

RESPONSE OF PROGRESSIVE HILLSLOPE DEFORMATION TO
PRECIPITATION¹

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Creep and earthflow are important natural erosional processes in deeply weathered cohesive soil on steep terrain. The movement of earthflows and mudflows is related to amount and frequency of precipitation, but this relationship is complex. And only a few studies have documented the nature of the relationship. The movement of a New Zealand mudslide was monitored for 14 years (Wasson and Hall 1982). Movement was observed during wet periods separated by inactivity during dry periods. During the wet years, short-term rainfall events triggered accelerated movement, but similar storms during the dry years produced no effect. In general, movement lagged behind periods of high rainfall and continued into periods of low rainfall. Unfortunately only one such rainfall cycle was observed.

Similar complex relationships have been reported by other researchers throughout the world (Campbell 1966, Hutchinson 1970, Prior and Stephens 1971, Keefer 1977). Attempts to develop a statistical relationship between rainfall and movement rate have had only limited success. One study found no clear relationship between movement rate and weekly rainfall (Prior and Stephens 1971). On a monthly basis, however, the coefficient of determination (r^2) between movement and rainfall was 0.50 (Prior and others 1971). In another study, the effect of summer-autumn rains on movement rates was relatively slight compared to that of winter-spring rains,

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Abstract: To document a relationship between progressive hillslope deformation and precipitation, boreholes on the Redwood Creek basin in northern California were surveyed semiannually from 1974 to 1982. Regressions were calculated between borehole displacement and an antecedent precipitation index (API) variable. Values for the API variable were obtained by summing daily API values over the time between borehole surveys, if the daily API value exceeded some threshold. The coefficient of determination, r^2 , was maximized by calculating a series of regressions with various API recession factors and thresholds. The "best" regressions had a recession factor of 0.99 and a zero threshold. Results suggest that creep and earthflow rates increase in response to precipitation and that graywacke and schist terrain respond to similar mechanisms of movement,

with a coefficient of determination of only 0.14 between seasonal movement and seasonal precipitation (Campbell 1966). Average annual movement rates (m/yr) reported in these studies were relatively high--13 to 85 (Hutchinson 1970), 5 to 25 (Prior and Stephens, 1971, Prior and others 1971), 4 (Campbell 1966), and 2 (Wasson and Hall 1982).

Long-term studies of subtle, progressive hillslope deformation and its distribution with depth are scant. First-year patterns and rates of movement were reported from four borehole inclinometer access casings located in northwestern California (Kojan 1967). On the basis of an analysis of an additional 7 years of measurement of these 4 casings and 31 additional ones, Ziemer (1977) concluded that the first-year rates (Kojan 1967) were excessively high and that no consistent rate or direction of movement could be detected because of continuing differential settlement in the boreholes. Several studies have documented the distribution of progressive slope movement with depth (Wilson 1970). A 10-year creep record of a 30° slope in western Washington showed that a 7.5-m deep borehole had downslope movement totaling 81 mm at the ground surface.

Creep and earthflow rates were recorded from boreholes monitored for 2- to 5-year periods in various geologic terrains in the Pacific Northwest (Swanston 1981). Depth of movement varied from near the surface to 17 m. Rate of movement varied from 0.5 to 104 mm/yr. A clear relationship was observed between seasonal rainfall and movement, but the detailed nature of this relationship was not shown (Swanston 1981). Movement on a storm-by-storm basis was not detectable. In one of the study areas--the Redwood Creek basin in northwestern California--regression analysis revealed total movement or movement rate to be correlated with precipitation on an annual and seasonal basis (Swanston and others, 1983).

