Real-Time Landslide Warning During Heavy Rainfall

David K. Keefer, Raymond C. Wilson, Robert K. Mark, Earl E. Brabb,
William M. Brown III, Stephen D. Ellen, Edwin L. Harp,
Gerald F. Wieczorek, Christopher S. Alger,* Robert S. Zatkin†

A real-time system for issuing warnings of landslides during major storms is being developed for the San Francisco Bay region, California. The system is based on empirical and theoretical relations between rainfall and landslide initiation, geologic determination of areas susceptible to landslides, real-time monitoring of a regional network of telemetering rain gages, and National Weather Service precipitation forecasts. This system was used to issue warnings during the storms of 12 to 21 February 1986, which produced 800 millimeters of rainfall in the region. Although analysis after the storms suggests that modifications and additional developments are needed, the system successfully predicted the times of major landslide events. It could be used as a prototype for systems in other landslide-prone regions.

THE SAN FRANCISCO BAY REGION IN CALIFORNIA HAS A long history of landslide problems. Landslides triggered by the 18 April 1906 San Francisco earthquake, for example, killed at least 11 people and caused considerable property damage (*1*). Since 1906, landslide risk in the region has increased substantially owing to population growth and development in hillside areas. Major causes of landslides include earthquakes, coastal erosion, construction activity, and heavy rainfall.

The most severe regional landslide disaster since 1906 was caused by an intense storm that produced 616 mm of rain in 34 hours on 3 to 5 January 1982 (*2*) and caused thousands of landslides. Landslides during that storm killed 25 people and caused more than $66 million in damage (*3*). Most of the fatal or damaging landslides were debris flows—relatively fluid masses of soil and water that can flow hundreds of meters or more, even on slopes of only a few degrees, at velocities of several meters per second.

The damage and casualties caused by these landslides in January 1982 led to research on a real-time, regional landslide warning system. To the best of our knowledge, this is the first system of its kind operating in the United States (*4*). The system was sufficiently developed to evaluate conditions and issue warnings when, on 11 February 1986, the National Weather Service (NWS) forecasted that a severe storm was approaching (*5*).

Topography, Geology, and Climate of the San Francisco Bay Region

A landslide warning system for the San Francisco Bay region must take into account variable geologic conditions, rainfall distribution, and topography. The region contains part of the California Coast Ranges, a northwest-trending series of mountain ranges with terrain varying from gently rolling hills to steep, rugged ridges separated by narrow canyons; altitudes range from sea level to 1284 m. The region is transected by the San Andreas and many other active faults. The rocks of the Coast Ranges vary greatly in composition, degree of consolidation, amount of deformation, and depth of weathering. Shale, siltstone, sandstone, and volcanic rocks predominate. Colluvium of variable depth and composition mantles nearly all slopes. Areas most susceptible to landslides have been described (*6*).

The region has a Mediterranean climate with warm, dry summers and cool, rainy winters. Virtually all precipitation occurs as rain, 90% of which falls during the months of November through April when storms generated over the Pacific Ocean pass through the region. Mean annual precipitation ranges from 250 to 2000 mm; coastal mountains generally receive the most precipitation and inland valleys the least (*7*). Because rainfall is strongly influenced by topography, precipitation from a single storm or during a given year can vary greatly over a short distance (*7*). Severe storms such as those in January 1982 and February 1986 can produce a large fraction of the mean annual precipitation in a few hours or days.

Storm Sequence of 12 to 21 February 1986

Precipitation during 12 to 21 February 1986 came from a series of moisture-laden storms that developed at the confluence of strong, zonal, westerly air flows over the eastern Pacific Ocean and then moved rapidly east-northeastward onto the California coast, through California, and into Nevada, northern Utah, southern Idaho, Wyoming, and Montana (*5*). Each storm produced rain of moderate intensity over a region about 500 km wide. After passage of a storm, weather stations along the storm track recorded little or no rain for several hours until the next storm arrived. Precipitation was heaviest at major orographic barriers oriented perpendicular to the air flow, particularly the Coast Ranges and Sierra Nevada of California and the northern Wasatch Mountains of Utah; maximum storm rainfall was 1260 mm, recorded in the Sierra Nevada (*8*). The center of the storm sequence passed about 80 km north of San Francisco, and rainfall in the San Francisco Bay region varied from 100 to 800 mm (Fig. 1).

Throughout California the storms caused 13 deaths, 67 injuries,

---

The authors are at the U.S. Geological Survey, 345 Middlefield Road, Menlo Park, CA 94025.

