Landslide Activity and Groundwater Conditions: Insights from a Road in the Central Sierra Nevada, California

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ABSTRACT

Stump Springs Road, a major timber-haul route in the central Sierra Nevada of California, suffered extensive landslide damage in the spring of 1982 and the spring of 1983. An estimated $1.3 million will be spent on major repair or reconstruction at sites widely distributed along a 23-km section. Geologic and geotechnical studies supporting remedial efforts yielded insight into the role of groundwater in these landslides. Landslide activity is a direct response to the nature of the precipitation event and the infiltration capacity and permeability of the materials present. During periods of infiltration, water percolates through coarse-grained, moderately permeable material until granitic bedrock is encountered. Groundwater then flows down gradient with the top of the saturated thickness roughly parallel to the bedrock surface. The importance of groundwater is seen in the dominance of flow-type movement. Calculated pore-pressure ratios typically reached 0.5 at the toe and 0.15 near the head. Observation wells at one landslide demonstrated that a failure surface coincided approximately with the depth to a saturated zone. Precipitation events influencing groundwater at the time of landslides included a rain-on-snow event in 1982 and an unusually deep snowpack in 1983. The majority of landslides occurred in response to the rain-on-snow event. This long-duration precipitation event included peak intensities of 1.4 to 1.8 cm per hour supplemented by snowpack losses equivalent to 13 cm of runoff. Even snowmelt from an unusually heavy snowpack produced significantly fewer landslides.

FIGURE 1 Index map showing the location of the Sierra National Forest.

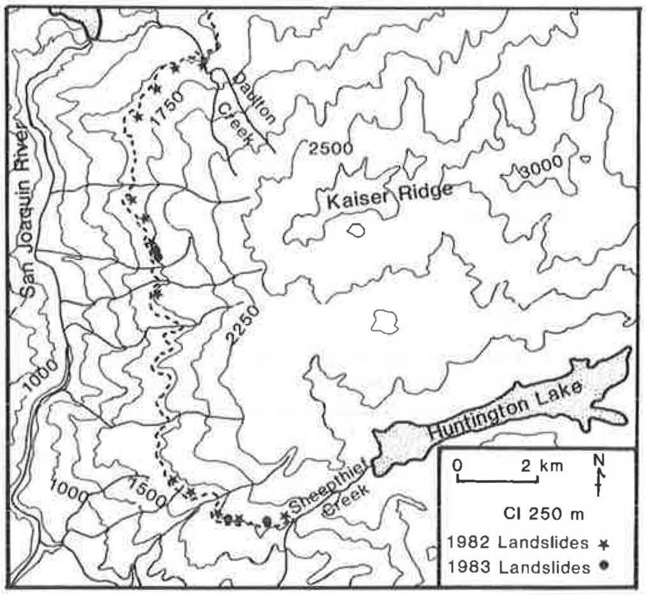

FIGURE 2 Detailed topographic map showing landslide-damage sites along Stump Springs Road (bold dashed line).

Stump Springs Road winds across the steep slopes high above the granite-lined gorge carved into the Sierra Nevada by the San Joaquin River. This 7-m-wide paved road is a major haul road for timber harvest on the Sierra National Forest (Figure 1; area in shaded square detailed in Figure 2). An estimated 90 million board-ft of timber will be accessed via Stump Springs Road or one other available road during harvest operations. The alternate road, Kaiser Pass, currently serves as a major corridor for recreational vehicle traffic. Adding loaded log trucks to the traffic on Kaiser Pass Road would be undesirable. It is also steeper and narrower in some sections than Stump Springs Road. The vital role of Stump Springs Road in future timber management makes its physical integrity of prime importance.