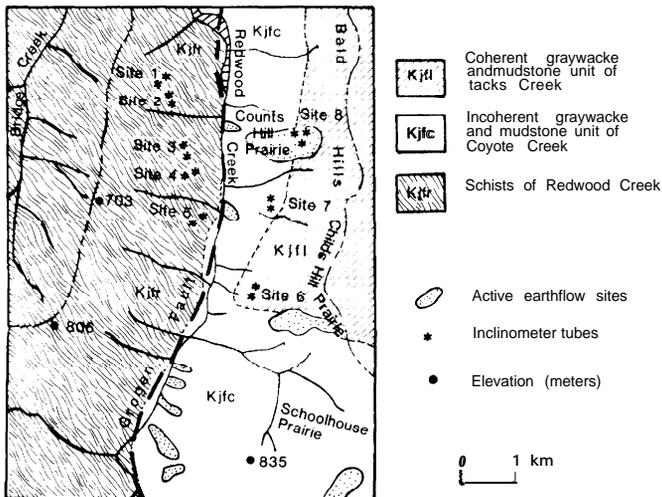


Figure 1--Boreholes within the graywacke and schist terrain of Redwood Creek, northwestern California. Source: Swanston and others 1983,

This paper described a more complete analysis of the Redwood Creek borehole data.

STUDY SITE

The geology, geomorphology, and climate of the 730-km² Redwood Creek drainage basin in northwestern California has been described in detail (Iwatsubo and others 1976, Swanston and others 1983). Redwood Creek flows northwesterly along its 90-km length to the Pacific Ocean. The study area (fig. 1) is at an elevation of 200 to 500 m about 10 km upstream from the Creek mouth. Redwood Creek follows the northwest trending Grogen fault near the study site. The western side of the basin is underlain by metamorphosed sedimentary rocks comprising the schists of Redwood Creek, and the eastern side is underlain by unmetamorphosed sedimentary rocks of graywacke sandstone and mudstone (Harden and others 1981). The average slope of 17° on the eastern graywacke side of the basin near the study site is slightly steeper than that on the western schist side on which the average slope is about 14°. Slope length is about 2200 m on both the graywacke and schist sides. Weathered parent material is found at depths that vary from less than 0.5 m near the ridges to more than 15 m on the middle and lower slopes.

The study area is characterized by a coastal Mediterranean-type climate of mild, wet winters and warm, dry summers with frequent fog. The nearest climatological station is located at Orick-Prairie Creek State Park, about 8 km downstream near the mouth of Redwood Creek. Temperature and precipitation data have been collected at this station for 45 years. Mean monthly maximum temperature in July ranges from 20° to 35° C, and mean monthly minimum January temperature ranges from 0° to 3° C. Mean annual precipitation is 1748 mm. The wettest year during

the 45-year record was 1974, when rainfall was 143 percent of the mean. The driest year was 1977, when rainfall was 46 percent of the mean. More than 90 percent of the annual precipitation falls between October and April. Snow is rare. May through September are usually dry months, with only an occasional convective thunderstorm. Precipitation near the study site is about 30 percent greater than that at Crick-Prairie Creek State Park, based on measurements made by the U.S. Geological Survey for several years. The coefficient of determination of the daily precipitation relationship between stations is 0.88. The longer and more complete record from Orick-Prairie Creek has been used for the analysis reported in this paper.

Redwood (*Sequoia sempervirens* [D. Don] Endl.) is the dominant tree in the study area, with associated Douglas-fir (*Pseudotsuga menziesii* [Mirb.] Franco), and western hemlock (*Tsuga heterophylla* [Raf.] Sarg.). Tanoak (*Lithocarpus densiflorus* [Hook. & Arn.] Rehd.) and Pacific madrone (*Arbutus menziesii* Pursh) become increasingly common on the drier, upper slopes. Grass-bracken-fern prairie usually replaces trees on the more active earthflows.

More than one-third of the Redwood Creek basin is unstable and subject to mass erosion (Colman 1973). The most obvious forms of mass erosion in the basin are earthflow complexes with slumping, translation, and flowing movement resulting in a hummocky topography. The margins of the earthflows commonly grade into less active creeping areas. On the steeper lower portions of hillslopes near stream channels, numerous small, discrete rotational and translational failures are found.

METHODS

Site Selection

Sites 1 through 5 were selected on the western schist side and Sites 6 through 8 on the eastern graywacke side of the basin (fig. 1). Site 8 was located in the grass-bracken-fern prairie vegetation of an active earthflow. The other sites supported, or recently supported until logged, a dense 500- to 1000-year-old redwood forest which, from observation of surficial features, appeared to be relatively stable. Site 6, a recently logged site, however, was near the margin of an active earthflow and some surficial active creep was indicated. No difference in deformation rate could be found between logged and unlogged sites.