---

*Present address: Rogers/Pacific, Inc., 396 Civic Drive, Pleasant Hill, CA 94523.
†Present address: Department of Geology, San Jose State University, San Jose, CA 95192.

temporary evacuation of 50,000 people, and more than $400 million in property damage (*8*). Much of the damage and most evacuations resulted from flood-induced breaks of dams and levees. Thirty-six counties, including all ten in the San Francisco Bay region, were declared eligible for federal disaster assistance (*9*).

Relations Between Rainfall and Landslides—the Basis of the Warning System

Whether a given slope produces a landslide depends on the balance between the shear strength of the slope material and the downslope component of the gravitational force imposed by the weight of slope material above a potential slip surface. Where all the necessary shear strength, soil density, geometric, and hydrologic parameters can be measured or accurately estimated, standard methods may be used for evaluating the stability of the slope (*10*). Predicting the likelihood of landslides throughout a large, complex region such as that around the San Francisco Bay, however, requires combining slope-stability theory with historical observations of rainfall and landslide occurrence along with reasonable simplifying assumptions concerning slope properties and flow of water through hillside soils.

Because we perceived debris flows as the most life-threatening landslides in the San Francisco Bay region, we concentrated our warning efforts on landslides of this type. Several relations between rainfall and debris-flow initiation have been developed from historical, worldwide (*11*) and regional data (*4, 12–15*). Caine (*11*) collected a worldwide data set of rainfall intensities, I_r, and durations, D, that triggered debris flows; he plotted a lower bound, or threshold, to this data set, expressed as

$$I_r = 14.82\,D^{-0.39} \qquad (1)$$

where I_r is in millimeters per hour and D is in hours. Other empirical relations (*12–15*) contain an expression for threshold antecedent precipitation (precipitation occurring before the critical storm period that contributes to saturating the soil) and an expression for critical storm precipitation that generates debris flows.

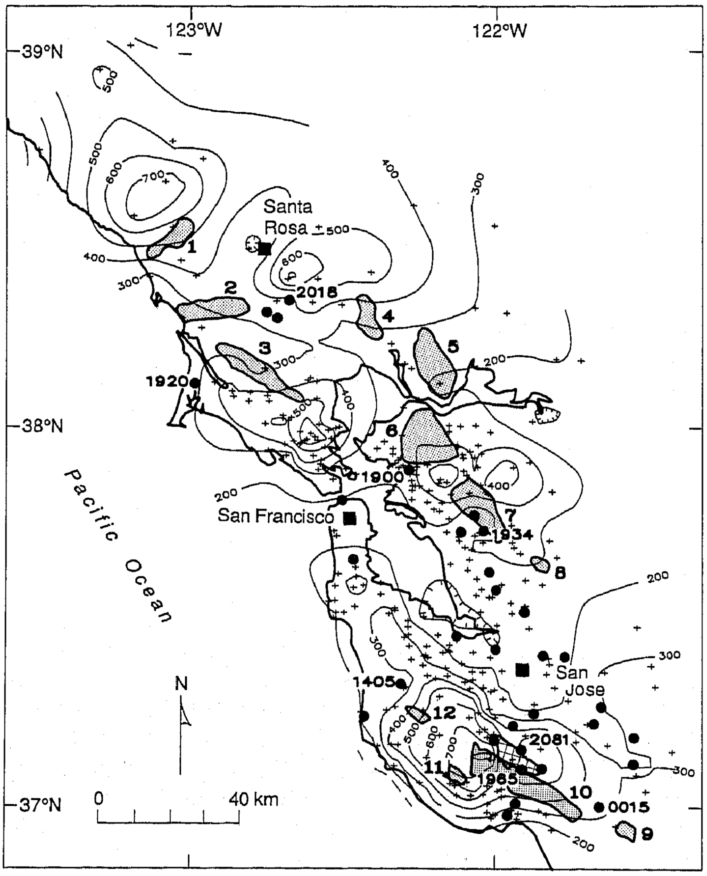

Fig. 1. Map showing locations of main landslide areas (shaded and numbered 1 to 12); ALERT telemetering rain gages (circles); other, nontelemetering rain gages (crosses); Lexington Burn area (grid-lined area at lower right); and contours of total precipitation from 12 to 21 February 1986 inclusive. Contour interval is 100 mm. Contours are based on smoothed data and thus do not conform to all individual rain gage readings. Data from nontelemetering rain gages were not available in real time but were used for analyses after the storms.

