Rock Noise in Landslides and Slope Failures

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•WHEN a rock specimen is placed under load in the laboratory, acoustic disturbances, known as subaudible rock noise (SARN) are emitted. With a sensitive pickup on the specimen and a high grain amplifier, these noises can be detected and, in fact, a number of people have studied rock noises in the laboratory (1-13). An application of this phenomenon is the detection of noises from stressed rock around tunnels and mines as a safety measure in underground work. With the support of the California Department of Highways, the authors have investigated the possible application of rock noise monitoring to landslide and slope stability problems, and discuss their findings in this report.

After constructing and field testing a suitable rock noise detector, a number of recently active landslides and highway cut slope failures in Northern California were monitored to determine whether or not slides emit detectable rock noises. A variety of types and conditions of material were represented in the study, including sheared shale, soft sandstone and claystone, serpentine, peridotite, gabbro, metamorphic rocks, disintegrated granite, volcanic flows, interflow zones of volcanic ash and stream sediments, and ancient slide debris. At each rock noise monitoring location, a preliminary subjective estimate of the state of activity of the slide was made. "Stable" denotes cuts thought to have been in a safe condition at all times; "active" denotes cuts in which there were recent slide scarps or other diagnostic forms of micro-relief, groundwater flowing at springs or drains, and/or recent tension cracks at the surface; "inactive" denotes cuts in which there had obviously once been movements and in which movements might recur, but which appeared to be in a safe state at the time of observation.

There was a definite correlation between the estimated state of activity and the rock noise rate in these slide areas (Table 1). Most of the areas of high noise rate experienced later movements whereas none of the quiet areas did.

INSTRUMENTATION AND PROCEDURE

A rock noise detection instrument consists of a geophone or probe, an amplifier, and a means of monitoring the output signals. Figure 1 shows the 4-channel instrument used in this work. A common power supply operating through a decoupling unit drives 4 high-grain (137 db) low-noise amplifiers which increase the voltage output of the four crystal probes to a sufficient level for recording on magnetic tape.

Drill holes should be provided for rock noise work, particularly in soft rocks and soils. Probes should be placed below the water table, if possible, to increase the coupling with the slide mass. Covering of shallow holes is recommended to exclude air noises.

Our first rock noise detector consisted of a single probe on a relatively short cable, an audio amplifier, and earphones. Although small and lightweight, this instrument had severe shortcomings for quantitative work; batteries lasted only about 15 min, and there was no permanent record of noises observed in the field. We built an instrument package allowing a longer (up to 3 hr) period of monitoring, used greater lengths of cable to allow positioning of probes at depth in drill holes, and recorded the output on magnetic tape.

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TABLE 1

SUMMARY OF ROCK NOISE DATA FROM SOME OF THE NORTHERN CALIFORNIA SLIDE AREAS UNDER STUDY

Location	Description	Initial Estimate of State of Activity	Rock Noises (per min)	Observed Movement Aug. 1963-Aug. 1964
HWY 101 near Arnold	Slide in sheared shale	?	<1	None
HWY 101 near Laytonville	Slump in fault zone, schist	Active	>10	Cracking and bulging about 10-ft net movement
HWY 101 North Laytonville	Slump in gabbro and schist	Inactive	<1	None
HWY 101 near Cummings	Slab slide in sheared shale	Active	>10	No change
HWY 101 - Sylvandale (north of Redway)	Cut for new highway in toe of old slide	Active	>10	About 30-ft net movement
HWY 101 near Miranda	New cut	Stable	<1	
HWY 299 near Weaverville	Rock slide disintegrated granite	Inactive	0	
HWY 99 near Shiloah	Rock falls in altered peridotite	Inactive	0	
Lands End, San Francisco	Creeping landslide in serpentine and serpentine clay	Active	>10	Continuous movement, about 2 in./mo

