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A technique for utilizing subaudible rock noise (SARN) to measure slope stability has been developed by the California Division of Highways. The technique and the equipment utilized are described and instructions for their application are presented. Several case histories are described to illustrate some of the types of problems to which SARN monitoring can be applied. The Division is planning to perform SARN monitoring as a routine method for stability evaluation and is assembling the necessary equipment.

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RONALD REAGAN, Governor

DEPARTMENT OF TRANSPORTATION
DIVISION OF HIGHWAYS
TRANSPORTATION LABORATORY
5900 FOLSOM BLVD., SACRAMENTO 95819

August 1973
Final Report
TL 632537
D-5-2

Mr. R. J. Datel
State Highway Engineer

Dear Sir:

Submitted herewith is a research report titled:

SUBAUDIBLE ROCK NOISE (SARN) AS A

MEASURE OF SLOPE STABILITY

Thomas Hoover
Co-Investigator

Ronald Mearns, E.G.
Principal Investigator

Supervised by

Marvin L. McCauley, E.G.

Very truly yours,

JOHN L. BEATON
Laboratory Director

Attachment

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The authors would like to acknowledge the work of Dr. R. E. Goodman and Mr. Wilson Blake, of the University of California, in completing the first phase of this study.

Several people of the California Division of Highways, Transportation Laboratory, were instrumental in the acquiring of field data. Special thanks is extended to them for their patience and help.

This is the final report of research covering a 7-year period from 1965 to 1972. This research was done in cooperation with the U. S. Department of Transportation (Federal Program No. HPR-1(8)D-5-2).

The contents of this report reflect the views of the Transportation Laboratory which is resonsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.



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# INTRODUCTION

It has long been known that audible sounds emitted by rock in underground mines and tunnels often precede some sort of failure of the rock. The sounds are caused by stressing of the rock and consist of pops and snaps.

Miners often referred to the occurrence of these noises as "talking rocks". It was not unusual for them to refuse to work in a mine or tunnel if there was too much "rock talk". The U. S. Bureau of Mines began a study of this phenomenon in 1937. In 1941 and 1942, the Bureau reported that audible noises were preceded and accompanied by subaudible sounds which could be used to locate areas of stressed rock that might be hazardous. This technique has become a commonly used safety precaution in underground workings.

In 1962, the Materials and Research Department of the California Division of Highways and the University of California at Berkeley started a two-phase cooperative research project on the technique.

The first phase was conducted by the University. Its purpose was to develop equipment and a technique which would permit detection of subaudible rock noise (SARN) at locations on the earth's surface and to determine if ground surface SARN was related to stability of the slope. Progress reports were published in 1963, 1964, and 1965. The conclusions arrived at in Phase 1 were:

1. SARN, which can be detected and analyzed, is present at the ground surface;

2. The SARN rate is higher for active landslide areas than in stable areas.

These conclusions are in agreement with the 1942, U. S. Bureau of Mines Report.

The second phase of the cooperative study was performed by the Transportation Laboratory (Materials and Research Department prior to July 1, 1973). It consisted of testing the applicability of SARN rates to highway problems and evaluating the SARN equipment developed by the University of California. The relocation of Highway 152 around the San Luis Reservoir was selected for this portion of the study. Several cuts were monitored for SARN rates during construction, and also during and after the following rainy season.



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The conclusions of the second phase were:

1. The SARN rate reflects the stability of the immediate area;

2. The SARN rate increases as the stability decreases;

3. The equipment developed by the University required modification to improve the signal to noise ratio.

4. Better field techniques were required.

The results of this cooperative study were sufficiently encouraging to warrant further development of the SARN method for monitoring slope stability. At this time continuation of the research was undertaken by the Transportation Laboratory.

This continuation involved the development of more sophisticated and more reliable SARN techniques as well as updating of the equipment utilized. This was accomplished by laboratory testing and the field monitoring of numerous geologically different areas with potential instability.



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## CONCLUSIONS AND RECOMMENDATIONS

The experience gained through equipment development and the data observed and analyzed both in the case histories included with this report and in ongoing projects indicate that subaudible rock noise (SARN) is directly related to instability.

SARN rates do not appear to be absolute measurements of activity, but rather provide a qualitative evaluation of stability, i.e., increases or decreases in SARN rates reflect decreases or increases in stability.

Given a site history and a SARN rate indicative of stability for the site, properly trained personnel can evaluate site stability by monitoring, and give a subjective decision as to the probability of failure at some time following the monitoring.

There is evidence that stability changes can be detected by SARN Monitoring up to several weeks in advance of other forms of monitoring. Additional experience with this phenomenon should lead to further applications of SARN monitoring.

Care must be exercised in selecting and training personnel to make such evaluations. Proper equipment for monitoring is also mandatory.

Based on the experience and knowledge gained during this research, further use of SARN monitoring as a means of slope stability evaluation is recommended. Because these decisions are subjective rather than absolute, it is also recommended that only experienced personnel be utilized for stability evaluations.



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## IMPLEMENTATION

Because of the number and variety of pieces of specialized equipment required to successfully conduct a SARN monitoring program, it appears that offering it as a service of the Transportation Laboratory is the most practical method of implementation. The time required to select and train a qualified operator and to keep him readily available would be a problem at the District level.

To effect this proposed service, the Transportation Laboratory has obtained the necessary equipment to perform on site multichannel SARN monitoring. This equipment has been permanently installed in a mobile laboratory and is continuously available. In addition to this capability, three sets of equipment for single channel SARN monitoring are in service.

There are five trained and experienced employees of the Transportation Laboratory available for directing or conducting SARN monitoring programs. Three of these employees are capable of training additional operators.

This service has already been utilized by Districts 04, 05, 07, 08, and 11, Ventura County, U. S. Bureau of Reclamation, U. S. Geological Survey, and the U. S. Forest Service for specific problems. SARN has also been used as a monitoring technique on other research projects.



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## OPERATORS

A good operator must have some knowledge of electronics in order to operate, test and maintain the equipment. In addition to an interest in electronics, he must be able to devote his full attention for extended periods of time to the sounds coming from the amplifier. He should possess no hearing defects, particularly in frequency response.

To perform a satisfactory job of monitoring, a trained operator must be there to schedule the monitoring in order to obtain the necessary backgound noise rates for him to make judgments about stability conditions.



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## EQUIPMENT

Equipment used by the Division of Highways for the detection, amplification, recording and analysis of SARN consisted of sets of components or systems. While there was some interchange of components between systems for experiments, for actual field work, the systems were left as originally established.

Three different systems have been developed during this research project. System 1 was the system developed by the University of California at Berkeley. System 2 was assembled from commercially available electronic equipment by personnel of the California Division of Highways in order to overcome some of the problems encountered with System 1; and System 3 utilizes commercially available SARN equipment which is the easiest to use and most versatile of all the systems. The SARN amplifier used in System 3 did not become available until after System 2 had been developed and used.

The various components of each of the systems are listed in Appendix 1. Also included in Appendix 1 are photographs of each component and some notes describing the equipment. Detailed specifications for the components can best be obtained by contacting the manufacturers or their sales representatives.

Each of the systems described were fully tested both as components and as systems. The frequency response, signal to noise ratio, sensitivity and adequacy as field instruments were determined in extensive laboratory and field tests.

Frequency response and signal to noise ratio measurements were accomplished simultaneously. A signal of known amplitude and frequency from a signal generator was fed to the component or system and the output was evaluated on an oscilloscope with the results tabulated for later comparisons.

Sensitivity and practicality were also evaluated at the same time. This was done while testing the sensitivity in various materials including sand, granitic, metamorphic and sedimentary rocks. At the same time the field capabilities and convenience factors were subjectively evaluated by those persons who would be required to use the equipment in the future.

The sensitivity was evaluated by first burying all of the types of transducers together. Subsequently, noises at measured distances from the microphones were generated. The noise was that of a drop hammer striking a stake which had been driven into the ground. By using this noise and increasing the distance from the noise to the microphones each system or combination



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of systems could be compared to the others. While this test has obvious limitations, it does permit comparative evaluation of the systems and allows a selection of components with optimum performance characteristics.

In assembling the systems described here, certain preliminary assumptions and decisions concerning the conduct of the study were necessary.

Several methods of detecting the noises in the ground are available such as accelerometers, geophones, or microphones. Since the University of California had elected to use microphones and work with audio frequency signals it was decided to retain that procedure for the entire project. The University also used an operator at the monitoring site as opposed to a telemetered system. This procedure was also adopted. This decision meant selecting lightweight, battery powered components so that the operator could move the necessary equipment onto the listening site.

A third and more limiting decision involved the taping of field data for laboratory analysis on strip chart recordings. Since the earlier University work used this method, it was believed expedient to continue in the same way. The poor noise characteristics of portable tape recorders, the inability of operators to obtain accurate field SARN rates because of the intensity and nature of the outputs of the amplifiers, and the time lag involved in making the laboratory analysis are just some of the problems resulting from this approach.

The SARN rate used by the University was obtained by playing the field tape back through a strip chart recorder and physically counting those events that were 5 times the amplitude of the background noise. The factor of 5 was arbitrary and based on a highly variable background noise level which was generated by both the amplifier and the tape recorder.

The background noise in System 2 was much more stable and resulted in the capability of counting noises only 2 times the amplitude of the background. This improvement also enabled the operator to obtain a field SARN rate by counting the noises he could hear.

Another method of obtaining a SARN rate while in the field was to feed the amplifier output to an oscilloscope and have the operator visually count the events just as he would on a strip chart recording. This method appears to be generally satisfactory. The amplitude factor, however, has to be estimated in a very short time so it may be somewhat less accurate than the laboratory method.



