great enough, slumps and earthflows develop and enlarge by progressive failure of the mantle materials. Substantial sections of drainage basins in the region are affected by these processes and are highly sensitive to any manipulations or impacts that change the stress distribution in the soil mass.

Creep and earthflow rates in various geologic terrains have been monitored since 1972 by bore-hole inclinometer methods. Depth of movement varies from near-surface to more than 17 meters. Undisturbed rates of movement are variable within all parent material types but are within the range of 0.5 to 104 mm/year. The highest rates occur above zones of incipient shear or extension flow marking changes in parent material type, degree of alteration, or structural weakness.

Slope exerts little control ove
are most sensitive to water co
sites show clear relationships
yearly movement, and movement
and winter rainy season or dur
a storm by storm basis was not
one harvested slope indicates a
the second year after disturbar
twice undisturbed rates.

L'érosion due au mouvement et
dérangeés et non-dérangeés dan
Ranges du Nord-Ouest des Etats-

Résumé. Les processus de glis
facteurs importants dans le tr
au sein des mouvements de masse
de grandes parties de la Chaîne
ouest pacifique. Les mouvement
pluvieuse d'automne et d'hiver.
le mouvement.

Slope exerts little control over variations in movement rate. Rates are most sensitive to water content of the parent materials. Monitored sites show clear relationships between seasonal rainfall and total yearly movement, and movement predominantly occurs during the fall and winter rainy season or during the spring snowmelt. Movement on a storm by storm basis was not detectable. Preliminary analysis of one harvested slope indicates a marked increase in movement beginning the second year after disturbance with post-impact rates more than twice undisturbed rates.

L'érosion due au mouvement et au écoulement de la terre sur les pentes derangeés et non-derangeés dans les montagnes des Coast et Cascade Ranges du Nord-Ouest des Etats-Unis.

Résumé. Les processus de glissements et mouvements de terrain sont des facteurs importants dans le transport de matières de surface vers le bas au sein des mouvements de masses de terrain complexes qui caractérisent de grandes parties de la Chaîne Côtière et des Cascades dans le nord-ouest pacifique. Les mouvements ont lieu surtout pendant la saison pluvieuse d'automne et d'hiver. L'abbatage d'arbres semble accélérer le mouvement.

INTRODUCTION

Soil creep, slumps, and earthflows occur as major processes of natural slope erosion and sediment transport to stream channels from slopes underlain by deeply weathered bedrock in the Coast and Cascade Ranges of Oregon, Washington and northern California, USA. Many of these slopes are within the commercial forest zone and are heavily affected by forest harvest activities, including clearcutting. The rates of movement of these processes under undisturbed conditions, movement variability within the mantle profile, response to climatic and geologic variables, and the influence on movement of forest harvest activities are therefore of major importance in determining the natural stability of a site and the sensitivity of a slope or drainage basin to management disturbance.

In 1972, a research program to monitor natural movement rates and the influence of natural and management-related variables on acceleration of movement was implemented on a variety of unstable geologic terrains scattered through the region. This paper discusses the relationships and trends indicated by the data from this program through the winter of 1978.

PROCESS CHARACTERISTICS

Creep occurs as a slow, downslope movement of mantle materials in response to long-term applications of gravitational stress. The mechanics of creep have been investigated experimentally and theoretically by a number of workers (Terzaghi, 1953; Goldstein and Ter-Stephanian, 1957; Saito and Uezawa, 1961; Culling, 1963; Haefeli, 1965; Bjerrum, 1967; Kojan, 1968; Carson and Kirkby, 1972; and others). The process and its interrelationships with slumping and earthflows in the Pacific Northwest has been characterized under natural conditions by Swanson and Swanston (1977).

In local areas where creep in
the soil and rock material, discre
earthflows develop and enlarge due
materials. Simple slumping takes
block of earth over a broadly conc
little break-up of the moving mate
moving material slips downslope an
by a flowage mechanism or by a com
rotational displacement of a serie

Under field conditions, local
degree and depth of parent materia
content of mantle materials lead t
process and rate of movement.

MANAGEMENT IMPACTS

In the Pacific Northwest, large po
by altered volcaniclastic rocks, hi
serpentine-rich rocks, and glacio-l
particularly prone to complex soil
highly sensitive to any manipulatio
passage of water or the basic distr
mantle. Engineering activities tha
drainage alteration frequently have
and earthflow activities (Schlicker
1961; Wilson, 1970; Swanston and Sw

The impact on these processes
has not been well documented. The
creep rates and slump and earthflow
involving modification of surface a
anchoring and reinforcing effect of

In local areas where creep induced stress exceeds the strength of the soil and rock material, discrete failure occurs and slumps and earthflows develop and enlarge due to progressive failure of the mantle materials. Simple slumping takes place as rotational movement of a block of earth over a broadly concave slip surface, involving very little break-up of the moving material. Earthflows occur where the moving material slips downslope and is broken up and transported either by a flowage mechanism or by a complex mixture of translational and rotational displacement of a series of blocks (Schuster and Krizek, 1978).