Hillslope Deformation

Hillslope deformation was measured as changes in the inclination of 76-mm-diameter grooved, polyvinyl-chloride tubes. The tubes were placed in 130mm-diameter boreholes drilled through the soil mantle and anchored 1 m into bedrock. The

annular space between tube and borehole wall was backfilled with sand and pea-gravel (Swanston and others 1983). Two boreholes were installed at each site, except Site 8, at which three boreholes were installed. Five sites (10 boreholes) were on the schist side and three sites (7 boreholes) were on the graywacke side of the drainage basin.

Inclination of the tubes was measured with a mechanical pendulum inclinometer, housed in a waterproof rigid carriage, and riding within the grooved tubing³. Inclination was measured at 0.5-m intervals from the bottom of the tube in two vertical planes 90° apart. The configuration of the tube was calculated by constructing a series of vectors oriented point-to-tail from the bottom of the tube to the surface. The center of the tube was assumed to pass through the centers of the vectors. The boreholes were surveyed semiannually--in late spring after the winter rains, and in late fall after the summer drought. Profiles of distance and direction of movement were constructed from these successive surveys (fig. 2). To construct a vertical profile of movement, the azimuth of maximum movement was identified from the plan view of casing deformation. The vector coordinates in 3-dimensional space were then projected onto a vertical plane oriented at this azimuth. Displacement of the borehole between surveys was defined as the movement at the surface obtained from this projected vertical profile (table 1).

Antecedent Precipitation Index

A common index to the residual effect of previous precipitation on current runoff or soil

³Grooved tubing and Model 200-B Inclinometer made by Slope Indicator Company, Seattle, Wash. Trade names and commercial enterprises or products mentioned for information only. No endorsement by U.S. Department of Agriculture is implied.

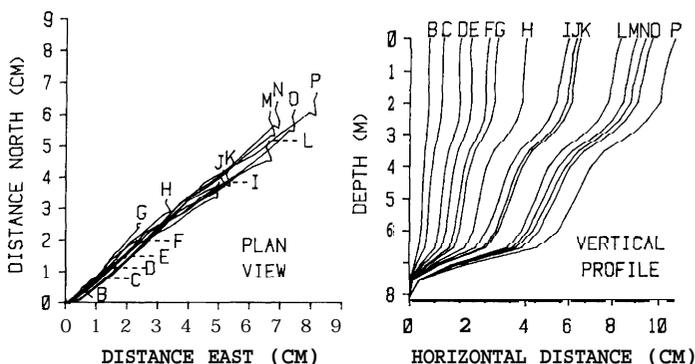


Figure 2--Plan view and vertical profile of borehole casing deformation since the initial survey for the 15 survey periods at Site 3B (table 1). The vertical profile was projected on a plane oriented at 47°, the azimuth of maximum movement.

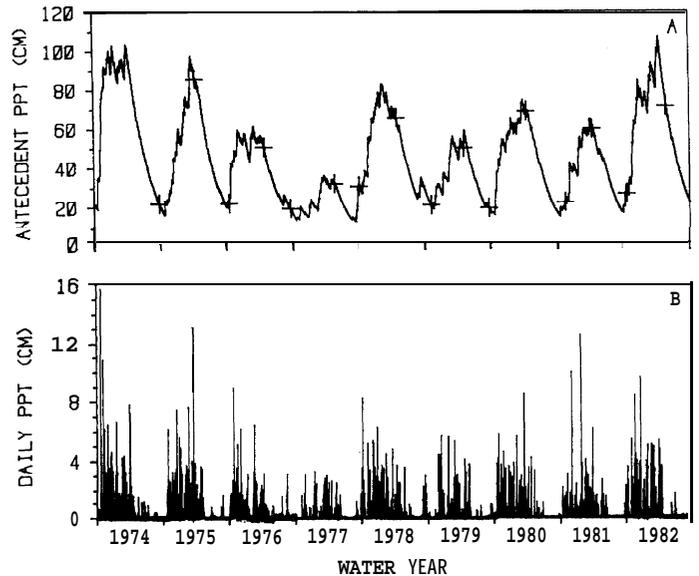


Figure 3--Daily antecedent precipitation, API (A), and daily precipitation (B) at Orick-Prairie Creek State Park for water years 1974 through 1982. Water year 1974 began October 1, 1973 and ended September 30, 1974. The + symbols in A denote borehole surveys. The API recession factor was 0.99.

