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EFFECTS OF FOREST CLEAR-CUTTING ON THE STABILITY OF NATURAL SLOPES

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ABSTRACT

The evidence for a cause and effect relationship between deforestation and mass-soil movement is reviewed. Little known work carried out by investigators in many parts of the world shows that forests play an important soil protective role and that deforestation or clear-cutting can promote not only soil erosion, but also deep seated slope failures.

A forest cover appears to affect the deep seated stability in two principal ways, viz., by modifying the hydrologic regime in the soil mantle and by mechanical reinforcement from its root system.

This report describes a theoretical stability analysis which should make it possible to predict the stability of a forested slope and assess the probable consequences of denudation on a more rational basis.

A field study presently being conducted in central Oregon is also described Slopes have been instrumented there in order to obtain quantitative data on soil moisture stress and soil mantle creep before and after clear-cutting.

INTRODUCTION

What is the role of a forest cover and other types of slope vegetation in preventing soil erosion and mass-soil movement? What impact do clear-cutting, road building, and other forest practices have on slope stability? These are timely and important questions because pressures are mounting from many sides to increase allowable timber cuts and to accelerate construction of access roads in our national forests.

This report briefly reviews available evidence for a cause and effect relationship between deforestation and mass-soil movement. A theoretical stability analysis is outlined herein which should make it possible to predict the stability of a forested slope and assess the probable consequence of denudation. The report also describes field studies which are being conducted in the Cascade Range of central Oregon in an attempt to determine more precisely the effects of clear-cutting (or deforestation) on slope stability.

This field of study has received very little attention from soil mechanics engineers and engineering geologists. This is unfortunate because there is a useful perspective that research workers in both professions can bring to bear on the problem. The need for such a study seems quite clear. Loss of soil due either to erosion or to mass-soil movement poses a multiple threat: first to the future productivity or regeneration of forests on the slopes of a watershed, next to the quality of streams and rivers draining the watershed (because of increased turbidity), and finally to human lives and habitation (particularly in the case of mass-soil movement).

This report is concerned primarily with the effects of clear-cutting on mass-soil movement (i.e., landslides, earth flows, slips, and the like) rather than with soil erosion (e.g., slope wash, rilling, and gullying). In other words, we will be discussing the effects of denudation on the deep-seated stability of a natural slope rather than on the top few inches of soil.

Clear-cutting, it should be pointed out, is a timber harvesting procedure in which all the vegetation is felled in a selected area. This is the usual logging practice in the redwoods of the North Coast ranges of California and in the vast tracts of Douglas fir in the Cascade Range of Oregon and Washington. Denudation is made more awesome and complete by burning the slash remaining after a logging or cutover operation as shown in Figure 1. Controlled slash burning is justified by various arguments, the foremost being that it eliminates a potentially serious fire hazard later on. What it does for soil erosion and slope instability, of course, is another question.

Figure 1. A clear-cut watershed, H. J. Andrews Experimental Forest, Oregon.

REVIEW OF THE LITERATURE

A review of the scientific literature on the subject quickly established a few salient points. First, was the fact that there has been little analysis and synthesis of available data and information—most of which is scattered in forestry journals around the world and in agency publications of limited circulation. A fair amount of useful information can be found in research notes published by the U. S. Forest Service. American engineering journals contain very little information on the subject. Japanese, Italian, and Russian workers, on the other hand, appear to have studied the problem to some extent and have reported their findings in their respective journals.

Another salient feature of the literature review was an overwhelming concensus which maintains that *forests do in fact play an important soil protective role and that deforestation (or clear-cutting) can promote not only erosion, but also mass-soil movement*.

It is interesting and, I believe, quite relevant to quote from a few of these references. Of particular interest is a study conducted by Bishop and Stevens (1964) on landslides in logged areas in southeast Alaska. They noted a tremendous increase in both the frequency of slides and the area affected after logging as shown in Figure 2. The slopes they studied were mantled with a glacial till soil (Karta soil series). The study area was located in the Maybeso Creek drainage near Hollis, Alaska.

Bishop and Stevens believe that the destruction of interconnected root systems and their gradual deterioration accelerated the frequency of slides

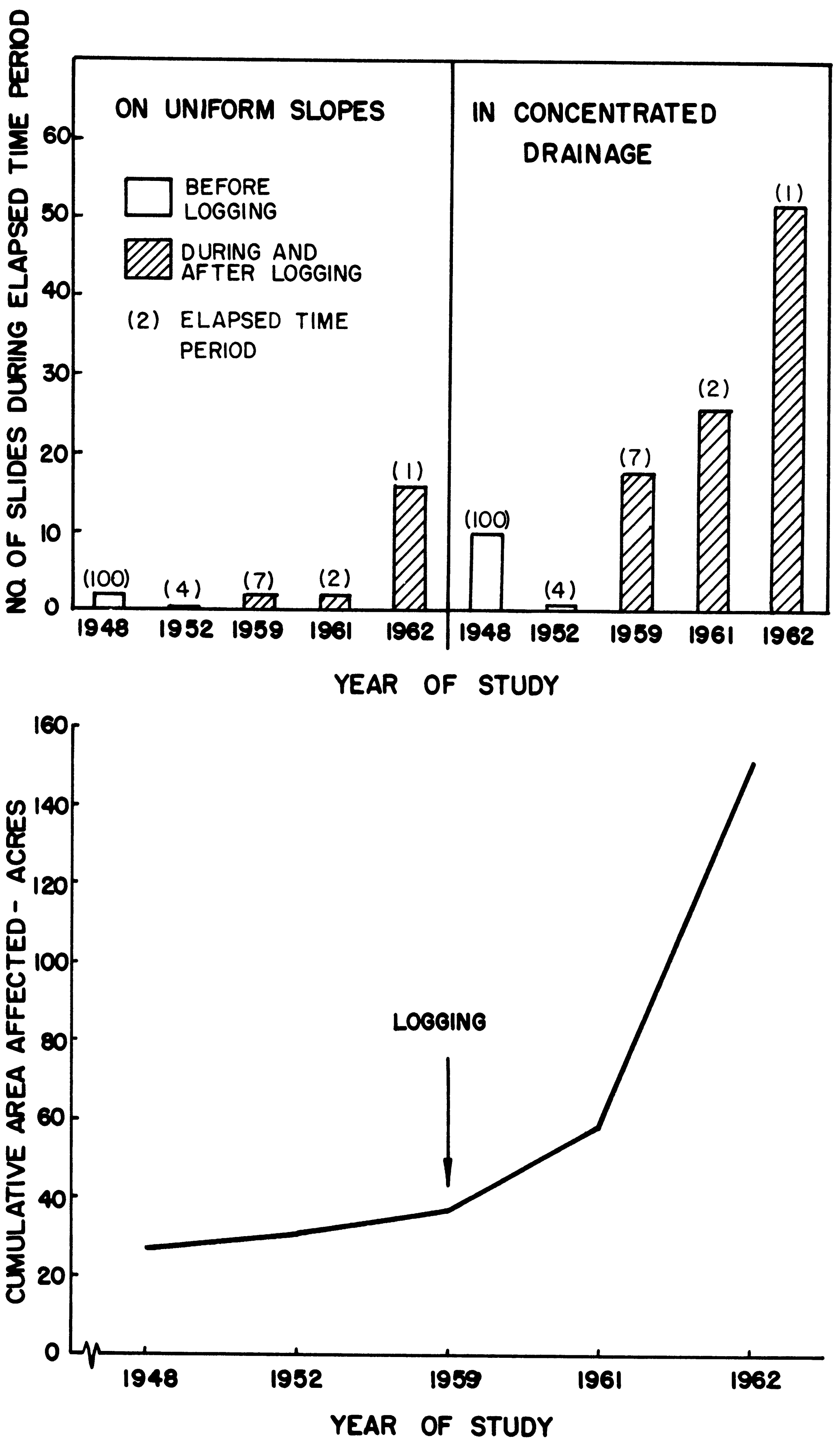

Figure 2. Frequency and acreage of slides before and after logging in Maybeso Creek Valley, Hollis, Alaska (after Bishop and Stevens, 1964).

after logging. They cite the time lag in slide activity after logging to support this view. They noted, for example, that inspite of the high degree of positive correlation observed generally between sliding and rainfall intensity there were fewer slides in 1959 when rainfall intensity was high than in 1961 when rainfall intensity was low.

Croft and Adams (1950) conducted a study of landslides and sedimentation in the North Fork of the Ogden River in the Wasatch Mountains of Utah. These authors concluded that before modern-day land use, landslides were rare, if not entirely absent in the drainage basin they studied. They too attributed recent occurrences of landslides largely to loss of mechanical root support by root systems of trees and plants chiefly as a result of timber cutting and burning.

Kittredge (1948) has observed that in the coast ranges near San Francisco many slips occur in wet years on the clay soils of heavily grazed grasslands. In contrast, slips do not occur on these same soils in the extensive plantations of eucalyptus more than 25 years old. Corbett (1966) examined the frequency and extent of soil slips on brushland converted to grassland in Southern California. Both the area affected and the number of soil slips were about five times greater on grass-covered areas as opposed to brush-covered areas as shown in Table 1.

Kawaguchi (1956, 1959) and his co-workers in Japan place great value on a well rooted forest cover as a means of minimizing landslide activity. They noted that landslides were far more prevalent in shrublands and grasslands than in forested areas. They also observed that the effectivness of the forest

TABLE 1

AREA AND NUMBER OF SOIL SLIPS IN BRUSH COVERED VS. CONVERTED SLOPES, SAN DIMAS EXPERIMENTAL FOREST, CALIFORNIA

(After Corbett, 1966)

Soil Type*	Acreage in Type		No. of Slips per Acre		Relative Area in Slips, %	
	Converted	Control	Converted	Control	Converted	Control
B/3R1-1	4.5	5.7	0	0	0	0
A/1R1-2	8.7	9.2	0	0	0	0
A/3R0-2	4.1	4.4	.49	0	1.3	0
A/3R1-2	26.3	26.8	.15	0	.3	0
A/2R1-3	81 0	77.2	1.98	.32	6.0	1.1
A/3R1-3	70.9	73.5	2.34	.38	9.4	1.7
B/3R1-3	10.8	11.2	.74	.09	2.4	.1
Ac/4R1-3	33.4	30.9	1.74	.06	8.6	.3
A/1R1-4	57.4	54.8	4.48	1.46	13.0	5.1
Ac/1R1-4	23.9	24.4	4.39	.70	13.4	1.8
Ac/2R1-4	33.1	39.6	3.41	.48	13.5	2.6
Totals	354.1	357.7	--	--	8.4	1.8
Averages	--	--	2.46	.48	--	--

*Soil symbols: The soils were mapped according to standard soil series criteria. Each series has been tentatively designated by a capital letter. The small 'c' shows that the soil is colluvial. The first numeral in the denominator is the soil depth class, the R1 is the rockiness class and the last numeral is the slope class. Source: Crawford, J. M. Soils of the San Dimas Experimental Forest. U. S. Forest Serv. Pacific SW. Forest & Range Exp. Sta. Misc. Paper 76. 20 pp., illus. 1962.

cover in preventing landslides increased with the age or maturity of the forest. Bernadini (1957) studied the occurrence of landslides in the mountains in the north of Italy. He recommended forestation as a principal control technique. In another article by Cappuccini and Bernadini (1957) on the causes, classification, and prevention of landslides, the authors state that an insufficient cover of vegetation is one of the most important causes of landslides.

A recent Russian book by Molchanov (1960) on the hydrologic role of forests contains an interesting chapter on the soil protective role of forests. Although the author makes no mention of the effect of deforestation on mass-soil movement, he does argue very strongly against the practice of clear-cutting on steep, mountainous slopes with a grade of greater than 20 percent. He cites increased rates of runoff, soil erosion, and subsequent turbidity in streams as reasons for desisting in the practice of clear-cutting, and advocates selective logging as a preferable alternative.

I was able to find only two references disagreeing with this concensus, viz., that deforestation promotes mass-soil movement. The first was a study by Ellison and Coaldrake (1954) of soil mantle movement in relation to forest clearing in south eastern Australia. These authors concluded that the forest they examined was no better than sod in restraining mass-soil movement. It should be pointed out, however, that the forest was a shallow rooted, rain forest with virtually no undergrowth or litter present on the forest floor. No eucalyptus was present in the forest either.

The second reference, was a study by Flaccus (1959) on landslides and their revegetation in the White Mountains of New Hampshire. He concluded that logging was not an important cause of landslides in the White Mountains. In fact, he maintained that removal of the forest cover might have a stabilizing influence because of elimination of the weight of the trees from the slope. This line of reasoning is incorrect. The downslope weight component of a forest is at best only a few percent of the total weight of the soil mantle. Furthermore, the weight component of the trees perpendicular to the slope (and hence to a potential slip surface) will also tend to increase the shear strength of the soil.

All of the preceding studies, with a few exceptions, appear to establish a cause and effect relationship between clear-cutting and mass-soil movement. These studies are largely observational in their approach; they do not clearly identify nor establish the critical combination of hydrologic, slope, and soil mantle conditions that lead to instability. In other words, there has been no rational attempt to predict what will be the factor of safety of a natural slope against sliding before and after clear-cutting. This is a difficult problem, but it is partly amenable to slope stability analyses based on principles of soil mechanics and on knowledge of soil-water-plant interactions. It is precisely this type of analysis which this report will describe in subsequent sections. Procedures will also be outlined for obtaining quantitative field data from instrumented slopes both before and after they are clear-cut.

THEORETICAL ANALYSIS

1. GENERAL CONSIDERATIONS

The stability of a slope depends on a delicate balance between forces. In general we can state that a slope fails when the shear forces on any potential failure surface exceed the shear strength. In soil mechanics, it is customary to express this balance of forces in terms of a factor of safety against sliding. This factor is commonly defined as follows:

$$F = \frac{\Sigma \text{ shear forces promoting sliding on a critical surface}}{\text{shear strength along the surface}}$$

A safety factor of one would indicate imminent or incipient failure. It is essential to note that this factor is calculated mainly to assess the danger of sudden or catastrophic slope failure. The possibility of slow yielding or creep taking place in the slope is not precluded by a calculated factor of safety slightly greater than one. Accelerated rates of creep can lead to landsliding even though shear stresses are below their critical or peak values. This is an important reason for monitoring creep rates in the course of a field study on the effects of deforestation, particularly where calculated factors of safety in forested slopes are already close to unity.

Soil constitutive relations, slope geometry, and pore water pressures are the primary factors that explain the behavior and stability of slopes. Any slope stability analysis must take these factors into account. This invariably means making a few simplifying assumptions in order to have a tractable mathematical solution. A major problem is to assess the probable mode of deformation, i.e., whether planar or rotational. This will depend largely on geologic conditions and slope geometry.

Fortunately, we are able to adopt in the present study the much simpler stability analysis based on planar modes of deformation. We can reasonably expect movements of this type when loose products of weathering overlie an inclined bedrock contact. The weathered material might be a clayey, residual soil, colluvium, or a thin mantle of glacial till. Forested slopes meeting this description are quite common to southeast Alaska, the Pacific Northwest, and the Rocky Mountain area.