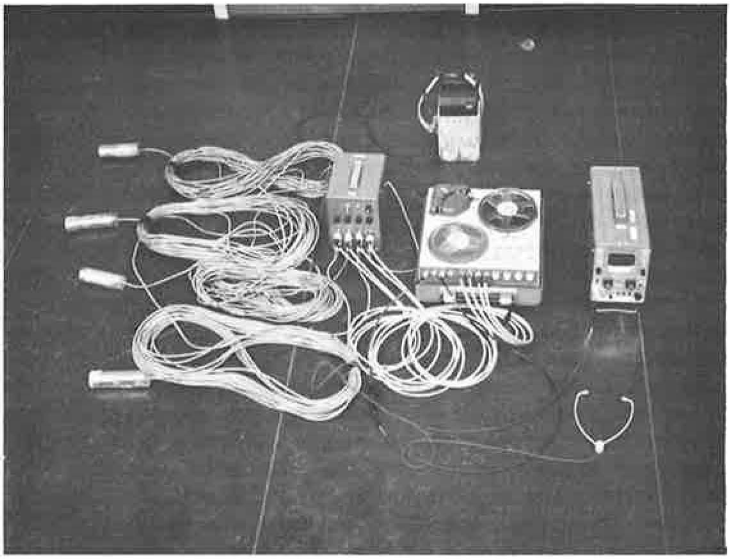

Figure 1. Components of a rock noise detection instrument.

However, a severe limitation was common to both instruments: they consisted of but a single channel.

Single channel rock noise monitoring is satisfactory for monitoring underground work or landslides provided previous work with two or more channels has established the identity of rock noises and allowed their differentiation from extraneous noise. There are many more sources of extraneous noise near the surface in landslides than there are deep underground in hard rock. Proximity to power lines, radio transmitters, wind and weather, traffic, and construction may make a landslide noisy whether or not there is slide movement. Some of these spurious noises are characteristic and distinct but some resemble true rock noises. Field study with a single channel had demonstrated a correlation between noise rate and slide activity. However, until later work was done with more than one channel, it was not possible to say conclusively whether any given noise event had originated in the slide or was instead some extraneous event such as dripping water or raveling of the sides of drill holes. A small noise near a probe can create intense sounds. To determine a true rock noise event, the investigators reasoned that although the raveling grains or water droplets could excite one probe, they could not possibly have enough energy to send a wave through the earth to a second probe situated more than 10 ft away. Moreover, a true rock noise event, as opposed to a demodulated radio signal, could be expected to travel with the velocity of sound in the medium; therefore, unless its source were equidistant from two probes it would arrive at the separated probes at different times.

To ferret out true SARN events from spurious noises, rock noise was recorded on 4 channels simultaneously, with probe spreads of up to 350-ft radius. Generally, the probe locations were suggested by the availability of drill holes. In the field, during recording, two of the four channels were monitored with earphones on one, and, occasionally, observation of the trace of a portable oscilloscope on a second. In the laboratory, the tape was played back through a 4-trace oscilloscope while listening with earphones on one or another of the channels. When an event appeared to be coincident on two or more channels, a written record was obtained using a high-frequency, direct-writing oscillograph. By playing back the tape at half speed and writing with a paper speed of 50 in./sec, time delays of less than 0.2 milliseconds could be resolved.

CHARACTER OF ROCK NOISE EVENTS AND EXTRANEOUS NOISE

Individual rock noises from landslides and slopes typically consist of high-frequency impulses, ranging from 100 to 1,000 cps, followed by several broadening crossovers. Several events may occur at close intervals creating a train of disturbances that may last for $^1/_{10}$ sec or longer. Figure 2 shows a record of a rock noise event. A sudden slippage on a slide during the period of monitoring can create an impulse followed by a damped standing wave if the probe is emplaced in a cased drill hole. Figure 3 shows a record reflecting this type of occurrence.

Earth materials attenuate high-frequency signals in much shorter distances than they attenuate low-frequency signals. Thus, most audio-frequency events are local in origin, originating from within 50 ft of the probe. The attenuation constant of earth materials can be obtained from laboratory experiments on representative samples. However, the frequency range of expectable events cannot be obtained in the laboratory, as the vibration frequency is a system property.

