THE UNIVERSITY OF MICHIGAN
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Interim Report

EFFECTS OF FOREST CLEAR-CUTTING ON THE STABILITY OF NATURAL SLOPES: RESULTS OF FIELD STUDIES

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DRDA Project 002790

supported by:

NATIONAL SCIENCE FOUNDATION
GRANT NO. GK-24747
WASHINGTON, D.C.

administered through:

DIVISION OF RESEARCH DEVELOPMENT AND ADMINISTRATION ANN ARBOR

August 1973

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ABSTRACT

Evidence for a cause and effect relationship between clear-cutting and mass-soil movement is reviewed. Previous reports (Gray, 1969 and 1970) have focused on the background and theoretical aspects of the problems. The present report, on the other hand, describes the results of field studies being conducted at three separate locations in the Western United States. The sites in question are situated in the H. J. Andrews Experimental Forest, Central Oregon; Klamath National Forest, Northern California; and the U. S. Naval Radio Station, near Arlington, Washington. Slopes have been instrumented there in order to obtain quantitative data on soil mantle creep rates and soil moisture stress before and after clear-cutting.

Critical, post clear-cutting data is still lacking from two of the sites at time of writing. Nevertheless, sufficient data is available from both this and other recent studies to permit drawing some general conclusions.

Trees enhance the strength and stability of soil on steep slopes mainly through machanical reinforcement by the root system and through soil moisture depletion by transpiration. Conversely, removal or cutting of trees on steep slopes can lead to accelerated creep rates and increased mass wasting. Direct evidence from the present study for this conclusion includes (1) higher creep rates in the soil around an inclinometer buried in the midst of an area of dead trees relative to creep movement in surrounding soil beneath live trees, (2) generally higher creep rates in a cutover slope in Oregon compared to creep rates in a nearby forested slope, and (3) generally much wetter conditions in cut-over slopes relative to soils in forested slopes.

In addition to these observations, it was found that creep rate in a cutover slope in Oregon was strongly correlated with precipitation. The same did not hold true for forested sites in the same area. With the exception of an active slide instrumented in California, creep rates for all slopes investigated averaged less than one tenth of an inch per year.

ABSTRACT (Concluded)

Stability analyses showed that surcharge due to weight of trees had a beneficial effect on stability, particularly when critical, saturated conditions develop in a slope.

I. INTRODUCTION

The practice of clear-cutting, a timber harvesting procedure, has led to considerable controversy in recent years. This issue became the focus of hearings on management practices in national timberlands held by the U.S. Senate Committee on Interior and Insular Affairs in Washington, D.C, during April of 1971. The record of these hearings (U.S. Senate Subcommittee on Public Lands, 1971) provides a wealth of information on this controversial subject.

The objective of the study described herein is to examine only one facet of the clear-cutting controversy, viz., its impact on the stability of natural slopes. By stability it is meant the subsurface stability of slopes (e.g., slumps, landslides, earth flows, etc.) as opposed to problems of surface erosion.

The study in question was initiated in the summer of 1968; well before the practice of clear-cutting came under intense public debate. Background information and analysis of the impact of clear-cutting on the stability of slopes was publised in earlier reports by Gray (1969, 1970). A fairly detailed literature survey, theoretical discussion, and description of field research methods can be found in these earlier publications. In addition to field studies a laboratory, hydrologic investigation into the effects of vegetation removal was also undertaken. This latter study was carried out with a tilting soil bin simulating natural slopes at The University of Michigan Botanical Gardens. Results of this investigation were reported by

Gray and Brenner (1970).

The purpose of the present report is to discuss and analyze the results of field studies carried out at three separate sites in the Pacific Northwest. The sites in question are located in Northern California, Central Oregon, and Northwest Washington. All of these sites had prior records of slope instability of one form or another. Slopes were instrumented at these sites in order to monitor changes in downslope movement (or creep rate) and soil moisture stress following clear-cutting. Both these factors are important parameters or indicators of slope stability.

Post clear-cutting data is still lacking at two of the sites which makes conclusions drawn from the study tentative in some cases. On the other hand, there is "side-by-side" data comparing the behavior of forested with nearby cutover slopes from sites in Oregon and Washington. This fact along with some other interesting results of the field study make a progress report appropriate at this time.

II. REVIEW OF PAST WORK

A. BACKGROUND INFORMATION

The purpose of this literature survey is to cite principally those publications which (1) have appeared since the last progress report (Gray, 1969), and (2) have an important bearing on the field research itself.

As noted previously the practice of clear-cutting for various reasons has come under intense public criticism (Burk, 1970; Carter, 1970; Bolle, 1970). Upon opening the Senate hearings (U.S. Senate Subcommittee on Public Lands, 1971) the Committee Chairman, Senator Frank Chruch declared, "We are here primarily to look into what has become one of the most controversial questions ever to involve our national timberlands—the practice of clear-cutting."

Igniting the controversy over clear-cutting were separate investigations into logging in the Bitterroot National Forest in Montana (Bolle _et_ _al_., 1970) and the Monongahela National Forest in West Virginia. Both studies emphasized the prevalence of abusive practices revolving around clear-cutting. Logging practices of the kind criticized in the Bitterroot and Monongahela studies are apparently also common on private timberlands. For instance, even progressive forest products companies sometimes clear-cut an entire section of 640 acres or 1 square mile (Carter, 1970).

Clear-cutting, it should be pointed out, is a silvicultural or harvesting procedure in which all timber over a certain minimum diameter is felled and removed. This method is normally employed in Douglas fir and redwood harvesting in the Western states. While no forester would equate clear-cutting with deforestation; the two are virtually synonymous when clear-cutting is carried out in mature, even age stands of timber. Evidence of this fact is visible in many clear-cut sites in Washington, Oregon, and California. Figure 1 is a photograph of only one of several clear-cut sites observed by the author—illustrating complete denudation.

B. EFFECT OF LOGGING OPERATIONS ON THE STABILITY OF SLOPES

As noted earlier by Gray (1969, 1970) there has been little information published in scientific or engineering journals on the effect of logging operations on the stability of slopes. What little information is available has been published in fugitive sources or agency publications of limited circulation. A fair amount of useful information can be found in research notes published by the U.S. Forest Service. Of particular interest in this regard is a study conducted by Bishop and Stevens (1964) on landslides in logged areas in southeast Alaska.

Bishop and Stevens noted a significant increase in both frequency of slides and the size of area affected by slides after logging. They attributed the destruction of interconnected root systems by gradual decay as a principal cause of sliding. This study and others like it have been reviewed in detail by Gray (1969).

More recent studies (Bailey, 1971; Rice and Krammes, 1970) also show a cause and effect relationship between logging and slope instability. Mass movements on steep slopes with unstable soils will be particularly sensitive to disturbances by man such as road building, timber harvesting, and vegetation

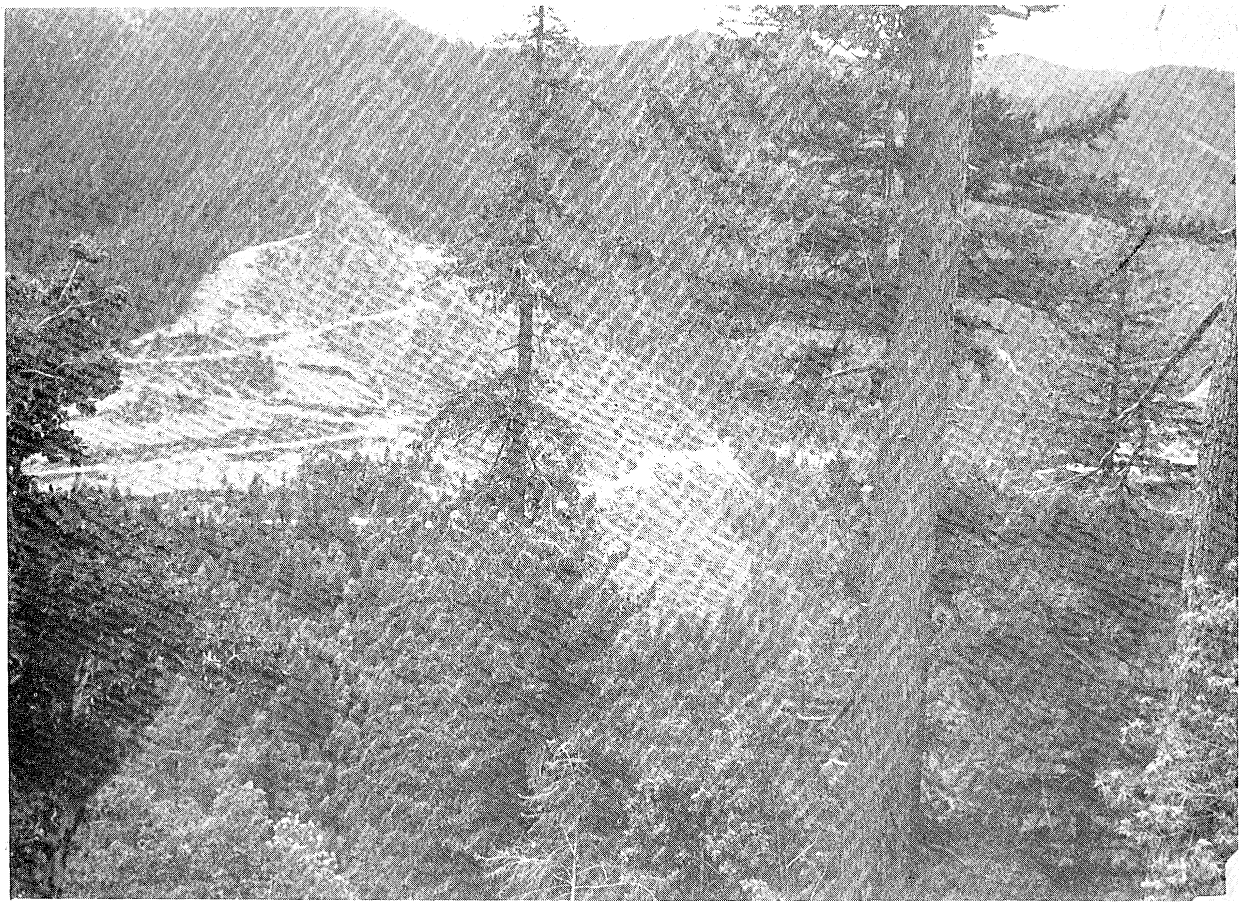


Figure 1. View of clear-cut site, Happy Camp Ranger District, Klamath National Forest.

manipulation. Many investigators (Dyrness, 1967; Gonsior and Gardner, 1971; and USDA, 1971) conclude that road building associated with logging plays the dominant role in slope stability problems. These same investigators concede, however, that timber harvesting *per se* on steep slopes, with subsequent destruction of stabilizing root systems can contribute to occurrence of shallow landslides.

The effect of vegetation manipulations or conversion of brush to grass cover has been studied by Bailey and Rice (1969) and Rice *et al.* (1969). Their study was conducted in the San Dimas Experimental Station in the San Gabriel Mountains of Southern California. They noted that the occurrence of slips was inversely related to the size and density of the slope vegetation. Conversion from brush to grass resulted in a sevenfold increase in shallow soil slips during the storms of November and December 1965. This amounted to an additional 135 m^3 of displaced soil per hectare of watershed.

C. EFFECT OF PLANT ROOTS ON SOIL SHEAR STRENGTH

A critical factor in the effect of clear-cutting on the stability of slopes is the role of plant roots on soil shear strength. Shear strength is the parameter which controls the resistance of a soil to sliding; the weaker a soil the more susceptible it will be to sliding.

Gray (1970) has outlined four ways vegetation is likely to affect the stability of slopes, viz.,

1. By mechanical reinforcement from roots
2. By soil moisture depletion resulting from transpiration
3. By surcharge from the weight of the trees
4. By wind throwing and root wedging.

The first two factors tend to increase shear strength and stability, the second has a neutral to stabilizing effect (even though this may seen counterintuitive at first glance), and the last has a destabilizing influence. Recent studies bearing on the significance and importance of the first two factors will be discussed next.

Endo and Tsuruta (1969) determined the reinforcing effect of tree roots on soil shear strength by running large scale direct shear tests on soil pedestals containing live tree roots. A schematic diagram of their test procedure is shown in Figure 2. The shear strength of the soil tested was found to increase directly with the bulk weight of roots per unit volume of soil. An empirical relation of the following form was obtained.

$$\Delta S_R = a(R+b) \tag{1}$$

where ΔS_R = increase in shearing strength

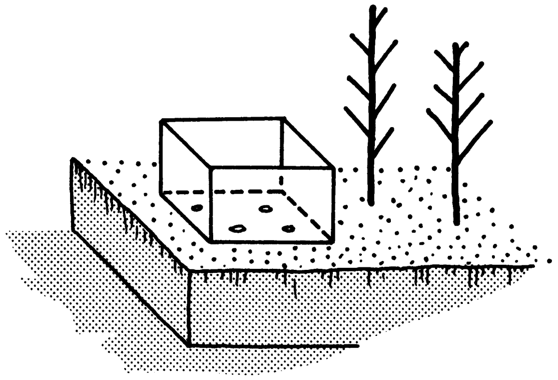
R = root density

a and b = empirical constants

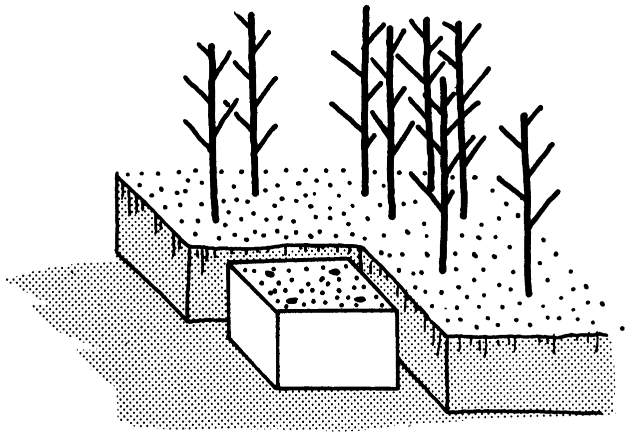
The shear strength at any depth in a soil layer with roots can be found by adding the shear strength increase ΔS_R to the usual Coulomb expression for shear strength. This leads to the following equations:

$$S = C + \sigma \tan \phi \tag{2}$$

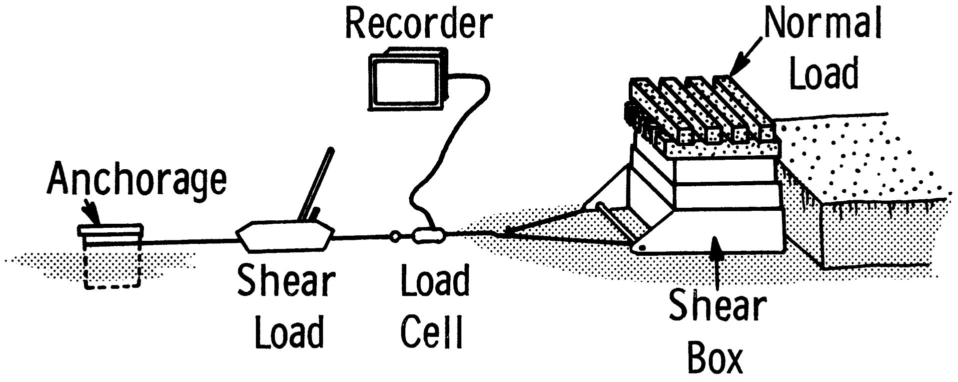
$$C = \alpha + \beta R \tag{3}$$



A. Soil Pedestal Guide Box in Place



B. Soil Pedestal Excavated and Exposed



C. Shear Box Emplaced Over Pedestal in Preparation for Test

Figure 2. Schematic diagram of in situ shear tests on soil pedestals containing plant roots (after Endo and Tsuruta, 1969).

where S = total shear strength, kg/cm^2

σ = normal stress, kg/cm^2

ϕ = angle of internal friction of the soil

C = a modified cohesion intercept to account for root reinforcement

α and β = empirical constants

Calculations from data on 49 different plots showed that $\alpha = 102$ kg/cm^2, $\beta = 0.094$, and $\phi = 33°$. The percent increase in shear strength can be found by dividing Equation (1) by (2) with $R = 0$ in the latter. This yields the following expression:

$$\% \text{ increase} = \frac{\Delta S_R}{S_{R=0}} \times 100 \qquad (4)$$

Equation (4) is shown plotted in Figure 3 for various values of R and σ. The curves show that root reinforcement is especially significant at low normal stresses or for shallow soil layers.

Manbeian (1973) likewise investigated the effect of plant roots on the shear strength of soil. He used a direct shear machine for this purpose which could accommodate large diameter soil samples containing roots of living plants. A photograph of his test setup is shown in Figure 4. A cohesive, slide susceptible soil (Los Osos silty clay loam) was used in his study.

Only the effects of herbaceous plant roots (alfalfa, barley, and sunflower) were investigated. Manbeian's results showed that both peak and residual shear strength were generally increased by as much as 2 to 4 times, respectively, in soil specimens containing roots. Typical results are shown in Table 1 and Figure 5. Strength increases reported by Manbeian in this case

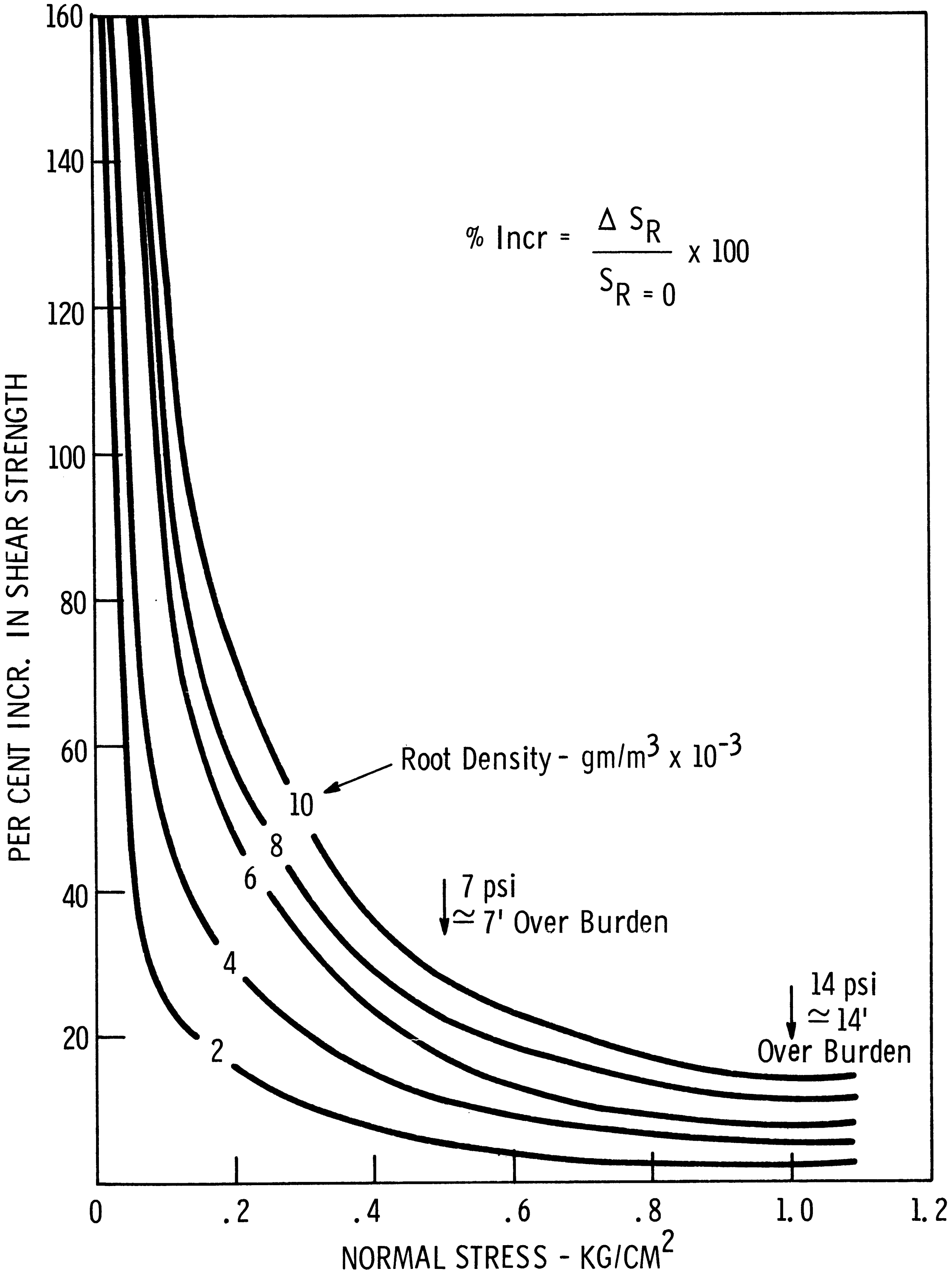


Figure 3. Increase in shear strength as a function of root density and normal stress (after Endo and Tsuruta, 1969).

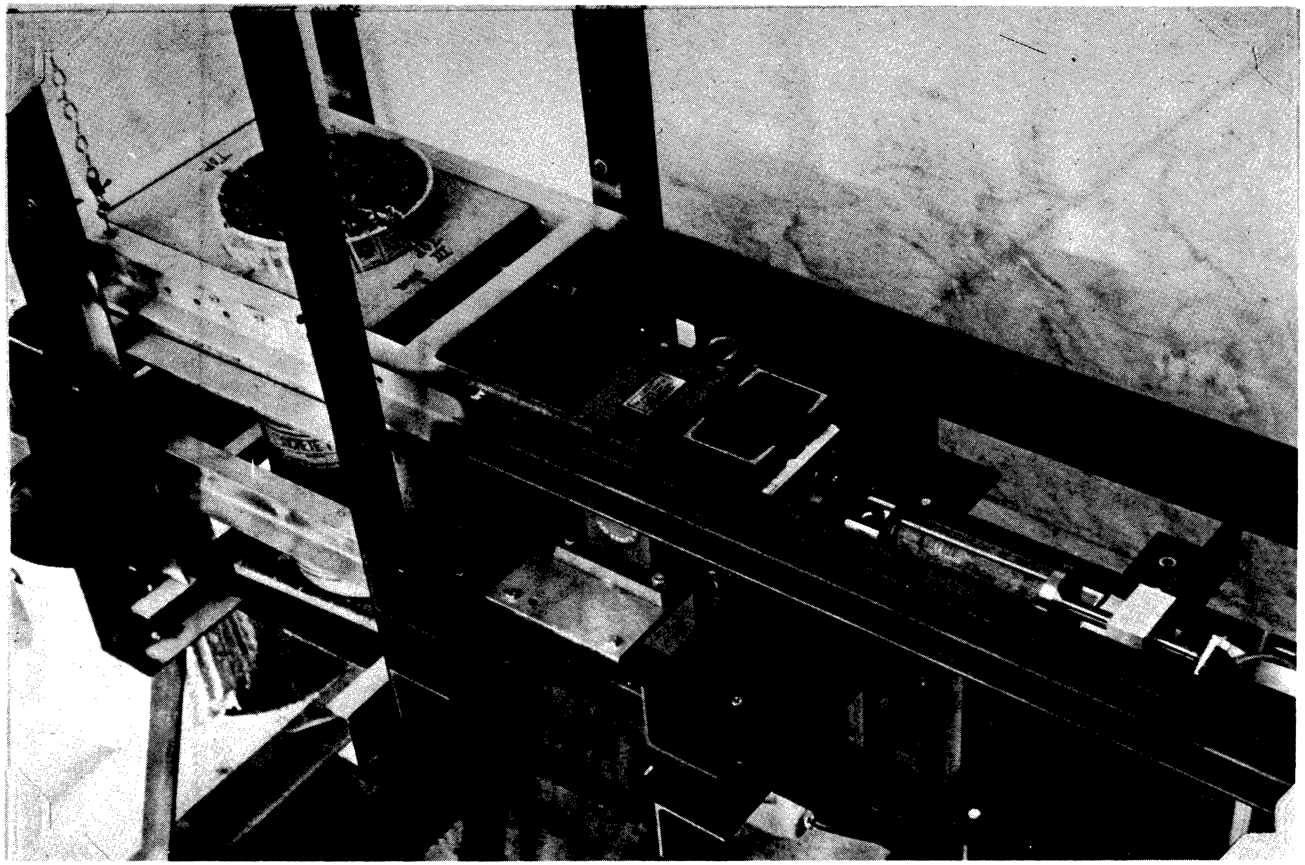


Figure 4. View of soil column containing plant roots being tested in direct shear (after Manbeian, 1973).

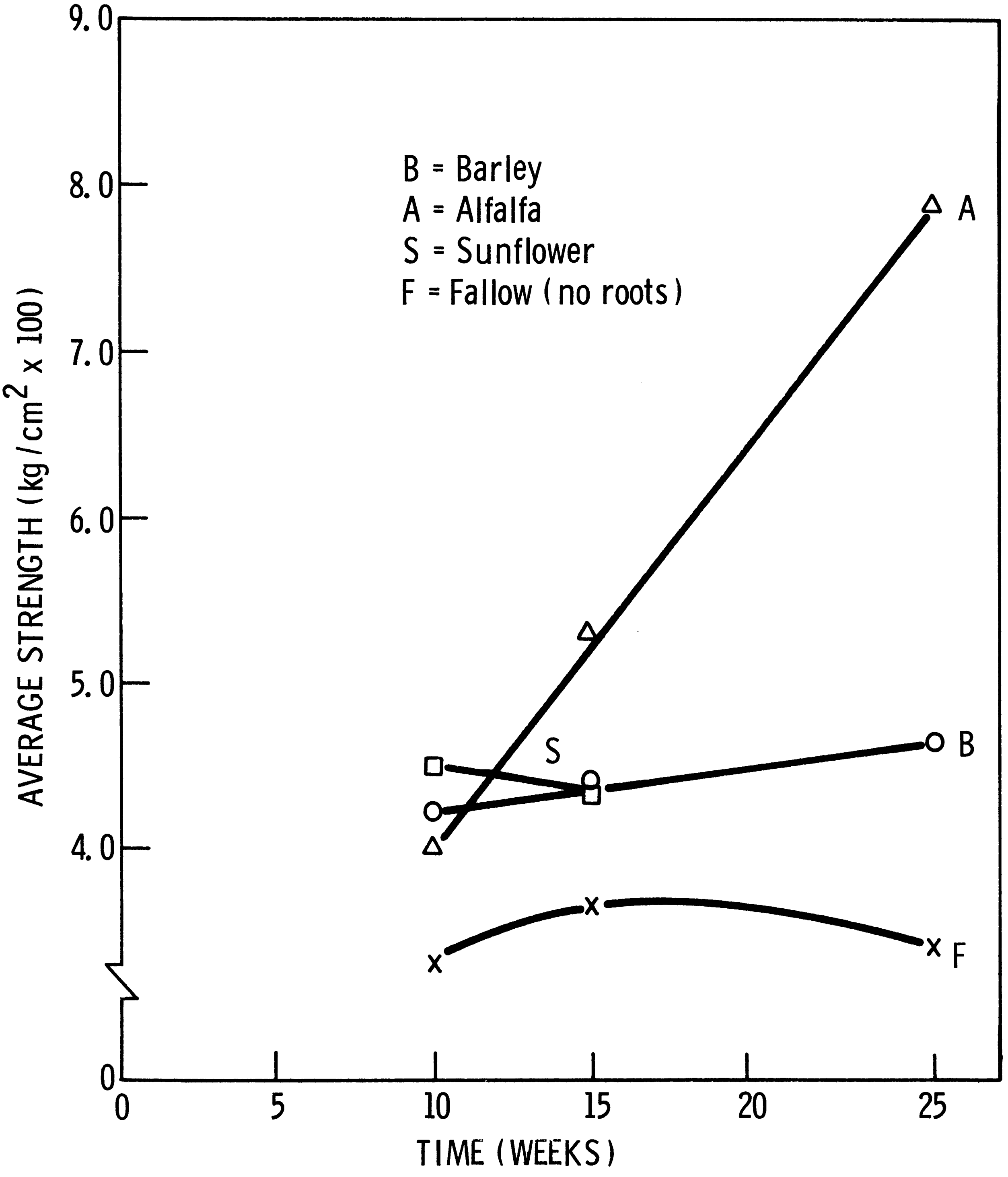


Figure 5. Variation of peak strength with time at 6-inch depth for soil containing roots of various plants (after Manbeian, 1973).

TABLE 1

PERCENT CONTRIBUTION OF ROOTS TO SHEAR STRENGTH FOR SOIL REINFORCED WITH GROWING PLANT ROOTS

(After Manbeian, 1973)

Plant Type	6-Inch Depth			12-Inch Depth			18-Inch Depth		
	10 Weeks	15 Weeks	26 Weeks	10 Weeks	15 Weeks	26 Weeks	10 Weeks	15 Weeks	26 Weeks
Peak Shear Strength									
Barley	128	120	137	128	100	100	106	---	108
Alfalfa	122	139	232	100	100	117	100	100	124
Sunflower	136	120	---	100	102	---	100	114	---
Residual Shear Strength									
Barley	186	125.6	181	164	147	122	191	138	121
Alfalfa	171	243	437	0	119	180	108	105	141
Sunflower	138	120	---	0	0	---	106	138	---

are for mechanical reinforcement alone; any strength increase attributable to soil suction was eliminated by saturating the samples just prior to shearing.

Manbeian concluded from his tests that the degree of contribution of roots to strength is a function of combined effects of root density, size, root tensile strength, root morphology, and plant type. Duration of the contribution was dependent on whether plants were perennial or annual, and on the rate of root decay. The author did not attempt, however, to delineate these functional relationships nor did he carry out any tests with woody plants, i.e., shrubs or trees.

Several investigators have looked into the role and effectiveness of tree roots in stabilizing soil on steep slopes and the time required for root decay to cause instability (Bishop and Stevens, 1964; Swanston, 1969; Swanston and Walkotten, 1970; and Rice and Krammes, 1970). These investigators credit tree roots with increasing the stability of soil mantles on steep slopes to varying extent. The reinforcing effect is believed to be more significant in the case of shallow soils (Rice and Krammes, 1970) and in cases where roots penetrate the soil profile into joints and fractures in bedrock (Swanston, 1969). Swanston actually excavated tree stumps hydraulically in order to determine the distribution of tree roots in a slope.

To the extent that live tree roots provide reinforcement; conversely, dead roots will cause loss of strength and resulting instability. Bishop and Stevens (1964) and Swanston and Walkotten (1970) conclude that the effectiveness of rooting as a factor in soil shear strength decreases with age and that soils on oversteepened slopes reach their minimum effective strength due to root anchorage approximately five years after cutting. This conclusion is based on observations of slopes supporting old growth Sitka spruce—western hemlock stands of timber.

Rice and Krammes (1970) suggest a more slowly deteriorating site (with respect to landslides) following logging. Their view is supported by observations of logged areas in the north coast of California. The authors present interesting photographic evidence of site deterioration commencing and accelerating some fifteen years after logging.

D. HYDROLOGIC INFLUENCE OF VEGETATION ON STABILITY

It is well established that high precipitation and storm activity are strongly correlated with landsliding and other mass-wasting events in steep slopes (Fredriksen, 1965; Flaccus, 1959; and Swanston, 1969). The influence of precipitation on landslide occurrence derives from its relation to ground water movement and soil moisture stress (Swanston, 1967; Bailey and Rice, 1969; Gray, 1970; and Gray and Brenner, 1970).

It is also well established that trees deplete soil moisture through transpiration (Bethlahmy, 1962; Patric _et al._, 1968; Gray and Brenner, 1970). Figure 6 is a photograph of a tilting soil bin used to study the hydrologic influence of vegetation in the study reported by Gray and Brenner (1970). A comparison of soil moisture response of this model slope in a cutover and vegetated condition, respectively, is shown in Figure 7. Soil moisture depletion by transpiration thus leads to high suctions which in turn improves shear strength and stability. Manbeian (1973), for example, has investigated the effects of soil suction on shear strength and shown this to be the case.

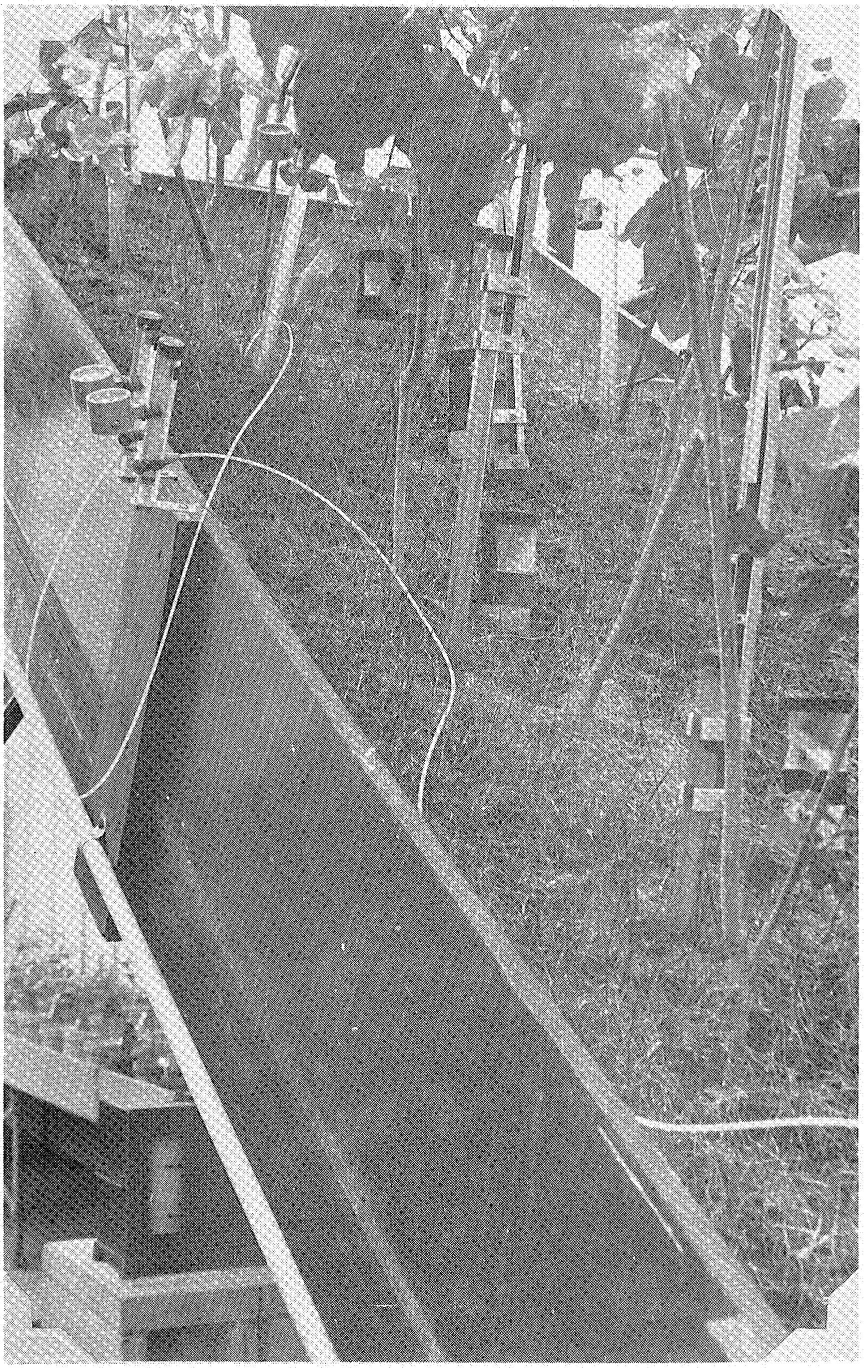


Figure 6. View of tilting soil bin used in experimental hydrologic study (after Gray and Brenner, 1970).