Under field conditions, local variations in soil properties, degree and depth of parent material weathering, and clay and water content of mantle materials lead to substantial variations in movement process and rate of movement.

MANAGEMENT IMPACTS

In the Pacific Northwest, large portions of drainage basins underlain by altered volcaniclastic rocks, highly sheared siltstones and mudstones, serpentine-rich rocks, and glacio-lacustrine silts and clays are particularly prone to complex soil mass movement processes. They are also highly sensitive to any manipulations or impacts that might alter the passage of water or the basic distribution of stresses in the soil mantle. Engineering activities that involve excavation and fills or drainage alteration frequently have dramatic impact on creep, slump, and earthflow activities (Schlicker et al., 1972, 1973; Jones et al., 1961; Wilson, 1970; Swanston and Swanson, 1976).

The impact on these processes from clearcutting and yarding alone has not been well documented. The effects of vegetation removal on creep rates and slump and earthflow activity are likely to be subtle, involving modification of surface and subsurface hydrology and the anchoring and reinforcing effect of root systems. Where creep or shear failure is a shallow phenomenon (less than 2 or 3 meters), the loss of root strength due to killing of the tree is likely to be significant (Swanston and Swanson, 1976; Burroughs and Thomas, 1977; Wu et al., 1979). In massive, deep-seated creep and failures of the slump and earthflow type, root anchoring and the lateral and vertical reinforcing effect of intertwining root systems is probably negligible (Swanston and Swanson, 1976). Increased moisture availability due to reduced evapotranspiration and altered surface runoff patterns can increase the volume of water at the site (Gray, 1970; Rothacher, 1971). This may result in greater duration and rate of the annual period of creep activity. The water is also free to pass through the rooting zone to deeper levels of active or dormant slump and earthflow failures.

SITE LOCATION AND MONITORING

Between 1972 and 1975, 35 bore hole inclinometer tubes were installed at 14 sites on 7 clearly defined complex soil mass movement terrains in the Coast and Cascade Ranges of northern California, Oregon, and Washington (Swanston, 1979)(Figure 1; Table 1). An attempt was made to install at least three tubes at each site in a downslope transect in order to demonstrate response similarities or detect differences in rate and movement mechanics with slope location. These inclinometer tubes were constructed of polyvinyl chloride (PVC) with a 76.2-mm inside diameter and were grooved longitudinally inside at 90°. The tubes were placed in 127-mm-diameter bore holes drilled through weathered mantle materials and anchored at the bottom in competent bedrock. The annular space between the tube and the bore hole wall was then backfilled with sand or pea-gravel. A mechanical pendulum with electronic readout, fixed in a rigid carriage riding in the grooves was then passed down the tube to measure changes in inclination of the tube over time since installation. Since all sites monitored lie within a region characterized

by high winter rainfall and fairl
semi-yearly, in the spring after
after the summer drought. The re
horizontal movement profile and r
rainfall, and any changes in pare

Eight sites were located on
in the northern California Coast
basin lies in a massive, earthflo
terrain developed on schists and
sandstones and siltstones of the
early Cretaceous age) (Strand, 19
underlying the west side of the b
bedded sandstone and siltstone un

Site 9 is located on creep-d
Coquille River (Baker Creek) in t
Oregon (Figure 1). Bedrock under
Otter Point Formation of late Jur
consisting of highly sheared and
argillite, mudstone, and volcanic

Site 10 is located on earthf
tributary to the Nestucca River (
Coast Ranges (Figure 1). The par
deeply weathered siltstones, sand
of Tertiary age (Schlicker et al.

Site 11 is located on active
to a tributary to the South Umpqu
Cascade Range of southern Oregon
materials at this site consist of
interbedded dacite flows belongin
Tertiary age (Peck et al., 1964;

by high winter rainfall and fairly dry summers, each tube was read semi-yearly, in the spring after fall and winter rains and in the fall after the summer drought. The resulting data provide plots of the horizontal movement profile and rate variations with depth, seasonal rainfall, and any changes in parent material properties or structure.

Eight sites were located on the slopes adjacent to Redwood Creek, in the northern California Coast Ranges (Figure 1). The Redwood Creek basin lies in a massive, earthflow-dominated complex mass movement terrain developed on schists and extensively sheared and altered sandstones and siltstones of the Franciscan melange (late Jurassic and early Cretaceous age) (Strand, 1962). Sites 1 through 5 are on schist underlying the west side of the basin. Sites 6 through 8 are on interbedded sandstone and siltstone underlying the eastern slope.

Site 9 is located on creep-dominated terrain on a tributary of the Coquille River (Baker Creek) in the Klamath Mountains of southwest Oregon (Figure 1). Bedrock underlying this terrain is part of the Otter Point Formation of late Jurassic and early Cretaceous age, consisting of highly sheared and altered greywacke with subordinate argillite, mudstone, and volcaniclastics (Beaulieu, 1971).

Site 10 is located on earthflow-dominated terrain adjacent to a tributary to the Nestucca River (Bear Creek) in the northern Oregon Coast Ranges (Figure 1). The parent materials underlying this site are deeply weathered siltstones, sandstones, mudstones, and volcaniclastics of Tertiary age (Schlicker et al., 1972).