Extraneous noise originating from direct action of wind on the probes sounds like wind and does not complicate rock noise recording. Figure 4a is a record of wind noise. Blowing charges do not cause static because the tubes are shielded. Ground noise generated by blowing trees is of low frequency.

Audio-frequency carrier signals, for example in a telephone line, may create a sustained tone. AC powerlines cause a loud hum which may be filtered out in the laboratory without loss of quality or detail. However, a very strong hum will saturate the amplifier at the gain settings necessary for rock noise recording. A good ground is always necessary.

The crystal probes, even though shielded, will pick up radio signals, especially if monitoring near a radio transmitter. The amplifier, being a nonlinear device, demodulates these signals. There is no confusion with rock noises when the radio message is clear, but when it is garbled or there is static, noises resembling rock noise events may occur. These events may appear on all channels but without measurable delay. At some localities, i.e., in cities at night, the background ratio noise may

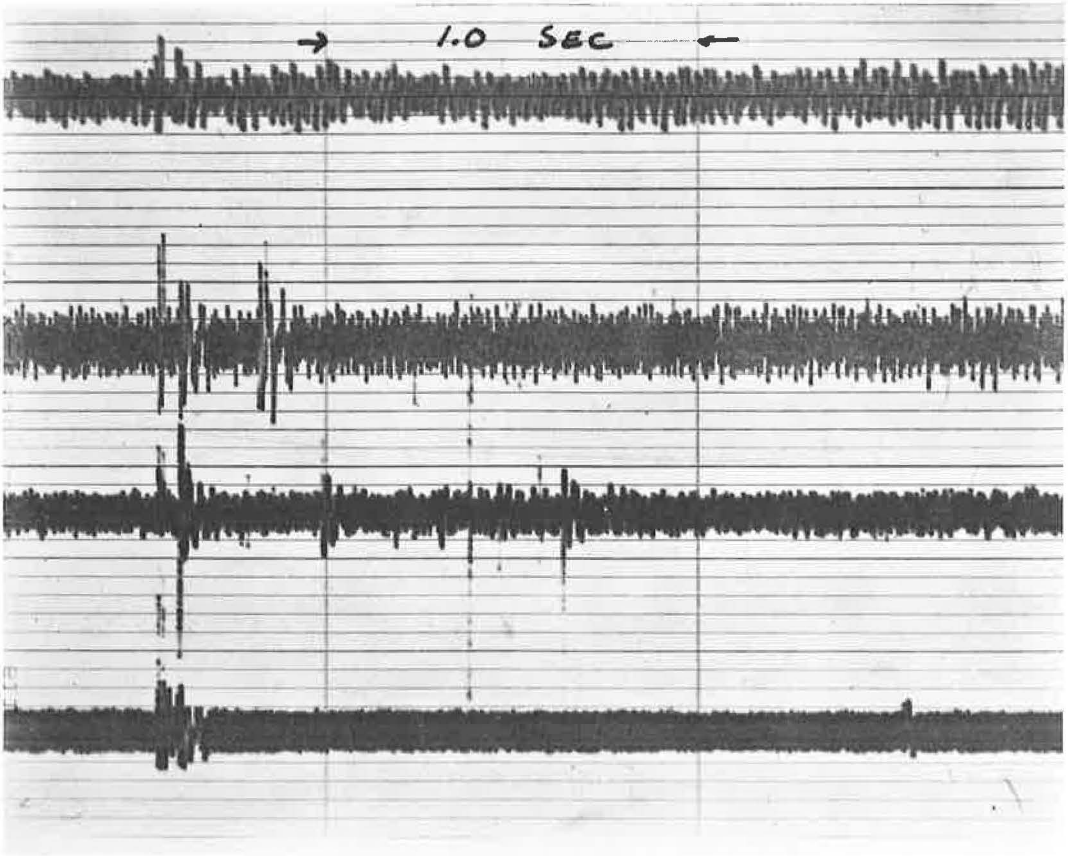

Figure 2. Record of rock noise at Lands End slide.

create a chatter of higher level than rock noise events, effectively blocking the possibility of success in rock noise monitoring.