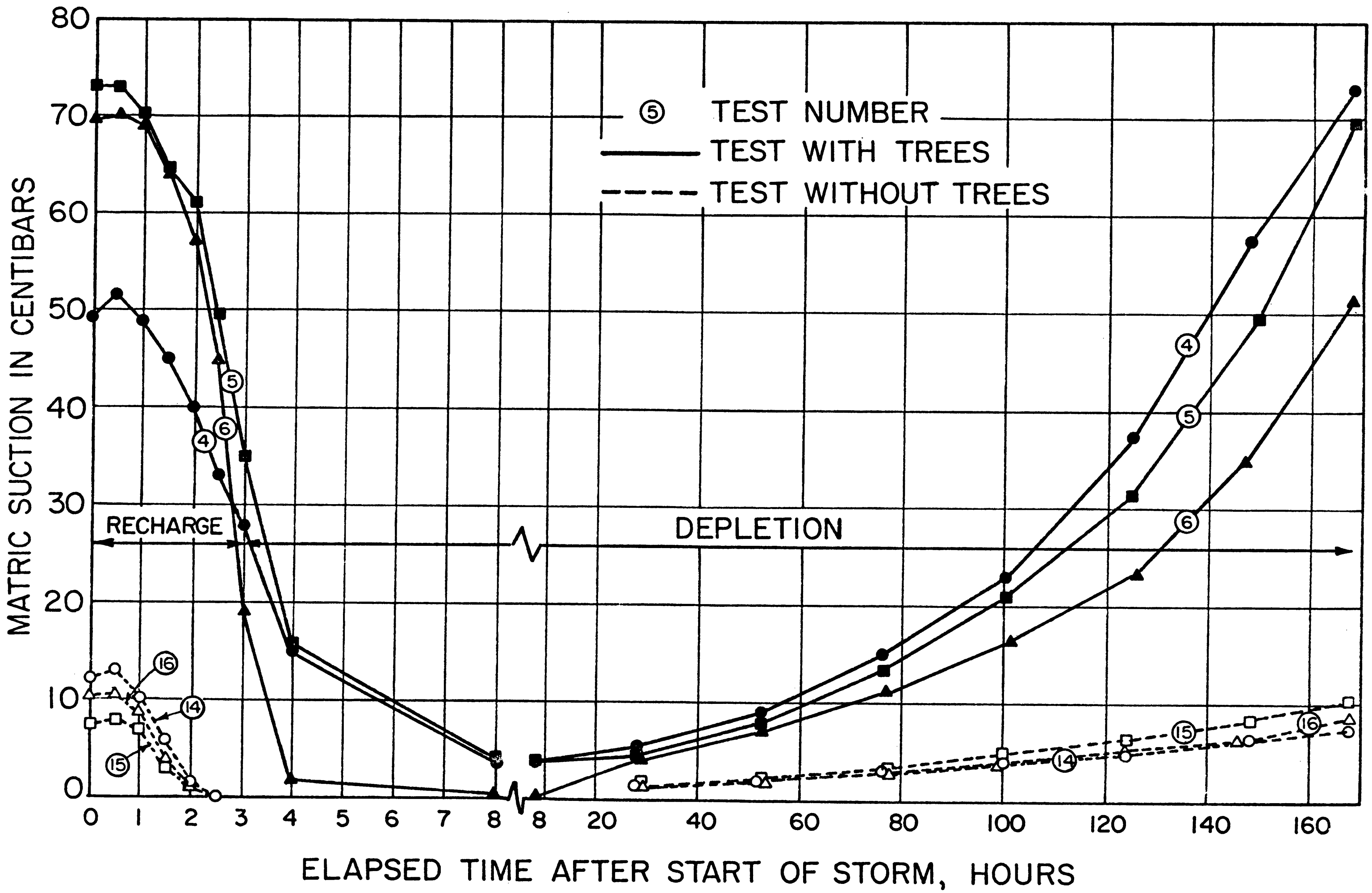


Figure 7. Soil moisture suction response of a model slope with and without tree cover (from Gray and Brenner, 1970).

The role of <u>transpiring</u>* vegetation in preventing landslides in actual practice has been subject to differing interpretations. Gray (1970) argued that forested slopes which tend to be drier may be able to tolerate a storm of greater intensity or duration before a critical, saturated condition develops. Rice and Krammes (1970) maintain that the importance of the role that transpiring vegetation plays in the occurrence of landslides depends upon climate. They believe that this contribution is probably negligible in climates where precipitation greatly exceeds potential evapo-transpiration. On the other hand, in more arid climates, where substantial moisture deficits develop each summer, differential use of water by different types of plant cover may significantly affect the occurrence of landslides.

Bailey (1971) provides some interesting insights in regard to the hydrologic influence of vegetation on stability. From geologic evidence he concludes that landsliding in mountainous terrain of northwest Wyoming was particularly active during Pleistocene glacial stages when lower temperatures and increased precipitation provided more ground moisture for increased pore pressures. Climatic interpretation allows an average 10-inch increase in precipitation for Pleistocene glacial stages compared to present day climatic data. This figure when compared to data from water yield studies indicates that removal of timber may temporarily produce moisture regimes in slopes as wet or wetter than conditions during the active Pleistocene period. Storey and Irwin (1970) and Rothacher (1970) have shown, for example, that in high precipitation

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*A distinction is made here between the role of transpiration and the contribution to shear strength from root reinforcement.

areas of the Oregon Cascades, clear-cut logging can increase annual water yield as much as 18 inches.

E. SOIL CREEP AND ITS SIGNIFICANCE

Soil creep is a slow, downslope movement or plastic deformation of soil on a slope. Soil creep does not necessarily mean slope failure; in fact, some investigators (Wilson, 1970) maintain it is difficult to differentiate between plastic deformation (creep) and incipient failure.

Other investigators (Saito and Uezawa, 1961) disagree, suggesting that it is possible to forecast slope failure by measuring surface creep rates. Saito and Uezawa show from field measurements and model experiments that the strain (or creep) rate in a mass of soil will increase rapidly just before failure occurs. Ter-Stepanian (1963) showed from a theoretical analysis that the down slope creep rate of an inclined soil layer was exponentially related to the piezometric level in the slope. As the soil layer neared full saturation the creep rate not only tended to accelerate markedly, but the factor of safety against slope failure also approached unity.

Measurements and analysis by Saito and Uezawa (1961) showed that "creep rupture life" or time to failure of a soil is related to creep rate as follows:

$$\log t_r = C - m \log \dot{\varepsilon} \tag{5}$$

where t_r = creep rupture life

$\dot{\varepsilon}$ = strain (or creep) rate

m and C = constants

This relationship was found to be valid over a wide range of strain rate (10^{-3} to $10^{3} \times 10^{-4}$/min) and was independent of the type of soil or testing method. The slope "m" of this equation on log-log paper was very close to unity (0.916). Setting the constant "m" equal to unity reduces the equation to the simple form:

$$t_r \dot{\varepsilon} = \text{constant} \qquad (6)$$

Therefore, creep rupture life or time to failure is inversely proportional to strain rate. This relationship was shown to be applicable to full scale field experiments on slope failure. Creep rates may thus be used as an indicator of the long term stability of slopes and any acceleration in creep rate used as a precursor of potential instability or slope failure.

Wilson (1970) in his Terzaghi lecture on ground movements related to instability noted that the most significant factors affecting creep rate are slope angle, type of soil, and amount and frequency of rainfall. The latter factor controls the piezometric level or soil moisture stress in a slope. Ter-Stepanian (1963) explicitly recognized the dependence of creep rate on these factors in his theoretical equations. In addition, he included the effect of surcharge on creep rate. Figure 8 is a schematic diagram of the creep model used by Ter-Stepanian, and Figure 9 is a plot of the creep equations showing creep rate as a function of piezometric level and slope surcharge.

Trees or vegetation can be expected to affect creep rates through their influence on soil moisture stress and soil characteristics.

Another important aspect of soil creep is its contribution to general

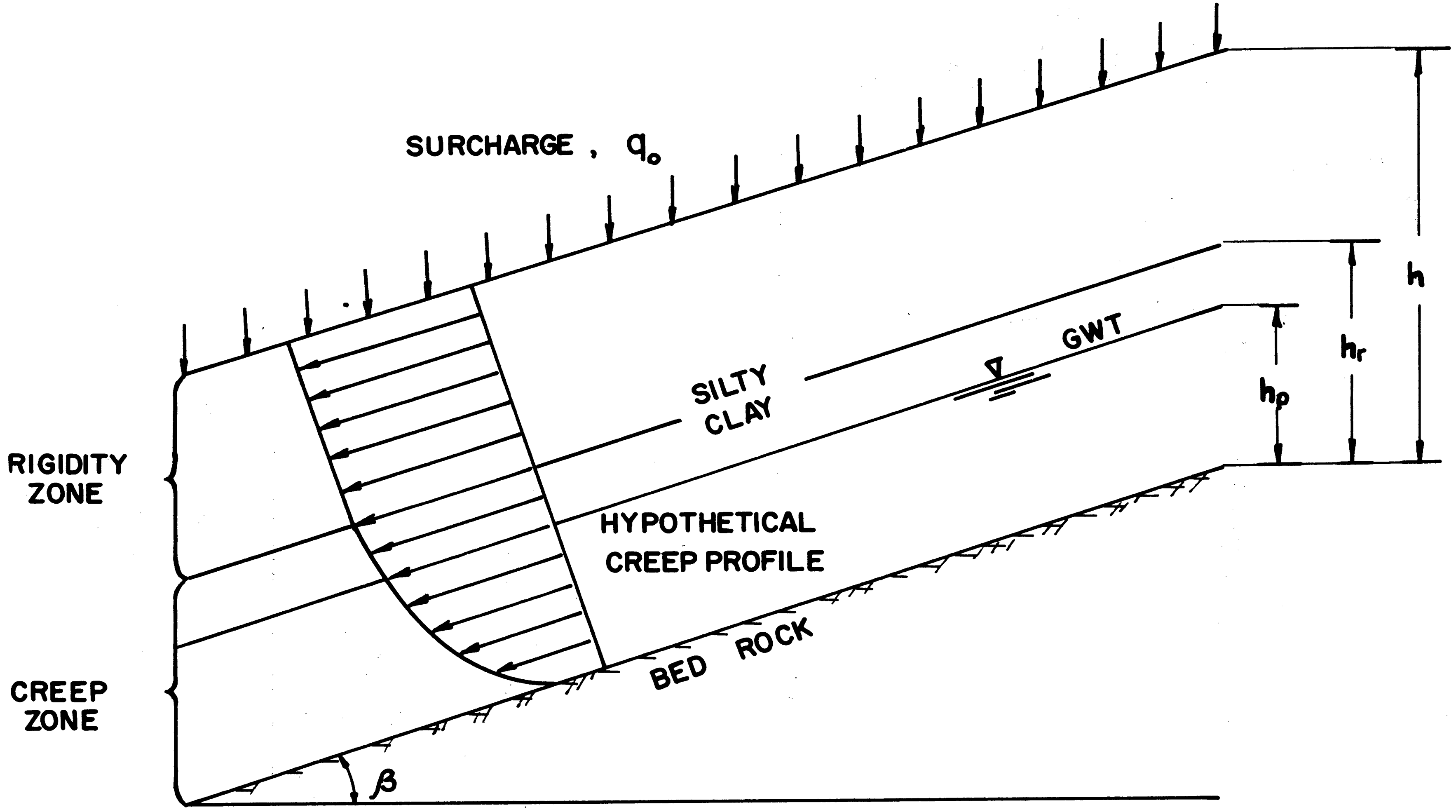

Figure 8. Schematic representation of slope geometry.

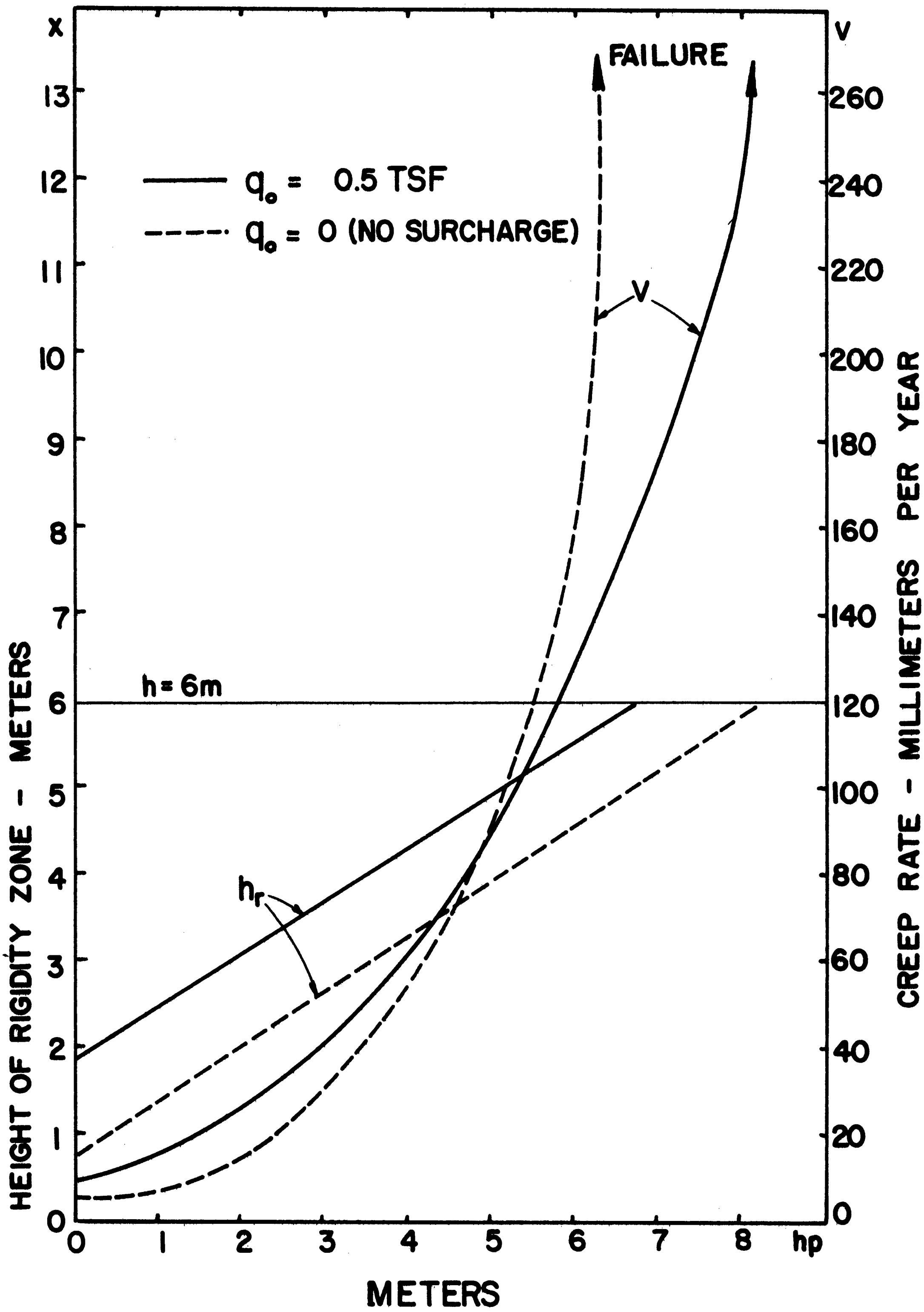

Figure 9. Surface creep rate as a function of piezometric level and surcharge (from Ter-Stepanian, 1963).

lowering or degradation of the land. Soil creep is an ubiquitous form of downslope movement in humid climates. Kojan (1969) has measured an average downhill velocity of about 11 mm/year (0.44 in./yr) on average slope of about 17° in the Northcoast Ranges of California. Swanston (1969) cites a rate of approximately 0.25 in./yr in the top 6-12 inches of soil in southeast Alaska. Creep studies (Wilson, 1970) carried out in Western Washington indicate a surface creep rate of approximately 0.32 in./yr averaged over a 10-year period. This rate was measured in a 25-foot section of a moderately compact, silty glacial morraine overlying phyllite bedrock. Schumm (1967) measured rates of surficial rock creep on barren hillslopes in Western Colorado on the order of 2 in./yr for slope angles of 30 degrees.

Kojan (1969) estimated that in the Eel River drainage of California, soil creep was producing about 260 metric tons of sediment per square kilometer of drainage basin. This volume is about 30 percent of the suspended load which Wallis (1965) has estimated for the area. This estimate, furthermore, was based on a conservative downhill velocity of only 6 mm per year for a 2.4-meter thick mantle; a much lower rate than many that Kojan measured.

Summing up; it appears that soil creep is an important indicator of the long term stability of slopes, acceleration in creep is a possible precursor of impending slope failure, and increases in creep rate can lead to increased sediment loads in streams. Creep rates are primarily dependent on slope angle, soil characteristics, and soil moisture stress. Trees and vegetation are likely to affect creep rates by modifying the latter two factors. For all of these reasons, field measurements of soil creep before and after cutting should be a useful method of assessing the impact of clear-cutting and vegetation removal on the stability of slopes.

III. LOCATION AND DESCRIPTION OF FIELD SITES

A. SITE SELECTION CRITERIA

The primary objective of the field research was to investigate the effect of forest clear-cutting on soil moisture stress and on the rate of downslope movement (or creep rate), respectively, in steep slopes. Two approaches are possible in this regard, viz., (1) a "before and after" clear-cutting comparison at a single site, (2) a "side-by-side" comparison of a forested and adjacent cutover site.

A secondary objective of the research was to analyze the stability of slopes at the various field sites and determine how changes in slope stability parameters such as soil moisture stress and soil shear strength can effect stability. As noted previously, these parameters can be effected by removal of slope vegetation.

In order to accomplish these objectives the following criteria were established for selection of a site:

1. A history of mass-soil movement or susceptibility to sliding
2. Reasonably steep slopes (> 60 percent)
3. Slopes with relatively uniform mantle of residual soil some 5 to 20 feet thick overlying an inclined bedrock contact
4. A recently clear-cup area adjacent to a virgin, forested area (both otherwise similar)—for a 'side-by-side' comparison
5. An area scheduled for clear-cuttin in the near future from which reliable base or control data could be obtained—for a 'before and after' comparison

6. Good climate and weather records

7. Year round accessibility

8. Field personnel avaiable at the site to monitor instruments and take readings when necessary.

On the basis of these requirements three different areas were selected in the Pacific Northwest. Sites in these areas were instrumented during successive summers starting with the H. J. Andrews Experimental Forest, near Blue River, Oregon (1968 and 1969); U.S. Naval Radio Station at Jim Creek, near Arlington, Washington (1970); and sites in the Klamath National Forest, near Happy Camp, California (1971).

Sites were also reconnoitered at Hubbard Brook experimental Forest, New Hampshire, and at Zena Creek in the Payette National Forest, Idaho. Both these latter areas has a history of slope instability associated in part with timber harvesting (Flaccus, 1959; Gonsior and Gardner, 1971), but were never instrumented because of logistical problems and other unfavorable site characteristics.

B. H. J. ANDREWS EXPERIMENTAL FOREST, OREGON

1. Location and Topography

The H. J. Andrews Experimental Forest is located in the Cascade Mountains about 40 miles east of Springfield, Oregon, and 5 airline miles north of the McKenzie Highway (U.S. 126) as shown in Figure 10. The entire 15,000-acre drainage of Lookout Creek, in the Willamette National Forest is included in the boundaries of the Experimental Forest. The Experimental Forest was

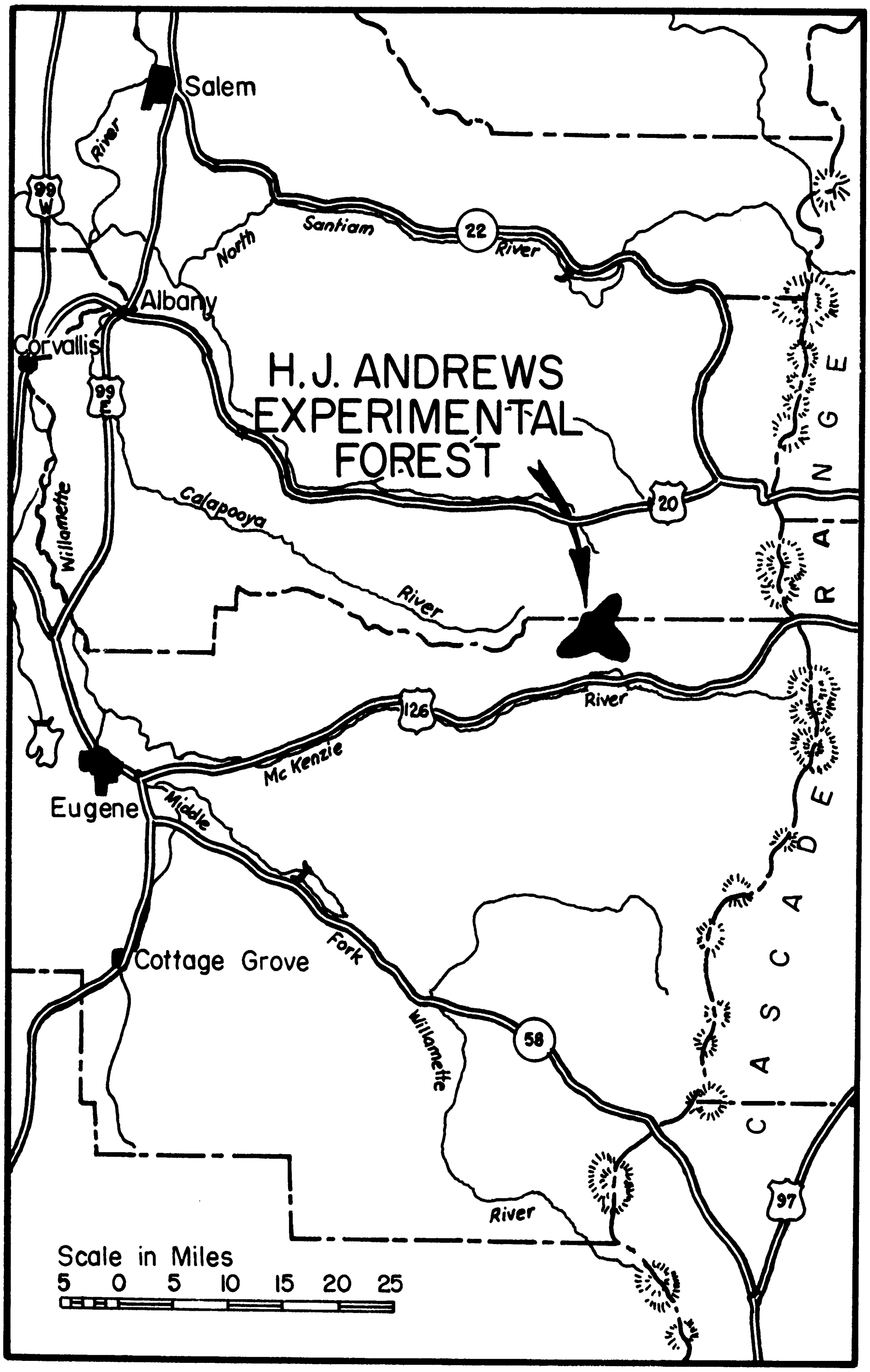

Figure 10. Map location of H. J. Andrews Experimental Forest.

established in July, 1948, and is administered by the Pacific Northwest Range and Forest Experimental Station, U.S. Forest Service.

Three different sites within the Experimental Forest have been instrumented as part of the slope stability studies. These include a clear-cut watershed (No. 1), and two forested watersheds, viz , No. 10 and No. 2-3, respectively. Watershed No. 1 was clear-cut by skyline crane in 1961, Watershed No. 10 is scheduled for clear-cutting in the summer of 1974, and Watershed No. 2-3* is a forested slope which will be left undisturbed indefinitely.

The surrounding terrain can be characterized as "ridge and ravine" topography with sharp ridges and steep slopes. Only about one-fifth of the area is in gentle slopes or benches. Elevations within the Experimental forest vary from about 1500 feet to more than 5000. Rock outcroppings occur frequently in steeper areas of the forest and old lava flows have formed lines of bluffs at some elevations.

The general topography and location of instrumented study sites are shown in Figures 11 and 12. Watersheds Nos. 1 and 10 are approximately 200 acres in size. Study sites on these two watersheds face north and southwest, respectively. Maximum side slopes in the vicinity of instrumented sites are about 70 percent for all watersheds. Photographs illustrating the nature of the terrain and vegetation in the vicinity of the study sites are shown in Figures 13 to 15.

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*Watershed No. 2-3 is a forested slope located between Watersheds Nos. 2 and 3.

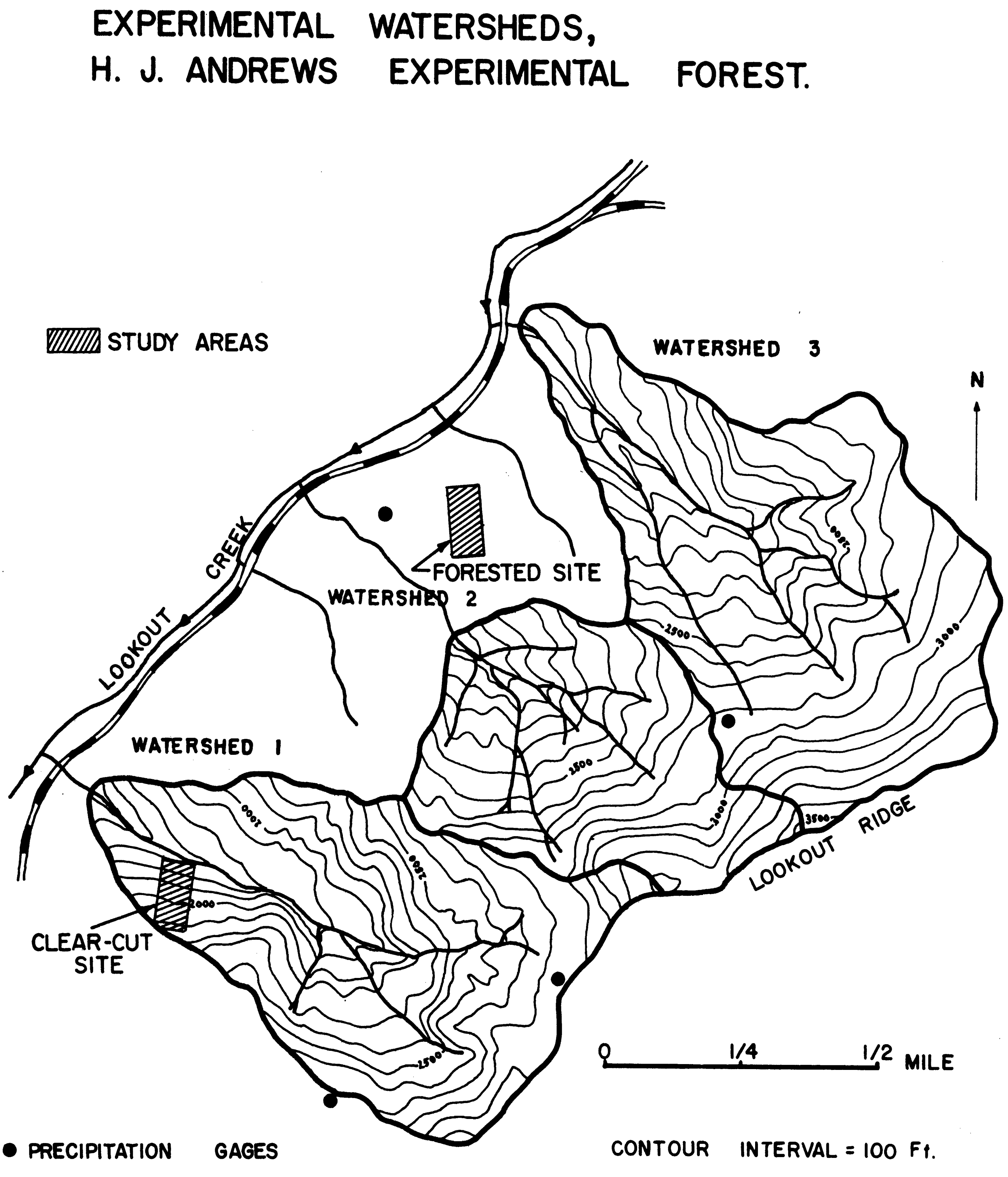


Figure 11. Location of field sites for "side-by-side" comparison of creep movement, H. J. Andrews Experimental Forest.

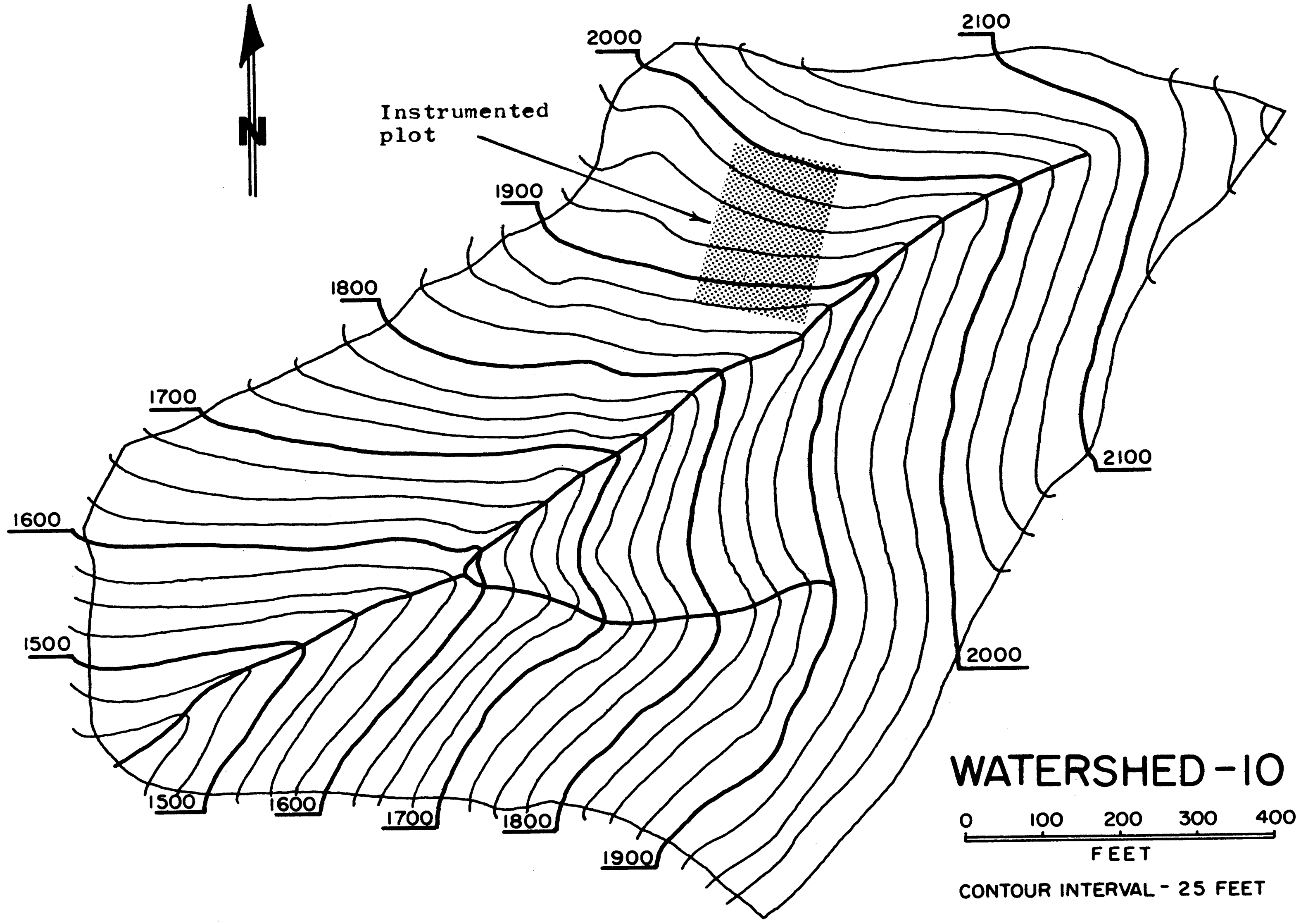


Figure 12. General topography and location of slope instrumentation in Watershed No. 10.

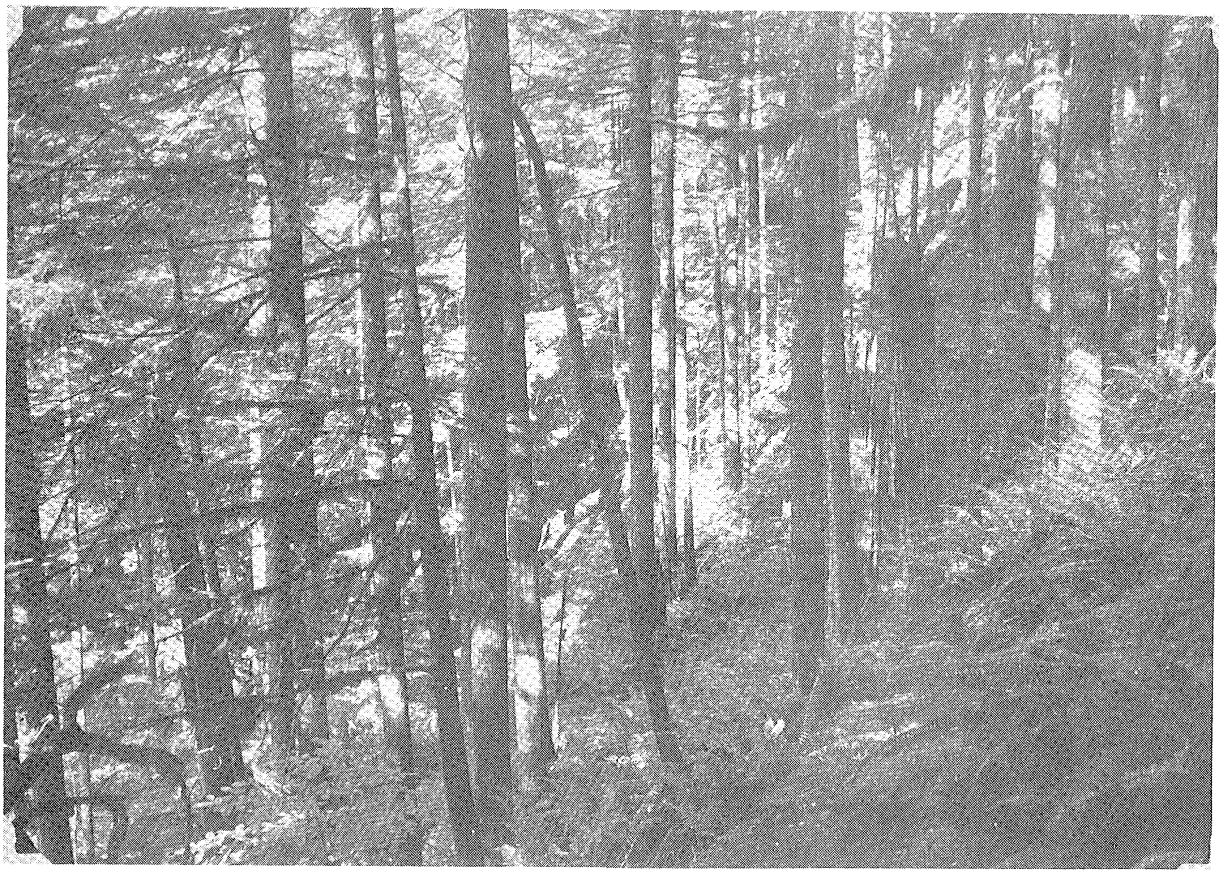


Figure 13. Typical view of forested slope, Watershed No. 2-3, H. J. Andrews Experimental Forest.