Stump Springs Road sustained serious damage in the spring of 1982 and the spring of 1983. Parts of the road were covered or undermined at points widely distributed along a 23-km section from its origin near Sheepthief Creek to near Daulton Creek (Figure 2). Most of the damage resulted from 17 landslides. Other sites were damaged by flood water. Although some damage necessitated only heavy maintenance, a total of 24 sites needed major repair or reconstruction to restore the road to full use. Under a public works contract construction began in the fall of 1983 and included 21 sites. Estimated construction cost, excluding temporary emergency repairs and engineering costs, was approximately $1.3 million. The majority of this cost is being borne by emergency relief funds from FHWA.

Major design considerations were (a) maximizing long-term structural stability and (b) minimizing cost. Proposed work includes installation of 7 reinforced-soil type retaining walls, 3 concrete crib retaining walls, and 10 fill replacements. Maximum wall heights vary from 2.7 to 6.8 m. Wall lengths range between 22 and 49 m. For the majority of sites, installation of drainage structures was considered essential to long-term structural stability of the site. Aggregate trench and blanket drains will be installed at fill replacement sites where significant amounts of groundwater are anticipated. Options for draining retaining walls are prefabricated systems consisting of nylon matting heatbonded to a geotextile or a solid plastic drainage core encased in a geotextile.

A number of geologic and geotechnical investigations were conducted in 1982 and 1983. Investigation objectives were to gain information for designing restoration measures rather than to make a scientific study of landslides. However, the data collected give some insight into the role of groundwater in these failures. Specifically, the triggering role of groundwater and approximate groundwater conditions at the time of failure can be recognized and groundwater conditions can be related to two unusual precipitation events.

LANDSLIDES AND GROUNDWATER

Landslides

A total of 17 landslides damaged parts of Stump Springs Road in 1982 and 1983. Thirteen landslides occurred during a rain-on-snow event on April 10-11, 1982. An additional four landslides resulted from unusual snowpack conditions in March 1983. The relationship of landsliding, groundwater conditions, and precipitation events will be examined later in this paper.

The landslides occurred both above and in the road prism. Landslides above the road more frequently involved unmodified, natural slopes than cut slopes. Except for three instances, landslides undermining the road occurred in natural slope material with limited fill material present. At two locations, the road crosses large paleolandslides. A failure occurred at each of these locations in 1982 and 1983. All landslides were shallow with failure surfaces within a few meters of the ground surface. Scarps averaged 35 m long; the longest was 50 m and the shortest was 15 m.

Physical Setting

Granitic bedrock underlies the entire road section affected by landslide activity (1,2). Landslides occurred in nearly equal numbers in each of three specific granitic units: the granite of Ordinance Creek, an unnamed quartz monzonite and granodiorite, and the Mount Givens granodiorite.

The slopes traversed by the damaged portion of the road are steep. The sideslope inclination varies from 40 to 80 percent; the average is about 70 percent. The natural slopes are made up of residual soil, colluvium, and glacial till overlying fractured granitic bedrock. These soils range in thickness from 0.3 to about 1.3 m with an average thickness of 0.8 m. The road fills are all composed of local soil material and granitic rock. Blocks of rock ranging up to 1.5 m in largest dimension were observed in the material exposed in some of the failures. At other sites the material contained little or no rock larger than 0.3 m in maximum dimension. The properties of the soil found on the natural slopes and in the road fills are fairly uniform along the affected segment of the road. The range and median values of the properties are shown in Table 1.

TABLE 1 Description of Natural Soils and Road Fill for Landslide Sites Along Stump Springs Road

Property	Range	Median
Liquid limit	Nonplastic to 35	Nonplastic
Plastic limit	Nonplastic to 20	Nonplastic
Plasticity index	Nonplastic to 15	Nonplastic
Permeability (cm/sec)	10^{-1} to 10^{-4}	10^{-2}
Unit weight (kN/m^3)	16.3 to 19.3	17.8
Particle size characteristics		
Gravel fraction (%)	10 to 35	25
Sand fraction (%)	45 to 80	60
Silt fraction (%)	5 to 20	10
Clay fraction (%)	0 to 15	5
Uniformity coefficient	5 to 25	9
Unified soil classification	SW,SP,SM,SC	SM
Cohesion (estimated) (kN/m^2)	0 to 2.5	1.2
Drained peak angle of internal friction (estimated) (degrees)	34 to 39	36

