Acoustic Monitoring of Landslides

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Three active landslides located in Eagle County, Colorado, were monitored with an acoustic emission (AE) recording device for an 8-month period beginning in January 1985. AE monitoring devices are used to detect the transient elastic waves generated by the release of energy within a material undergoing failure. The slides were also instrumented with groundwater observation wells and inclinometer boreholes. Groundwater data and displacement measurements gathered from these devices and data collected from surface movement observations were correlated with the AE data. Significant increases in levels of AE activity were recorded at least 30 days before the observation of movement at each of the slides. Rises in groundwater levels recorded at many of the observation stations appear to have triggered the slides. AE signals recorded after the initial failure of the slides correlated with the rates of movement measured at surface displacement observation stations. This study has successfully demonstrated the ability of a properly installed AE monitoring system to detect premovement stresses in soil slopes. AE can be used as an early warning system to reduce hazards to life and property on high-risk soil slopes, road cuts, tailings dumps, dams, foundations, and other civil structures.

In this paper are presented the results of an analysis of three unstable soil and talus slopes using acoustic emissions (AEs) monitoring and traditional field techniques. This study was part of a Colorado Division of Highways effort to characterize landslides that are affecting major highways in Eagle County, Colorado (Figure 1).

The ability to determine the state of stress and stability of a soil mass has been a primary objective of the engineering community for many years. Instruments such as inclinometers and tiltmeters yield valuable information about the direction and amount of movement in a failing earth slope. However, they are limited to measuring movements after failure has begun. There exists a need for easily applied and inexpensive instrumentation technologies that can monitor the relative instability of a soil structure before failure.

BACKGROUND

AEs have also been called microseismics, microsonics, and subaudible rock noise (SARN). These phenomena have been defined as "the transient elastic waves generated by the rapid release of energy within a material" *(1)*. One of the first discoveries of acoustic emissions was made in the late 1930s by the U.S. Bureau of Mines. Researchers found that the quantity and duration of bursts of seismic energy in underground mines were a function of the state of stress of the rock *(2)*.

AE monitoring has also been used by researchers to investigate failure in other media such as metals, concrete, and composite materials *(3, 4)*. Recently, researchers have been investigating the possibility of adapting this technique to the evaluation of soils *(5)*. AE monitoring has proven effective in the following fields:

- Soils
  - Dams, embankments, cuts, fills
  - Settlements
  - Lateral movement
  - Laboratory
- Rock
  - Mine safety
  - Subsidence
  - Open cuts
- Civil Structures
  - Concrete
  - Steel
- Other
  - Avalanche control
  - Composite materials

Characteristics of Acoustic Emissions

Acoustic emissions, as do all seismic signals, occur as waveforms that are characterized by transient displacements on the order of 0.00000001 in. and frequencies of 10 to 1,000,000 cycles per second *(1)*. A record of acoustic emissions generally consists of individual bursts or events separated by periods of relative quiescence (Figure 2). Each event is composed of a series of counts. AE monitoring systems record the number of seismic events and counts per sample interval that equals or exceeds a preset signal threshold level.

AE signals are emitted over a wide range of frequencies, and monitoring systems must be tailored to the material under investigation *(6)*. Figure 3 shows how AE frequencies compare with other types of ground vibration studies and how characteristic AE frequencies vary with types of material.

Acoustic Emissions in Soils

Friction is probably the most dominant mechanism for the release of acoustic energy in soils. As an unstable soil mass

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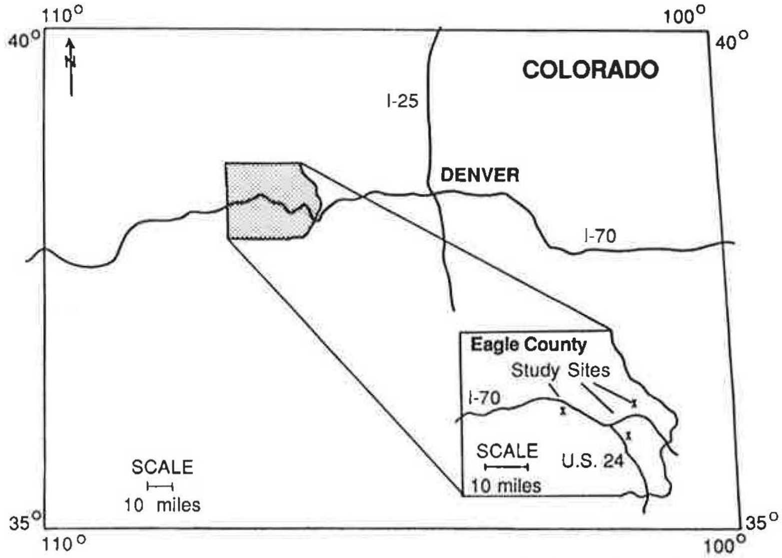

FIGURE 1 Location map, state of Colorado with Eagle County and study areas identified.

fails, individual particles of material in the failure zone or zones abrade one another (Figure 4). This abrasion releases energy in the form of heat and acoustic emissions.

Acoustic emissions are rapidly attenuated in unconsolidated materials. The signal-sensing instruments must therefore be positioned close to the source of the AE activity. Because failures in soils are often deep-seated, high modulus waveguides are used as a path to transmit the AE events to an accessible surface location. Waveguides can include metal tubing or reinforcing bars that are positioned to intercept the potential failure surface (Figure 5).

