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TECHNICAL REPORT NO. 65-2

STUDY OF SHORT-PERIOD SEISMIC NOISE
SEMIANNUAL TECHNICAL SUMMARY REPORT NO. 4
1 July to 31 December 1964

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THE GEOTECHNICAL CORPORATION

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TECHNICAL REPORT NO. 65-2

STUDY OF SHORT-PERIOD SEISMIC NOISE
SEMIANNUAL TECHNICAL SUMMARY REPORT NO. 4
1 July to 31 December 1964

E. J. Douze
Principal Investigator

Sponsored by:

THE GEOTECHNICAL CORPORATION
3401 Shiloh Road
Garland, Texas

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IDENTIFICATION

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Project Title: Study of Short-Period Seismic Noise
ARPA Order Nos. 292-62, 292-63
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Date Contract Terminates: 15 August 1965
Amount of Contract: $364,577
Project Scientist Name and Telephone Number: E. J. Douze, BR 8-8102

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ILLUSTRATIONS

STUDY OF SHORT-PERIOD SEISMIC NOISE
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ABSTRACT

The report presents the results of studies of short-period seismic noise, signal levels, and signal-to-noise ratios. Section 2 describes the wave types present in the noise between periods of 1.0 and 6.0 sec. Section 3 describes the results of an experiment in optimum filtering. Appendices 1 and 2 are studies on the effect of seismometer burial and of topography on wind-induced noise. Appendix 3 describes an orientation course for foreign personnel conducted at The Geotechnical Corporation.

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STUDY OF SHORT-PERIOD SEISMIC NOISE
SEMIANNUAL TECHNICAL SUMMARY REPORT NO. 4
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1. INTRODUCTION

The purpose of this report is to present the results of study of short-period seismic noise, signals, and signal-to-noise ratios performed under Contract AF 49(638)-1150.

The body of the report consists of two studies that were essentially complete on 31 December 1964. Section 2 summarizes the results of a study of seismic noise in the period range between 1.0 and 6.0 sec. Data from recordings with two seismometers in the deep hole at the Fort Stockton, Texas, LRSM site are needed to complete the study.

Section 3 reports on an attempt to maximize the signal-to-noise ratio by making the response of the recording system the inverse of the noise spectrum. The Las Cruces, New Mexico, LRSM site was used in the experiment. Further analyses of the results obtained are necessary to finish this study.

Other studies are in progress, but are not reported here because they have not reached a point where either final or preliminary results can be reported. Three studies that have been previously reported are given as appendices.

Appendix 1 is a preliminary report on the behavior of noise in shallow holes. The desirable depths of holes and the signal-to-noise improvements that can be expected are given.

Appendix 2 is a study on effect of vault location topography on the amount of wind noise recorded by the seismograph. Results indicate that wind noise can often be minimized by judicious location of vaults.

Appendix 3 is a report on Phase I of the special orientation program conducted in Garland for foreign technical personnel.

2. MICROSEISMS IN THE PERIOD RANGE OF 1.0 TO 6.0 SEC

Studies of short-period microseisms have shown that the coherence between seismographs at different locations decreases rapidly to extremely small values for periods less than 1.0 sec. Periods greater than 1.0 sec usually show high values of coherence. In general, this statement holds true for coherence both in the horizontal (arrays) and vertical (deep-hole) directions.

It is therefore appropriate to study the microseisms of periods smaller and greater than 1.0 sec separately.

The following sources of information have been employed:

        a. Amplitude-depth relationships in deep holes;
        b. Phase velocities across arrays;
        c. Particle motion diagrams.

2.1 AMPLITUDE-DEPTH RELATIONSHIPS

Figure 1 shows the experimental ratios of deep-hole (5182 m) noise amplitudes to surface noise as a function of frequency for a deep-hole site near Fort Stockton, Texas. The theoretical normalized amplitude ratios of the fundamental and first-higher-mode Rayleigh waves, and of compressional-wave noise at this depth are shown. To compute the compressional-wave amplitudes, sine waves at vertical incidence were assumed, and the velocity layering at the site was taken into account.

There is a close resemblance in behavior with depth of the compressional-wave and the first-higher-Rayleigh mode. Because of this similarity, it is difficult to distinguish the two types of waves.

For periods greater than 4.5 sec, the ratio, as expected, indicates the presence of fundamental-mode Rayleigh waves. Between 1.5- and 4.5-sec period, the ratio can be explained by a mixture of compressional and first-higher-mode waves in the spectrum. With two deep-hole seismometers at depth (presently in operation), it will be possible to calculate the amount of power in each mode.
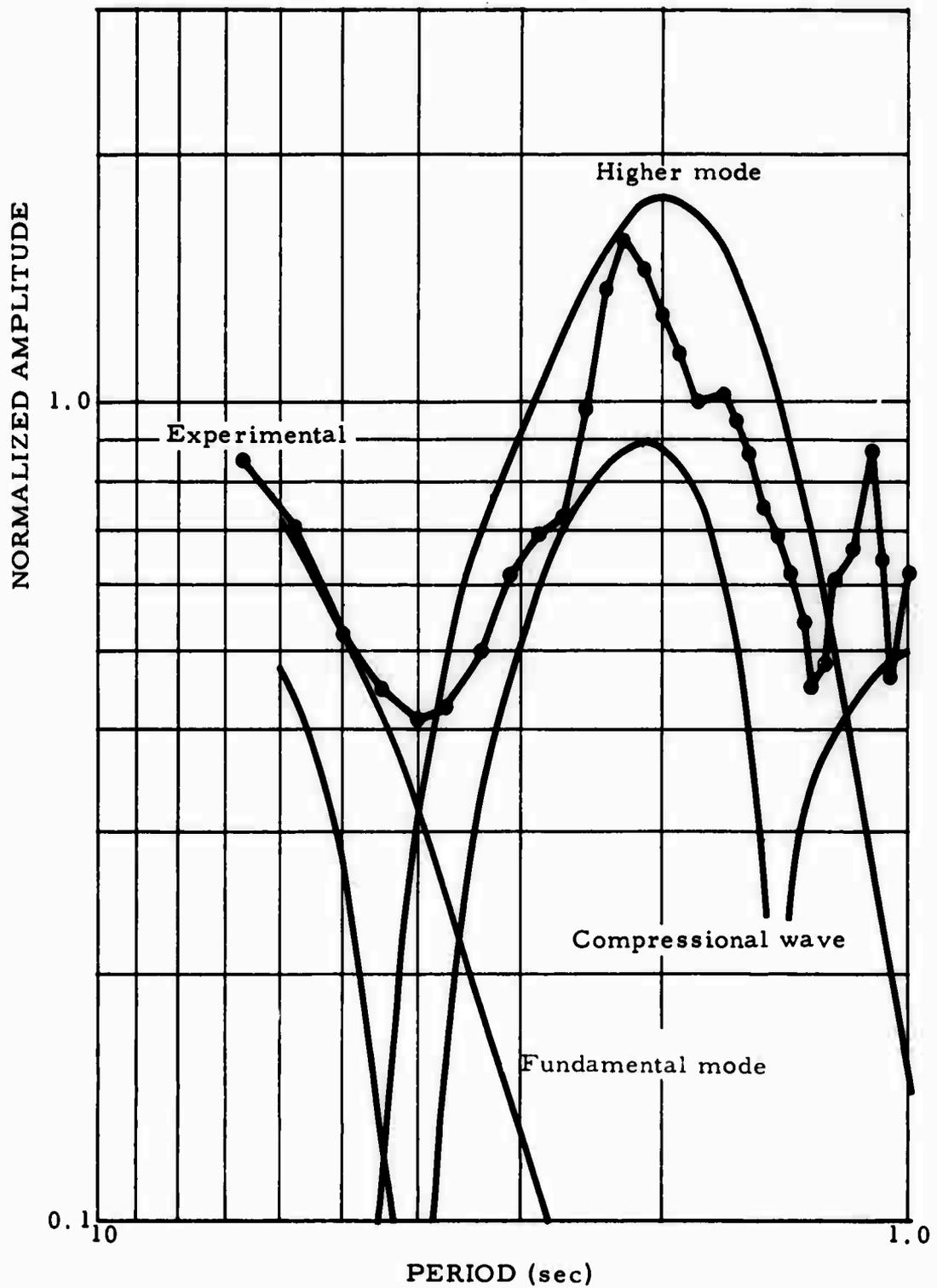
Figure 1. Deep-hole (5182 m) vertical noise spectrum divided by
surface noise spectrum. Theoretical amplitudes are included.
Fort Stockton, Texas

2.2 PHASE VELOCITIES

Pha .e velocity measurements have concentrated mainly on the spectral peak
at approximately 3.0-sec period found at some sites close to the East Coast
of the United States. Velocity and direction measurements taken from
Cumberland Plateau Seismological Observatory recordings indicated a velocity
across the array of 3.5 km/sec. The velocity of 3.5 km/sec is close to what
would be expected if the first-higher-mode Rayleigh wave predominated in
the noise. The direction of approach indicated that a storm in the North
Atlantic was the source of these microseisms.

2.3 PARTICLE-MOTION DIAGRAMS

Particle-motion diagrams of the behavior of the 3.0-sec microseisms
obtained from the Franklin, West Virginia, site (figure 2) showed flat
retrograde orbits. The theoretical Rayleight-wave orbits are presently
being computed; however, flat orbits of the type obtained are typical of the
orbits obtained theoretically for the first-higher mode in similar velocity
sections.

Particle-motion diagrams of the 6-sec microseisms showed the usual high
retrograde orbits typical of fundamental-mode Rayleigh waves of this
period.

2.4 CONCLUSIONS

The period range between 4.0 and 1.0 sec is a complex mixture of funda-
mental and first-higher-mode Rayleigh waves together with body waves.
The energy in each type of wave varies with location and with time. The
microseisms between 6.0 and 4.0 sec are composed of fundamental-mode
Rayleigh waves.

3. LAS CRUCES, NEW MEXICO, FILTERING EXPERIMENT

The purpose of this experiment was to determine if signal detection and
identification could be improved by shaping the seismograph response to the
inverse of the noise.

Figure 2. Particle-motion diagram
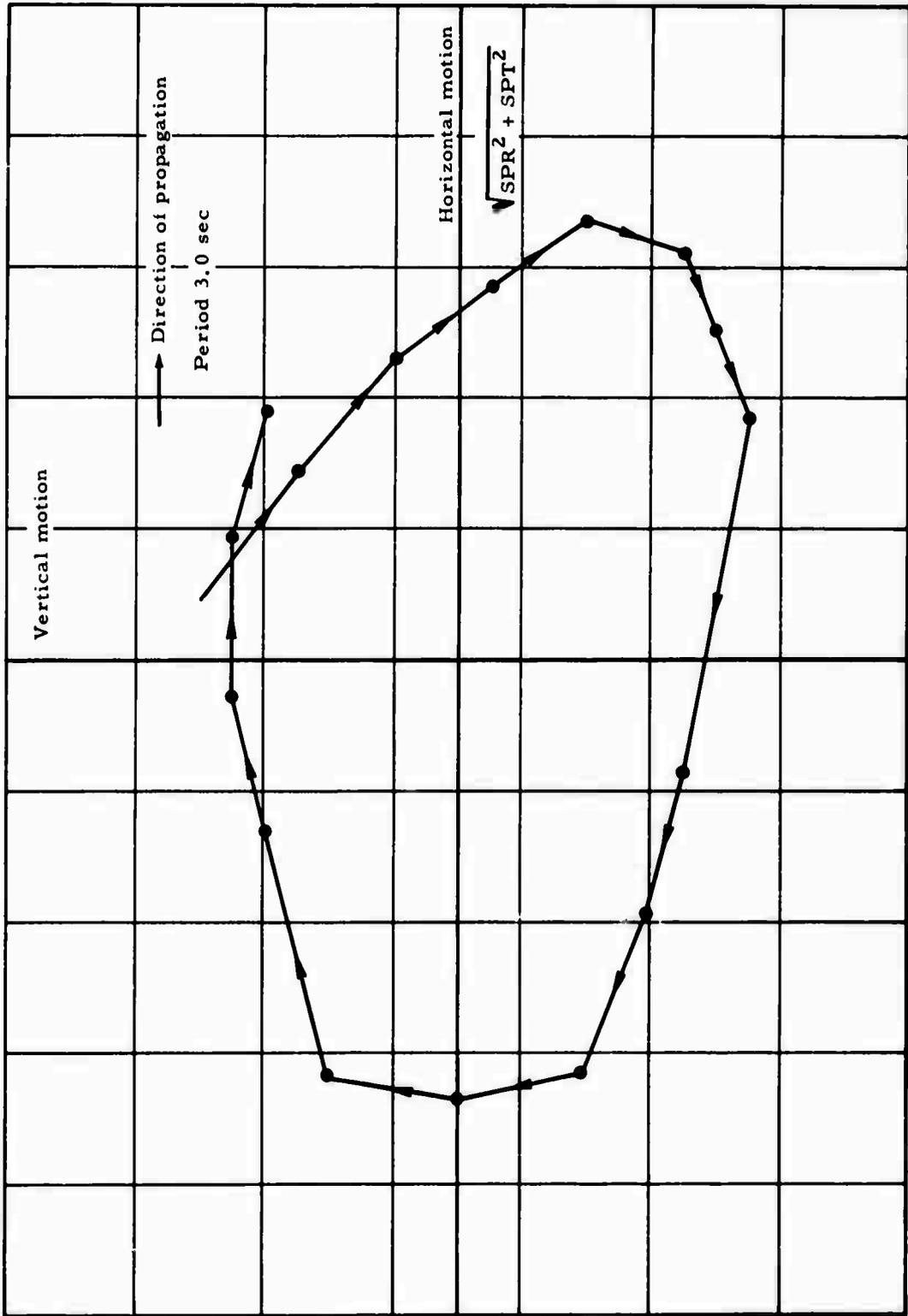
The Las Cruces, New Mexico, LRSM site was chosen because of its relatively low noise level. The amplitude spectra of the noise at this site are shown in figure 3. The minimum noise curve shows a dip at 1.0 cps which corresponds to the period at which most teleseismic events are recorded.

The signal is more band-limited than the noise. Therefore, a weighted transfer function that passes data relatively unreduced in the passband (a region of high signal probability) and highly reduced in the reject band (a region of low signal probability) should provide an improvement in the signal-to-noise ratio by reducing the noise more than the signal.

3.1 INSTRUMENTATION

Data from the following systems were recorded simultaneously on tape:

a. System 1-A, unfiltered narrow-band, Johnson-Matheson short-period vertical seismometers with nominal passband from 0.8 to 1.0 cps;

b. System 1-A, filtered narrow-band system as above with the addition of selected filters;

c. System 2-B, broad-band, Johnson-Matheson short-period vertical seismometer with nominal passband from 0.8 to 12.5 cps;

d. System 3-C, broad-band, Geotech 18300 short-period seismometer with nominal passband of 0.8 to 12.5 cps;

e. System 4-D, broad-band horizontal, Johnson-Matheson short-period seismometer with nominal passband from 0.8 to 12.5 cps;

f. LRSM vertical, Benioff short-period seismometer with nominal passband from 1.0 to 5.0 cps;

g. LRSM horizontal, Benioff short-period seismometer with nominal passband from 1.0 to 5.0 cps.