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A means of obtaining a SARN rate in the field has been tested and proven successful. It involves System 3, eliminates the tape recorder and feeds the amplifier output directly into a battery powered strip chart recorder. This system shows tremendous potential and is being incorporated into the system now being assembled for use throughout the state.

One other procedure that has been followed in this study of SARN is based on a need for a broad frequency band system. The exact nature of the origin of the noises was not investigated and a literature search has not turned up a completely satisfactory explanation that is applicable to all the conditions under which we have been able to detect SARN. It seems most probable that the SARN phenomenon represents a number of noise making mechanisms. It is known that the sound transmission characteristics of different materials are highly variable. The degree of saturation of the material also affects the sound transmission characteristics. In order to overcome the uncertainty of the frequency range of the original sound and to assure detection of the SARN in spite of the effect of the transmitting media, the University decided to use as wide a frequency band as could be obtained. Analysis of data obtained by the Transportation Laboratory indicates that the frequency of detected SARN ranges from about 30 to about 3000 Hz. Most SARN analyzed was between 140 and 1400 Hz. Although these measurements may be influenced by the frequency response characteristics of the detecting system, they do indicate the general range of SARN frequencies encountered in this study.

System 1

For this system, a barium titanate crystal, cantilever mounted, in a lucite housing was used as a transducer. A three-stage tube type amplifier with very high gain capabilities was constructed for use with the above described transducer. The amplifier output was recorded on a single-channel battery powered tape recorder.

The problems encountered with this system were numerous and varied. Although the transducer was sensitive and durable, it was hand machined and thus expensive. It was found that radio frequency interference was being detected either within the housing or the connecting cable which necessitated the installation of shielding. The amplifier was microphonic, so that it could pick up and amplify noises without their being detected first by the transducer. Because of design deficiencies, the amplifier also had feedback between stages that resulted in a high level of internally generated electronic noise. Rearrangement of internal components and installation of shielding did much to reduce this problem.



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The power requirements of the amplifier were high and external high voltage high capacity batteries were required. Although these problems were alleviated, it was concluded that the system was not a practical field tool.

System 2

This system resulted from experimentation with various commercially available electronic components.

Three types of transducers were tried: a rochelle salt contact microphone, a hydrophone, and a hydrophone with a built-in preamplifier. The contact microphone was clearly the most sensitive and was the smallest. The rochelle salt crystal was fragile, would melt and was water soluable. It was thus necessary to transport them in insulated, padded boxes and to waterproof them. The low price more than compensated for these disadvantages so that this microphone was adopted as the main transducer for System 2. The hydrophones worked satisfactorily only when submerged in water, a condition not always attainable. The preamplified hydrophone demonstrated the usefulness of preamplification. It was possible to use up to 1000 feet of cable without significant loss of signal strength and without reducing the signal to noise ratio. The desirability of this feature is obvious since it permits monitoring of an active landslide without endangering the operator or the remainder of the equipment. It also could be used in very deep borings since it was designed to withstand the high hydrostatic pressures.

Two types of amplifiers were tried; a sound level meter and a charge amplifier. These work on different principles and so are described separately.

The sound level meter is a standard noise level measuring device consisting of a high gain low noise amplifier with built-in frequency filters and a very accurate stepped attenuator. For our purpose, only the amplifier was used. No attempt was made to measure or interpret the significance of the signal amplitude. No problems were encountered in using this equipment in the field. It eventually was used as the basis for System 2.

The charge amplifier detects and amplifies a change in potential. In laboratory tests it proved very sensitive, had very low noise and excellent fidelity. However, when used in the field, it frequently did not detect noises that the other systems were recording. A literature review and discussions with electronics engineers resulted in the conclusion that charge amplifiers will not function properly at very low signal strengths. The use of charge amplifiers has been discontinued and no future experimentation is anticipated.



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A two channel battery powered tape recorder was selected for recording the amplifier output. A number of recorders were considered but only one stereophonic battery powered recorder was available. The frequency range of this recorder is more limited than any of the other components; it does introduce some noise onto the tape and it has a limited battery life especially in very low or very high temperatures. The reason the stereophonic recorder was considered essential was the need to simultaneously record and play back SARN from two separate transducers. Some work by the University indicates that it may be possible to locate the source of SARN by analysis of data from two transducers.

System 3

System 3 resulted from the introduction of commercially available equipment designed specifically for SARN monitoring.

The transducers are small, lightweight, waterproof and durable. They contain preamplifiers with the attendant advantages previously described. The amplifiers generate low internal noise and impart very high amplification to the input signal. They operate from internal rechargeable batteries which also power the preamplifiers in the transducers. Electronic filters built into the system can be used if necessary or desirable for selecting the frequency to be monitored.

The output of these amplifiers can be tape recorded or visually evaluated on an oscilloscope or both. The previously mentioned direct strip chart recording in the field is also available to permit on-site evaluations.

Ongoing monitoring of current projects is being conducted with System 3 and extensive use of this system is anticipated in the future. The only real problem with this system has been an occasional loss of function of the transducers. Several reasons for these failures have been discovered and include cracking of the housing, water in the preamplifier or the cable, and breaking of wires in the cables or connectors. The manufacturer is currently modifying the design of the transducer. It is believed that fewer failures will occur in the future and that repairs will be more readily effected.



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## PROCEDURES

The operating instructions for performing SARN monitoring are presented in Appendix 2.

Instructions for operating both the single channel portable equipment (System 2) and the multichannel equipment (System 3) are included.

System 3 is the most versatile and dependable and will be the basis for the SARN monitoring service. System 2 was retained to permit monitoring of sites not accessible to the mobile laboratory.

The same laboratory procedures apply to both systems and are also described in Appendix 2.



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## SARN MONITORING

To conduct a successful SARN monitoring program, it is necessary to have a clear understanding of the exact nature of the problem and a clearly defined goal to be achieved by the monitoring.

SARN monitoring has been used for hazard evaluation, evaluation of stability conditions, construction control, evaluation of landslide correction measures and location of zones of activity. Examples of each of these are described in the case histories included in Appendix 3.

The above list does not represent all possible uses of SARN monitoring nor is it intended to suggest that SARN monitoring is the only or best way of attaining a given objective.

The use of SARN monitoring is limited by the presence of extraneous noise from various sources. Such noise can give erroneously high noise rates or can mask entirely the desired noises. Intense rainfall, jet airplanes, highway traffic, ocean tides, thermal expansion or contraction of the rock, heavy construction equipment or trains, movement of vegetation caused by wind, and the activity of insects and mammals have all caused problems in the interpretation of data.

In order to monitor SARN, it is essential that the transducers be properly located. The factors to consider in selecting monitoring sites include location of the slide, type of material, groundwater conditions, landslide structure and accessibility.

All SARN monitoring to date has been set up by engineering geologists experienced in landslide studies. The planned SARN monitoring service of the Transportation Laboratory will be under the direction of an engineering geologist.

In a series of tests to determine the distance over which an artificially induced SARN noise could be detected, the following observations were made. The maximum distance was 120 feet and was obtained in moist disintegrated granite. The minimum distance was 28 feet in dry loose sand. Hard, unweathered rock itself was a good sound transmitter but, because it was highly jointed at our test site, did not carry the sound as far. It is therefore necessary that the moisture conditions, the soil or rock type and the most likely location of the noise source be known in order to select the most favorable location for the transducer.

Using System 3, it is possible to place several transducers to assure that some of them will be in favorable locations. In order to avoid interference from airborne noise, it is desirable



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to place the transducers in borings a minimum of 15 feet deep. Where borings are not available, the transducers must be placed in intimate contact with in-place material and buried as deeply as is practical.

In monitoring several active landslides, it has been found that the SARN rate increases sooner and attains higher values near the head of the slide than at the toe. Apparently tension generates more detectable SARN than compression.

The noise rates of active slides have been determined and range from as low as 3 or 4 to rates too high to be counted using the visual system. The rate appears to be generally related to the degree of activity. However, no quantitative relationships have been detected. It has therefore been necessary to determine a background rate for each problem individually and then monitor for significant changes in that rate.

To determine a background rate it is necessary to determine seasonal and diurnal variations as well as the time distribution of SARN for the particular landslide. Although there are some areas where sounds are generated at a constant rate, it is much more common for them to occur in groups or bursts. These bursts may last a few seconds to a few minutes depending on the degree of activity. The length of monitoring time required to establish a SARN rate can be established from the above information. It has been found that in areas of actual movement a meaningful rate can be established with five minutes of monitoring. In most areas where movement is not occurring 15 minutes of monitoring has proven adequate. However, the monitoring period and interval between are variable and must be determined for each location. The validity and usefulness of the monitoring program are based on this determination so only skilled and experienced operators should be used for this work.

Some spectral analysis of SARN has been performed, and frequencies between 30 and 3000 Hz have been detected. Both compressional and shear wave vibrations have been detected. In agreement with seismic theory, it appears that high frequencies are attenuated as the distance from the source increases. It is possible to subjectively estimate the proximity of the noise source to the transducer by the tone of the sound. For given material and moisture conditions, it may be possible to arrive at an objective distance by performing spectral analysis of the sounds. The research necessary to accomplish this has not been performed.

Work by the University of California and the U. S. Bureau of Mines indicates that the source of the SARN can be located if the noise can be detected and identified by several geophones. This technique was not thoroughly studied as part of this project



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for several reasons. Most masses of unstable soil and rock are heterogeneous and anisotropic so that no reliable way of obtaining a meaningful velocity for the various frequency of sound waves being generated was found. In active areas it was impossible to identify which sound correlated to which on the various records. Obtaining time differences of milliseconds appeared to be more accurate than the tape transport speed of the tape recorder. Finally, with the equipment available at the time of this study, it was possible to only tape record two sites at a time which is not enough to pinpoint a noise source. Correlating data from more than one of the types of tape recorders used proved too difficult. Tape transport speeds at the time of recording was not necessarily the same as at the time of playback, nor was the speed of one recorder the same as another. Starting the two recorders at exactly the same time also proved impractical.