2. VARIABLES AFFECTING SLOPE STABILITY

It is instructive before proceeding further with the stability analysis to inquire what are the variables that can affect or alter the balance of forces in a natural slope—and more specifically to determine what is the likely effect of vegetation on some of these variables. Variables affecting slope stability have been conveniently grouped by Varnes (1958) into those tending to reduce shear strength on the one hand and those increasing shear stress on the other as shown in Table 2. Possible ways vegetation might affect the balance of forces are as follows:

a. Mechanical reinforcement from the root system

b. Slope surcharge

c. Wind levering and root wedging

d. Modification of soil moisture distribution and pore water pressures.

It is worth commenting briefly on each one of these effects.

TABLE 2

FACTORS CONTRIBUTING TO INSTABILITY OF EARTH SLOPES

(After Varnes, 1958)

Factors that Contribute to <u>High Shear Stress</u>	Factors that Contribute to <u>Low Shear Strength</u>
A. Removal of Lateral Support 1. Erosion - bank cutting by streams and rivers 2. Human agencies - cuts, canals, pits, etc. B. Surcharge 1. Natural agencies - wt of snow, ice and rainwater 2. Human agencies - fills, buildings, etc. C. Transitory Earth Stresses - earthquakes D. Regional Tilting E. Removal of Underlying Support 1. Subaerial weathering - solutioning by ground water 2. Subterranean erosion - piping 3. Human agencies - mining F. Lateral Pressures 1. Water in vertical cracks 2. Freezing water in cracks 3. Swelling 4. Root wedging	A. Initial State 1. Composition - inherently weak materials 2. Texture - loose soils, metastable grain structures 3. Gross structure - faults, jointing, bedding planes, varving, etc. B. Changes Due to Weathering and Other Physico-Chemical Reactions 1. Frost action and thermal expansion 2. Hydration of clay minerals 3. Drying and cracking 4. Leaching C. Changes in Intergrannular Forces Due to Pore Water 1. Buoyancy in saturated state 2. Loss in capillary tension upon saturation 3. Seepage pressure of percolating ground water D. Changes in Structure 1. Fissuring of preconsolidated clays due to release of lateral restraint 2. Grain structure collapse upon disturbance

a. Mechanical reinforcement from the roots: Indirect evidence reported in the literature suggests that this may be the most important effect of trees on slope stability. Presumably deep-rooted species of trees or woody shrubs whose roots penetrate through the soil mantle to bedrock would enhance stability the most. Conversely, removal of such a vegetal cover with subsequent rotting and deterioration of the roots would have the most serious consequences. Root density studies as a function of depth have been reported in the literature (Gaiser, 1952; Patric et al., 1965), but no studies have been reported which isolate the contribution to slope stability of various root systems.

b. Surcharge: At first glance this would appear to increase shear stress, but the effect is largely negated by a concomitant increase in shear strength due to the confining effect of the surcharge as shown in Figure 3. Furthermore, Bishop and Stevens (1964) estimate that the surcharge due to the weight of the forest (spruce and hemlock) amounts to only 50 psf. This is equivalent to a layer of soil only 6 inches thick. Although the surcharge will have little effect on the calculated factor of safety, it will affect creep rates to some extent as shown later.

c. 'Wind throwing' and 'root wedging': Strong winds blowing parallel to the slope will exert an overturning moment on the trees. This can lead to so-called wind throwing of trees which creates localized disturbances in the soil mantle. Wind throwing is a fairly common occurrence in some forests but it normally affects only aged and diseased trees. The total down slope force created by a wind blowing through a forest and hence its overall effect on slope stability has never been evaluated. The effect of root wedging, an alledged tendency of roots to penetrate a soil thereby loosening it up or opening cracks and fissures, likewise is presently unknown. Judging by evidence reported in the literature, particularly the observations by Bishop and Stevens (1964), the beneficial effects of root systems on slope stability far outweigh any possible adverse effects.

d. Modification of soil moisture distribution and pore water pressure: Trees transpire water through their leaves and this in turn depletes soil moisture. Hoover (1953) has measured the ability of a pine forest to deplete soil moisture to considerable depth and to reduce or eliminate the runoff from winter rains. Soil moisture depletion produces negative pore water pressure (or suction), which as seen previously (Table 2), is conducive to slope stability. A forest can also intercept moisture either in the crowns of trees or in the ground litter.

Interception and transpiration tend to either mitigate or delay the onset of waterlogged conditions in a slope. All other things being equal, a forested slope might not reach critical saturation as

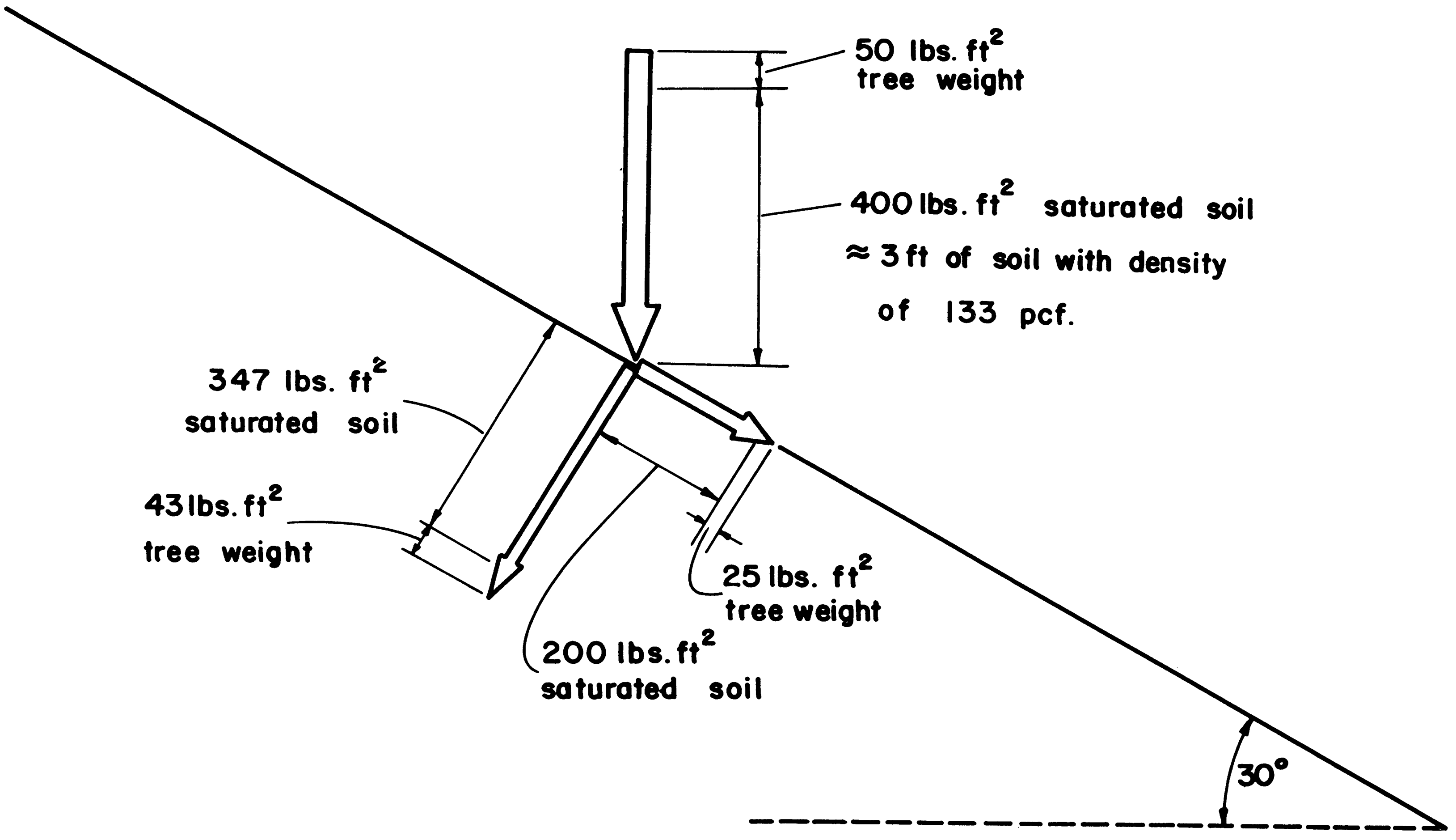

Figure 3. Vector diagram showing effect of hypothetical tree and saturated soil weights on the shear and normal forces at the bedrock contact.

quickly nor exhibit such high pore water pressures (piezometric levels) after intense storms as a denuded (clear-cut) slope. This is somewhat equivalent to saying that forested slopes may be able to tolerate storms of greater intensity and duration than cut-over slopes, i.e., before a critical failure condition is reached.

Bethlahmy (1962) has obtained some interesting data on soil moisture content from a clear-cut plot and adjacent forested plot in a virgin, Douglas fir-hemlock forest in the Cascade Range of Oregon. His findings clearly support the views expressed above. Both the extent of soil moisture depletion and the time required for recharge* were considerably higher in the virgin, forested plot. These trends are schematically illustrated in Figure 4. This behavior is by no means peculiar to Douglas fir forests in the Cascade Range. Bethlahmy cites several studies by other investigators which show similar trends, in areas of widely diverse climatic and soil conditions. It is important to point out, however, that Bethlahmy only studied first-year effects of timber removal on soil moisture. Studies by Hallin (1967) showed that after three years, low vegetation which invades a cut-over plot is nearly as effective as old growth timber in depleting moisture. Figure 5 compares soil moisture in cut-over and adjacent timber in a Douglas fir area in southwest Oregon. It appears, therefore, that the first year after cutting is likely to be the most critical as far as soil moisture and its effect on slope stability is concerned.

In the next section, we shall show how both the factor of safety against sliding and the creep rate in a slope are explicitly related to the piezometric level in a slope. Fortunately, piezometric levels or soil moisture stress can be measured quite accurately and precisely in a soil by means of piezometers and tensiometers. Ideally, a slope should be instrumented with recording piezometer-tensiometers such as those described by Watson (1967). The recording feature is desirable in order to follow the soil-moisture stress response during and immediately after intense storms. Another alternative is to instrument with maximum recording piezometers such as those used by Swanston (1967) in his soil water piezometry study in a landslide area in southeast Alaska. These devices are relatively simple; they record only the maximum height of rise of the ground water table—the most critical condition with regard to slope stability.

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*The time required for the soil to reach field capacity or the degree of saturation corresponding to the maximum amount of water the soil can hold against the force of gravity.

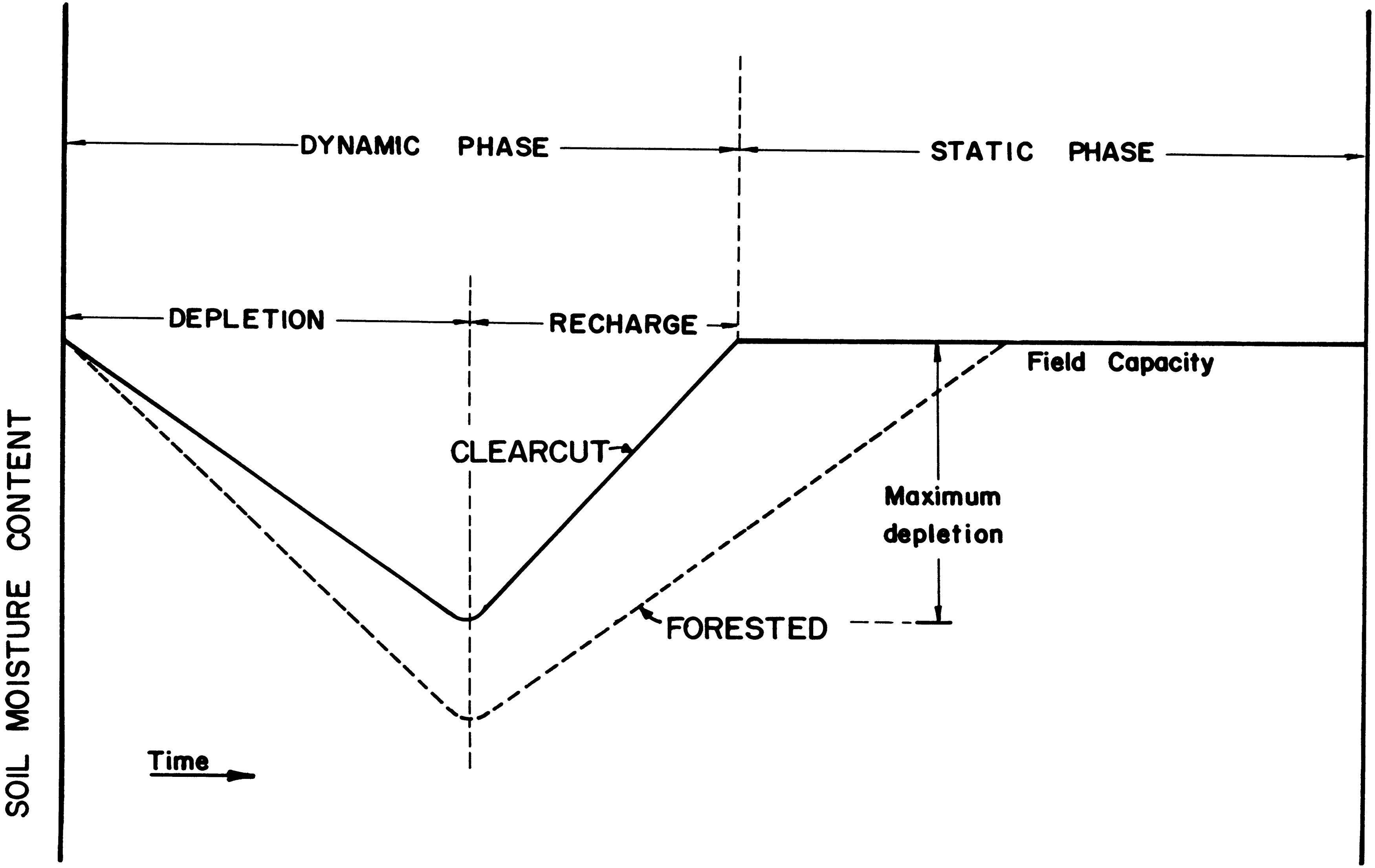

Figure 4. Idealized representation of soil moisture cycle in forested and clear-cut areas.