The response characteristics of the systems used are shown in figure 4. Two types of filters were operated in the field: One a "Twin T" and the other a high-pass filter. The Twin T notch filter is often considered to be a frequency filter. It is actually a type of transversal filter or phase-shift
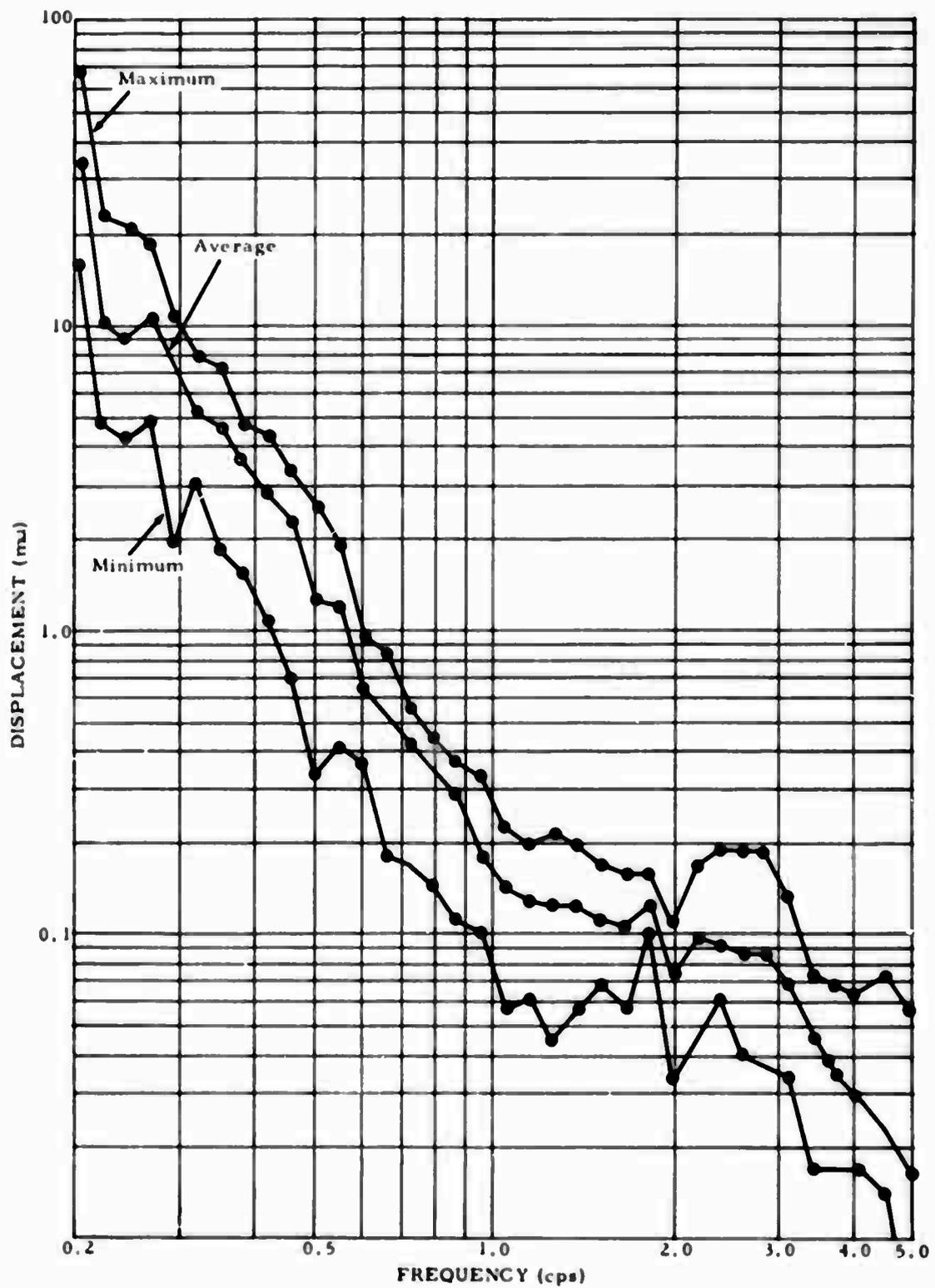
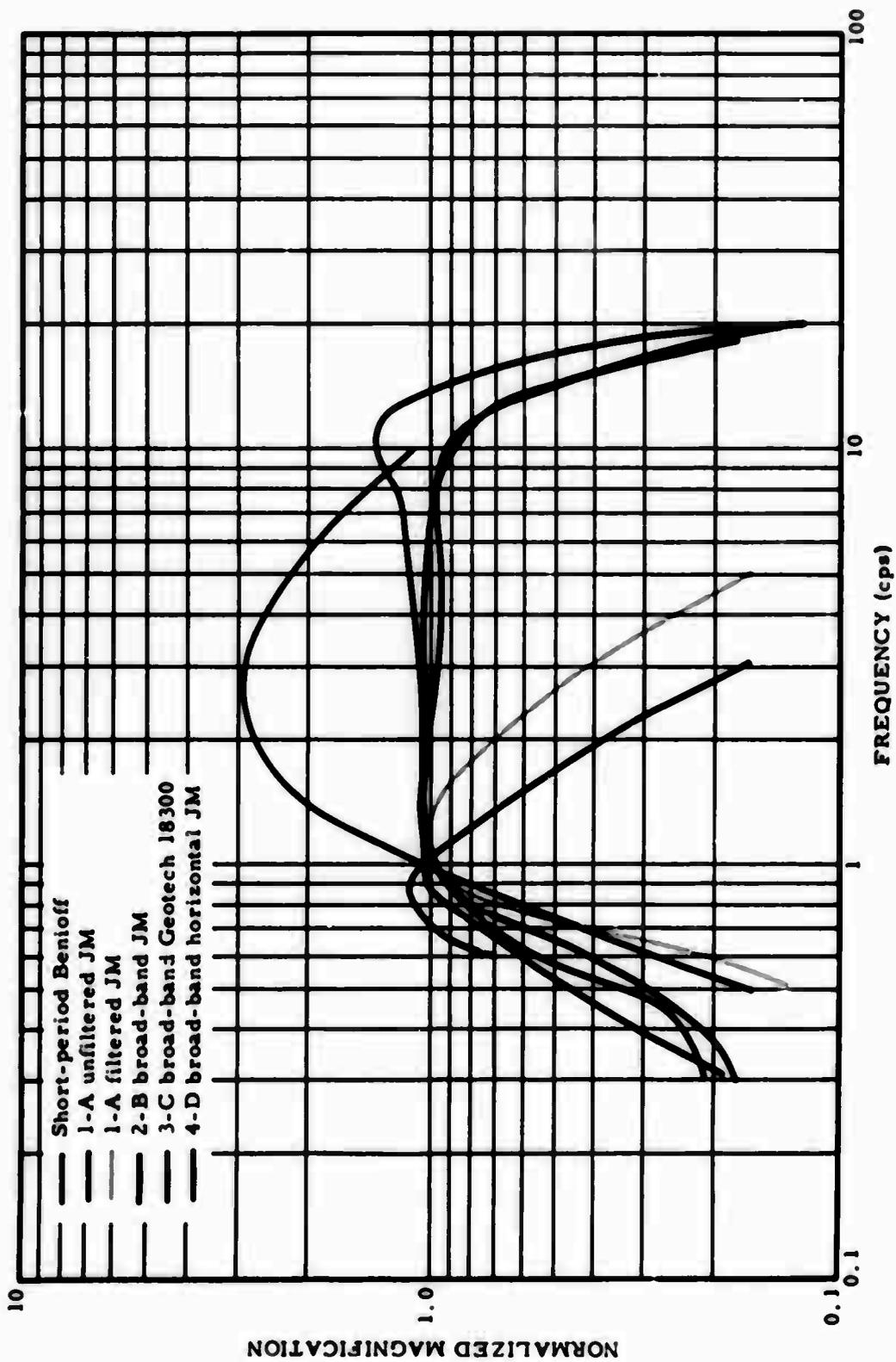Figure 3. Noise spectra at Las Cruces, New Mexico, 8-10 June 1964

Figure 4. Normalized response characteristics of the seismograph systems used at Las Cruces, New Mexico

filter, because it operates by destructive interference between a phase-lagging signal and a phase-leading signal. One requirement for the operation of this type of network is that the noise to be rejected be amplitude and frequency stationary for 3 to 5 time constants ($\frac{1}{f_o}$ of the filter) before the destructive-interference cancellation can be effective. For 3-, 4-, and 6-sec periods, this requires reasonable time and frequency stationary for about 10 to 20 sec. The Geotech 6324-9 filter for use in the Geotech Model 4300 PTA is a 6.0-sec (0.167-cps) filter of this type. For use in the field, additional 3.0-sec and 4.24-sec filters of this type were constructed and operated.

The second type of filter used in the field was the integrating (low-pass) and differentiating (high-pass) first-order filter. The Krohn-Hite variable filter and the Geotech 16307 variable filter are both filters of this type. Used as high-pass filters, the time constant T of these filters is the reciprocal of the 3-db frequency, which gives sufficient rejection to the 3- to 6-sec microseisms for $T = 1$ sec.

Thus, the required filter memory is about 3 to 5 time constants or effectively about 3 to 6 sec. Thus, this type of filter demands effective stationary for a much shorter time than the phase-filtering approach above.

3.2 ANALYSES

The recordings produced by all the systems were analyzed (to date, only by visual measurements) to see if an improvement in the signal-to-noise ratio was obtained and whether the accuracy of detecting the first motion of a signal was improved by filtering channel 1-A. Figure 5 shows an example of a signal as recorded by the various seismograph systems.

Two analysts working independently measured amplitudes and periods of signals and noise recorded by the different seismograph systems.

The results indicate that an analyst can pick approximately 10% more signals from the filtered records. From 90% to 100% of the total signals located on all the seismograph traces were found on the filtered 1-A records while 80% to 85% of the total number of signals were found on the standard LRSM (1-A) recordings.
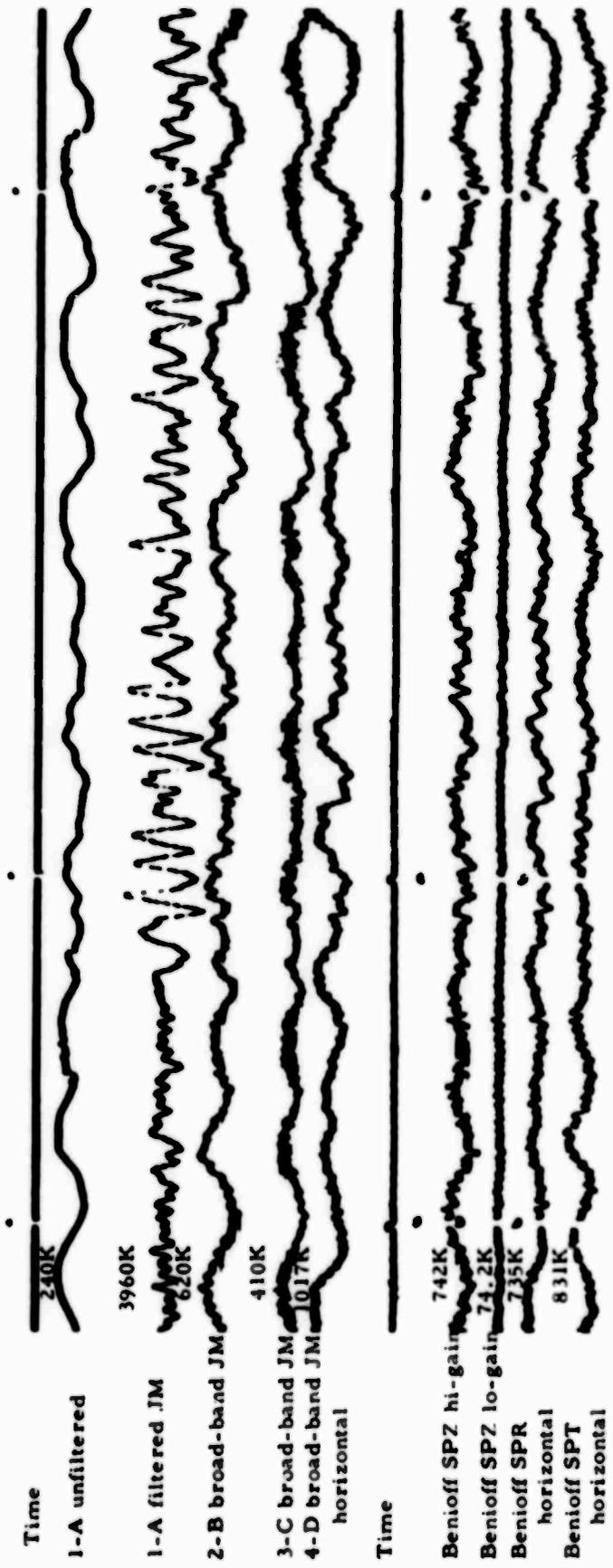
Figure 5. Signal recorded by all systems used at Las Cruces, New Mexico. Magnifications at 1 cps (X10 enlargement of 16-mm film)

About 70% of the signals were detected in the broad-band recordings. No improvement in the detection of first motion was obtained with the filtered system.

3.3 CONCLUSIONS AND RECOMMENDATIONS

The comparisons of the filtered data with the LRSM and broad-band data indicated that detection of signals was improved by using a system with a response shaped to the inverse of the noise at a given site. There was no increase in the accuracy of picking a more exact arrival time and consequently no increase in the ability of an analyst to determine the direction of first motion.

One application for the use of this system would be in the automated analysis of data where at least one criterion for detection would be that a signal exceed a certain threshold level. Any threshold level set for the broad-band and LRSM system above the long-period noise would miss many of the small signals which have less amplitude than the noise at periods >3.5 sec. With the filtered system the threshold could be lowered considerably with an increase in the number of these small signals that could be detected. This system would be an aid to the analyst in serving as a flag to indicate that a closer look should be taken at the other traces.

APPENDIX 1 to TECHNICAL REPORT NO. 65-2

TECHNICAL REPORT NO. 64-135, NOISE ATTENUATION IN SHALLOW HOLES

TECHNICAL REPORT NO. 64-135

NOISE ATTENUATION IN SHALLOW HOLES

THE GEOTECHNICAL CORPORATION
3401 Shiloh Road
Garland, Texas

11 January 1965

CONTENTS

ILLUSTRATIONS

NOISE ATTENUATION IN SHALLOW HOLES

ABSTRACT

Short-period seismograph recordings in shallow holes (< 300 m) indicate that significant improvements in performance are sometimes obtained at shallow depths. Wind noise attenuates rapidly and becomes insignificant at depths less than 60 m. In the presence of low-velocity weathered layers, the normal background noise decays rapidly with depth and significant improvements in the signal-to-noise ratios are obtained.

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NOISE ATTENUATION IN SHALLOW HOLES

INTRODUCTION

In the course of deep-hole experiments (Douze, 1964a) performed for
VELA-UNIFORM, a number of shallow holes were drilled for the placement
of surface-reference seismometers of the same type used in the deep holes.

Seismograms from these shallow-hole instruments showed that an appreciable
reduction in the noise level, as compared with an instrument at the surface,
was obtained under some conditions. For this reason, considerable interest
has been generated in placing seismometers at depths sufficient to eliminate
surface effects such as wind-induced noise. It is hoped that the preliminary
results presented in this report will aid in future planning. Considering the
cost of drilling shallow holes, it is desirable to place the seismometer at
the minimum depth compatible with the results desired.

The instruments used at the surface were Short-Period Vertical Benioff
Seismometers, Geotech Model 1051. The shallow-hole seismograph system
has been previously described in detail by Shappee (1964). Wind velocities
were recorded with an anemometer. Only a vertical-motion seismometer
has been available to date for measurement and all references to the noise
in this report will refer to the vertical component.

The following shallow-hole sites are discussed in the body of this report:

a.   Apache, Oklahoma: 38° 49' 59" N, 98° 26' 09" W, shallow hole of 18.3 m depth in high-velocity limestone; compressional-wave velocity 5.8 km/sec.

b.   Wichita Mountains Seismological Observatory, Oklahoma: 34° 43' 05" N, 98° 35' 21" W, shallow hole of 61 m depth in competent granite; compressional-wave velocity 3.8 km/sec.

c.   Pinedale, Wyoming: 42° 27' 24" N, 109° 33' 04" W, shallow hole of 61 m depth, weathered zone of unknown thickness and velocity.

d.   Winner, South Dakota, shallow holes of 56 m and 302 m depths, weathered zone 30 m thick with a compressional-wave velocity of 0.59 km/sec, overlying shales with a velocity of 1.810 km/sec.

Some other shallow holes were available, but will not be discussed because they were not studied in detail and contributed nothing new to the information presented here.