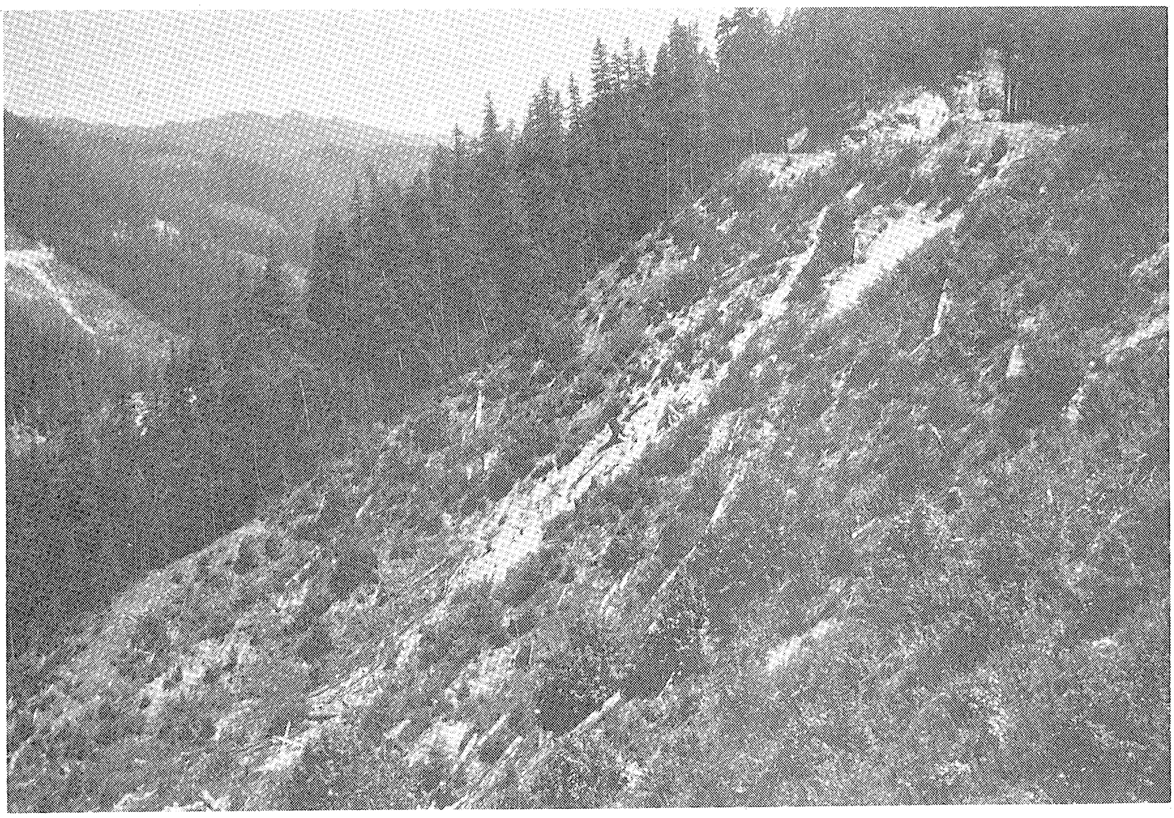


Figure 14. View of clear-cut slope adjacent Watershed No. 10, H. J. Andrews Experimental Forest.

Figure 15. View of clear-cut watershed (No. 1), H. J. Andrews Experimental Forest.

2. Soils and Geology

The principal soil types found at the H. J. Andrews Experimental Forest are all of volcanic origin. A residual clay loam, formed from andesite and basalt, is common on the steeper slopes and on ridgetops. A residual silty clay loam—formed from agglomerates, tuff, and breccia—is characteristic of midslope and low-ridge positions. This soil is very unstable and easily disturbed by road construction. The third soil, a clay loam formed from colluvial materials, occupies gentle slopes and benches. All three soil types support forest vegetation and are strongly acid.

Slope instability appears to be strongly correlated with soil type. Dyrness (1967) examined the relationship between mass-movement events and various site factors. He found that mass soil movements occurred much more frequently in areas of pyroclastic rocks (tuffs and breccias) than in areas where the bedrock is comprised of basalt or andesite. In addition, greenish tuffs and breccias appeared to be more unstable than their reddish counterparts. The unstable nature of these materials is even more apparent when one notes that 64 percent of the mass-movements were on greenish tuffs and breccias which make up only 8 percent of the total area. Soil instability is partly related to a clay mineralogy. Dominant clay minerals are montmorillonite, Kaolinite, and chloritic intergrades. The more unstable soils are those containing montmorillomite as the principal clay mineral (Paeth, 1970).

The instrumented site in Watershed No. 1 is located on largely colluvial material whereas the site in Watershed No. 10 is located on a residual soil derived from tuff. The thickness of soil or depth to bedrock at these sites ranges from 11 to 16 feet.

3. Climate and Hydrology

Precipitation is heavy, varying from 89 inches per year in the lower reaches of Lookout Creek to as much as 140 inches per year along the highest ridges. Rain predominates at the lower elevations, but considerable snowpack developes on the higher slopes. Approximately 82 percent of the annual rainfall on the Experimental Forest occurs from October through March, filling the watershed's natural storage to capacity. Summers tend to be hot and dry with the result that considerable soil moisture depletion (soil water suction) develops in forested slopes.

4. Vegetation

The predominant forest type, Douglas fir, occurs in a complete range of size classes—from seedlings to large over mature timber. The older age classes, however, are by far the most common. Varying amounts of western hemlock, western red cedar, and sugar pine together with a few hardwood species such as big leaf maple also grow in the forest.

Several understory plant communities have been identified on the forested slopes (Rothacher et al., 1967). The type of plant species in these communities reflect the slope and moisture conditions to a considerable extent. A sword-fern community, for example, is found in the areas where moisture is abundant. It is located along drainages, on steep north- and east-facing slopes, and in seepage areas. This is the dominant type of vegetation in the instrumented plot in the cutover watershed (No. 1) and it also occurs in parts of the forested watershed (No. 10).

A vine maple-Oregon grape community commonly occurs under a timber stand of variable density and is indicative of a fairly productive site for Douglas fir and hemlock. This understory community is typical of the instrumented plot in the forested watershed (No. 10).

Mature species of Douglas fir were found growing in Watershed No. 10 with a basal diamer of 4 feet or more. Merchantable volumes of timber in these watershed average 50,000 to 65,000 board feet per acre, and basal areas of all stems 2 inches and over range from 300-500 square feet per acre (Rothacher et al., 1967). Using these figures we calculated (assuming 10 lb per board-ft) that on the average the trees produce a stress of 1000 to 1500 psf immediately beneath their base. When the weight of the trees is spread out over the entire slope, the surcharge drops to 12-15 psf. On the other hand, if the surcharge is calculated according to the procedure adopted by Bishop and Stevens (1964), the stress ranges from 60 to 80 psf. This latter surcharge calcualtion is based on a density of 100 trees per acre and tree weight distributed over an area of 75 square feet.

Examples of both forested and clear-cut areas are shown in Figures 13 to 15.

5. Slope Stability Problems

Numerous slides and other types of mass-soil movements have occurred on steep slopes in the Experimental forest. A study of mass-soil movements, particularly those occurring during severe storms in the winter of 1964-65, was reported by Fredriksen (1965) and Dyrness (1967).

Dyrness described a total of 47 mass movement events. He recorded at each movement site the type of movement, soil characteristics, and general character of the area including such factors as aspect, slope angle, elevation, and prior disturbance by man if any. Earth flows were the dominant type of mass movement followed by slumps.

Dyrness also attempted to assess possible relationships between mass soil movements and certain site characteristics. Several interesting relationships emerged. The influence of roads on mass soil movements was overwhelming with 126 events per 1000 acres in road areas compared with 0.4 events per 1000 acres in undisturbed areas. Some influence of logging was also observed with a ratio of 3.9 in logged areas compared to 0.4 in undisturbed areas. It was not clear to which category a mass-wasting event was assigned if the area was both logged and roaded. This situation is quite common as shown in Figure 16.

The frequency of mass soil movements was also strongly correlated with soil type as mentioned previously. Other site characteristics correlating with increased frequency of movement included northwest exposure, elevation range 2300 to 2600 feet, and slopes in the range 60 to 70 percent.

C. U.S. NAVAL RADIO STATION, WASHINGTON

1. Location and Topography

This site is located in the watershed of Jim Creek about 12 miles east of the town of Arlington, Washington. The site is characterized by a deep,

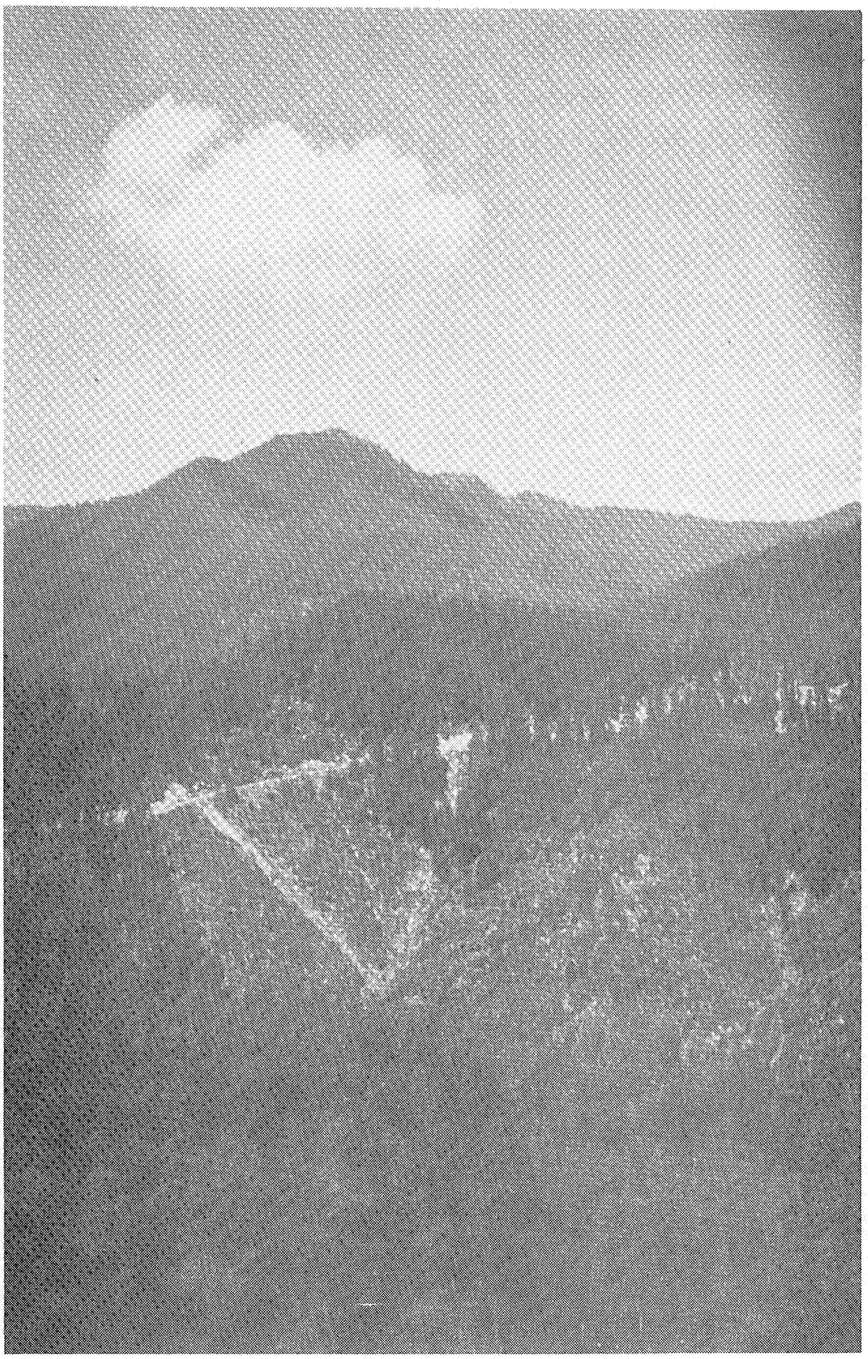


Figure 16. Earth flows in a "logged" and "roaded" slope, H. J. Andrews Experimental Forest.

glacial valley some 8000 feet wide by 2000 feet deep which has been substantially modified in the past by landslides. This valley is bounded to the northeast by Wheeler Mountain and to the southwest by Blue Mountain. The Naval Station is situated in the midst of Mount Baker National Forest. A map showing the location and topography of the site is given in Figure 17.

Because of its favorable topography and location, the site was selected by the U.S. Navy for a major radio communications facility. Two hundred-foot towers were erected on opposite ridges to support an overhead aerial system spanning the valley below. Soon after construction of the antenna system the Navy decided that gound vegetation on the valley sides beneath the antennas was interfering with radio operations. The Navy consequently removed all woody vegetation directly underneath the antennas.

This site was of particular interest because portions of the watershed has not been cutover. This provided a tailor made location for a side-by-side comparison of soil mositure stress and creep rates in forested as opposed to adjacent cutover slopes. The extent of timber removal at Jim Creek is shown in the topographic map in Figure 17. A view of a forested and cutover portion of a slope separated by an abrupt tree line on the Wheeler Mountain side of the valley is shown in Figure 18. General views illustrating the topographic features and denudation of valley sides are shown in Figures 19 and 20.

2. Soils and Geology

The bedrock of the site is mostly interbedded graywacke, slate, and phyllite. Surficial deposits in general consist of talus on the upper slopes

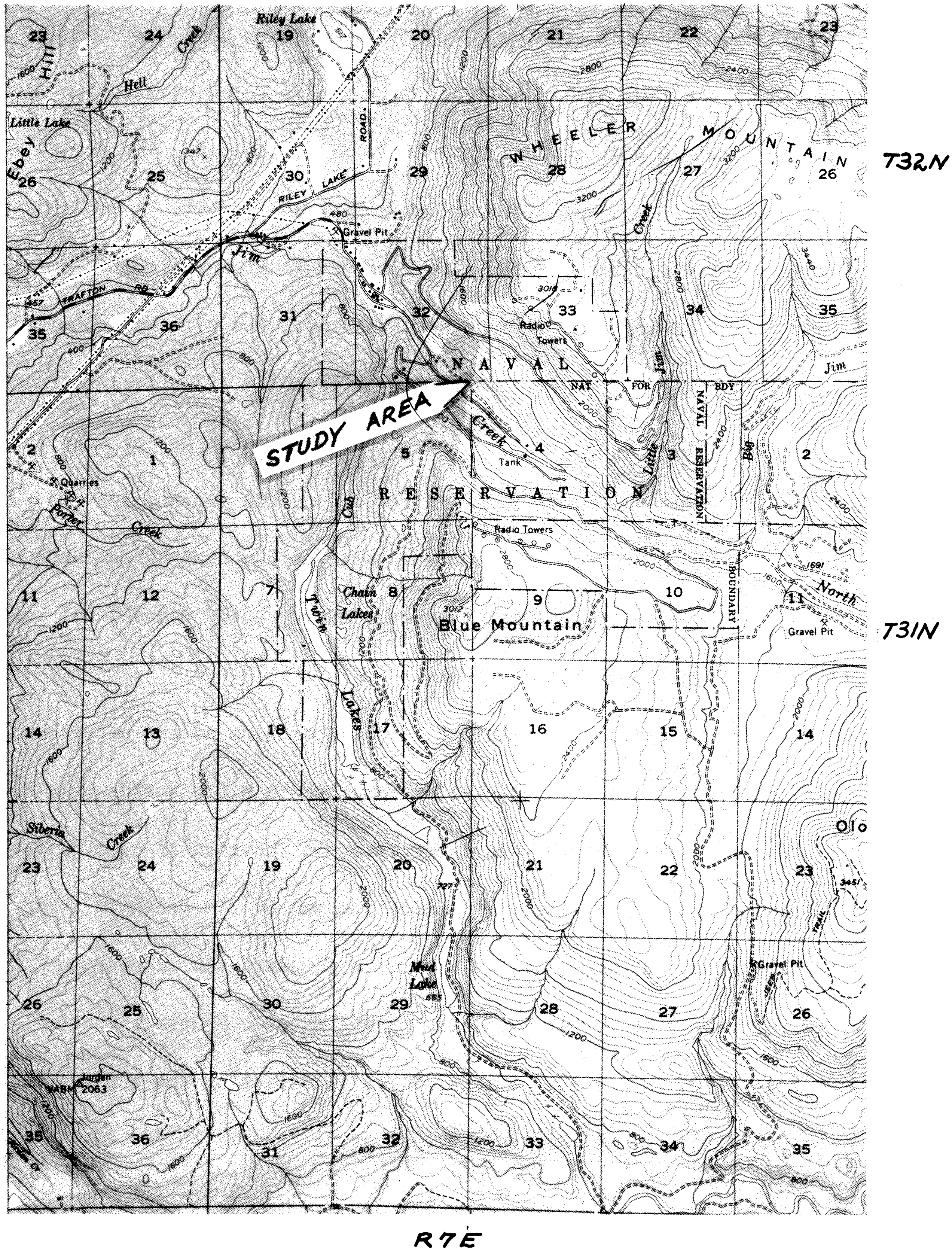


Figure 17. Location of field site at the U. S. Naval Radio Station, near Arlington, Washington (from USGS Granite Falls quadrangle).

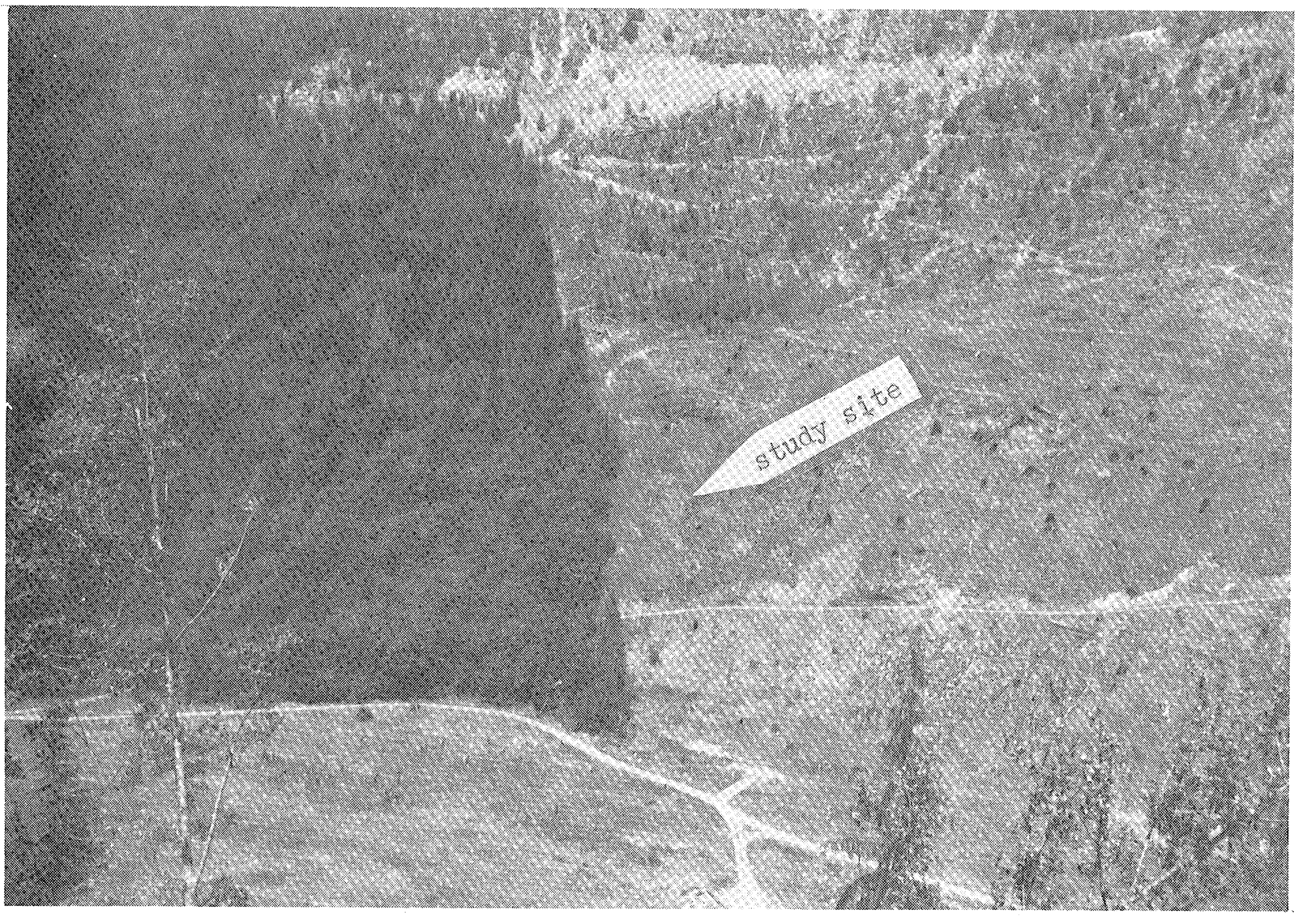


Figure 18. Forested and cutover portions of slopes at the U. S. Naval Radio Station.

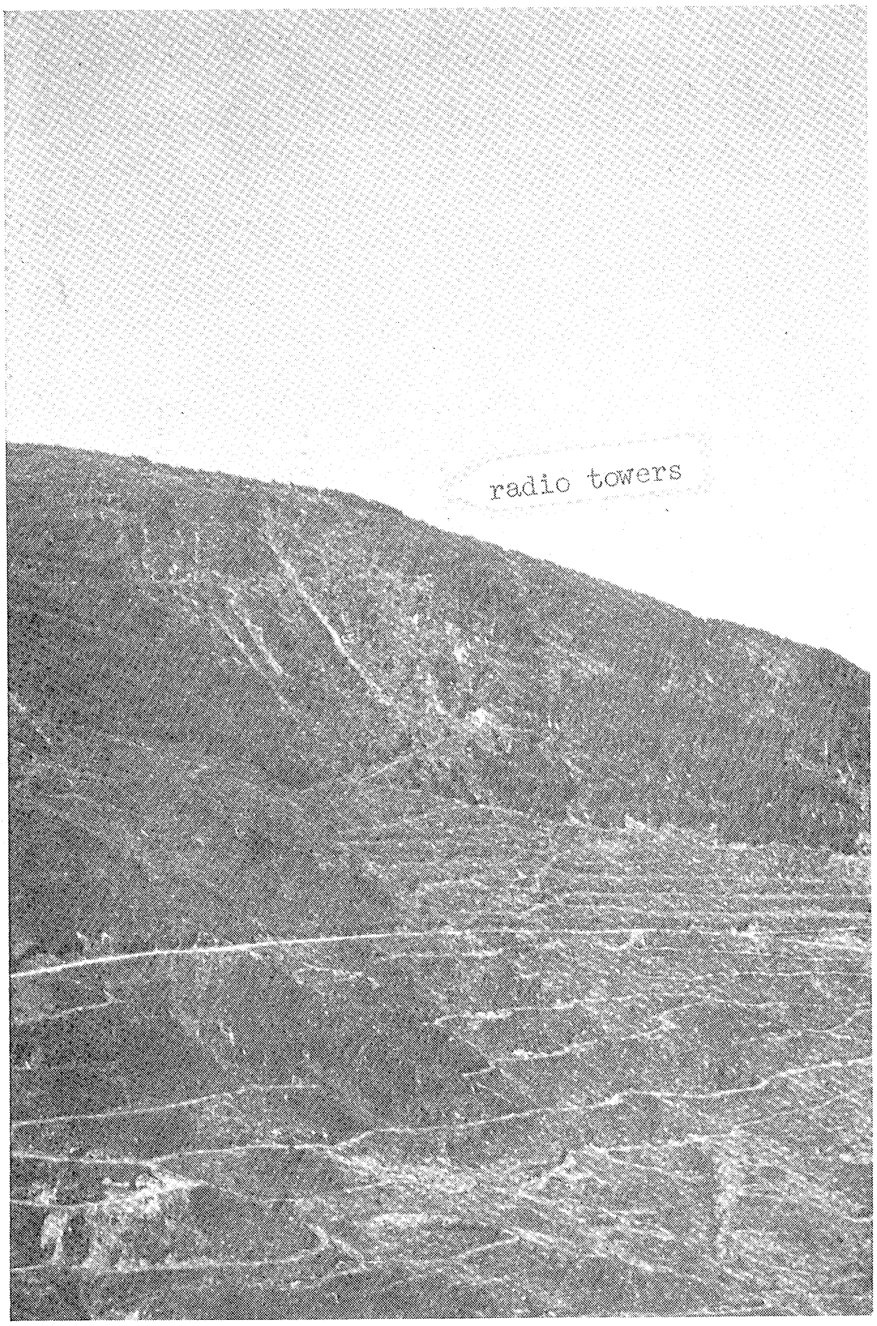


Figure 19. View of cutover slopes on valley sides, U. S. Naval Radio Station.

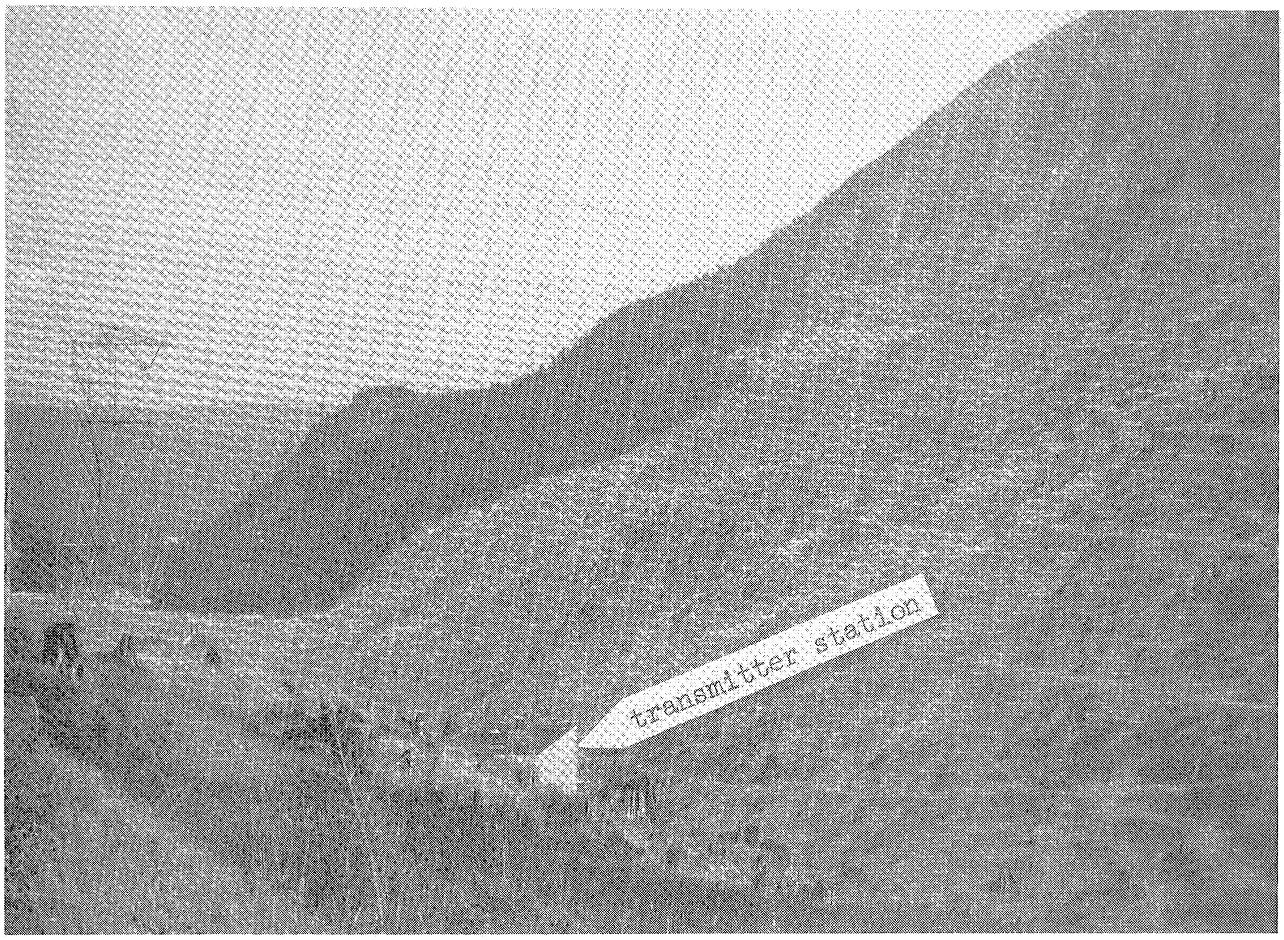


Figure 20. Down valley view showing extent of denudation of slopes at U. S. Naval Radio Station.

and deposits of glacial till on the lower slopes. The soils and geology at the site have been described in detail by Crandell and Waldron, 1952; and Waldron, 1954.

Talus deposits are more common to the upper parts of the valley sides above 2000 feet elevation. They typically consist of angular cobbles and boulders in a matrix of sandy silt. Talus slides occur on the upper slopes in the winter.

Deposits of glacial till blanket the lower slopes to depths of 25 feet in some places. Soil depths at the instrumented site are shallow, however, ranging from only 4 to 7 feet.

The till was deposited as a lateral moraine by a valley glacier. It consists of angular fragments of phyllite, slate, and graywacke in a matrix of well-graded silty sand. Till deposits toward the base of the slope are slightly cohesive and relatively impermeable.

3. Climate and Hydrology

The area receives an average of 30 inches of precipitation per year. Dry weather usually ends in October, and heavy storms then follow with precipitation rates as high as 2 inches in 24 hours and intensities as high as 0.5 in./hr.

The glacial till deposits in general are permeable and, during wet weather water content approaches the liquid limit. The ground water table is very close to the ground surface in some cutover areas. One manifestation of high ground water levels are numerous spring water discharges which are found in cutover portions of the valley. Some of these springs have triggered small slides or slumps in places.

4. Slope Stability Problems

The till deposits or moraine on the lower slopes have a very hummocky and uneven topography suggesting a long history of instability. Landslide debris from higher up has been strewn across parts of the moraine. The presence of seeps, numerous scarps, and cracks in the slope is further evidence of slope instability.

Soon after the Navy removed the vegetation beneath the antennas, springs and seeps appeared on the denuded hillsides. Slides and other types of mass-soil movements also increased with alarming frequency. The Navy was particularly concerned about a steep, unstable hill mass which threatened their transmitter station (Shannon and Wilson, 1956; Wilson, 1967). This building was constructed near the valley bottom where it narrowed into a steep stream gorge. In addition to taking remedial measures in an attempt to control hillside springs and seeps, the Navy also instituted a monitoring program in 1956 to detect any movement in the hill mass above and behind the transmitter station.

Active creep and sliding still continues today in many portions of the valley. Cracking and dislocation of concrete drainage ditches installed on the slopes attest to this fact. The Navy maintains a "slope patrol" to look for signs of new distress and it keeps a wary eye on creep movements recorded in the inclinometer installation above the transmitter station.

D. KLAMATH NATIONAL FOREST, CALIFORNIA

1. Location and Topography

The study sites are located in the mountainous western portion (Klamath Mountains) of the Klamath National Forest. Two main sites were instrumented in this region, viz., in the Clearview sale and the Little South Fork areas. These two sites are located approximately 10 airline miles southwest and northwest, respectively, from the town of Happy Camp as shown in Figure 21. A third site was also instrumented near a road crossing on Middle Creek, Condrey Mountain; but this site was destroyed by a landslide and was abandoned.

The region is characterized by rugged terrain with steep and dissected slopes. Mass-wasting has played an active role in the evolution of the surrounding landscape. Many fossil landslides occur in the region and these have a vivid topographic expression. Fossil landslides, some 1/2 mile long and 1/4 mile wide, show as smooth rounded tongues of debris and hummocky, stairstep slumps.

Two separate sites were actually instrumented in the Little South Fork area. One is a large, reactivated fossil landslide which was cutover several years ago. The influence of tree removal on the velocity of downslope movement in this slide is unknown because no records or observations were made prior to timber harvesting. Fossil slides often develop deep soils and are relatively stable under modern, climatic conditions. Unfortunately, logging and road construction in the region sometimes reactivates slippage (Hicks and Collins, 1970). The other site in the Little South Fork area (referred to as

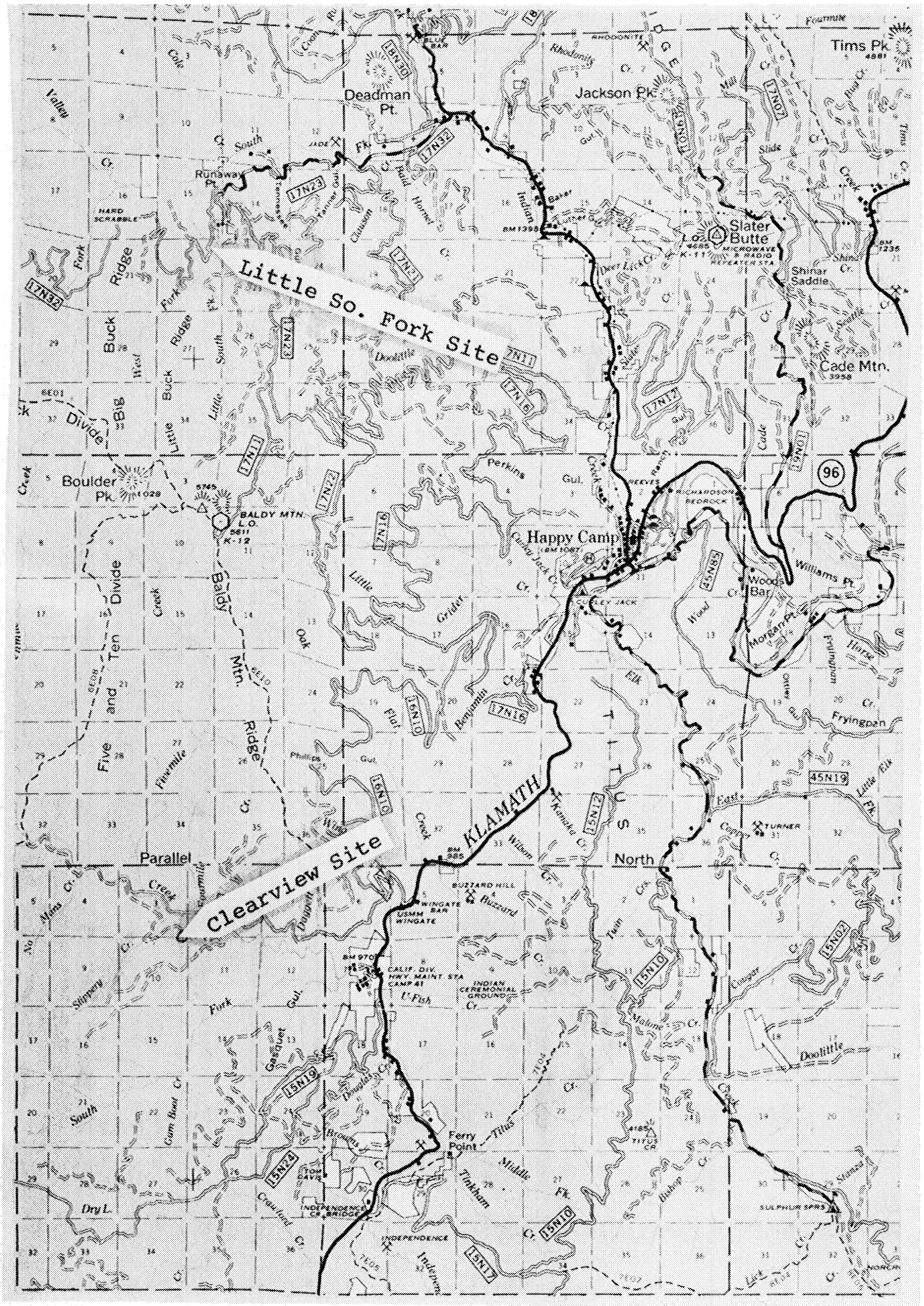


Figure 21. Location of field study sites in the Klamath National Forest (from USFS recreation map, Happy Camp Ranger District).

the Little South Fork annex) is nearly adjacent and is an active slide. It still retains a tree cover, although many trees are canted at extreme angles as a result of deep seated movement. Both these sites were instrumented to obtain an estimate of the extent and rate of deformation in slide areas.