Triggering by Groundwater

The influence of groundwater on these landslides is evident from their mode of movement. Levee-like deposits adjacent to the path of many landslides along with muddy swash marks high on adjacent trees indicate a fluid deformation (3). Movement was commonly rapid to extremely rapid. In 1982 a debris avalanche originating from a broad drainage divide achieved a velocity of 7.5 m/sec (4). A debris flow on March 4, 1983, moved rapidly enough to make noise and attract the attention of residents on a nearby slope. Debris was observed being hurled over a downslope escarpment. A steel culvert 76 cm in diameter and 18 m long was torn loose and rafted 91 m down slope.

According to accepted classification criteria (5), 12 of the 13 landslides occurring in 1982 are debris flows or avalanches. The remaining landslide is a debris slide. Three of the four landslides occurring in 1983 were debris flows. Again, a single debris slide occurred in 1983. Both debris slides incorporated a significant component of flow movement in their deformation.

Reconnaissance conducted within days of the failures usually found (a) a sharp boundary between the undisturbed material and the landslide mass, (b) a landslide mass consisting of churned material, (c) no evidence of surface water entering the slide area, and (d) significant, sometimes copious, amounts of groundwater seeping from within the landslide scar. This seepage often persisted for weeks and was commonly concentrated in the upper part of the slide path. Seepage was often not visible on adjacent undisturbed slopes.

The conclusion that groundwater triggered these landslides is supported by field evidence. Saturation by water was involved in every failure. Although surface water contribution to slide areas was found in four instances, groundwater seepage was evident at all landslides. Subsurface drainage on this forested granitic terrain is expected to be the main mechanism for slope drainage (6,7). Slide locations were about equally common on planar, convex, and concave slope elements. Concave slope form would likely be predominant where surface water was the cause of saturated conditions.

Groundwater Conditions at Failure

Groundwater conditions along Stump Springs Road during periods of landslide damage were governed by the nature of the precipitation event and the infiltration capacity and permeability of the natural soil and road-fill material. As shown in Table 1, the soils are coarse-grained and thus moderately permeable. These coarse materials overlie a much less permeable, fractured bedrock.

During periods of infiltration, water percolates downward through surficial soils and road fill until bedrock or some other less permeable layer is encountered. The groundwater then flows down gradient roughly parallel to the bedrock surface (8). Figure 3 shows a scaled cross section of a 1982 debris flow at Sheepthief Creek. It is reconstructed as a representative landslide based on surveyed topography and seismic data. Granitic bedrock is overlain by colluvial soil and limited road fill material. The bedrock surface roughly parallels the ground surface. Seismic velocities for the surficial soils are about 300 m/sec. By contrast, the underlying bedrock has a velocity of 1700 m/sec. A density increase of nearly 5.5 times that of the overlying material suggests a substantial decrease in hydraulic conductivity.

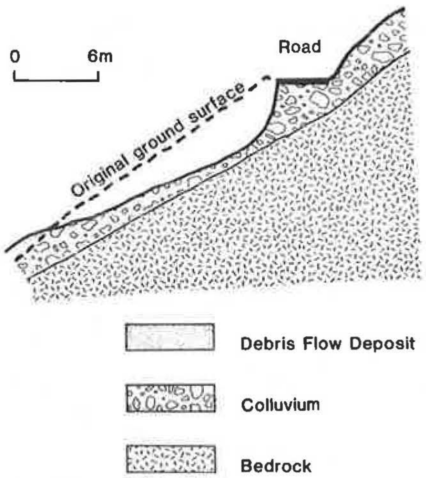

FIGURE 3 Cross section of subsurface conditions at a representative debris flow.