For the San Francisco Bay region, Mark and Newman (*12*) analyzed data from the January 1982 storm and concluded that damaging landslides (primarily debris flows) were most abundant where prestorm rainfall since 24 September 1981 exceeded 300 to 400 mm and where storm rainfall exceeded 250 mm and 30% of mean annual precipitation. Other empirical relations developed for this region from historical data by Wieczorek (*13*) and Cannon and Ellen (*14*) suggest thresholds of antecedent precipitation of 250 to 400 mm and the threshold combinations of rainfall intensity and duration during the triggering storm that are plotted in Fig. 2.

Whereas these empirical thresholds were developed solely from observational data and simple statistics, analytical expressions yielding similar results may be derived from existing slope-stability theory with reasonable simplifying assumptions. The shear strength of material at a point within a slope is expressed as (*16*)

$$s = c' + (p - u_w)\tan\phi' \qquad (2)$$

where s is the shear strength of the slope material, c' is the effective cohesion of the material, ϕ' is the effective friction angle of the material, p is the total stress normal to a potential slip surface, and u_w is the pore-water pressure. The stability of the slope and the position of the slip surface thus depend on the strength parameters (c', ϕ') of the slope material, the height and inclination of the slope and the density of the slope material (which determine p), and the distribution of pore pressures (u_w) within the slope.

Our first simplifying assumption, which derives from Terzaghi's work on landslide initiation (*17*), is that rainfall promotes initiation of debris flows and landslides of other types primarily by infiltrating into a hillslope, accumulating in a saturated zone above a permeability barrier (in many cases the base of the colluvium), and increasing the pore-water pressures within the slope material. The increases in u_w cause the effective overburden stress ($p - u_w$) and thus the shear strength to decrease until the slope fails. Before rainfall can increase pore-water pressures, however, the slope materials must already contain enough moisture to fill the capillary porosity and neutralize the soil suctions (negative pore pressures) in dry soils. This requirement explains the observed importance of antecedent precipitation in most landslide-prone areas, including the San Francisco Bay region. The required moisture content is approximately equal to the field capacity—the maximum amount of moisture that a soil can hold against free gravitational drainage.

Our second assumption is that, for any given slope, there exists a critical level of the pore-water pressure, u_{wc}, acting on a critical area on the developing slip surface, at which the slope becomes unstable. For example, for the highly idealized model of an infinite slope composed of cohesionless materials ($c' = 0$), where both the slip surface and the piezometric surface are parallel to the ground surface, the critical pore-water pressure may be calculated as (*18*)

$$u_{wc} = Z\gamma_t\left(1 - \frac{\tan\theta}{\tan\phi'}\right) \qquad (3)$$

where Z is the depth of slip surface, γ_t is the total unit weight of the slope material, and θ is the slope inclination.

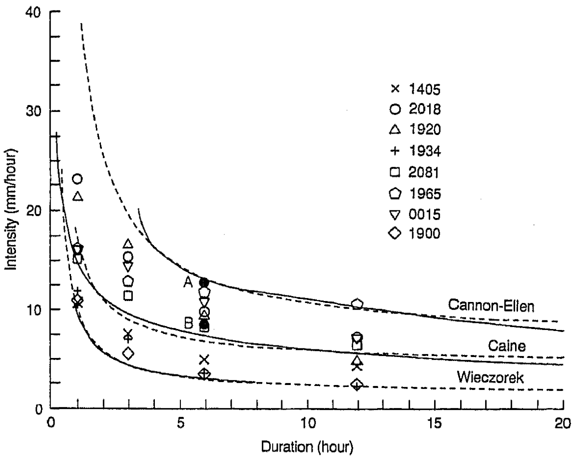

Fig. 2. Rainfall intensity and duration thresholds for initiation of debris flows on susceptible slopes. Published empirical curves are shown by solid lines; curves resulting from numerical fitting by using Eq. 5 are shown as dashed lines. The Cannon-Ellen threshold is for abundant debris flows from natural slopes in areas of the San Francisco Bay region having average annual precipitation greater than 660 mm (*14*). The Caine threshold is for individual debris flows on natural slopes based on worldwide data (*11*). The Wieczorek threshold is for individual debris flows near La Honda, California (*13*), site of ALERT rain gage 1405 in Fig. 1. Also plotted are points indicating the maximum rainfall intensities for intervals of 1, 3, 6, and 12 hours recorded at various ALERT rain gages in and near landslide areas during the 12 to 21 February 1986 storms; numbers beside the symbols denote the various ALERT gages, situated as shown in Fig. 1. Points A and B are the 6-hour rainfall forecasts noted in the warning issued at noon on 14 February; point A was the maximum forecast for the region, and point B was the specific forecast for the Lexington Burn area.