Talking and traffic noise are recognizable disturbances. Construction activities such as pile driving and percussion drilling do not create difficulties if they are sufficiently distant that the high-frequency portion of their energy input to the ground has been attenuated, i.e., around 500 ft.

Slipping of the probe in the bore hole and raveling of grains onto the probe constitute perhaps the most troublesome sources of extraneous noise in the case of single channel surveys. Even a silt particle causes a sharp snap if it falls onto a probe. Sedimentation on top of a probe positioned below the water table in a drill hole can also cause noise. Intense events lasting $\frac{1}{20}$ sec or longer and appearing only in the channels representing one drill hole were believed to have originated from one of these sources (Fig. 4b). In covered boreholes in hard rock, raveling does not occur.

LOCATION OF ORIGIN OF ROCK NOISE EVENTS

The 4-channel rock noise survey procedure was used because it allowed greater coverage of the slide volume in shorter time, and because receipt of a signal on all four channels makes it theoretically possible to compute the position of the focus of the signal, assuming the medium to be homogeneous.

Let the geophones be positioned at coordinates P_1 (X_1, Y_1, Z_1), P_2 (X_2, Y_2, Z_2), P_3 (X_3, Y_3, Z_3), and P_4 (X_4, Y_4, Z_4), as shown in Figure 5. The wave created by a