It must be noted that wind noise is not stationary and that noise measurements at different times will not be the same even when the wind velocities are the same.

Figure 1 shows a drawing of the type of vault in which the surface seismometers were installed.

Fiberglas aluminum against tank

Bulk vermiculite in burlap. Bags 8" thick

Sand bags-good seal

Plastic cover

Fill around and over with bulk rock wool

Fiberglas aluminum out

Polystyrene around under & over seismometer

Dirt retainer

Optional Lamp

2-50W Bulbs in series

Fiberglas aluminum up

3/4" Plywood

"U" Dip in cables inside

Cement poured on bedrock

Bedrock

1-1/4" (1-5/16" O. D.) black pipe, 3 or 4, driven into drilled 1-1/4" hole

NOTE:
For horizontal seis. both heaters in series

Figure 1. Surface vault

METHODS OF MEASURING THE NOISE

Two methods of measuring the noise level were employed: visual analyses and spectral analyses. It must be emphasized that there is no simple relationship between the two methods. Whereas the spectral analyses were used to determine the behavior with depth of individual frequencies, the visual analyses were used as a measure of the interference the noise causes to an analyst trying to detect a signal.

Visual Analyses

The noise-distribution curves given in this report were obtained by measuring the largest noise amplitude present in the 10-sec interval immediately following a 5-min mark.

The amplitudes were not corrected for instrument response, and the magnifications at 1 cps were used to obtain the millimicron (mμ) values. Samples were taken during times when the cultural activity in the vicinity was minimum; 100 samples were taken simultaneously at the surface and at depth. All measurements of amplitude were peak-to-peak.

This method of measuring the noise essentially defines the detection capability of the site. The results are given as "probability-of-occurrence" curves (see

figure 2) which determine the probability that a noise pulse of the same amplitude as a signal will occur at approximately the same time. The slopes of the curves give a measure of the variability of the noise amplitudes.

The periods of the pulses measured are also plotted to allow a comparison of the periods predominant at each depth.

The method has the advantage of ease of measurement and gives consistent, reproducible results by visual analysis; however, it should not be taken as a substitute for spectral analysis of the noise.

The probability-of-occurrence curves give a good indication of the decrease in noise level with depth without making any attempt to distinguish between the decay of the different frequencies which occur in the noise.

Computer Analyses

Power spectra of the noise at the surface and in the shallow holes and cross spectra between the samples were run on a CDC 1604 computer by the Seismic Data Laboratory, Alexandria, Virginia.

The samples used were picked from the film records in an attempt to obtain typical examples of the noise at times when no signal energy was present. Sample lengths varied between 150 and 200 sec, with a total lag of 5 percent

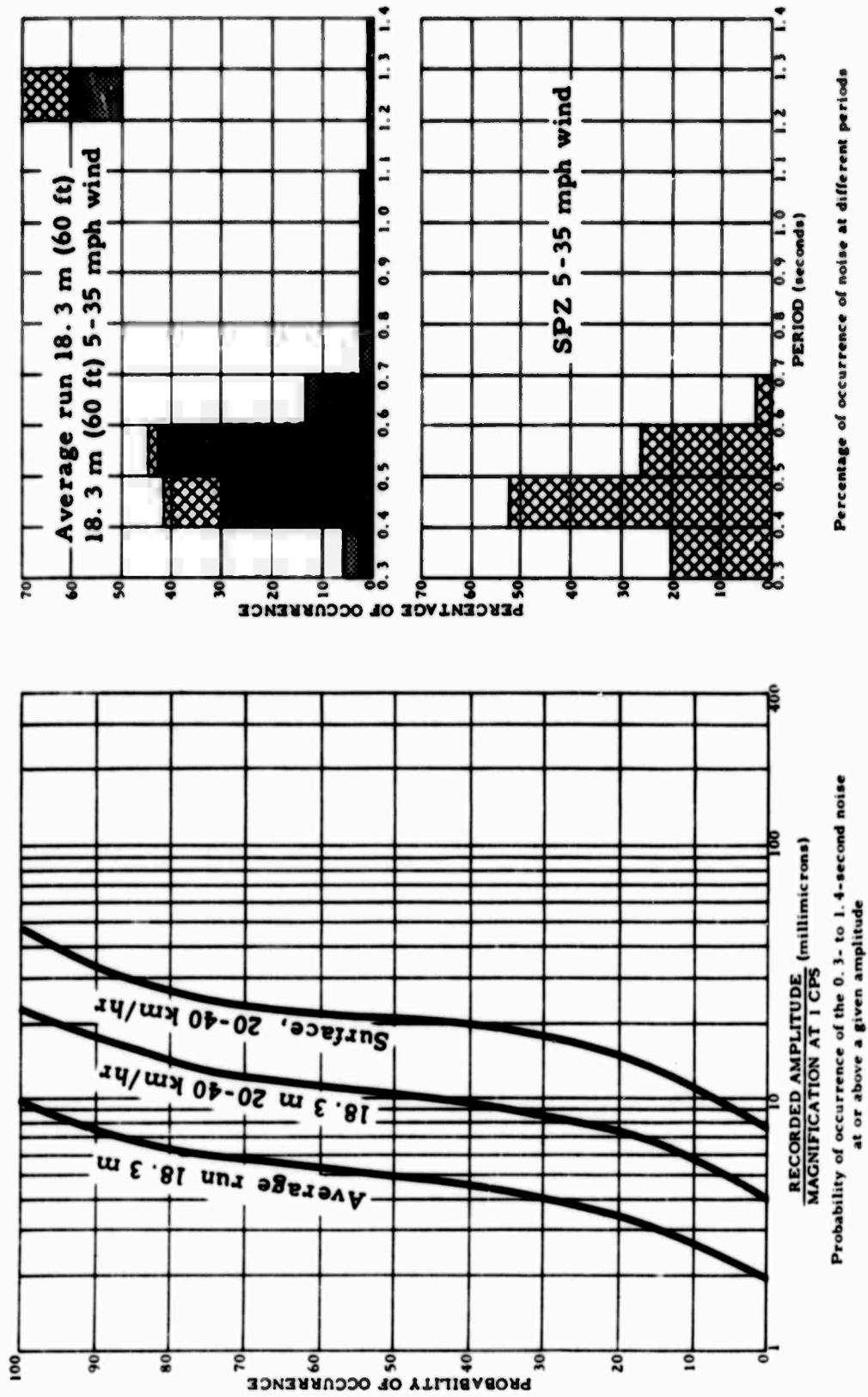TR 64-135   -5-

Figure 2. Probability of occurrence and percentage of occurrence of the 0.3-1.4 sec noise at the surface and 18.3 m in the shallow well, Apache, Oklahoma

of the sample. This procedure resulted in approximately 40 degrees of freedom in both cases (Blackman and Tuckey, 1958), and a 90 percent confidence level that the values obtained are within ±3 db of the actual values.

The power spectra were not corrected for instrument response. Because of the identical responses of the seismographs used, the ratio of the deep-hole spectrum divided by surface spectrum used in interpretation are correct for all frequencies. The magnifications at 1 cps were used to calibrate the spectra; therefore, only the values at 1 cps are correct ground-motion values.

The noise was recorded on tape at sufficient magnification so that the tape noise did not affect the results obtained.

EXPERIMENTAL RESULTS

Apache, Oklahoma

The 18.3-m hole at this site is in extremely high velocity limestone (5.8 km/sec). The weathered zone is very thin and the surface seismometer was placed in the same material as the shallow-hole seismometer.

The background noise in the period range of interest (0.3 to 1.3 sec) consisted almost entirely of 0.5-sec-period noise. The peak has an average amplitude of approximately 0.5 mμ as measured from power spectra; and is therefore among the quietest sites in the continental U. S. For a more thorough description of this type of noise see Douze (1964b).

During times when the wind was not blowing, measurements indicated no discernible difference between the seismograph noise levels at the surface and the 18.3-m depth.

The hole was not sufficiently deep to eliminate the wind noise completely. Figure 2 shows the reduction of wind noise at 18.3 m during a time the wind was blowing 20-40 km/hr together with the normal noise level during quiet days. The surface seismograph noise level increased by 12 db over the value obtained during windless days. The 18.3-m seismograph showed an increase of 6 db, indicating that although the noise level was decreasing rapidly, the depth was not sufficient to eliminate the wind noise. As a rule, no appreciable wind noise was seen on the surface seismograph until the wind was blowing approximately 20 km/hr. This is in agreement with previously published information (Bradford, Shumway, and Griffin, 1964).

Wichita Mountains Seismological Observatory, Oklahoma

At this location the surface and shallow-hole seismometers are located in granite with a compressional-wave velocity of approximately 3.8 km/sec. During most of the time of operation the shallow-hole seismometer was at 61 m. No wind noise was detected by the seismometer at this depth.

When the wind was not blowing, the noise levels (by visual measurement) of the surface and shallow-hole seismographs were almost identical.

For a limited amount of time, two seismometers were operated in the shallow hole at depths of 18 m and 36 m. The highest wind velocity which occurred was 30 km/hr. At this velocity some wind noise was seen on 18 m seismograph trace; no wind noise was detected by the seismometer at 36 m.

Wind noise varies considerably from vault to vault across the WMSO array, depending on the protection of the location from the wind. For details on this study see The Geotechnical Corporation Technical Report No. 64-134 (in press). The location of the shallow hole is at one of the more protected locations in the array.

Pinedale, Wyoming

The velocities and thickness of the weathered zone are not known at this site. The shale at the bottom of the hole has a compressional-wave velocity of approximately 3 km/sec.

As the shallow-hole seismograph was primarily intended as a surface reference for deep-hole operations (to be reported in the near future), it was operated at 61 m during most of the duration of the experiments. A complete set of measurements under different wind conditions and at different depths could not be obtained.

On the average, during windless days, the noise level (from the 50 percent probability of occurrence) decreased gradually from the surface to 0.7 times the surface value at 61 m.

The following table gives the results obtained from visual analyses under the different conditions available.

Depth of shallow-hole seismometer	Fifty percent probability of occurrence		Wind velocity
	Surface	Shallow hole	
32 m	2.5 mμ	2.0 mμ	0-8 km/hr
32 m	6.5 mμ	2.8 mμ	35-50 km/hr
46 m	2.7 mμ	2.0 mμ	0-8 km/hr
61 m	4.0 mμ	2.3 mμ	30-35 km/hr
61 m	6.8 mμ	2.3 mμ	50-60 km/hr

The visual analyses show that the shallow-hole seismograph, when located at 61 m, was not noticeably affected even when extreme wind conditions were encountered. As can be seen from the mμ values given above, this site had a low seismic background in the period range where amplitudes were measured.

The signal amplitude decreased slightly with depth to an average value of 0.9 the surface amplitude. Therefore, the signal-to-noise ratio was improved by a factor of 1.3.

Figure 3 shows the ratio of surface spectrum divided by shallow-hole spectrum at 46 m under three different wind conditions. The wind velocities given are the velocities measured with an anemometer during the time of the sample. On the windless day, the ratio is approximately 2 over the range of periods where signals usually arrive. This represents the decrease in amplitude with depth of microseismic background composed of traveling waves (probably both
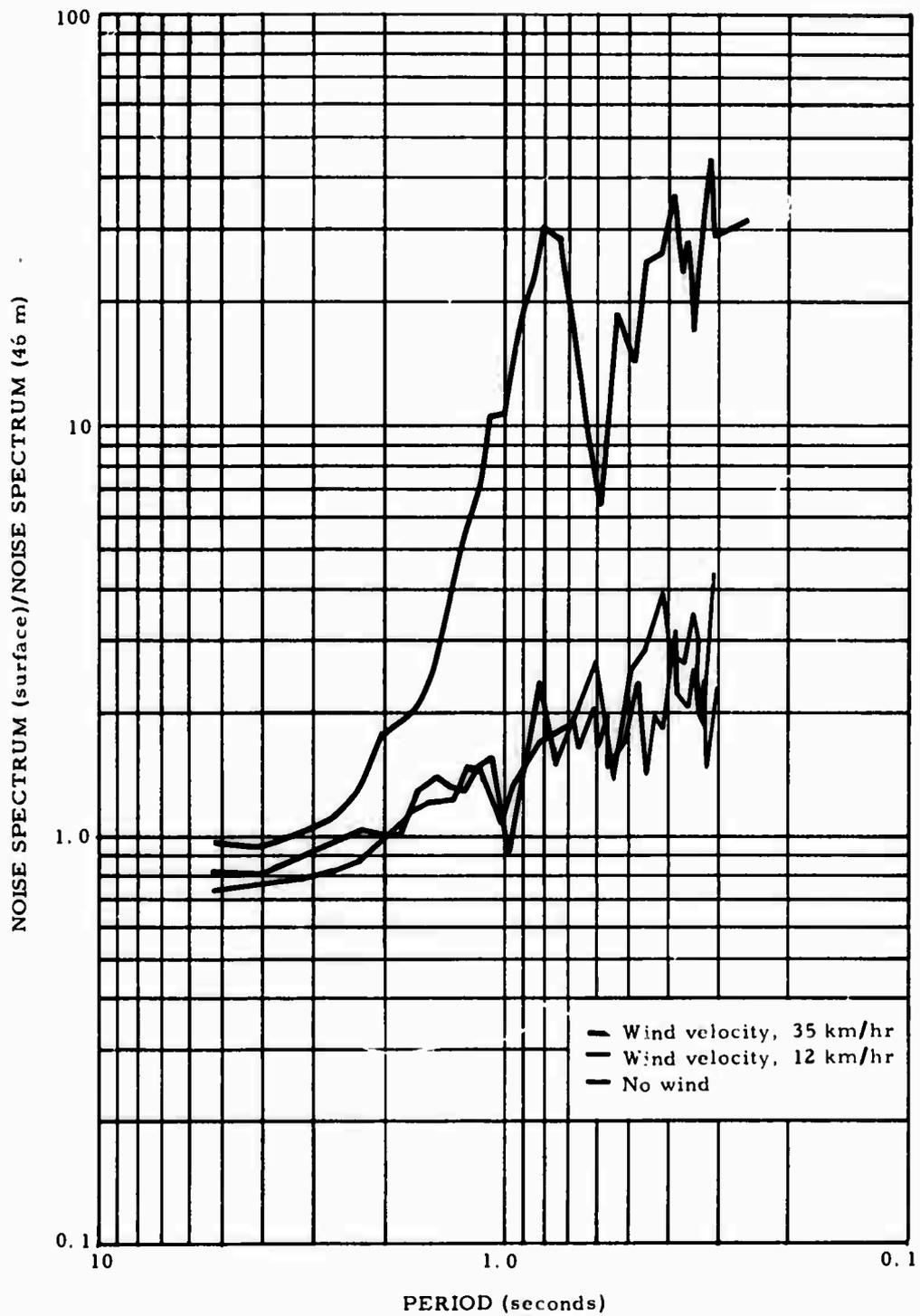
Figure 3. Surface-noise spectrum divided by the noise
spectrum at 46 m depth, Pinedale, Wyoming

surface and body waves). The sample with a wind velocity 12 km/hr is not much different although a slight increase in the ratio was found. However, when the wind reached a velocity of 35 km/hr, the ratio became quite large because the wind noise was greatly attenuated at 46 m. The apparent discrepancy between the visually measured values and the ratio is caused by the fact that the ratio is from power spectra in $m\mu^2/cps$, while the visual measurements are in $m\mu$.

The ratio falls off rapidly at the longer periods However, this does not necessarily indicate that wind noise is not generated at these periods. The spectra of the noise indicates that the energy in the 6-sec microseisms is over 100 times greater than at periods around 1.0 sec; at these large amplitudes, the wind noise would become negligible if the wind-induced noise spectrum was white.