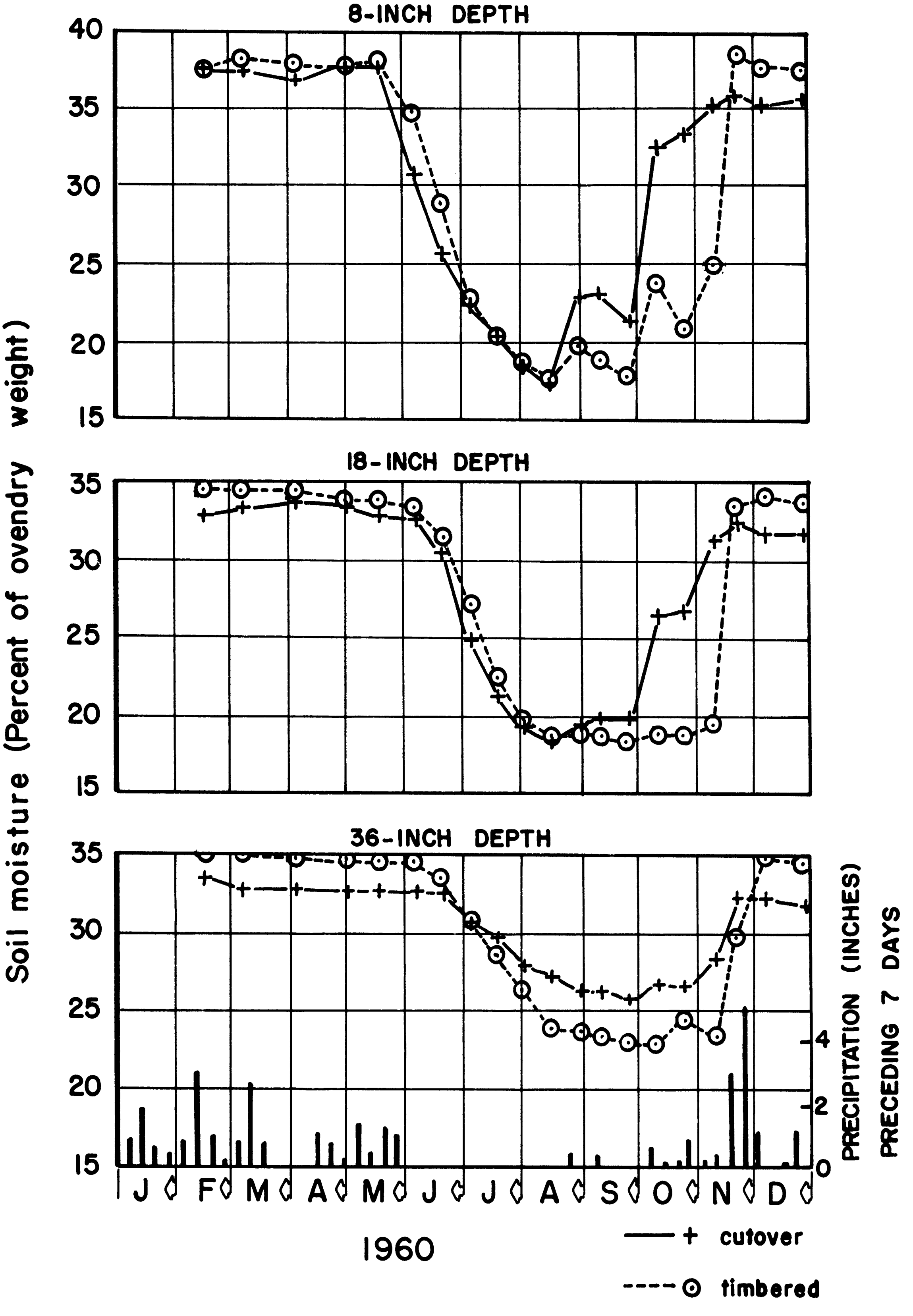

Figure 5. Comparison of soil moisture in cut-over and adjacent timber in Southwest Oregon three years after felling (after Hallin, 1967).

3. SLOPE STABILITY EQUATIONS

As discussed previously, it is possible to adopt in this study a slope stability analysis based on planar deformation. A useful stability analysis of this type has been developed by Ter-Stepanian (1963) and also by Yen (1969). These analyses are both similar; each of them permits calculation of creep rates in the soil mantle. They differ mainly in their criteria for the threshold stress at which yielding or creep first occurs. Yen's criterion is based on residual shear strength parameters as obtained from a constant strain rate, triaxial test; whereas Ter-Stepanian's is based on a yield stress determined directly from a rheological type test. Yen's approach is adopted in the present study.

The basic assumptions on which the stability analysis was derived are as follows:

a. The soil behaves as a quasi rigid, visco plastic solid during shearing deformation. The relation between shear stress and velocity gradient of shearing deformation is shown in Figure 6 and by the following equation

$$\tau = \tau_o + \eta G \tag{1}$$

where τ = shear strength; τ_o = yield stress; η = coefficient of viscosity; and G = velocity gradient of shearing deformation.

b. Soil creep along a slope begins when the shearing stress is equal to or greater than the residual strength of the soil:

$$\tau_o \geq C_r + \sigma \tan \varphi_r \tag{2}$$

where C_r, σ, and φ_r are residual cohesion, effective stress, and the residual internal angle of friction at the potential plane of failure, respectively, as shown in Figure 7. Also shown in Figure 7 is the Coulomb failure envelope based on peak, shear strength values. This line represents the locus of stress states which would produce sudden failure or land sliding. In between the two envelopes are stress

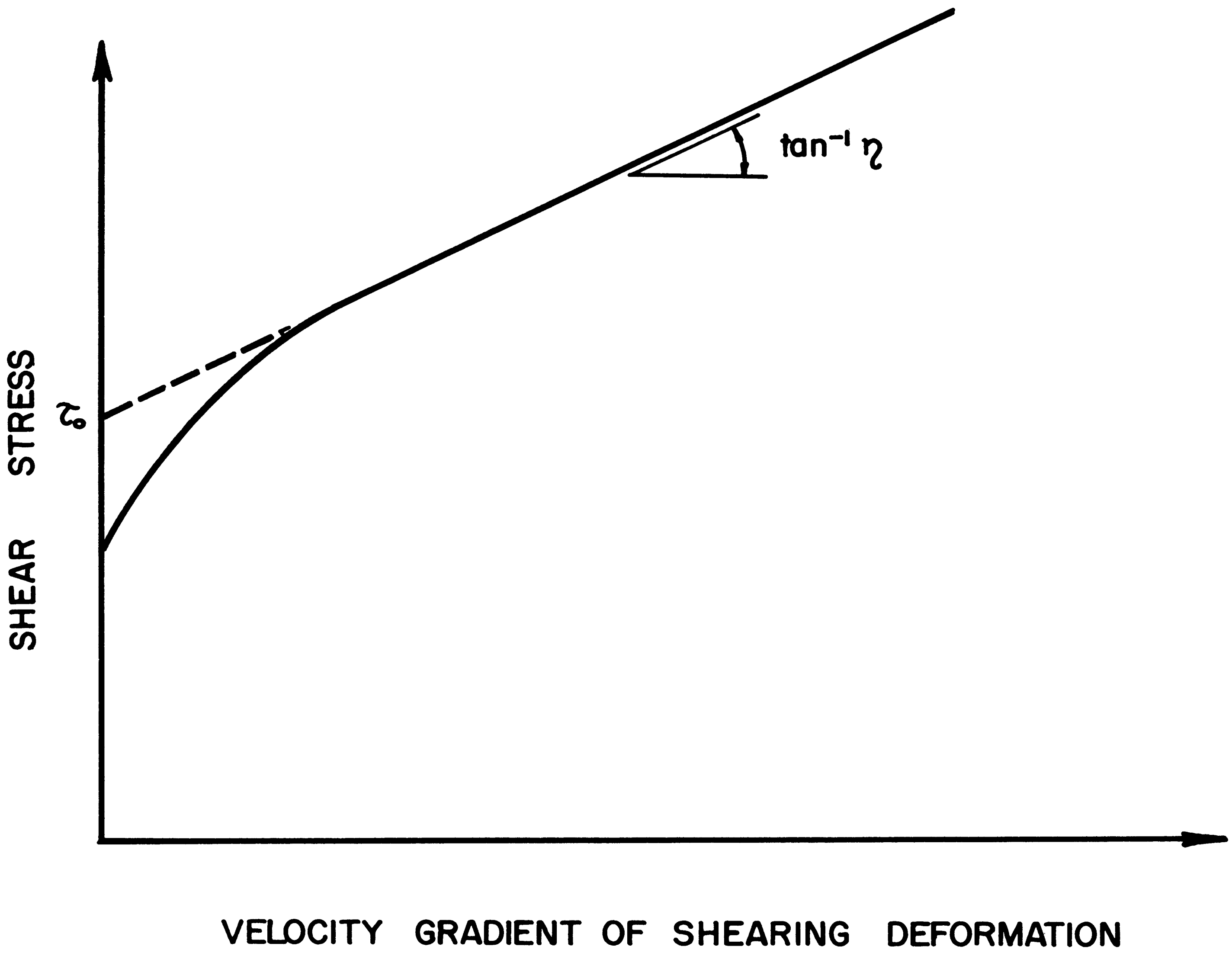

Figure 6. Shear stress vs. velocity of shearing deformation in an idealized clay soil.

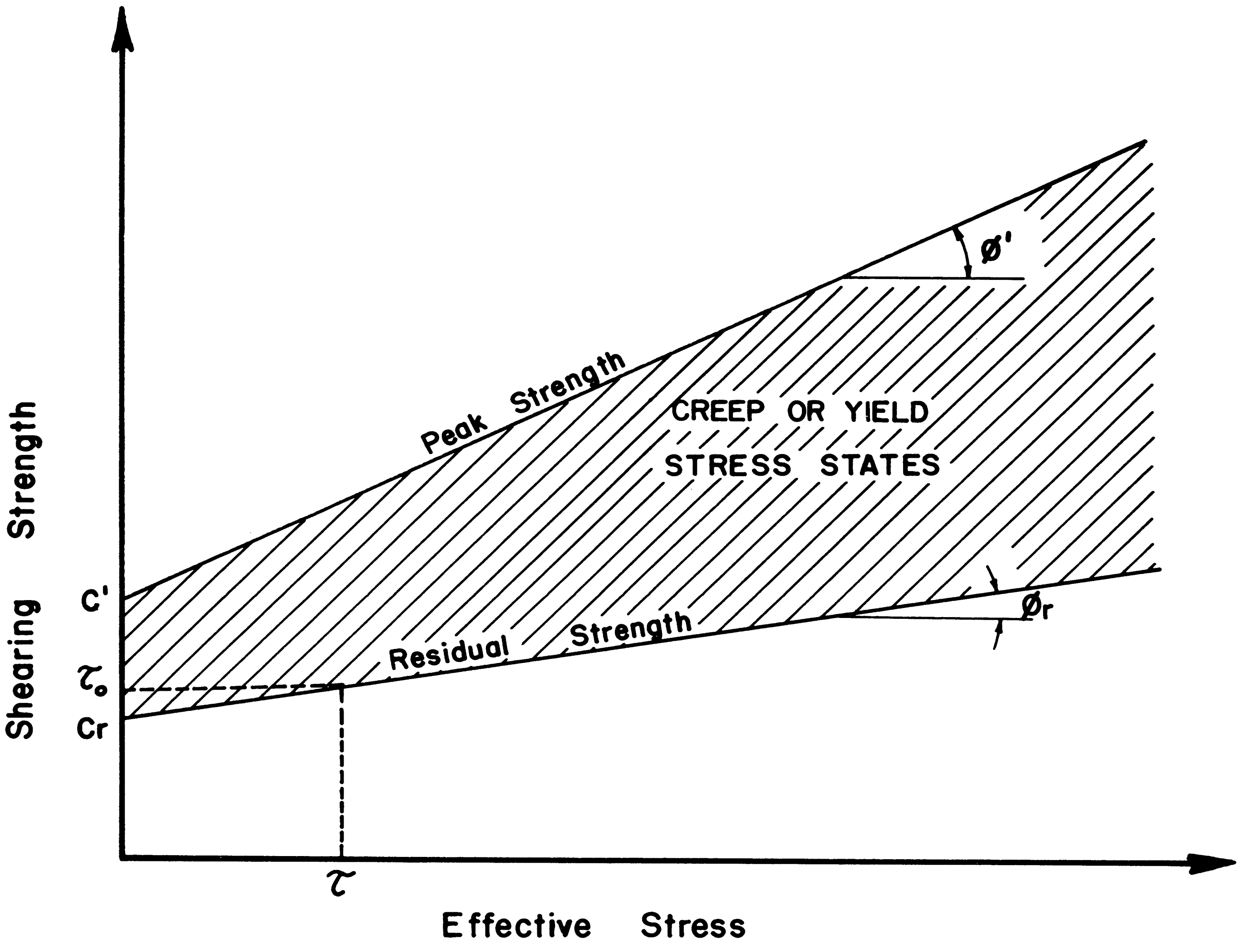

Figure 7. Shear strength characteristics of soils in natural slopes (after Yen, 1969).

states likely to produce slow yielding or creep.

c. For simplicity in analysis the slope is assumed to be an infinite slope. Such a slope has constant angle of inclination β, and identical vertical cross sections at any point of the slope. The thickness of the soil mantle is also much less than the height of the slope. These assumed conditions reflect reasonably well the slope geometry of many forested slopes. When calculating the stability of such slopes the influence of edges of the sliding body may be neglected.

   The geological structure of the slope is shown schematically in Figure 8. A saturated or partially saturated layer of clayey, residual soil of vertical thickness h, lies on an inclined bedrock surface. The piezometric level in the slope is at a height, h_p above the contact. The soil layer creeps along the inclined plane of contact. The soil will creep within a zone of a certain thickness or height above the contact denoted by, h_r. The soil which is above this height will be in a phase of rigidity, i.e., it will be displaced as a whole with no relative movement occurring within it. The height of the rigidity zone was shown by Ter-Stepanian to be proportional to the piezometric level in the slope. The weight of a forest cover can be replaced by a uniformly distributed load with intensity q_o.

d. Consolidation or swelling of the soil during creeping are assumed to be negligible. This implies deformation at constant volume with pore pressure a variable controlled only by hydrologic conditions in the slope—these in turn being affected by slope vegetation and climate.