Many more sophisticated slope-stability models exist (*10, 19*), but regardless of the details of the ground-water flow field of a given hillside, we assume failure will occur when u_w reaches the critical value, u_{wc}. We then assume that there will be a critical volume of water, Q_c, that can be retained in the saturated zone before u_w rises to u_{wc}. This critical volume of water may be expressed in terms of a volume per unit area of the slope, yielding dimensions of length (in millimeters). From volumetric considerations

$$Q_c = \frac{u_{wc}}{\gamma_w} n_{ef} \tag{4}$$

where γ_w is the unit weight of water and n_{ef} is the effective soil porosity, that portion of the total porosity remaining after the slope material has reached field capacity.

Our final simplifying assumptions are that (i) all of the rainfall that falls on the slope infiltrates, at least initially, into a saturated zone above the potential slide plane, and (ii) although the precise mechanisms and pathways by which water drains from the hillslope are unknown, the total rate of drainage is proportional to the thickness of the saturated zone. Under these assumptions, the saturated zone would retain all of the rainfall at the onset of a storm, but the drainage rate would increase as the rainfall accumulates, reaching a maximum when (and if) the slope fails. We approximate the drainage by its average rate I_o, which has the same units as rainfall intensity (in millimeters per hour). For storms in which the average rainfall intensity is relatively constant, the combination of intensity and duration required to emplace the critical volume of retained water to initiate a debris flow (or landslide of another type) on a given hillslope may be calculated as (*20*)

$$(I_r - I_o) D = Q_c \tag{5}$$

The values of the threshold parameters, I_o and Q_c, depend on the steepness and geometry of the hillslope, the position of the slip surface, and the mechanical and hydrological properties of the slope materials. For a small, homogeneous area, these parameters may be estimated from careful measurements of rainfall, pore-water pressures, and slope displacements (*21*). However, reasonable numerical estimates of I_o and Q_c may also be obtained for broad, highly variable regions, provided sufficient data are available on rainfall conditions and the occurrence of debris flows. For example, for durations of 1 to 24 hours, Caine's relation (Eq. 1) can be approximated by an expression with I_o = 4.49 mm/hour and Q_c = 13.65 mm. The Cannon-Ellen curve for abundant debris flows can be approximated by an expression with I_o = 6.86 mm/hour and Q_c = 38.1 mm, and the Wieczorek curve for single debris flows at the La Honda test site (locality 1405 in Fig. 1) by an expression with I_o = 1.52 mm/hour and Q_c = 9.00 mm (Fig. 2).

Landslide Warnings and Occurrence During the Storms of 12 to 21 February 1986

Landslide warnings issued during the storms were based on NWS Quantitative Precipitation Ratio Forecasts (QPRF) (*22*), real-time monitoring of the Automated Local Evaluation in Real Time (ALERT) network of telemetering rain gages, and comparisons of the actual and predicted rainfall with the threshold curves in Fig. 2. We based our judgments about whether to recommend warnings primarily on the Cannon-Ellen threshold (Fig. 2) but also used the Wieczorek threshold to evaluate conditions in some especially susceptible areas. (For both thresholds we used the numerically fitted, dashed curves.)

The ALERT rain gage network in the San Francisco Bay region contains 45 stations (Fig. 1) and is operated by NWS in cooperation with other federal, state, and local government agencies. Designed originally for flood and flash flood warnings, the system can measure high-intensity rainfall at remote locations and telemeter the data to receiving stations for real-time monitoring and analysis and rapid issuance of warnings (*23*). Each rain gage station is a self-contained unit consisting of a power supply, an electronics and radio transmission package, and a tipping-bucket rainfall-measuring mechanism; each 1-mm increment of rainfall causes the unit to transmit a station identification code and rainfall accumulation value (*23*). The signal transmitted by the unit can be received and processed by anyone who has an appropriate radio receiver and a microcomputer or minicomputer for data collection, analysis, and display. The U.S. Geological Survey (USGS) maintains an ALERT receiver in Menlo Park, California, and during the storm we monitored the ALERT network from our offices and homes on portable computer terminals connected to this receiver by telephone modems.