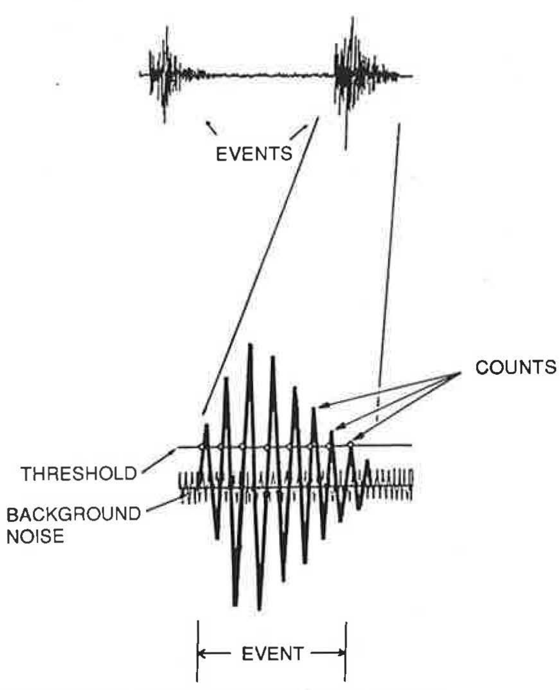

FIGURE 2 Elements of acoustic emission event.

Monitoring Equipment Used in This Study

The AE monitoring system used for this project consisted of (a) an accelerometer with a 30-kHz resonance frequency, (b) a 15- to 45-kHz bandpass filter, and (c) a signal conditioning and analyzing unit. The system was equipped with variable gain and sampling rates, an adjustable threshold setting, and a digital display. Steel pipes ½ in. in diameter were chosen as waveguides for this investigation and doubled as groundwater observation wells. The accelerometer was shielded from stray airborne acoustic signals. Figure 6 shows photographs of a typical AE monitoring station.

DESCRIPTION OF STUDY AREAS

A reconnaissance trip was made to each of the study areas to identify locations for AE and groundwater observation stations. These locations were grouped near the crown, middle, and toe areas of each slide. An additional monitoring station was located outside the boundary of each of the slides so that background AE activity recordings could be made during the course of the study for comparison with the landslide AE activity readings. Finally, a location for at least one inclinometer hole per slide was identified. Installation of these monitoring stations was accomplished in the winter of 1985.

Battle Mountain Slide

The Battle Mountain slide is located on US-24, 2 mi south of Minturn (Figure 7). This is a deep-seated rotational failure in a red, micaceous, sandy, clayey silt. In previous years this slide had been stable throughout the winter and subject to severe movement in the spring and summer. Several groundwater observation wells had been installed and it was known that the level of groundwater in the landslide fluctuated with the seasons, with highs recorded in the spring and summer and lows

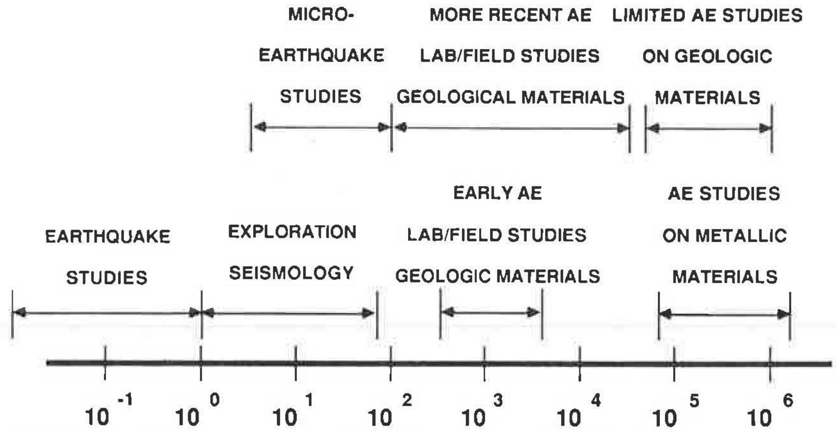

FIGURE 3 **Frequency range (Hz) of monitoring facilities *(6)*.**

occurring in the fall and winter. Six combination AE and groundwater observation stations were installed at the Battle Mountain study area (Figure 8).

Vail Slide

The Vail landslide is located on the north side of the westbound lanes of Interstate 70 in East Vail (Figure 9). The slide appears