The tape recording speed used for SARN monitoring was uniformly 1-7/8 inches per second. This was adopted as the standard because it was the only speed available on the original tape recorder. Use of this speed was continued even with the more versatile tape recorders in order to reduce the number of variables requiring consideration in this research.

Although some fidelity is lost at this slower speed, it was assumed that all significant SARN events would still be detected. Two field experiments with simultaneous recording at different tape speeds verified this assumption. Higher tape speeds are planned for future monitoring to achieve better fidelity. Analysis of high fidelity recordings should provide additional useful information.

Various playback speeds were tested in making laboratory strip chart recordings. A speed of 7-1/2 inches per second was selected because it had the best measured signal to noise ratio on the strip chart records. The variations in signal to noise ratios result primarily from variations of frequency response in tape recorders, tapes amplifiers, and galvanometers.

A portion of a typical strip chart recording is shown in Plate 1. There are two simultaneous records shown. The dark bands are the background noise and the periodic spikes are SARN. The signals that exceed twice the width of the background are counted as SARN. The strip chart recording shown represents approximately 1 minute and the SARN rate was determined to be 8 per minute.



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PLATE 1 - SARN Strip Chart Recording



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# APPENDIX 1

## Equipment

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SYSTEM 1

Equipment List

1. University of California Microphone
2. University of California Amplifier
3. Norelco Tape Recorder
4. Honewell Visicorder Model 906B

System 1 Field Equipment

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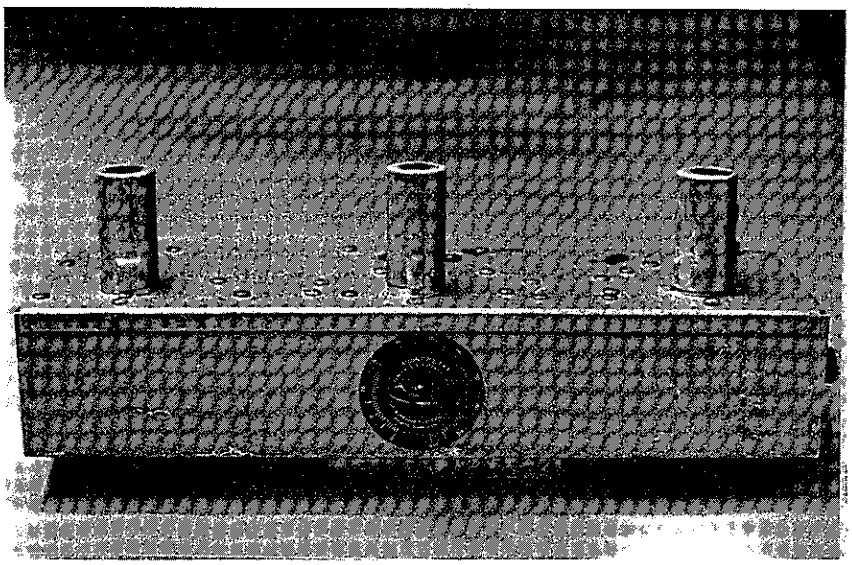

University of California Amplifier
A specially designed and constructed, tube type, amplifier.
SIZE: approximately 5 x 5 x 16 inches
FREQUENCY RESPONSE: 140-700 Hz
LIMITATIONS: A narrow frequency response, extremely microphonic to airborne noises, requires an external power supply.
COST: unknown

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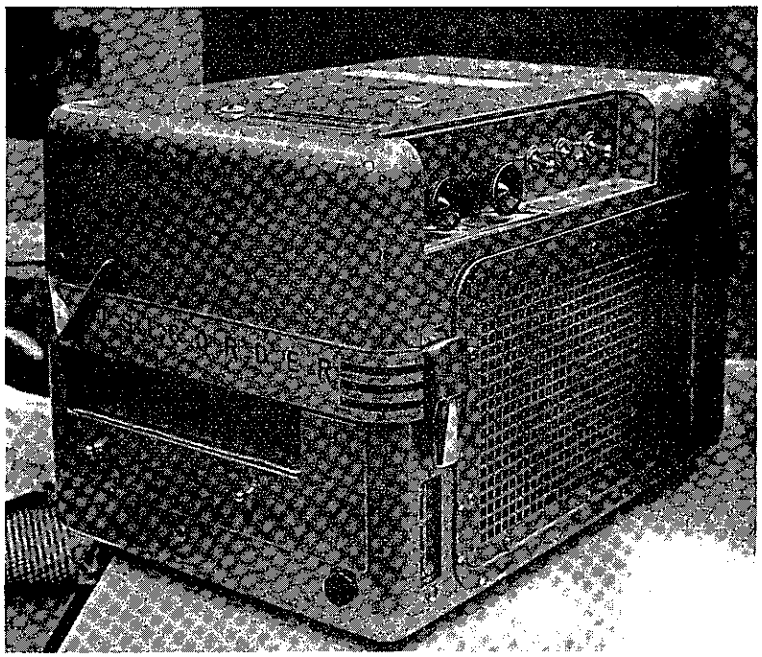

Honeywell Visicorder Model 906B
SIZE: 14" x 10" x 9-1/2"
FREQUENCY RESPONSE: 0-2,000 Hz
LIMITATIONS: Must be used in Laboratory
COST: $3,900

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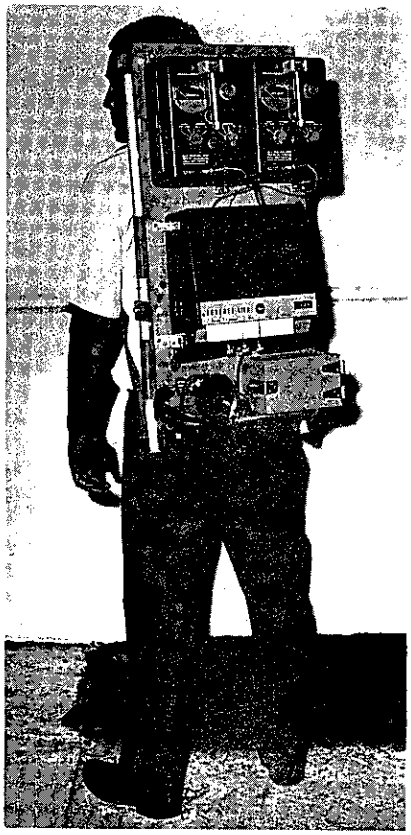
SYSTEM 2

Equipment List

1. Electrovoice Contact Microphone Model 805
2. Atlantic Research Hydrophone LC-50
3. Chesapeake Preamplified Hydrophone PC-101A
4. General Radio Sound Level Meter Type 1551-C
5. Kistler Charge Amplifier Model 504M21
6. Roberts Tape Recorder Model 6000
7. Clevite-Brush Lightbeam Oscillograph Mark 2300
8. Hewlett-Packard Data Amplifier Model 2470A



System 2 Field Equipment Mounted on a Pack Frame

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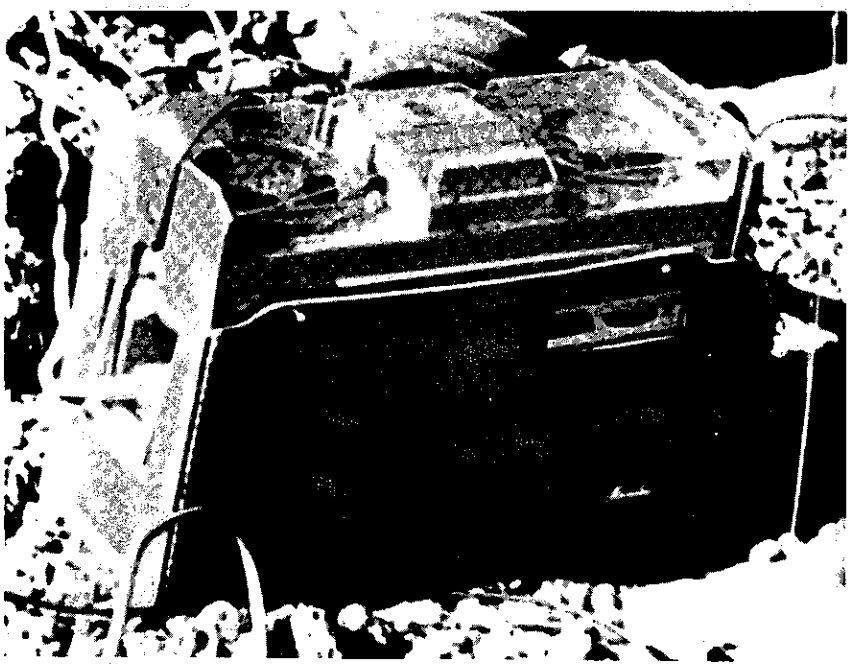

Norelco Tape Recorder
A portable battery operated tape recorder (no longer available).
SIZE: approximately 12" x 9" x 4-1/2"
FREQUENCY RESPONSE: 100-6,000 Hz
LIMITATIONS: Single-Speed 1-7/8 rps and narrow frequency response.
COST: approximately $90