moisture is the antecedent precipitation index, API (fig. 3). The daily API value is calculated by the exponential law of decay:

$$API_t = API_0 e^{-\lambda \Delta t} + P_t$$

in which API_t is the index value at time t , API_0 is the index value when $t = 0$, λ is the decay constant characteristic of the particular recession, and P_t is the precipitation that occurred at time t during the interval Δt . If Δt is 1 day, the term $e^{-\lambda \Delta t}$ can be replaced by a recession factor K , and

$$API_i = K \cdot API_{i-1} + P_i$$

in which i is the day number since the beginning of the calculation.

The analytical objective was to regress the amount of borehole displacement, Y , on some function of daily precipitation. Various authors (for example, Wasson and Hall 1982) have reported that apparently some minimal amount of precipitation is required before movement occurs. Included in the precipitation function, therefore, is a threshold that must be exceeded before precipitation becomes effective,

The independent variable, X , for climate, was obtained by summing the daily API values over the time between the semiannual borehole surveys, if the daily API value exceeded some threshold value. The threshold was established on the basis of a percentage of the maximum daily API value observed during the study for a given recession

Table 1--Borehole displacement at the soil surface along the azimuth of maximum movement, Redwood Creek Basin, California 1974-1982.

Survey and date	Displacement between surveys at								
	Schist sites			Graywacke sites					
	3A	3B	4A	6A	6B	7A	8A	8B	8C
	mm								
A 10/74	--	--	--	--	--	--	--	--	--
B 4/75	9	8	4	--	--	--	--	--	--
C 10/75	5	6	-1	--	--	--	--	--	--
D 4/76	13	6	6	--	--	--	--	--	--
E 9/76	4	4	-2	--	--	--	--	--	--
F 5/77	5	7	4	28	13	3	2	5	0
G 10/77	4	3	1	13	7	-1	0	1	-1
H 5/78	15	11	4	254	198	16	4	47	76
I 11/78	5	16	16	58	49	-5	0	-2	7
J 5/79	8	3	5	56	42	7	4	11	10
K 9/79	5	2	-4	25	17	0	-1	-3	3
L 4/80	13	13	8	77	109	19	4	24	26
M 11/80	10	6	2	29	42	-1	1	-3	6
N 4/81	3	4	3	10	37	10	3	13	8
O 10/81	6	3	-4	72	18	-1	0	0	2
P 6/82	10	9	25	140	239	23	2	43	35

factor, Therefore, when API_i is greater than the threshold,

$$X = \sum_{i=m}^n API_i$$

in which m is the day of the survey beginning the period, and n is the day before the next survey.

The coefficient of determination, r^2 , between the displacement of the borehole, Y, and the API variable, X, was maximized by calculating a series of regressions with various values of the recession factor, K, and the threshold (table 2). The recession factor was allowed to vary from 1.0 to 0.1. The larger the recession factor, the greater the API carryover from year-to-year. A recession factor of 1.0 allows no decay and X simply becomes the accumulated precipitation since the beginning of the study. One additional model was included: the total precipitation during each survey period, PPT. The threshold was allowed to vary from 0 to 100 percent of the maximum API during the study,

DISCUSSION AND RESULTS

Measurement Problems

The measurement of borehole deformation with time presents several problems. If the bottom of the borehole is anchored in stable material, the projected deformation of the borehole at the surface should equal the actual surface movement. If the borehole penetrates only a portion of the moving mass, however, the projected sur-

face displacement will underestimate the actual surface movement. When the plotted profiles were observed, all of the boreholes except those of Site 4B appeared to have penetrated the moving mass and to be anchored in stable material. The borehole at Site 4B was 7.6 m deep. The depth of movement at this site was about 13 m, on the basis of measurements from the 18.6-m deep borehole at Site 4A.

Table 2--Coefficient of determination (r^2) of regressions between displacement of borehole, Y, and antecedent precipitation index (API) variable, X, for various values of the recession factor, K, and the threshold for the 15 survey intervals at site 3B.