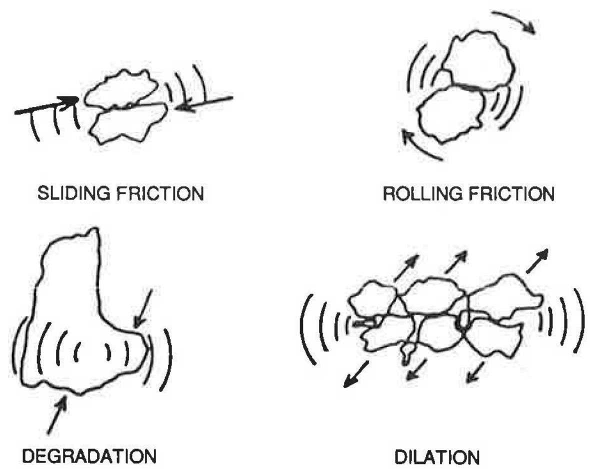

FIGURE 4 **Sources of acoustic emissions in unconsolidated material.**

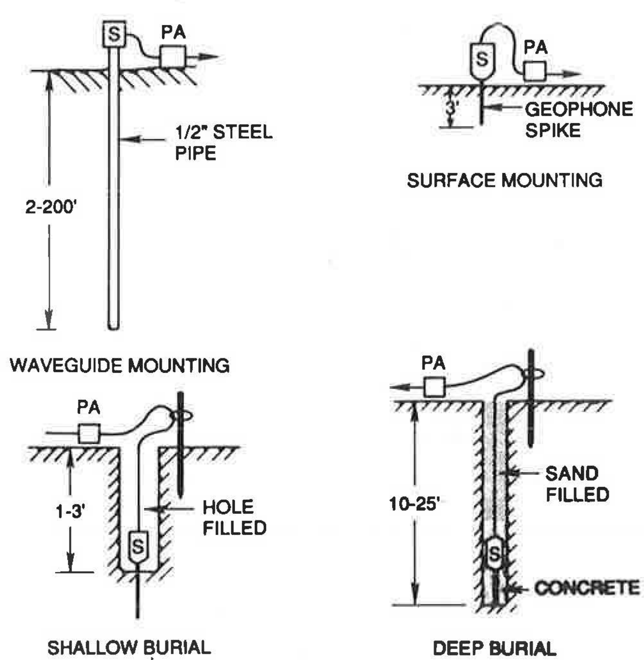

FIGURE 5 **Methods used to mount AE sensors (S = sensor, PA = preamplifier).**

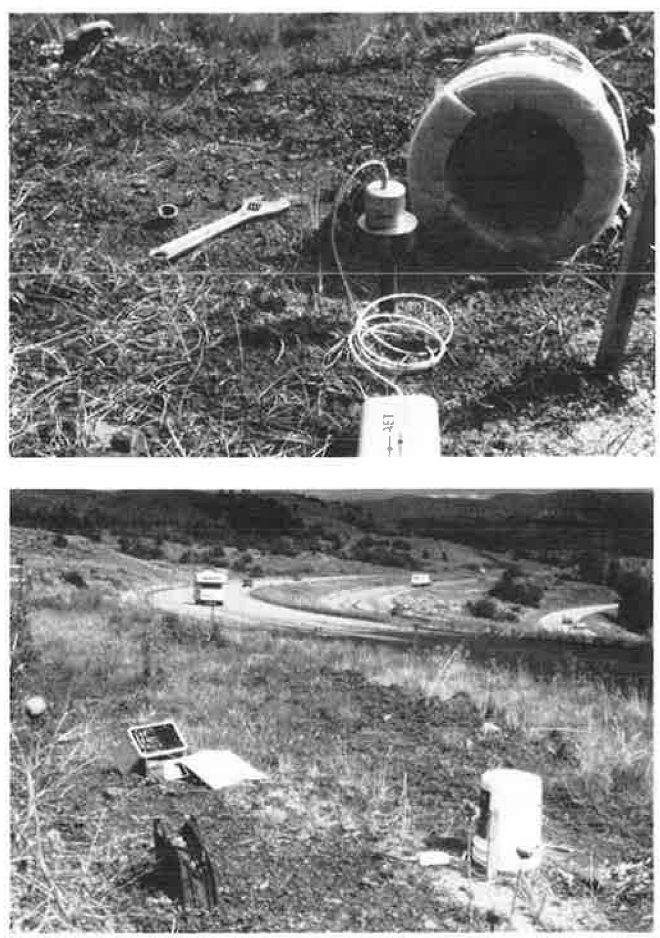
FIGURE 6 **Photographs of typical AE monitoring station.**