Based on the preceding assumptions and borrowing from Ter-Stepanian (1963) analysis, we can write down the following useful expressions. A detailed derivation of these equations can be found in Ter-Stepanian's article.

a. <u>Height of the rigidity zone</u>

$$h_r = a + b\,h_p \tag{3}$$

where

$$a = \frac{q_t \tan\beta - p_t \tan\phi_r}{\gamma \tan\beta - \gamma' \tan\varphi_r}$$

$$b = \frac{\gamma_\omega \tan\phi_r}{\gamma \tan\beta - \gamma' \tan\varphi_r}$$

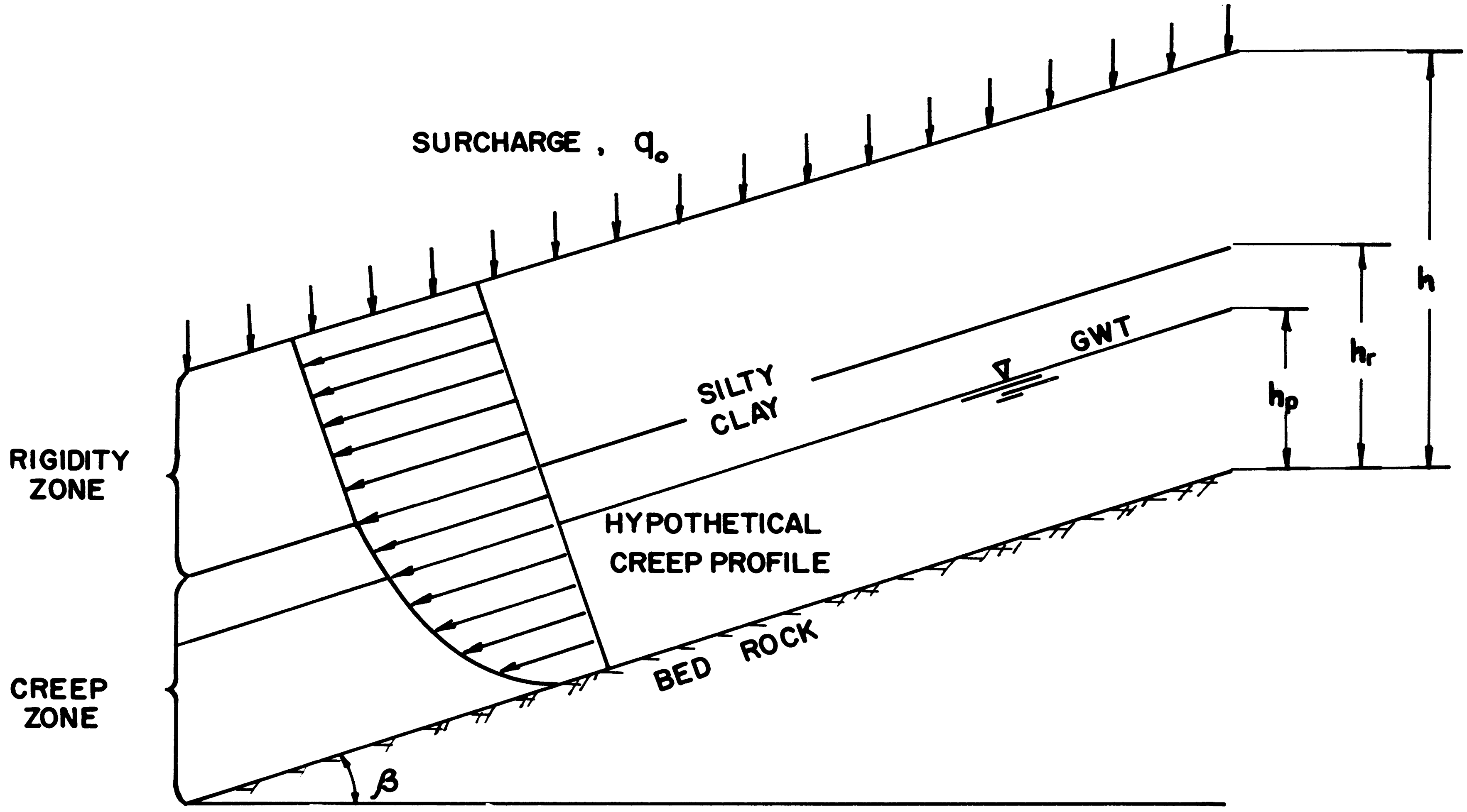

Figure 8. Schematic representation of slope geometry.

and

$$q_t = q_o + \gamma h$$

$$p_t = \frac{c' \cot \Phi'}{\cos^2 \beta} + q_o + \gamma h$$

b. <u>Factor of safety of the slope</u> (against complete failure)

$$F = \frac{\tan \Phi'}{q_t \tan \beta} (p_t - \gamma_\omega h_p) \qquad (4)$$

c. <u>Allowable height of piezometric level</u>

$$h_a = \frac{p_t}{\gamma_\omega} - \frac{F}{\gamma_\omega} q_t \frac{\tan \beta}{\tan \varphi'} \qquad (5)$$

(the critical height occurs when F = 1)

d. <u>The maximum rate of planar depth creep</u>

$$v = \lambda \cos \beta \Bigg[\left(\frac{\gamma}{\gamma'} \tan \beta - \tan \varphi_r \right) h_r$$

$$+ \frac{\tan \beta}{\gamma'} \left[\frac{\gamma}{\gamma'} (p_t - \gamma_\omega h_p) - q_t \right] \ln \left(1 - \frac{\gamma' h_r}{p_t - \gamma_\omega h_p} \right) \qquad (6)$$

where

$$\lambda = \frac{c' \cot \varphi' + \sigma'}{\eta}$$

The various symbols used in these equations are defined as follows:

h = vertical height or thickness of the soil mantle
h_r = height of the rigidity zone
h_p = height of the piezometric level
h_a = allowable height of the piezometric level
v = rate of planar depth creep
q_o = surcharge pressure on slope
γ_ω = density of water
γ = saturated density of soil
γ' = buoyant density of the soil
c' = effective cohesion

ϕ' = effective internal angle of friction
φ_r = residual internal angle of friction
σ' = effective normal stress
β = slope angle
η = coefficient of soil viscosity
F = factor of safety against slope failure

4. SLOPE STABILITY PREDICTIONS

With the help of the preceding expressions (Eqs. (3)-(6)), it is possible to determine the influence of a key variable such as piezometric level on slope stability. Let us examine, for example, the dependence of both height of rigidity zone h_r, and rate of planar depth creep v, on the piezometric level h_p. This can be illustrated by assigning reasonable values to the other parameters in Eqs. (3) and (6), and by plotting graphically the ensuing relationship h_r vs. h_p and v vs. h_p. In the following example, we will consider two cases of special interest, viz., (a) a loaded slope, $q_o = 0.5$ TSF, (b) a free soil layer, $q_o = 0$. The assigned values for the other parameters are:

β = 16°
h = 6.0 meters
γ = 1.82 tons (m)/m^3
c' = 0.1 TSF
ϕ' = 24°
φ_r = 12°
$\eta = 1.2 \times 10^{-8}$ kg sec cm^{-2} at $\sigma' = 1.0$ kg/cm^2

The results of calculations and the relationships in question are shown in Figure 9. Several interesting features emerge from this graphical plot. Note that as the piezometric level approaches the surface of the soil layer the creep rate accelerates markedly. Also note that the acceleration in creep rate is more pronounced for the free soil layer than it is for loaded slope. In other words, at high piezometric levels surcharge caused by the weight of

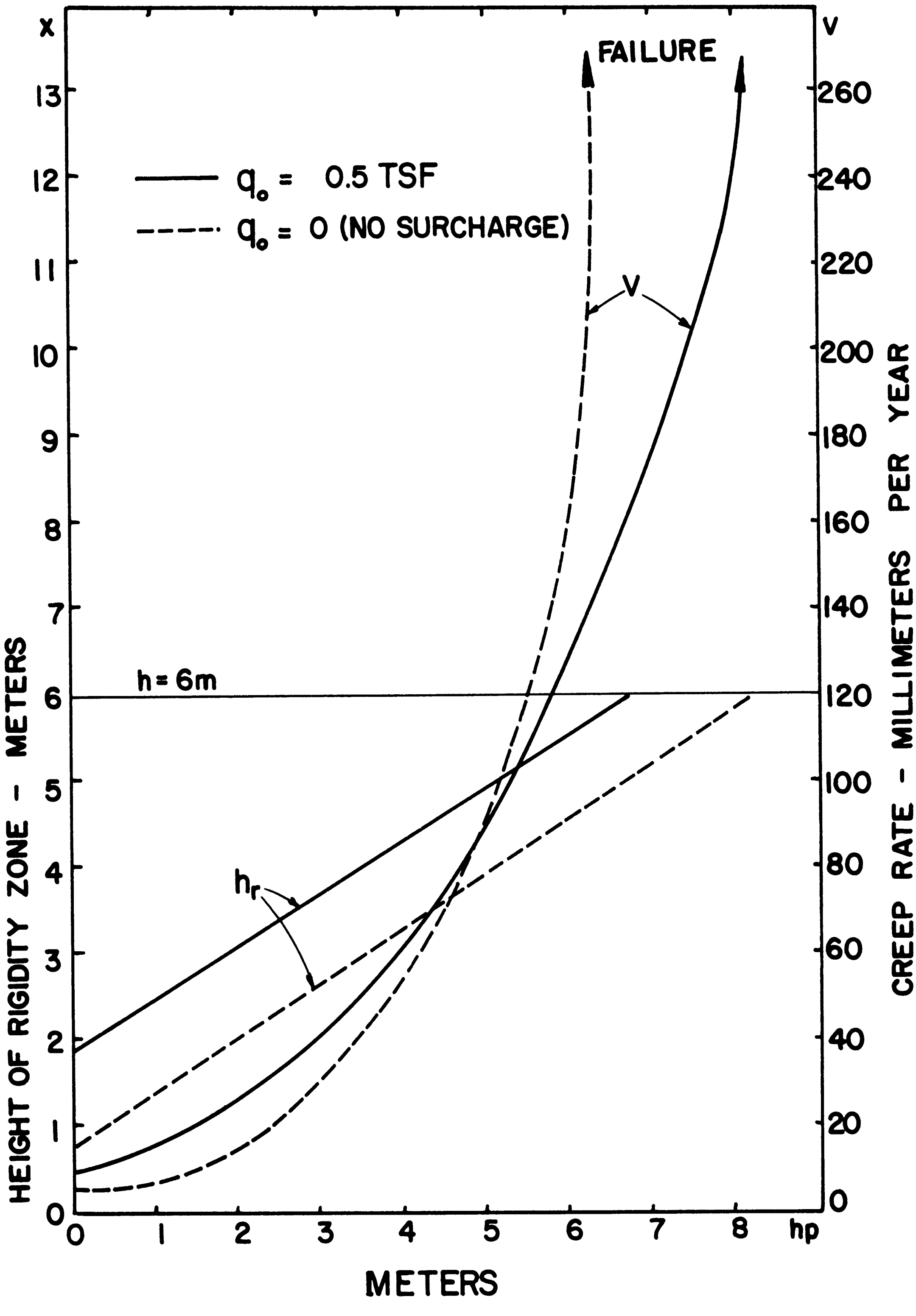

Figure 9. Relation between the rate of planar creep of slope v, the height of rigidity zone h_r, and the piezometric level (after Ter-Stepanian, 1963).

a forest would have a beneficial effect.

Of greater importance perhaps in the present study are the use of Eqs. (4) and (5) which permit calculation of the factor of safety F, against failure and the allowable piezometric level, respectively. The former makes it possible to classify forested areas in terms of susceptibility to slope failure based on slope data and measurements of soil strength properties and average piezometric levels. The latter, on the other hand, makes it possible to evaluate the probable effect of clear-cutting on slope stability. If it can be shown, for example, that a piezometric level in a forested slope is already dangerously close to the critical value, then clearly it would be unwise to proceed with clear-cutting assuming this is likely to result in yet higher piezometric levels.

One additional forecasting or prediction technique presents itself in conjunction with these equations. As mentioned previously, the piezometric level in a slope is also affected by climatic conditions (i.e., by rainfall rates). This means that by doing a little advance soil water piezometry in an area it should be possible to develop empirical correlations between rainfall rates and piezometric levels in both forested and cut-over slopes. Swanston (1967) was able to develop such a correlation by using a regression analysis to fit rainfall data to piezometric information obtained from a particular area. Figure 10 illustrates graphically such a correlation for a drainage basin he studied in southeast Alaska.

By using supplementary slope data and soil shear strength information from the same area studied by Swanston it is possible to calculate the critical piezometric level from Eq. (5). The slope and soil data used in such a calculation are the following:

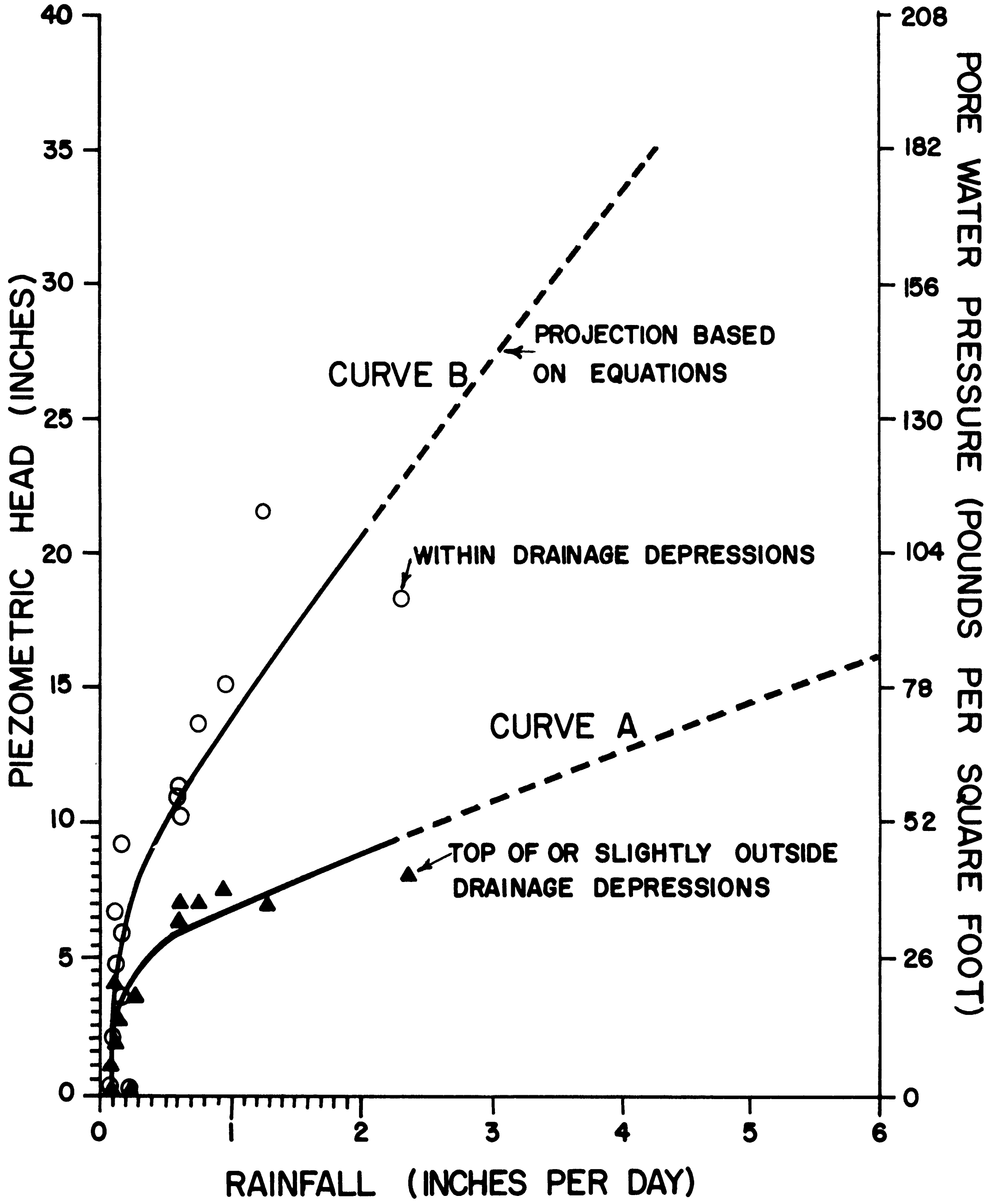

Figure 10. Graph of average piezometric head vs. accumulated rainfall per day in a landslide area in Southeast Alaska (after Swanston, 1967).

$\beta = 37°$ (range: 35 to 40)

$\varphi' = 35°$

$c' = 0$

$h = 3'$

$q_o = 0$

$\gamma = 95$ pcf

With this information the critical piezometric level was calculated to be 31 inches. From Figure 10 this is seen to correspond to a rainfall rate of 4 inches per day within slope drainage depressions (curve B). Rainfall rates of this magnitude are not uncommon in this area (Miller, 1963). The important fact is that extensive mass soil movements are known to have occurred in this very region (Swanston, 1967) during periods of just such precipitation intensity.