The QPRF is issued by NWS in Redwood City, California, at least twice a day and more often during severe storms. Each forecast gives predicted rainfall for the following four 6-hour periods at each of 17 grid points in northern and central California, including two points within the area of Fig. 1. From the QPRF it is possible to derive predicted rainfall at any locality in this region for which the average monthly precipitation is known. During storms, the QPRF thus provides relatively detailed predictions of imminent rainfall while the ALERT network allows continuous rainfall monitoring and comparison of actual with predicted rainfall.

Landslide warnings during the storms of 12 to 21 February 1986 were transmitted to local radio and television stations as advisories in NWS Special Weather Statements and Flash Flood Statements based on the advice of USGS. In addition, the California state geologist and California State Office of Emergency Services were notified directly by USGS. The first warning was issued for a 6-hour period beginning at noon Pacific Standard Time (PST) on 14 February 1986 (Fig. 3). By that time, threshold seasonal antecedent precipitation of 250 to 400 mm (*12–14*) had been exceeded

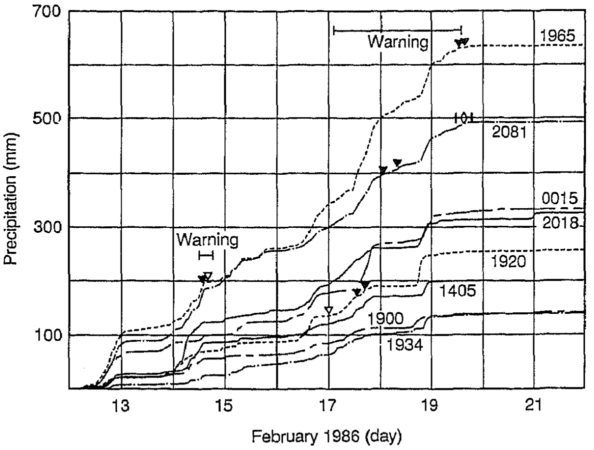

Fig. 3. Cumulative precipitation recorded by selected ALERT rain gages (numbered as on Fig. 1) in and near main landslide areas during storms of 12 to 21 February 1986, times for which landslide warnings were issued (horizontal bars), and times of landslides reported by eyewitnesses (diamond is slump, filled triangles are debris flows, and open triangles are landslides of undetermined type). Landslide symbols are plotted on trace of nearest ALERT rain gage record.

throughout most of the San Francisco Bay region. The warning was based on our monitoring of rainfall to that time and an NWS forecast of an additional 50 mm of rain in the next 6 hours. The text of the warning was as follows:

> Due to continued very heavy precipitation in the Lexington Burn area of the Santa Cruz Mountains, the USGS and NWS advise of an increased hazard of mud slides and debris flows. This is based upon earth measurements taken in the burn area by the USGS and estimated rainfall from the Weather Service continuing at approximately 2 inches per 6 hours. If the precipitation rate increases to 3 inches per 6 hours or more, the USGS advises that mudslides are possible throughout much of the San Francisco Bay area. Persons living in the mountainous areas of the Bay area should watch for earth slippage and be prepared to move to safe ground.

Precipitation of 3 inches (76 mm) per 6 hours corresponds to a point slightly below the Cannon-Ellen threshold (point A, Fig. 2). The Lexington Burn area (Fig. 1) is 56 km^2 of steep, predominantly chaparral-covered terrain that burned in July 1985. Previous studies of burned, chaparral-covered slopes in other regions, including mountains near Los Angeles, California, have suggested that such slopes are exceptionally susceptible to debris-flow generation (*24*); high susceptibility of parts of the Lexington Burn area was also suggested by the occurrence of small debris flows earlier in the 1985–1986 winter (*25*). We therefore recommended a warning for this area when the NWS predicted rainfall substantially above the Wieczorek threshold, even though the predicted rainfall (point B, Fig. 2) was below the Cannon-Ellen threshold.

A second series of landslide warnings was issued for a 60-hour period, beginning at 0200 PST on Monday, 17 February, and ending at 1400 PST on Wednesday, 19 February. Numerous landslide warnings were included in Flash Flood Statements broadcast by NWS during this time; a typical broadcast message read as follows:

> The National Weather Service is issuing a flash flood warning which will run until 12 midnight Monday night for the counties of Marin, Napa, and Sonoma. Moderate to heavy rain is falling and will continue to fall over these counties throughout the day over saturated ground and into already swollen rivers and streams, creating a dangerous flash flood situation. With the ground being saturated, the potential for mud slides and mud flows has increased with several reports of slides in this area coming into the Weather Service office. Persons in the warning areas should be prepared to move to higher ground immediately if heavy rain or flooding is observed or if a hillside is noticeably weakening or about to give way.