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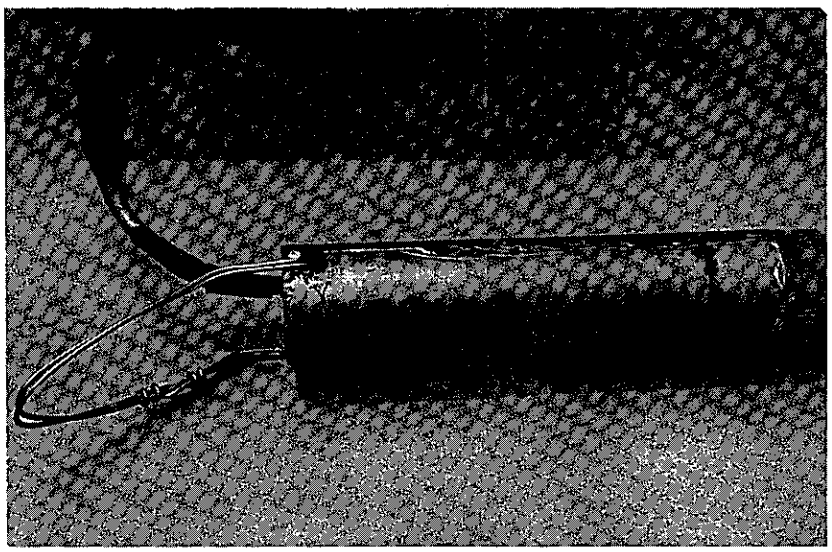

University of California microphone
A barium titanate ceramic disc mounted on
a cantilever enclosed in a lucite case.
Note brass shielding.
SIZE: approximately 1-1/2" Diameter 6" long
FREQUENCY RESPONSE: 20-20,000 Hz
LIMITATIONS: Must be handmade
COST: Approximately $500

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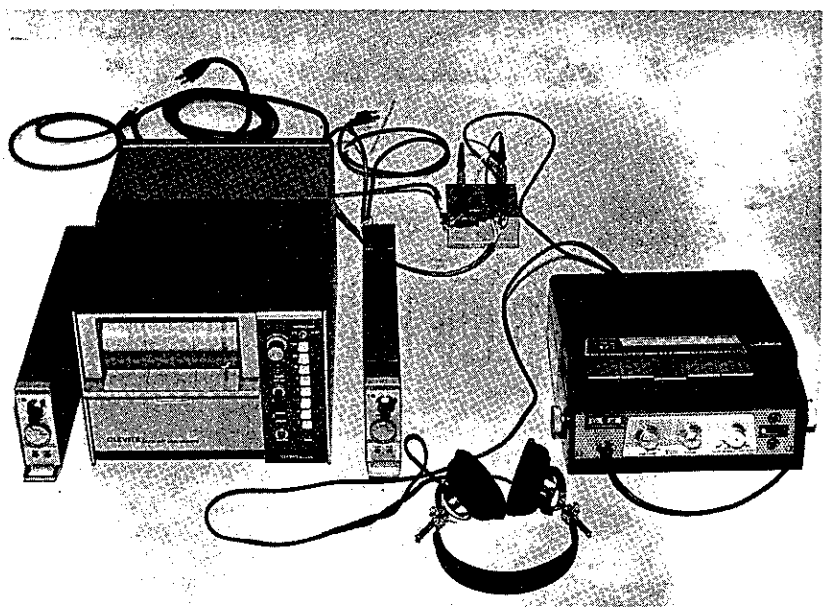

System 2  Laboratory Equipment

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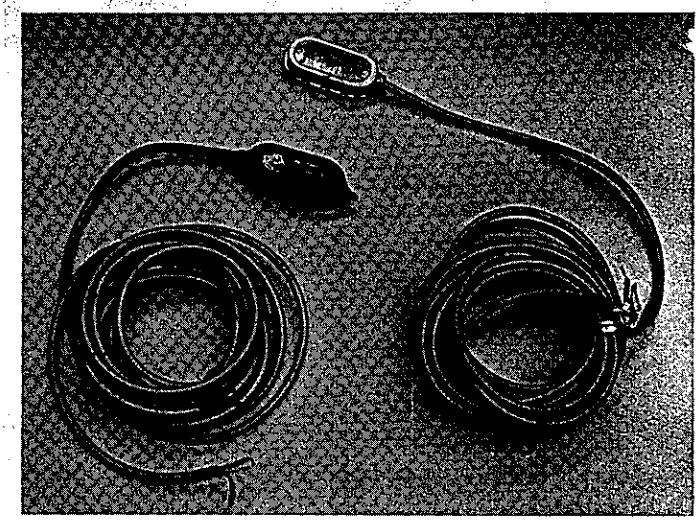

Electro Voice Model 805 Contact Microphone
A rochelle salt crystal mounted on a cantilever in a zinc case.
SIZE: approximately 2-1/4" x 1-1/16" x 1/2"
FREQUENCY RESPONSE: 20-10,000 Hz
LIMITATIONS: Must be water sealed, crystal melts at high temperature (over 110°F).
COST: $13.00

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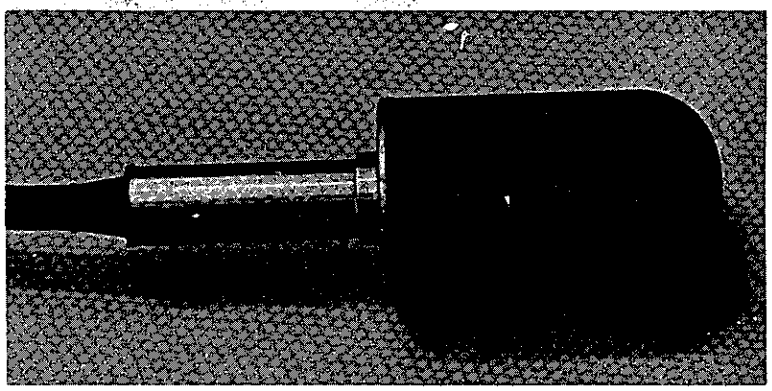

Atlantic Research Corporation Model LC-50
Hydrophone
A piezoelectric transducer, it generates a signal with pressure changes using lead-zirconate titanate as the sensing element.
SIZE: approximately 1-3/4" diameter 5" long
FREQUENCY RESPONSE: 0.1-5,000 Hz
LIMITATIONS: Usable for SARN less than 5,000 Hz
COST: $300.00

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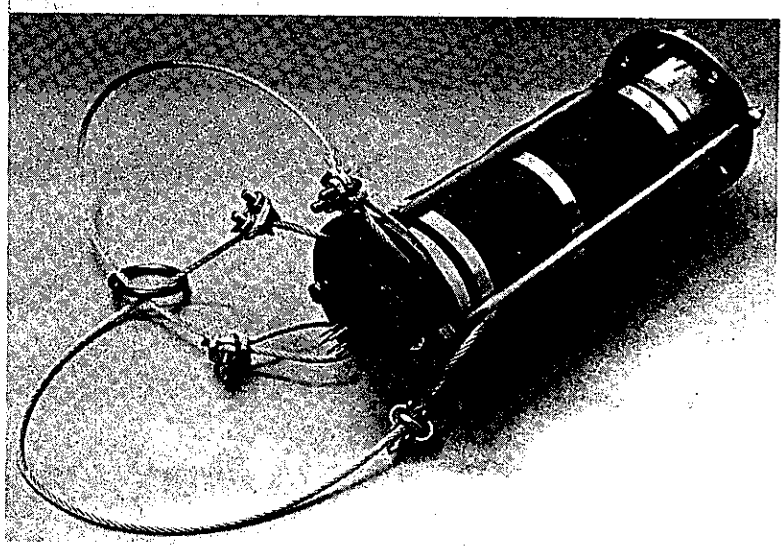

Chesapeake Model PC-101A Preamplified Hydrophone
A preamplified lead-zirconate titanate piezo-electric transducer.
SIZE: approximately 3" diameter 12" long
FREQUENCY RESPONE: 2-3,000 Hz
LIMITATIONS: It must be fluid coupled. (Suspended in water.) It also requires an external power source.
COST: $895.00

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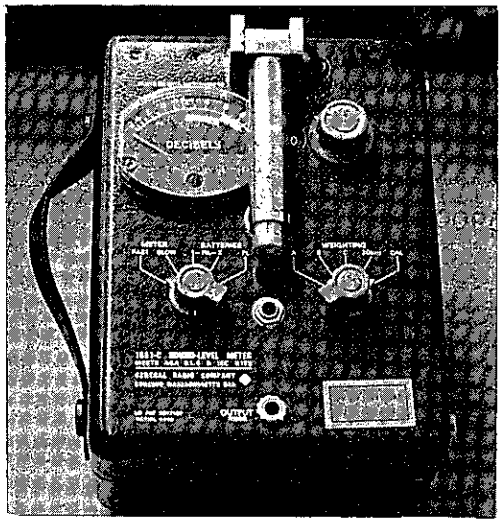


General Radio Company Sound Level Meter -
Model 1551-C9703
A tube type high gain amplifier.
SIZE: approximately 7-1/4" x 9-1/4" x 6-1/8"
FREQUENCY RESPONSE: 20-20,000 Hz
LIMITATIONS: Requires warm-up time.
COST: $600.00

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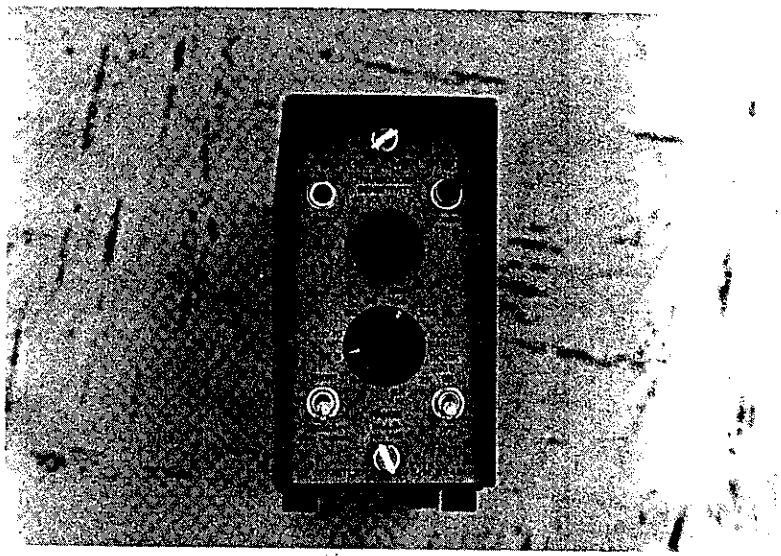