The Clearview sale site is forested and was instrumented in order to obtain a "before-and-after" comparison of creep rates following clear-cutting. This site is scheduled for logging during the summer of 1973.

2. Soils and Geology

The geology of the Klamath Mountains is complex; they consist essentially of metamorphic rocks intruded by granitic and ultramafic masses. The metamorphic rocks are mainly schist, phyllite, slate, chert, and marble. The granitic rocks are granodiorite, quartz diorite, and hornblende diorite. Thrust faults, trending north-south and dipping east, separate major lithologic boundaries. Many of the ultramafic bodies were intruded along the thrust faults.

In the Klamath Mountains, the three major rock units, (1) granitic, (2) metamorphic, and (3) ultramafic, are associated with different soil types and these in turn present various stability problems (Hicks and Collins, 1970).

Weathering decomposes and disintegrates granite to a depth of several feet. Weathered granite breaks down readily to sand-and-silt size particles. Granitic terrain is particularly subject to surface erosion and debris flows. Slope stability problems in granitic areas are similar to those described by Gonsior and Gardner (1971) in their study of slope failures in the Idaho batholith.

Among the metamorphic rocks, the Jurassic Galice formation, composed principally of slate and phyllite, contains numerous landslides. The abandoned site on Condrey Mountain was situated on a decomposed graphitic schist. These graphitic zones are very unstable expecially in the presence of water.

Highly fractured and sheared serpentized ultrabasics are a characteristically weak foundation material found throughout the western part of the Klamath National Forest. The Little South Fork sites are underlain by unstable, serpentine soils ranging in depth from 8 to 12 feet.

The Clearview site is underlain by a thick section of moist gravelly-clay colluvium ranging in depth from 15 to 20 feet. A metamorphic, disintegrated slate comprised much of the rock fragments in this material.

3. Climate and Hydrology

Precipitation in the Klamath Mountains is fairly high averaging about 55 inches per year. Most of this precipitation falls as rain during the winter months. Long periods of rain interspersed with high intensities (1 to 2 inches per hour) accentuate the low degree of stability found throughout the Klamath Mountains. Evidence exists (Hicks and Collins, 1970) that clear-cutting on or above a fossil landslide will increase the water content or influx of water into weak landslide material, and this may lead to ground saturation and failure.

4. Vegetation

Like the other study areas, Douglas fir is the dominant species on forested slopes in the region. Incense cedar and Ponderosa or yellow pine are also prevalent. These latter forest species thrive on harsh, serpentine soils, where Douglas fir will not.

5. Slope Stability Problems

The Klamath Mountains portion of the Klamath Nation Forest (where the study sites are located) is particularly susceptible to mass wasting on a grand scale due to the combination of steep terrain, high precipitation, both duration and intensity), and a wide range of unstable surficial materials and bedrock. In such a precarious setting, road construction and logging sometimes create problems.

Dunlap and Moore (1970) have provided a detailed account of serious soil erosion and mass-wasting in the region...most of it associated with logging operations. Hicks and Collins (1970) likewise have described slope stability problems in the area. Four specific situations were discussed by these latter investigators (1) landslides due to road cuts, (2) landslides due to ground water increases in or downslope of clear-cut areas, (3) reactivation of fossil landslides, and (4) debris flows.

IV. SLOPE INSTRUMENTATION

A. MEASUREMENT OF SOIL MANTLE CREEP

The two principal objectives of the slope instrumentation were measurement of creep rates and soil moisture stress before and after clear-cutting. This section describes the field instrumentation and procedure used to measure rates of downslope movement or soil mantle creep.

A commercially available inclinometer known as a Slope Indicator was selected for this purpose. Inclinometers are used extensively in civil engineering practice to investigate the performance of embankments and to monitor earth movements in natural slopes. These devices basically consist of a pendulum-activated transducer enclosed in a watertight torpedo, which is lowered down a near-vertical casing, measuring the inclination from vertical of the casing at frequent intervals. Lateral movements in a slope deflect the casing, thus changing its inclination. Changes in inclination with time can be translated back into a deformation versus depth curve which varies with time. From these curves it is then possible to calculate creep rates in the soil mantle.

The inclinometer (or Slope Indicator) used in the present study has been described in detail by Wilson (1962). It consists of a pendulum-actuated Wheatstone-bridge circuit enclosed in a wheel-mounted torpedo whose azimuth is controlled by vertical grooves formed in the walls of special extruded aluminum casing. The output from the sensing element of the device can be remotely read at a control box at the top of the casing. The control box at the ground surface is connected to the instrument with a multiwire conductor having a stranded steel cable in the center. This cable is used to support the weight of the instrument while it is lowered down the casing. The grooved deformable casing, which comes in sections 5 feet or 10 feet long, is joined together with couplings which are also grooved. The sensitivity of the instrument is one part in 1000, which means a change of inclination of as little as 3 minutes of arc can be read. This corresponds to a lateral movement of a tenth of an inch in 10 feet. A photograph showing the inclinometer, control box, and the top part of the aluminum casing is shown in Figure 22.

The installation of the slope indicator casing is a fairly difficult and critical step. It is important that the casing be in effective contact with the surrounding soil so that changes in inclination reflect movements in the entire soil mantle and not just local movement and settlement around the casing as a result of the installation procedure. To insure that this would be the case we adopted the procedure of drilling a slightly oversized hole, inserting the casing, and backfilling the annular space with dry sand. The diameter of the drilled hole was 6 inches, that of the casing, 3 inches.

By using a so-called single grain, air dropping technique it was possible to obtain a backfill with a minimum void ratio (or maximum relative density) which completely occupied the annular space and which could deform, but not compress. This technique of backfilling is one recommended by the manufacturer of the Slope Indicator. It is also a technique of depositing dry sand which has been investigated extensively in the Soil Mechanics Laboratory at The University of Michigan and which has been found consistently and reliably to give minimum void ratios. 'Single grain air dropping' and minimum void ratios can be achieved in the field by raining a uniformly graded, dry sand through a

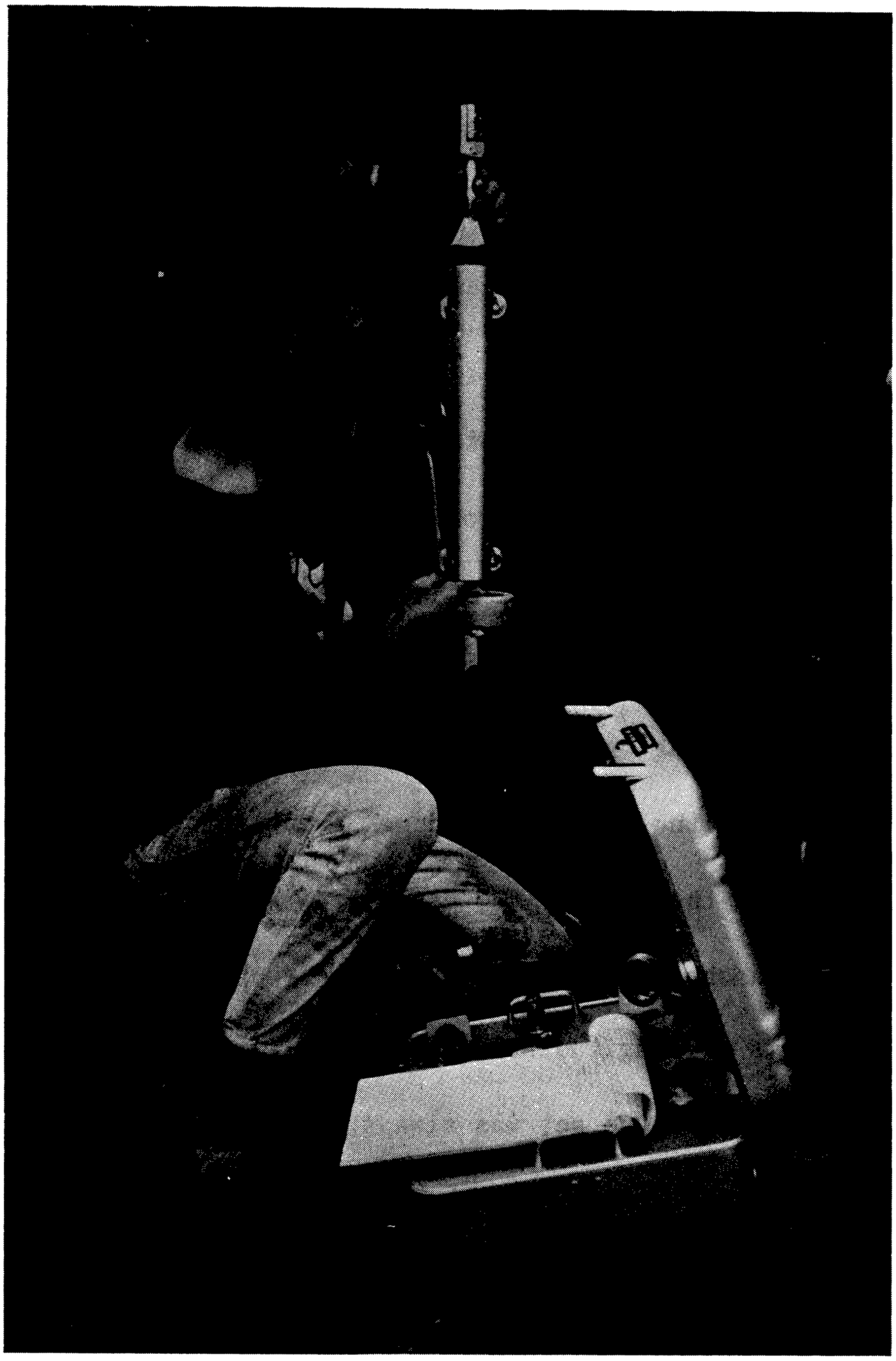


Figure 22. Slope indicator, control box, and top of casing or tubing.

sieve with a mesh size slightly larger than the grain size of the sand. Figure 23 is a photograph illustrating a backfilling operation in progress. We used a dry, 30-mesh, Monterey sand for backfilling purposes. It is important that there be no free or standing water in the hole during backfilling.

The holes for the slope indicator casing were drilled using a portable, two-man, gasoline-powered flight auger. The photograph in Figure 24 shows a hole being drilled with this equipment at the field study site in central Oregon. The power auger was used down to a depth of about 10 to 12 feet. Past this depth it was more practical to use a hand bucket auger and accessory drilling tools. We used an Acker drill set for this purpose.

The bottom of the casing was anchored in fractured bedrock. This was achieved by drilling into the fractured bedrock about a foot with a chopping bit and then bailing out the debris. We assume in the data analysis that the bottom of the casing, anchored in the fractured bedrock, remains fixed in place.

There are two sets of longitudinal grooves, perpendicularly opposed to one another, in the casing. One set was always oriented down slope when the casing was installed in the holes. The wheels on the slope indicator torpedo (or instrument housing) trackdown one set of grooves thus keeping it on a fixed azimuth. By lowering the instrument down the casing in these two mutually perpendicular directions it is possible to obtain the azimuth and magnitude of the maximum horizontal movement.

In the case of those watersheds scheduled for clear-cutting, it was necessary to install the casing in such a manner that it would not be damaged during logging operations. Accordingly, a coupling and removable section were attached to the casing about 18 inches below the ground surface. Each of the holes

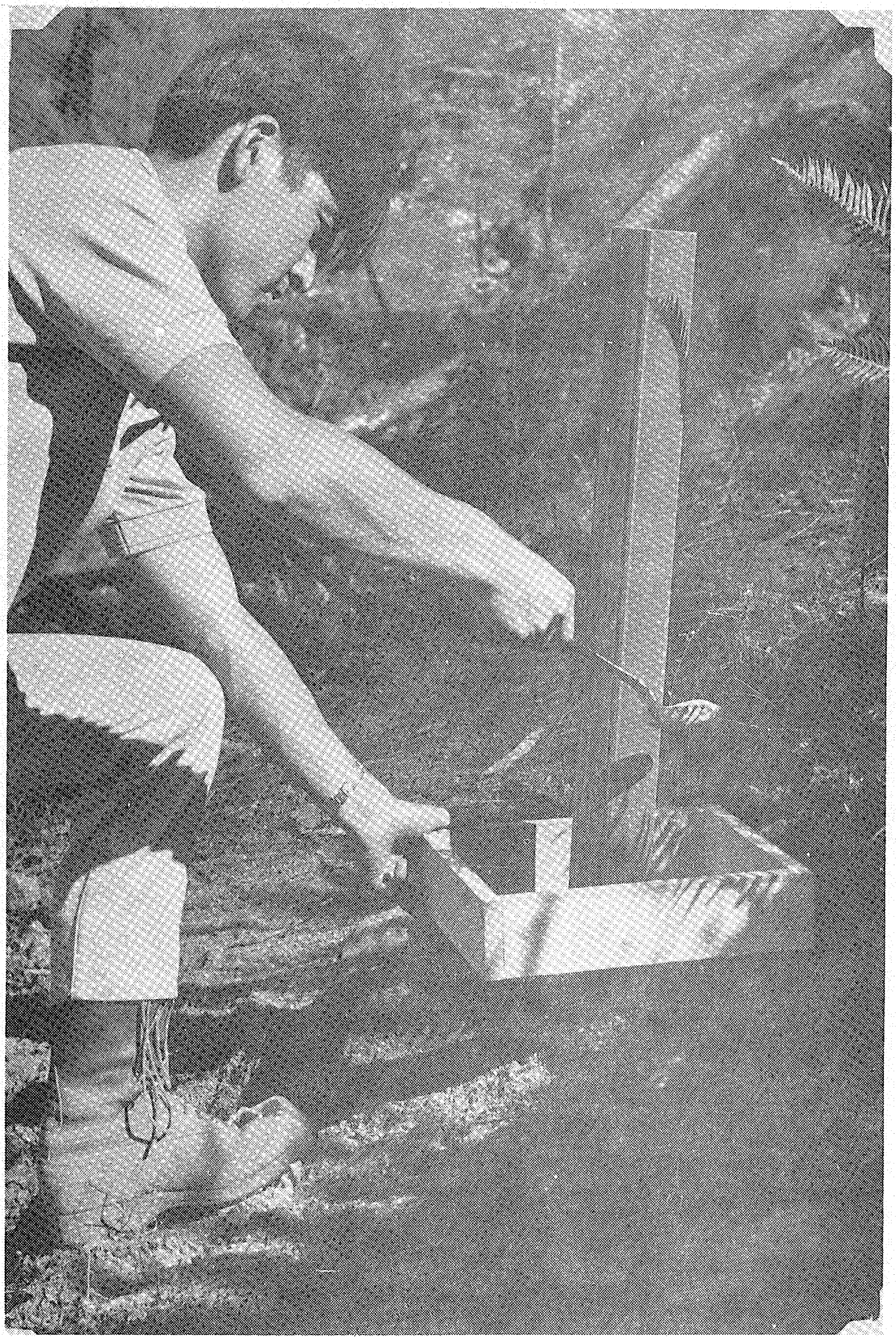


Figure 23. Backfilling around slope indicator casing using the "single grain air dropping" technique.

Figure 24. Drilling a hole for a slope indicator tube using a portable, power auger.

was then carefully surveyed so that they could be relocated without the tops of the casings being visible above ground. When the time comes for logging, the top sections of the casing will be removed, the casing capped, and the top of the hole filled in completely.

Six inclinometer tubes were installed in a random pattern in Watershed No. 1 (clear-cut), five in Watershed No. 2-3 (forested), and six in Watershed No. 10 (forested). In the case of Watershed No. 10, one of the inclinometers was installed in the midst of an area of dead Douglas fir trees. This inclinometer is located only 6 feet away from a large diameter Douglas fir snag as shown in Figure 25. The location or siting pattern of the inclinometer tubes at the Oregon sites is shown in Figures 26 and 27.

Nine inclinometer tubes were installed in a line parallel to the slope but straddling the tree line at the U.S. Naval Radio Station as shown in Figure 28. In addition, an inclinometer installed by the Navy, in a deep section of glacial till on a slope immediately above the transmitter station was also monitored.

A total of eleven inclinometer tubes were installed at the various sites in the Klamath National Forest; seven in the Little South Fork area, three in the Clearview sale site, and one in the Condrey Mountain site. The location pattern for the inclinometer tubes at these sites is shown schematically, in Figure 29.

B. MEASUREMENT OF SOIL MOISTURE STRESS

There are several alternative methods of measuring soil moisture stress.

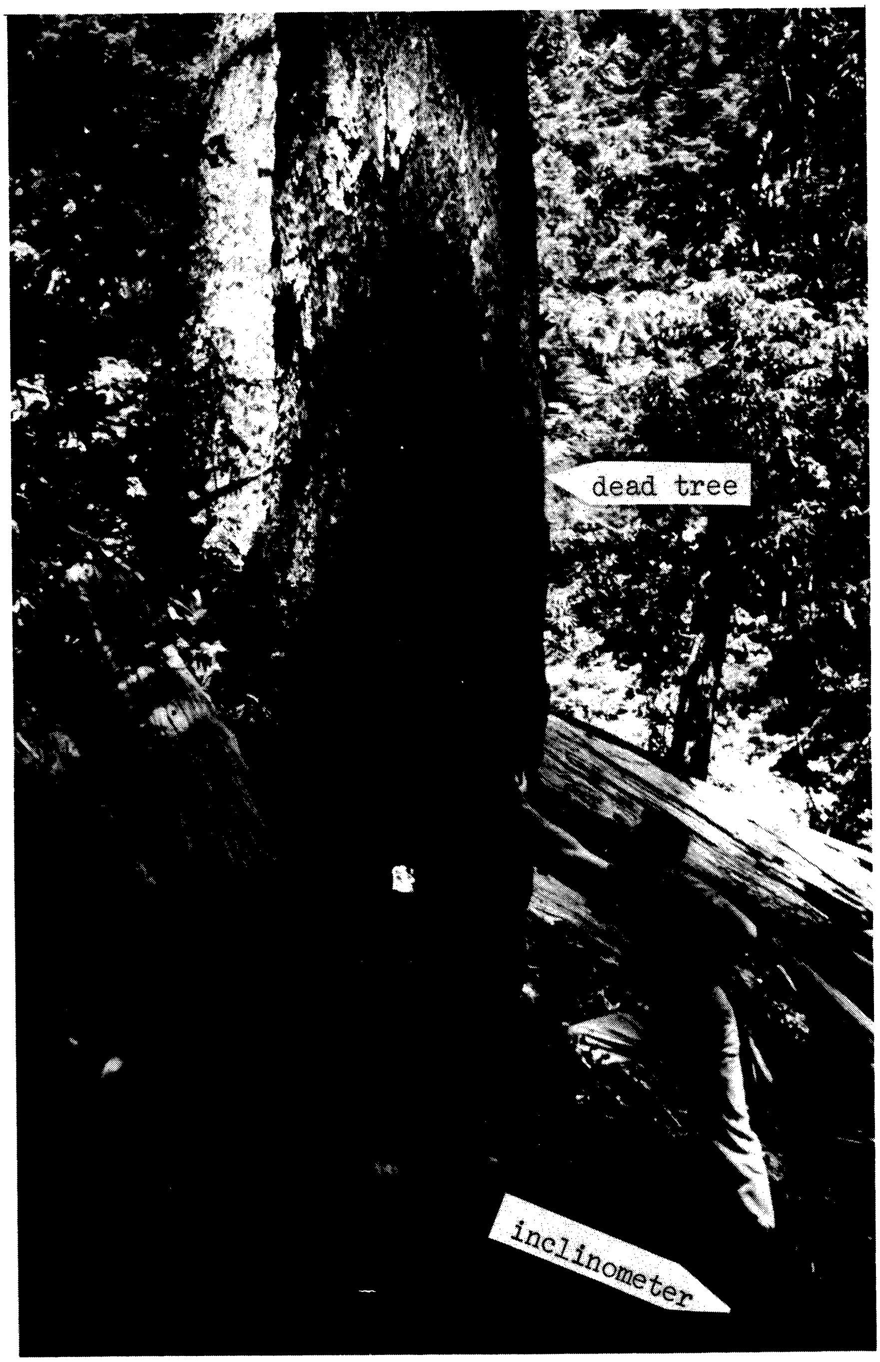


Figure 25. Douglas fir snag (dead tree) located next to inclinometer tube No. 4, Watershed No. 10, H. J. Andrews Experimental Forest.

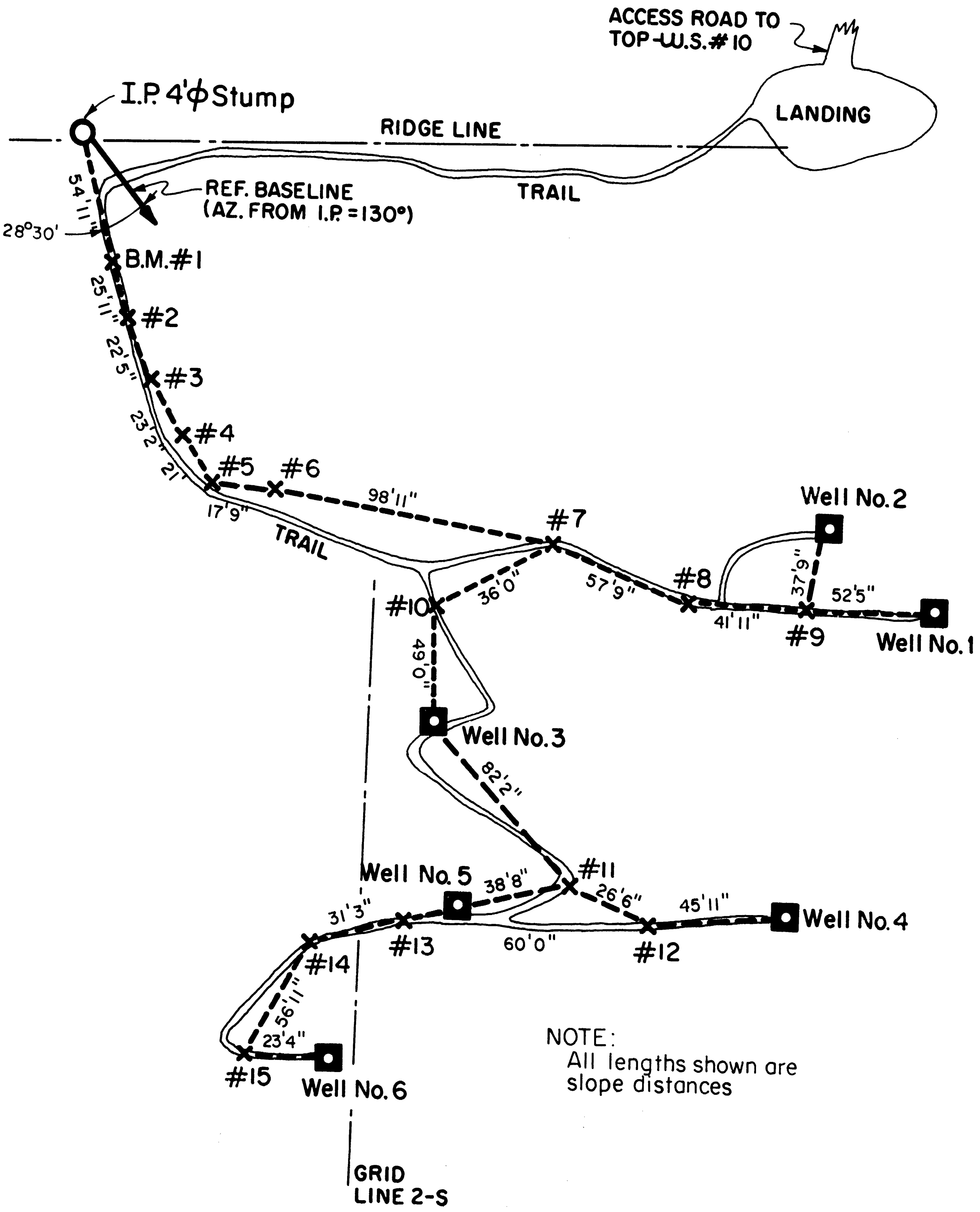


Figure 26. Surveyed location of inclinometer tubes, Watershed No. 10, H. J. Andrews Experimental Forest.

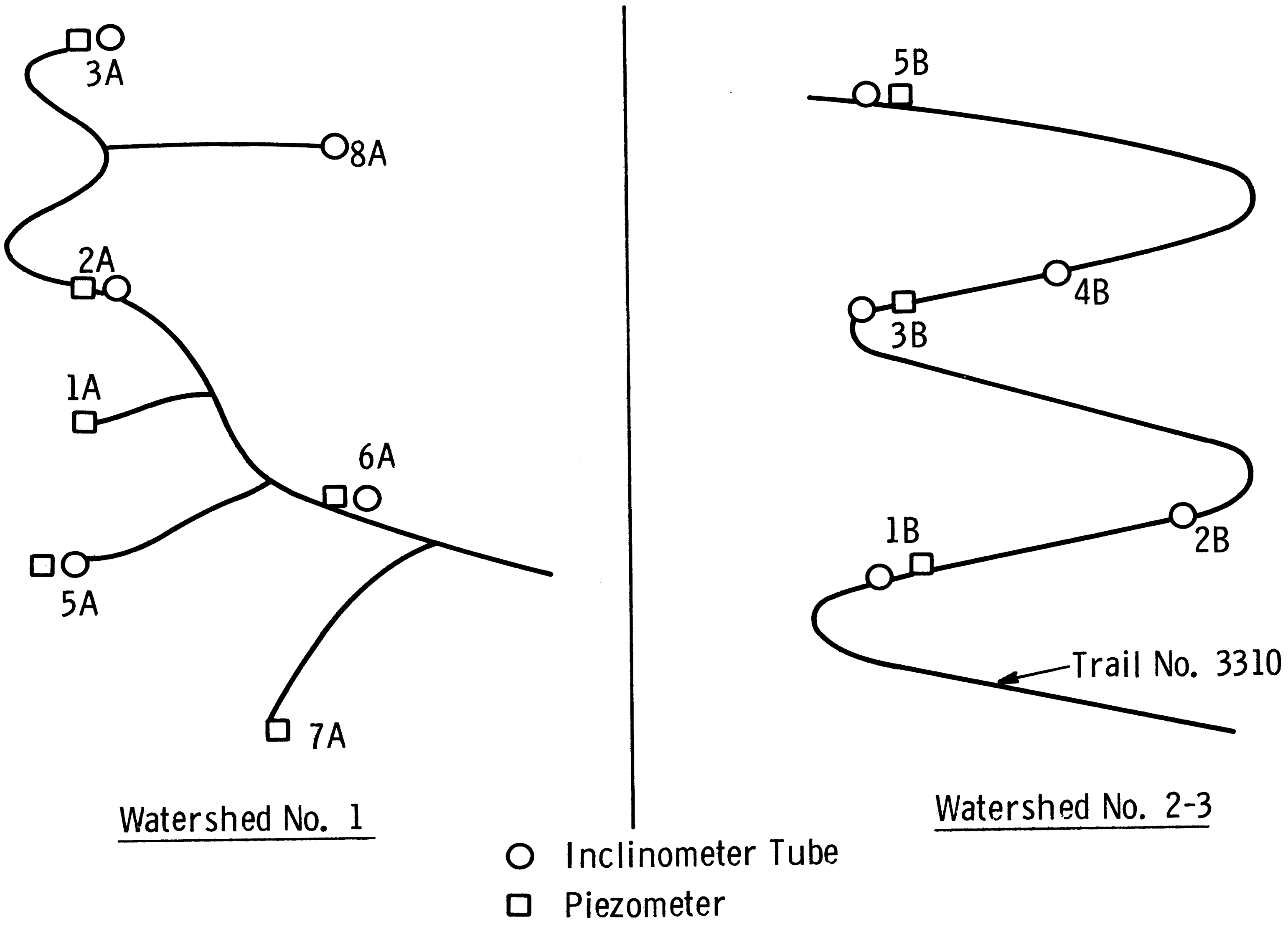


Figure 27. Approximate location or siting pattern of inclinometers in Watersheds No. 1 and No. 2-3, H. J. Andrews Experimental Forest.

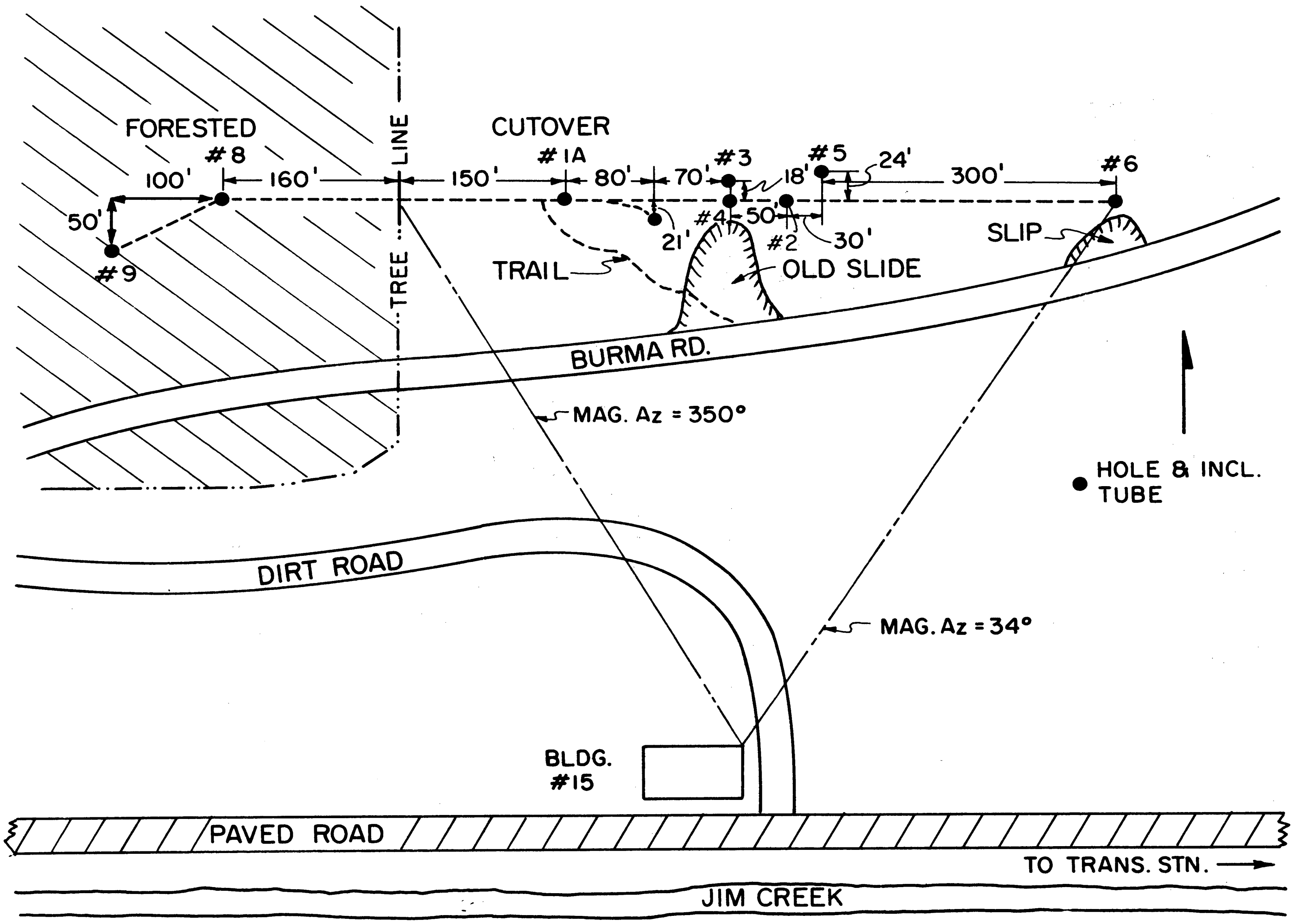
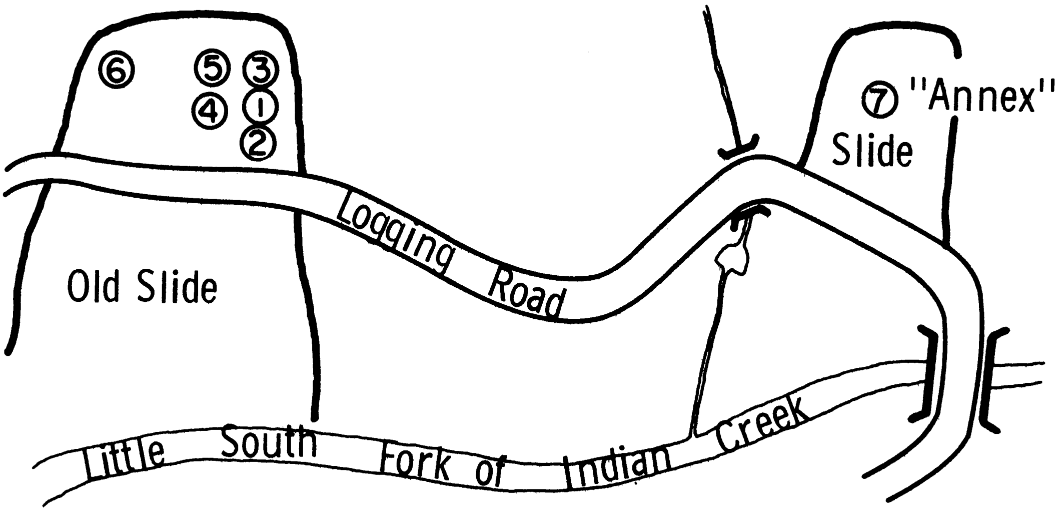
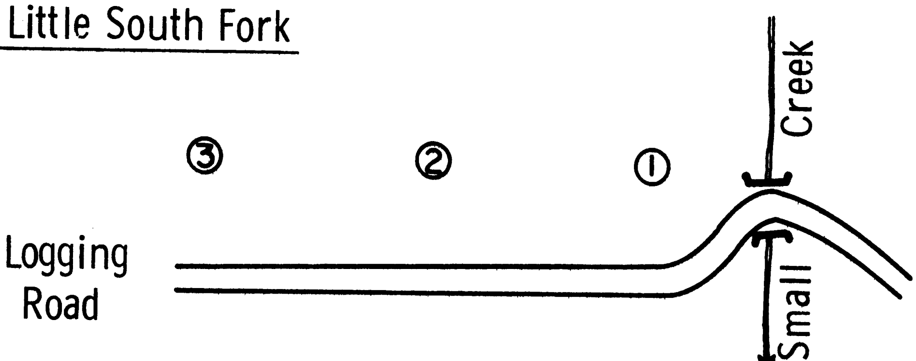


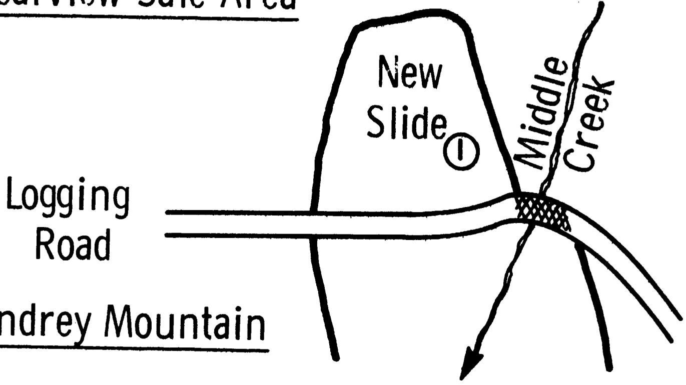
Figure 28. Inclinometer tube locations, U. S. Naval Radio Station, Jim Creek, Washington.



A. Little South Fork



B. Clearview Sale Area



C. Condrey Mountain

Figure 29. Siting pattern for inclinometer tubes installed at various sites in the Klamath National Forest.

These include conventional piezometers, maximum recording piezometers, conventional tensiometers, and recording tensiometer-piezometers. The advantages and limitations of each of these methods in regard to the present study has been discussed previously by Gray (1969).