These landslide warnings were specific concerning time but, because of the complex topographic and geologic conditions and the preliminary stage of development of the warning system, were issued for large areas rather than specific localities.

The precise times of ten landslides caused by the storm are known from eyewitness reports (Fig. 3), and the reported times of eight of the ten landslides coincided with the times for which landslide warnings had been issued. The first two reported landslides occurred on the afternoon of 14 February, during the first warning period. Six of the eyewitness-reported landslides occurred during the 17 to 19 February warning period; the remaining two landslides occurred slightly before and slightly after this period (Fig. 3).

The storms produced numerous debris flows and landslides of other types in the San Francisco Bay region. On the basis of observations from the ground and from low-altitude flights in fixed-wing aircraft we identified 12 main landslide areas (Fig. 1), each of which contains several tens to several hundred landslides caused by the February 1986 storms. We estimate that landslides in the region caused approximately $10 million (*26*) of the reported total $164-million damage (*27*) resulting from storms in the ten San Francisco Bay region counties. A debris flow that crushed a house near Boulder Creek in Santa Cruz County (area 11, Fig. 1) caused the only landslide-related death in the region attributable to the storms.

North of San Francisco Bay, in the zone containing areas 1 to 4 in Fig. 1, debris flows were abundant in both the January 1982 and February 1986 storms. However, during the 1982 storm, which was shorter but more intense than the 1986 storm sequence, most debris flows were generated by rapid and near complete fluidization of permeable, granular colluvium (*28*). In contrast, observations throughout the zone and detailed mapping of a 2-km^2 section of area 4 suggested that a higher proportion of the 1986 debris flows were generated by partial mobilization of slower moving landslides, primarily shallow slumps and block slides (*29*), in relatively impermeable, clayey colluvium. This contrast may be explained by differences in rainfall duration and intensity. During the 1982 storm, rainfall was evidently intense enough to build pore-water pressures to critical levels in rapidly draining granular materials but did not persist long enough to do so in less permeable, clayey materials. Conversely, the 1986 storms were not generally intense enough to build pore-water pressures to critical levels in rapidly draining materials but did last long enough to cause such buildup in less permeable soils.

East and south of San Francisco Bay (areas 5 to 9, Fig. 1) the February 1986 storm caused slumps, slow earth flows (*29*), and debris flows. Debris flows were generated both by partial mobilization of slower moving landslides and by direct fluidization of colluvium in hillside swales and along the channels of small first-order streams. Although debris flows were the most numerous landslides, they were less abundant than in the January 1982 storm, whereas slumps and slow earth flows, which commonly occur in clayey colluvium, were more abundant. We speculate that this contrast also may be explained by the longer duration and lower rainfall intensities of the 1986 storm sequence.

Debris flows and slumps were the predominant landslides west of San Francisco Bay in the Santa Cruz Mountains (areas 10 to 12, Fig. 1). Although our observations are incomplete there because of the particularly rugged terrain, geologic complexity, and dense vegetation cover, the observations did show that significantly fewer debris flows occurred in 1986 than in 1982. The 1986 storm sequence produced slumps and debris flows in a variety of materials including man-made fill, granular colluvium, clayey colluvium, and weathered granite, shale, and sandstone.

The Lexington Burn area (Fig. 1), noted in the landslide warning of 14 February, produced few debris flows during the 1986 storms—a result at variance with our expectations. Preliminary interpretation of data from this area (*30*) suggests that few debris flows occurred because (i) water-repellent soil layers, formed by burning chaparral and associated with debris-flow generation elsewhere (*24*), were discontinuous in the Lexington Burn area; (ii) root networks in the area survived the July 1985 fire, and vegetation had resprouted on most slopes before the February 1986 storms; and (iii) soils are generally thin, and relatively little loose, surficial material was available for mobilization.

Rainfall intensities for the most intense 1-, 3-, 6-, and 12-hour bursts of precipitation during the February 1986 storms at ALERT stations near the main landslide areas are shown in Fig. 2. Only one burst at one station exceeded the Cannon-Ellen threshold for abundant debris flows; however, all bursts exceeded one or both of the other thresholds. These data are consistent with observations that fewer debris flows occurred in the San Francisco Bay region during the 1986 storms than during the January 1982 storm, during which rainfall did exceed the Cannon-Ellen threshold in many areas (*14*).