During associated precipitation events, hydrostatic pore pressures and seepage forces increased because of the greater saturated thickness of overlying soils and groundwater flow. This reduced shear strength of the soils to the point that failure occurred (9,10). The magnitude of the total groundwater forces during the storm was estimated by back analysis of the roadway failures. A slope stability model using noncircular failure surfaces was utilized in this back analysis. The stability model assumes parallel side forces on each slice and thus satisfies all equilibrium conditions.

The strength parameters used in the stability evaluation are those median values given in Table 1. These values were estimated from the results of the material classification tests. In the back analysis, the groundwater conditions were characterized by the pore-pressure ratio (r_u), which is defined as follows (11):

$$r_u = w^h/z \qquad (1)$$

where

w = unit weight of water = unit weight of soil,
h = piezometric head, and
z = vertical thickness of slide.

At the toe of the failure r_u was found to have reached a maximum of about 0.5, whereas near the head of the slide r_u was about 0.15. This suggests that the failures were initiated at the original toes of the slides and then retrogressed headward.

Additional evidence relating groundwater saturation to failure was developed at the 1983 debris slide. This failure is a reactivation of paleolandslide material. Observation wells consisting of 3.8-cm plastic pipe were installed in mid-May 1983 after movement had apparently ceased. Three observation wells installed in the slide mass encountered water at depths from 122 to 152 cm below ground. Water saturated a thickness between 30 and 60 cm below this depth. Initially, water stood in these observation wells at levels ranging from 43 to 84 cm below ground rather than the 122- to 152-cm depths at which water was first encountered during installation. These levels fell back to or near the original depth at which water was found by the end of 3 months. No significant precipitation occurred during this period. The rate of water decline among wells averaged 5.0 cm per week. The initial high level is taken as indication of high pore-water pressure associated with the saturated zone.

The observation wells provided information on the depth to a failure surface in this landslide. A fourth observation well was located adjacent to the main scarp. Water was first encountered at a depth of 152 cm in this well. This depth was approximately the same level as the seepage line in the exposed headscarp surface. Continuing deformation affected an observation well just above the toe. A metal mandrel on a line of known length could not be withdrawn from the well due to shearing at the bottom (12). This occurred 2 weeks after installation. The top of the sheared zone was determined by dropping other mandrels with different lengths down the well and measuring the depth reached. This observation and the depth from the weighted line showed that shearing extended from 140 to 215 cm below the surface. These are nearly the same depths at which the saturated zone was encountered in this observation well. Thus a failure surface and the zone of groundwater saturation appear to coincide at both the headscarp and toe of this landslide.

The importance of groundwater is reflected in the predominance of flows in landslides along Stump Springs Road. Observations of site conditions support the critical role of saturated thickness of soil over bedrock in dictating slope stability.

GROUNDWATER AND PRECIPITATION EVENTS

Rain-on-Snow Event

The role of rapid melting of shallow snowpacks during rainfall in initiating landslides is being explored in recent research (13,14). This work involves areas in the western Cascade Range of Oregon that host warm snowpacks similar to those in the Sierra Nevada. Unlike cold snowpacks of the Rocky Mountains, warm snowpacks are subject to rapid melting during rainfall (13).

A rain-on-snow event in 1982 created the first episode of damaging landslide activity along Stump Springs Road. On April 10-11, 1982, a major frontal storm passed over the central Sierra Nevada. Although meteorologic data are not available for Stump

Springs Road, nearby stations closely approximate conditions during this storm [Figure 4 (points 1, 2, and 3 show location of Peckinpah, Tamarack, and Huntington Lake precipitation stations; these stations are referenced in Figures 5, 6, and 7)]. Peckinpah Meadow and Tamarack Ridge stations provide representative records of rainfall during this 48-hr period [Figure 5 (note the multiple peak intensities reached during the storm)]. Total precipitation ranged from 15.5 to 22.4 cm. Maximum intensities varied between 1.4 and 1.8 cm/hr. Temperatures remained above 0°C during most of the storm.