Kistler, Charge Amplifier - Model 5532
A solid state charge amplifier.
SIZE: approximately 3" x 6" x 9"
FREQUENCY RESPONSE: 50-100,000 Hz
LIMITATIONS: Charge amplifiers are not acceptable for low amplitude signals.
COST: $662.00

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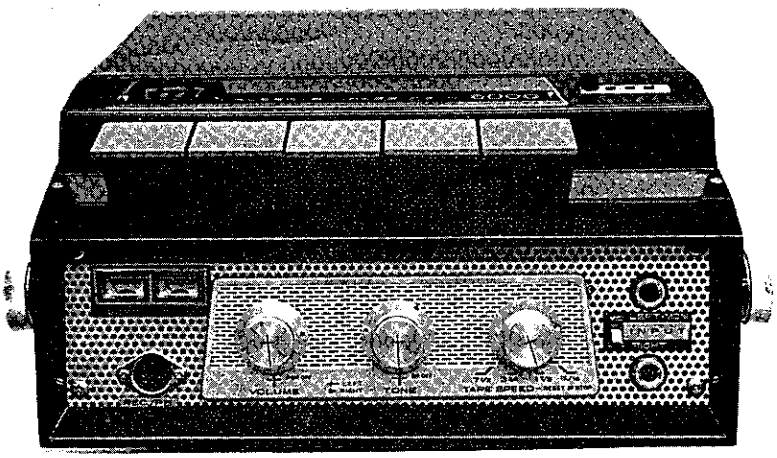

Roberts Model 6000S Tape Recorder
A battery-operated stereo tape recorder using cross field recording.
SIZE: approximately 5" x 11" x 12"
FREQUENCY RESPONSE: 20-7,000 Hz
LIMITATIONS: Must be battery operated to eliminate 60-cycle pulses, is only 2 channel.
COST: $375

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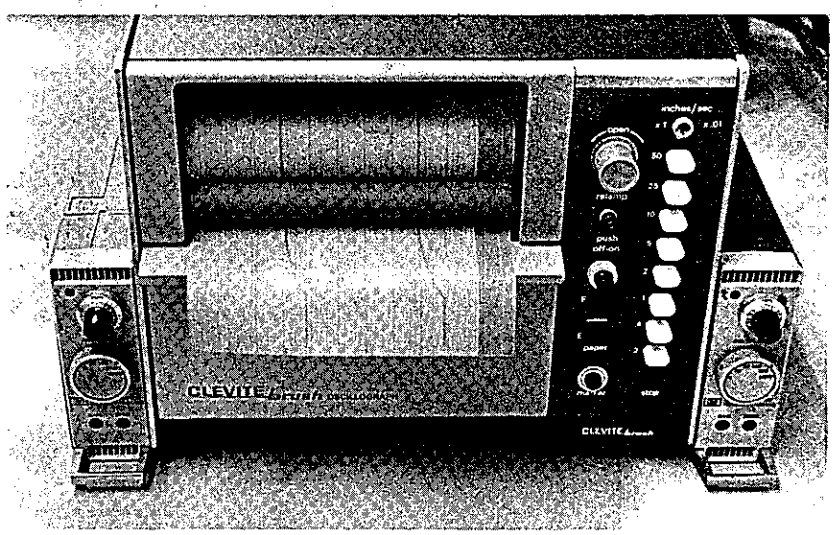


Clevite Brush Model 16-2300-00 Oscillograph Recorder
An 8-channel oscillograph
SIZE: approximately 19" x 11" x 9"
FREQUENCY RESPONSE: 2-6,000 Hz using 5,000 cps galvanometers.
LIMITATIONS: Must be used in Laboratory.
COST: $2,405

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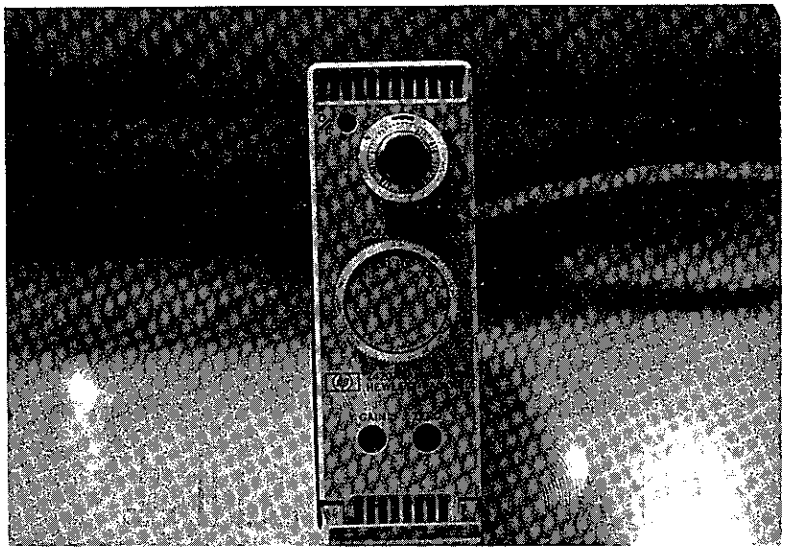

Hewlett-Packard Model 2470A High-Gain Data Amplifier
A high-gain differential amplifier for reliable amplification of low-level noises.
SIZE: approximately 15" x 5" x 1-1/2"
FREQUENCY RESPONSE: 0-20,000 Hz
LIMITATIONS: None
COST: $810

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SYSTEM 3

Equipment List

1. Geo-Recon Transducers
2. Geo-Recon Geo-Monitor MS-1
3. Geo-Recon Geo-Monitor MS-2
4. Roberts Tape Recorder Model 610X
5. Honeywell Visicorder Oscillograph Model 2206

System 3 Field Equipment

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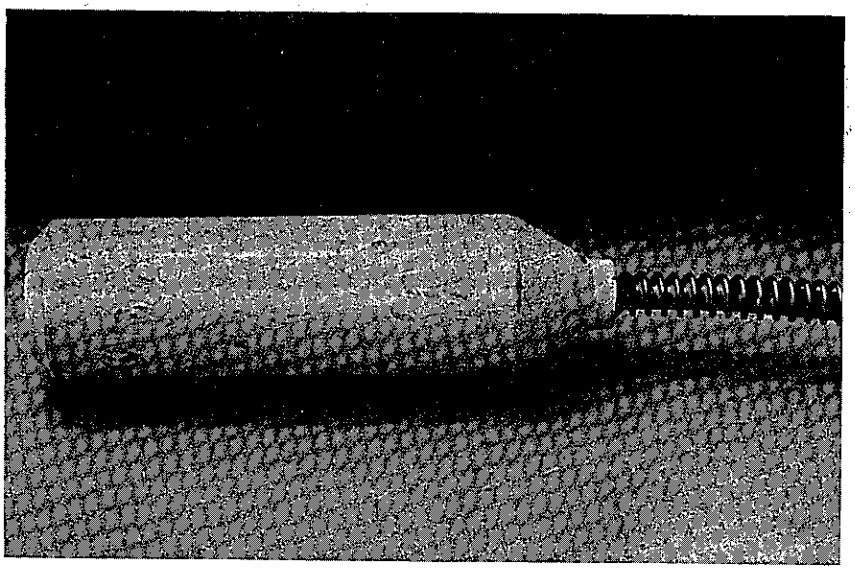

Geo-Recon Preamplified Transducer
A lead zirconate titanate ceramic transducer in a solid casing.
SIZE: approximately 1-3/4" diamter 6" long
FREQUENCY RESPONSE: 4-40,000 Hz
LIMITATIONS: Fairly large size.
COST: $320.00

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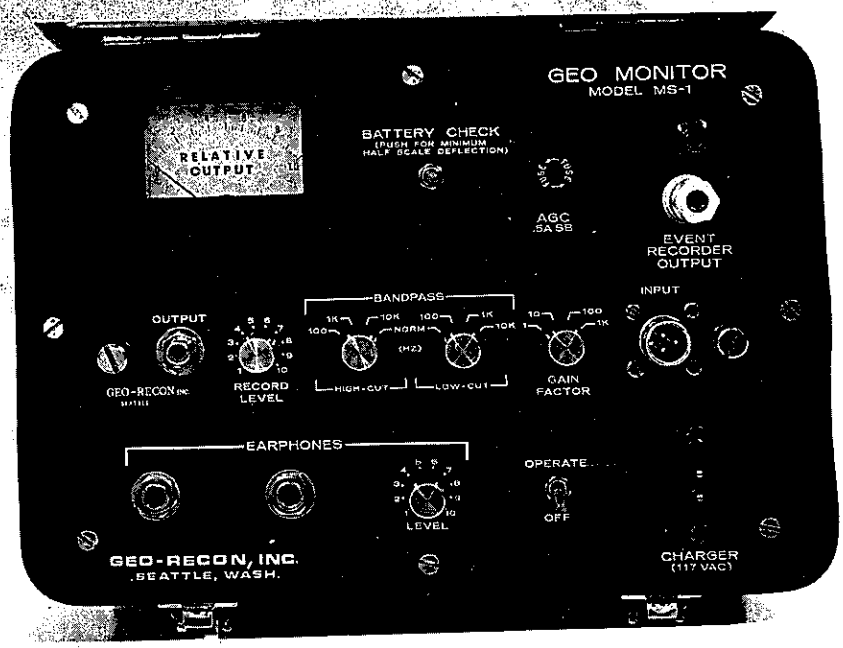