Using this approach it should be possible to calculate critical rainfall rates for a given area. Once this information is available, it might then be possible to assess the risk of proceeding with a clear-cut operation based solely of weather records and weather forecasts for a region.

FIELD STUDY DATA

1. LOCATION OF STUDY AREA

Several areas were initially considered for a field study. These included slopes in the White Mountains of New Hampshire, Cascade Range of Oregon, and slopes on the Idaho batholith. The basic requirements we established for selection of a site were:

a. A history of mass-soil movement or susceptibility to sliding

b. Reasonably steep slopes (> 60 percent)

c. Slopes with a relatively uniform mantle of residual soil some 5 to 20 feet thick overlying an inclined bedrock contact.

d. A recently clear-cut area adjacent to a virgin, forested area (both otherwise similar)—for a 'side-by-side' comparison

e. An area scheduled for clear-cutting in the near future from which reliable base or control data could be obtained—for a 'before and after' comparison

f. Good climatic and weather records

g. Year round accessibility

h. Field personnel available at the site to monitor instruments and take readings when necessary.

On the basis of these requirements we selected the H. J. Andrews Experimental Forest in central Oregon as the most suitable site for an initial field study. Slopes on the Idaho batholith also appeared to be reasonably good candidates, and should be considered for subsequent field studies.

The H. J. Andrews Experimental Forest, one of several experimental forests in the Pacific Northwest, was established in July, 1948. The entire 15,000-acre drainage of Lookout Creek, in the Willamette National Forest, was set aside for research purposes—primarily for finding better methods of forest management.

The experimental forest is administered jointly by the administrative and research branches of the U. S. Forest Service. Research work in the forest is done by the Pacific Northwest Forest and Range Experiment Station through its research center at Corvallis, Oregon.

Headquarters of the experimental forest are at Blue River Ranger Station, Blue River, Oregon. The forest itself is about 40 miles east of Springfield, Oregon, and 5 airline miles north of the McKenzie Highway (U.S. 126) as shown in Figure 11.

Two different watersheds within the experimental forest have been instrumented in the slope stability studies: A clear-cut watershed (No. 1) and a forested watershed (No. 10). The former was clear-cut by skyline crane in 1961, the latter is scheduled for clear-cutting in the summer of 1971. The lower side slopes of Watershed No. 1 were instrumented in the summer of 1968, and the upper side slopes of No. 10 in the summer of 1969.

The general topography and location of slope instrumentation for Watershed No. 1 is shown in Figures 12 and 15 (shaded portion of picture, middle right side); that of No. 10, in Figure 13. These two watersheds are approximately a couple of hundred acres in size. One faces north, and the other faces southwest Maximum side slopes in each range from 80 to 100 percent. Average side slopes i

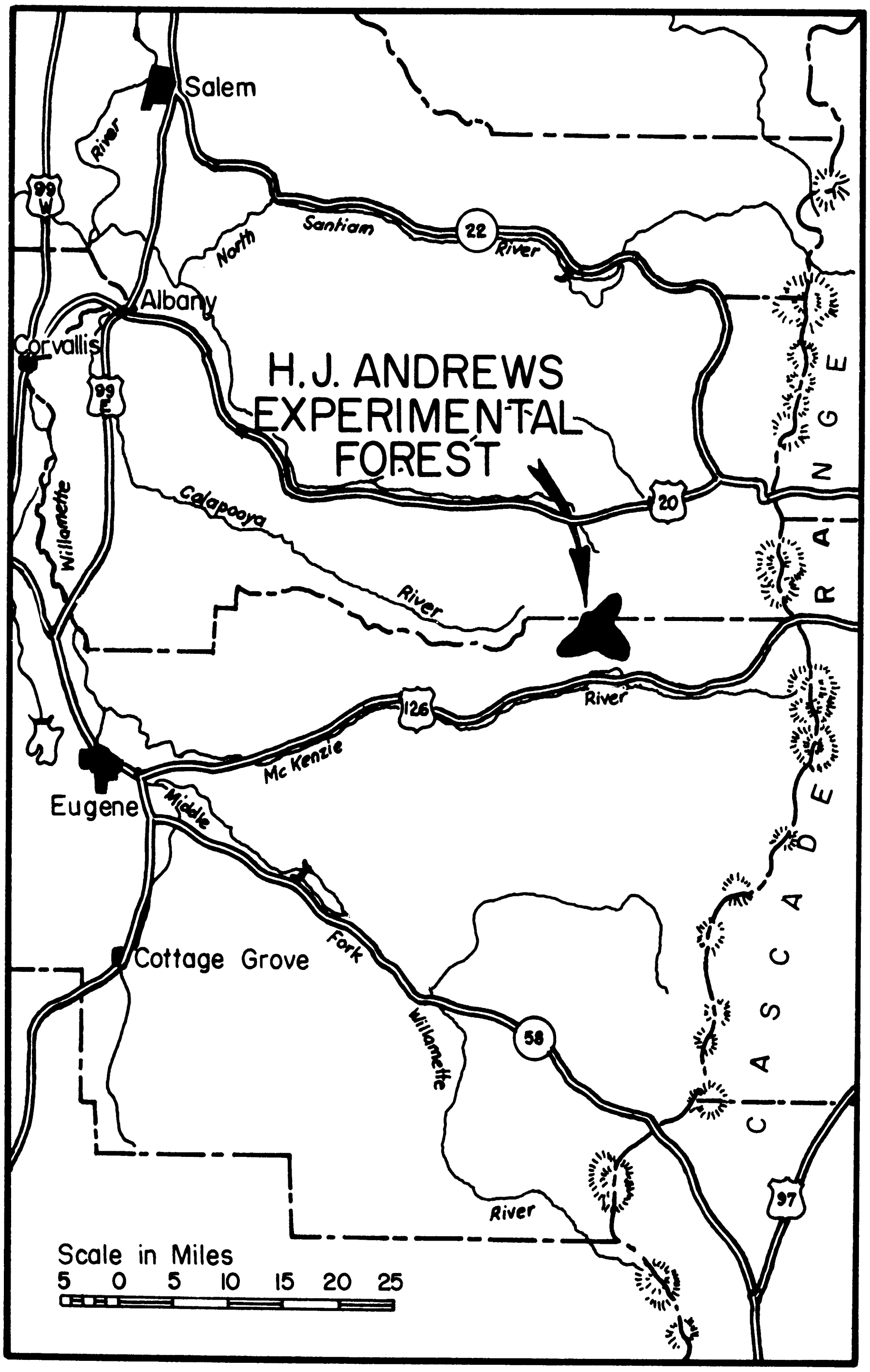

Figure 11. Map location of H. J. Andrews Experimental Forest.

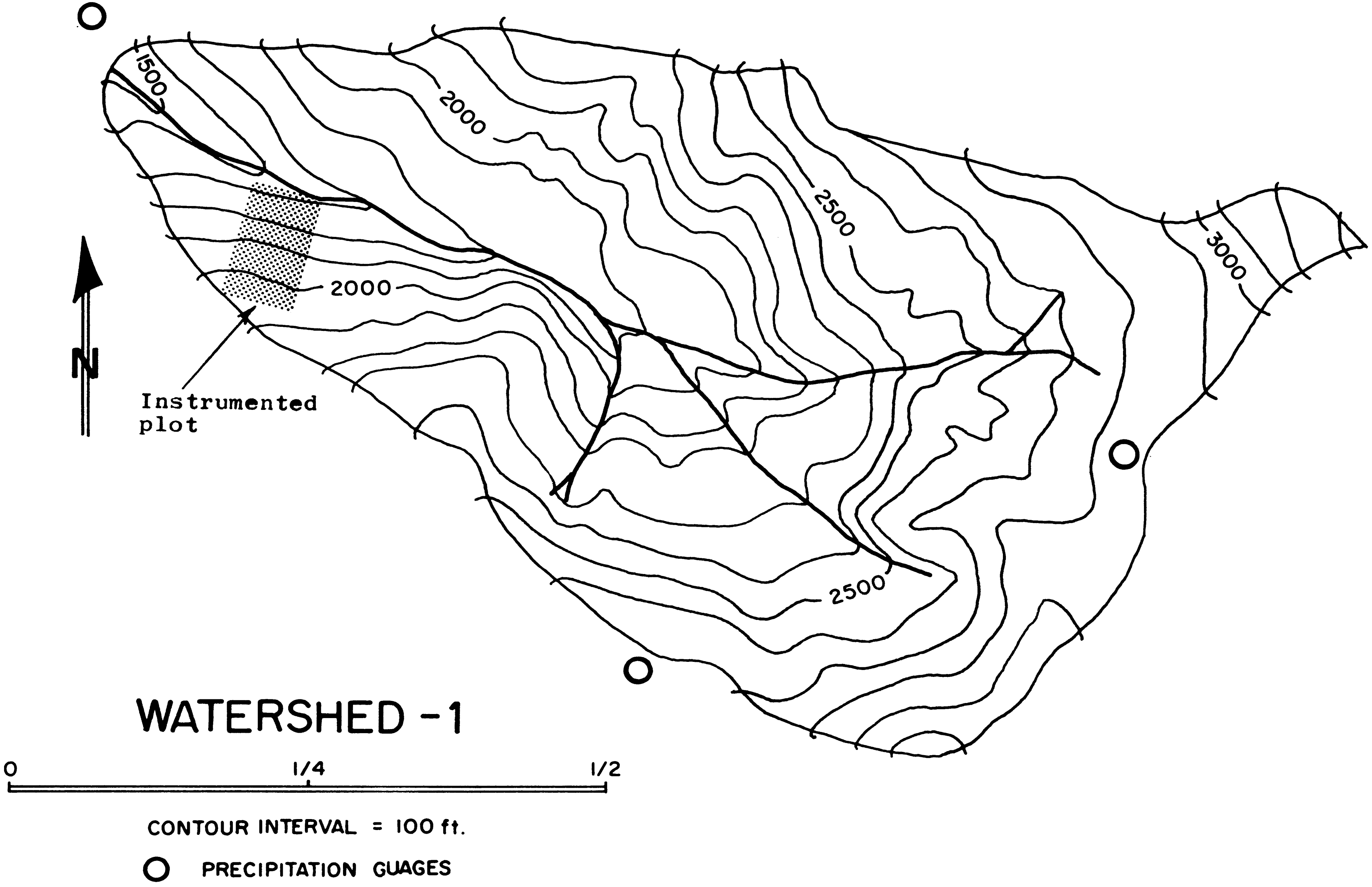

Figure 12. General topography and location of slope instrumentation in Watershed No. 1.

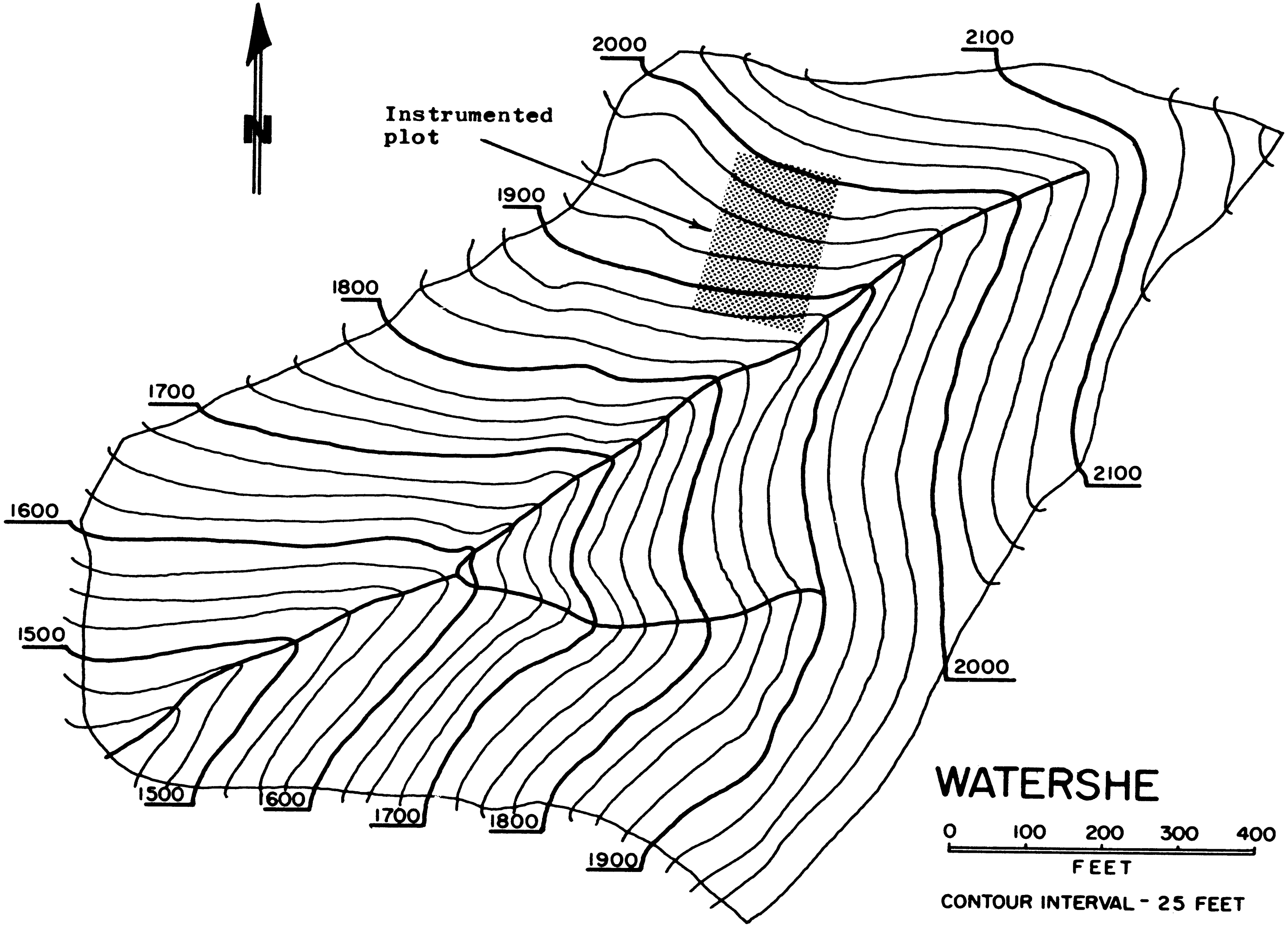

Figure 13. General topography and location of slope instrumentation in Watershed No. 10.

the vicinity of the instrumented plots are about 70 percent for both watersheds.

2. TOPOGRAPHY, CLIMATE, AND SOIL

A complete description of the physiography and climate of the study area is contained in publications by Bernstein and Rothacher (1959); and Rothacher, Dyrness, and Fredriksen (1967). The description which follows is quoted directly from these publications.

The area in question is dominantly mature topography with sharp ridges and steep slopes. Only about one-fifth of the area is in benches or gentle slopes. 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.

Precipitation is heavy, varying from about 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 develops on the higher slopes. Mean temperatures within the forest range from 35°F in January to 65° in midsummer. Extreme temperatures—below 0° or above 100°—are uncommon.

The three principal soil types 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.