With the notable exception of the cutover portion of the site in Washington, all the sites exhibited soil moisture suctions (negative pore pressures) during most of the year. We decided, therefore to monitor the soil moisture regime with tensiometers. Where ground water tables or piezometric levels develop in the slope, such as the site in Washington, the inclinometer tubes served as piezometers as well. Furthermore, by adjusting the zero point of a tensiometer it is possible to use it as a piezometer over a limited range. One foot of rise in the groundwater table above the porous, measuring tip corresponds to about 3 centibars.

A total of six tensiometers were installed adjacent to the inclinometer holes in Watershed No. 10, H.J. Andrews Experimental Forest. Three tensiometers were installed adjacent the inclinometer holes in the Clearview site, Klamath National Forest. Four-foot long, Bourdon gage type tensiometers were used. These have a sensitivity of only 1 or 2 centibars compared to 1 or 2 millibars for the mercury manometer type, but they are far more rugged. The tensiometers were installed with their measuring tips 5 feet below the surface of the ground and their tops recessed about a foot below the ground surface in a 4-inch diameter cased hole. Figure 30 is a schematic illustration of a typical tensiometer installation.

Tensiometers will cavitate and eventually lose their water at negative

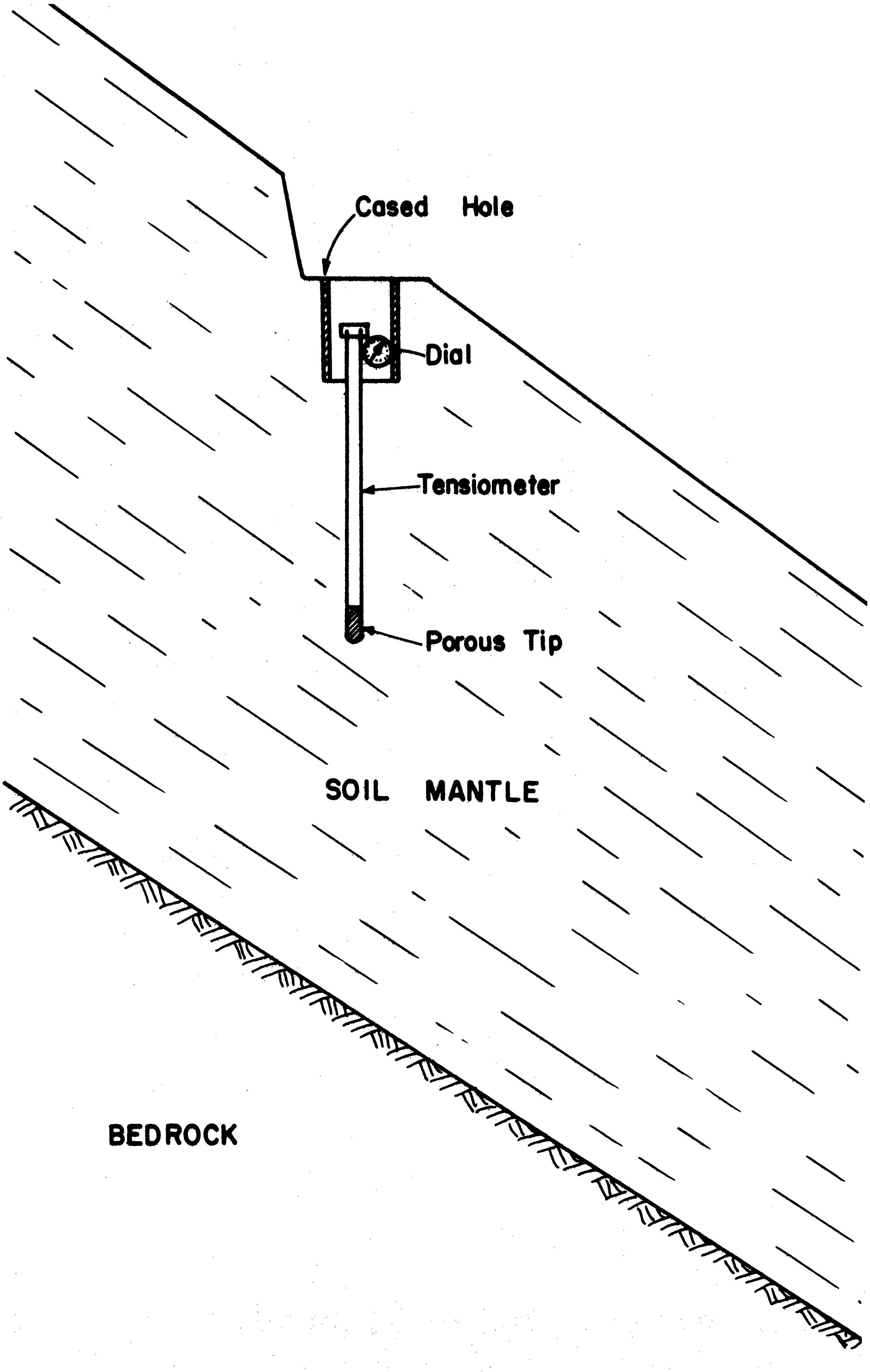


Figure 30. Schematic diagram of a typical tensiometer installation.

pressures or suctions greater than 1 bar. Suctions on this order and higher are common in the top few feet of a forested slope, expecially during the summer months (Patric <u>et al</u>., 1965). For this reason it was necessary to recharge the tensiometers at the end of the summer and also be careful in taking subsequent readings to ensure that low readings in fact meant saturated conditions in the slope and not a spurious effect of cavitation.

Tensiometers were scheduled to be read at least once a month and after major storms. This schedule was not consistently followed because of access problems at the sites. The data from the tensiometers was compared with precipitation records in order to determine the relationship between soil moisture stress and antecedent precipitation in a forested slope. The same procedure will be followed after clear-cutting and the soil moisture response compared to the forested condition.

V. SOIL PROPERTY TESTS

A. SOIL SAMPLING

Both disturbed an undisturbed samples were obtained from the instrumented plots. Disturbed samples were retrieved from the soil brought up by the power auger during drilling of the inclinometer holes. These samples were placed in sealed plastic bags and used for water content determination, Atterberg limits tests, and grain size analyses.

Relatively undisturbed samples were retrieved by means of a thin-walled piston sampler or Shelby tube. These samples are 2 inches in diameter and 12 inches long. As soon as possible after being brought to the surface the ends of the sample tubes were waxed and capped to prevent moisture loss. These samples were later extruded from their tubes for possible use in triaxial strength tests and for determination of the _in situ_ soil density.

Both disturbed and undisturbed samples were obtained from the soil profile down to fractured bedrock whenever possible. A portable, hydraulic sampling unit was used in conjunction with an Acker drill set for either drilling or sampling. It consisted of a small tripod which could be anchored to the ground by means of screw augers and a hydraulic piston at the top which could exert a one-ton push or pull on the drill string while it was rotated by the operator.

B. MEASUREMENT OF _IN SITU_ SHEAR STRENGTH

The shear strength of soils from the various sites was measured by means of an Iowa bore hole, direct shear device. The operation of this instrument has been described in detail by Handy and Fox (1967). Its main advantages are speed of operation, in situ capability, and elimination of sampling disturbance.

The device consists of a head or packer consisting of two half-cylinders with a serrated outer surface which are expanded against the sides of a bore hole with a known normal stress. The packer is attached to a yoke which in turn is connected to a string of pulling rods extending up the hole as shown in Figure 31. The normal stress is applied against the sides of the hole a sufficiently long time to allow for consolidation. The packer is then pulled up the hole at a steady rate by means of a hand operated, worm gear assembly. This upward, tangential force is converted to a shear stress by transferring the force to a hydraulic weighing platform on which the worm gear assembly rests.

The tangential or shear load is increased until it reaches a maximum or steady value. This shear stress and the corresponding normal stress is recorded. The shear stress is then released, the normal stress increased to a new level, and the entire procedure repeated. It is not necessary to move the measuring head to a new location each time. The failure envelope and shear strength parameters can thus be obtained quickly and directly in the field.

By using the bore hole shear device it was possible to obtain a shear strength profile as a function of depth in a fraction of the time required for triaxial strength tests. A photograph of the device in use in the field is shown in Figure 31.

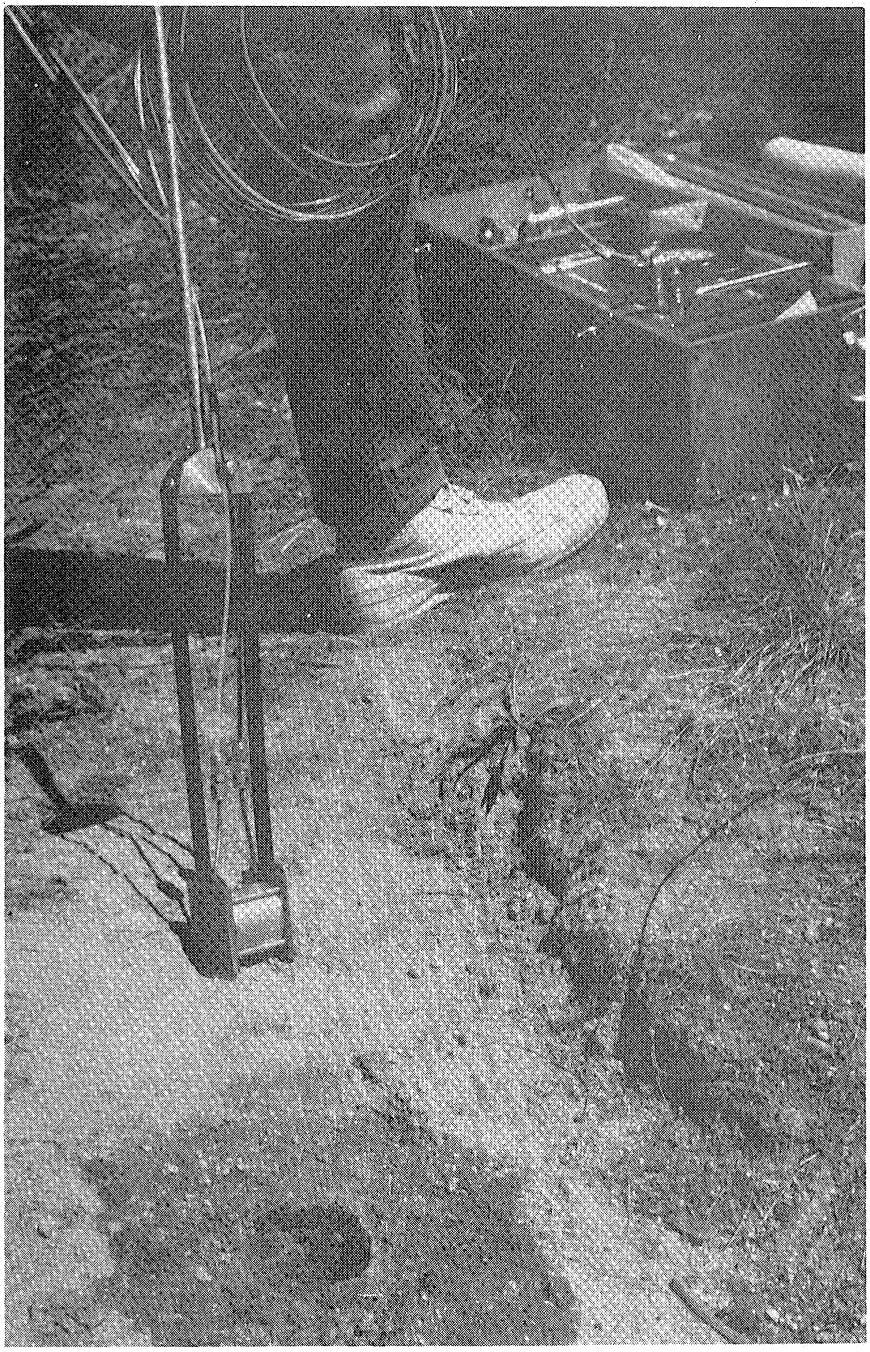


Figure 31. Bore-hole, direct shear device showing expandable head attached to pulling rods.

VI. RESULTS OF FIELD MONITORING

A. CREEP MOVEMENT

1. H. J. Andrews Experimental Forest

Creep movement was monitored in Watersheds No. 1 and No. 2-3 for a "side-by-side" comparison of a clear-cut and an adjacent forested area. Creep was also monitored in Watershed No. 10 for a "before-and-after" comparison; however, the post clear-cutting data is still lacking for this site.

Creep profiles for each of the inclinometer holes at these sites are presented in Figures 32 through 38. A creep profile is a record of the downslope movement as a function of depth and time. The bottoms of the inclinometer tubes extend into fractured bedrock and are assumed to remain fixed. Downslope movement is measured relative to the bottom of the tubing. The creep profiles have been plotted in terms of cumulative dial change readings. These readings can be converted to displacements by multiplying by a constant of .003. A conversion scale is shown at the bottom of most of the profiles.

The inclinometers are designed to provide information on the direction of movement. One set of grooves was oriented as nearly possible in a down dip direction (perpendicular to the strike of the slope). Maximum movement occurs approximately in this direction; hence, only the results of creep in this downslope direction (identified as north-south in the data sheets) are included in this report. Some movement perpendicular to this direction was recorded in a few holes; Figure 39 gives an idea of the extent of this lateral movement in such a hole.

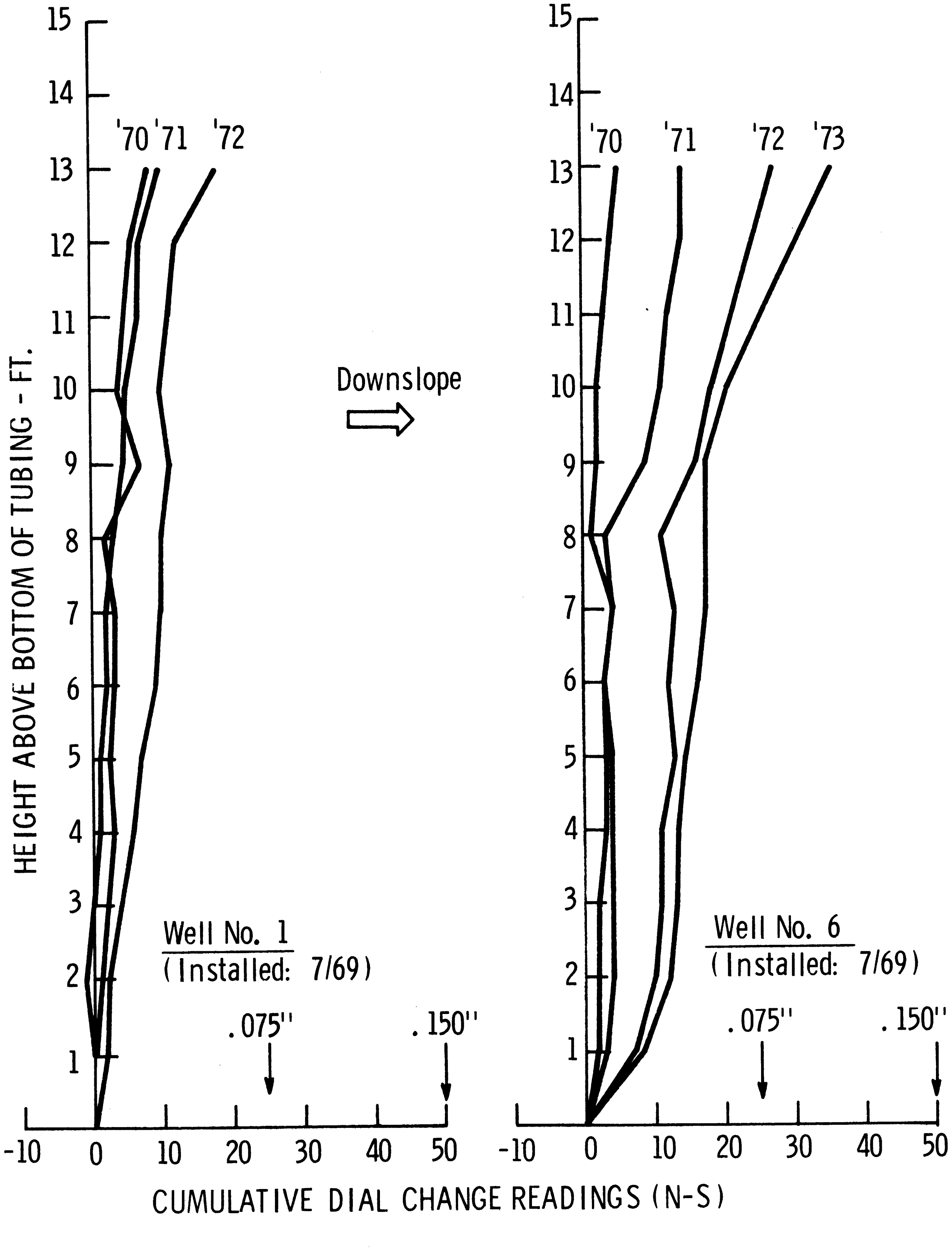


Figure 32. Creep profiles, Watershed No. 10 (forested), H. J. Andrews Experimental Forest.

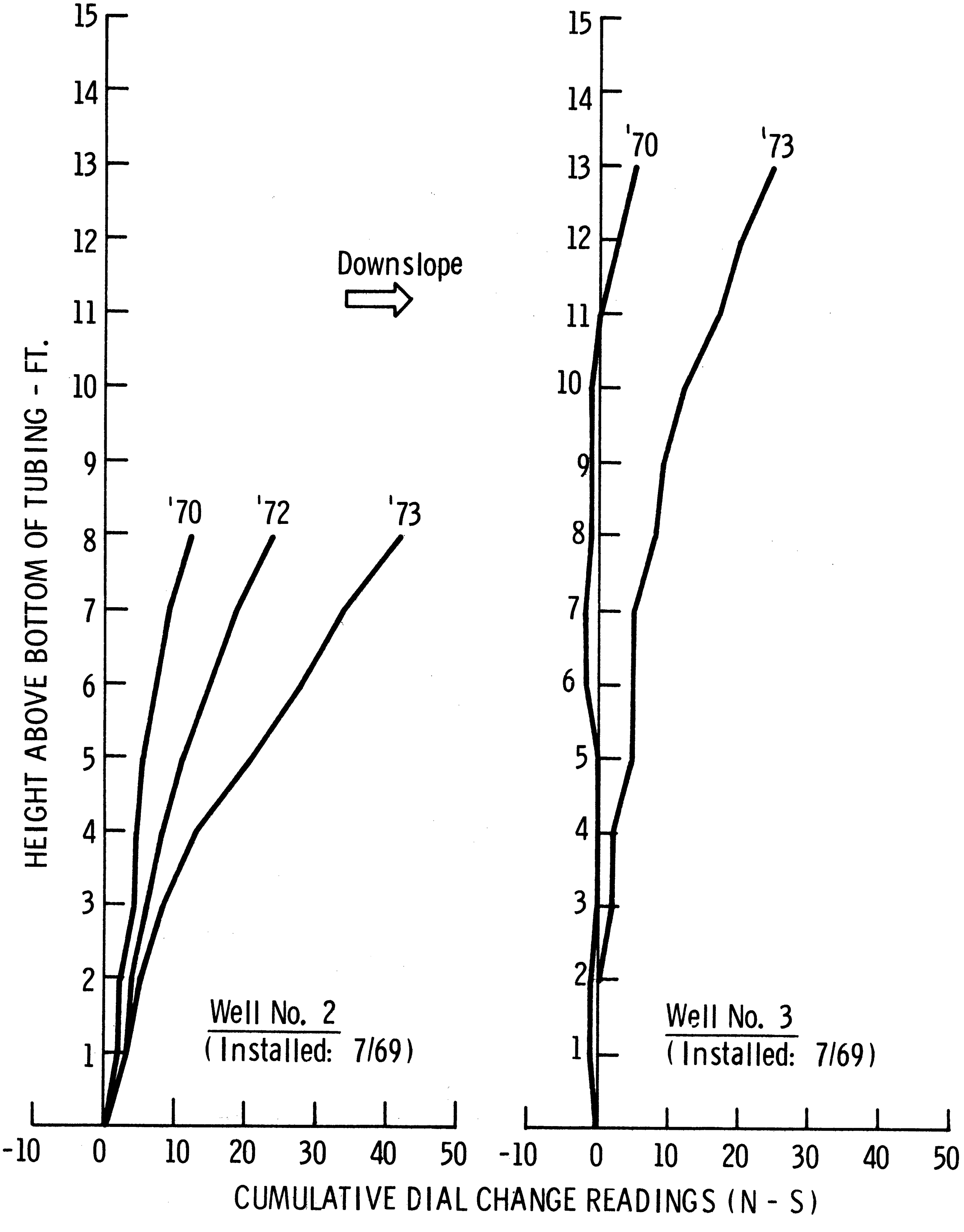


Figure 33. Creep profiles, Watershed No. 10 (forested), H. J. Andrews Experimental Forest.

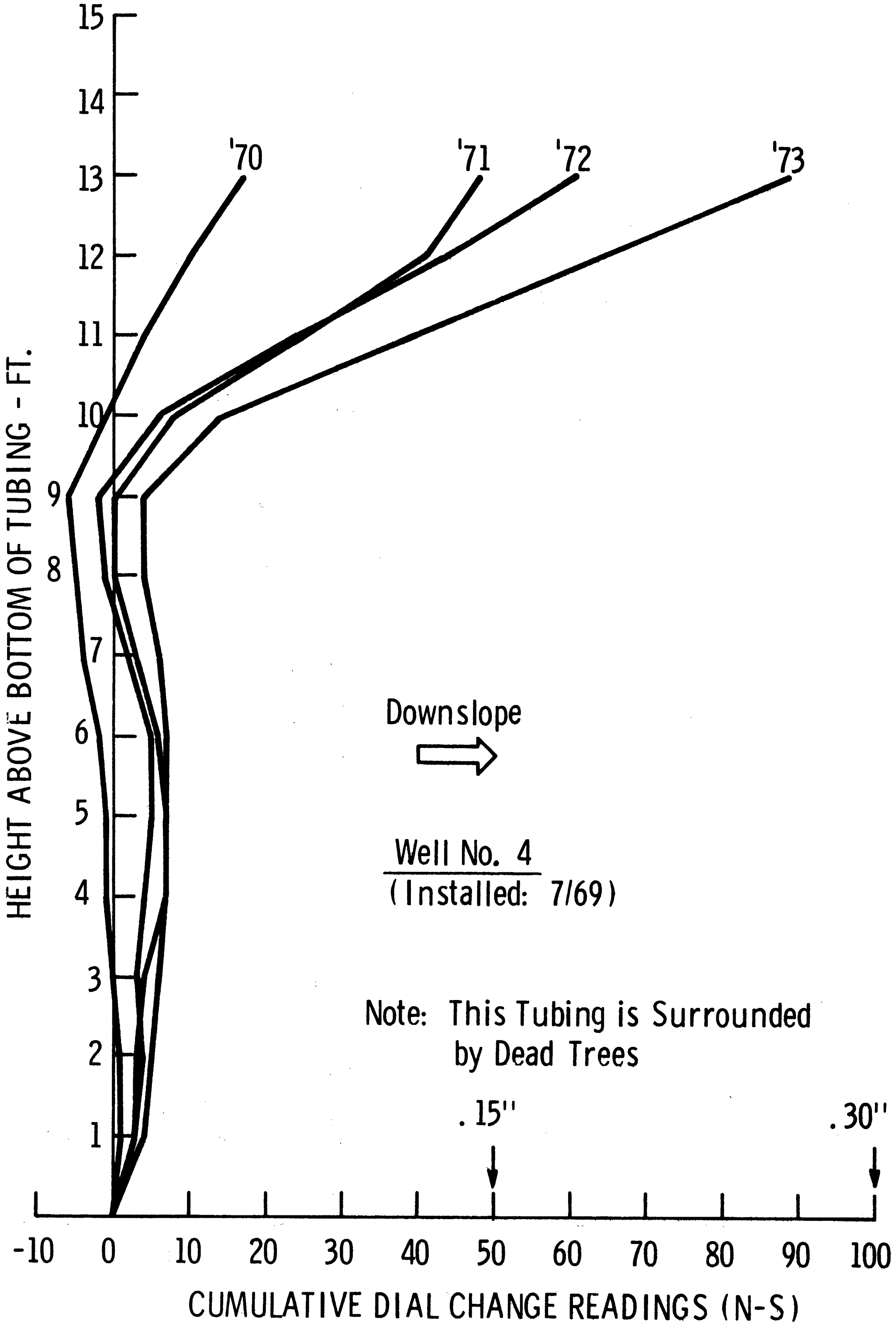


Figure 34. Creep profiles, Watershed No. 10 (forested), H. J. Andrews Experimental Forest.

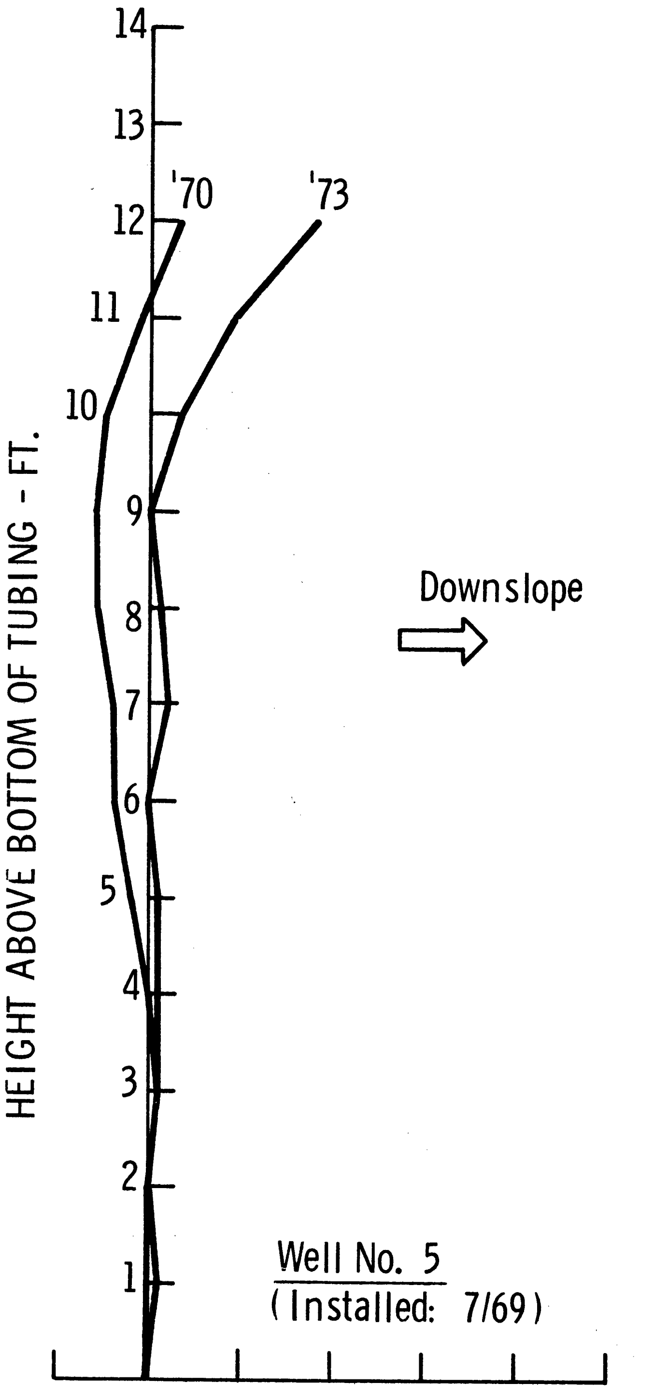


Figure 35. Creep profiles, Watershed No. 10 (forested), H. J. Andrews Experimental Forest.

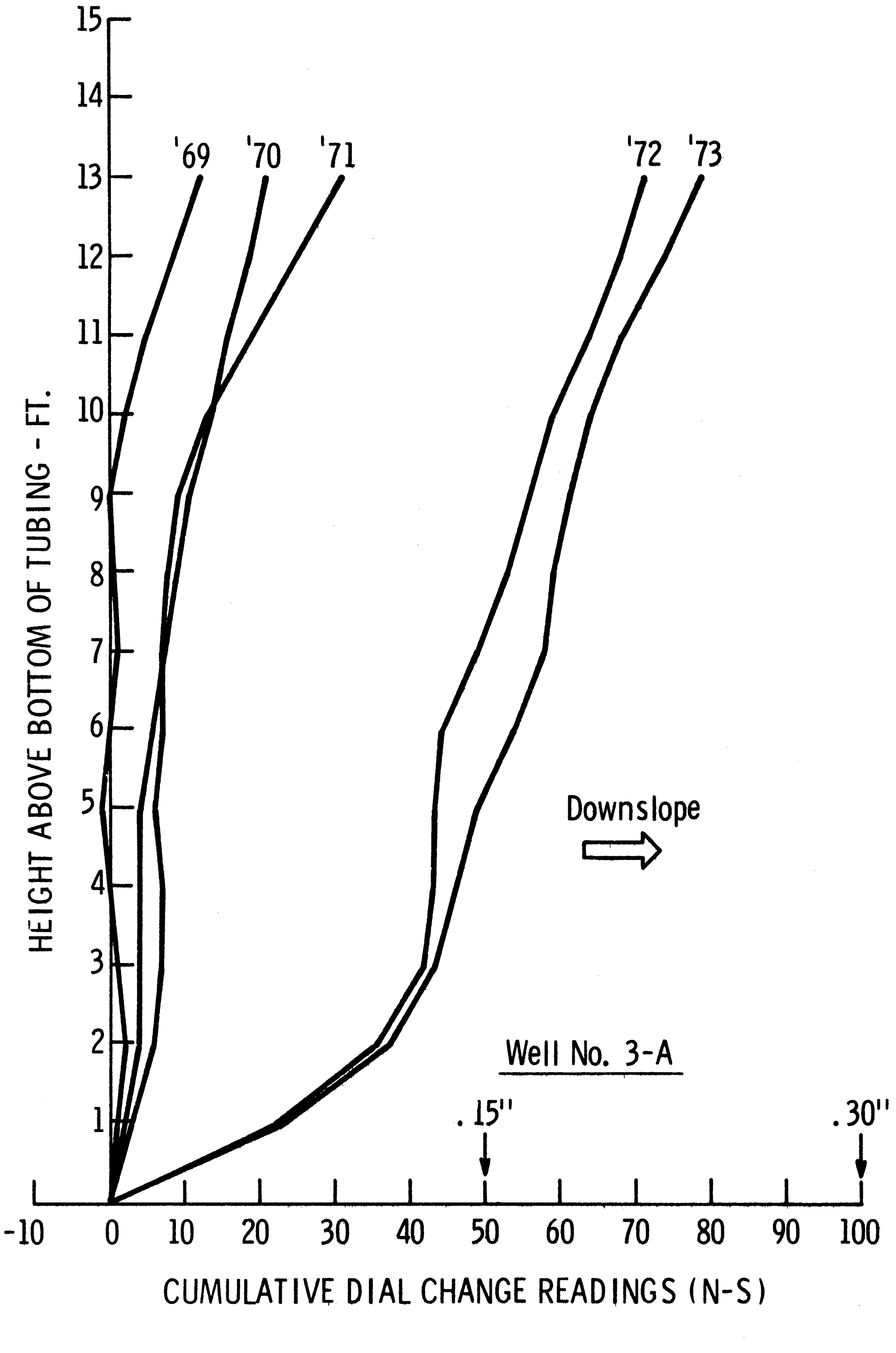


Figure 36. Creep profiles, Watershed No. 1 (clear-cut), H. J. Andrews Experimental Forest.

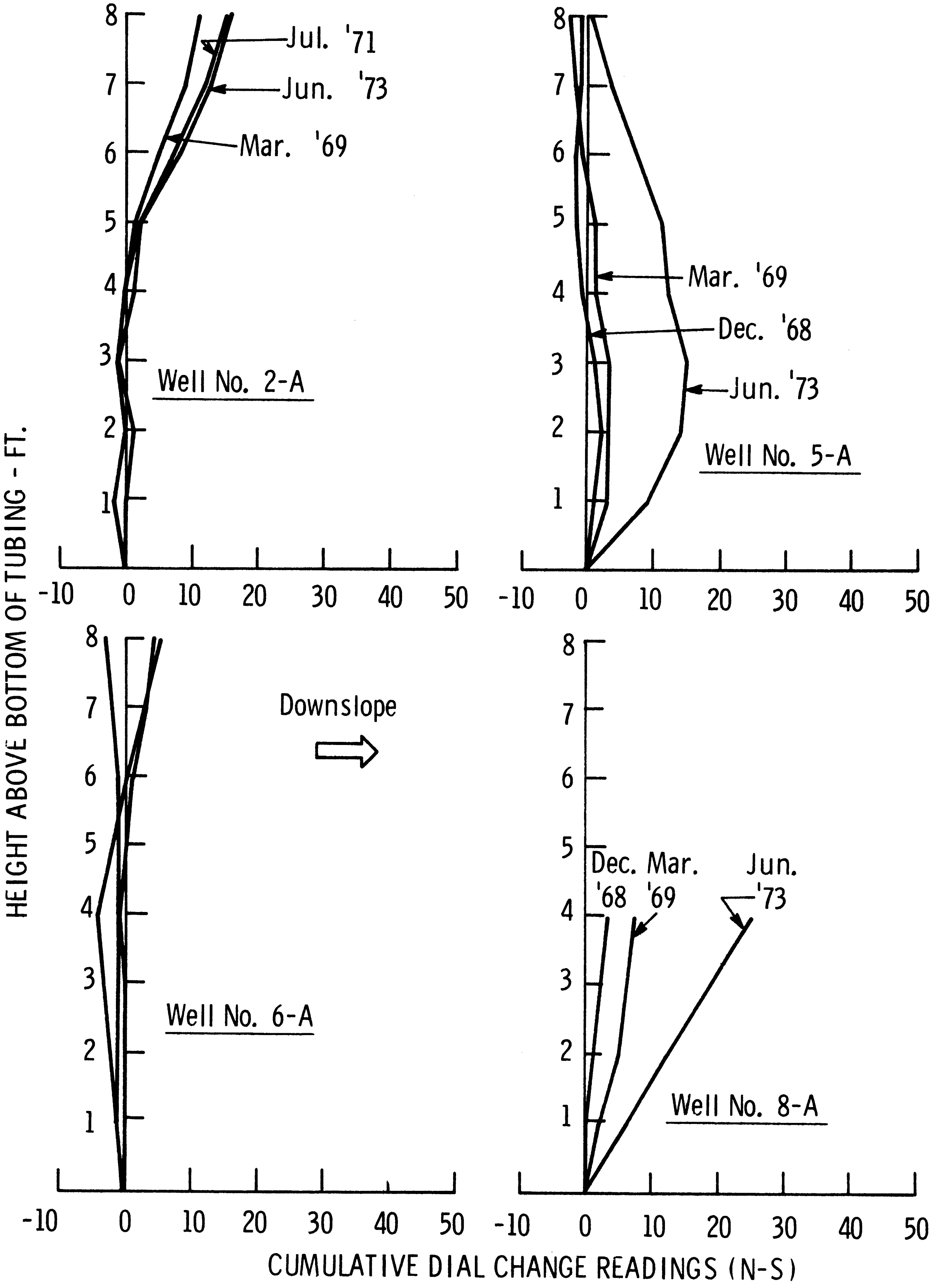


Figure 37. Creep profiles, Watershed No. 1 (clear-cut), H. J. Andrews Experimental Forest.