K	Max. API	Threshold ¹					
		0	10	20	30	40	50
	<u>cm</u>	<u>r^2</u>					
1.00	1488	0.04	0.03	0.02	0.01	0.01	0.01
.99	107	<u>.25</u>	.22	.20	.18	.16	.12
.97	51	.16	.14	.14	.13	.12	.08
.94	33	.14	.13	.13	.11	.09	.06
.90	24	.14	.13	.12	.09	.06	.04
.80	19	.13	.13	.09	.05	.04	.03
.60	17	.13	.11	.07	.03	.01	.01
3PPT	205	.13	.12	.08	.03	.01	.01

¹Percent of maximum API.

²Underline denotes maximum coefficient of determination.

³A recession factor of PPT is the total precipitation during each survey period.

It would be desirable to measure surface movement independently to verify that actual movement equals projected surface displacement obtained from borehole deformation. Measurement of surface movement, however, requires that there be stable reference points and that the measurement error does not exceed the movement. In the Redwood Creek terrain, exposed bedrock or other stable features are rare and remote from the study sites and direct visibility of the ground surface is obscured by the forest. Projected surface borehole displacement between surveys ranged from 0 to 254 mm (table 1). The required precision for an independent measurement of surface movement between surveys would be about 5 mm over a distance of 1 km without direct visibility. Because such precision is required, an independent measurement is impractical.

If the borehole deformation is to represent actual deformation of the hillslope, a stable continuity must exist between the borehole tube and the surrounding materials. Without such continuity, actual hillslope deformation is obscured by continued differential settlement in the borehole around the inclinometer tube (Ziemer 1977). The backfilling technique used was successful at all but two boreholes (Site 2A and Site 5B) on the basis of the stability of the borehole data between surveys.

Potential length of the inclinometer survey record is inversely related to the rate of deformation per unit of borehole depth. If the borehole deformation is large over a narrow depth zone, the curvature of the access tube can prevent passage of the inclinometer along the tube. When this occurs, movement of only the upper portion of the soil mantle can be measured, a situation analogous to the borehole being too shallow. If the study objective is to identify relative rates of deformation with depth, this presents no problem if several surveys can be completed before the tube becomes impassable. If the study objective is to monitor borehole deformation for a long time, however, deformation rate becomes a serious problem. Almost all of the movement at Site 7B occurred between a depth of 8.5 and 9 m and the borehole became impassable after September 1979. The boreholes at Sites 6A and 6B became impassable below a depth of 6.5 m, but the mode of deformation of these boreholes appeared to be relatively uniform with depth and no identifiable zones of shear. The borehole displacement for Sites 6A and 6B (table 1) are for 6.5-m-deep boreholes, and are conservative estimates of the total movement for these two sites.

Random instrument error becomes progressively more important as the amount of borehole deformation decreases. In practice, displacement of about 2 mm over a 10-m depth can be measured. Displacement at Sites 1A, 1B, 2A, 2B, 5A, and 5B fell within this range, and no consistent direction or rate of movement was detected.

Graywacke and Schist Sites

The boreholes installed in graywacke terrain in Redwood Creek were more active than those in schist terrain. Semiannual surface displacement of boreholes installed in graywacke varied from 0 to 254 mm, and semiannual displacement in schist from 0 to 25 mm. All 7 boreholes installed in graywacke showed consistent movement, whereas movement was too small to be detected in 7 of the 10 boreholes installed in schist.

Of the original 17 boreholes, 9 boreholes yielded data of sufficient duration and quality to regress the amount of borehole displacement on the API variable (table 1). Regressions were calculated to identify the combination of recession factor and threshold that yielded the maximum coefficient of determination for each borehole. For the sites on the schist side, the "best" regression consistently had a 0.99 recession factor and zero threshold (table 3, fig. 4A). The maximum coefficient of determination for schist Site 3A was 0.56; for 3B, 0.25; and for 4A, 0.47. Each regression was statistically significant at the 1 percent level, each with a different set of regression coefficients. To develop a single regression to characterize the area by combining the schist sites, sites should be selected to be more representative of the entire schist area by locating the boreholes by some scheme such as stratified random sampling.