3. FOREST TYPES

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 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 cut-over 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 diameter of 4 feet or more. Merchantable volumes of timber in these watersheds 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 calculation 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 14 through 16.

4. MASS-SOIL MOVEMENTS IN THE STUDY AREA

A study of mass-soil movements in the H. J. Andrews Experimental Forest, particularly those occurring during severe storms in the winter of 1964-65, was reported by Fredriksen (1965) and Dyrness (1967). A melting snowpack and a storm which dumped over 13 inches of rain in a 4-day period (sometimes reaching intensities as high as 0.5 inch per hour) combined to produce conditions highly favorable to mass-soil movement.

Dyrness described a total of 47 mass movement events. He recorded at each movement site the type and specific characteristics of the soil, general character of the area, and an assessment of factors influencing soil or debris movement.

Mass movements studied by Dyrness and grouped on the basis of their morphological characteristics are shown in Table 3. A landslide classification system developed by Varnes (1958) was adopted in his study. Earth flows were the dominant type of mass movement. These generally occur when the soil becomes saturated, and the internal pore water pressure builds up thus decreasing shear

Figure 14. Typical view of a forested slope, H. J. Andrews Experimental Forest.

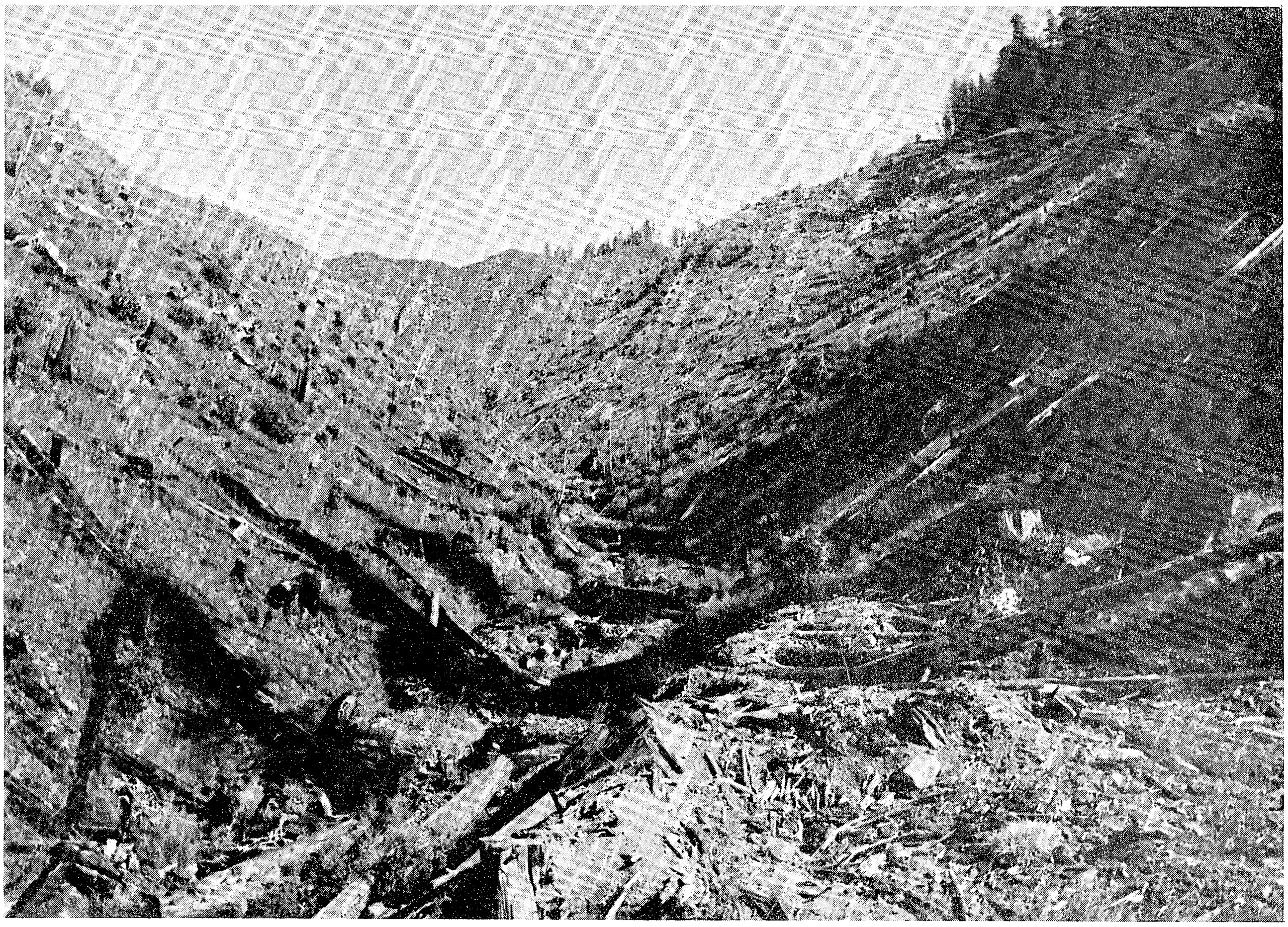

Figure 15. View of a cut-over or clear-cut watershed, H. J. Andrews Experimental Forest.

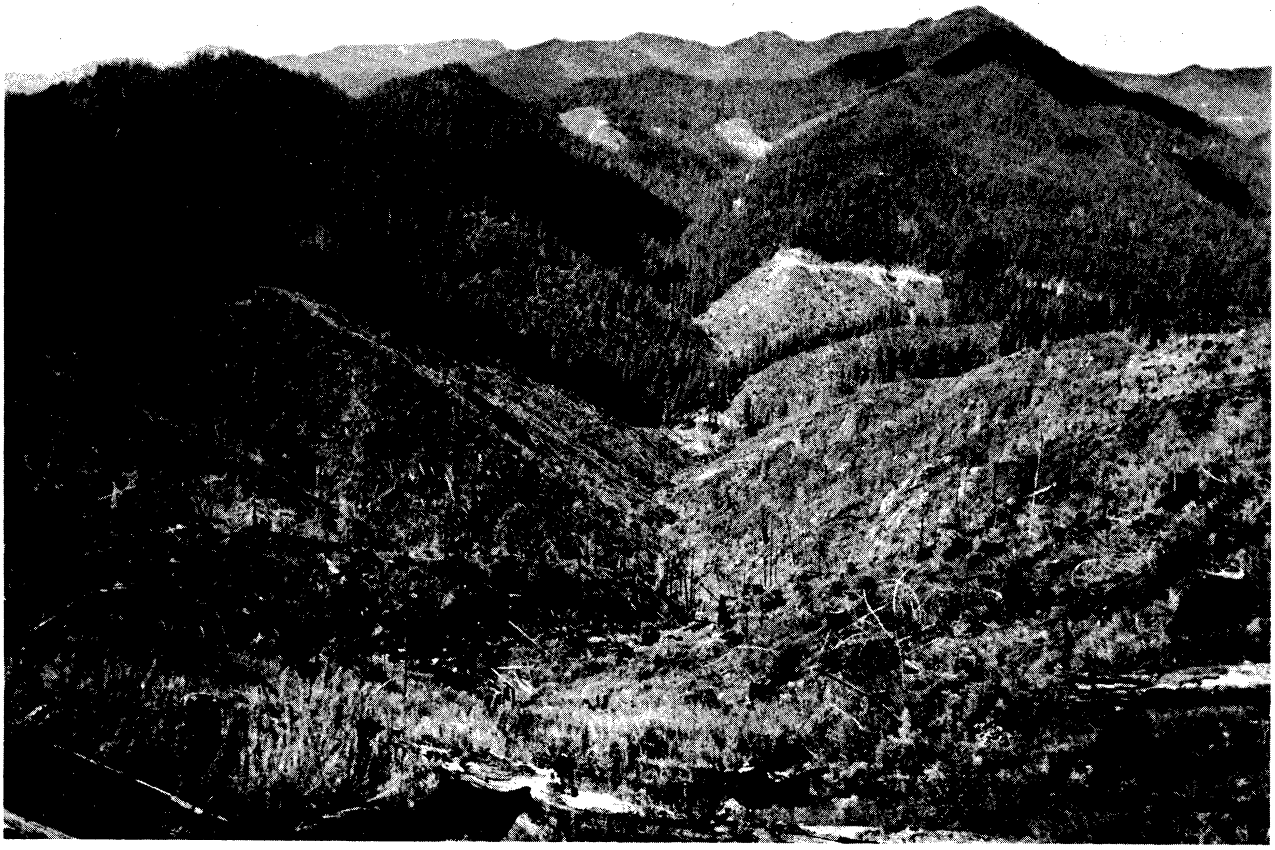

Figure 16. Composite view of clear-cut watershed (foreground) and forested slopes (background).

TABLE 3

MASS MOVEMENTS OCCURRING ON THE H. J. ANDREWS EXPERIMENTAL FOREST DURING THE WINTER OF 1964-65, BY MORPHOLOGICAL CLASS

(After Dyrness, 1967)

Morphological Class	No. of Events	Material Moved, cu yd
Earthflow	18	104,600
Slump with earthflow	7	14,525
Slump	3	4,050
Earthflow causing channel scour	5	82,350
Slump causing channel scour	4	106,300
Debris slide causing channel scour	2	7,500
Channel scour	3	26,300
Roadfill washout	3	1,050
Avalanche with rilling	1	100
Debris avalanche with earthflow	1	1,000
Totals	47	347,775

strength everywhere in the soil mass. When failure occurs the entire soil mass breaks up and flows out in a generally tongue-shaped form. In an earth slide, on the other hand, failure is usually restricted to a few well defined shear surfaces and the soil mass does not disintegrate.

Dyrness also classified mass movements in the H. J. Andrews Experimental Forest according to type of disturbance or mode of action as shown in Table 4. The object in this case was to focus attention on the source area of the mass movement event. Fewer events occurred in undisturbed, forested areas compared to logged areas, but the former contained the largest volume of material. These observations per se are inconclusive as regards the impact of clear-cutting alone because road building associated with logging activity contributes heavily to mass soil movement as shown in Table 4. Furthermore, the observations reported in Table 4 do not really take into account the fact that substantially more acreage is in forested or undisturbed areas (85 percent) as opposed to clear-cut or otherwise disturbed areas. This means, that all things being equal, the chances of finding a greater number of mass movement events in undisturbed areas are statistically better. In fact, the opposite was observed.

TABLE 4

MASS MOVEMENTS OCCURRING ON THE H. J. ANDREWS EXPERIMENTAL FOREST DURING THE WINTER OF 1964-65, BY MODE OF ACTION OR DISTURBANCE (After Dyrness, 1967)

Type of Disturbance	No. of Events	Material Moved, cu yd
Roadfill failure	12	40,900
Road backslope failure	5	14,400
Road backslope and fill failure	6	38,325
Events caused by road drainage water	8	86,450
Road removed by stream	3	4,350
Events in logged areas	8	22,150
Events in undisturbed areas	5	141,200
Totals	47	347,775

Dyrness also attempted to assess or determine possible relationships between mass soil movements and certain site characteristics shown in Table 5 and Figure 17. Several interesting relationships emerged. The influence of roads on mass soil movement 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 is also shown with a ratio of 3.9 in logged areas compared to 0.4 in undisturbed areas.

TABLE 5

RELATIONSHIP BETWEEN OCCURRENCE OF MASS MOVEMENT EVENTS AND CERTAIN SITE FACTORS IN THE H. J. ANDREWS EXPERIMENTAL FOREST

(After Dyrness, 1967)

Site Factors	Mass Movement Events, %	Total Area, %	No. of Events per 1000 Acres
Disturbance:			
Undisturbed	10.6	84.6	0.4
Logging	17.0	13.6	3.9
Road construction	72.4	1.8	125.9
Substratum in movement area:			
Greenish tuffs and breccias	63.8	8.0	25.0
Reddish tuffs and breccias	29.8	29.2	3.2
Andesite colluvium	4.3	42.7	.3
Basalt and andesite residuum	2.1	20.1	.3
Soil series:			
Soils from reddish tuffs and breccias	48.9	22.8	14.2
Frissel Series	27.6	9.3	9.3
McKenzie River Series	21.3	13.5	4.9
Soils from greenish tuffs and breccias	38.3	9.1	37.2
Limberlost Series	25.5	4.1	19.5
Budworm Series	4.3	3.0	4.4
Slipout Series	8.5	2.0	13.3
Soil from andesite colluvium			
Carpenter Series	10.6	34.9	.9
Rock land	2.1	4.1	1.6
Elevation (feet):			
1400-1700	2.1	2.7	2.5
1700-2000	8.5	6.2	4.3
2000-2300	31.9	8.8	11.4
2300-2600	40.4	10.9	11.6
2600-2900	12.8	13.1	3.0
2900-3200	2.1	10.9	.6
Over 3200	2.1	47.4	.1
Slope (percent):			
0-15	2.1	5.9	1.1
15-30	0	25.2	0
30-45	14.9	34.6	1.3
45-60	36.2	22.8	5.0
60-75	31.9	8.4	11.9
75-90	14.9	2.5	18.7
Over 90	0	.6	0
Aspect:			
North	8.5	16.8	1.6
Northeast	14.9	5.0	9.3
East	8.5	5.9	4.5
Southeast	17.0	11.4	4.7
South	0	11.9	0
Southwest	4.3	16.8	.8
West	19.2	9.9	6.1
Northwest	25.5	19.3	4.1
Level	2.1	3.0	2.2

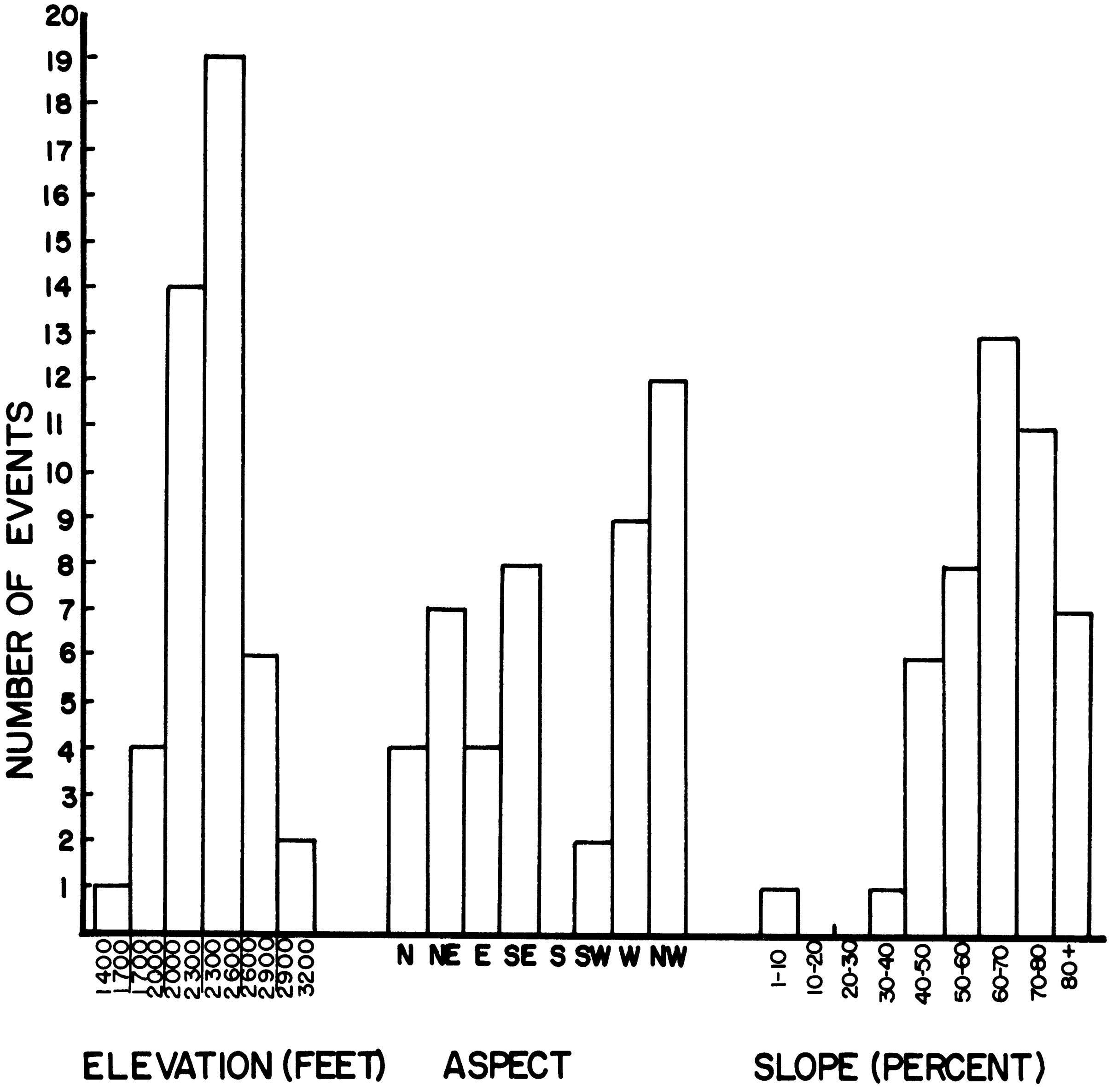

Figure 17. Relationship between number of mass movements and elevation, aspect, and slope (after Dyrness, 1967).