Site 11 is located on actively creeping terrain on slopes adjacent to a tributary to the South Umpqua River (Coyote Creek) in the western Cascade Range of southern Oregon (Figure 1). The underlying parent materials at this site consist of extensively altered, welded tuffs and interbedded dacite flows belonging to the Little Butte formation of Tertiary age (Peck et al., 1964; Kays, 1970).

Two sites are located on a complex mass movement terrain on slopes adjacent to Lookout Creek in the western Cascade Range of west-central Oregon (Figure 1). The underlying bedrock at these sites is also part of the Tertiary Little Butte formation, consisting of extensively weathered tuffs and breccias (Peck et al., 1964; Swanson and James, 1975). Site 12 is located on a partially active earthflow. Site 13 is on creeping terrain.

Site 14 is located on actively creeping terrain adjacent to a tributary to the Wenatchee River (Coulter Creek) in the east central Cascade Range of Washington (Figure 1). The parent materials at this site are interbedded glacio-lacustrine silts and sands of Quarternary age.

DATA ANALYSIS AND RESULTS

Changes in inclination of bore hole tubes were measured at 0.5-meter intervals from the bottom of the hole. The bottom of the hole was assumed to be fixed in place based on the competence of the rock determined during drilling and the lack of change in inclination during successive readings over the monitored period. Measurements at each interval were made in two planes at 90°. This provided data for a plot of distance and direction of movement between successive readings. Variability in direction and distance of movement between successive readings at each interval was occasionally large. This is due to several factors, including: 1) changing flow characteristics of the soil in response to water content; 2) differential adjustment of individual blocks within the moving mantle, and 3) settlement and differential movement of the inclinometer tube within the drill hole due to insufficient backfilling. In addition, many of the holes consistently reversed direction indicating a net negative or upslope movement during summer

low moisture periods suggesting
rich materials dominated the mov
of surface movement of hole B-2,
southwest Oregon illustrates thi
(Figure 2).

For purposes of constructin
comparing profile changes over t
individual interval points into
of maximum movement (PMM). An a
graphically from the general dir
points over the total period of
site 9, the PMM was chosen at 22
profile was then constructed for
interval measurements from the b
these graphical displays provide
direction of movement, movement
movement rates with depth and sea
results is presented in Table 1.

DISCUSSION

All but five of the bore hole inc
and consistent downslope movement
record ranging from 2 to 5 years.
RC-5B, B-4, CL-4, CL-5) exhibit
less than 1.0 mm/year and either
initial configuration of the tub
the end of the record period.

1/ The computer analysis, me
by R. R. Ziemer, USDA Forest Ser
Range Experiment Station, Arcata

low moisture periods suggesting that shrinkage phenomena in the clay-rich materials dominated the movement profile during this time. A plot of surface movement of hole B-2, site 9 in the Klamath Mountains of southwest Oregon illustrates this clearly for 3 out of 4 record years (Figure 2).

For purposes of constructing a vertical profile of movement and comparing profile changes over time, it was necessary to project individual interval points into a single plane designated the plane of maximum movement (PMM). An approximate PMM for each hole was determined graphically from the general direction of a plot of surface movement points over the total period of monitoring. In the case of hole B-2, site 9, the PMM was chosen at 225 degrees (Figure 2).[1/] A vertical profile was then constructed for each set of readings by summation of interval measurements from the bottom to the top of the hole. Together, these graphical displays provide a means for estimating the dominant direction of movement, movement configuration at depth and variation in movement rates with depth and season. A summary of site locations and results is presented in Table 1.

DISCUSSION

All but five of the bore hole inclinometer tubes installed show detectable and consistent downslope movement along the PMM over a period of record ranging from 2 to 5 years. The five exceptions (holes RC-2B, RC-5B, B-4, CL-4, CL-5) exhibit annual rates of surface movement of less than 1.0 mm/year and either fluctuate back and forth around the initial configuration of the tube or show a net upslope movement at the end of the record period.

[1/] The computer analysis, methodology, and plots were developed by R. R. Ziemer, USDA Forest Service, Pacific Southwest Forest and Range Experiment Station, Arcata, Ca.

Depths of detectable movement vary from 1.0 meter to 16.5 meters with the greatest depths indicated for active earthflows. The deepest movement profiles are developed at earthflow sites 4, 8, and 10 in schist and deeply weathered sandstone and siltstone of the northern California and northern Oregon Coast Ranges. The average movement profile depth for these sites is 11.2 meters (standard error = 1.3 meters). Other sites in this parent material have an average movement profile depth of 7.5 meters (standard error = 0.5 meter) (sites 1-3, 5-7). The average movement depth for sites established in deeply weathered volcaniclastics of the western Cascade Range of Oregon is 5.5 meters (standard error = 0.9 meter) (sites 11-13). Site 9, on sheared and altered greywacke in the southwest Oregon Klamath Mountains has an average depth of movement of only 3.2 meters (standard error = 0.7 meter). Movement depth of the glacio-lacustrine sands and silts at site 14 averages 6.5 meters (standard error = 1.6 meters).