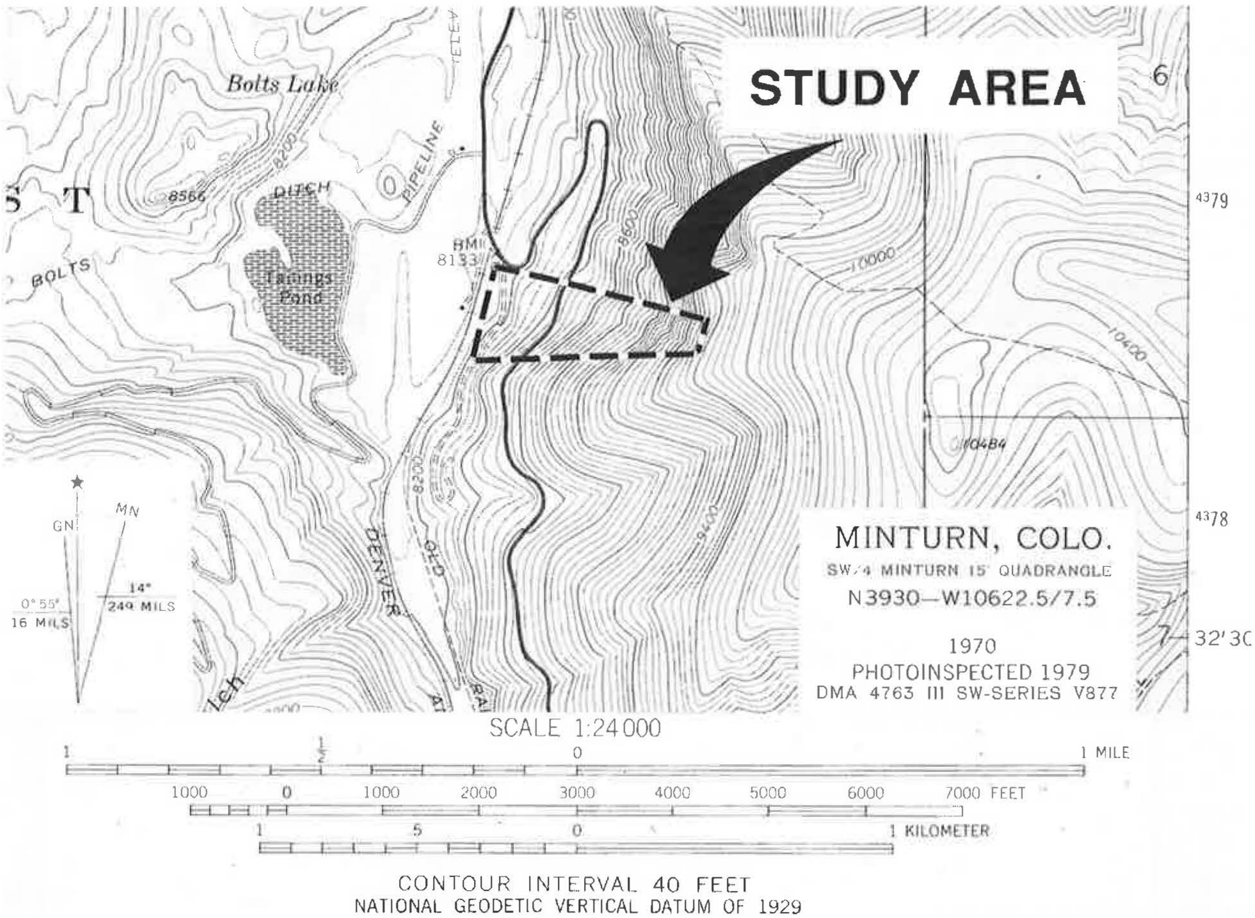

FIGURE 7 Topographical map of the Battle Mountain slide and surrounding area.

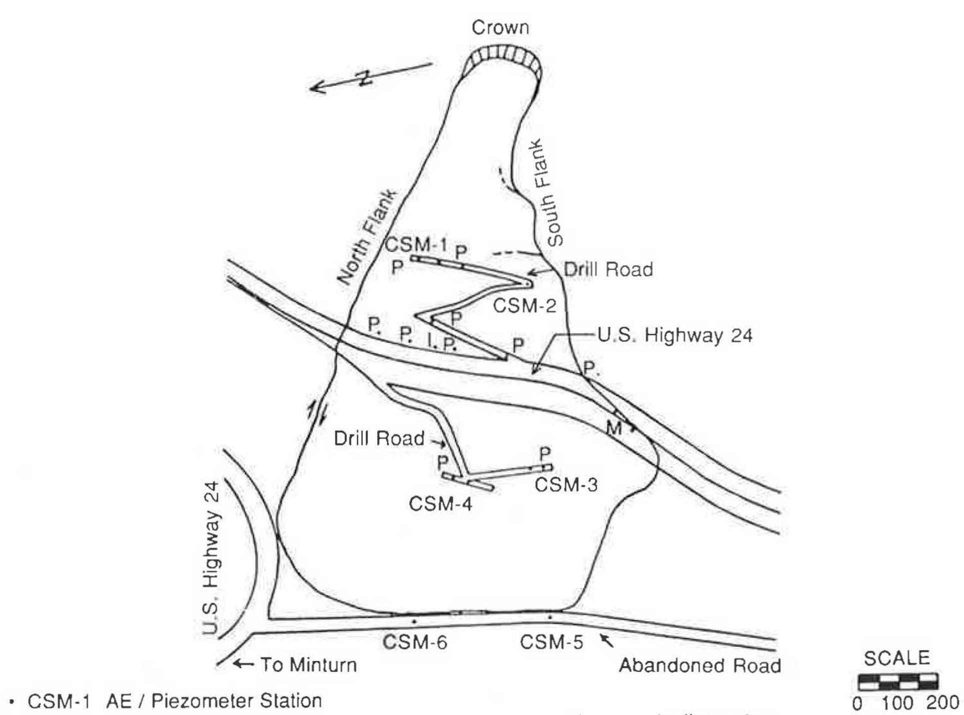

FIGURE 8 Map of the Battle Mountain slide with AE station locations.

to have two divergent directions of movement with the western half of the slide moving slightly to the west and the eastern half of the slide moving slightly to the east. Although the data are incomplete, features identified in both halves of the slide indicate that the western portion is failing in a fairly deep rotational fashion and the eastern half, located outside the array of AE monitoring stations, is failing as a series of wedges of soil (slumps) caused by the oversteepening of the tow of the slope during highway construction. The soil at this site is a red micaceous silt containing occasional clasts of feldspathic sandstone (Figure 10). The Vail landslide was instrumented with a total of five combination AE and groundwater observation stations, one inclinometer hole, and six electronic distance measuring stations.

Wolcott Slide

The Wolcott slide is located along the Interstate 70 right-of-way 1.5 mi east of the Wolcott exit (Figure 11). This slide is traceable across both the east- and the westbound lanes of I-70 as well as the frontage road (US-6). This site has been subjected to recurrent movement every spring for the past several years.