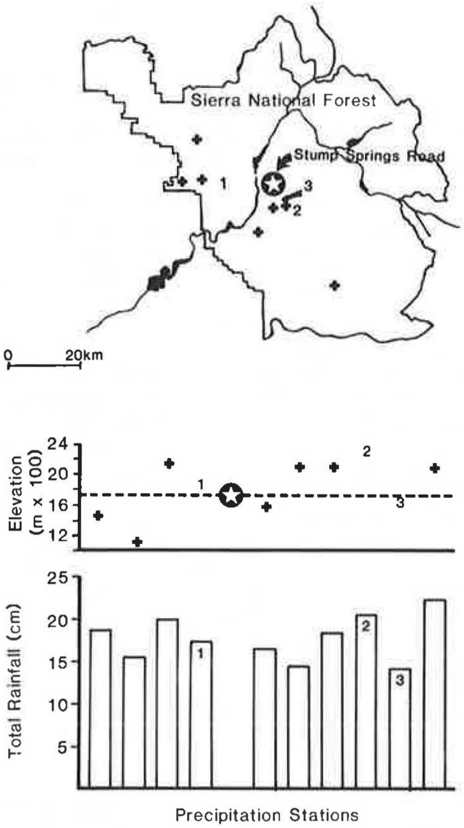

FIGURE 4 Index map showing the location of precipitation stations in relation to Stump Springs Road, elevation of each station, and total precipitation received at each station during the 48 hr of the April 10-11, 1982, storm.

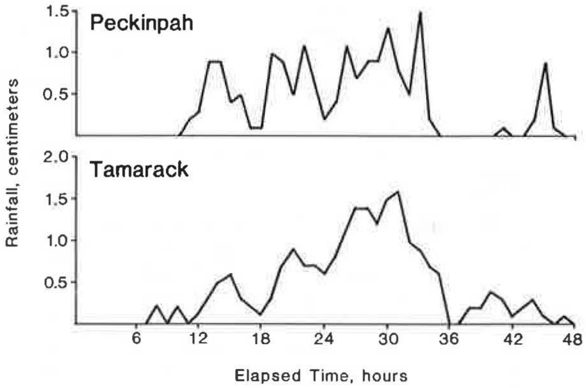

FIGURE 5 Continuous rainfall during April 10-11, 1982, storm recorded at Peckinpah and Tamarack precipitation stations.

Recorded snowpack losses during the storm ranged from 0.4 to 0.5 m. Based on water content at that time, snowmelt was equivalent to an additional 13 cm of runoff during the storm. From these figures, it is easy to visualize the development of pore-water pressures and seepage forces that were great enough to cause 13 landslides even in the moderately permeable, cohesionless soils along Stump Springs Road.

Unusual Snowpack Conditions

Snowpack accumulation in the Sierra Nevada during the winter of 1982-1983 was unusually deep and persisted late into the spring. Snow data from Huntington Lake are presented for 1982 and 1983 in Figure 6. (Long-term averages for snow depth are not available for this station.) The unusual nature of the 1983 snowpack is not fully seen when compared with the greater-than-normal snowpack of 1982. The cumulative precipitation for both years compared with the long-term normal gives a clearer picture (Figure 7). Most precipitation at Huntington Lake is received as snow during the year. The long-term average is based on records from 1942 and 1981. The persistence of the snowpack is reflected by the amount of snow recorded in May and June. A rare July snow survey was initiated at some higher-elevation snow courses.