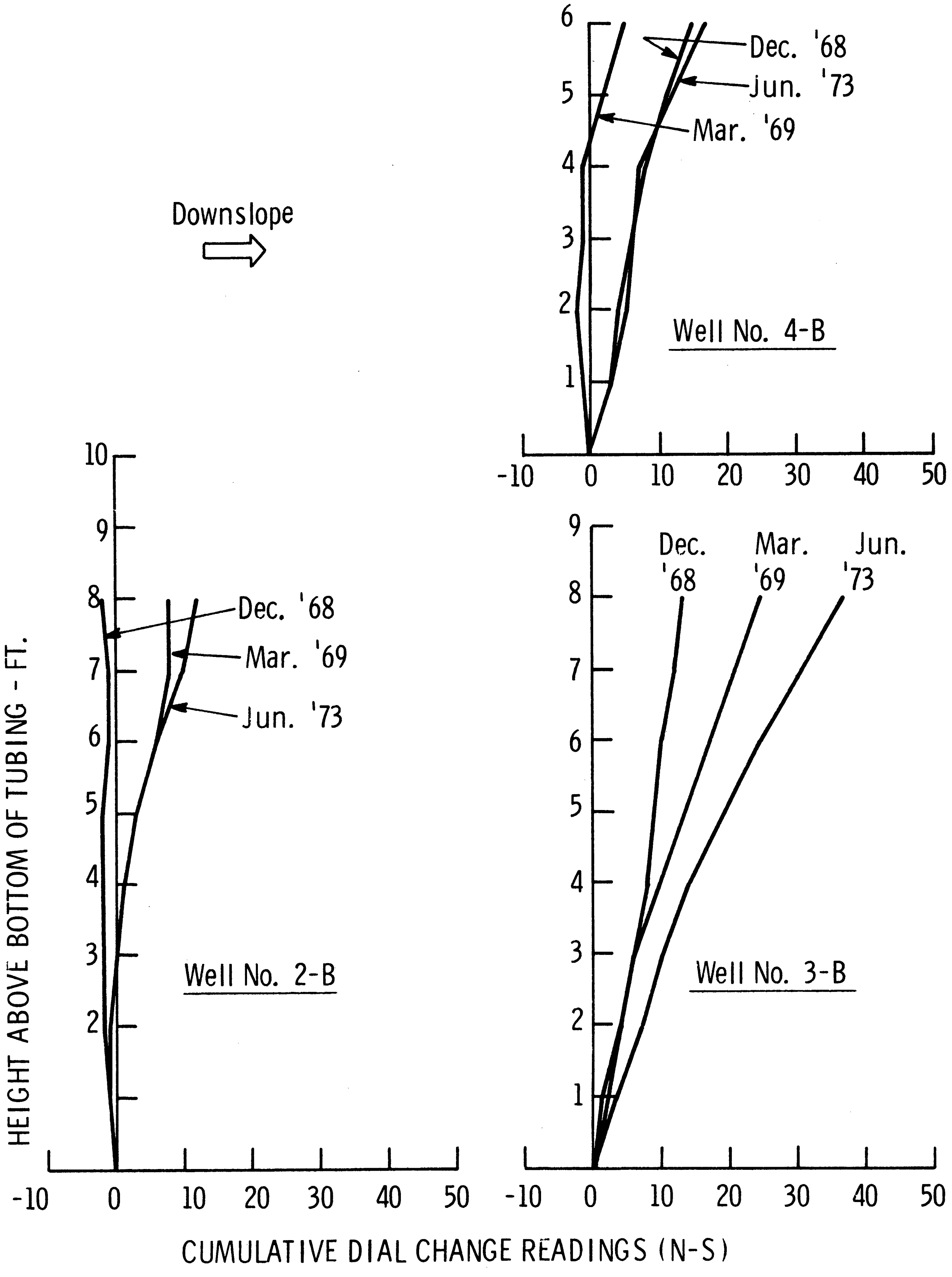


Figure 38. Creep profiles, Watershed No. 2-3 (forested), H. J. Andrews Experimental Forest.

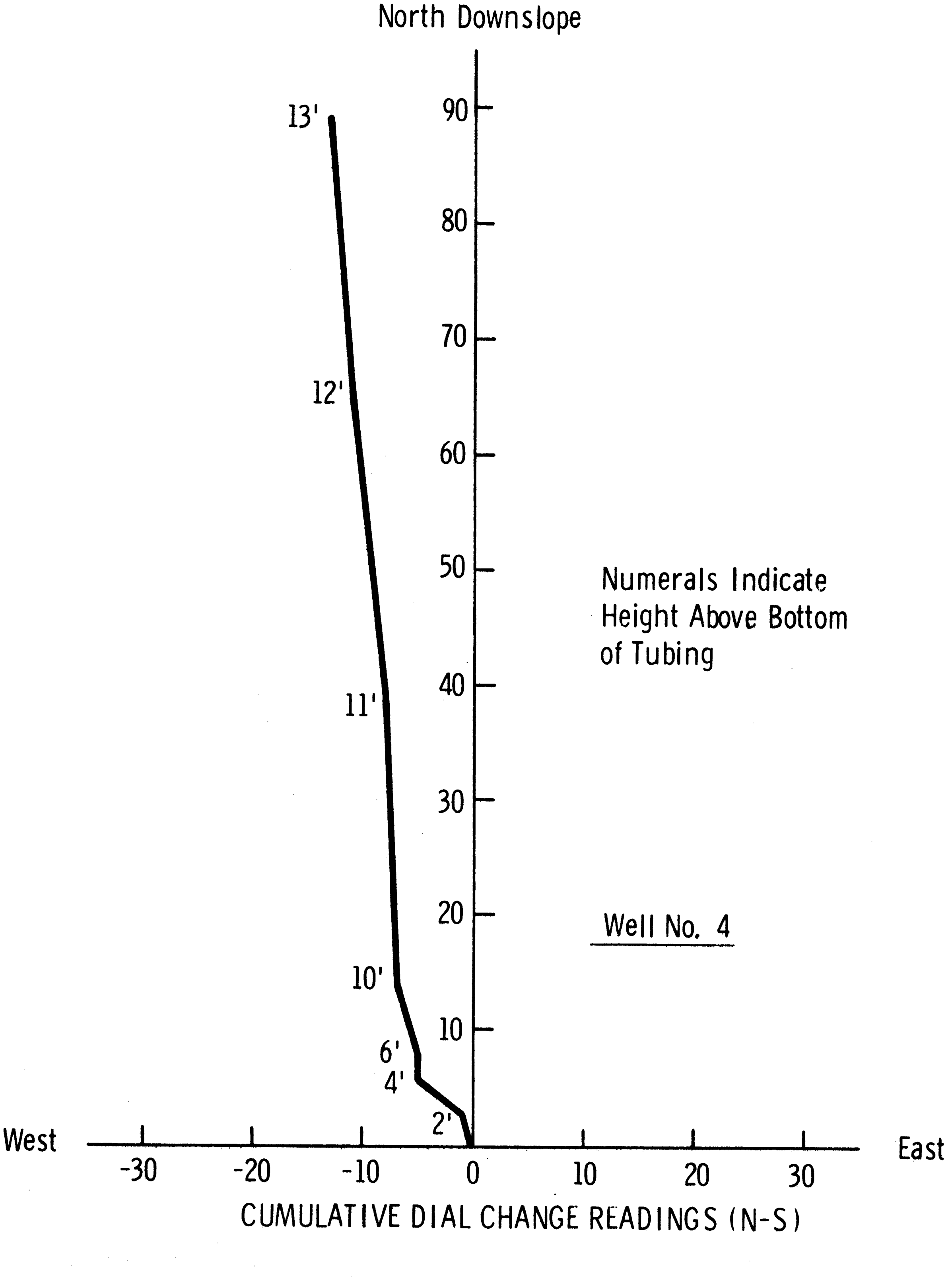


Figure 39. Polar diagram of total creep movement (1973), Watershed No. 10 (forested), H. J. Andrews Experimental Forest.

2. U.S. Naval Radio Station

Creep profiles are presented in Figures 40 and 41. Results of creep measurements commissioned earlier by the Navy in the thick section of glacial till behind the transmitter station are shown in Figure 42.

It is premature to compare creep profiles in the forested and cutover portions of the slope at this time because a different installation procedure was used in each case, and this has affected the results. The soils in the forested slope were so dry, loose, and stony that it was impossible to drill a hole through the soil mantle that would not cave in. Consequently, the inclinometer tubes in the forested area were installed in pits which were dug and backfilled by hand. This same procedure was used to install the inclinometers above the transmitter station.

A serious limitation of this method is that settlement of the backfill inevitably occurs and leads to spurious or apparent creep movement if the initial reading is used as a reference (Wilson, 1970). Unfortunately, no intermediate readings were taken between the initial readings in the summer of 1970 and the readings in the summer of 1973. Therefore, it is uncertain how much of the apparent creep shown in Figure 41 is caused by settlement of the backfill as opposed to true soil mantle creep.

This same problem was encountered to a lesser extent in some of the inclinometer holes in the forested slope No. 2-3 in the H. J. Andrews Experimental Forest. These holes were drilled, with an auger but here too the soil was quite dry and loose. As a result, the sides of the holes tended to slough off and enlarge during drilling. Settlement movement as opposed to creep was

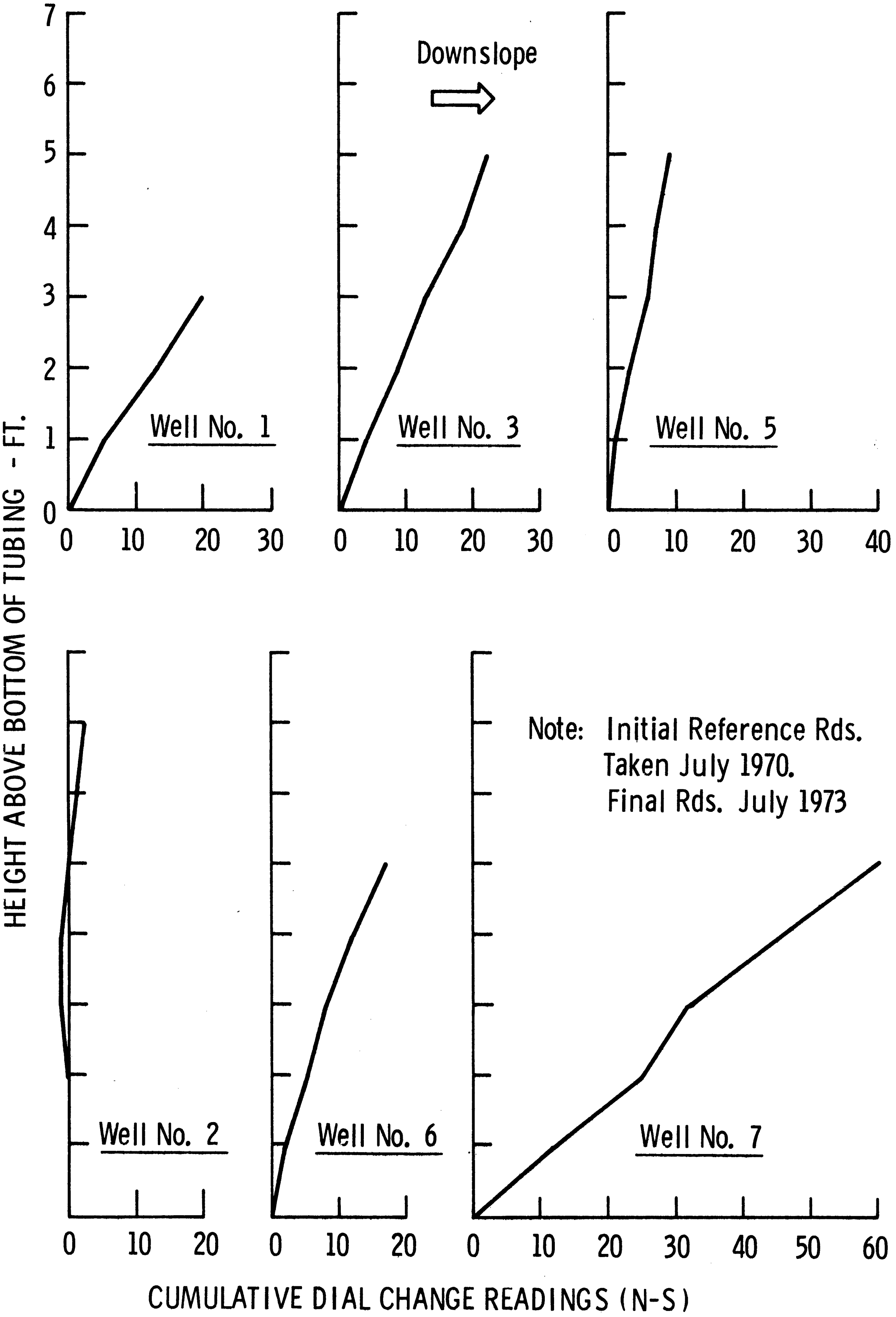
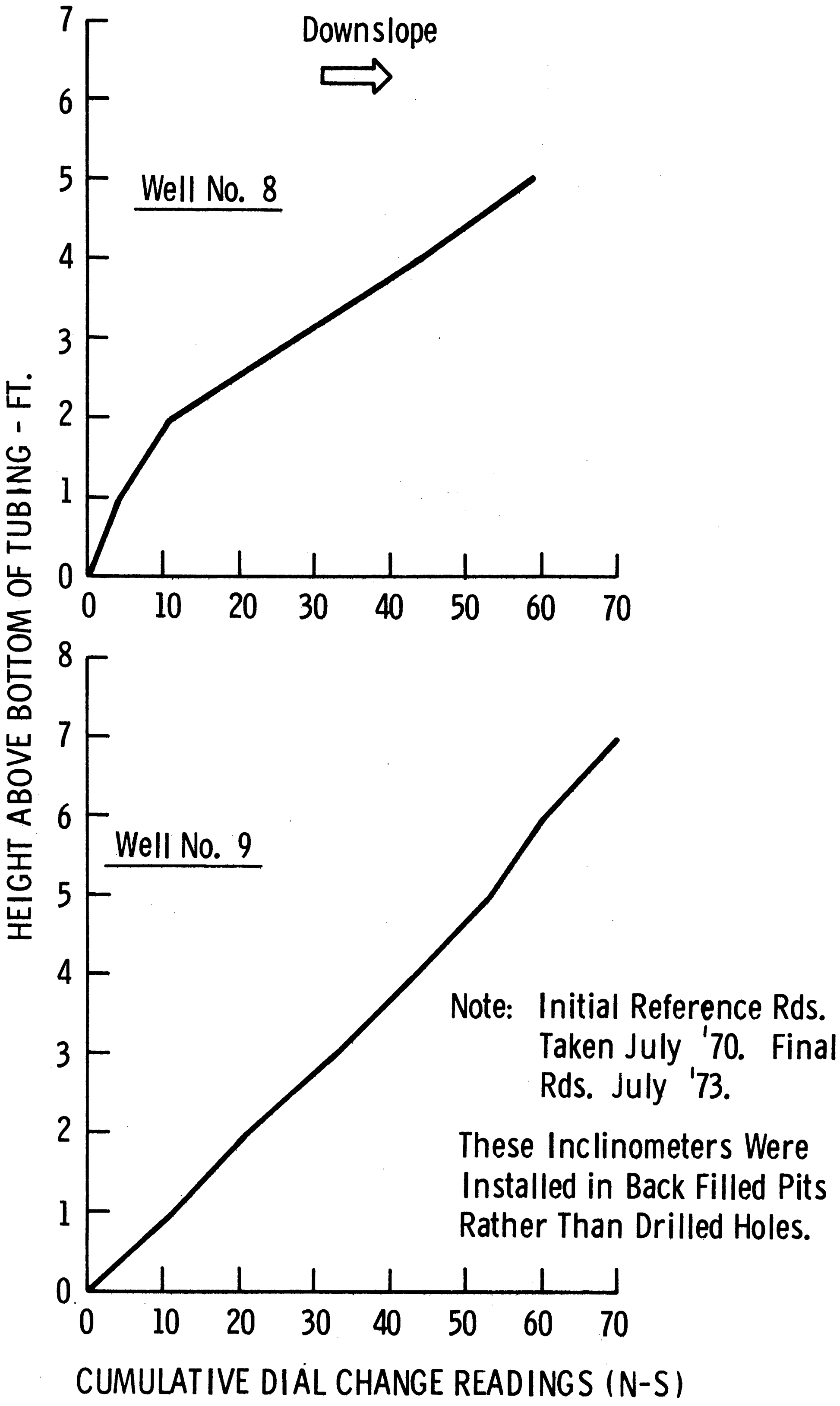


Figure 40. Creep profiles, cutover slope, U. S. Naval Radio Station.



Note: Initial Reference Rds. Taken July '70. Final Rds. July '73.

These Inclinometers Were Installed in Back Filled Pits Rather Than Drilled Holes.

Figure 41. Creep profiles, forested slope, U. S. Naval Radio Station.

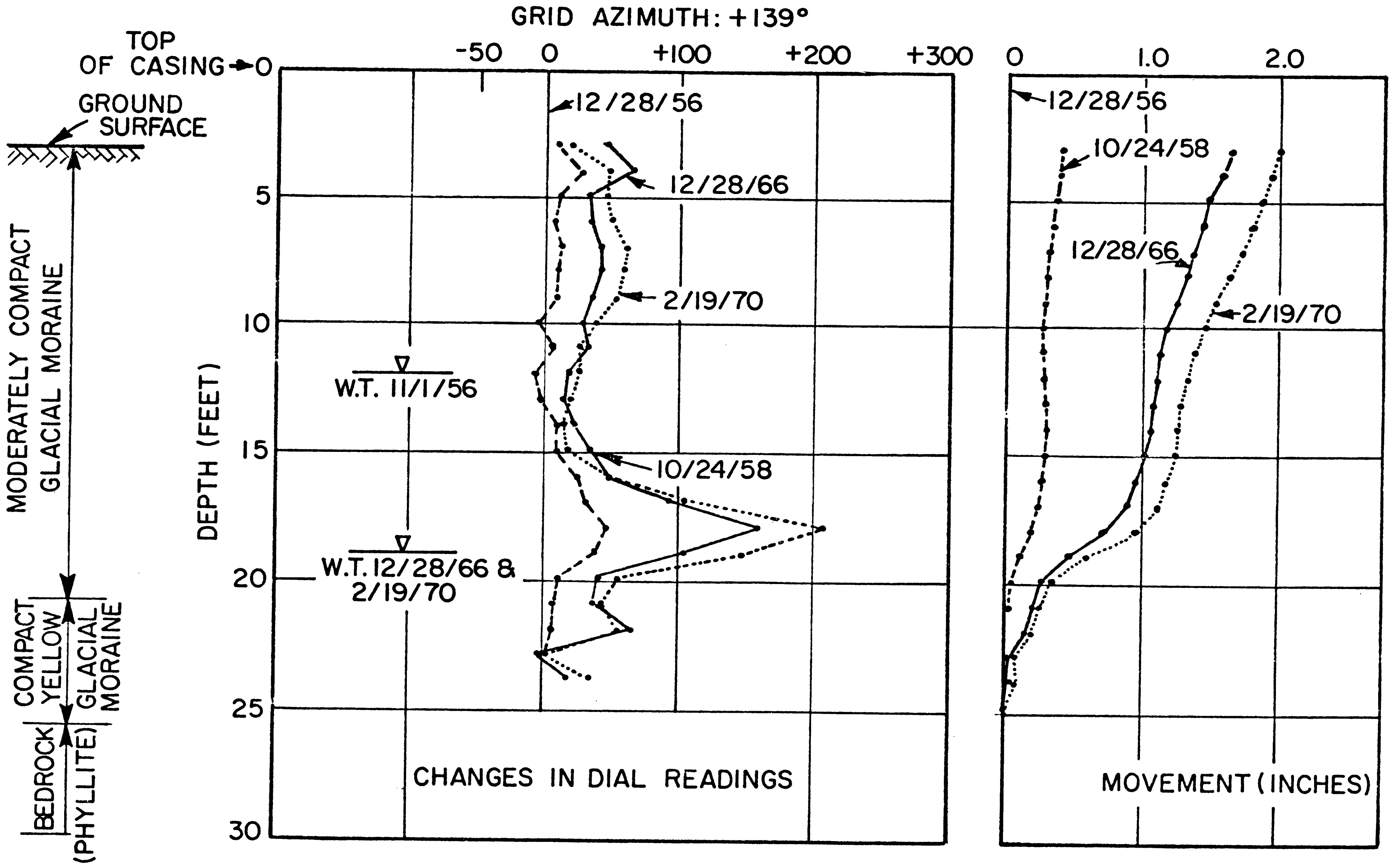


Figure 42. Record of creep movement in the cutover slope above the transmitter station, U. S. Naval Radio Station (from Wilson, 1967 and 1970).

detected here as shown by the high initial movement during the first few months followed by almost imperceptible movement in subsequent years (refer to Figure 38).

3. Klamath National Forest

Creep profiles from the Clearview and Little South Fork sites are presented in Figures 43 through 45. Post clear-cutting data from the Clearview site is still lacking as the site was not scheduled for cutting until the summer of 1973. The Little South Fork site is an active landslide area which was instrumented to obtain an idea of rates of movement in such areas. The creep profiles for the Little South Fork site indicate substantial rates of downslope movement on the order of 2 inches per year at the surface.

B. SOIL MOISTURE STRESS

The soil moisture stress history recorded by the tensiometers in Watershed No. 10 (forested), H. J. Andrews Experimental Forest is presented in Figures 46 and 47. Lapses appear in the soil suction record because of site access difficulties and other problems. The monthly precipitation history is also plotted on these same figures. Soil moisture suction curves appear almost as inverse mirror images of the precipitation curves; as precipitation increases soil suction drops off and vice versa.

An attempt was made to look for a relationship between soil suction and antecedent precipitation of different duration using the data from tensiometer No. 2 as shown in Figures 48 and 49. A three-month antecedent precipitation total appeared to give the best relationship although scatter of data was still

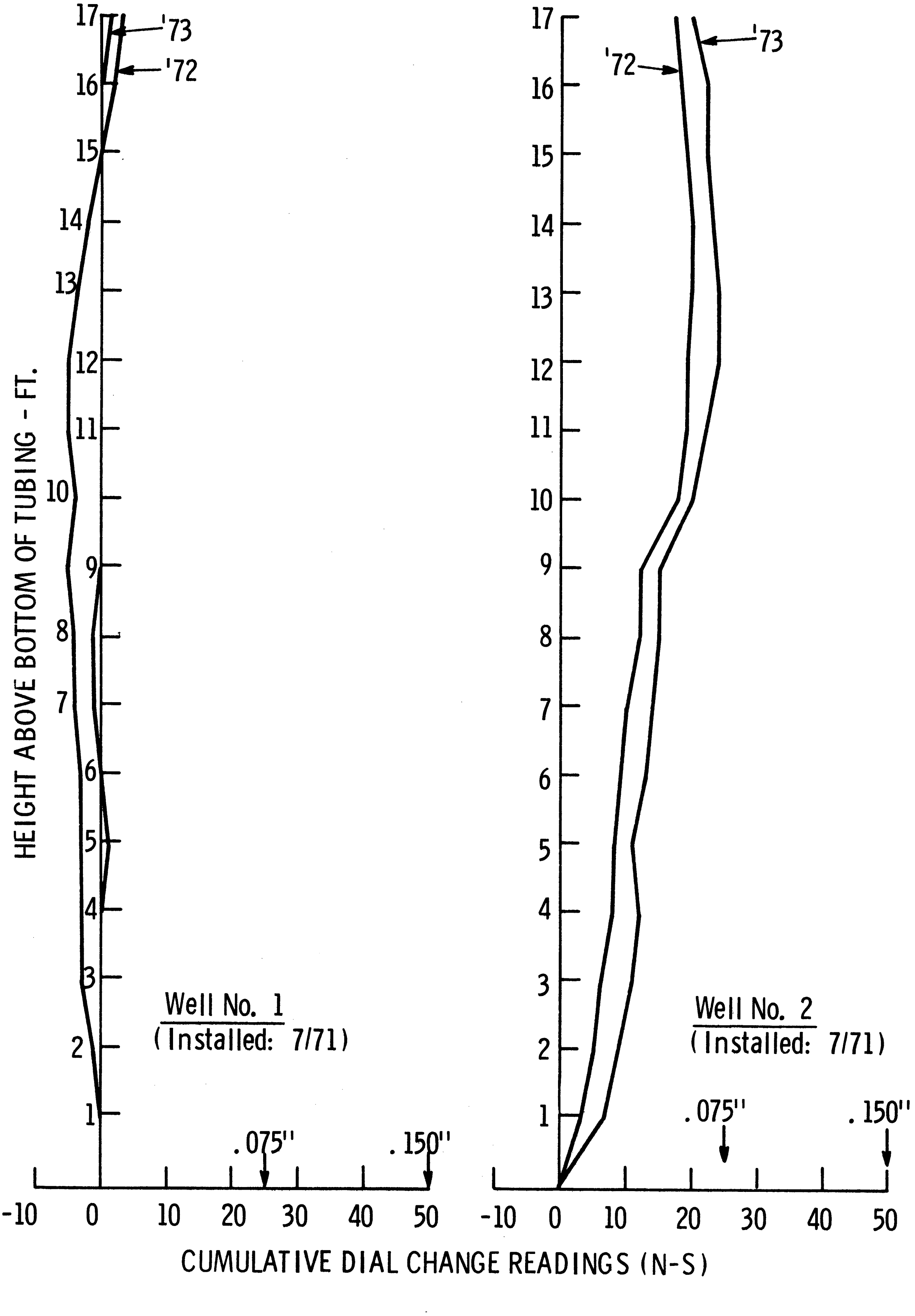


Figure 43. Creep profiles, Clearview sale site, Klamath National Forest.

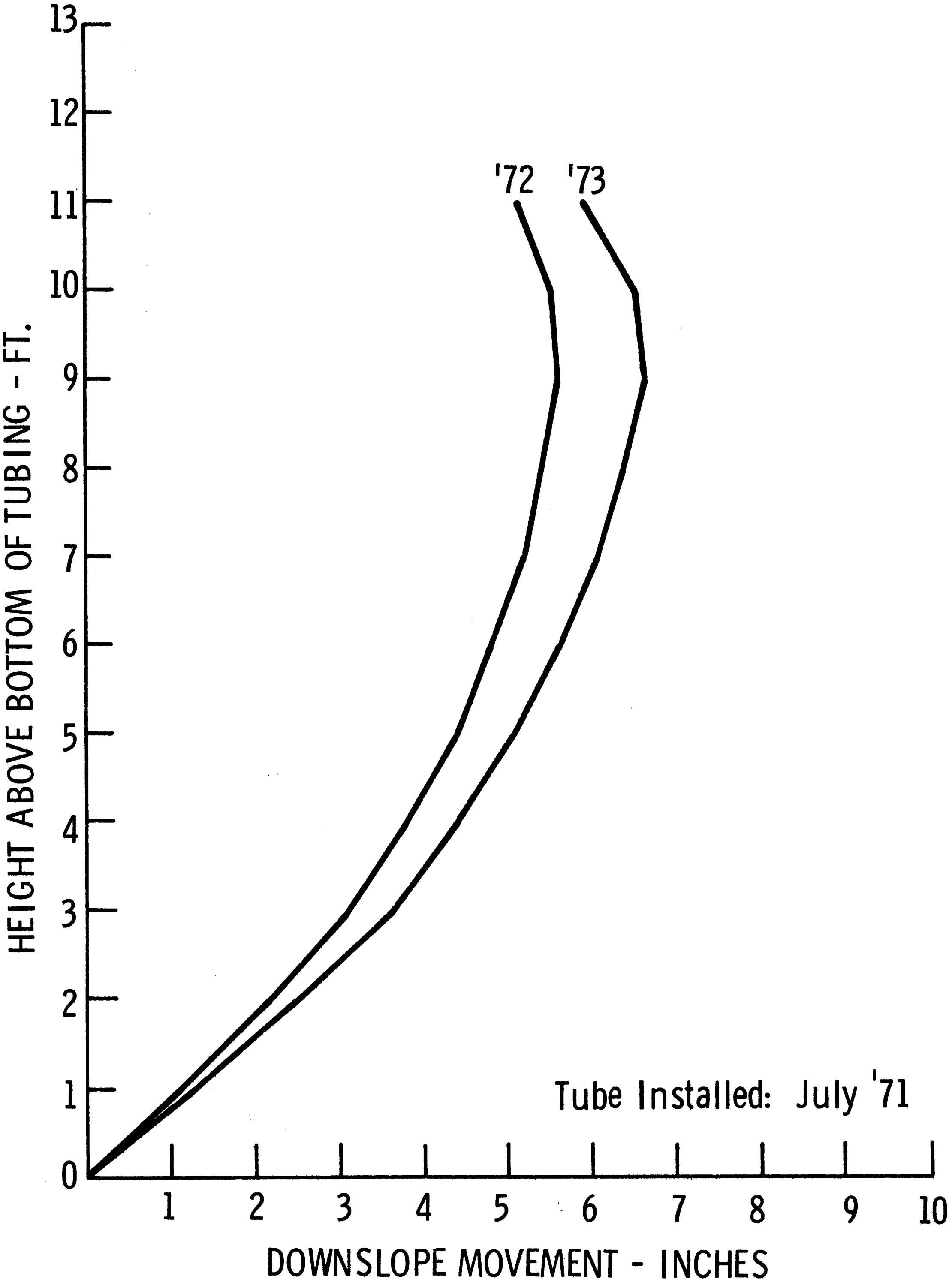


Figure 44. Creep profiles, Little South Fork annex slide, Klamath National Forest.

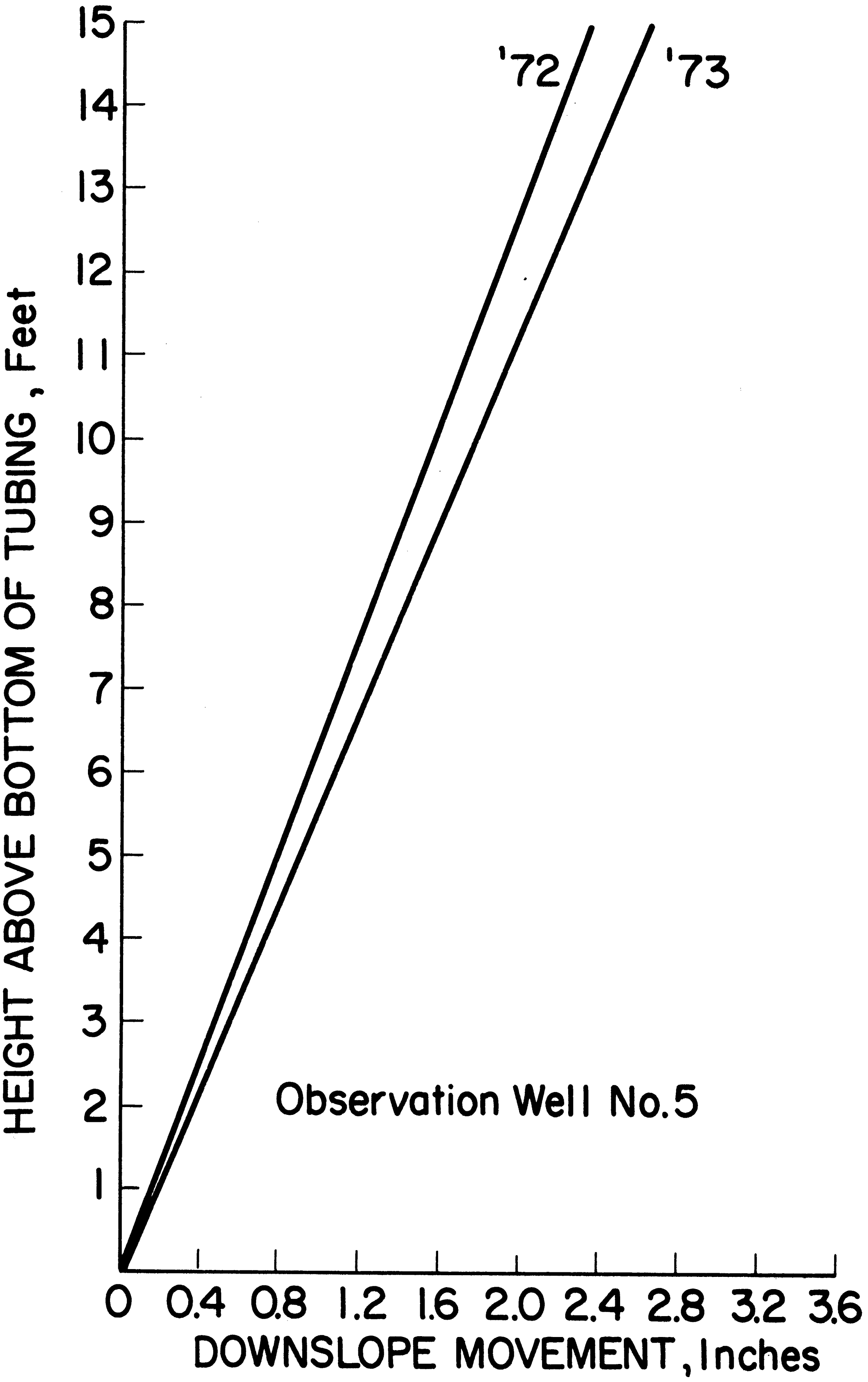


Figure 45. Creep profiles, Little South Fork landslide, Klamath National Forest.

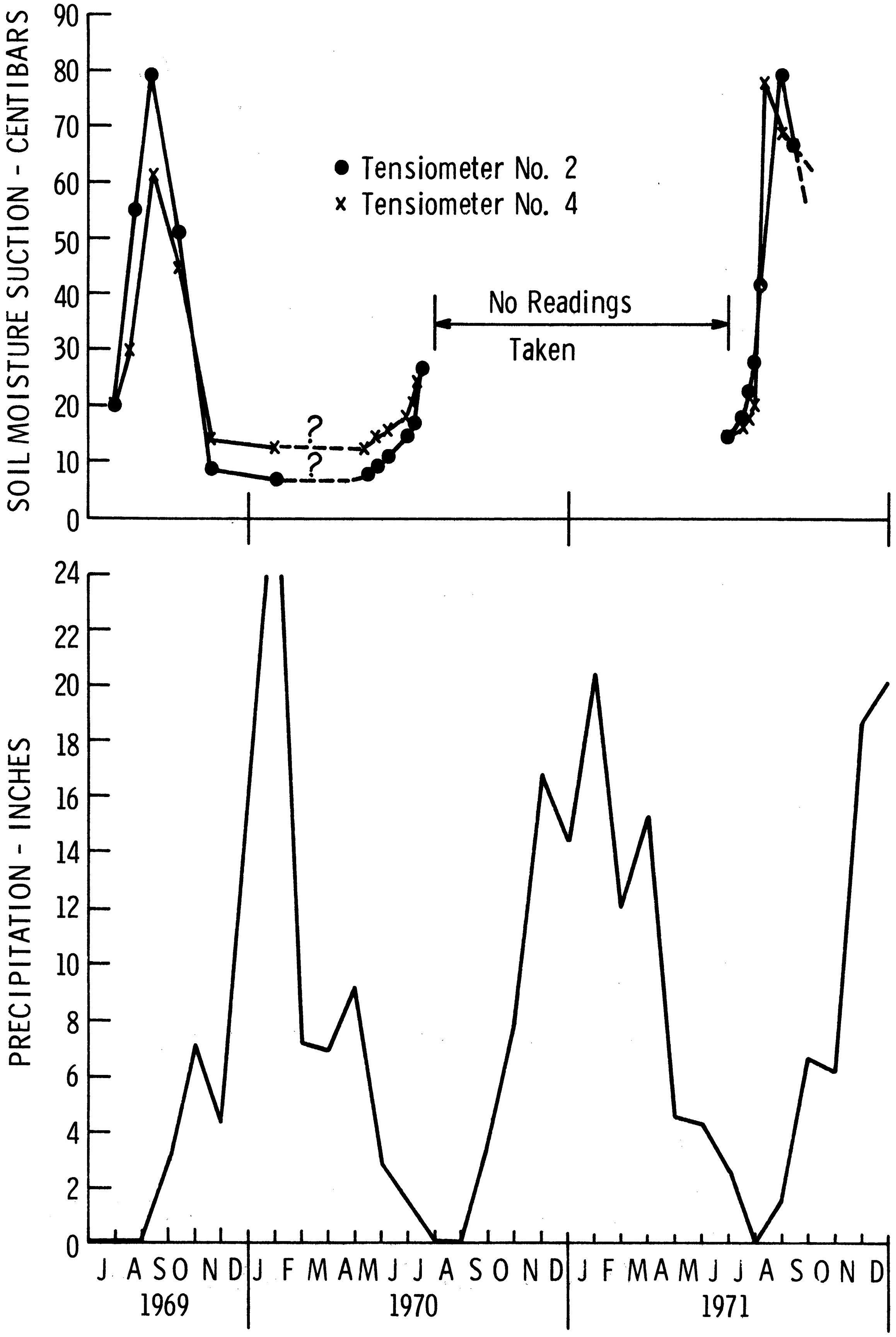


Figure 46. Soil moisture suction and precipitation vs. elapsed time, Watershed No. 10, H. J. Andrews Experimental Forest.