Figure 4 shows the ratios for depth of 32 m obtained from samples while the wind was still and when it was blowing 12 km/hr and 30 km/hr. The features observed are essentially the same as those discussed above. The ratio during the time the wind was blowing 30 km/hr is not as large as at the greater depth (46 m) principally because the shallow seismometer also recorded appreciable wind noise.
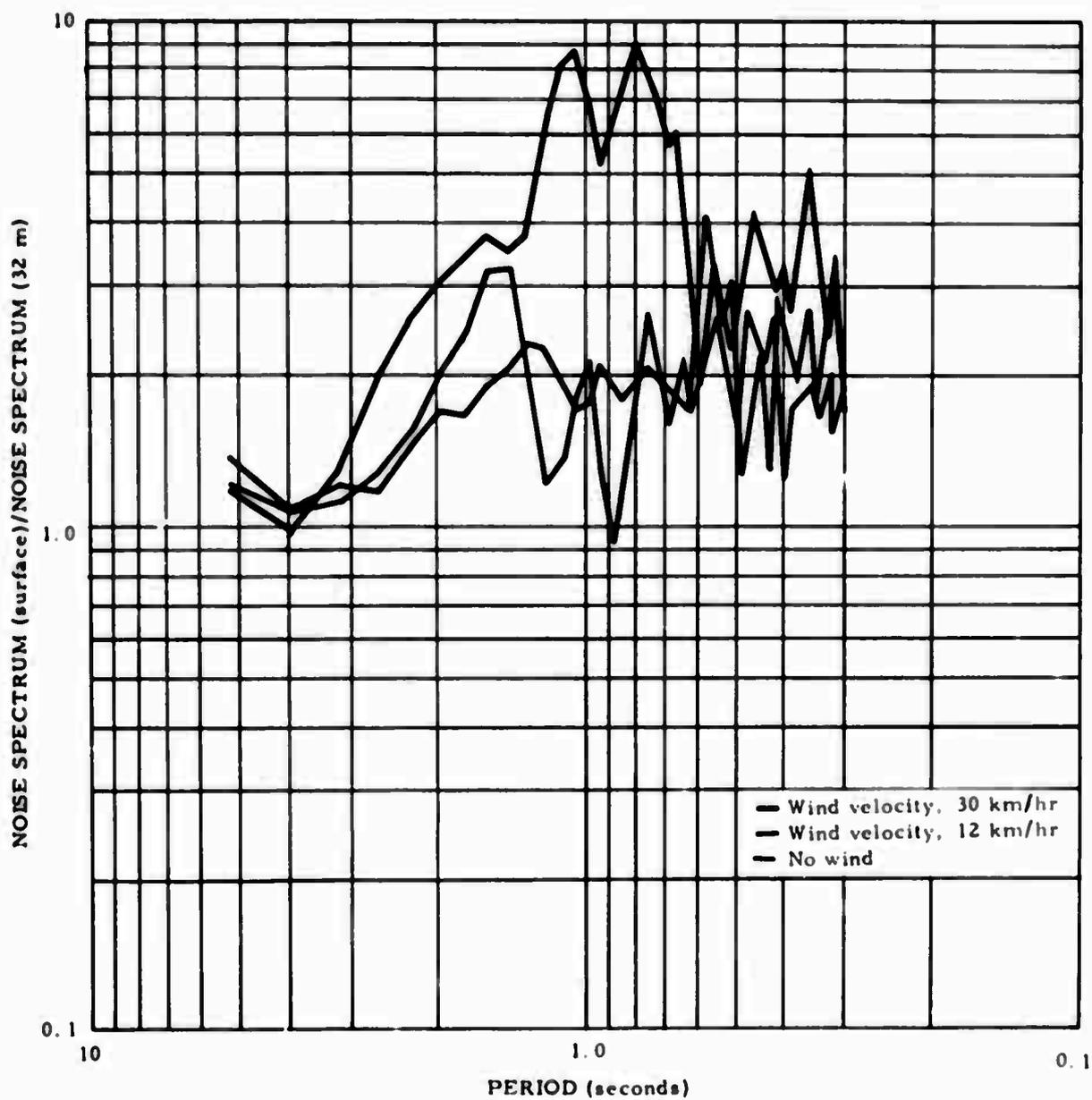
Figure 4. Surface-noise spectrum divided by the noise
spectrum at 32 m depth, Pinedale, Wyoming

On the windy day (30 km/hr) the large ratio at periods around 1.0 sec was caused by the fact that the wind-induced noise was concentrated at these periods (see figure 5). The peaks in the shallow-hole spectrum between 0.7 and 0.4-sec period are caused by wind noise and were not attenuated at this shallow depth.

The large decrease in the noise level around 1.0-sec period on a windless day in figure 4 cannot be explained at present. The ratio at a depth of 46 m shown in figure 3 does not exhibit this behavior.

Figure 6 shows the coherence between the surface and the shallow-hole (at 46 m) noise during a windless day. The coherence decreases rapidly from the longer periods and becomes small for periods less than 1.0 sec. Theoretical considerations (Bradner, Haubrich, and Munk, 1964) show that a value of 0.05 can be expected when the coherence is actually zero.

The low coherences obtained between the noise at the surface and at shallow depths are typical of sites where low-velocity zones are present. The reasons for this behavior are not well understood at present. The low coherences could partly be explained by the presence of energy confined to the weathered layer. This energy was therefore not recorded in the shallow well.
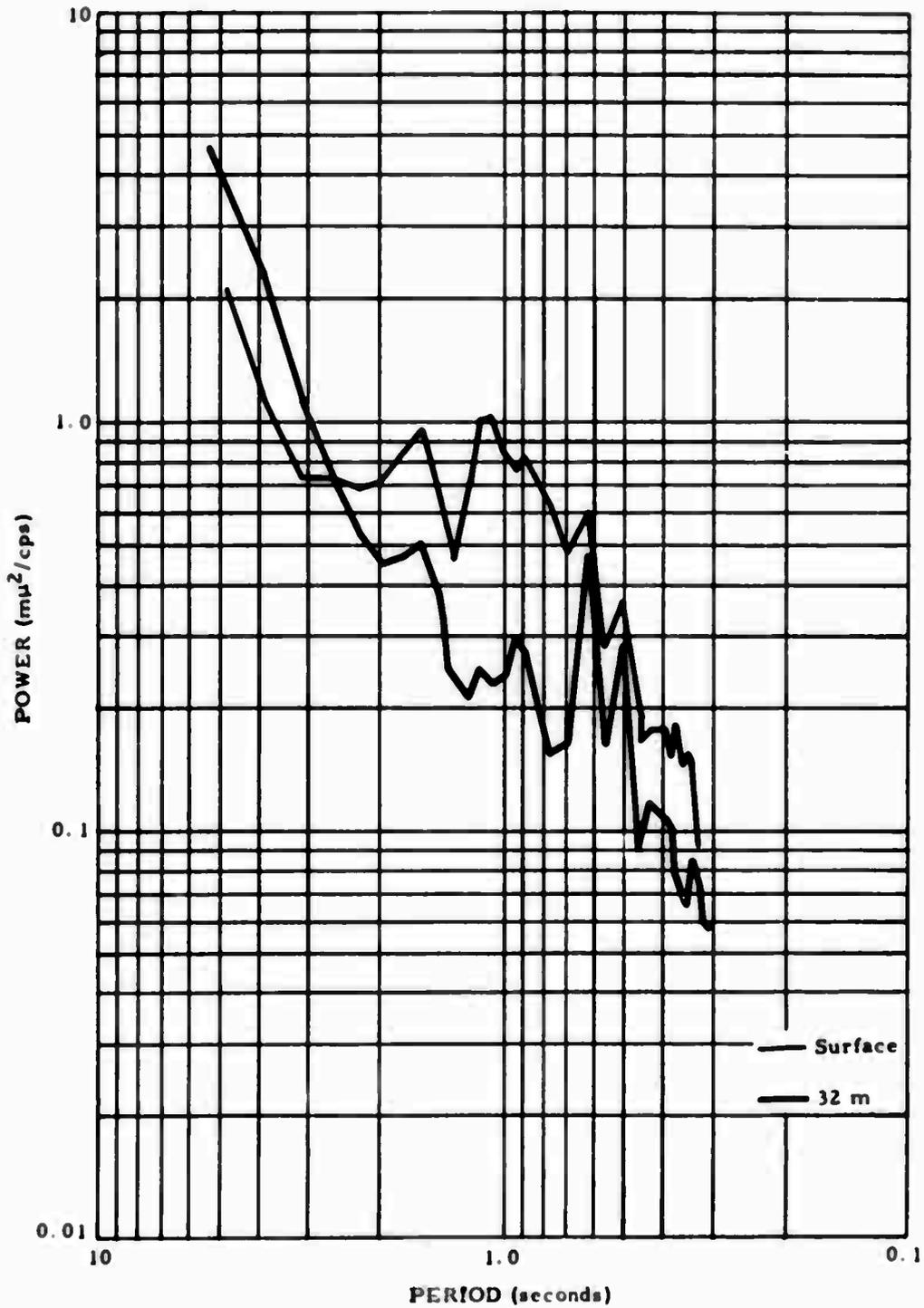
Figure 5. Power spectra of the noise at the surface and
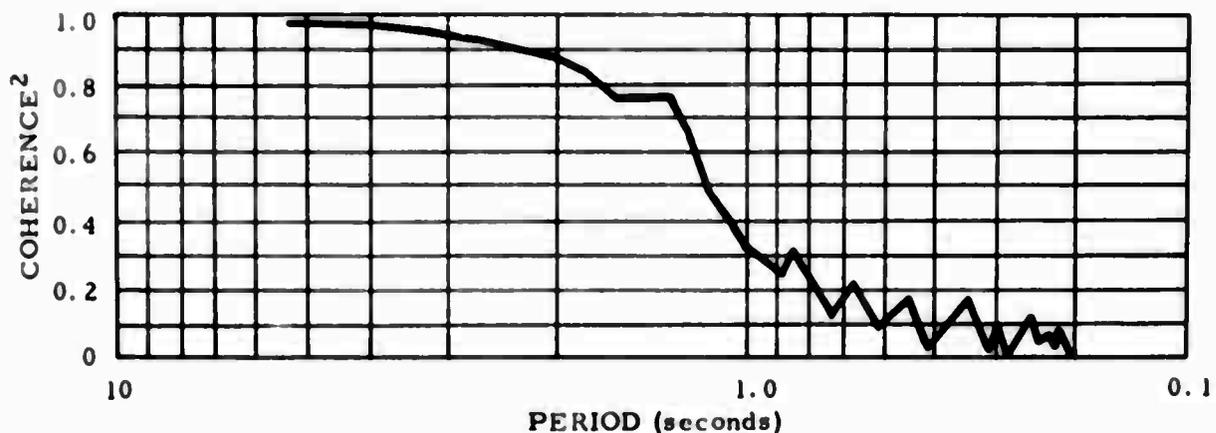at 32 m. Wind velocity, 30 km/hr, Pinedale, Wyoming

Figure 6.   Coherence between the noise at the surface
and at 46 m on a windless day

Winner, South Dakota

At this site, the noise level was so large (average 26 mμ by visual

measurements) that wind noise was not observed on the surface recordings

and was therefore not a factor in the improvement obtained at shallow depths.

The recordings obtained can easily be divided into two segments distinguished

by the level of background noise.   Nighttime records exhibit a lower level of

background noise than daytime records.   This suggests a cultural origin for

the noise even though the site was quite isolated from the more common sources

of cultural noise, such as highways and centers of population.

As an average, the noise level decreased from 26 mμ at the surface to 16 mμ

at a depth of 56 m and to 5 mμ at a depth of 302 m.   At all depths, the

individual data points (obtained on different days) scattered widely. The scatter could not be connected (except for differences between night and day) with any factor such as wind velocity.

Because of the differences in velocities and densities between the surface and the different depths, and because of the interference between incoming and surface-reflected signals, the signal amplitude also decreased with depth. The average amplitude at 302 m was only 0.33 times the surface amplitude. Therefore, on the average the signal-to-noise ratio (as measured visually) only increased by a factor of 1.9 despite the large decrease in noise levels with depth.

Examples of the theoretical Rayleigh wave and compressional wave (assuming sine waves at vertical incidence) amplitude-depth relationships in the presence of a low-velocity weathered zone are shown in figure 7. The velocities and densities below 302 m were postulated from sonic and density logs from wells in the general vicinity. A Poisson's Ratio of 0.27 was assumed to obtain the shear velocities. The rapid decrease in amplitude with depth and the change of phase from in phase to 180 deg out of phase close to the surface are a result of the low-velocity zone. These results indicate that a knowledge of the velocities in the weathered layer is necessary in order to understand the behavior of waves of higher frequencies with depth.
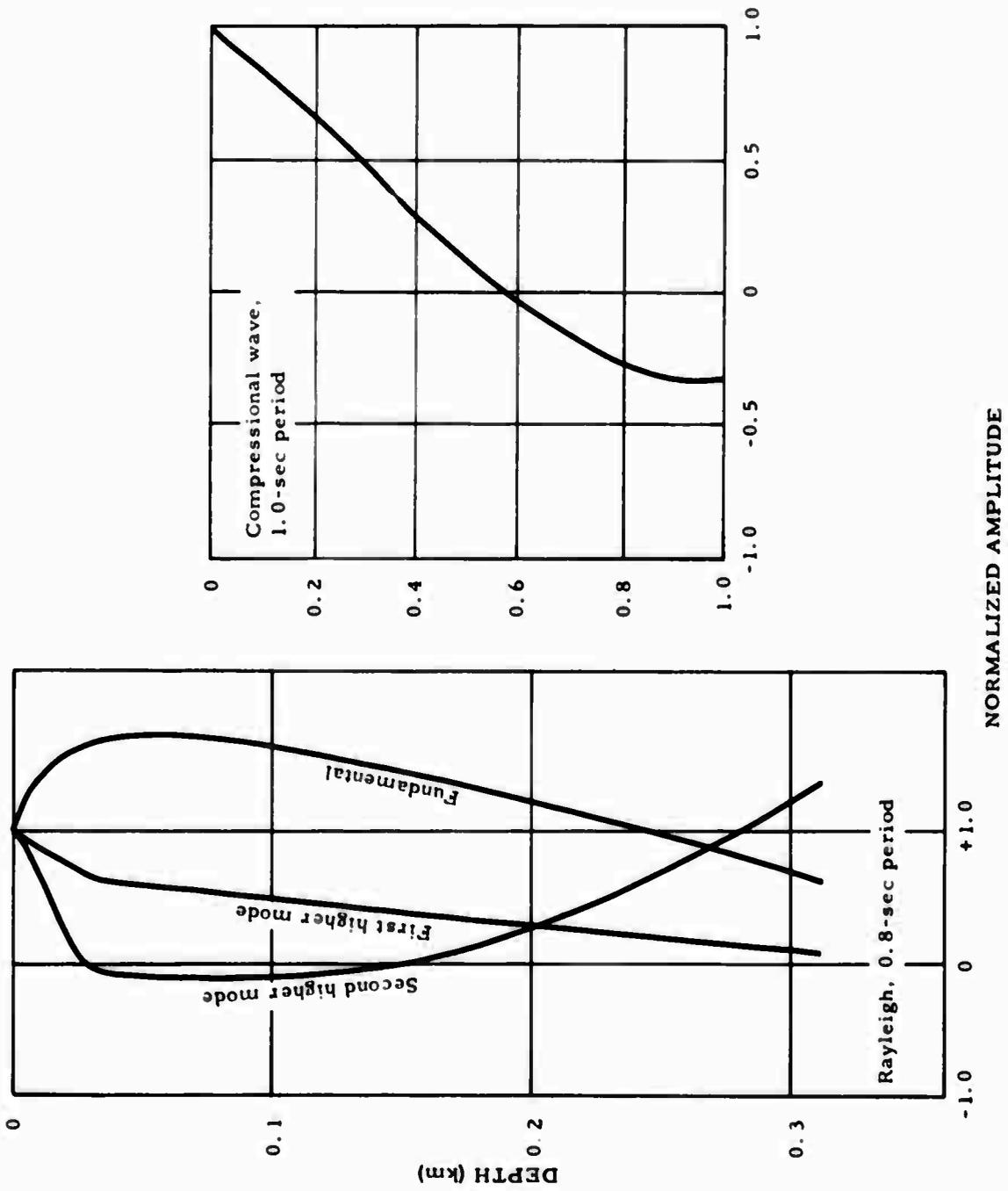
Figure 7. Amplitude depth relationships of Rayleigh and compressional waves

Figures 8 and 9 show the spectra of the noise at the surface and at 302 m. Because of the differences between daytime and nighttime recordings, samples from both of these times were analyzed. In the period range between 0.3 and 1.4 sec, the daytime spectra typically showed two large peaks, one at 0.5 sec and one at approximately 0.35 sec. The peak at 0.35 sec was much smaller during the night, indicating that the source was cultural activity.