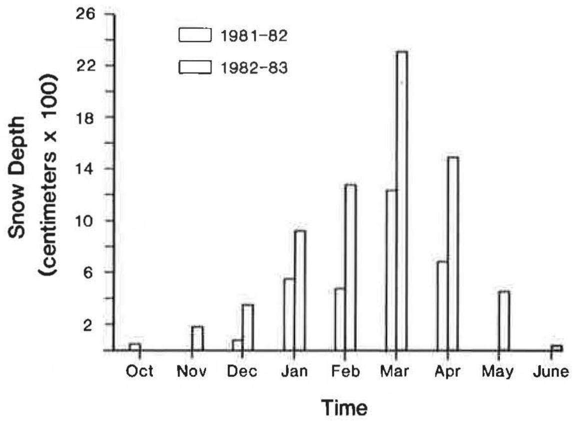

FIGURE 6 Snow depth recorded at Huntington Lake precipitation station.

Groundwater recharge is accomplished annually by snowmelt water. In 1983 recharge was unusually great. This led to groundwater conditions that initiated four additional landslides along Stump Springs Road.

Comparison Between Precipitation Events

Three times as many landslides occurred in 1982 as in 1983. This suggests that groundwater conditions initiating failure are more readily achieved by snowmelt during rainfall than by snowmelt from greater-than-normal accumulation. The duration and intensity of contributing precipitation events can be a factor in triggering debris flows. Campbell (15) demonstrated a threshold requirement of 254 cm for total seasonal antecedent rainfall in the Santa Monica Mountains of southern California. Studies near La Honda, California, indicate that an additional threshold of rainfall intensity is needed (16). Insufficient data are available for a valid comparison of intensity or duration for the 1982 and

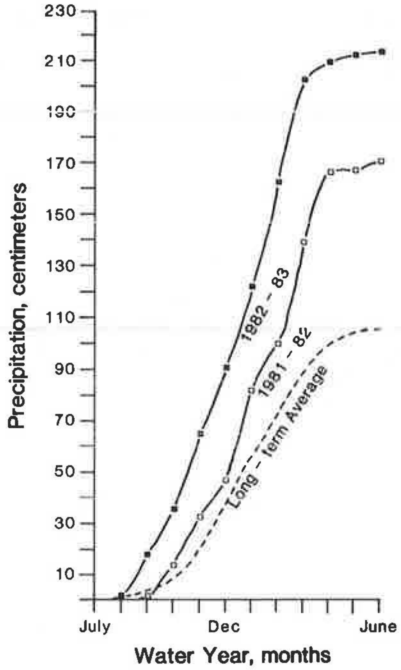

FIGURE 7 Cumulative precipitation at Huntington Lake precipitation station for the July to June water year.

1983 precipitation events. It is likely that antecedent moisture requirements were met immediately before peak intensities of the 1982 snowmelt-during-rainfall event. This is based on the extended period of precipitation before several peak intensities shown in Figure 5.

DISCUSSION

Landslide activity along Stump Springs Road is a direct response to the infiltration capacity and permeability of the natural soil and road-fill material and the nature of the precipitation event. Failure occurred under conditions of high water content as reflected in the proportion of landslides classified as flows or avalanches. The absence of surface water contribution and dominance of subsurface drainage in granitic terrain indicates groundwater as the triggering mechanism. A mantle of colluvial soil or road fill over less permeable bedrock is a condition associated with debris flow activity in other parts of the western United States (8,15, 17).

Because the bedrock surface roughly parallels the steep ground surface, the tendency for failure is enhanced. It appears that both antecedent moisture values and certain intensities must be met to cause failure. Snowmelt-during-rainfall events appear more likely to meet these conditions than snowmelt from normal or even greater-than-normal snowpacks.

Landslide phenomena in the Sierra Nevada are largely unstudied. The observations discussed in this paper show that circumstances promoting landslides are similar to those in some well-studied localities. The role of snowmelt-during-rainfall events in generating landslides requires further study. The general relationships developed in the Cascade Range appear applicable to the Sierra Nevada. It is unclear how to relate antecedent moisture and rainfall-intensity threshold values to this type of precipitation event. In addition, the relationship of landslide occurrence to frequency of triggering storm must accommodate rain-on-snow events. This information would greatly improve the ability to reduce landslide hazard to roads in the Sierra Nevada and the Cascade Mountains.

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