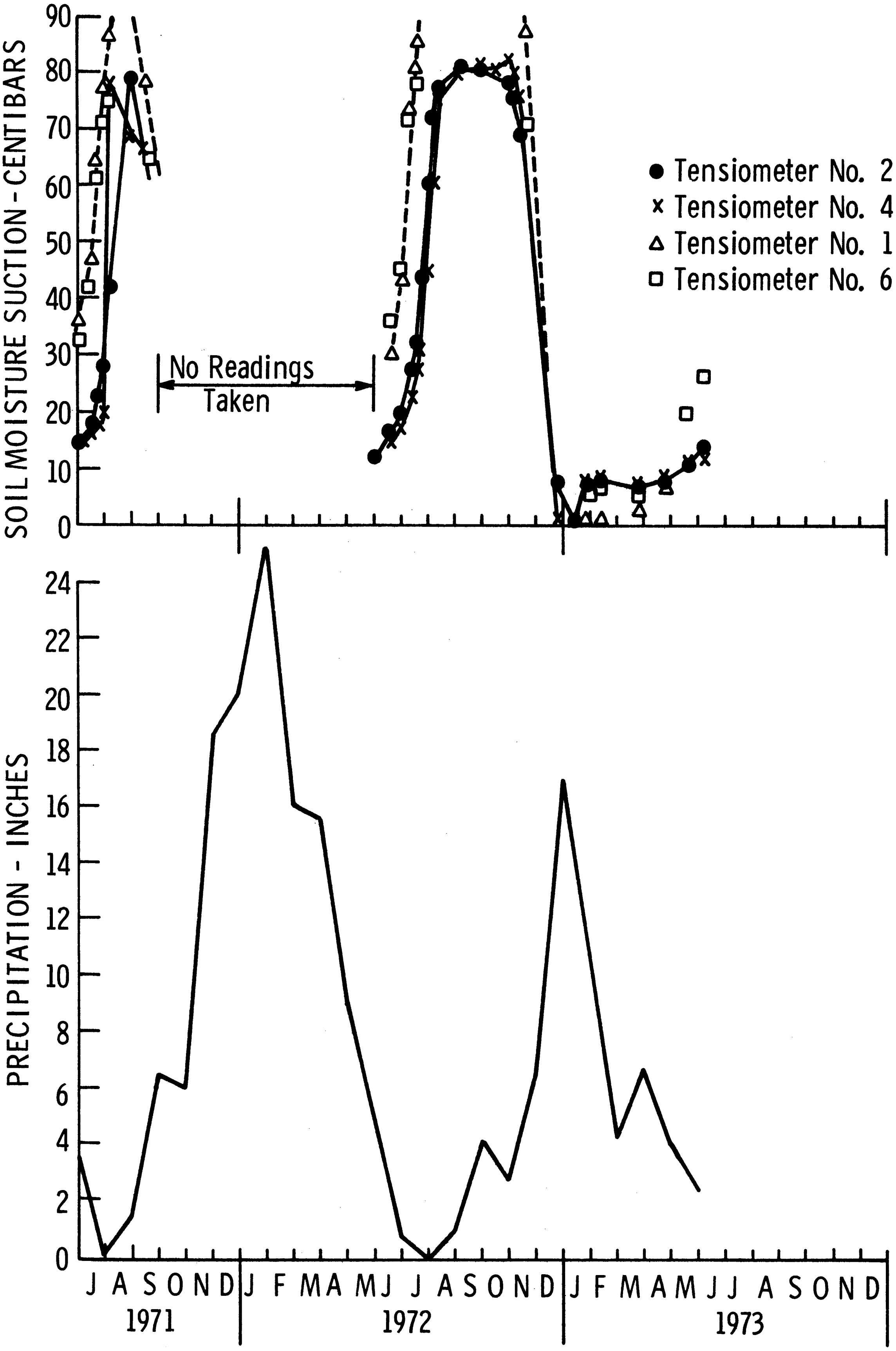


Figure 47. Soil moisture suction and precipitation vs. elasped time, Watershed No. 10, H. J. Andrews Experimental Forest.

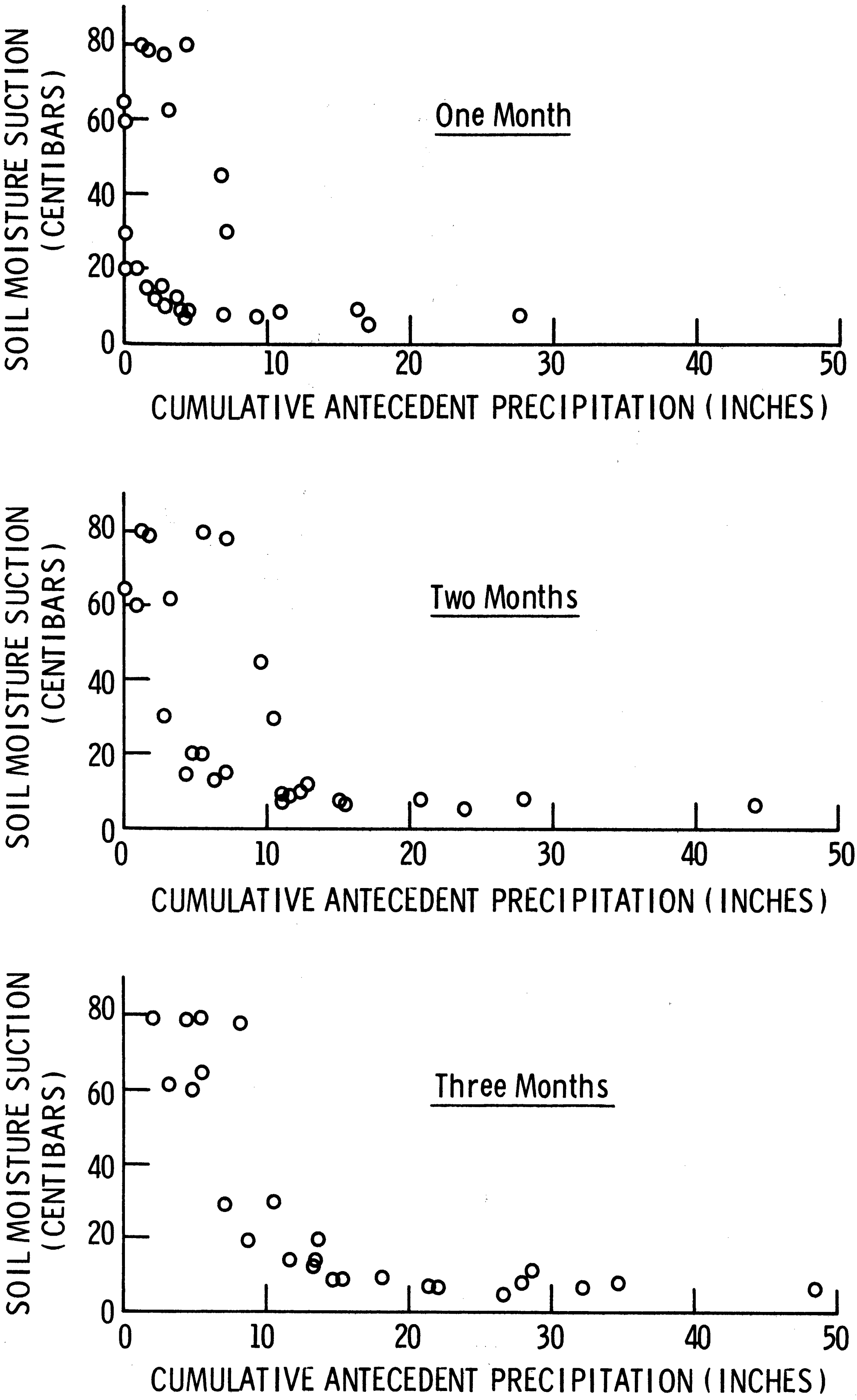


Figure 48. Soil moisture suction vs. antecedent precipitation, tensiometer No. 2, Watershed No. 10, H. J. Andrews Experimental Forest.

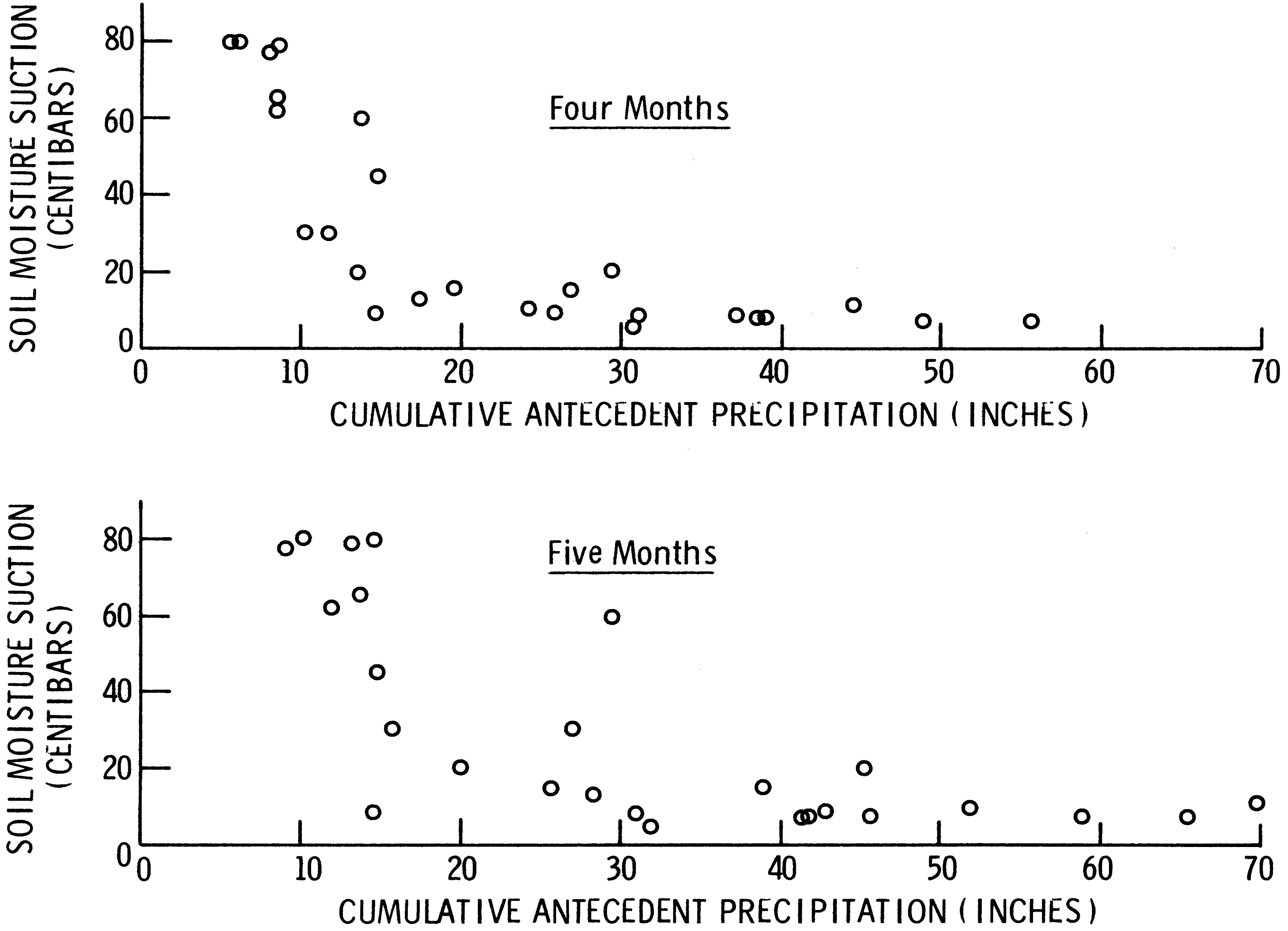


Figure 49. Soil moisture suction vs. antecedent precipitation, tensiometer No. 2, Watershed No. 10, H. J. Andrews Experimental Forest.

considerable. Soil moisture suction vs. three-month antecedent precipitation for all of the tensiometers is shown plotted in Figures 50 through 53. These relationships will be examined again when the watershed has been clear-cut.

Site access problems at the Clearview site in the Klamath National Forest precluded obtaining sufficient tensiometer data to establish any meaningful correlation between soil moisture suction and precipitation. A positive water pressure or ground water table was observed in the inclinometer tube located in the slide at Little South Fork annex. The water table was observed to be about 4 feet below the ground surface or 8 feet above the bedrock contact during midsummer. Springs and seeps emerging in a road cut at the toe of this slide were further proof of high piezometric levels in the slope mass.

High piezometric levels were also noted in the inclinometer tubes installed in the cutover portions of the valley slopes at the U.S. Naval Radio Station. Inclinometer holes dug in the forested area, on the other hand, were quite dry. Piezometric levels during the summer of 1973 in the cutover portion of the slope are shown in Figure 54. A record of piezometric levels in the deep inclinometer well installed in the cutover slope behind the transmitter station was shown in Figure 42.

C. SHEAR STRENGTH AND INDEX PROPERTIES

The results of <u>in situ</u> shear strength tests using the Iowa bore hole, direct shear device are shown in Figures 55 to 57. Failure envelopes of soils from three different sites and at various depths were obtained directly as shown on the diagrams. Shear strength parameters, viz., the angle of internal

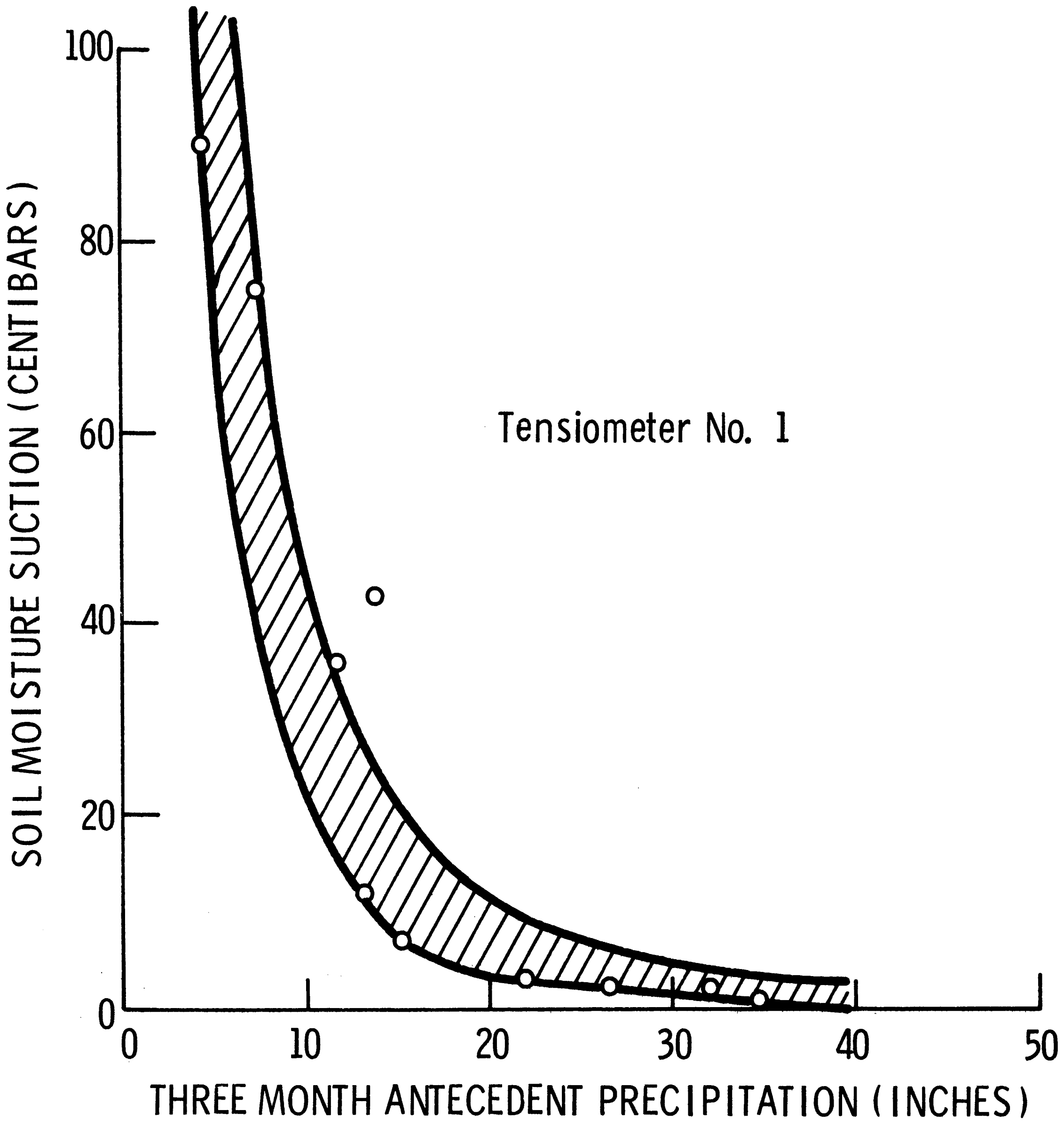


Figure 50. Soil moisture suction vs. three-month antecedent precipitation, Watershed No. 10 (forested), H. J. Andrews Experimental Forest.

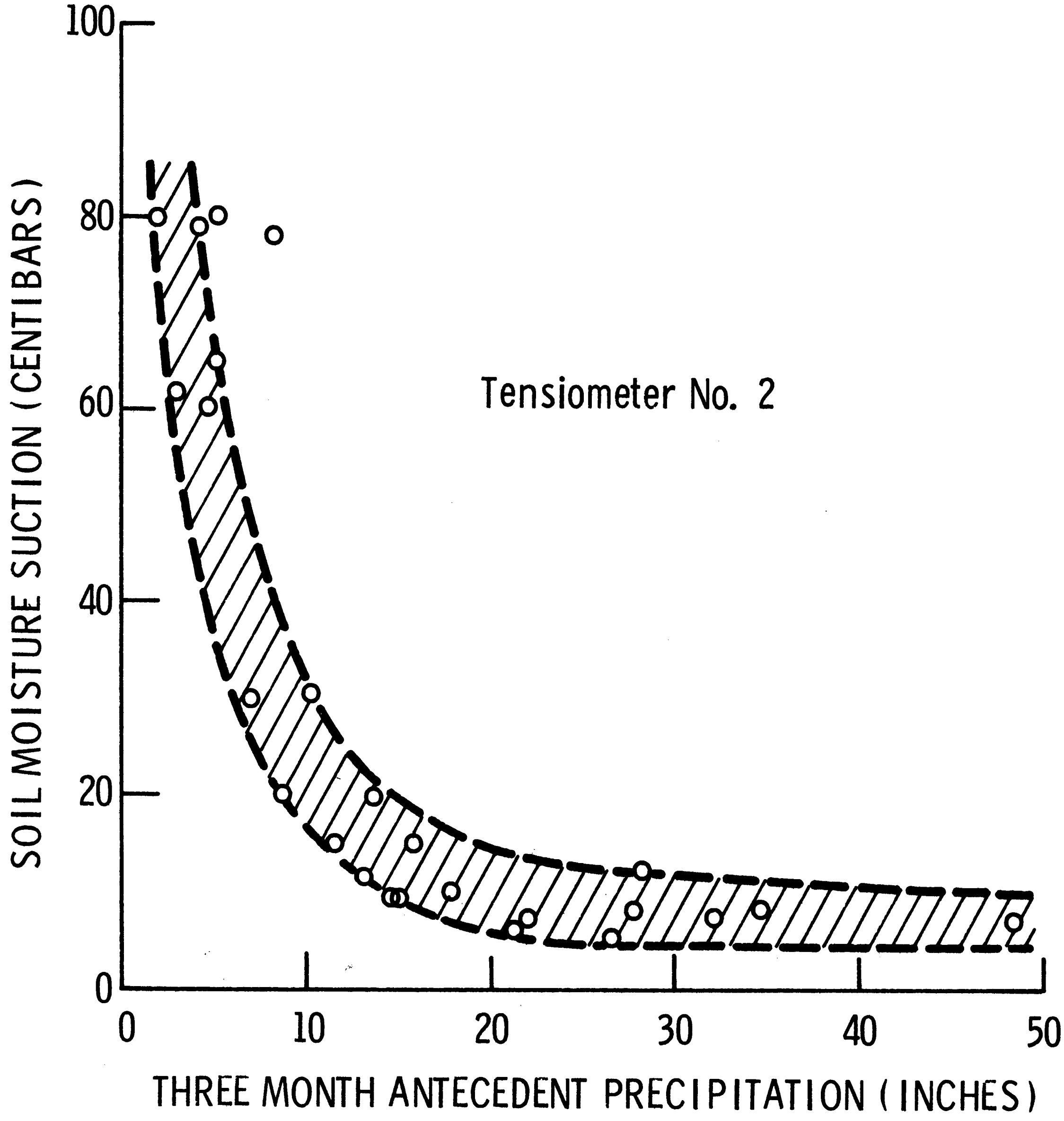


Figure 51. Soil moisture suction vs. three-month antecedent precipitation, Watershed No. 10 (forested), H. J. Andrews Experimental Forest.

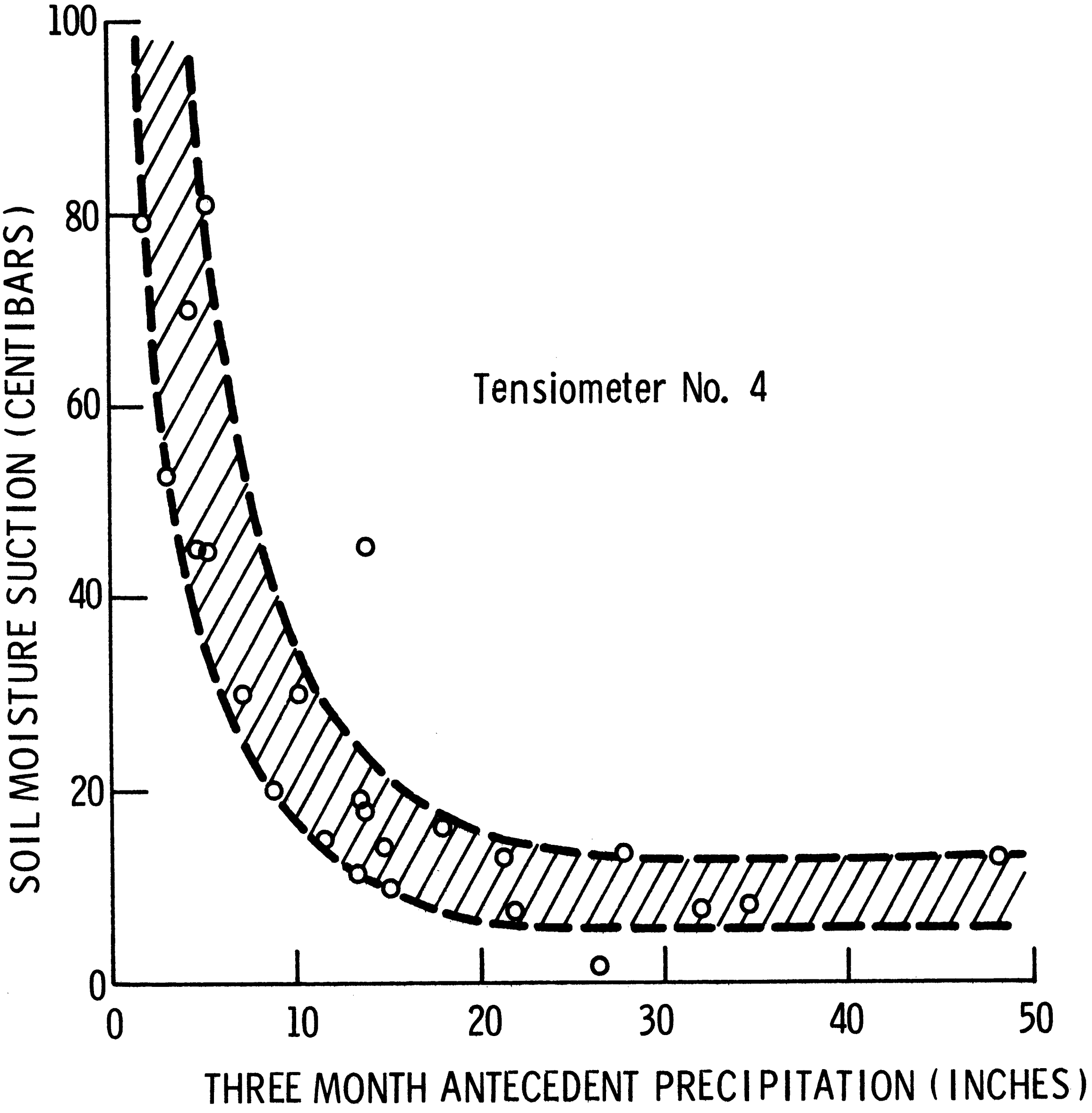


Figure 52. Soil moisture suction vs. three-month antecedent precipitation, Watershed No. 10 (forested), H. J. Andrews Experimental Forest.

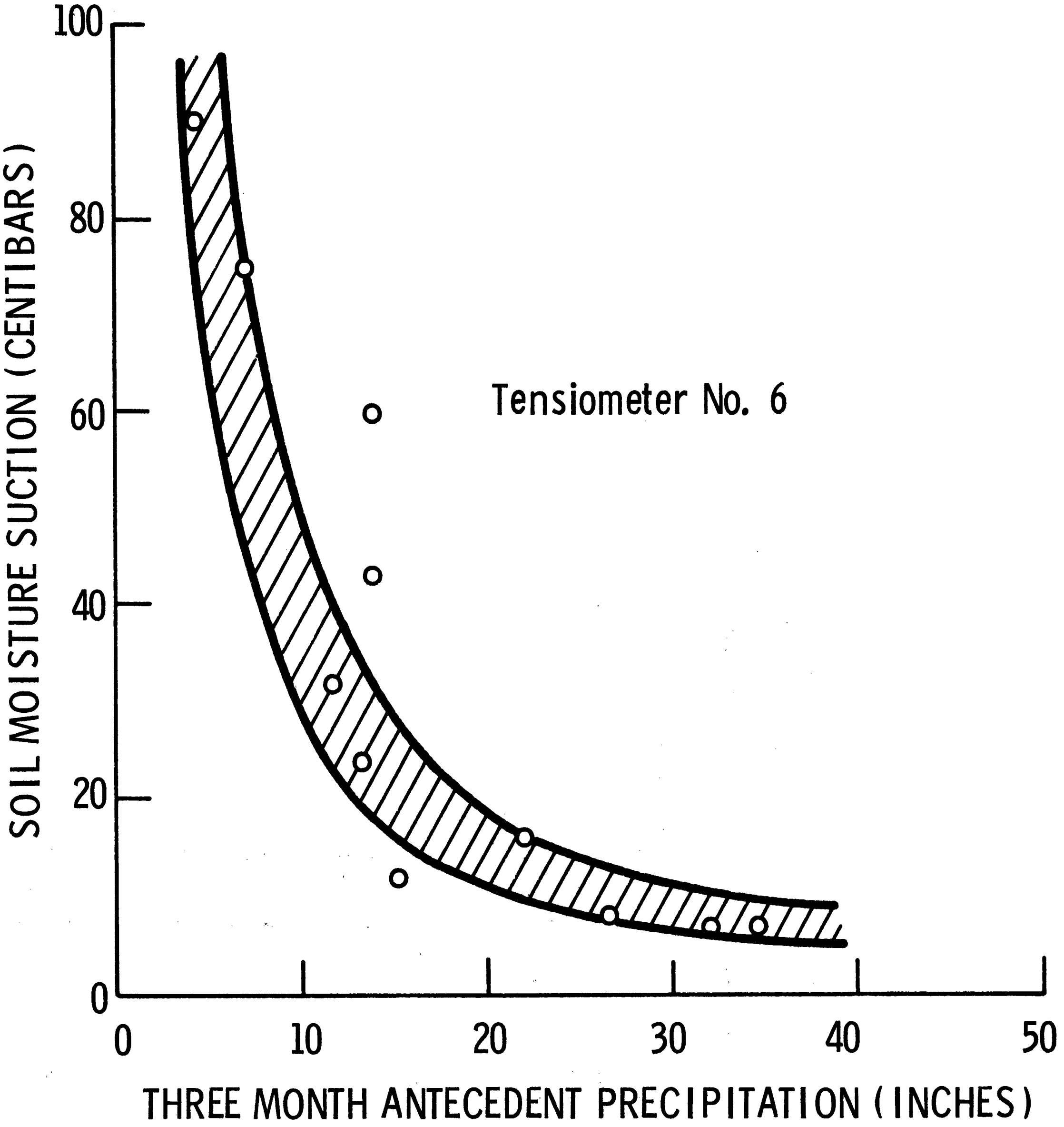


Figure 53. Soil moisture suction vs. three-month antecedent precipitation, Watershed No. 10 (forested), H. J. Andrews Experimental Forest.

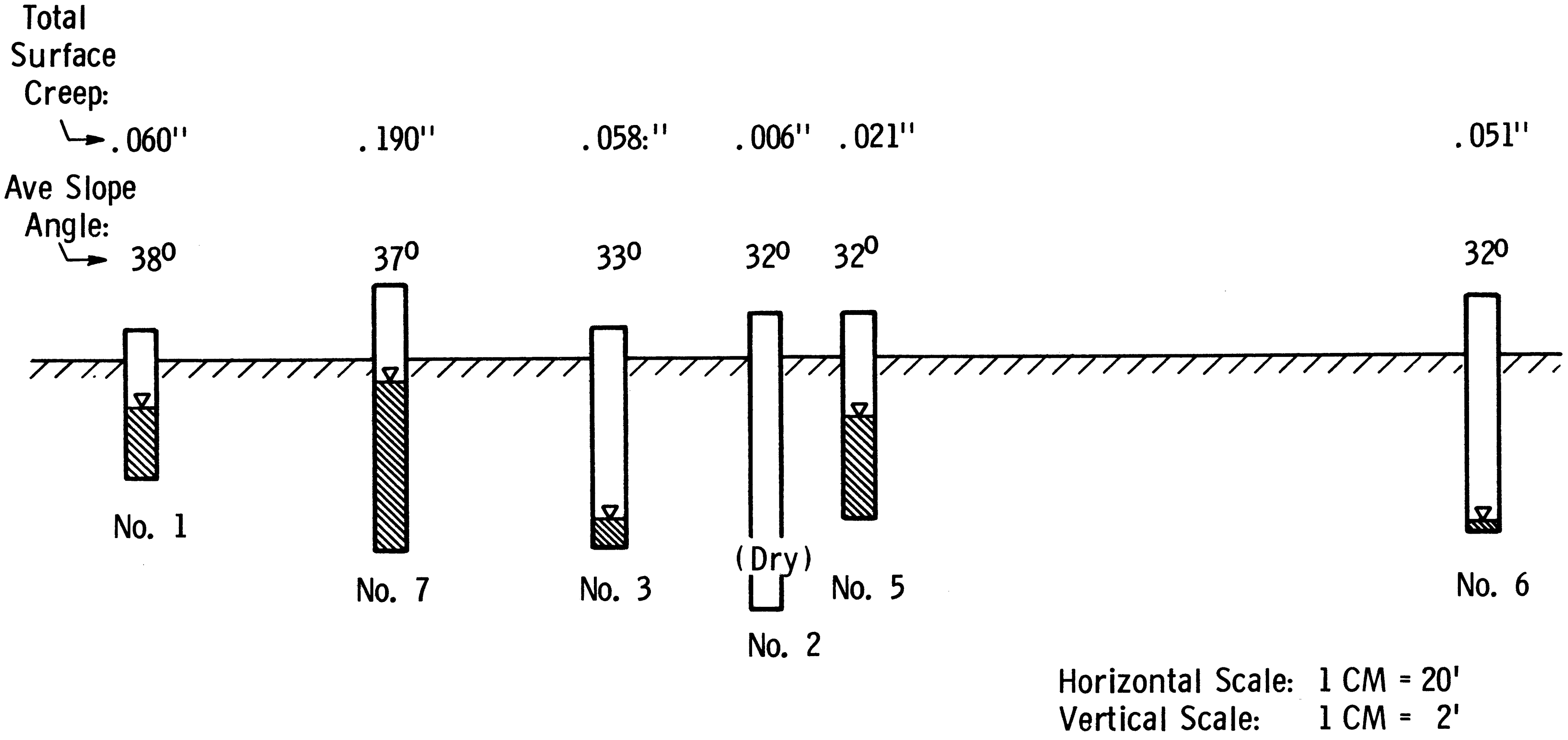


Figure 54. Piezometric levels (July 1973) and surface creep movements measured in inclinometer tubes located on cutover slope, U. S. Naval Radio Station.

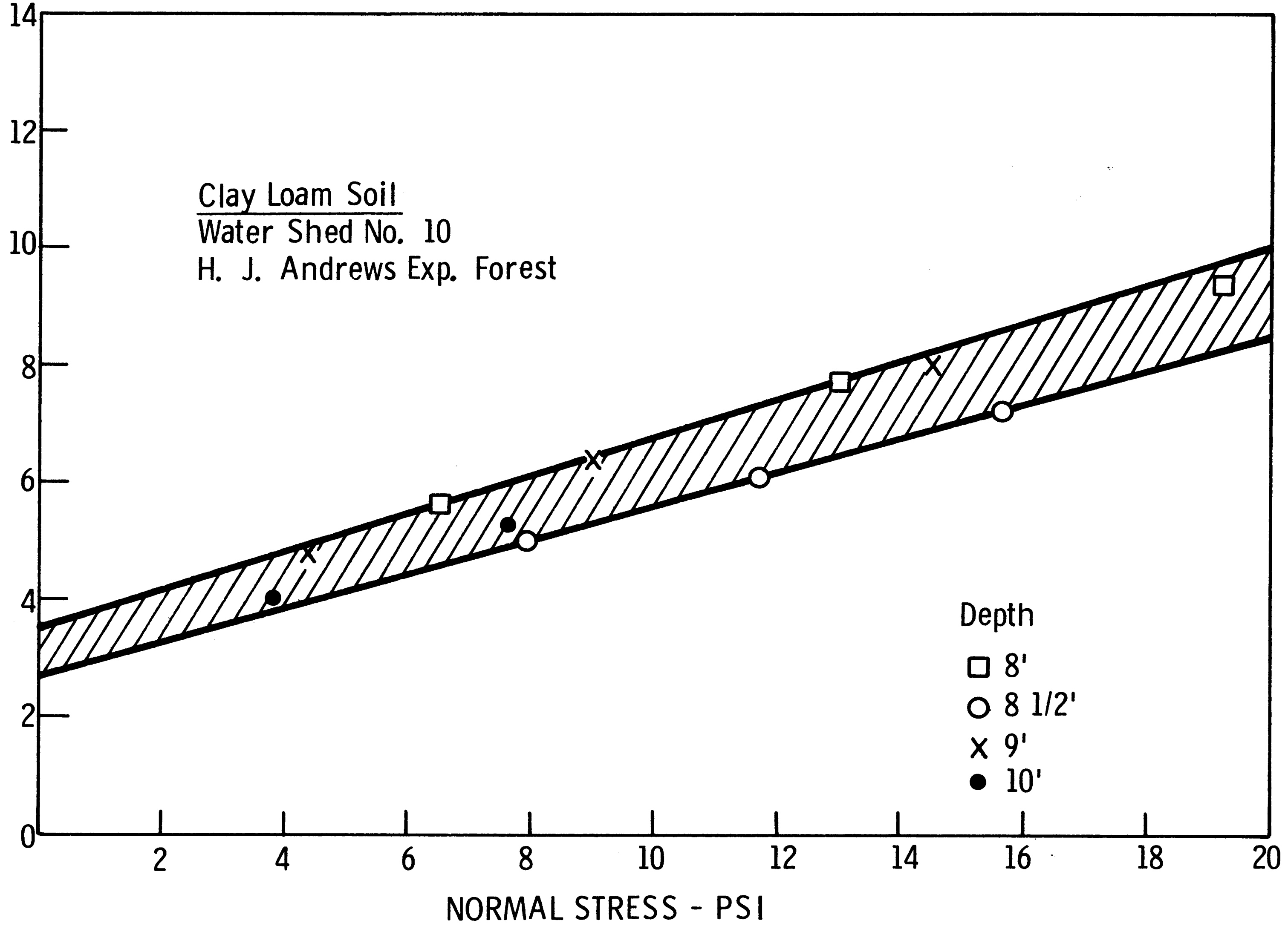


Figure 55. In situ shear strength failure envelope, Watershed No. 10, H. J. Andrews Experimental Forest.