Geo-Recon Noise Monitor Amplifier -
Model MS-1
A solid state high-gain amplifier.
SIZE: approximately 10" x 8" x 7"
FREQUENCY RESPONSE: 4-40,000 Hz
LIMITATIONS: Single channel does not allow stereo recordings, poor fidelity.
COST: $995

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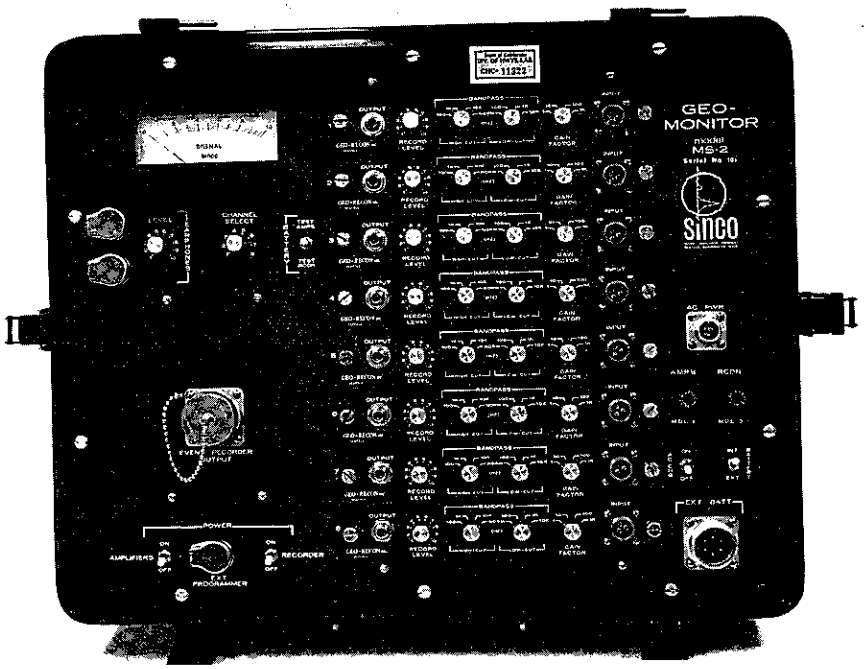


Geo-Recon Model MS-2 Noise Monitor
Amplifier System
An 8-channel, solid state noise monitoring system.
SIZE: approximately 20" x 9" x 16"
FREQUENCY RESPONSE: 4-40,000 Hz
LIMITATIONS: Poor fidelity, not readily portable.
COST: $5,140

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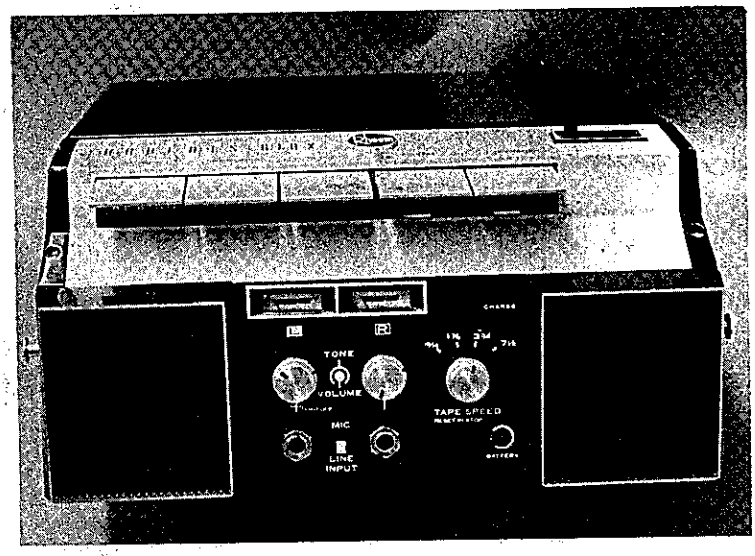


Roberts Model 610X Tape Recorder
SIZE: approximately 5" x 11" x 12"
FREQUENCY RESPONSE: 20-7,000 Hz
LIMITATIONS: Must be battery operated to eliminate 60-cycle pulses, is only 2 channels.
COST: $227

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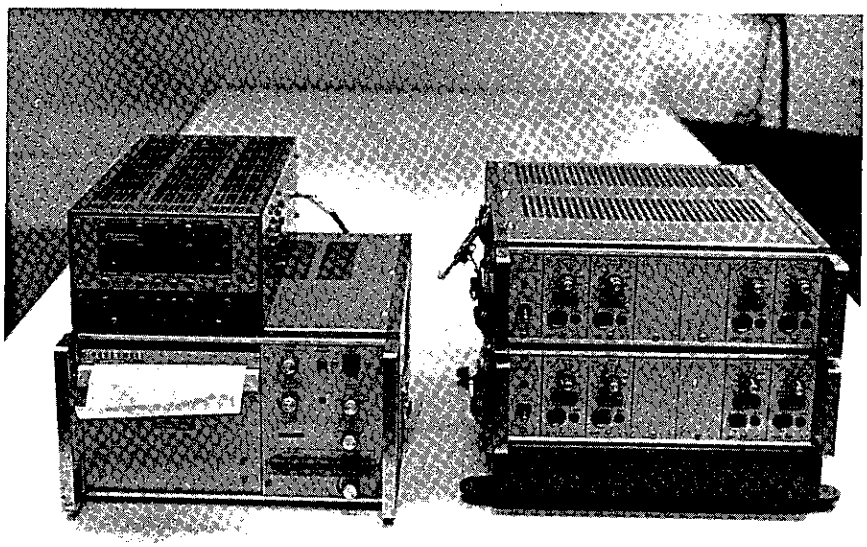

Honeywell Model SN.2-262-AFC
Visicorder System
A portable oscillogrpah amplifier system.
SIZE: approximately 13" x 20" x 21"
FREQUENCY RESPONSE: 0-13,000 Hz
LIMITATIONS: Very high power requirements.
COST: $4,352

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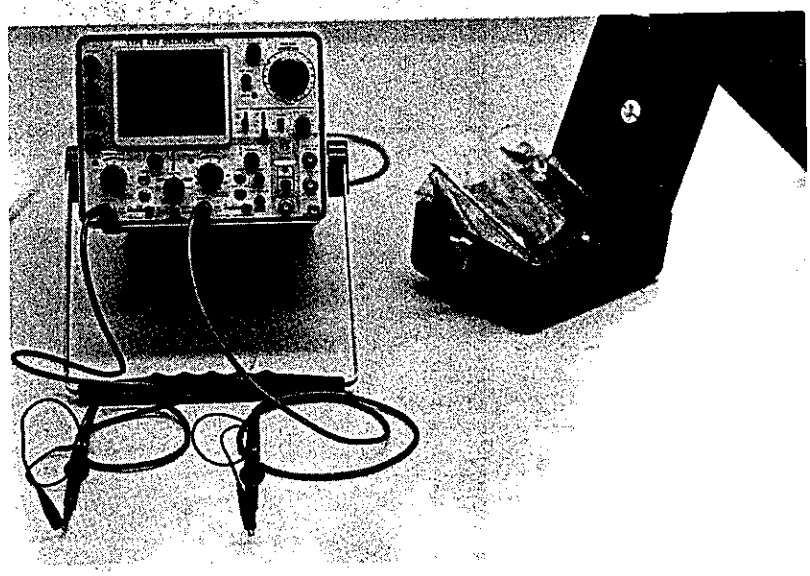
# MISCELLANEOUS EQUIPMENT

Equipment List

1. Tektronix Oscilloscope Type 422
2. Earphones



Tektronix Model 422 Dual Trace Oscilloscope
A portable oscilloscope with two input channels.
SIZE: approximately 7" x 7" x 14"
FREQUENCY RESPONSE: 0-15,000,000 Hz
LIMITATIONS: Only two channels.
COST: $2,050

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# APPENDIX 2

## Procedures

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SARN FIELD PROCEDURE
SYSTEM 2

I. Set-up and Procedure for Audible Monitoring

A. Microphones - The microphone should be placed at least 15 minutes before starting a recording. They should be insulated as much as possible to avoid airborne noises. Contact with the ground should be as intimate as possible to obtain the best noise transfer. Immersion in water or mud is desirable, but dry con-act is suitable if the microphone is firmly held in place against the rock or soil.

B. Amplifiers - Connect the microphones to the amplifiers and the power supply (if necessary) and allow the amplifier to warm up for at least one minute. Monitor the location to make sure everything is working properly and that the gains on the amplifier are adjusted satisfactorily.

C. Audible monitoring is now performed by counting the SARN. This requires training and experience.

II. Set-up and Procedure for Taped Monitoring

A. Tape Recorder - Set record speed at 1-7/8. Introduce recording onto the tape - location, date, amplifier(s) used, gain settings and which track of the tape. Connect to amplifier (make sure voice microphone is disconnected) and with record switch down, set recording level to minimize deflection of needle by back-ground noise.

B. Start tape recorder and record for 15 minutes (use stop watch if possible) or any desired length of record. (15 minutes is usually sufficient.)

C. If possible, monitor continuously, either by listening or by watching the record level meter or the meter on the ampli-fier. Any malfunctions can thus be detected and corrected with a minimum time loss.

D. Keep all components and connectors dry and as clean as possible to prevent malfunctions.

E. Unless absolutely necessary, do not adjust the gains on either the amplifier or the tape recorder while making a recording.