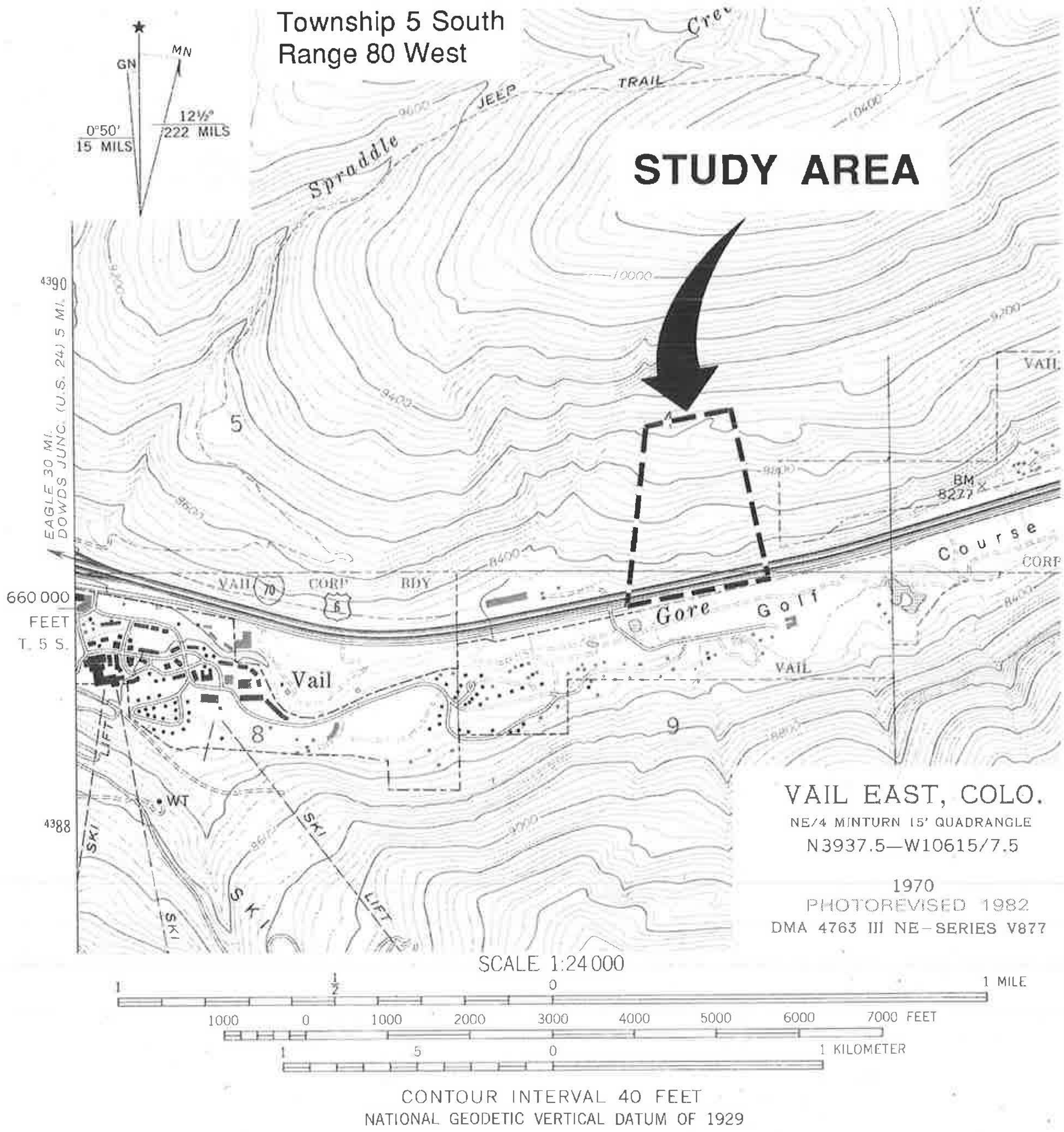

FIGURE 9 Topographical map of the Vail slide and surrounding area.

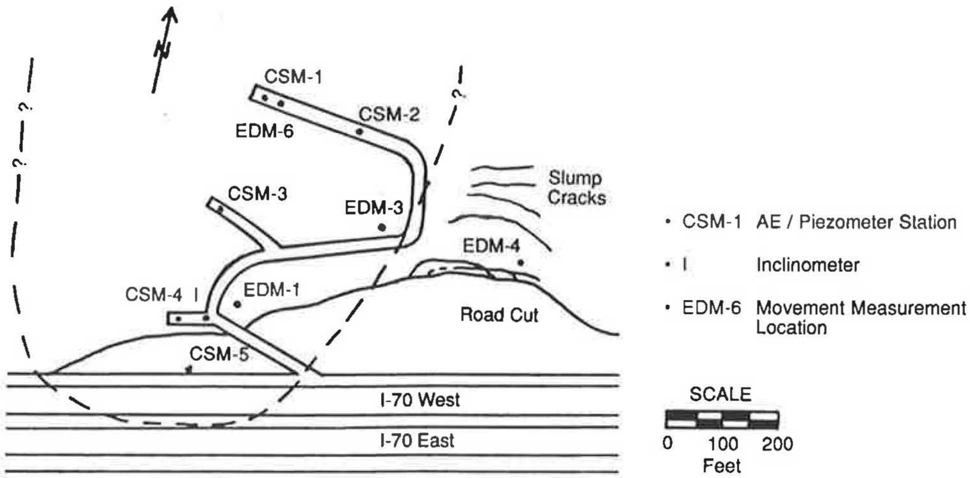

FIGURE 10 Map of the Vail slide with AE station locations.