Conclusions

A real-time, regional landslide warning system has been developed for the San Francisco Bay region. It is based on empirical and analytical relations between rainfall and landslide generation, real-time regional monitoring of rainfall data from telemetering rain gages, NWS precipitation forecasts, and delineation of areas susceptible to landslide generation. By developing appropriate rainfall-landslide relations, the system can be adapted for use in other landslide-prone regions.

The warning system was used to issue the first regional, public landslide warnings in the United States during the storms of 12 to 21 February 1986, which produced 800 mm of rain in the San Francisco Bay region. According to eyewitness accounts of landslide occurrence, the warnings accurately predicted the times of major landslide events.

The February 1986 storms produced hundreds of landslides in the San Francisco Bay region but caused much less landslide damage than the disastrous storm of 3 to 5 January 1982 and only one landslide-caused death. The comparatively low damage and casualty rates are due largely to the occurrence of fewer landslides overall and fewer fast-moving debris flows in particular in February 1986 than in January 1982. However, response to the landslide warnings and to the storm effects showed that the population of the region was better prepared for an event of this type than was the case in 1982. For example, several local government agencies used the landslide warnings as part of the basis for planning emergency response and, in some cases, for recommending temporary evacuation of hazardous areas (*26*).

Analysis of landslide occurrence during the 1986 storms suggests several modifications and additional developments for improving the warning system. First, the rainfall-landslide relations (Fig. 2 and Eq. 5) need refinement to account for the effects of long-duration, moderate-intensity rainfall, to relate rainfall to landslide initiation with a more rigorous model, and to treat the initiation of landslides other than debris flows. Second, measurements of soil moisture and pore-water pressures are needed to provide better calibration of the rainfall-landslide relations. As part of this effort, telemetering piezometers have been installed at the La Honda ALERT station to provide real-time measurement of pore-water pressures in hillside soils (*21*). Third, the warning system needs to be formalized and automated so that information can be relayed faster and more effectively during a developing storm. Finally, additional research is needed concerning topographic, hydrologic, and geologic conditions of landslide sources so that future warnings can more precisely specify hazardous areas.