The spectra taken at the same time from recordings with the seismometer at 302 m show that the 0.5-sec peak was still present, but the one at 0.35 was greatly attenuated. The ratios given in figure 10 show a low value at the exact period where the peak in the daytime spectra was found, resulting in an attenuation by a factor of 20. The attenuation was considerably less during the night (a factor of approximately 3). The attenuation was quite different for all periods less than 2.0 sec between nighttime and daytime.

Figure 11 shows the attenuation of the noise at a depth of 56 m. Only the peak at approximately 0.35-sec period on the surface spectra is attenuated to any extent.

DISCUSSION

The decrease in short-period noise amplitudes with depth in shallow holes (< 300 m) is caused principally by the following two factors:

Figure 8. Power spectra of the noise at the surface with
separate plots for day and night. Winner, South Dakota
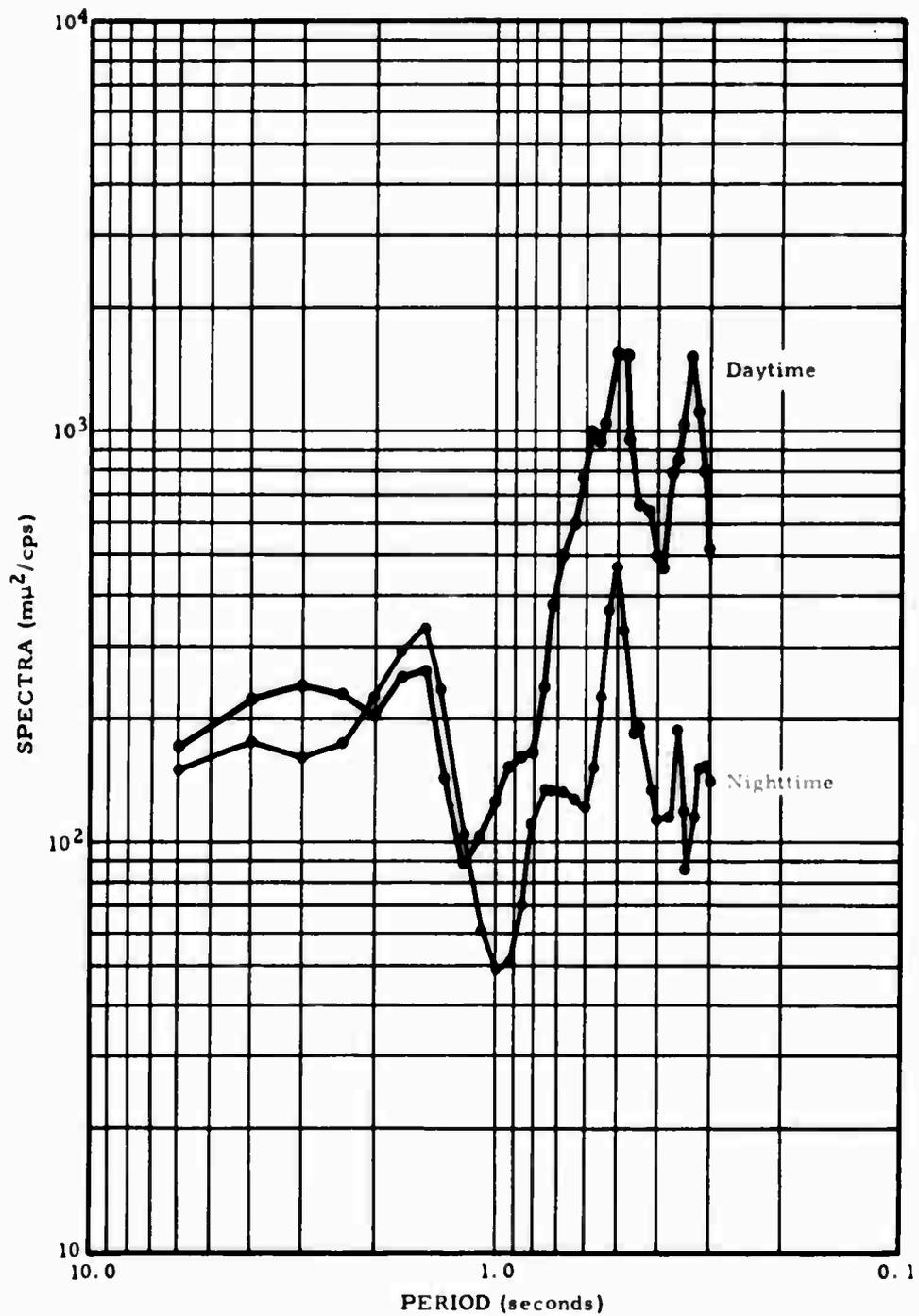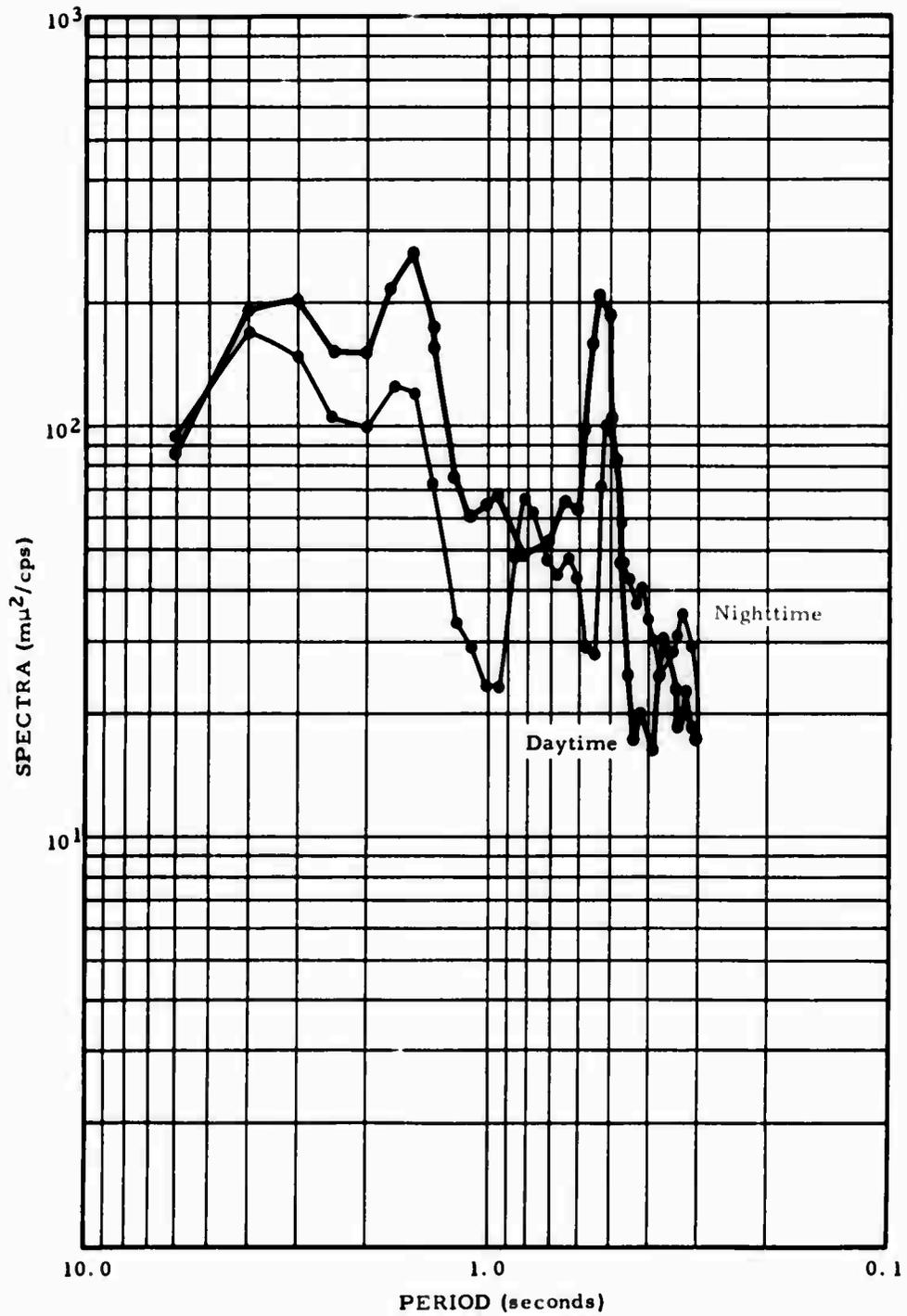
Figure 9. Power spectra of the noise at 302 m with
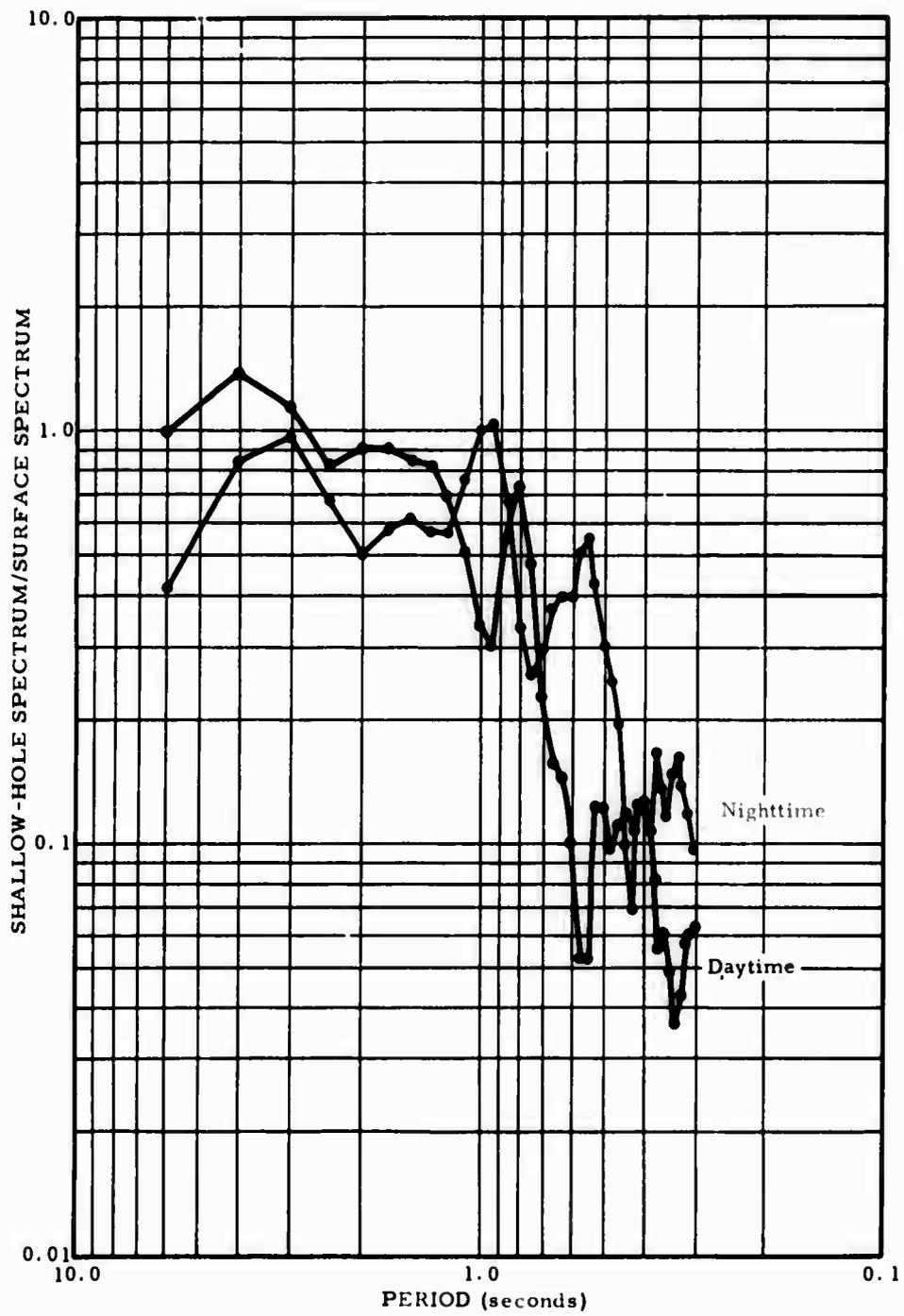separate plots for day and night, Winner, South Dakota

Figure 10. Power spectra of the noise at 302 m divided
by surface spectra with separate ratios for day
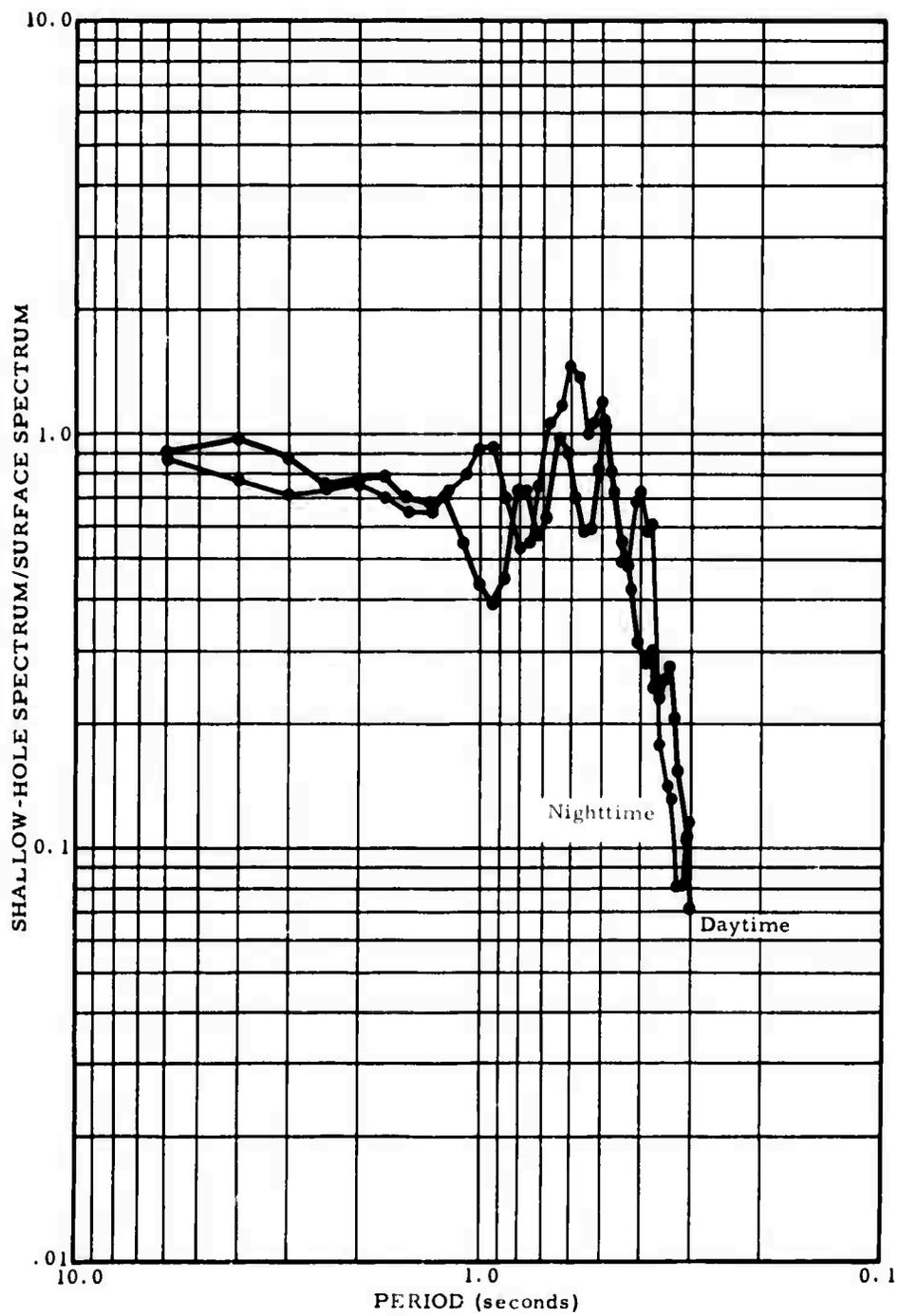and night. Winner, South Dakota

Figure 11. Power spectra of the noise at 56 m divided
by surface spectra with separate ratios for day
and night. Winner, South Dakota

a. The decrease in amplitude with depth of the normal background noise that is composed of travelling waves, both surface and body waves. Surface waves decrease in amplitude from the free surface; the decrease is quite rapid in the presence of a low-velocity zone. Higher mode Rayleigh wave amplitudes increase again after going through a nodal point; however, this behavior is usually not a factor at the shallow depths being considered here.

b. The rapid decrease in amplitude with depth of wind-induced noise. The probable cause of this type of noise are the pressure variations, associated with high wind velocities, which cause displacements of the free surface. Khorosheva (1958) has published a formula from which the displacement from a circular load acting a halfspace can be calculated.

$$\text{displacement } (Z) = \frac{Po(\lambda + 2\,\mu)}{2\,\mu(\lambda + \mu)} \quad [\ (Z^2 - r^2)^{1/2} - Z\ ]$$

$$+ \frac{Po\ Z^2}{2\,\mu} \left[\frac{1}{(Z^2 - r^2)^{1/2}} - \frac{1}{Z} \right]$$

where λ and μ = Lame's constants

      Po   = pressure/unit area

      r   = radius of load area

      Z   = depth

The wind noise detected by the seismograph is, in practice, caused by the superposition of a large number of loads. However, some conclusions can be drawn by the use of this simple formula. The elimination of the wind noise at depths less than 60 m indicates that the diameter of the pressure cells (which cause wind noise in the period range discussed here) are small because the displacements only extend to depths on the order of the diameter of the perturbations.