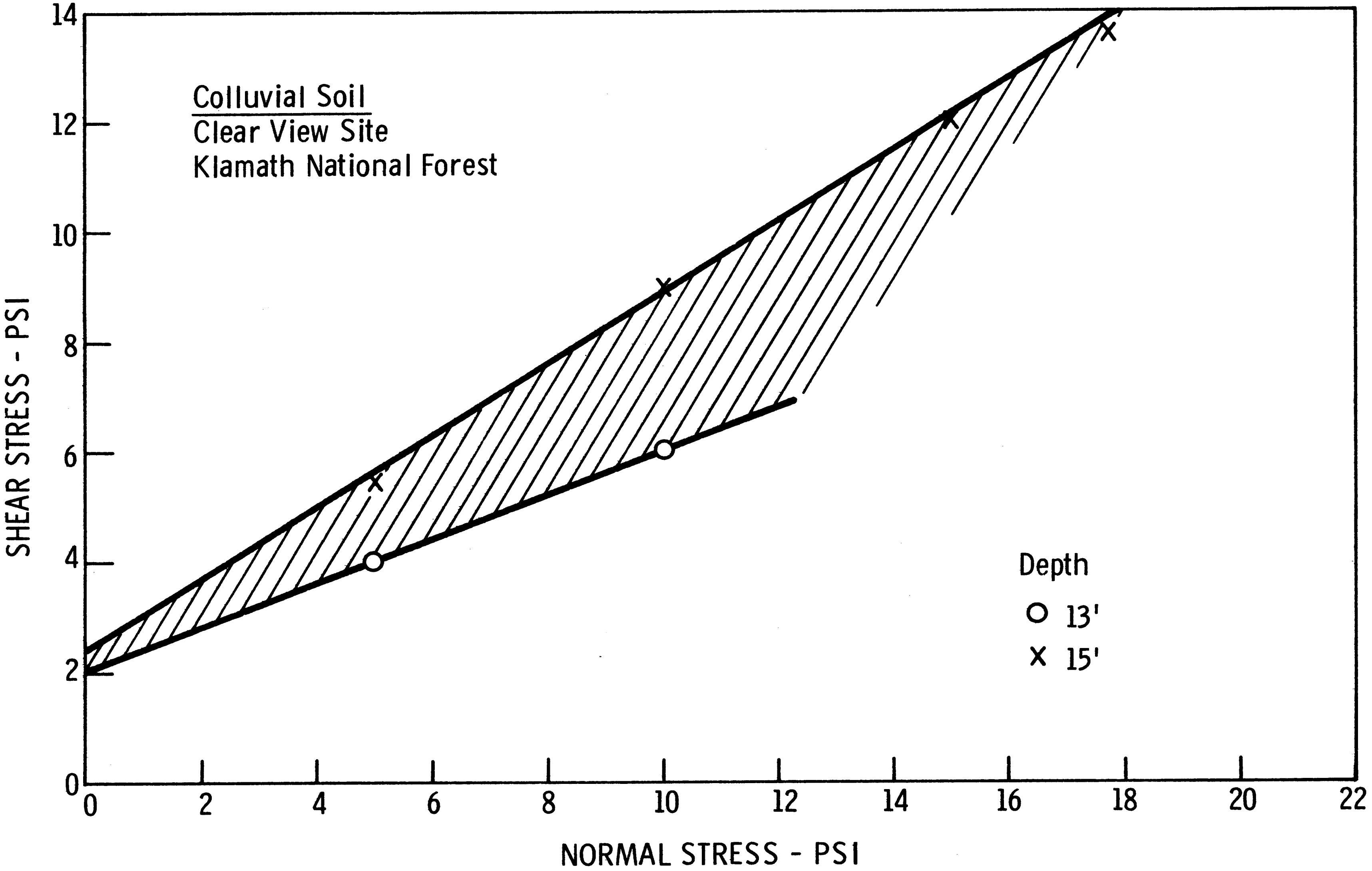


Figure 56. <u>In situ</u> shear strength failure envelope, Clearview site, Klamath National Forest.

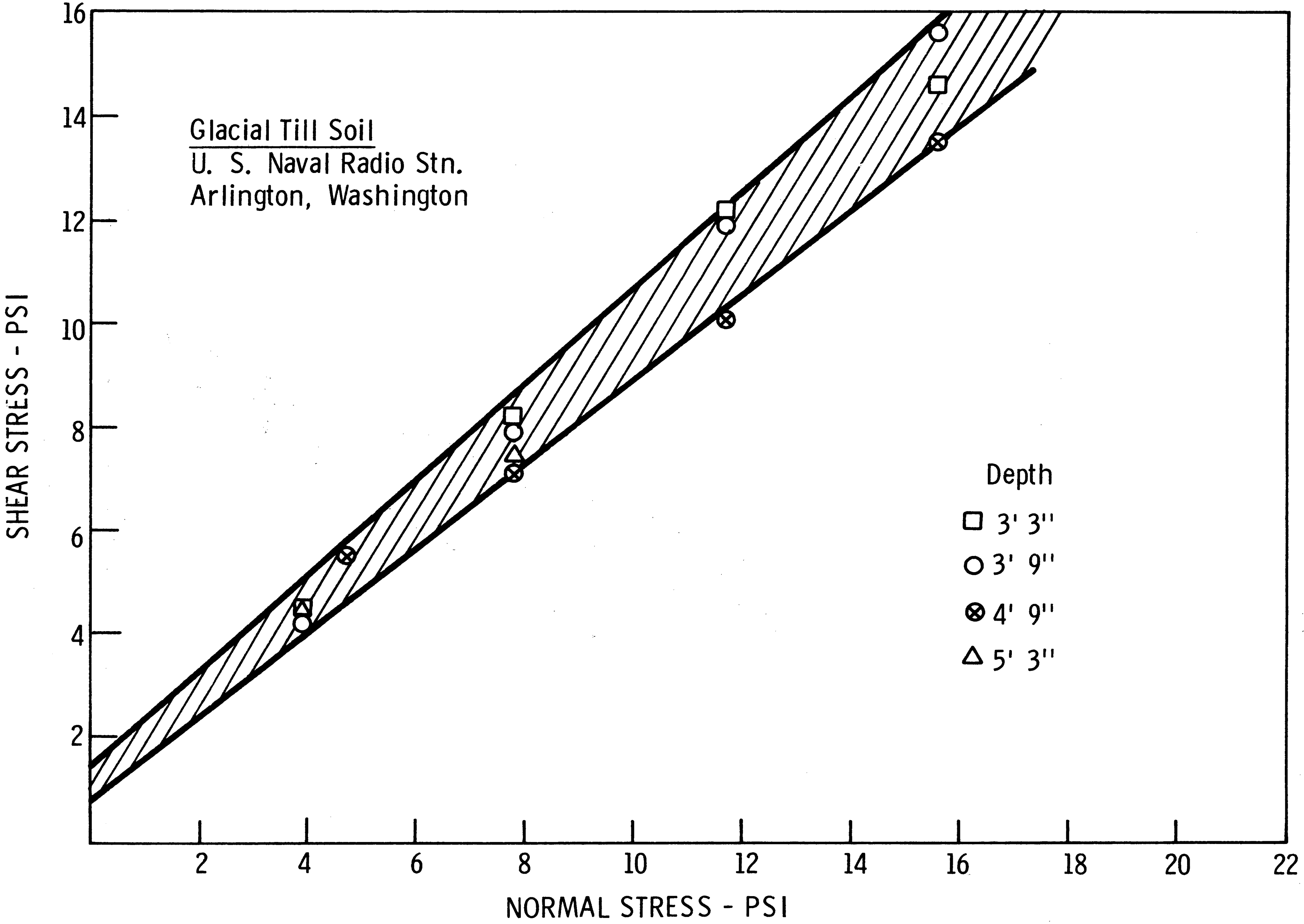


Figure 57. *In situ* shear strength failure envelope, U. S. Naval Radio Station.

friction and cohesion intercept, were obtained from the failure envelopes and are summarized in Table 2.

TABLE 2

IN SITU SHEAR STRENGTH PARAMETERS OF SOILS
FROM VARIOUS SITES

Site Location	Type of Soil	Depth Interval (feet)	Friction Angle (degrees)		Cohesion Intercept (psi)	
			Range	Avg.	Range	Avg.
Watershed No. 10, H. J. Andrews Experimental Forest	clay, loam	8-10	16-18	17	2.7-3.5	3.1
Clearview site, Klamath National Forest	gravelly, clay, colluvium	13-15	22-32	27	2.0-2.4	2.2
U. S. Naval Radio Station	glacial, till	3- 5	39-42	40	0.8-1.4	1.1

Grain size distribution and plasticity data from the soil in Watershed No. 1 (Oregon) and the glacial till soil from the U. S. Naval Radio Station (Washington) are summarized in Table 3.

TABLE 3

GRAIN SIZE DISTRIBUTION AND PLASTICITY DATA OF SOILS FROM SELECTED FIELD SITES

Source or Origin	Depth, ft	Natural Water Content, %	Atterberg Limits, %			Grain Size Distribution, %		
			Liquid Limit	Plastic Limit	Plasticity Index	% Clay	% Silt	Sand & Gravel
Hole No. 3-A, Watershed No. 1, H. J. Andrews Experimental Forest	2	32	54	44	10	19	27	54
	4	28	40	36	4	18	26	56
	5	31	50	42	8	22	33	45
	6	56	70	57	13	23	38	39
	8	62	61	52	9	34	23	43
	10	30	37	32	5	17	25	58
Inclinometer hole* above transmitter station, U. S. Naval Radio Station	15	27	27	23	4	30% gravel 30% sand 20% fines		
	18	54	64	46	18			
	19	26	27	20	7			

*Data from report by Shannon and Wilson (1956).

VII. ANALYSIS AND DISCUSSION OF RESULTS

A. SIGNIFICANCE OF CREEP MEASUREMENTS

Unfortunately no "before-and-after" comparisons of creep rates can be made at time of writing this report. There are, however, some results from side-by-studies and general information on creep rates which are worthy of comment.

A comparison of creep movement in slopes in a clear-cut watershed (No. 1) and a forested area (No. 2-3) in Oregon is shown in Figure 58. The amount of creep displacement generally increases with height above the bottom of the inclinometer tubing (which is assumed to remain fixed). Accordingly, it is necessary to compare creep profiles at the same height above bottom. The profiles being compared in Figure 58 are for two inclinometers exhibiting the greatest amount of downslope movement in their respective areas, viz., No. 3-B (forested) and 3-A (clear-cut). Creep movement was seemingly greater initially in the inclinometer tube in the forested slope, but this was due to settlement of backfill around the tube or casing as explained previously. Once settlement movement ceased, the downslope movement or creep rate in the forested slope has been noticeably less than the clear-cut slope.

A comparison of creep rates between forested and cutover portions of the slope at the U.S. Naval Radio Station is not possible at this time for reasons already explained. The inclinometers in the forested slope were installed in backfilled pits in which considerable settlement movement has occurred. Insufficient data is available at present to distinguish between true soil mantle

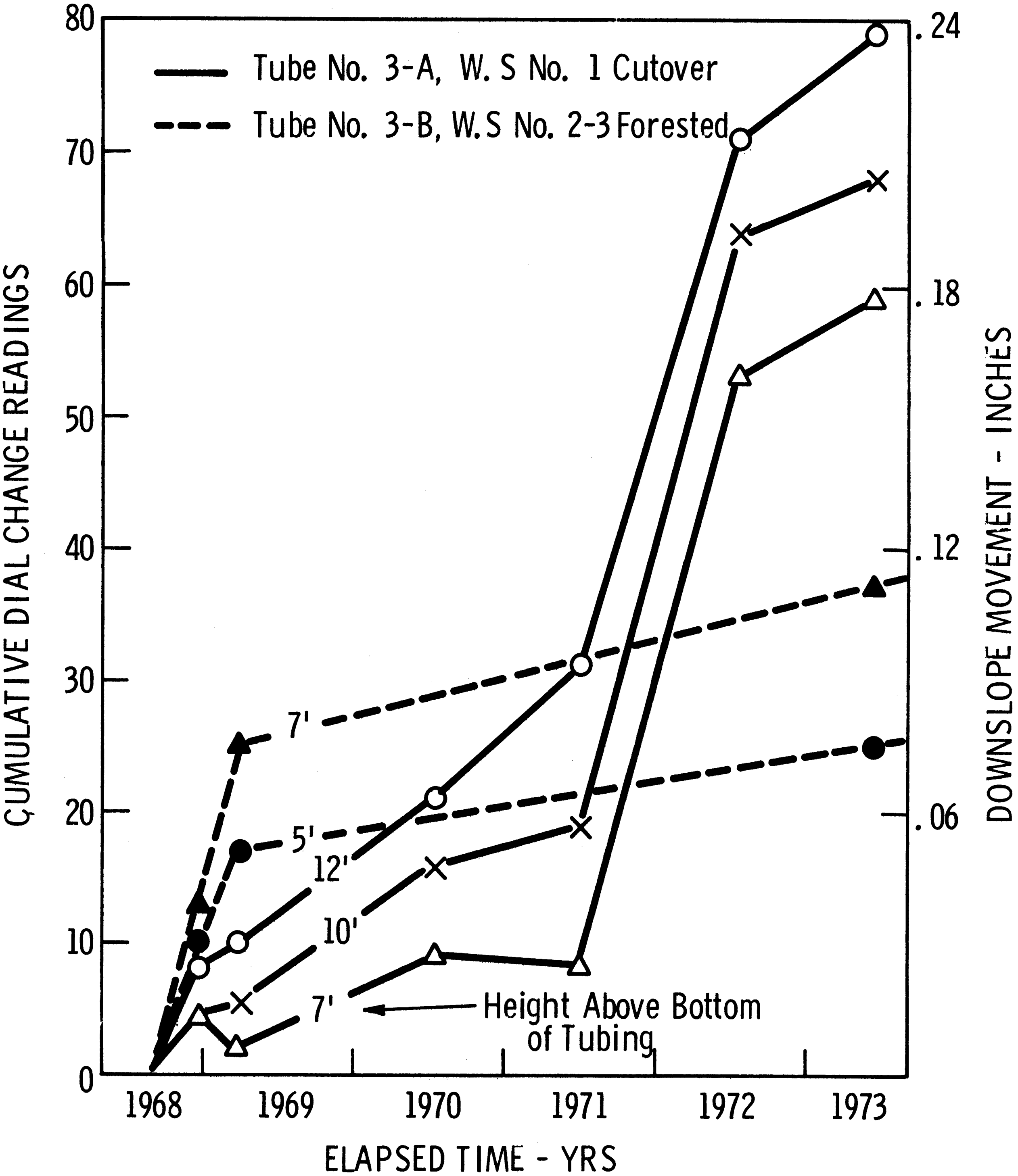


Figure 58. Comparison of creep movement between forested and clear-cut sites, H. J. Andrews Experimental Forest.

creep from settlement movement of the backfill.

Watershed No. 10 in Oregon has not yet been clear-cut; nevertheless, some extremely interesting data has emerged from the study in this regard because one of the inclinometer tubes is situated in an area of dead trees. Inclinometer tube No. 4 is located, in fact, only a few feet away from a large diameter, Douglas fir snag as shown previously in Figure 25. This area then simulates a slope where loss of root reinforcement is likely occurring because of tree mortality and subsequent root decay.

The creep rate in the near surface soil surrounding inclinometer tube No. 4 is three our four times greater than the creep rates in the soil surrounding the remaining tubes in Watershed No. 10. This observation seems to support the hypothesis that root decay and subsequent loss of reinforcement from the root system can lead to accelerated creep rates and mass wasting.

With the exception of the slide which was instrumented in the Little South Fork area in the Klamath National Forest, creep rates measured to date appear to be considerably lower than those reported by other investigators. Surface creep rates in the slopes investigated in this study appear to average less than a tenth of an inch per year. The 10-year average surface creep rate for the soil behind the transmitter station at the U.S. Naval Radio Station is approximately 0.3 inch per year. Over a 10-year period about 1 inch of this movement has occurred in the top 5 feet of soil, and 2 inches in the bottom 20 feet (Wilson, 1970). Creep rates are affected noticeably in some cases by precipitation as will be discussed in the next section.

The active slide in the Little South Fork area, Klamath National Forest, has an average surface creep rate of some 2 inches per year as shown in Figure 44. Creep movement in the forested slope in the Clearview site, on the other hand, has been barely perceptible as shown in Figure 43.

B. CREEP RATE VS. ANTECEDENT PRECIPITATION

As discussed earlier investigators have related creep rates in soil to frequency and intensity of precipitation (Wilson, 1970) or to piezometric levels in a slope (Ter-Stepanian, 1963). High precipitation or storm activity was also shown to be strongly correlated with landsliding and mass wasting on steep slopes (Fredriksen, 1965; Flaccus, 1955; and Swanston, 1969).

A creep rate vs. precipitation correlation is shown plotted in Figure 59 for a clear-cut watershed (No. 1) in Oregon. The degree of correlation appears to be very good in this case with creep rates increasing almost exponentially for precipitation totals exceeding 60 inches per year. Precipitation totals used in plotting the graph include only the winter months (November, December, January, and February) because it is the intense and prolonged winter rains which matter, i.e., which tend to saturate the ground and develop piezometric levels in the slope.

The same trend was observed in the sites in the Klamath National Forest. Most of the creep movement at these sites (see Figures 43 to 45) occurred during the climatic year 1971-72 which was relatively wet (59 inches) as opposed to the climatic year 1972-73 which was quite dry (37 inches).

The correlation shown plotted in Figure 59 did not hold for forested sites in the H. J. Andrews Experimental Forest. This lack of correlation is shown in Figure 60. Only tube No. 6 in Watershed No. 10 appeared to follow the same

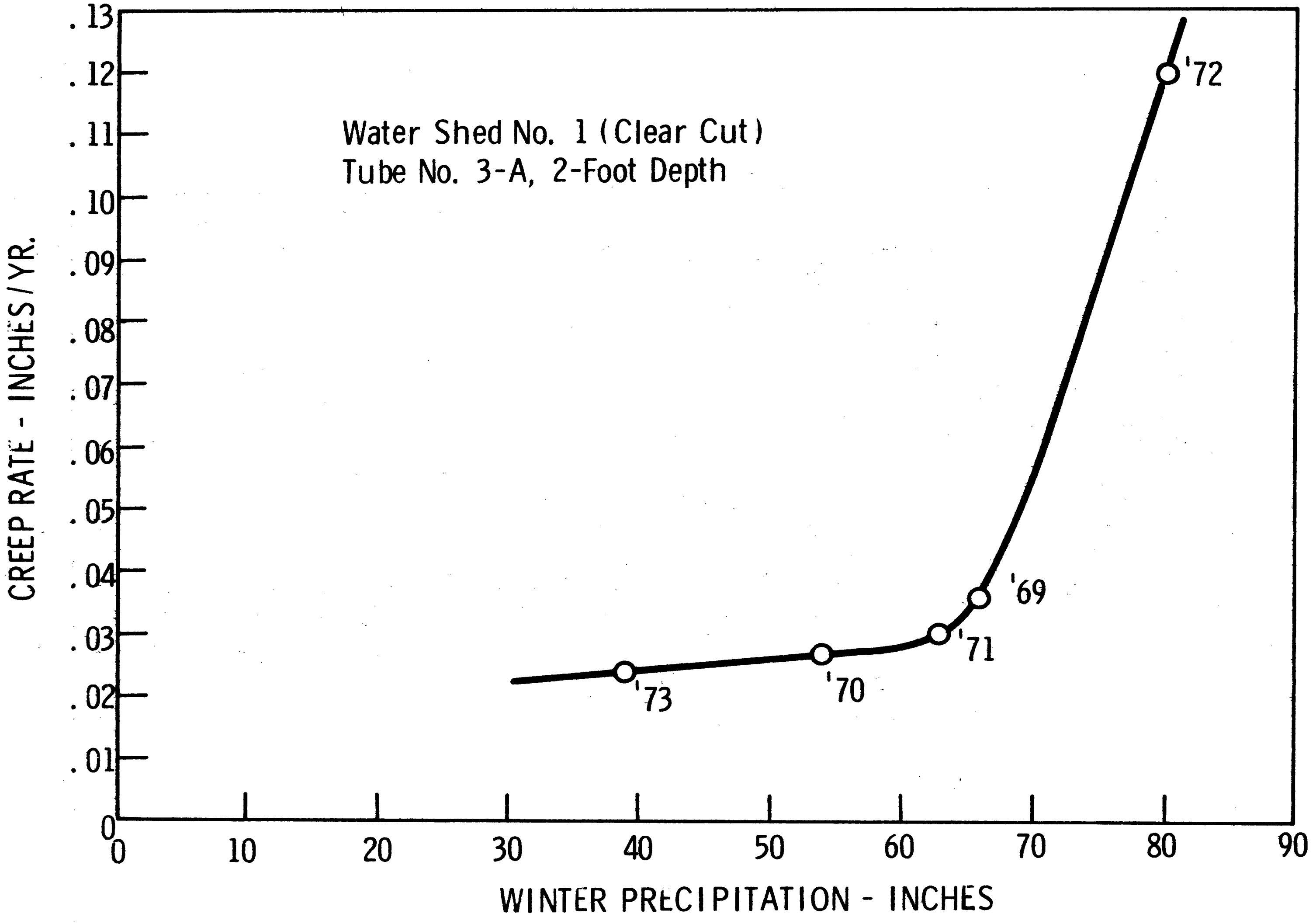


Figure 59. Surface creep rate vs. winter precipitation (November-February) in a clear-cut watershed, H. J. Andrews Experimental Forest.

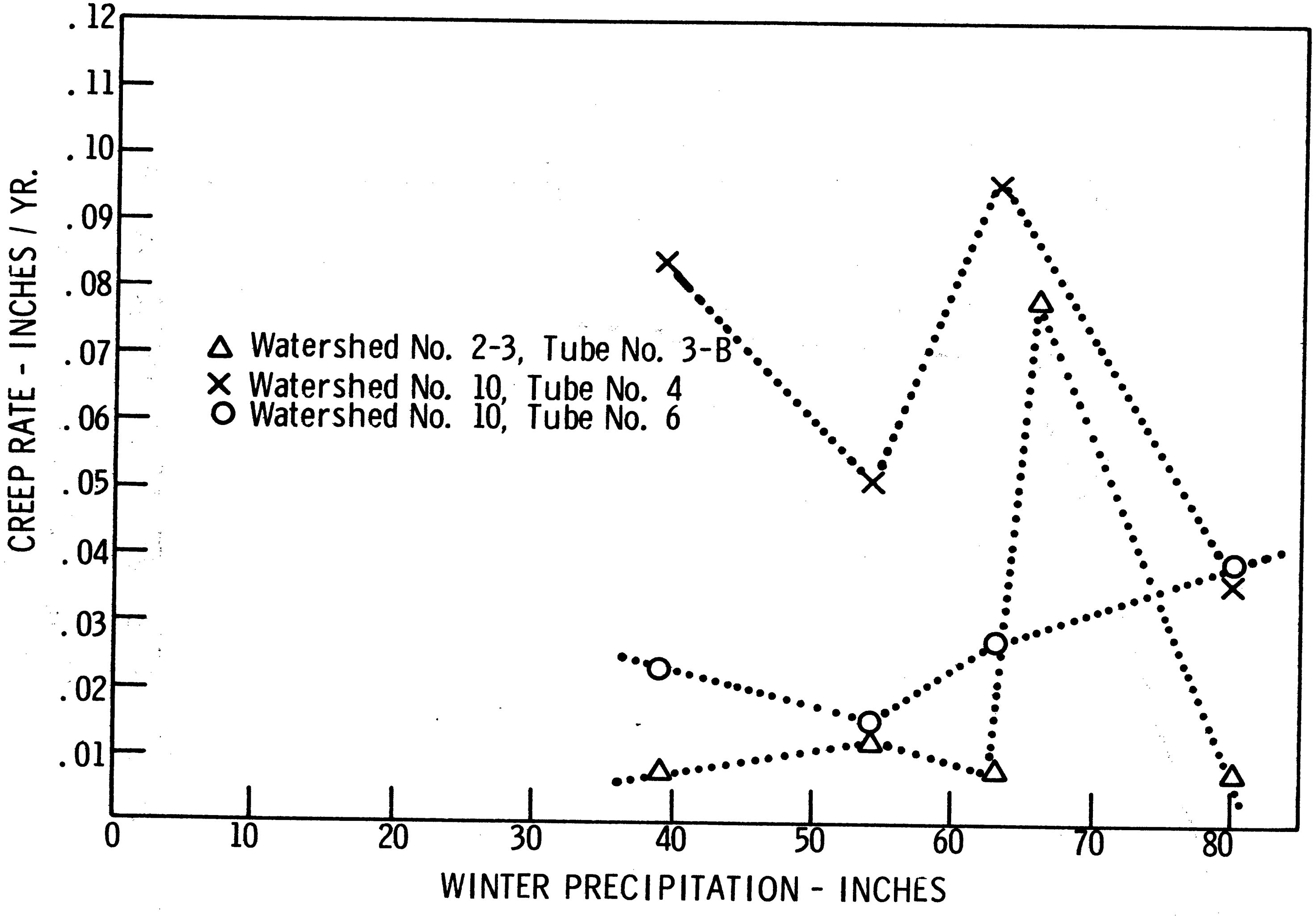


Figure 60. Surface creep rate vs. winter precipitation (November-February) in forested watersheds, H. J. Andrews Experimental Forest.

trend of increasing creep rate with increasing precipitation. The reason for this anomalous behavior is not apparent. A possible explanation is some sort of moderating effect from the presence of the forest or alternatively the possibility that the precipitation data which was measured at a climatic station near Watershed No. 1 does not apply to Watershed No. 10.

C. INFLUENCE OF SOIL MOISTURE STRESS

A general observation throughout the entire field study was the noticeably wetter conditions in clear-cut or cutover slopes as opposed to forested slopes. Nowhere was this more apparent than at the U.S. Naval Radio Station at Jim Creek. Holes drilled in the cutover portion of the slope nearly all had standing water in them (refer back to Figures 42 and 54) as opposed to holes in the forested portion which were quite dry.

The slide in the Little South Fork area had a surprisingly high ground water table as described previously. High ground water tables in turn lead to high pore water pressures in the soil and reduced resistance to sliding. The next section of this report contains an analysis of the effect of a rise in the ground water table on the safety factor against sliding.

Finally, it is interesting to note that the soil around inclinometer tube No. 4 in Watershed No. 10 (Oregon) which is creeping much faster than its neighbors is also much wetter. This can be established by inspecting the soil moisture suction record shown in Figure 47.

D. SLOPE STABILITY ANALYSES

Three of the sites were analyzed for their factor of safety against sliding. The effect of (1) a rise in ground water table and (2) an increase in surcharge due to weight of trees on the slope was determined.

An infinite slope stability analysis and planar deformation model were employed. Geologic control and geometry of the slopes in question, viz., a relatively shallow soil mantle overlying an inclined bedrock contact, make this approach valid. The following slope stability equation derived by Ter-Stepanian (1963) for this case was used:

$$F = \left[\frac{c' \cot \phi'}{(q_o + \gamma_h) \cos^2 \beta} + 1 - \frac{\gamma_w h_p}{q_o + \gamma_h} \right] \frac{\tan \phi'}{\tan \beta} \qquad (7)$$

where F = factor of safety against sliding

q_o = surcharge due to weight of trees, psf

h = thickness of soil mantle, ft

h_p = height of ground water table above bedrock contact, ft

γ = saturated density of soil, pcf

γ_w = density of water, pcf

β = average slope angle

ϕ' = effective angle of friction, degrees

c' = effective cohesion intercept, psf

The shear strength parameters c' and ϕ' were obtained from the results of the bore hole shear test results tabulated in Table 2. Average slope angles were measured at each site by means of an Abney level; these are tabulated in Table 4. The thickness of the soil mantle at each site was calculated from the average depth to bedrock as indicated by the average depth of inclinometer tubing installed. In the case of Jim Creek two different depths were used

TABLE 4

SUMMARY OF SITE AND SOIL PARAMETERS USED IN SLOPE STABILITY ANALYSES

Site	Soil Mantle Thickness, h (ft)	Average Slope Angle, β (degrees)	Average Friction Angle, ϕ' (degrees)	Average Cohesion Intercept, c' (psf)	Estimated Soil Density, γ (pcf)
Watershed No. 10, H. J. Andrews Experimental Forest	15	34	17	446	102
Clearview site, Klamath National Forest	17	32	27	316	122
U. S. Naval Radio Station	5 20	30	40	158	100

because of the considerable difference in soil mantle thickness behind the transmitter station relative to the site we instrumented. Saturated or moist densities were estimated from Shelby tube samples retrieved from the sites. All the necessary data for the stability analyses is summarized in Table 4.

The results of the stability analyses are tabulated in Table 5. Safety factors have been calculated for the following cases:

1. Moist soil but no ground water table ($h_p = 0$)
2. Completely saturated conditions ($h_p = h$)

The above calculations have been carried for both a surcharged and free slope ($q_o = 0$). The surcharge caused by the weight of trees has been estimated at 75 psf following the method suggested by Bishop and Stevens (1964).

Slope stability calculations show that safety factors, even for the worst case of complete saturation, are still greater than unity. A safety factor greater than unity means the slope is safe against catastrophic sliding but this does not preclude creep movement, particularly if the factor of safety is close to unity. The stability of the slope in Watershed No. 10, Oregon, appears marginal; however, the calculated safety factor is probably conservative as negative pore pressures prevail most of the year and the shear strength parameters used in calculating the safety factor were slightly lower than those determined in triaxial tests.

When the ground water table rises in the slope and complete saturation occurs, then the picture changes dramatically as shown by calculated safety factors in Columns 2 and 4 in Table 5. Slopes at both the sites in Oregon and California become unstable as the calculated factors of safety drop below unity.

TABLE 5

FACTOR OF SAFETY AGAINST SLIDING FOR VARIOUS ASSUMED CONDITIONS AT FIELD STUDY SITES

Site		Factor of Safety			
		No Surcharge ($q_o = 0$)		With Surcharge ($q_o = 75$ psf)	
		$h_p = 0$	$h_p = h$	$h_p = 0$	$h_p = h$
Watershed No. 10, H. J. Andrews Experimental Forest		1.08	0.80	1.05	0.79
Clearview site, Klamath National Forest		1.15	0.74	1.14	0.74
U. S. Naval Radio Station	h = 5'	2.18	1.28	2.09	1.30
	h = 20'	1.64	0.73	1.63	0.76

The shallow soil slope at the U.S. Naval Radio Station at Jim Creek remains stable, but the deep soil slope behind the transmitter station would fail if the water table exceeded a certain level. This critical piezometric level was calculated and found to be equal to 14 feet. The present water table was lowered to approximately 6 feet above the contact. When excessive movement was first noticed in the slope mass behind the transmitter station in 1956, the water table stood approximately 12 feet above the sliding contact—dangerously close to the critical level just calculated.

The effect of surcharge from the weight of trees was minor. It tended to have a beneficial effect on stability for saturated conditions, particularly for slopes mantled with soil having a high angle of internal friction. This same beneficial effect of surcharge under saturated conditions was noted by Ter-Stepanian (1963) as shown by its effect on creep rate (refer to Figure 9). This should set to rest the mistaken notion that the weight of trees has a destabilizing influence.

VIII. CONCLUSIONS

As noted in the introduction conclusions drawn from the field research to date will be tentative in some cases because critical, post clear-cutting data is still lacking from two of the sites. Nevertheless, sufficient data is available from side-by-side studies and the recent work of other investigators to state the following conclusions:

1. Trees enhance the strength and stability of soil on steep slopes mainly through mechanical reinforcement by the root system and by soil moisture depletion from transpiration.

2. Removal or cutting of trees on steep slopes can lead to accelerated creep rates and increased mass wasting. Recent work of other investigators supports this view; so too does the following evidence from the present study:

    a. Higher creep rates in soil around an inclinometer in the midst of an area of dead trees relative to creep movement in surrounding soil supporting live trees in Watershed No. 10, H. J. Andrews Experimental Forest.

    b. Generally higher creep rates in a cutover slope (Watershed No. 1) compared to creep rates in a nearby forested slope (watershed No. 2-3), H. J. Andrews Experimental Forest.

    c. Generally wetter conditions in soils in cutover slopes relative to soils in forested slopes.

3. The results of comparative creep studies at the Naval Radio Station are inconclusive as a result of settlement movement in backfilled pits in which the inclinometers were installed in the forested portion of the slope. Additional readings in subsequent years will be required here to distinguish between the soil mantle creep and settlement.

4. Creep rates are strongly correlated with precipitation in the clear-cut watershed (No. 1) in the H. J. Andrews Experimental Forest. The same did not hold true in the forested sites.

5. Surface creep rates in the slopes investigated averaged less than a tenth of an inch per year. A notable exception was the active slide in the Little South Fork area which averaged 2 inches per year.

6. Results of stability analyses show that the slopes presently have adequate safety factors against sliding provided saturated conditions do not develop. This requirement is especially critical in the case of the California (Clearview) and Oregon (Watershed No. 10) sites which had calculated factors of safety approaching unity.

7. Surcharge from the weight of trees generally has a beneficial effect on stability particularly when critical, saturated conditions develop in a slope.

IX. ACKNOWLEDGMENTS

The research described herein is supported by Grant No. GK-24747 from the National Science Foundation. The Pacific Northwest Forest and Range Experiment Station, U.S. Forest Service, kindly made available the study areas in the H. J. Andrews Experimental Forest. Logistical aid and manpower assistance were furnished by U.S. Forest Service personnel in the Klamath National Forest. The permission of the U.S. Navy to instrument a site at the Naval Radio Station at Jim Creek likewise is acknowledged.

Several persons in the U.S. Forest Service have been particularly helpful and instrumental in making the field studies possible. They include Ross Mersereau, Field Research Supervisor, and Dick Fredriksen, Soil Scientist, both with the Pacific Northwest Forest and Range Experiment Station; and Bill Hicks, Engineering Geologist, presently with the Rouge River National Forest.

Frank Somagyi assisted with the analysis of field data, calculation of slope stability, and preparation of this report.

Last but not least the assistance of the many students, both graduate and undergraduate, who helped with the field work is greatly appreciated. Installation of the inclinometers on steep slopes often without benefit of existing trails was a backbreaking and demanding task. Persons assisting in this capacity over a four-year period include Peter Brenner, In-Kuin Kim, Ted Webster, Steve Flodin, Jerry Carignani, Maurice Cooper, and Dana Bayuk.

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