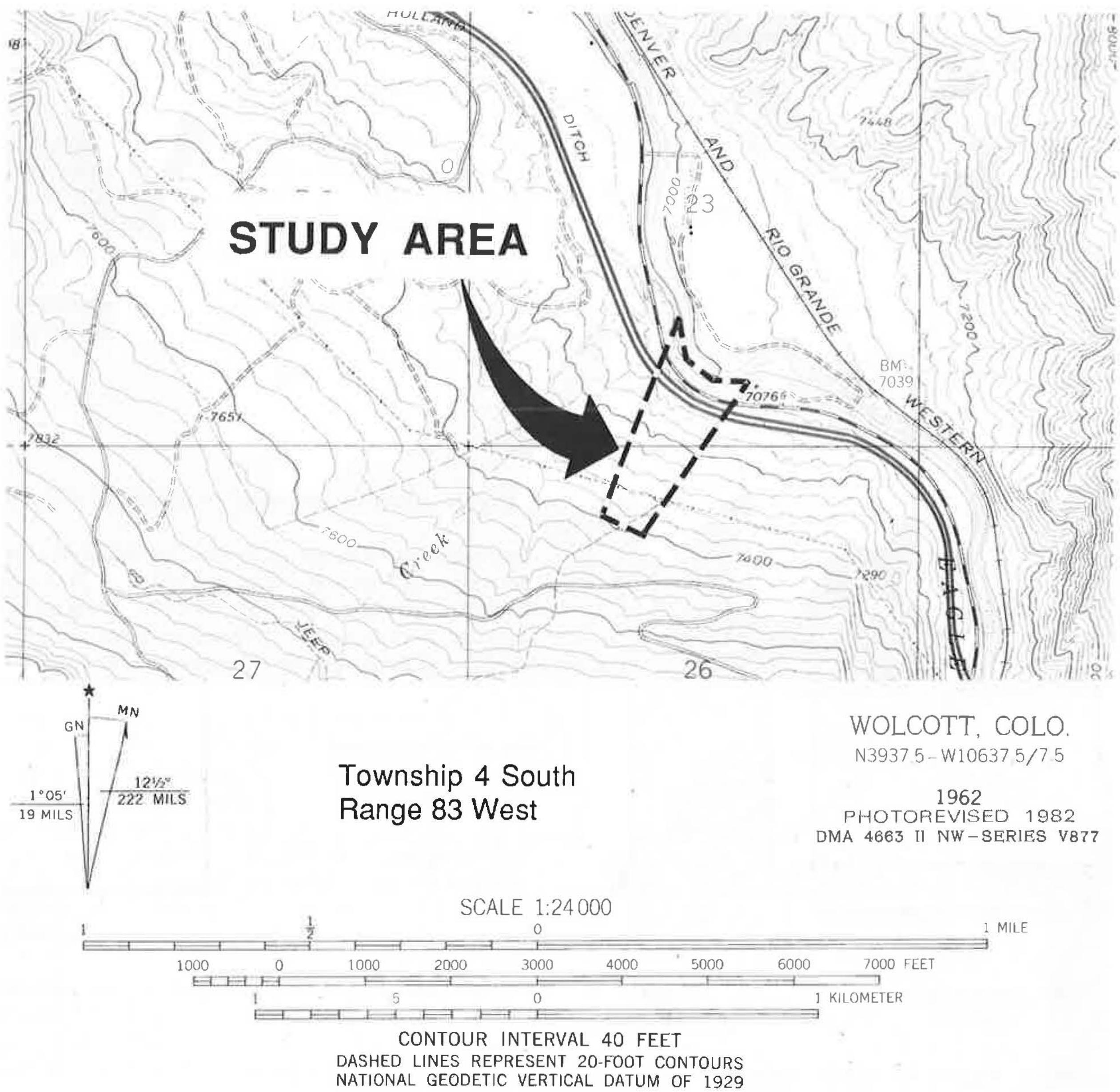

FIGURE 11 Topographical map of the Wolcott slide and surrounding area.

Six AE and groundwater observation stations and three inclinometer holes were installed at the Wolcott slide (Figure 12). All of the holes drilled at the Wolcott slide penetrated a thin mantle of soil underlain by a gray sandy silt, a massive quartzose sandstone, and thinly bedded gray silty shales.

Inclinometer readings identified a shallow dip-slope failure zone located in the thinly bedded shales. The hummocky texture of the study area and surrounding slopes indicates that the Wolcott slide is one of many failures that have occurred along slip surfaces found within the thinly bedded shales.

Movement of the slide was probably triggered by rising groundwater levels during spring runoff. Stability is further reduced by the erosive action of the Eagle River at the tow of the slide. Periods of maximum erosion occur during the high-runoff season (Figure 12) *(7)*.

Summary Comparison of Study Sites

The Battle Mountain and Vail slides are deep-seated rotational failures of soil and colluvium. The Wolcott slide is a shallow dip-slope failure that is moving along a bedrock-controlled failure surface. Movement of all three slides appears to be triggered by rising groundwater associated with spring runoff. These slides provided an excellent opportunity to characterize AE in a variety of geologic conditions.