F. Be sure tape recorder batteries are fully charged and keep spare set available.

G. Be sure tape heads are clean at all times.

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SARN FIELD PROCEDURE
SYSTEM 3

I. Set-up and Procedure for Audible Monitoring

A. Transducers - The transducer(s) should be placed at least 15 minutes before starting a recording. This generally permits the ground disturbed by placing the transducer to return to predisturbance SARN rates. They should be insulated as much as possible to avoid airborne noises. Contact with the ground should be as intimate as possible to obtain the best noise transfer. Immersion in water or mud is desirable, but dry contact is suitable if the transducer is firmly held in place against the rock or soil.

B. Amplifiers - Connect the transducer(s) to the amplifier(s) and allow the amplifier(s) to warm up for at least one minute. Monitor each channel to make sure everything is working properly and that the gains and filters on the amplifier(s) are adjusted satisfactorily.

C. Audible monitoring is now performed by counting the SARN.

II. Set-up and Procedure for Taped Monitoring

A. Tape Recorder - Set record speed at 1-7/8. Verbally identify recording on the tape - location, date, amplifier(s) used, gain settings and which track of the tape. Connect to amplifier (make sure voice microphone is disconnected) and with record switch down, set recording level to minimize deflection of needle by background noise.

B. Start tape recorder and record for 15 minutes (use stopwatch if possible) or any desired length of record. (15 minutes is usually sufficient.)

C. If possible, monitor continuously, either by listening or watching the record level meter or the meter on the amplifier. Any malfunctions can thus be detected and corrected with a minimum time loss.

D. Keep all components and connectors as dry and clean as possible to prevent malfunctions.

E. Unless absolutely necessary, do not adjust the gains on either the amplifier or the tape recorder while making a recording.

F. Be sure tape recorder and amplifier batteries are fully charged and keep spare set available.

G. Be sure tape heads are clean at all times.

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SARN LABORATORY PROCEDURE
FOR SYSTEMS 2 and 3
Visual Record Evaluation

I. Equipment List

A. Brush Oscillograph Recorder
B. Hewlett-Packard 2470A amplifier(s)
C. DuPont Lino-writ 7W spec 2 paper
D. "Junction Box"
E. Connector cable(s) between amplifier(s) and "Junction Box"
F. Connector cable(s) between amplifiers and Brush Recorder
G. Tape Recorder
H. Connector cable between tape recorder and "Junction Box"
I. Galvanometers for Brush Recorder -100 Hz and 5,000 Hz

II. Set-up

A. Amplifiers
1. Connect hook-up cable to back of amplifier
2. Plug in power cable
3. Connect input cable to color coded output of "Junction Box"
a. Connect shielding to ground
4. Connect output cable to input of Brush Oscillographic Recorder

B. Brush Recorder
1. Make sure input is connected to proper galvanometer
2. Plug into power supply
3. Check paper to be sure there is enough to complete the recordings

C. Tape Recorder

1. Check condition of batteries to assure adequate charge. Four to five hours of playing time will run the battery down and overnight charging is required. Flashlight batteries can be used but their life is very short. Under no conditions should external power be used for playback because it generates unacceptable electronic noise.

2. Connect output of tape recorder to input on "Junction Box".

III. Operation

A. Set potentiometers on "Junction Box" to full open

B. Turn on amplifier(s) and Brush Recorder and allow a 30-minute warm-up time.

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C. Check galvonometer alignment

D. Check tape recorder playback speed setting - 7-1/2 ips

E. Set tape recorder gains to provide galvanometer deflections. This is not a critical adjustment.

F. Find the start of the recording on the tape and set the tape counter to 000. This will permit easy location of the start of each recording.

G. Play the tape and adjust the amplifier gains until the deflections of the galvanometers caused by the background noise are about equal. This adjustment should be carefully done. The tape recorder gain should then be carefully adjusted so that the background noise band width measured on the strip chart recording will be about one-tenth of an inch. Minor adjustments may be needed at the start of each recording.

H. Rewind the tape to the beginning. (000 on counter)

I. Turn on the Brush Recorder by pushing the proper paper speed button, usually 0.4 ips. At the start of a run, allow about six inches of paper to run out so that fresh photosensitive paper is being used. Then start the tape recorder and make visual records.

J. On the back of the paper record the following information:

1. Location, recording date, amplifier(s) used, gain settings and which track if more than one. Also record tape speed, paper speed and which galvanometer was used.

2. After completing the playback, note the counter reading for future reference.

K. Using proportional dividers, count any signals with twice the amplitude of the background (2:1 signal to noise ratio). The resulting number divided by the length of recording in minutes is the counts per minute. (SARN rate)

Strange shaped peaks or abnormal background traces should be explained if possible by listening to the tape recording. Any unidentifiable or unexplainable peaks should be disregarded.

L. Laboratory playbacks should be made and interpreted by the operator who did the field work as soon as possible after the field work has been completed. Any deviation from this condition has been found to reduce the value of the data.

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# APPENDIX 3

## Case Histories

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# CASE HISTORIES

The following case histories are examples of the types of problems to which SARN has been applied. These examples were selected as being typical.

A general description of the problem and the SARN study are included as well as the results. Details of these and other studies can be obtained by contacting the authors.

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CASE HISTORY #1
ROCKY CREEK

In March of 1970 a section of the ocean bluff adjacent to California Highway 1 collapsed as the result of undercutting by surf action. The south abutment of a 38 year old concrete arch bridge was located immediately outside the head of the slide. Cracks were found within a few feet of the structure foundations and the approach fill to the abutment settled several inches.

Since this is the only reasonable access to approximately 100 miles of coast between Carmel and Morro Bay, and the tourist season was just beginning, it was necessary to determine immediately the hazard involved in continued use of the bridge and its south approach.

Monitoring locations were selected in the slide mass, in various fractures at the head of the slide, and adjacent to the foundation of the structure. The monitoring was started within four days of the original slide and the initial SARN rates were sufficiently high to warrant concern. Around the clock monitoring was started and it was immediately observed that the SARN rate increased gradually as the tide came in and that at the time the tide began dropping the SARN rate decreased suddenly. Based on this observation, it was decided to only monitor the incoming tide cycles. After two days the noise rate became regularly lower and at the end of two weeks had stabilized. Monitoring was terminated at that time.

Based on the decreasing SARN rate and the lack of noise in the structure foundation, it was decided that the structure had not been distrubed and that the remainder of the slope including the bridge approach had stabilized. The road was repaired and kept open with no further problems. To assure future stability, a sea wall was built to protect the toe of the slope.

System 2 equipment was used to perform this monitoring.

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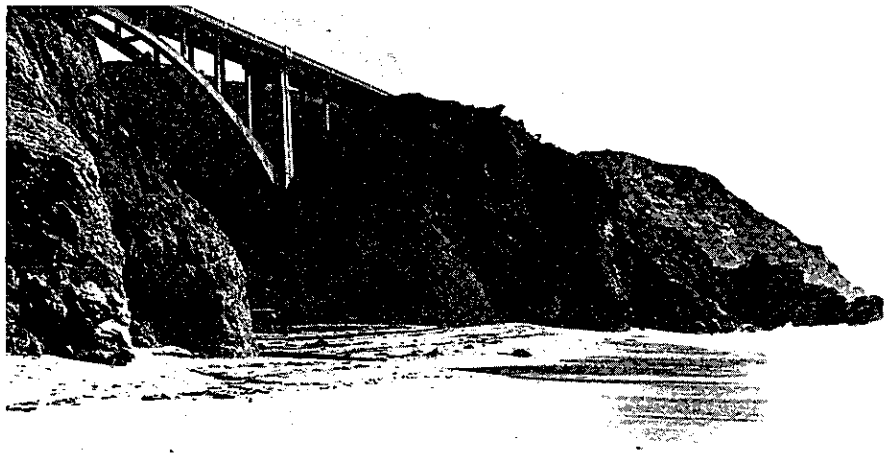
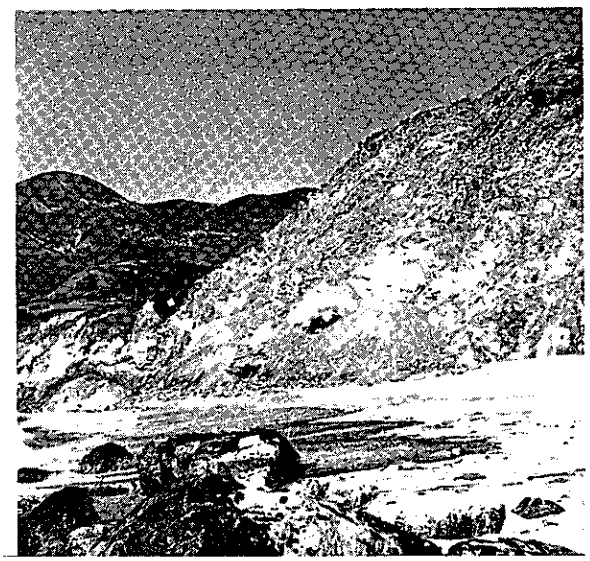


Rocky Creek Bridge



Landslide

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Cracks at Head
of Landslide

Cracks in Pavement
of South Bridge Approach

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CASE HISTORY #2
ANDERSON GRADE

The construction of deep cuts always increases the possibility of failures which might be predicted or detected if monitored for SARN. The location of Interstate 5 near Yreka, in Siskiyou County, necessitated the construction of five cuts over 100 feet deep in sheared, foliated, and fractured, fined grained metamorphic rock, thus presenting the Transportation Laboratory the opportunity to monitor stability conditions.

Monitoring was begun in March 1968, prior to construction to establish a SARN rate indicative of stable slopes for the area. The first records were obtained in original ground. As construction progressed, the listening locations were moved to the uppermost bench on the cut face.