Movement within the mantle is characterized by three major types of profile configuration indicative of the process mechanics dominating at the site. Active slump and earthflow locations consistently exhibit a block-gliding type profile with primary movement taking place above a thin zone of shear (Figure 3). Creep locations generally exhibit either a progressive deformation profile with greatest movement at the surface or an extension flow type profile with the greatest movement taking place over a broad deformation zone at some depth below the surface (Figure 4). Minor block-gliding is frequently present within a creep profile as small offsets indicative of local failure or minor mechanical shifting. Also, some progressive and extension-flow deformation above the shear zone is usually present within the earthflow profile.

Rates of surface movement a
and among all terrain and bedroc
year to as high as 158.3 mm/year
locations. The 15 earthflow inc
study sample have an average sur
(standard error = 11.9 mm/yr).
schists and the sheared and alte
northern California and in north
surface rates of 42.5 mm/year (s
year (standard error = 18.0 mm/y
movement at inclinometer sites i
western Cascade Range are much l
4.3 mm/year (standard error = 0.
average rate of actively creepin
features are in an inactive or n

Sites subjected primarily t
uniform movement. The average s
yr. with a standard error of 0.5
occur at tube locations in the w
Cascade Range in Oregon. These
year with a standard error of 0.
all other sites is 2.7 mm/yr. wi

Slopes vary from gentle to
with major gradient changes comm
individual tube locations. Slop
over variations in movement rate
sensitive to water content of th
of movement activity occurs dur
during the spring snowmelt when

Rates of surface movement at undisturbed sites are variable within and among all terrain and bedrock types ranging from as low as 0.3 mm/year to as high as 158.3 mm/year. The highest rates occur at earthflow locations. The 15 earthflow inclinometer tube locations in the total study sample have an average surface movement rate of 38.6 mm/year (standard error = 11.9 mm/yr). Earthflow rates are greatest in the schists and the sheared and altered sandstones and siltstones of northern California and in northern Oregon Coast Ranges, with average surface rates of 42.5 mm/year (standard error = 17.8 mm/yr) and 70.4 mm/year (standard error = 18.0 mm/yr), respectively. Rates of earthflow movement at inclinometer sites in the weathered volcaniclastics of the western Cascade Range are much lower with an average surficial rate of 4.3 mm/year (standard error = 0.7 mm/yr). This rate approaches the average rate of actively creeping terrain suggesting that the earthflow features are in an inactive or near-dormant state.

Sites subjected primarily to creep processes exhibit much more uniform movement. The average surface rate for all locations is 3.0 mm/yr. with a standard error of 0.5 mm/yr. The highest rates of creep occur at tube locations in the weathered volcaniclastics of the western Cascade Range in Oregon. These sites exhibit average rates of 3.6 mm/year with a standard error of 0.4 mm/yr. The average creep rate for all other sites is 2.7 mm/yr. with a standard error of 0.7 mm/yr.

Slopes vary from gentle to steep at all sites (ranging from 5 to 30°) with major gradient changes commonly occurring within 30 meters of individual tube locations. Slope gradient exerted no detectable control over variations in movement rate or process. Rates appear to be most sensitive to water content of the mantle materials. The predominance of movement activity occurs during the fall and winter rainy season or during the spring snowmelt when soil moisture levels are high. This difference in seasonal movement occurs either as a surge during winter wet periods followed by either summer inactivity or an upslope recession due to shrinkage of the clay fraction, or a wintertime acceleration of a smaller dry season rate (Figure 3). Average rates of winter movement at these sites range up to about 7 times the base or summer rates. Ten of the 35 inclinometer tube locations (tubes RC 1-A, 1-B, 2-A, 5-A; B 1 and 3; A-2; BR-1; CL-1 and 2) exhibit predominantly summer dry season movement occurring as a movement surge after 1 to 2 years of inactivity. At these locations, such summer surging is not preceded by abnormal winter rainfall. This suggests that a triggering mechanism may be active at these locations requiring that soil moisture content of the soil mass increase over time to a point where mobilization of the clay fraction occurs. Site 12 in the western Cascades of central Oregon was monitored at 3-week intervals during the winter of 1977 in order to ascertain movement response to individual storm events. Such response was not detectable with the inclinometer system at this site during the monitored period, although stake arrays at the surface do pick up movement at a daily and weekly resolution.

Twelve of the 14 sites were designated for eventual timber harvest. Two, sites 9 and 14, have been felled and yarded allowing for some initial comparisons of movement rate before and after management impact. Only one, site 9 in the Klamath Mountains of southwest Oregon, has been monitored long enough during the post-logging period to indicate any movement trends. Preliminary analysis of data from the four tube locations at the site indicates an increase in creep rate beginning the 2d year after felling (Figure 5). Monitoring of all the tube locations began the winter of 1974 and the summer of 1975. The site was logged during the fall of 1976, and movement continued at the pre-logging rate until the winter of 1977 and summer of 1978 when movement surges occurred.