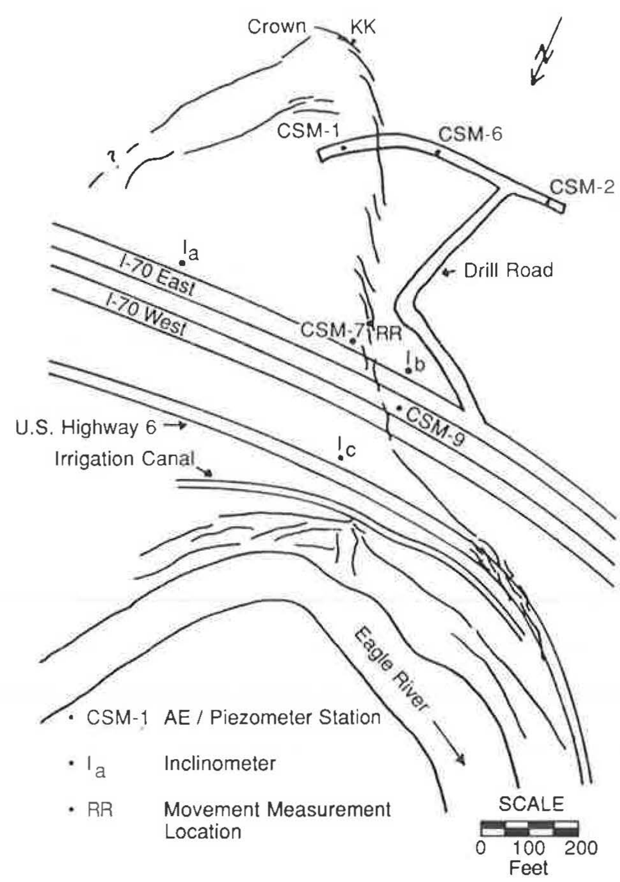

FIGURE 12 Map of the Wolcott slide with AE station locations.

DATA COLLECTION AND ANALYSIS

Installation of Monitoring Systems

One-half-inch steel pipes were slotted and placed in 4-in. drill holes to form combination groundwater observation wells and continuous waveguides from the surface to bedrock. The holes were backfilled with sand to ensure proper coupling of the waveguides with the surrounding soil.

Data Collection Procedures

The signal threshold level and gain (signal amplification factor) were set and recorded to facilitate comparisons among recording sessions. Fifteen 1-min intervals of acoustic emissions were recorded at each of the observation stations. Weather and ground conditions, groundwater levels, and highway traffic levels were recorded in order to evaluate the sensitivity of the monitoring system to environmental conditions.

Methods of Data Analysis

Individual readings of the number of counts and events recorded for each 1-min sample were averaged for each observation period to obtain representative levels of AE activity. The average AE counts and events data and the ratio of counts per event were then plotted at the proper calendar date for each observation station (Figure 13).

These data plots were correlated with data collected from the other types of instrumentation installed at each of the study sites (Figures 14 and 15).

RESULTS

Analysis of Acoustic Emissions Counts and Events Data

The number of AE counts and events recorded in the months of February and March was quite low (Figure 13). These low levels of activity, generally less than 100 counts per minute, represent baseline values considered characteristic of a stable condition as recorded at the control stations located outside the slides.

AE activity increased in March and April. These increases, representing changes in the stability of the slides in response to rising groundwater levels, were recorded at least 30 days and as much as 50 days before any movements were observed at the slides. The amount of such advance warning varied among stations within each slide, and significant increases in AE activity were not recorded at every observation station. This is because different portions of the slides experienced different loading conditions and moved at different rates as verified by field observations.

The ability to identify changes in AE activity was a function of the observation interval used in this study. The observations were made monthly in the winter, biweekly in the spring, and weekly in the summer. Because increases in AE activity recorded before failure were measured in the spring when data

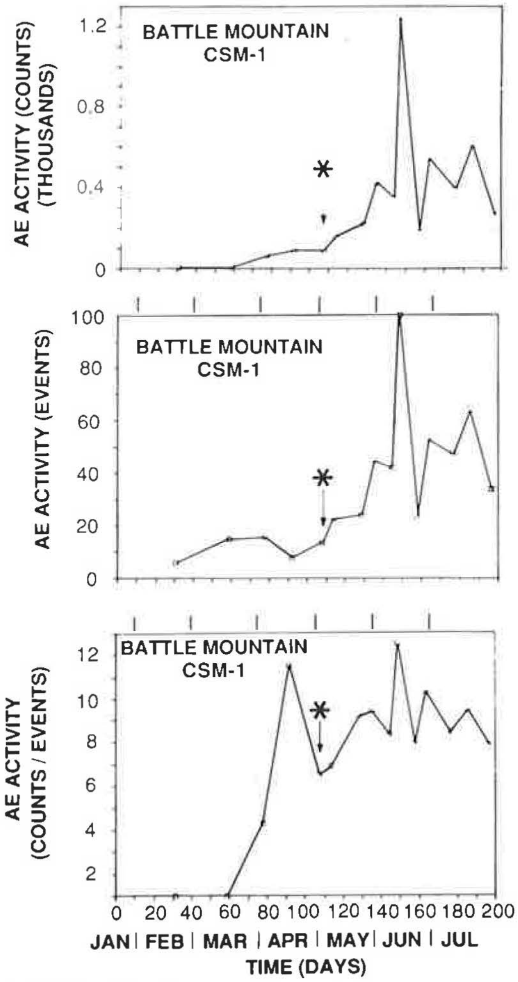

FIGURE 13 Sample AE counts, events, and counts/event ratio data plots (star indicates first observed movement of slide).

were collected on a biweekly basis, the exact time at which AE activity increased might have been as much as 13 days before the date recorded. A more detailed analysis of slide activity would suggest the use of a continuous monitoring system.

After the initiation of movement, AE activity continued to increase at many of the observation stations, but in some cases AE activity dropped off to relatively low levels. These different responses of the AE monitoring system to the initiation of movement appear to be a function of the mode of failure experienced at the slides.

Observations of displacement recorded by Shine *(8)* at the Battle Mountain slide revealed that movement was sporadic with periods of high rates of movement followed by periods of relative quiescence. This pattern of movement, commonly referred to as stick-slip, was identified in the records of AE activity collected at several observation stations at the slides (Figure 15). AE activity reached a maximum in mid-June that coincided with the maximum rate of movement of the slides.