It is also clear 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.

Other site characteristics correlating strongly with increased frequency of movement included northwest exposures, elevation range 2300 to 2600 feet, and slopes in the range 60 to 70 percent. These relationships are shown more clearly in Figure 17.

A photograph of a typical slope failure in a disturbed area is shown in Figure 18.

Figure 18. Slide occurring in a disturbed area, H. J. Andrews Experimental Forest.

SLOPE INSTRUMENTATION

1. MEASUREMENT OF SOIL MANTLE CREEP

The two principal objectives of the slope instrumentation where 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

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[*] Manufactured and distributed by Slope Indicator Company, Seattle, Washington.

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 in one part in 1000, which means a change of inclination of as little as three 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 19.

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 oversize 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

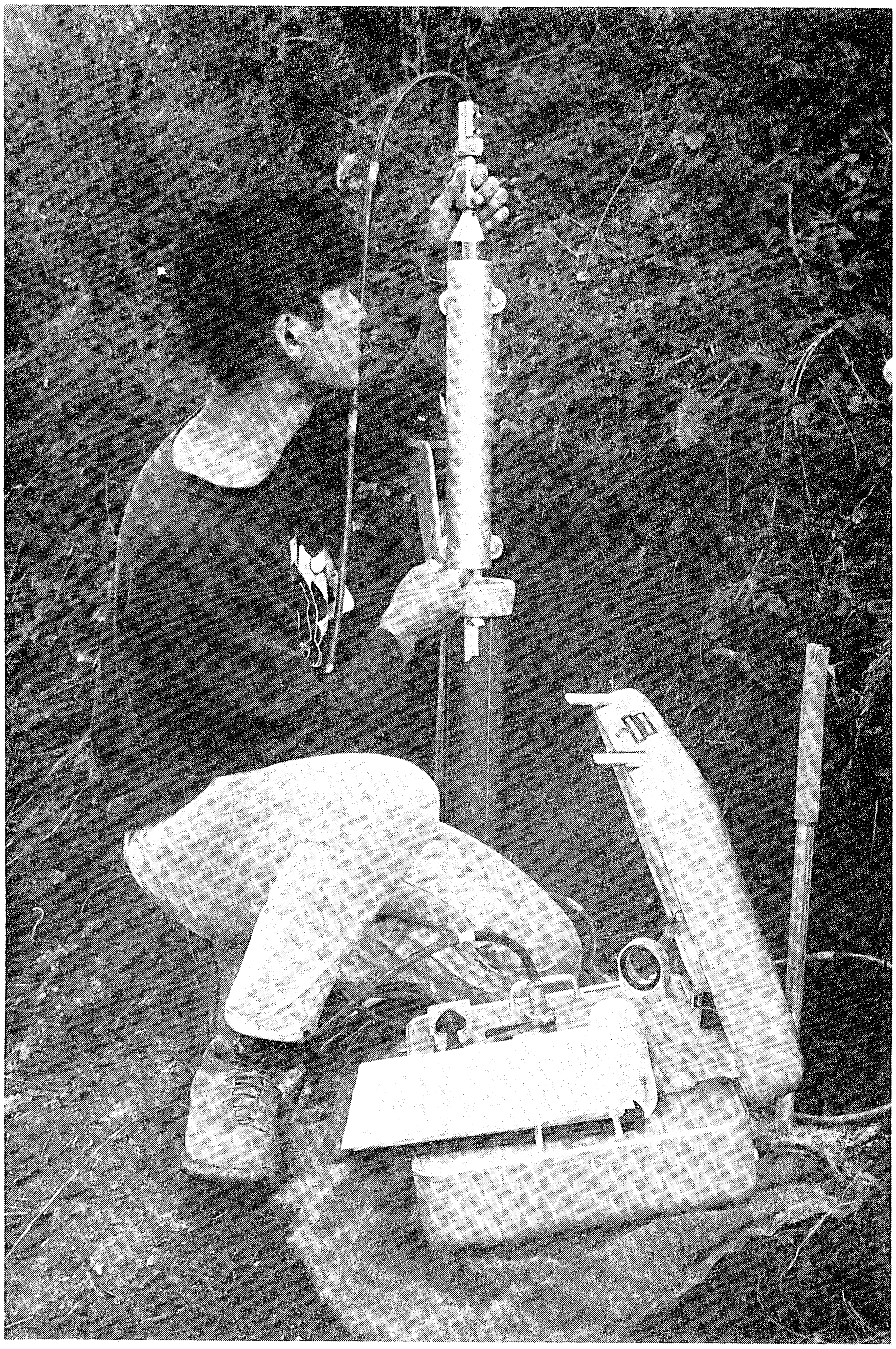

Figure 19. Slope indicator, control box, and top of casing.

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 sieve with a mesh size slightly larger than the grain size of the sand. Figure 20 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 21 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. The deepest holes we drilled bottomed out in fractured bedrock at about 17 feet. Most of the holes in the forested watershed (No. 10) averaged closely around 15 feet in depth, whereas the holes in the cutover watershed (No. 1) ranged from 6 to 17 feet.

We will 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

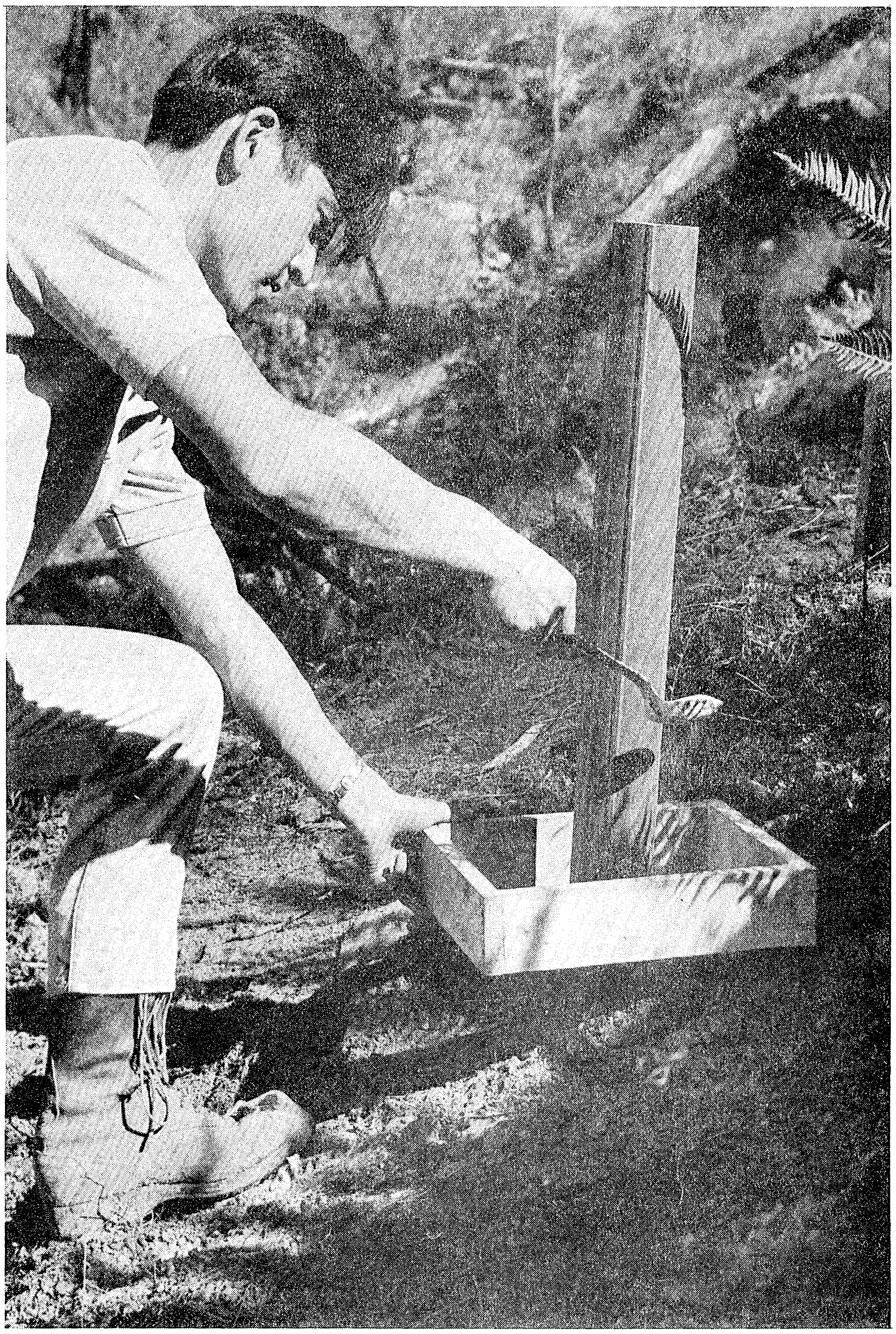

Figure 20. Backfilling around slope indicator casing using 'single grain, air dropping' technique.

Figure 21. Drilling a hole for slope indicator casing using a portable, power auger.

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 Watershed No. 10 which is scheduled for clear-cutting in 1971, 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 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 casings will be removed, the casing capped, and the top of the hole filled in completely.

A view of a typical inclinometer tube installation in a slope is shown in Figure 22. A piezometer tube is also shown protruding above the ground just to the right of the casing or tubing. Six inclinometer tubes were installed in a random pattern in Watershed No. 1, and five in Watershed No. 7 as shown in Figures 12 and 13, respectively. Inclinometer readings are taken initially upon installation and thereafter once or twice a year.

2. MEASUREMENT OF SOIL MOISTURE STRESS

There are several alternative methods of measuring soil moisture stress. The method one selects depends upon a consideration of such factors as:

a. Range of soil moisture stress, i.e., whether positive or negative (suction) pressures will be measured

Figure 22. View of a typical inclinometer tube installation.

b. Ruggedness, reliability, and long-term stability of measuring system

c. Cost

d. Response time

e. Continuous or intermittent recording capability.

The most suitable type of measuring system with respect to items (a), (d), and (e) appeared to be a recording tensiometer-piezometer utilizing a differential pressure transducer. Such a system has been developed and described in detail by Watson (1967). This system could be adapted to give a continuous record of the soil moisture stress from several well points by means of a scanning switch both during and after major storms. Critical piezometric pressures are most likely to develop during these periods.

Items (b) and (c), on the other hand, are fairly severe limitations of such a system particularly in view of the funding limitations of the present study. We decided to use, therefore, the following simpler, least costly measuring methods:

a. Maximum recording piezometers: The highest or maximum piezometric level is the most critical with regard to slope stability (refer to Eqs. (4) and (5)). A piezometer that can record this information is accordingly quite useful, even though nothing is revealed about the rate at which the maximum height is reached nor the starting point. Such a piezometer was developed and used by Swanston (1967) in his study of soil water piezometry in southeast Alaska.

   His piezometer was based on a very simple, but effective principle. As the water level rose in an outer piezometer tube, it carried up with it powdered cork in an inner tube (which could be removed). As the water level started to descend after reaching the point of maximum rise, the powdered cork adhered to the walls of the inner tube thus marking the maximum height of rise. This could be noted by pulling out the inner tube. Once this was done, the cork could be washed down and the cycle again repeated. A schematic diagram of this type of piezometer is shown in Figure 23.

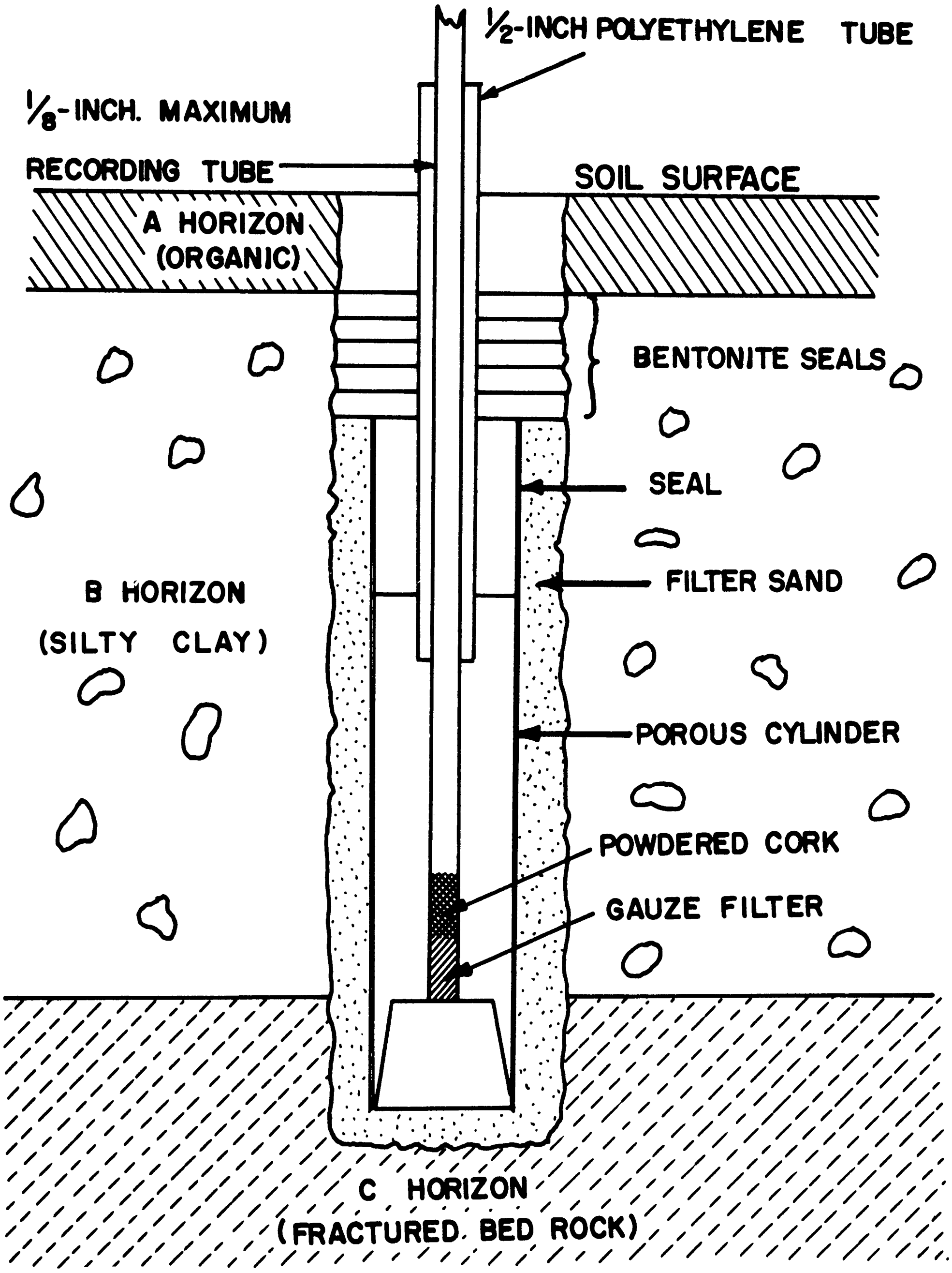

Figure 23. Schematic diagram of a maximum recording type piezometer (after Swanston, 1967).