Assuming that λ and μ are approximately equal (Poisson's Ratio 0.25), the depth to which the wind noise will reach is inversely proportional to the rigidity. Thus, wind noise will be eliminated more rapidly with depth in competent rocks; this is in agreement with the experimental results.

CONCLUSIONS

At the sites with low levels of background noise (e.g., Pinedale and Apache), the wind induced noise is entirely eliminated at depths of approximately 60 m in low-velocity sediments, and at approximately 40 m in competent rocks.

At sites where the noise level is somewhat higher (4-6 mμ by visual measurement), the wind noise would probably not be observed at shallower depths than those indicated in the preceding paragraph.

It is of interest to note that almost none of the wind energy is converted

to travelling waves as shown by the lack of increase in the noise level at

depths below which the wind noise reaches.

At the sites with high background noise levels (e. g., Winner), the wind

noise is not significant at the surface because it cannot be seen in the back-

ground noise except at extreme wind velocities. Under these conditions, the

decrease in the noise level with depth will depend mainly on the presence or

absence of a low-velocity weathered layer. In the absence of a weathered

zone, only a very small improvement in the signal-to-noise ratio will be

obtained at shallow depths, because the noise and signal amplitudes will

decrease at approximately the same rate. In the presence of a low-velocity

layer, an appreciable decrease in the noise level is obtained. The signal

amplitude decreases with depth less rapidly than the noise; therefore, an

improvement in the signal-to-noise ratio is obtained. At these noisy sites,

the noise level will probably continue to decrease with depth until depths on

the order of 2 to 3 km are reached (Douze, 1964a). It must be pointed out

that at intermediate depths (around 1 km) the destructive interference

between the incident and surface reflected signal (typically around 1.0-sec

period) will largely cancel the improvement obtained in the noise level.

ACKNOWLEDGEMENT

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APPENDIX 2 to TECHNICAL REPORT NO. 65-2

TECHNICAL REPORT NO. 64-134, PHYSICAL AND TOPOGRAPHIC FACTORS AS RELATED TO SHORT-PERIOD WIND NOISE

TECHNICAL REPORT NO. 64-134

PHYSICAL AND TOPOGRAPHIC FACTORS AS RELATED
TO SHORT-PERIOD WIND NOISE

by

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28 December 1964

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PHYSICAL AND TOPOGRAPHIC FACTORS AS RELATED
TO SHORT-PERIOD WIND NOISE

ABSTRACT

Median values of seismic noise in the period range of 0. 3 to 1. 3 sec were
obtained from recordings at vaults of the Pole Mountain and WMSO arrays.
Interquartile ranges were used to measure dispersions about the medians.
Medians of the noise at Pole Mountain ranged from 0. 91 mμ to 2. 20 mμ in
November 1962.   The former value was obtained for a vault that was located
in dense granite at the base of a massive granite outcrop; the latter value was
obtained for a vault in a slab of dense granite located on a grassy plain.   This
indicated that topographic shielding from wind rather than density of bedrock
affected noise.   As a test of this idea, wind protection numbers were assigned
to vaults Z1 through Z9 of the WMSO array based on comparative topographic
shielding with respect to a known wind direction.   Noise values increased as
wind numbers decreased.   Topographic protection and walk-in vault construction
limited wind noise at WMSO.

TR 64-134

PHYSICAL AND TOPOGRAPHIC FACTORS AS RELATED
TO SHORT-PERIOD WIND NOISE

INTRODUCTION

This paper presents amplitude and spectral data on wind noise. Data were obtained from seismic recordings at vaults of the Pole Mountain array, Wyoming, and the triangular array at WMSO (Wichita Mountains Seismological Observatory). The noise at a vault site is defined as the median value picked from a plot of cumulative percentage of occurrence versus ground displacement amplitude in millimicrons. Median values were correlated with rock velocities and topographic settings of respective sites.

Prior to this study, Alsup and Guyton (1964, p. 195) observed a relationship between rock types and Maximum Satisfactory Operational Magnification (MSOM) of seismograph stations. They showed that high-magnification sites, excluding mine sites, were located on dense rock. Thus, the author first attempted to relate seismic noise to velocities of the rocks near the tank vaults of the Pole Mountain array, Wyoming. Noise correlated poorly with velocity. There was, however, a trend indicating that as topographic shielding from wind increased, the noise decreased. The same trend was also observed at WMSO during periods of strong winds. Spectral plots confirmed this relationship.

In order to plot topography versus noise, numbers from one to seven were assigned to vault sites based on relative topographic shielding from the prevailing wind. As an example, vaults atop hills or ridges were given a number one. At WMSO, wind protection numbers were related to horizontal distances windward from the vault in question to the next highest map contour. That is, the greater the horizontal distance to the next contour, the lower the wind protection number.

ANALYSIS OF SHORT-PERIOD WIND NOISE AT THE POLE MOUNTAIN ARRAY

Background

Soon after the Pole Mountain array (figure 1) began operation on 9 December 1961, it was found that most tank vaults in weathered rock were noisier than the tank vaults in dense granite. Thus, the UKAEA (United Kingdom Atomic Energy Authority) which operated the array decided to improve it by finding more dense rock for the noisy vaults on the Blue (east-west) line and by establishing a new Green (north-south) line (see figure 1). The open circles on the map show the vault locations on the Red line that were abandoned.

Pole Mountain and the surrounding terrane are part of the Sherman batholith that consists largely of coarse-grained, reddish, slightly-porphyritic granite. There are also some fine-grained, micaceous granites that weather more
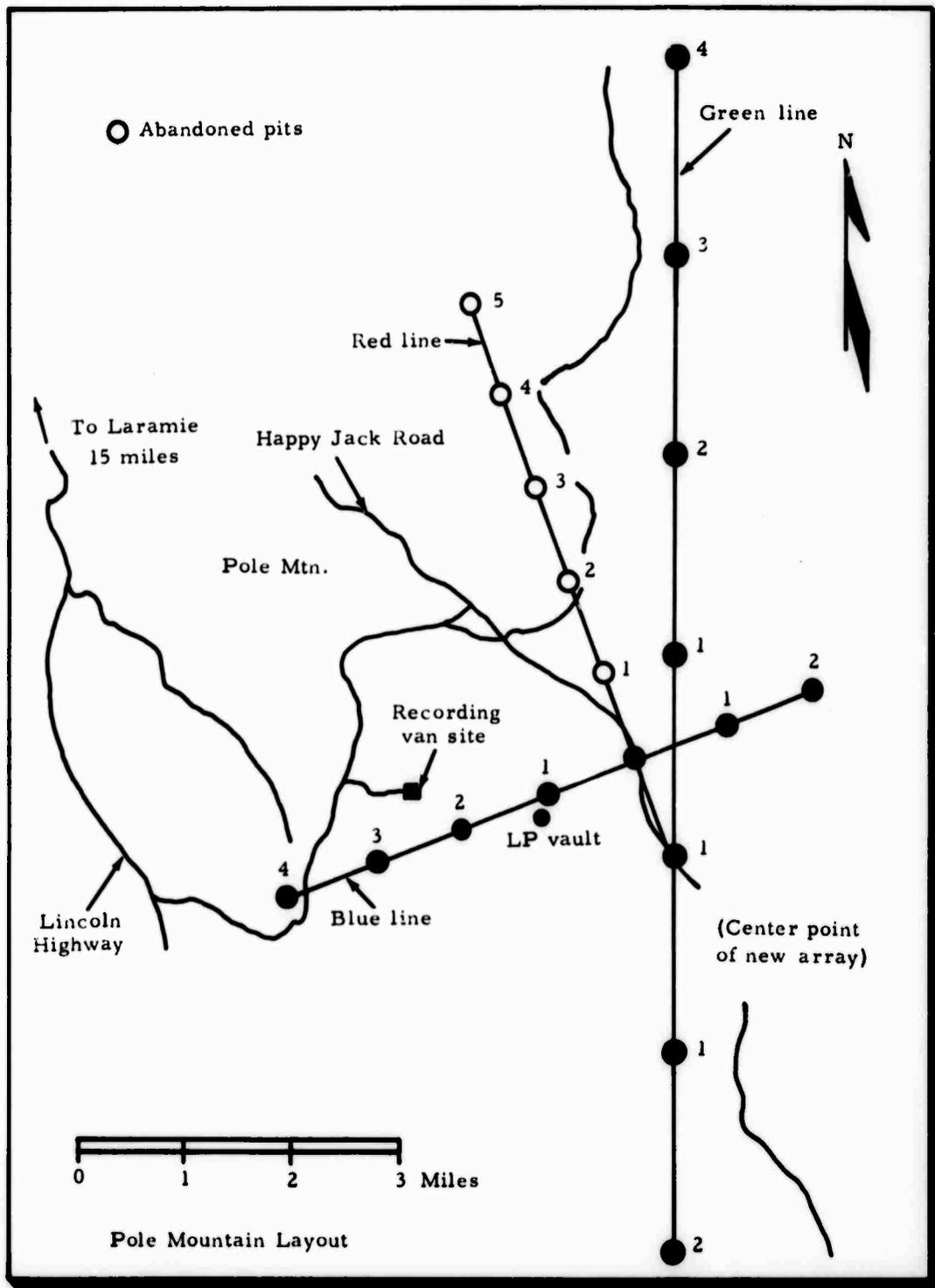
Figure 1.   Map of Pole Mountain array, Wyoming

severely than the coarse granites. As an aid in site selection, shallow refraction surveys were made by Geotech (The Geotechnical Corporation) during the period 28 June to 2 July 1962. The resulting velocities are shown in tables 1 and 2. GS 1 (Green South 1) and GS 2 (Green South 2) had not been located by the surveying crew so no refraction surveys were made. Of the vaults of the original array discussed in this paper, BW 3 (Blue West 3) and RS 1 (Red South 1) were set in coarse granite, whereas BW 1, BW 4, and BE 2 (Blue East 2) were set in weathered rock (see velocities, table 1). The RS 1 vault was overlain by about 5 ft of weathered rock having a velocity of 2205 ft/sec as shown in the column of tables 1 and 2 entitled "Weathered layer velocity." All the vaults of the Green line and all the relocated vaults of the Blue line were set in dense granite (see velocities in table 2) except BW 1, which was set in weathered granite having a velocity of 5500 ft/sec. The dashes in the weathered-layer-velocity column of tables 1 and 2 indicate that the rock containing the vault is exposed at the surface.

UKAEA Recording and Playout

The seismographs at Pole Mountain consisted of Willmore vertical or horizontal seismometers, amplifiers in each vault, corresponding amplifiers in the recording van, and a 24-channel FM tape recorder in the van. All the vaults studied contained Mark I (MKI) vertical seismometers that had

Table 1. Velocities and noise statistics for Pole Mountain array vaults during June 1962 noise sampling period

Station	Velocity vault rock in ft/sec	Velocity weathered layer in ft/sec	Median displacement amplitude mμ	Lower quartile mμ	Upper quartile mμ	Interquartile range mμ	Median period
RS1	11,500	2,205	0.79	0.61	0.94	0.33	0.51
BW1	3,000 est	1,500 est	0.78	0.40	0.97	0.57	0.53
BW4	3,000	1,500	0.90	0.69	1.17	0.48	0.45
BE2	3,000 est	1,500 est	0.99	0.93	1.59	0.60	0.47
BW3 MI	13,200	-	0.90	0.69	0.99	0.30	0.48
BW3 MII	13,200	-	0.97	0.59	0.99	0.40	0.47

Table 2. Velocities and noise statistics for Pole Mountain array vaults during November 1962 noise sampling period

Station	Velocity vault rock in ft/sec	Velocity weathered layer in ft/sec	Median displacement amplitude mμ	Lower quartile mμ	Upper quartile mμ	Interquartile range mμ	Median period
RS1	11,500	2,205	0.98	0.71	3.65	2.84	0.54
BW1	5,500	-	2.09	0.94	5.63	4.69	0.56
BW4	9,375	-	1.18	0.91	2.67	1.76	0.54
BE2	12,500	-	0.99	0.82	2.18	1.36	0.52
GN2	12,050	-	0.91	0.70	1.32	0.62	0.54
GN1	9,050		1.99	1.03	3.44	2.41	0.52
GN4	11,250		2.20	0.96	4.52	3.56	0.56

damping factors of 0.18 critical. In addition, BW 3 contained a Mark II
(MKII) vertical seismometer that had a damping factor of 0.92 critical.

For this study, the UKAEA sent 10 rolls of noise data replayed from tapes
recorded prior to site selection in June 1962; and 10 rolls of noise data
replayed from tapes recorded after site selection in November 1962. These
replayed data had been recorded on paper using an 8-channel Sanborn recorder.
Each roll contained hourly noise playouts about 2 min long for one 24-hour
period from as many as seven seismometers. The remaining channel was
used for the timing trace. Noise playouts of June recordings were obtained
for RS 1, BW 1, BW 4, BE 2, BW 3 (MKI), and BW 3 (MKII). Noise playouts
of November recordings were obtained for RS 1, BW 1, BW 4, BE 2, GN 2,
GN 1, and GN 4. All noise data were played out using a 4-cps low-pass filter.
Because it was necessary to replay the calibration pulses with the filters out,
replay system response curves were provided by the UKAEA to correct for
filter insertion loss or gain.

Reduction and Processing of Pole Mountain Array Data

Each 2-min playout was sampled by measuring the peak-to-peak amplitude
in millimeters of the largest noise amplitude present in the 10-sec interval
following the second minute mark. Measurements of pulse amplitude, pulse

frequency, insertion loss of the playback filter, and frequency response factor of the seismometer were recorded in tabular form suitable for FORTRAN coding. The daily-noise samples for each seismometer were combined. Thus, there were six sets of noise samples for the June period and seven sets of samples for the November period. A FORTRAN program was written for a CDC 160A computer to calculate ground velocities for each set and convert to ground displacement (see appendix).