REFERENCES AND NOTES

1. A. C. Lawson *et al.*, *The California Earthquake of April 18, 1906* (Publ. 87, Carnegie Institution of Washington, Washington, DC, 1908; reprinted by Carnegie Institution of Washington, 1969).
2. R. K. Mark *et al.*, *U.S. Geol. Surv. Open-File Map OF-83-16* (1983).
3. S. D. Ellen *et al.*, *U.S. Geol. Surv. Prof. Pap. 1434*, in press; C. L. Creasey, *ibid.*
4. A potential landslide warning system covering the 1050-km^2 area of Hong Kong has been proposed by E. W. Brand, J. Premchitt, and H. B. Phillipson [*Proceedings of the Fourth International Symposium on Landslides*, Toronto, 16 to 21 September 1984 (Univ. of Toronto Press, Ontario, Canada, 1984), vol. 1, pp. 377–384]. In the Hong Kong area, antecedent rainfall evidently has little effect on landslide initiation. Debris-flow warning systems in Japan are described by K. Yano [*Proceedings of the International Congress: Interpraevent 1984*, Villach, Austria, 6 to 9 June 1984 (Forschungsgesellschaft für vorbeugende Hochwasserbekämpfung, Klagenfurt, Austria, 1984), vol. 2, pp. 167–180].
5. "Synoptic situation—storm series of February 12–21, 1986" (National Weather Service, Redwood City, CA, 6 March 1986).
6. A compilation of references on landslides in the San Francisco Bay region is included in C. S. Alger and E. E. Brabb [*U.S. Geol. Surv. Open-File Rep. 85-585* (1985), p. 16].
7. S. E. Rantz, "Mean annual precipitation and precipitation depth-duration-frequency data for the San Francisco Bay region, California," *U.S. Geol. Surv. Open-File Rep.* (1971).
8. *Storm Data* **28**, 4 (February 1986) (National Climatic Data Center, Asheville, NC).
9. *Interagency Flood Hazard Mitigation Report in Response to the February 21, 1986 Disaster Declaration* (FEMA-758-DR-CA, Federal Emergency Management Agency, Washington, DC, 1986). Santa Cruz County included as part of the region.
10. R. N. Chowdhury, *Slope Analysis* (Elsevier, Amsterdam, 1978).
11. N. Caine, *Geogr. Ann.* **62A**, 23 (1980).
12. R. K. Mark and E. B. Newman, *U.S. Geol. Surv. Prof. Pap. 1434*, in press.
13. G. F. Wieczorek, in *Reviews in Engineering Geology*, J. E. Costa and G. F. Wieczorek, Eds. (Geological Society of America, Boulder, CO, 1987), vol. 7, pp. 93–104; ——— and J. Sarmiento, *U.S. Geol. Surv. Prof. Pap. 1434*, in press.
14. S. H. Cannon and S. D. Ellen, *Calif. Geol.* **38**, 267 (1985); S. H. Cannon, *U.S. Geol. Surv. Prof. Pap. 1434*, in press.
15. R. H. Campbell, *U.S. Geol. Surv. Prof. Pap. 851* (1975).
16. K. Terzaghi, *Bautechnik* **16**, 343 (1938) [translated by L. Bjerrum, in *From Theory to Practice in Soil Mechanics: Selections from the Writings of Karl Terzaghi*, L. Bjerrum *et al.*, Eds. (Wiley, New York, 1960), pp. 174–180].
17. ———, in *Application of Geology to Engineering Practice, Berkey Volume*, S. Paige, Ed. (Geological Society of America, New York, 1950), pp. 83–123.
18. Adapted from A. W. Skempton and F. A. DeLory, in *Proceedings of the Fourth International Conference on Soil Mechanics and Foundation Engineering*, London, 12 to 24 August 1957 (Butterworth, London, 1957), vol. 2, pp. 378–381.
19. For example, R. M. Iverson and J. J. Major [*Water Resour. Res.* **22**, 1543 (1986)] assert that slope stability is minimized when the vector of ground-water seepage makes an angle equal to ϕ' above the slope.
20. R. C. Wilson, *Assoc. Eng. Geol. Annu. Meet. Abstr. Program* **29**, 69 (1986).
21. Instrumentation installed for this purpose at the La Honda landslide test site (location of ALERT rain gage 1405 in Fig. 1) is described by C. S. Alger, R. K. Mark, and G. F. Wieczorek [*Eos* **66**, 911 (abstr.) (1985)].
22. G. E. Barbato, "Quantitative precipitation forecasting in northern and central California by the National Weather Service" (National Weather Service, Redwood City, CA, 1987).
23. "Automated Local Evaluation in Real Time: A cooperative flood warning system for your community" (National Weather Service, Salt Lake City, UT, 1981).
24. W. G. Wells II, in *Proceedings of the Chaparral Ecosystems Research Conference*, J. J. DeVries, Ed., University of California, State of California, and U.S. Forest Service, Santa Barbara, CA, 16 and 17 May 1985 (California Water Resources Center Report No. 62, University of California, Davis, CA, 1986), pp. 57–62, and references therein.
25. D. K. Keefer *et al.*, *Geol. Soc. Am. Abstr. Programs* 18, 652 (1986).
26. Estimate is based on our field observations and on damage reports from county planning departments, road departments, and emergency services agencies.
27. Estimate by California State Office of Emergency Services, March 1986, included in (*5*).
28. S. D. Ellen, *U.S. Geol. Surv. Prof. Pap. 1434*, in press.
29. Landslides classified by the system of D. J. Varnes [*Landslides: Analysis and Control*, R. L. Schuster and R. J. Krizek, Eds. (Spec. Rep. 176, National Academy of Sciences, Washington, DC, 1978), chap. 2]. "Debris flows" as used herein include flows in both fine and coarse soils. "Slumps" and "block slides" are more coherent landslides, consisting of one or several blocks that slide on planar (block slides) or curved (slumps) basal slip surfaces. "Slow earth flows" move primarily by sliding on planar basal shear surfaces with subsidiary internal flow; velocities are usually less than 1 m/hour.
30. D. K. Keefer *et al.*, *Assoc. Eng. Geol. Annu. Meet. Abstr. Program* **29**, 53 (1986).
31. Development of this warning system was made possible by the cooperation of J. H. Henderson, meteorologist in charge, and the staff of the National Weather Service Forecast Office, Redwood City, CA. We are grateful to the more than 300 volunteers of the USGS Rainfall Observers Network, who provide rainfall data from throughout the San Francisco Bay region for analyses after storms. B. V. Vassil collected some of the eyewitness accounts of landslide occurrence. The manuscript benefited from comments by R. M. Iverson and R. W. Jibson.