Analysis of Acoustic Emissions Average Counts per Event Ratio Data

Before failure, plots of the average AE counts per event (C/E) ratio are significantly different from the plots of either the AE counts or events data. For example, at Battle Mountain slide Station CSM-1, a gradual increase in both the number of AE counts and events was recorded, whereas the C/E ratio shows a low level of activity followed by a marked increase (Figure 13). This dramatic increase occurred about 50 days before the first observed movement of the slide. Subsequent C/E ratio data closely correlated with the rates of movement of the slides.

The C/E ratio offers an additional measure of relative stability and appears to provide a more sensitive precursor to movement.

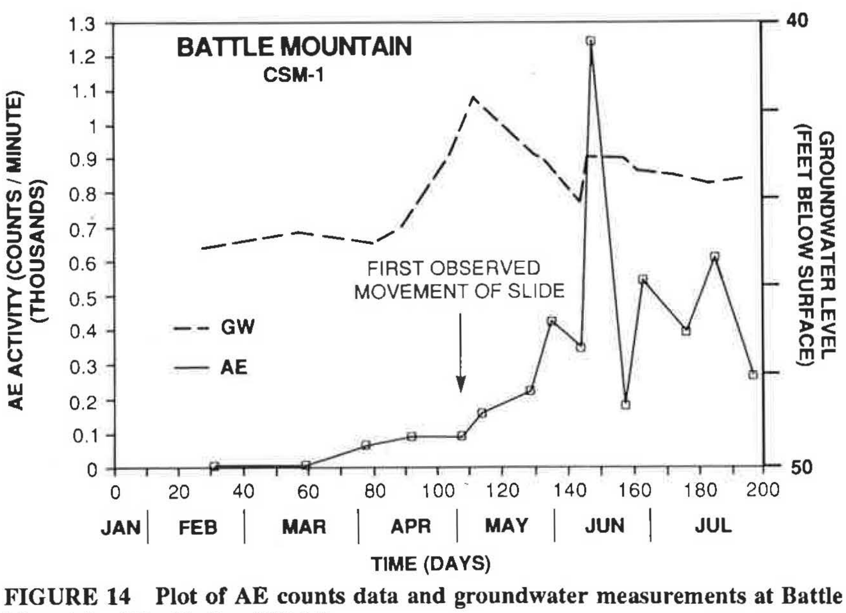

FIGURE 14 Plot of AE counts data and groundwater measurements at Battle Mountain slide Station CSM-1.

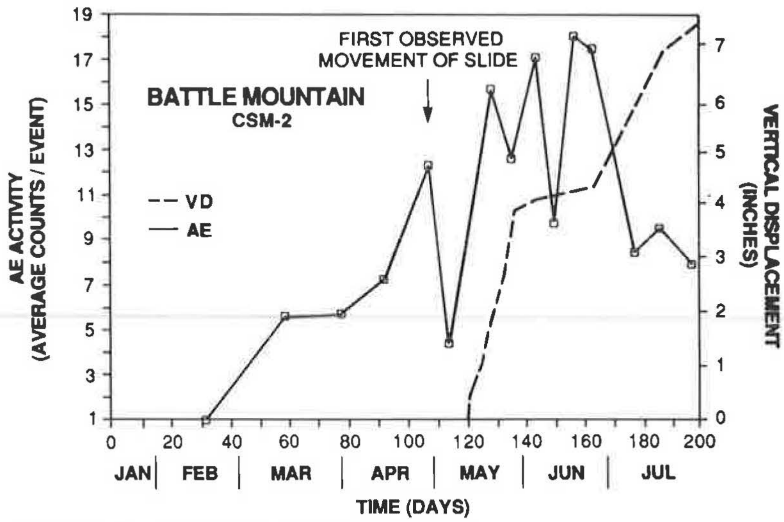

FIGURE 15 Plot of AE average counts/event ratio and surface movement data for Station CSM-2 at the Battle Mountain slide.

CONCLUSIONS AND RECOMMENDATIONS

Acoustic emissions monitoring systems installed in three distinctly different landslides accurately tracked changing conditions of stability. Increases in AE activity were recorded at least 30 days in advance of movement at each of the slides.

The location of AE observation stations at a study site is critical for recording representative data. Because acoustic emissions monitoring systems are extremely sensitive, they are also sensitive to many other acoustic signals. An AE monitoring system should include shielding and filters to eliminate noise from unrelated sources such as highway traffic and running water.

Relatively large areas can be monitored with a few carefully placed observation stations. The 1/2-in. steel pipes used as waveguides in this study were effective in transmitting low-level AE signals from deep-seated failures to sensors located at the surface.

Several methods of analysis should be used for a thorough evaluation of AE data. The number of AE counts, the number of AE events, and the ratio of average counts per event all describe different aspects of the quantity and duration of AE activity and hence slope stability.

An accurate record of changes in slope stability depends on the frequency of observation. Continuous monitoring of AE activity during critical periods would provide the most detailed record of changes in slope stability.

Monitoring of AE activity at stabilized sites would be useful for determining the long-term success of corrective actions and could be used to identify local areas within a site that might require additional attention.

Although this study was limited to landslides, AE monitoring can readily be applied to other areas. Tailings dumps, dams, and foundations are a few examples of potentially high-risk structures that can be effectively evaluated with AE monitoring systems.

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