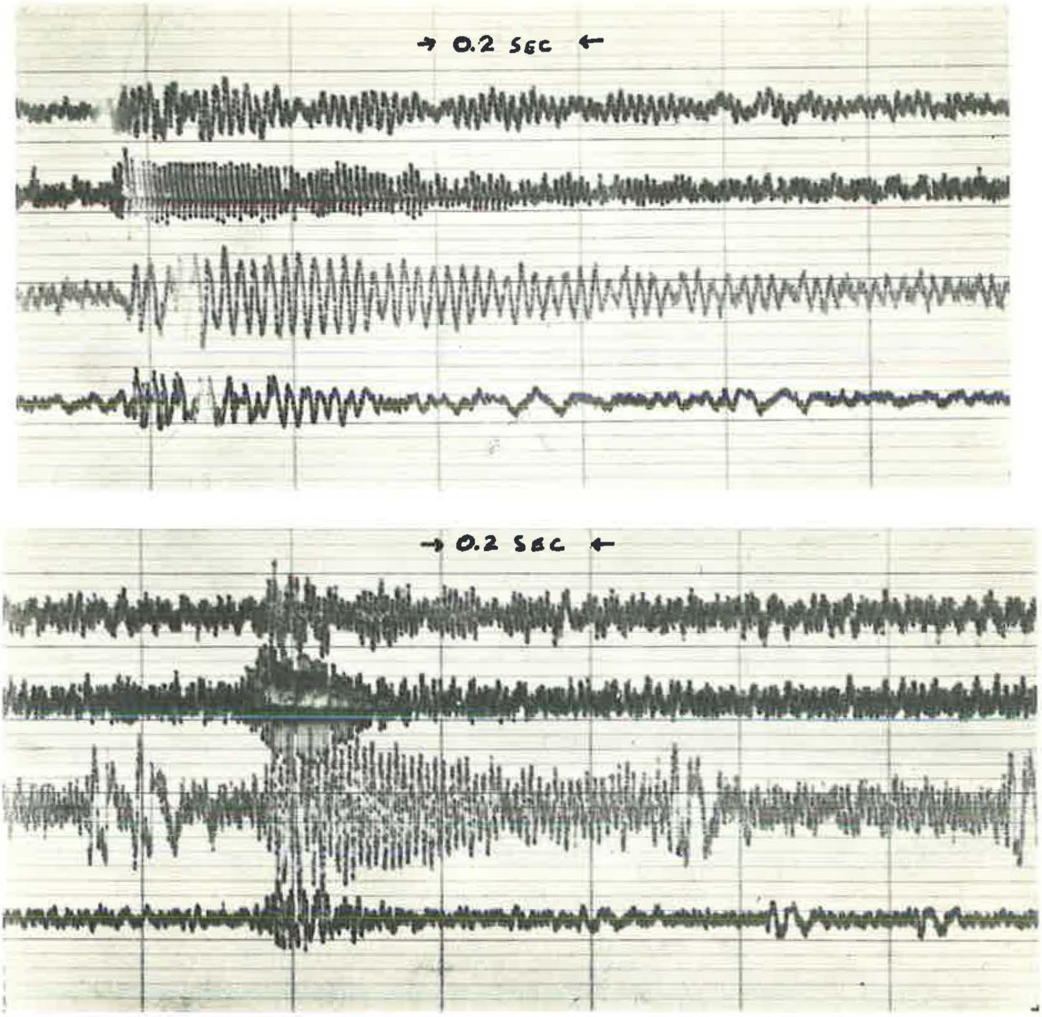

Figure 3. Rock noise records showing sudden slippage on slide.

disturbance at P_o (X_o, Y_o, Z_o) strikes P_1 at time t_1, P_2 at time t_2, P_3 at time t_3, and P_4 at time t_4.

L_1 is the unknown distance from P_o to P_1, and L_{1j} are the differences in focal distances from P_1 and P_j, as shown in Figure 5. If c is the wave velocity in the medium

$$c\,\Delta t_{1j} = L_{1j}$$

$$= \sqrt{(X_j - X_o)^2 + (Y_j - Y_o)^2 + (Z_j - Z_o)^2} - \sqrt{(X_1 - X_o)^2 + (Y_1 - Y_o)^2 + (Z_1 - Z_o)^2}$$

$j = 2, 3, 4$

where Δt_{1j} are the 3 differences in arrival time (delay times) between probe positions 1 and 2, 3, and 4.