In addition, a second FORTRAN program, called Noise Statistic, was written to calculate and print out on paper the following: (1) percentage of occurrence versus amplitude, (2) percentage of occurrence versus period, (3) a plot of the former, (4) a plot of the latter, (5) cumulative percentage of occurrence versus amplitude, (6) cumulative percentage of occurrence versus period, (7) a plot of the former, and (8) a plot of the latter.

Analysis of Data

From the plots of cumulative percentage of occurrence versus amplitude, values were taken for the median, the lower quartile, and the upper quartile. The interquartile range, the difference between the upper and lower quartile, is an indication of the range scatter about the median, and is referred to as dispersion in this paper. These values for the June and November periods are presented in tables 1 and 2 along with the velocity information. Amplitudes

and periods of noise at GN 2 and GN 4 during the November sampling period are shown in figure 2. Figure 3 shows plots of median ground displacement amplitudes versus velocities for June and November. The June plot shows the median amplitudes for all vaults are about the same throughout the velocity range. The November plot shows some association: the product-moment correlation coefficient, r, (Ostle, 1963, p. 36, 224, and 225) of the plot is only -0.48.

Because of the low correlation, some other relationship was sought because vault sites having about the same velocities had differing noise levels. The two sites having the greatest difference, GN 4 and GN 2, also differ in their topographic setting. The former was located in a flat area, whereas the latter was located below the south side of a high outcrop. Assuming that the prevailing wind in November was from the northwest or north, wind protection numbers based on their topographic settings were assigned to all vaults in dense granite, as shown in table 3.

Table 3. Pole Mountain array wind protection numbers

Vault	Topographic Setting	Wind Protection No.
GN 4	Flat grassland	2
GN 1	Flat forestland	3
BW 4	South slope	4
BE 2	South slope	4
GN 2	South slope protected	5
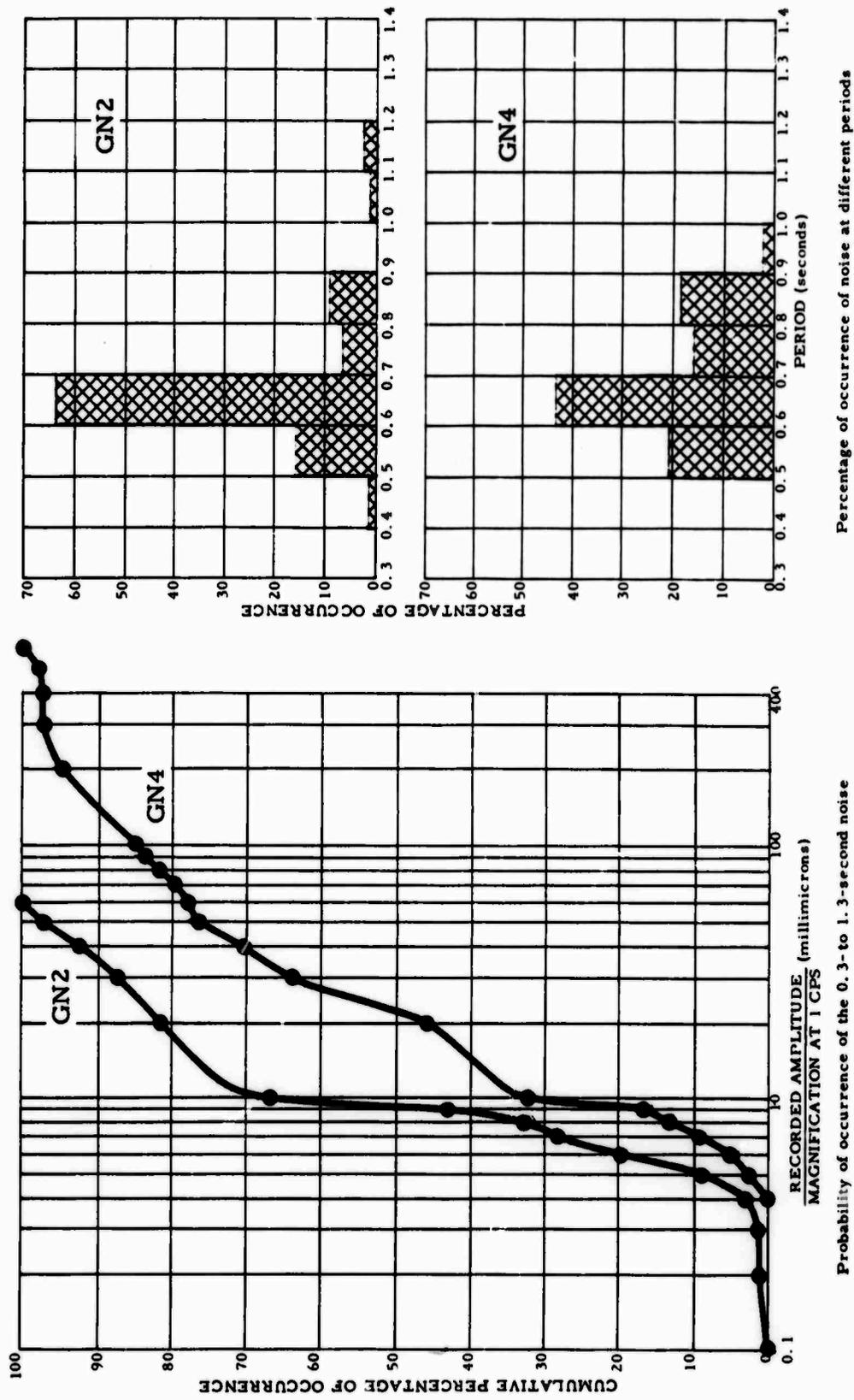
Figure 2. Cumulative percentage of occurrence vs amplitude and percentage of occurrence vs period of 0.3- to 1.3-sec noise at GN2 and GN4 during November sampling period
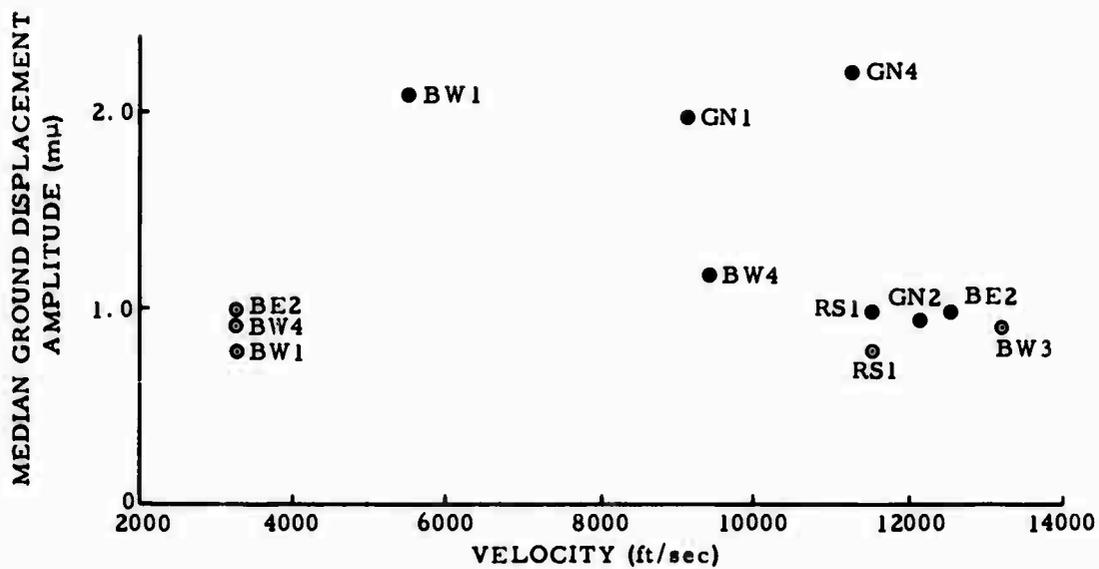
Figure 3. Plot of median ground displacement amplitude vs velocity
for Pole Mountain array vaults during June sampling period
(open circles) and November sampling period (dots)
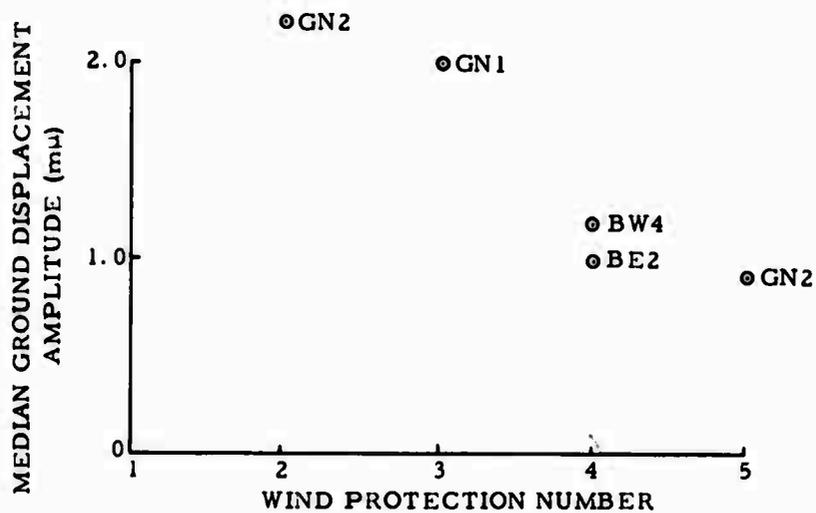
Figure 4. Plot of median ground displacement amplitude vs wind
protection number for Pole Mountain vaults in dense surface
rock for November noise sampling period

Site RS 1 was located on a ridge that supports very few trees. The original BW 1 was located on the south slope of a small divide, and the vault was relocated at the bank of a stream bed about 300 ft southeast of the original location. The original BW 4 was located on the north side of a small stream valley; the vault was relocated in a rolling area about 1500 ft west of the original vault. The original BE 2 vault was located near a stream bed, and was relocated in a rocky area on the south slope of a divide about 600 ft southeast of the original vault. BW 3 was originally located about 250 ft south of a prominent outlier called Brady Rock. As for the new vaults, GN 1 was located in a flat, forested area; GN 2 was located on the south side of a prominent outcrop; and GN 4 was located on a flat grassland.

Wind protection numbers versus median ground displacement amplitudes are shown in figure 4 for the November period. The product-moment correlation coefficient is -0.95 indicating that as topographic protection increases, the noise decreases. The low median displacement amplitude and low dispersion for GN 2 (table 2) indicated that the vault was virtually unaffected during windy periods.

RS 1 was anomalous in that it had a low displacement value even though it was on a ridge. It is suggested that the weathered material overlying the vault offers protection from wind. However, the relatively large interquartile-range value (table 2) indicated that wind energy was transmitted to the vault

through the weathered layer. BW 1 was anomalous in that it had a relatively large displacement value but was on a south slope. This is a possible indication that sites in weathered rocks are noisier regardless of their protection. However, there is the possibility that the higher noise level at BW 1 was caused by westerly winds, which were common at the Cheyenne Weather Station during November 1962.

In order to test the idea that topographic protection from wind limits ground displacement, background noise at vaults Z1 through Z9 of the WMSO array was sampled during periods of strong northerly and southeasterly winds. The analyses of ground displacements are discussed in the following section.

ANALYSIS OF SHORT-PERIOD WIND NOISE AT THE WMSO ARRAY

Reduction and Processing of WMSO Array Data

To find a day when strong winds, about 30 mph, were blowing at WMSO, the daily weather maps published by the U. S. Department of Commerce were scanned for the spring of 1964. Wind speeds and directions for WMSO were assumed to be similar to those at the Oklahoma City Station. Film records (16-mm) of vaults Z1 through Z9 were obtained for 7 April when a 30-mph northerly wind was blowing and for 6 May when a 30-mph south-easterly wind was blowing.

The largest noise amplitude in the period range of 0.3 to 1.3 sec present in the 10-sec interval following a 5-min mark was measured for each vault. Amplitudes were corrected for instrument response, and the magnification at 1 cps was used to obtain the ground displacements in millimicrons. All measurements of amplitudes were peak-to-peak, and 100 samples were taken for each vault on 7 April and 6 May. For comparison purposes, 40 samples were taken for each vault on 8 April when a northerly wind was blowing about 12 mph. Amplitude, period, and instrument-response correction for the samples from each vault were recorded in tabular form for FORTRAN coding. Magnifications at 1 cps for each seismograph were calculated previously by WMSO personnel.

A FORTRAN program was written to calculate ground displacement, given the magnification, amplitudes, and response-curve corrections on IBM cards. Paper printout for each vault consisted of magnification, noise-pulse amplitude, response correction factor, period, and displacement. Card output consisted of pulse frequency and displacement. Thus, there was no need to modify the Noise Statistic program used to analyze the Pole Mountain data. Printout from the Noise Statistic program for the WMSO data consisted of the statistics given in the section on processing of the Pole Mountain array data.

Analysis of WMSO Data

The WMSO array under study is shown in figure 5 superimposed on a topographic map copied from a map of the Mount Scott Quadrange, Oklahoma, published by the U. S. Geological Survey of the Department of the Interior.

Vault 6 of this array is a walk-in vault, whereas the rest are tank vaults. The walk-in vault is a concrete building containing a pier that is attached to surface rock. The other vaults are tanks set with their tops flush with the surface. Thus, all vaults are probably set in the layer of low transmission velocities. Johnson-Matheson (JM) vertical seismometers were located in these vaults. Vault installation and instrumentation at WMSO before place-ment of the triangular array are discussed by Gudzin and Hamilton (1961).

In order to study the relationship between wind noise and topography for different wind directions, the topographic equivalents and wind protection numbers were modified as shown in table 4. Thus, these wind protection numbers can be used for any wind direction by referring to the topographic map.