Three inclinometer tube locations
and tractor skidding. The fourth
in the middle of the site. The l
its perimeter. Pre-logging surfac
locations were 2.8 mm/year (standa
(standard error = 4.2 mm/yr.), and
yr.) in a downslope direction from
(about 15 meters from the ridge to
5.7 mm/year (standard error = 4.3
= 6.9 mm/yr.), and 6.3 mm/year (st
high standard error of estimate in
of movement occurring in the 2nd ye
period. The post-logging rates for
are more than twice the pre-logging
lower tube location is more than 4
undisturbed tube location, movement
(1975) was 1.2 mm. Movement was ne
1976 and 1977. A small surge of 4.
1978 coincidental with the movement
suggesting that this control tube h
harvest activity around it.

A comparison of annual rainfal
station (Powers, Oregon) (NOAA, 197
the site indicates below average ra
occurring in the area during the 2
accelerated movement (804.9 mm and
absence of any indicated above-norma
suggests a direct link between accel

Three inclinometer tube locations were directly impacted by both felling and tractor skidding. The fourth remained undisturbed in a leave area in the middle of the site. The leave area was logged entirely around its perimeter. Pre-logging surface rates for the three disturbed tube locations were 2.8 mm/year (standard error = 0.2 mm/yr.), 3.8 mm/year (standard error = 4.2 mm/yr.), and 1.5 mm/year (standard error = 2.2 mm/yr.) in a downslope direction from the upper edge of active ground (about 15 meters from the ridge top). Post logging rates are respectively 5.7 mm/year (standard error = 4.3 mm/yr.), 9.3 mm/year (standard error = 6.9 mm/yr.), and 6.3 mm/year (standard error = 6.7 mm/yr.). The high standard error of estimate in all cases is due to the predominance of movement occurring in the 2nd year of both the pre- and post-logging period. The post-logging rates for the upper and middle tube locations are more than twice the pre-logging rate. The post-logging rate at the lower tube location is more than 4 times the pre-logging rate. At the undisturbed tube location, movement during the year preceding logging (1975) was 1.2 mm. Movement was negligible (less than 0.2 mm) during 1976 and 1977. A small surge of 4.3 mm occurred during the summer of 1978 coincidental with the movement acceleration in the other holes suggesting that this control tube has also been influenced by the harvest activity around it.

A comparison of annual rainfall records from the nearest weather station (Powers, Oregon) (NOAA, 1976, 1977) with movement activity at the site indicates below average rainfall (29-year average, 1 565.2 mm), occurring in the area during the 2 years (1976 and 1977) preceding accelerated movement (804.9 mm and 1 406.4 mm, respectively). In the absence of any indicated above-normal moisture at the site, this strongly suggests a direct link between accelerated movement and harvest activity.

SUMMARY

Creep and earthflow processes are significant factors in the transport of mantle materials downslope within the complex mass movement terrain characteristic of large portions of the Coast and Cascade Ranges of northern California, Oregon, and Washington.

Movement is highly variable in quantity and timing with movement strongly dependent on type of parent material and water content of the materials in the active zone. Rates are most sensitive to water content of the parent materials with the majority of monitored sites showing a predominance of movement during the fall and winter rainy season.

Preliminary assessment of data from one site directly impacted by felling and yarding suggests an increase in creep rate beginning the second year after disturbance.

REFERENCES CITED

Bjerrum, L. (1967) Progressive failure in slopes of over consolidated plastic clay and clay shales. Am. Soc. Civil Eng. Proc., J. Soil Mech. and Found Div., v. 93, pp. 1-49; illus.

Beaulieu, J.D. (1971) Geologic formations of western Oregon. Oregon Dep. Geol. and Min. Ind. Bull. 70, 70 p., illus.

Burroughs, E.R. and B.R. Thomas (1977) Declining root strength in Douglas fir after felling as a factor in slope stability. USDA For. Serv. Res. Pap. INT 190, 27 p., illus.

Carson, M.A. and M.K. Kirkby (1972) Hillslope form and process: Cambridge Press, London, 475 p., illus.

Culling, W.E.H. (1963) Soil creep and the development of hillside slopes. J. Geol., vol. 71, pp. 127-161, illus.

Goldstein, M. and G. Ter-Stepanian (1957) The long-term strength of clays and deep creep of soils. Fourth Intern. Conf. Soil Mech. and Found. Eng. Proc., vol. 2, pp. 311-314, illus.

Gray, D.H. (1970) Effects of fo
natural slopes. Assoc. En
illus.

Haefeli, R. (1965) Creep and p
and ice. Sixth Intern. C
vol. 3, pp. 134-148.

Jones, F.O., D.R. Embody and W
Columbia River Valley, no
Prof. Pap. 267, 98 p., il

Kays, M. (1970) Western Cascad
region, Oregon. Oregon D
vol. 32, pp. 81-94.

Kojan, E. (1968) Mechanics and
Sess., Intern. Assoc. Eng

National Oceanic and Atmospher
Climatological Data, Oreg

National Oceanic and Atmospher
of Climatological Data, (

Peck, D.L., A.A. Griggs, H.G.
H.M. Dole (1964) Geology
western Cascades Range i
56 p., illus.

Rothacher, J. (1971) Regimes
logging. In Forest Land
State Univ., Corvallis,

Saito, M. and H. Uezawa (1961
International Conf. Soil
315-318, illus.