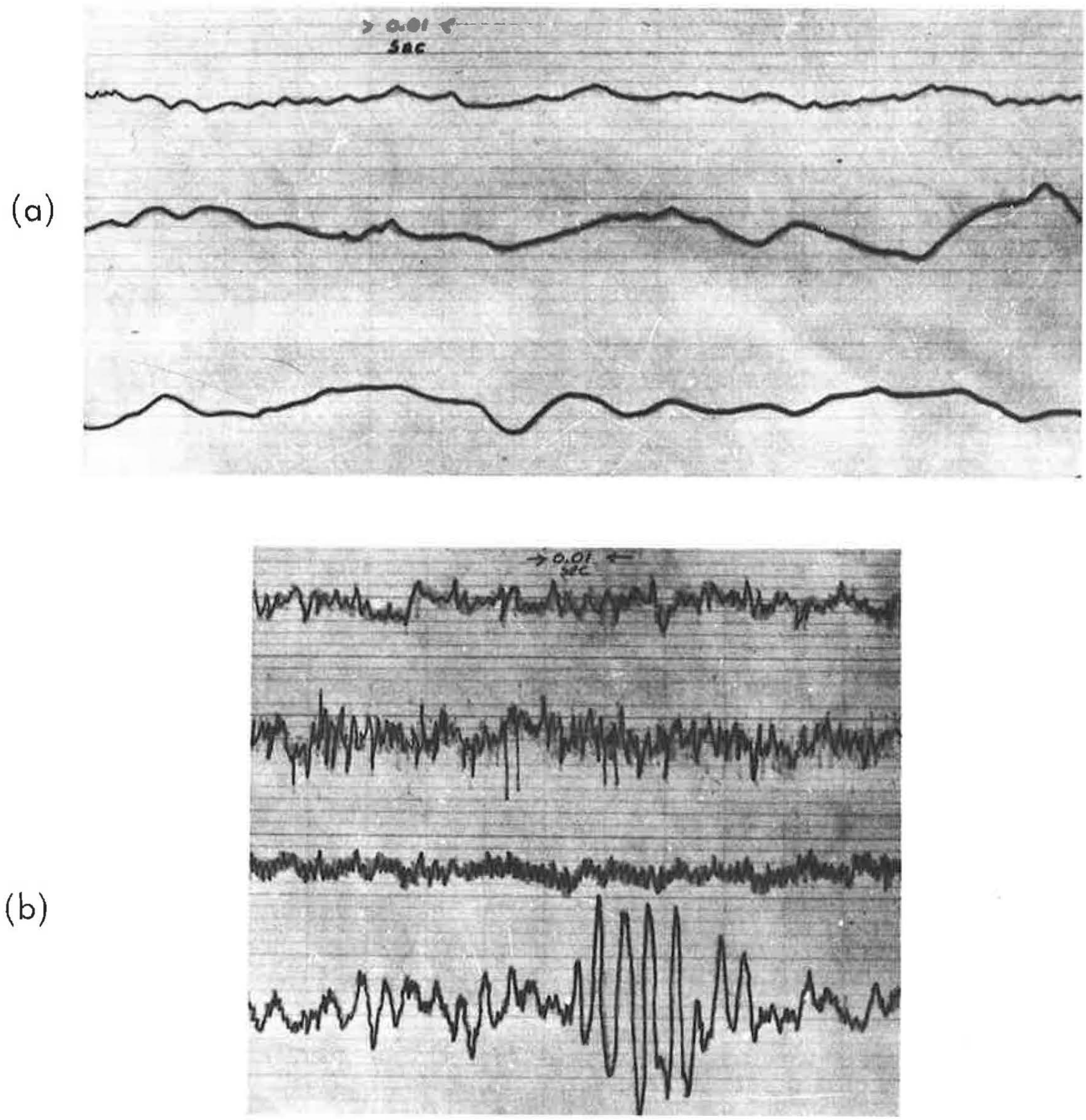

Figure 4. Oscillograph records: (a) wind noise; (b) noise from raveling grains in a borehole.

After simplification and manipulation, these three equations in three unknowns (X_0, Y_0, Z_0) have been solved by iteration on a digital computer.

To check the validity of this method of calculation and the ability of the instrumentation and interpretation techniques to resolve the focus coordinates from actual data, a laboratory experiment was performed. A circular tank 3 ft in diameter and 2 ft high was filled with run of crusher stone and mixed with water to a uniform and essentially homogeneous consistency. Four geophones were placed in the soil and an energy impulse was generated at a known coordinate. The wave velocity was determined from knowledge of the shock time and the first arrival time at any given probe. Figure 6 shows a typical determination of focus coordinates.

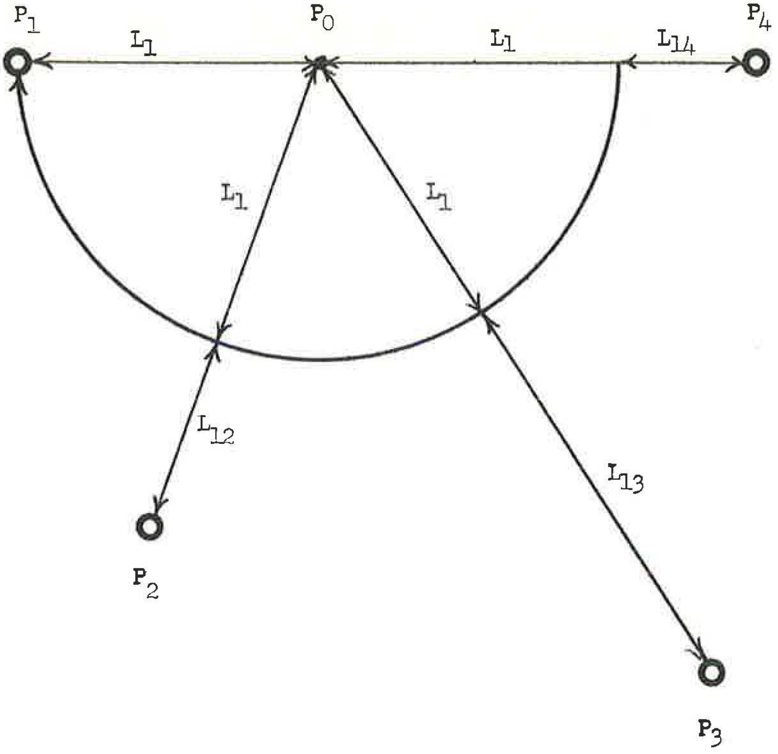

Figure 5. Geometry of delay time analysis.