To compare the regressions, their estimated variances were summed across all sites and the sums ranked by increasing variance. Although these sites were not randomly selected and cannot

Table 3--Estimated regression variance of displacement at the schist sites for various values of recession factor, K, and threshold for the 15 survey intervals,

K	Threshold ¹	Variance for site ²			Sum of variances	Rank ³
		3A	3B	4A		
		<u>mm²</u>				
0.99	0	6	14	33	54	1
.99	10	7	15	34	56	2
.97	0	7	16	38	60	3
.94	0	7	16	39	63	4
.90	0	8	16	40	64	5
PPT	0	8	16	41	65	6

Mean Displacement
(mm/survey)

8 7 5

¹Percent of maximum API.

²Underline denotes smallest variance for the site.

³Ranked by increasing sum of the variances over three sites.

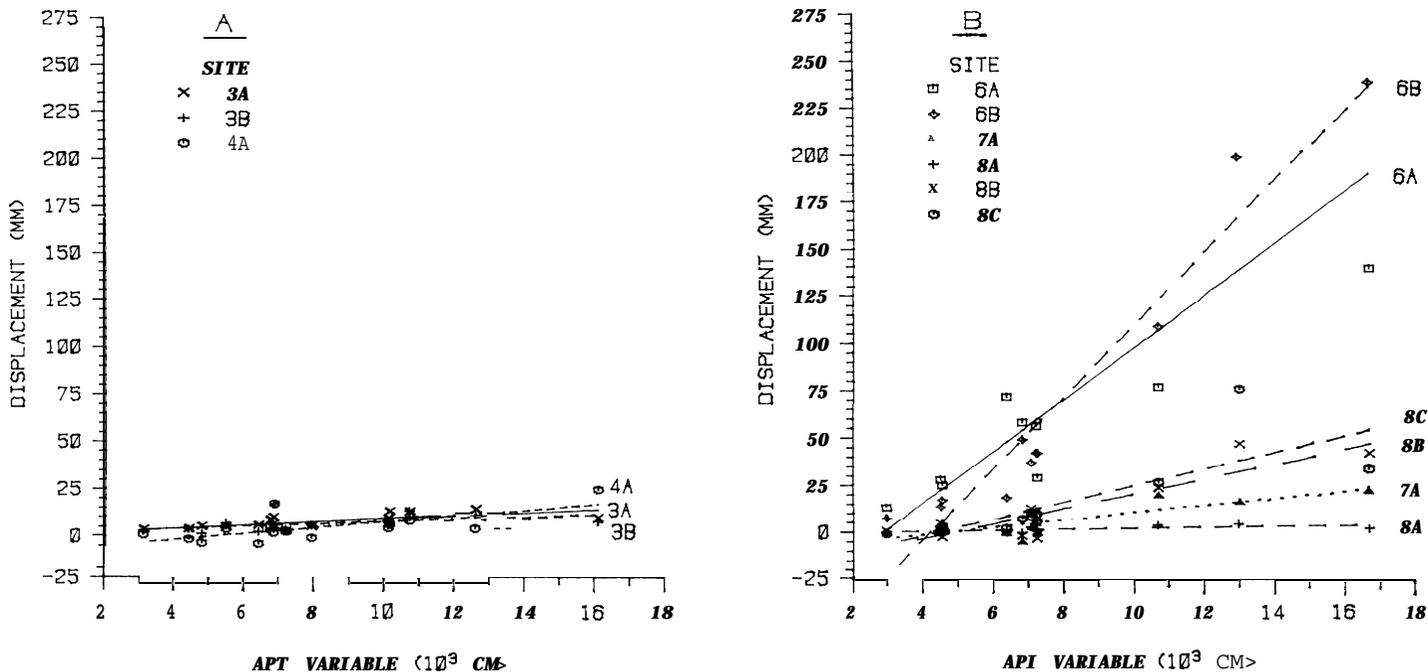


Figure 4--Relationship between borehole displacement and API variable for each survey period for: (A) schist Sites 3A, 3B, and 4A; and (B) graywacke Sites 6A, 6B, 7A, 8A, 8B, and 8C. The API variable was the sum of the daily API values for each survey period, using a recession factor of 0.99 and a zero threshold.

strictly be considered independent, the sums of variances provide a heuristic measure for ranking the regressions and some indication of their relative size.