Gray, D.H. (1970) Effects of forest clearcutting on the stability of natural slopes. Assoc. Eng. Geol. Bull., vol. 7, pp. 45-67, illus.

Haefeli, R. (1965) Creep and progressive failure in snow, soil, rock and ice. Sixth Intern. Conf. Soil Mech. and Found. Eng. Proc., vol. 3, pp. 134-148.

Jones, F.O., D.R. Embody and W.L. Peterson (1961) Landslides along the Columbia River Valley, northeastern Oregon. U.S. Geol. Surv. Prof. Pap. 267, 98 p., illus.

Kays, M. (1970) Western Cascades volcanic series, South Umpqua Falls region, Oregon. Oregon Dept. Geol. and Min. Industries, Ore Bin, vol. 32, pp. 81-94.

Kojan, E. (1968) Mechanics and rates of natural soil creep. Proc. 1st Sess., Intern. Assoc. Eng. Geol., Prague, pp. 122-154.

National Oceanic and Atmospheric Administration (1976) Annu. Summ. of Climatological Data, Oregon. Vol. 82, No. 13, p. 5.

National Oceanic and Atmospheric Administration (1977) Annu. Summ. of Climatological Data, Oregon. Vol. 83, No. 13, p. 5.

Peck, D.L., A.A. Griggs, H.G. Schlicker, F.G. Wells and H.M. Dole (1964) Geology of the central and northern parts of the western Cascades Range in Oregon. U.S. Geol. Surv. Prof. Pap. 449, 56 p., illus.

Rothacher, J. (1971) Regimes of streamflow and their modification by logging. In Forest Land uses and the Stream Environment, Oregon State Univ., Corvallis, Ore. pp. 40-54.

Saito, M. and H. Uezawa (1961) Failure of soil due to creep. Fifth International Conf. Soil Mech. and Found. Eng. Proc., vol. 1, pp. 315-318, illus.

Schlicker, H.G., R.J. Deacon, J.D. Beaulieu and G.W. Olcott (1972) Environmental geology of the coastal region of Tillamook and Clatsop Counties, Oregon. Oregon Dept. Geol. and Min. Ind. Bull., 74, 164 p., illus.

Schlicker, H.G., R.J. Deacon, G.W. Olcott and J.D. Beaulieu (1973) Environmental geology of Lincoln County, Oregon. Oregon Dept. of Geol. and Min. Ind. Bull., 84, 116 p., illus.

Schuster, R.L., and R.J. Krizek (1978) Landslides, Analysis and Control. Natl. Res. Counc., Transp. Res. Board Special Report 176, 234 p., illus.

Strand, R.G. (1962) Geologic map of California. Olaf P. Jenkins Edition, Weed Sheet. California Div. Mines and Geol., 1 sheet, 1:250,000.

Swanson, F.J. and M.E. James (1975) Geology and geomorphology of the H.J. Andrews Experimental Forest, Western Cascades, Oregon. USDA For. Serv. Res. Pap., PNW-188, 14 p., illus.

Swanson, F.J. and D.N. Swanston (1977) Complex mass-movement terrains in the western Cascade Range, Oregon. In Landslides. Geol. Soc. Am. Rev. in Eng. Geol., vol. III, pp. 113-127, illus.

Swanston, D.N. (1979) Effect of geology on soil mass movement activity in the Pacific Northwest. In Forest Soils and Land Use. Proc. of the 5th North American Forest Soils Conf. Colorado State Univ., Fort Collins Colorado August 1978, pp. 89-116, illus.

Swanston, D.N. and F.J. Swanson (1976) Timber harvesting, mass erosion and steepland forest geomorphology in the Pacific Northwest. In Geomorphology and Engineering, pp. 199-221, illus. D.R. Coates, ed., Dowden, Hutchinson and Ross, Inc., Stroudsburg, Pa.

Terzaghi, K. (1953) Some miscellaneous notes on creep. Proceedings 3rd Intern. Conf. on Soil Mech. and Found. Eng., vol. 3, pp. 205-206.