The first arrival determination was as follows:

$t_0 =$ 2/18 cm × 5 msec/cm = 0.555 msec
$t_1 =$ 3.4/18 cm × 5 msec/cm = 0.943 msec
$t_2 =$ 3.75/18 cm × 5 msec/cm = 1.041 msec
$t_3 =$ 6.9/18 cm × 5 msec/cm = 1.930 msec

The velocity calculations were the following:

6 in./0.555 msec = 10,810 ips
10.1 in./0.943 msec = 10,710 ips
11.25 in./1.041 msec = 10,800 ips
20.9 in./1.930 msec = 10,830 ips

The calculated impulse coordinates (8.852, 0.974, 5.046) were within $^1/_{10}$ in. of the true focus, in which the coordinates were 8.75, 1.00, 5.00.

Despite the success of the laboratory experiment, difficulty was experienced in focus determination in the field. Blast experiments (Fig. 7) with known focus and probe coordinates demonstrated extreme velocity variations and attenuation of the high frequency portion of the blast energy over short distances in slides in soft, clayey materials. In landslide material, a successful focus determination of a natural rock noise event has not yet been accomplished. Instrumental difficulties of one sort or another limited the number of hours of rock noise records successfully obtained on all four channels simultaneously. Rock noise events that were recorded on all channels could not be analyzed because of the effect of casing in the drill holes, or because of velocity differences resulting from the fact that probe emplacements were on either side of the water table or on either side of the slide boundary. Consistent velocities were obtained only in holes all above or all below the ground water table at small separations.

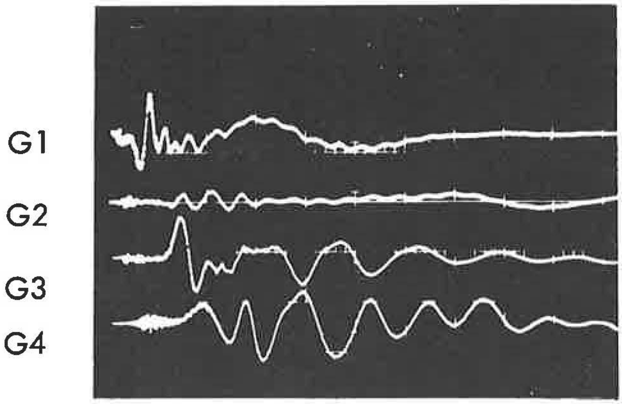

Figure 6. Typical determination of focus coordinates.

Figure 7. Blast experiment at Sylvandale slide.

DISCUSSION OF DATA

Sylvandale Slide

In August 1963, limited rock noise monitoring in a new freeway cut near Sylvandale on Highway 101 showed a very high rate of rock noise activity. Field investigation of the gently sloping hillside above the cut revealed large deep cracks throughout a large region. Subsequently large movements of approximately 30 ft have occurred and the limiting escarpments of a half-elliptical sliding mass roughly 100 ft long and 600 ft in maximum width have become evident. The slide (Fig. 8) appears to be a reactivated region of a large older landslide and is located in a sequence of shales between two ribs of resistant sandstone of the Franciscan Formation.

Considerable corrective work has been performed, most notably flattening of the highway cut slope and installation of drains. There is evidence of continuing minor movements in shear displacements on the latest cut face. However, the upper regions of the slide have shown no evidence of change since December 1963.

Figure 8. Sylvandale slide.