For the sites on graywacke, the "best" regression for each site had a different recession factor-threshold combination (table 4). The

maximum coefficients of determination for the graywacke sites were consistently higher than for the schist sites: for Site 6A, 0.60; for 6B, 0.96; for 7A, 0.95; for 8A, 0.71; for 8B, 0.93; and for 8C, 0.65. A global model would be preferable to a different model for each site. One heuristic method is to select the global model that minimizes the sum of the individual

Table 4--Estimated regression variance of displacement at the graywacke sites for various values of recession factor, K, and threshold for the 11 survey intervals.

K	Threshold. ¹	Variance for site ²						sum of variances	Rank ³
		6A	6B	7A	8A	8B	8C		
		<u>mm</u> ²							
0.99	0	<u>2291</u>	402	28	2	73	223	3019	1
.99	40	2570	<u>287</u>	27	3	65	248	3200	2
.98	0	2414	568	12	2	31	205	3231	3
.97	0	2611	855	9	2	<u>26</u>	<u>215</u>	3718	4
.94	0	2847	1228	6	1	29	229	4341	5
.90	10	3014	1251	<u>5</u>	2	31	243	4546	6
.90	0	2955	1416	<u>6</u>	1	32	237	4647	7
PPT	0	3183	1751	6	<u>1</u>	42	262	5246	8
Mean displacement (mm/survey)		69	70	6	2	12	16		

¹Percent of maximum API.

²Underline denotes smallest variance for the site.

³Ranked by increasing sum of the variances over six sites.

regression variances. The model having the lowest sum of the variances had a 0.99 recession factor and zero threshold (fig. 4B)--the same model as that for the schist sites. The sum of the variances for the individual "best" models was 2815 mm^2 and for the global "best" model was 3019 mm^2 --an increase in variance of about 7 percent. This represents an increase in standard deviation of 2 mm, which is equivalent to the instrument error.

Detailed physical interpretation of the results of this study should be made with care. Movement rates for the Redwood Creek sites were generally so small that, even with semiannual surveys movement could not be detected in 7 of 10 boreholes installed in schist. Movement in graywacke was greater, but only at Site 6 was it great enough to expect movement could be detected with frequent surveys. Semiannual surveys mask the short-term response of movement to individual storms. It is long-term rates, however, that are significant from the geomorphic point of view,

CONCLUSIONS

Deformation rates vary spatially on hillslopes and with time. Because of the study design, average deformation rates were not calculated for the graywacke and schist terrains. To justify such a calculation, a randomized design and many more boreholes would be required. Such an intensive installation is seldom justifiable. Even if the problem of spatial variability was addressed by dramatically increasing the number of boreholes, the problem of time variability would remain. Long-term monitoring of boreholes is expensive and impractical because the access tubes become impassible within a few years. One solution is to develop a model by which a relatively short-term record of slope movement can be extended using a parameter for which a long record is available. In this study, daily precipitation, converted to an antecedent precipitation index, was such a parameter.

Results of the study imply several relationships. It is generally accepted that the primary relationship between precipitation and mass movement rate is through water within the earthflow. An API recession factor of 0.99 implies that for any amount of precipitation, p , 69 days are required to reach an API of $p/2$ and 138 days to reach $p/4$. For the precipitation regime at Redwood Creek, residual API averaged 16 mm at the end of the summer, and ranged from 13 to 22 mm between 1974 and 1982. The residual value becomes the initial API value for the next year. Smaller recession factors not only yield less residual to be carried to the next year, but also imply a reduced importance of winter precipitation on borehole deformation rate during the dry summer. Precipitation between the spring and fall surveys accounted for 15 percent of the annual total, whereas the sum of the daily API values using a

0.99 recession factor during this period was about 40 percent of the annual total. The finding that the global "best" recessions have a recession factor of 0.99 implies that creep and earthflow rates increase quickly in response to precipitation and continue for weeks or months after it has ceased. That no threshold was found to be significant implies that the soil does not dry sufficiently to require some initial precipitation to build up pore water pressure before movement begins. That the same "best" regressions were found in the graywacke and schist terrain suggests that both materials respond to similar mechanisms of movement.

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