Wilson, S.D. (1970) Observation

slope instability. J. Soi

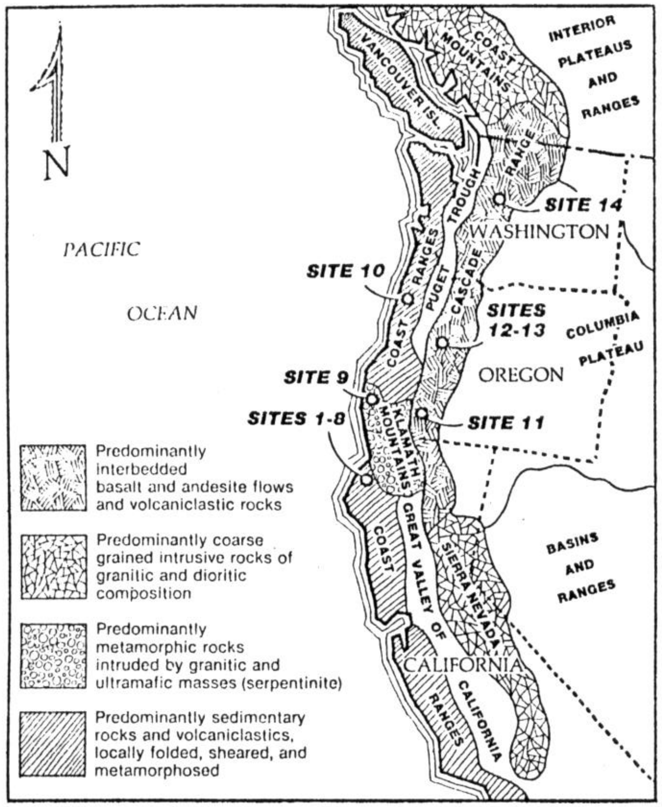
Eng. Proc., vol. 96, pp. 1

Wu, T.H., W.P. McKinnell III an

Prince of Wales Island, Al

Wilson, S.D. (1970) Observational data on ground movements related to slope instability. J. Soil Mech. and Found. Div., Am. Soc. Civil Eng. Proc., vol. 96, pp. 1521-1544, illus.

Wu, T.H., W.P. McKinnell III and D.N. Swanston (1979) Landslides on Prince of Wales Island, Alaska. Canadian Geotech. J., v. 16.



IGURE 1. Regional map of the Pacific Northwest, USA, showing major physiographic units, dominant rock types, and creep and earhtflow monitoring-site locations.

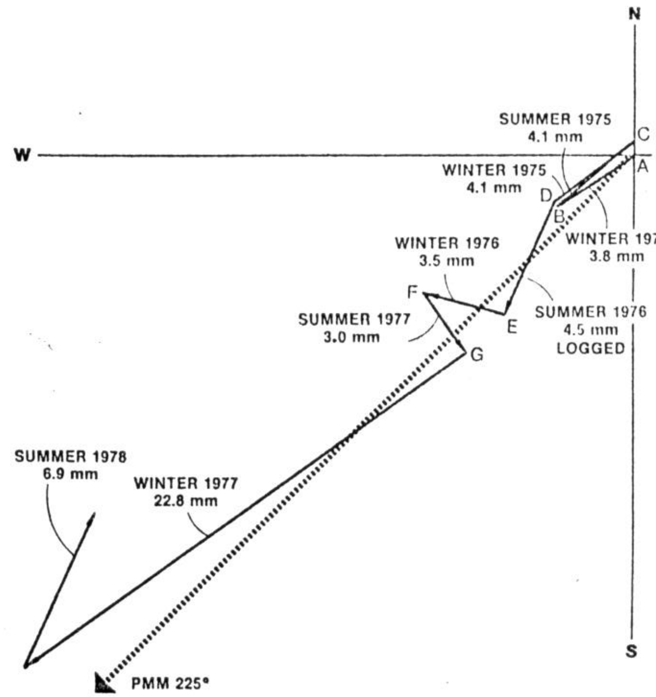


FIGURE 2. A plot of the surface movement of hole B-2, site 9, in the Klamath Mountains of southwest Oregon showing the variability in distance and direction between successive seasonal readings. The plane of maximum movement is determined by the direction of maximum extension of the plotted points.

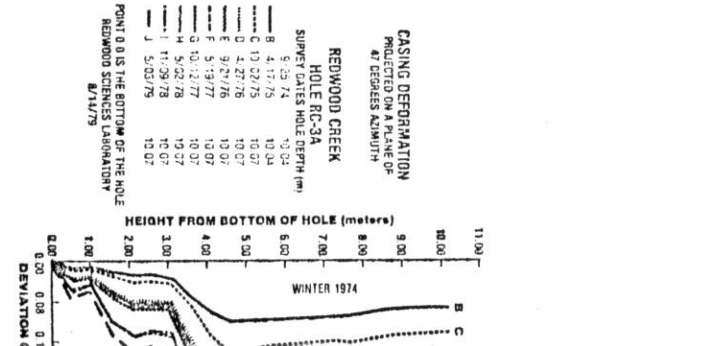


FIGURE 3. A plot of casing c
RC-3A, site 3, Rec
Ranges is pervasiv
the Franciscan mel
movement taking pl
shear extending fr
Predominant moveme

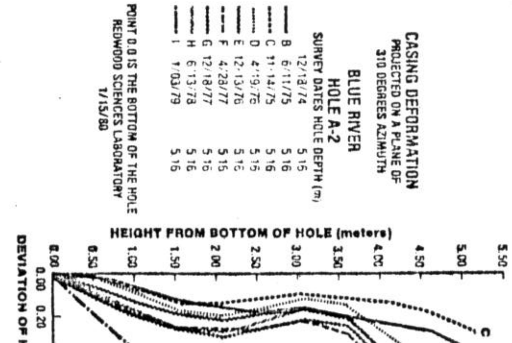


FIGURE 4. A plot of casing
A-2, site 12, in
Oregon. Bedrock
the Little Butte
minor movement un
is progressive wi
some extension fl