Maximum recording piezometers of this type were installed in Watershed No. 1. During the first year of operation it was observed that positive heads were only being recorded in two observation wells which were very close to the main drainage. We decided, therefore, in subsequent installations to install tensiometers instead.

b. Tensiometers: Tensiometers appear to provide more information than piezometers which are sensitive to only positive pressures. To begin with, the soil mantle exhibits negative pressures or suctions over most of the year. With tensiometers it is possible to check if the effects of clear-cutting on the soil moisture cycle as indicated by the idealized curve in Figure 4 also apply to the study area in question.

Furthermore, by adjusting the zero point of a tensiometer it is also possible to use it as a piezometer over a limited range. One foot of rise of the ground water table above the porous, measuring tip corresponds to about 3 centibars.

A total of six tensiometers were installed in watershed No. 10 adjacent to the inclinometer holes. 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 24 is a schematic illustration of a typical tensiometer installation.

Tensiometers will cavitate and be sucked dry at negative pressures greater than 1 atmosphere. Suctions on this order and much higher are common in the top few feet of a forested slope. Figure 25 gives some idea of the variation in suction beneath a forested plot as a function of depth and time at two different locations.

Although high suctions were considered to be a possible problem if tensiometers were used, it was found that at the depths they were installed tensions were not excessive. With only one exception tensions were observed to stabilize in the range 20 to 40 centibars during the month of July. Suction should have been high then because of high rates of transpiration and low rainfall.

The tensiometers are being read twice a month and after major storms.

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* Manufactured by Soil Moisture Equipment Company, Santa Barbara, California.

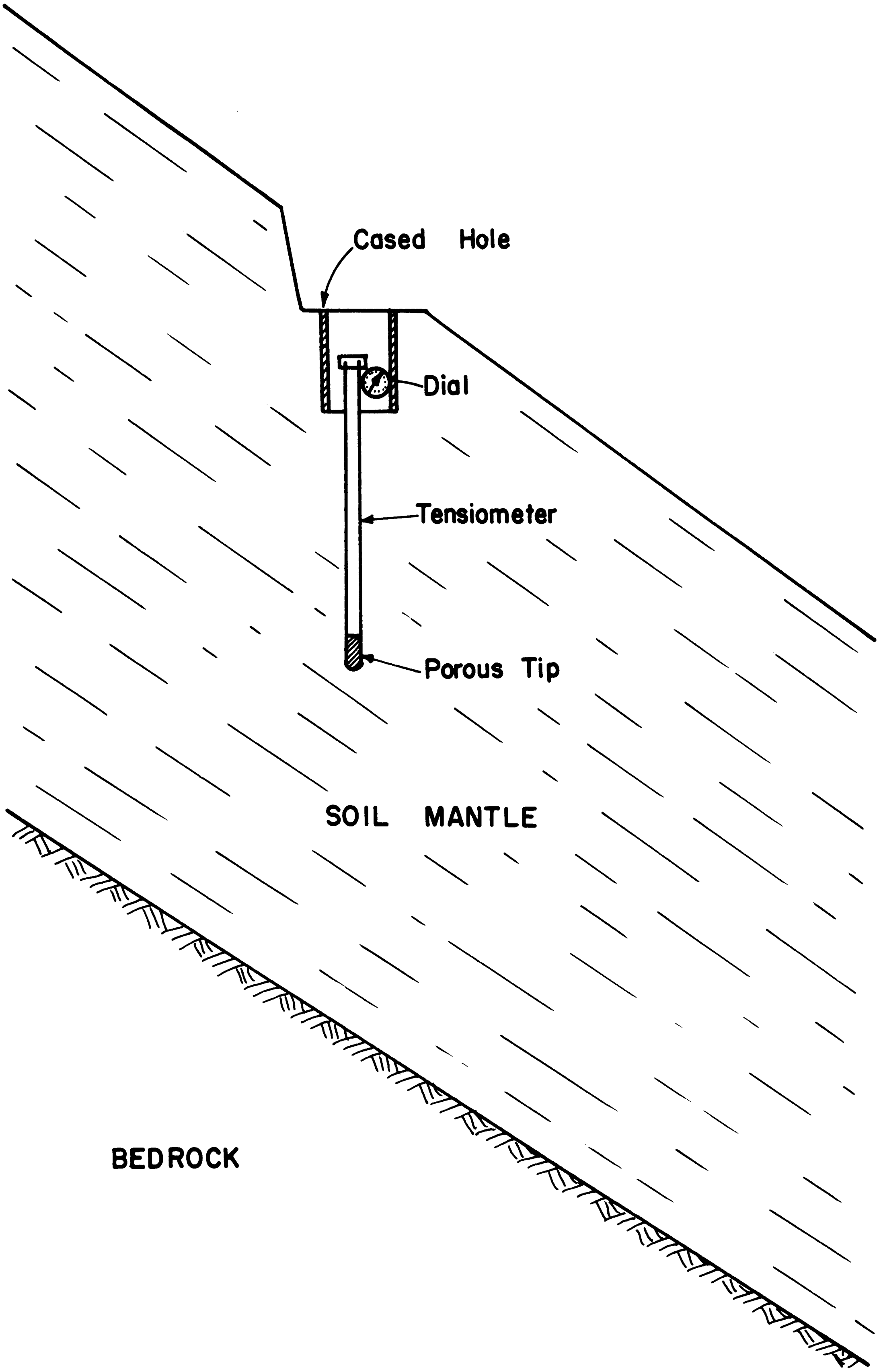

Figure 24. Schematic diagram of a typical tensiometer installation.

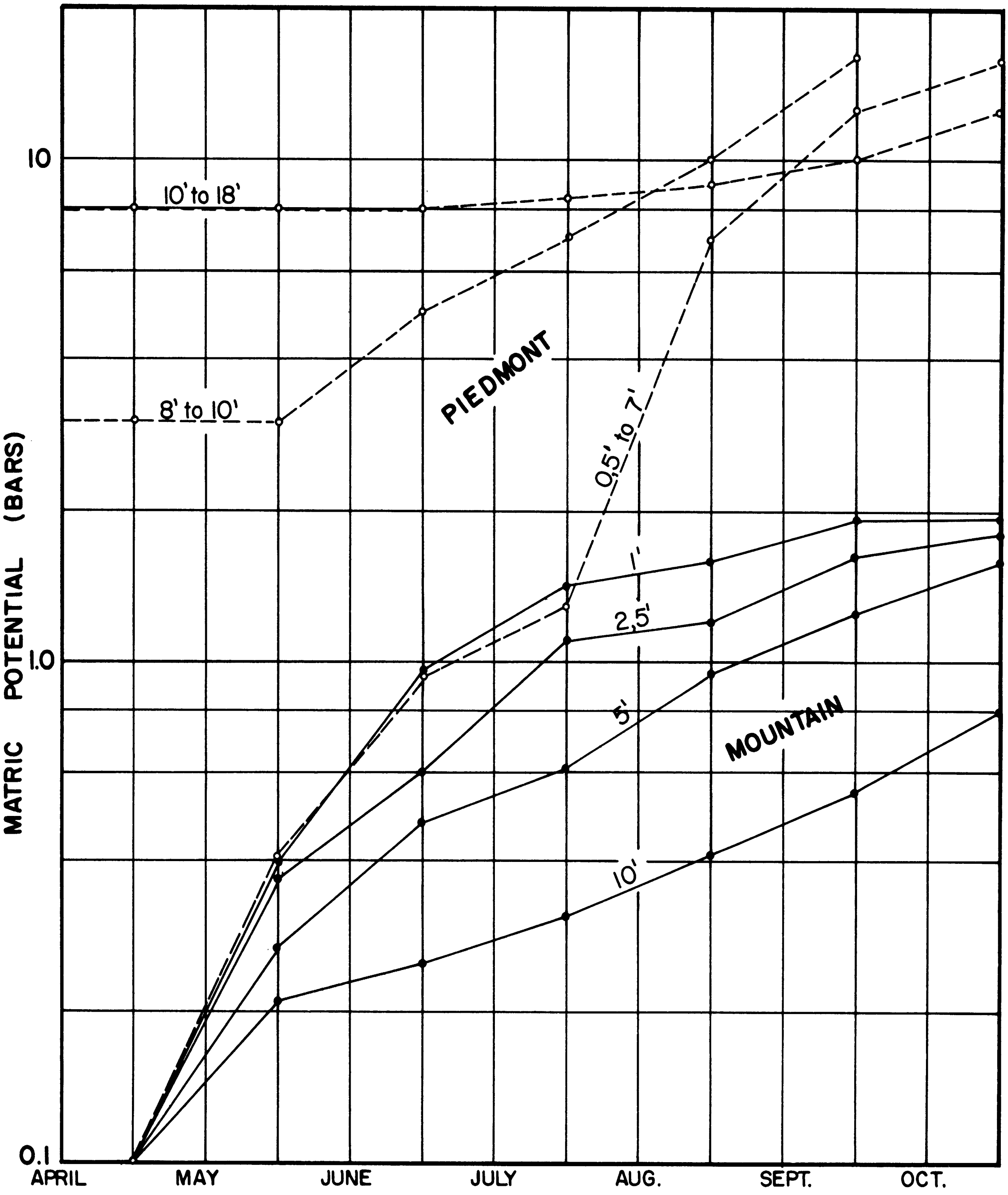

Figure 25. Average matric potential by depth in mountain and piedmont plots (after Patric et al., 1965).

SOIL PROPERTY TESTS

1. SOIL SAMPLING PROGRAM

Both disturbed and undisturbed samples were obtained from the instrumented plots in both Watersheds Nos. 1 and 10. Disturbed samples were retreived from the soil brought up by the power auger during drilling of the inclinometer holes. These samples were placed in sealed plastic bags and are being 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 use in triaxial tests and for determination of the in situ soil density.

Both disturbed and undisturbed samples were obtained from the entire soil profile down to fractured bedrock whenever possible. Figure 26 shows a portable, hydraulic sampling unit in operation. This unit was used in conjunction with the Acker drill set mentioned previously 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.

2. INDEX AND STRENGTH PROPERTIES

Index and strength property tests are in progress at the time of writing this report. The results of these tests and slope stability analyses using this

Figure 26. Soil sampling in progress using a portable, hydraulic sampler.

test data will follow in a subsequent report. It will be possible, using the theoretical analysis for planar deformation described previously, to calculate a critical piezometric level for the instrumented slopes. This calculated value can then be compared with observed piezometric levels in the field.

Index property tests consist of Atterberg limits tests, water content determinations, and grain size analysis. Preliminary clay mineralogy tests* have already been run on soils from the H. J. Andrews Experimental Forest. The dominant clay mineral appears to be montmorillonite with some choritic intergrades.

Shear strength parameters, viz., the effective internal angle of friction and the cohesion, are being determined by undrained triaxial tests. There is always some doubt whether the shear strength so determined represents the true in situ shear strength. This question has not yet been resolved, particularly in the case of natural slopes where stress history is very important and soil variability much greater, however, strength tests on soil samples at least provide a first approximation.

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*Pacific Northwest Range and Forest Exp. Sta., Progress Report Cooperative Agreement No. 50, June 30, 1968.

DISCUSSION AND CONCLUSIONS

It is fair to conclude from an analysis of published literature on the subject that there exists a definite cause and effect relationship between forest clear-cutting and mass-soil movement. Studies carried out in many different parts of the world appear to support this conclusion. Work by Bishop and Stevens (1964) in Alaska, Dyrness (1967) in Oregon, Corbett (1966) in California, and Croft (1950) in Utah, in particular lends strong support to this conclusion.

It also appears evident from a review of the literature that there has been little synthesis of available data and few attempts to identify the critical combination of hydrologic, slope, and soil mantle conditions that lead to instability. There has been no real attempt, in other words, to calculate soil mantle creep rates or factors of safety against slope failure (before and after clear-cutting) using established principles of soil mechanics and soil moisture stress information. Most of the studies while extremely useful and interesting suffer somewhat from being observational as opposed to analytical.

A theoretical stability analysis is outlined in this report which should make it possible to predict the stability of a forested slope and assess the probable consequences of denudation. It is shown possible, for example, to calculate a critical piezometeric level or critical rainfall rate for a watershed given certain information about the slope geometry, hydrology, and soil properties.

A forest cover appears to affect the deep seated stability of a slope in two principal ways, viz., by modifying the hydrologic regime in the soil mantle and by mechanical reinforcement from the root system. The former is likely to be important only in the first year following clear-cutting and burning, i.e., before invading vegetation has had a chance to take hold. Evidence in the literature suggests that the effect of the root system is far more important and that gradual deterioration of a tree root system leads to progressively greater slope instability with time.

A field study has been undertaken at the H. J. Andrews Experimental Forest in central Oregon in order to obtain quantitative data on the effects of clear-cutting on slope stability. This area was selected because it had a record of slope instability and because it had many of the requisite characteristics for a suitable study area as outlined in the report. The field study consists essentially of instrumenting slopes in order to measure rates of soil mantle creep and soil moisture stress before and after clear-cutting.

It is far too early to conclude anything from the field study in Oregon. We estimate that a total of six years will be required before we have sufficient data on which to base conclusions. This is necessarily a long-term type of study.

Instrumentation of additional slopes with a history of slope instability—particularly following logging operations—would be very useful. Slopes on the Idaho batholith, for example, appear to be good candidates for such a study.

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