The slopes were monitored at approximate one month intervals throughout the life of the construction contract and for a few months following.

SARN rates indicated that stable conditions existed. No major failures occurred on any of the monitored cut slopes.

A small failure involving the edge of a bench did occur in one cut slope. It was near a monitoring site and the noise rates at that time were 1.1, 3.3, 2.2, and 1.5 events per minute.

The failure occurred sometime between the 3.3 and the 2.2 readings. It is believed that had readings been taken in that interval a clear pattern of increasing SARN would have preceded the failure.

The failure to clearly detect a problem at this location appears to have been the result of too long an interval between monitoring periods. Jobs subsequently have been monitored at various intervals, from several times per day up to a maximum of two weeks. The interval between monitoring is now determined on each project individually after considering background noise rates, importance of results and cost.

System 2 was used to monitor this project.

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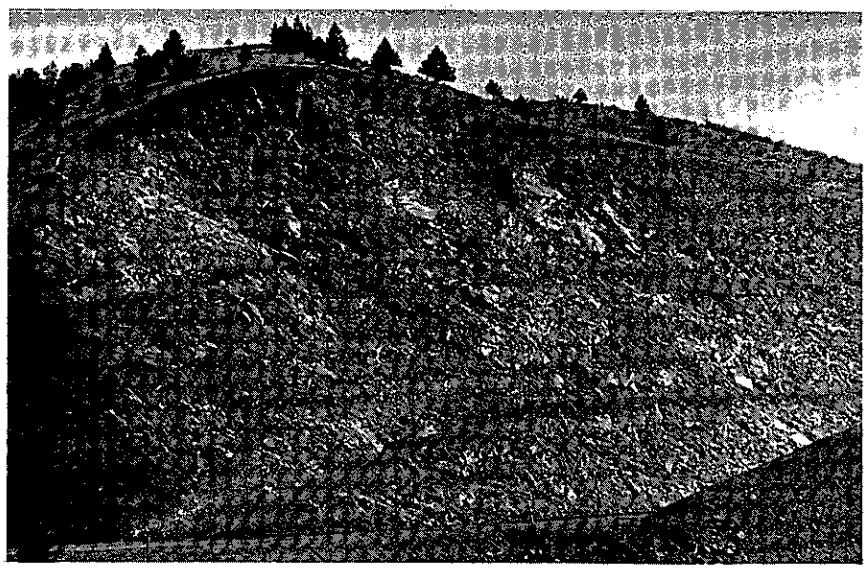

Sta. 778 Typical Cut Slope

Sta. 810 Cut Slope where small
Failure occurred.

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## CASE HISTORY #3
## VENTURA

An example of the use of SARN as a construction control tool occurred on a project for Ventura County.

A relatively small landslide had developed below a county road and had begun to cause roadway displacement. This facility, which provided access to an extensive housing area, appeared to be in danger of failure. Also, enlargement of the slide headward would have endangered two homes on the uphill side of the road. Another house downhill from the slide had experienced severe damage to its driveway and appeared to be endangered if the roadway collapsed.

In an effort to stabilize the area, the county decided to inject a lime-silica slurry onto the slide plane. Since the slurry injection required pressure and could conceivably lubricate the slide plane it was feared that the correction process might trigger a failure. To reduce the possibility of triggering a failure SARN monitoring was used to control the rate of slurry injection.

Background noise rates were established at four carefully selected monitoring locations. The locations had to be near enough to the injection points to immediately detect SARN rate changes and yet far enough away to eliminate interference caused by the presence of pumping and drilling equipment.

Monitoring was started prior to and continued daily after the pumping operation. The SARN rate always increased as soon as pumping was started. When the rate reached 60 to 80 per minute, pumping was stopped until the rate returned to the pre-pumping level. The project was completed using this procedure with no failure of the slide or further damage to either the county road or the houses.

This monitoring was completed using System 2.

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Landslide from Below
Note Houses above the Head

Damaged Driveway to
House Below the Slide

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CASE HISTORY #4
AMERICAN CANYON

A slide, in sandstone, of major proportions threatened the highway, 10-Sol-80, near Cordelia. This slide was to be stabilized during the continuation of highway construction. It was believed that the removal of the slide material and resloping the hill might possibly trigger failure of the remainder of the hill. It was therefore desirable to stabilize this slide with a minimum amount of excavation.

The district correction called for extensive dewatering, mostly by horizontal drains, and unloading of the head of the slide. It was decided that SARN monitoring, as part of our research, would be allowed. The purpose of this monitoring was to determine if SARN monitoring could be used to evaluate the effectiveness of a landslide correction.

In February 1969, before correction work was started, monitoring was initiated. Monitoring was done in cracks, inclinometer holes, and ground water level observation wells. These locations were distributed across the slide near the head.

Our interpretation of the data is that at the start of our study the noise rate was abnormally high due to slide activity. This high noise rate continued into the time of correction work partly due to slide activity and partly due to correction activities themselves. It is clearly evident that at some point during correction work the noise rate dropped and has generally remained low through April 1970. It is our opinion that this data indicates successful correction of this slide. We also believe that the stability of the area can be determined in the future with reasonable accuracy.

This study demonstrated the usefulness of the rock noise technique and also the effectiveness of the slide correction work.

This monitoring was accomplished using System 2.

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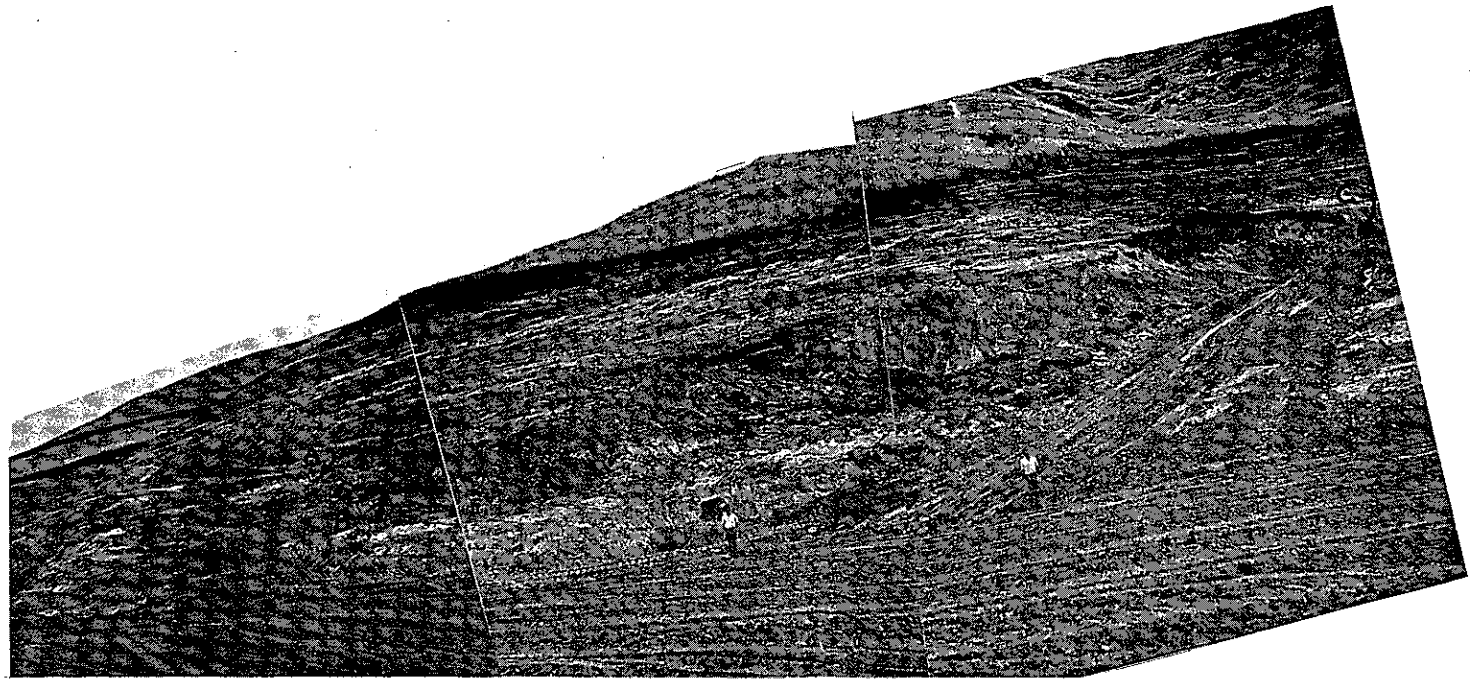

OVERALL VIEW OF SLIDE

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CASE HISTORY #5
PRINCESS ESTATES

Realignment of California Route 14 in Los Angeles County resulted in crossing a large active landslide. Subsequent to adoption of the alignment the County approved plans for a subdivision on the downslope side of the freeway. The subdivision was built and occupied prior to construction of the freeway. Several homes in the subdivision had been destroyed and numerous others had been damaged primarily as the result of having been constructed in a slide area.

Although the highway construction had been designed for crossing the landslide,there remained the possibility of possible disturbance of adjacent property. The fill on which the road was to cross the landslide caused heaving and movement which damaged several homes.

Surveying, slope indicators, and SARN monitoring were all utilized to insure that human life was not endangered and to control the construction rate to prevent an abrupt failure. Monitoring results indicated sufficient instability to warrant relocation of the road and lowering of the grade.

One use of the SARN monitoring on this project was to locate the zones of activity within the slide mass. This was accomplished by monitoring at regular depth intervals in several drill holes. These determinations were subsequently verified with slope indicator readings. Although not quantitative, SARN results were immediately available at low cost and by using graphical techniques to present the data, it was possible to define the area involved in the movement.



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