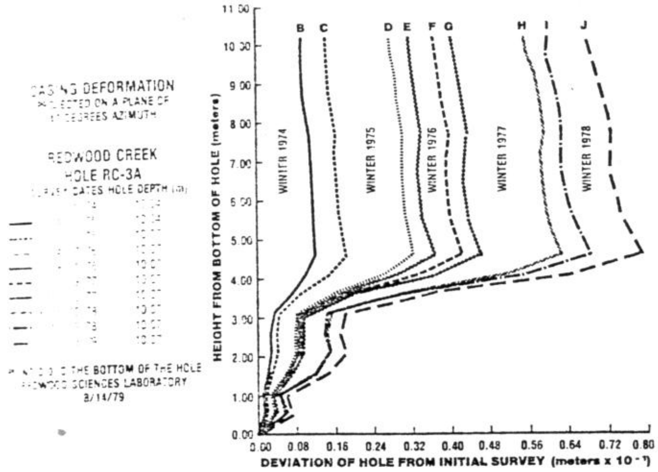


FIGURE 3. A plot of casing deformation over a 5-year period for hole RC-3A, site 3, Redwood Creek northern California Coast Ranges is pervasively sheared sandstone and siltstone of the Franciscan melange. This is an earthflow site with movement taking place as block-gliding above a zone of shear extending from about 5.5 to 7 metres in depth. Predominant movement is during the winter rainy season.

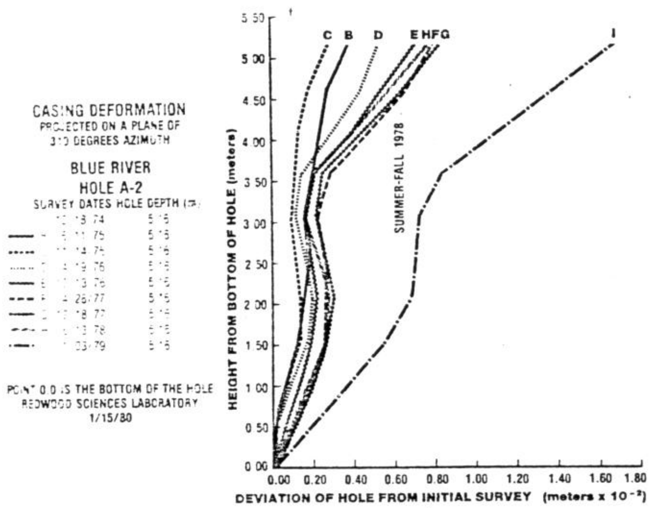


FIGURE 4. A plot of casing deformation over a 5-year period for hole A-2, site 12, in the western Cascade Range of west-central Oregon. Bedrock is deeply weathered tuffs and breccias of the Little Butte series. This is a creeping site exhibiting minor movement until the summer and fall of 1978. Movement is progressive with greatest movement at the surface, but some extension flow is occurring below 1.70 metres.

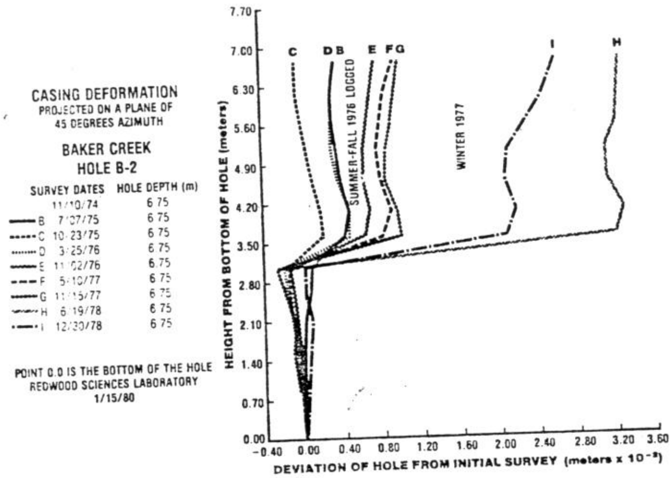


FIGURE 5. A plot of casing deformation over a 4-year period for hole B-2, site 9, in the Klamath Mountains of southwest Oregon. Bedrock is sheared and altered greywacke with subordinant argillite and mudstone of the Otter Point Formation. Movement is of the block-glide type above a shear zone between 3.2 and 3.7 metres. Movement is minor through the summer of 1977. A movement surge occurred during the winter of 1977. The area was logged in the fall of 1976.

Erosion and Sediment
Steeplands. I.A.H.S. Pu

Lithologic and weatheri
process, eastern Raukum

A.J. Pearce and R.D. Bl
P O Box 31-011, Christc
C.S. Nelson, Department
University, Hamilton, N

Abstract. Slope forms and i
reflect the lithologic chara
Tertiary sedimentary rocks.
other minerals, and the pres
to be important in determin
consolidated shales and mar
Localised leaching of carbo
pyrite appears to be an imp
isolated complex failures i
clay fraction is dominated

Les influences de l'effet
et les processus de pentes,

Résumé. On trouve que les
inférés, réflettent de pro
trois groupes de rochers C
argiles, les proportions d
présence ou l'absence du c
en déterminant la forme et