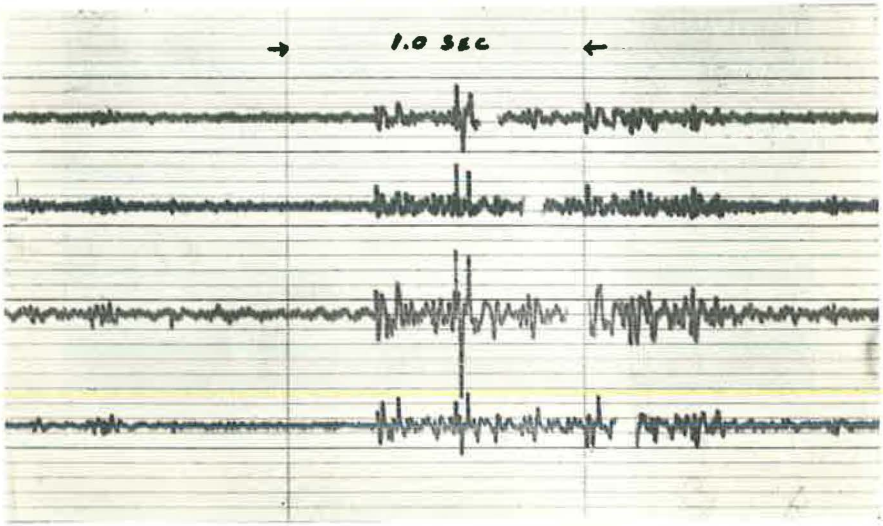

Figure 9. Rock noise record from northern slide extremity at Sylvandale, January 1964.

The slide was monitored a number of times for periods of several hours during the year following its discovery. The upper region of the slide, which now appears inactive, has been quiet since December 1963. Near the top of the cut face, high rock noise rates preceded large movements as the slide spread into previously undisturbed ground (Fig. 9).

Lands End Slide

This slide, located on the Golden Gate at the northwest extremity of San Francisco, has had a long history of activity consisting of intermittent major movements followed by periods of creep (see Fig. 10). The last major movement occurred in 1955.

Figure 10. Lands End slide, April 1964.

The slide is located in sandstone and Franciscan serpentine locally altered to clay. Slope indicators emplaced in the slide, under the direction of H. B. Seed, have shown that creep is presently continuing at a rate of up to ½ in./mo.

Rock noise surveys have been carried out intermittently at Lands End since May 1963. Probes have been positioned at various depths in cased slope indicator holes. The average rock noise rate has remained very high, from 25 to 40 SARN/min. The rate is independent of the duration of monitoring, indicating that in an actively creeping landslide, a 10-min monitoring period is sufficient to determine the rock noise rate. Some of the events were recorded coincidently with delay on two or more channels when spreads of less than 60 ft were employed. When two geophones were placed in a single hole, the majority of events appeared, with suitable delay, on both channels.

Highway Cut in British Columbia

Soon after excavation of the first bench of a large mountainside highway cut, in granite, a continuous crack opened up 300 ft above the highway. Inclined holes several feet long were drilled into the suspected projection of the surface crack and rock noise monitoring was performed in April 1964. This survey showed an extreme rate of rock noise, greater than 40 SARN/min. Subsequent to this survey, new cracks opened, minor rock falls occurred, and the safety of the cut became so questionable that a warning system was installed and continuous watch was initiated. A second rock noise survey, made a month later, showed a noise rate of less than 1 SARN/min, suggesting that the cut had stabilized at least temporarily. Although cracks have continued to open, a major rock fall has not occurred in the three months following this survey.

CONCLUSION

During the two years of this investigation, about 50 hr of rock noise recordings were made and some 15,000 noise events were examined in the laboratory. About 40 separate slides or cuts were monitored. We have reached the following conclusions concerning the applicability of the rock noise method to landslides and cut slopes.

1. There is no question that actively creeping landslides generate detectable audio frequency disturbances.
2. Because of the necessity to distinguish rock noise from extraneous sources of noise, such as raveling of the sides of boreholes, radio static, and telephone messages, a multichannel survey should be performed.
3. Most rock noises received by a probe in a landslide originate within a distance of 100 ft.

4. The rate of attenuation of high-frequency signals and the variation of wave velocities over short distances in soft landslide materials makes it difficult to determine the focus of a rock noise event. In rockslides focus determination is practical.
5. No rock noises have been detected in rock cliffs and steep rock cuts subject to frequent rock falls.
6. Rock noise monitoring does forewarn of accelerated movements in landslides and rockslides.

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