Table 4. WMSO array wind protection numbers and topographic equivalents

Wind Protection Number	Topographic Setting
1	Hilltop or ridge
2	Unprotected slope
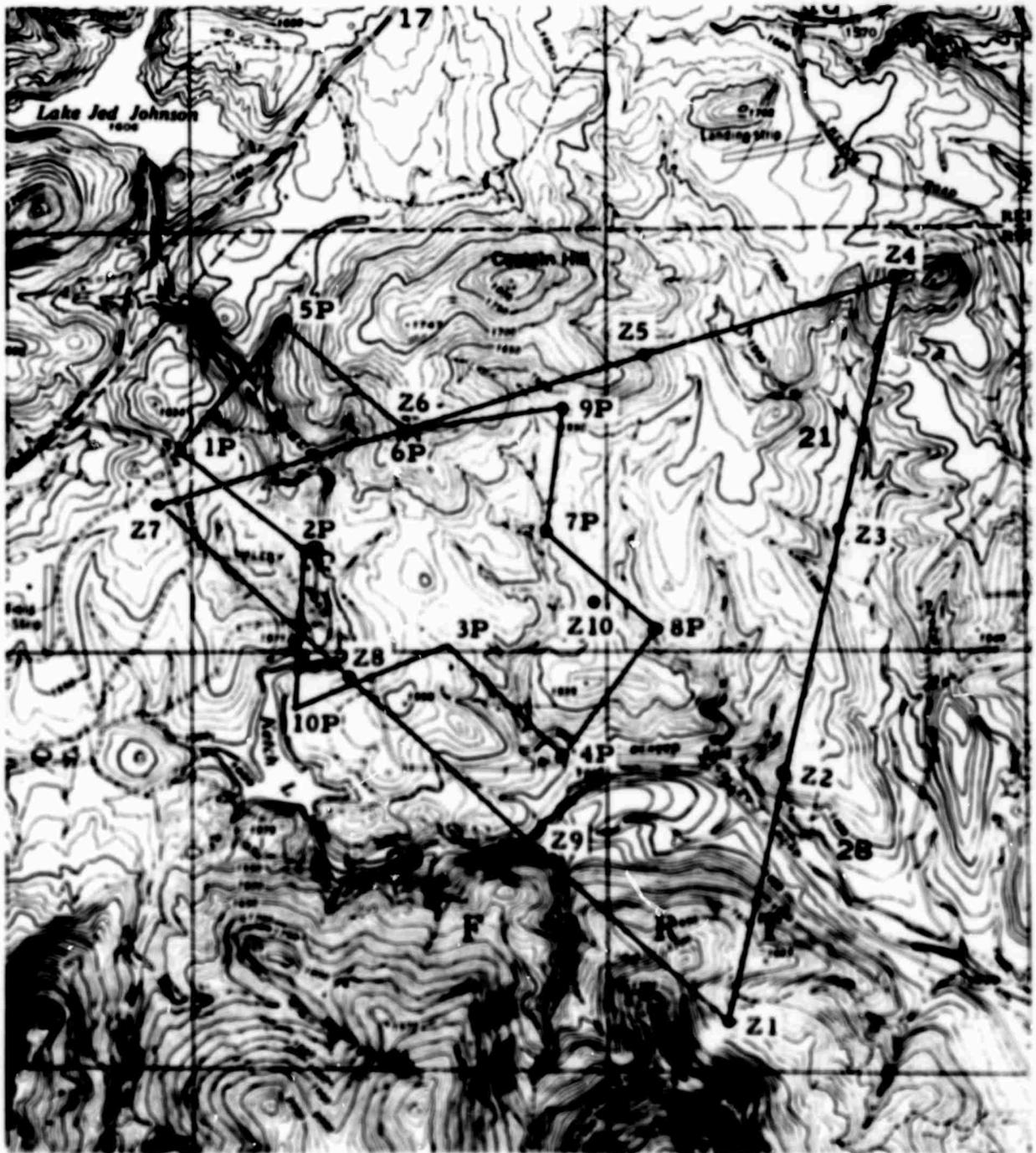
Figure 5. Topographic map showing vault locations at WMSO array, Oklahoma

Wind Protection Number	Topographic Setting
3	Slightly protected slope
4	Unprotected lowland
5	Slightly protected lowland
6	Protected slope
7	Protected lowland

Curves of cumulative percentage of occurrence versus amplitude and percentage of occurrence versus period for vaults Z3 and Z4 for 7 April are shown in figure 6. Tables 5, 6, and 7 summarize the statistical information obtained from the curves of 7 April, 8 April, and 6 May, respectively. Plots of wind protection numbers versus median displacements for 6 May, 7 April, and 8 April are shown in figure 7. The median displacements on 7 April are greater than on 6 May because the wind blew continuously on 7 April, whereas the wind slackened after about 12 hours on 6 May. Thus, noise-pulse amplitudes were high throughout the entire record of 7 April, but amplitudes lessened on 6 May when the wind died.

Strong Southeasterly Wind of 6 May 1964

The product-moment correlation coefficient for the plot in figure 7 is -0.72, indicating good negative linear correlation between the wind protection numbers and wind noise. Z9, which is located on the north side of a hill
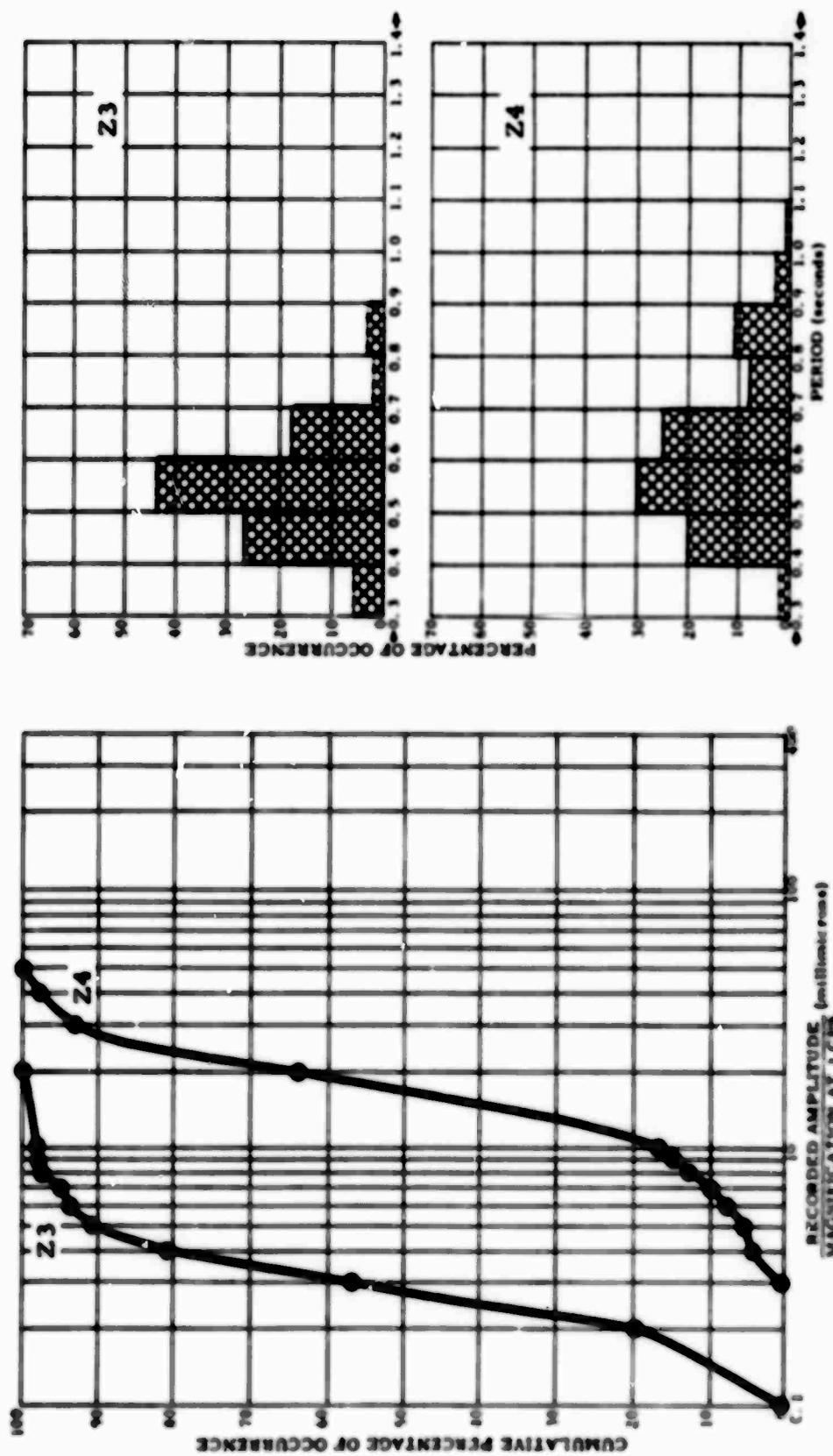
Figure 6. Cumulative percentage of occurrence vs amplitude and percentage of occurrence vs period of 0.3- to 1.3-sec noise at Z3 and Z4 during period of 30-mph northerly wind on 7 April 1964

Table 5. Noise statistics for WMSO array during period of
30-mph northerly winds on 7 April 1964

Station	Wind protection no.	Median displacement amplitude mμ	Lower quartile mμ	Upper quartile mμ	Interquartile range mμ	Median period
Z1	3	3.00	1.92	5.00	3.08	0.51
Z4	1	17.6	13.5	22.5	9.0	0.48
Z7	1	14.9	10.0	17.5	7.5	0.51
Z2	4	3.07	2.20	3.91	1.71	0.43
Z3	7	2.78	2.17	3.63	1.46	0.43
Z5	3	2.95	2.01	4.04	2.03	0.47
Z8	2	6.04	3.59	9.12	5.53	0.45
Z9	2	4.17	2.60	7.46	4.86	0.45
Z6	6	2.18	1.67	2.70	1.03	0.46

Table 6. Noise statistics for WMSO array during period of
12-mph northerly winds on 8 April 1964

Station	Wind protection no.	Median displacement amplitude mμ	Lower quartile mμ	Upper quartile mμ	Interquartile range mμ	Median period
Z1	3	1.89	1.31	2.50	1.19	0.49
Z4	1	2.78	2.10	3.53	1.43	0.53
Z7	1	2.48	2.13	3.13	1.00	0.53
Z2	4	1.58	1.19	2.05	0.86	0.47
Z3	7	1.64	1.21	2.18	0.97	0.47
Z5	3	1.88	1.41	2.30	0.89	0.48
Z8	2	2.09	1.61	2.57	0.96	0.51
Z9	2	1.89	1.51	2.65	1.14	0.52
Z6	6	2.08	1.58	2.57	0.99	0.48

Table 7. Velocity and noise statistics for WMSO array during period of 30-mph southeasterly winds on 6 May 1964

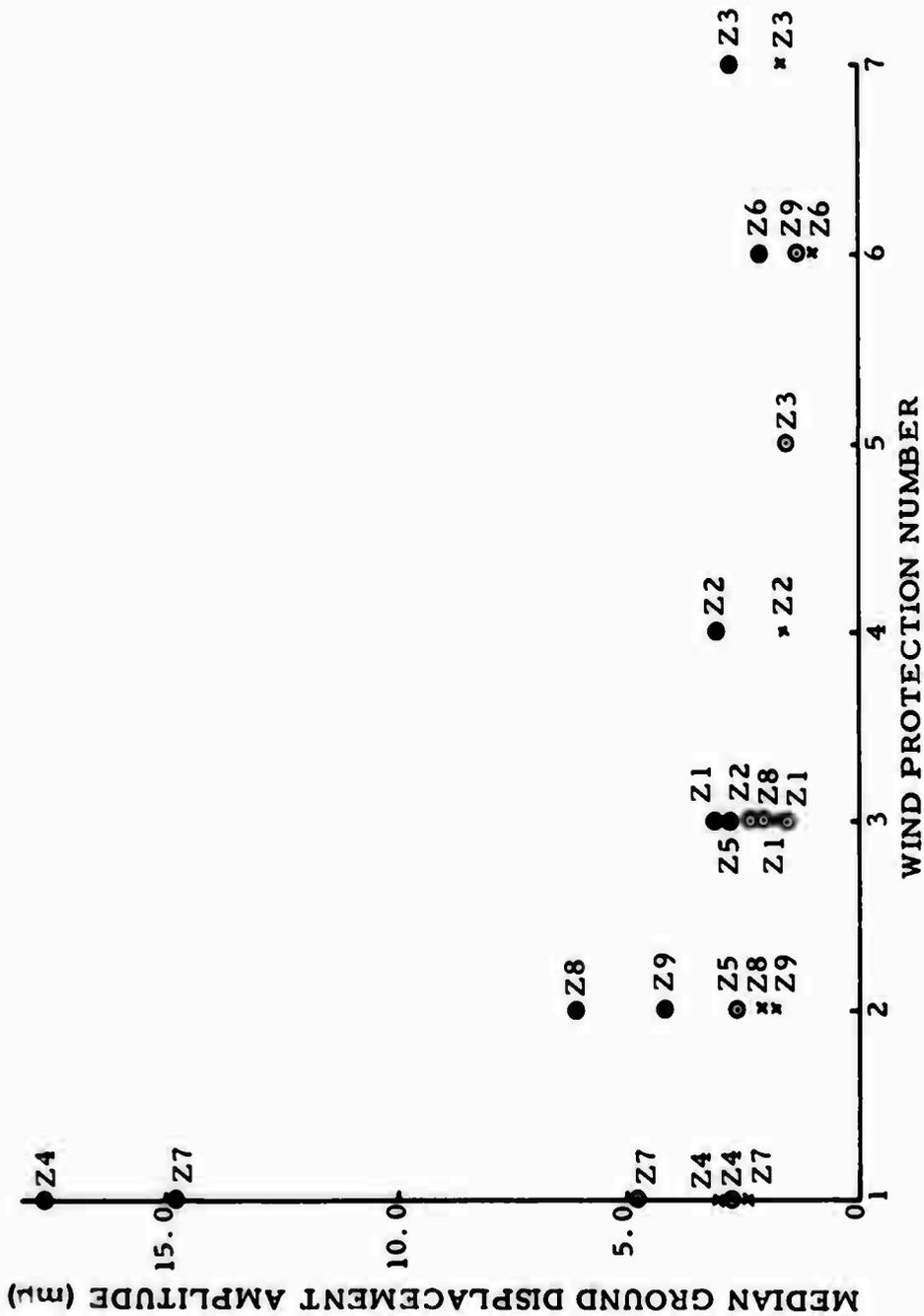| Station	Wind protection no	Velocity vault rock in ft/sec	Velocity weathered layer in ft/sec	Median displacement amplitude mu	Lower quartile mu	Upper quartile mu	Interquartile range mu	Median period
Z1	3	No data	No data	1.59	1.43	4.34	2.91	0.51
Z4	1	1.260	1.260	2.71	1.39	7.96	6.57	0.54
Z7	1	1.300	1.300	4.95	1.78	12.00	10.22	0.51
Z2	3	1.620	1.620	1.73	1.18	3.42	2.24	0.43
Z3	5	1.320	1.320	1.59	1.38	2.88	1.50	0.46
Z5	2	1.370	1.370	2.57	1.52	4.06	2.54	0.46
Z8	3	1.390	1.390	1.69	1.37	3.47	2.10	0.47
Z9	6	2.000	2.000	1.29	1.03	3.05	2.02	0.48
Z6	3	2.480	2.480	1.89	1.19	2.58	1.39	0.48

Figure 7. Plots of median ground displacement amplitude vs wind protection numbers for WMSO array vaults during periods of 30-mph southeasterly winds on 6 May 1964 (open circles), 30-mph northerly winds on 7 April 1964 (dots), and 12-mph winds on 8 April 1964 (x's)

at its base, has the lowest median displacement amplitude of 1.29 mμ. Z3, located in a stream bed, has a median displacement amplitude of 1.59. Z5, Z4, and Z7 at high topographic positions exposed to the southeasterly winds have median displacement amplitudes of 2.57 mμ, 2.71 mμ, and 4.95 mμ, respectively. Thus, the median at Z7 was about 12 db greater than the median at Z9. The dispersion at Z7 (10.22 mμ) was about 17 db greater than the dispersion at Z6 (1.39 mμ), the walk-in vault.

Strong Northerly Wind of 7 April 1964

The plot of wind protection numbers versus median ground displacements (figure 7) suggest a nonlinear regression. The median of 17.6 mμ at Z4 was 18 db greater than the median of 2.18 mμ at Z6. Of the two vaults having the largest median values, Z4 was exposed directly to the northerly wind and Z7 (14.9 mμ) was on a ridge, but leeward of a hill. Z7 was the noisier of the two on 6 May when it was exposed directly to the southeast wind. Z9, which was not protected from the northerly wind, had a median value of 4.17 mμ. That was about 10 db greater than the median value of 1.29 mμ during a period when Z9 was protected from strong southeasterly winds. Because of sampling differences for the different wind directions, 10 db is probably too high. The increase in dispersion of 8 db may be a more realistic value for the increase in noise at Z9 during the period when exposed to the northerly wind.

Light Northerly Wind of 8 April 1964

The plot of wind protection numbers versus median ground displacement amplitudes (figure 7) again suggests a nonlinear regression. The highest median value is 2.78 mμ for Z4; the lowest is 1.58 mμ for Z2. Thus, the median value for Z4 is about 5 db greater than that for Z2. For some reason, median values for Z6 and Z3 are larger than expected. This may be due to the small sample of 40 noise values that were used to obtain the median.

Velocity versus Noise

Figure 8 is a plot of velocity versus median ground displacement for the WMSO array vaults during the period of strong northerly winds. Weathered-layer velocities are used. This plot shows a negative trend, but the variations in noise between vaults Z4 and Z3, having about the lowest velocities, is almost as great as the variation in noise between vaults Z4 and Z6, having the greatest difference in velocities. A regression line could be fitted to the points, but any predictions based on this line would be uncertain because of the scatter caused by topographic effects.
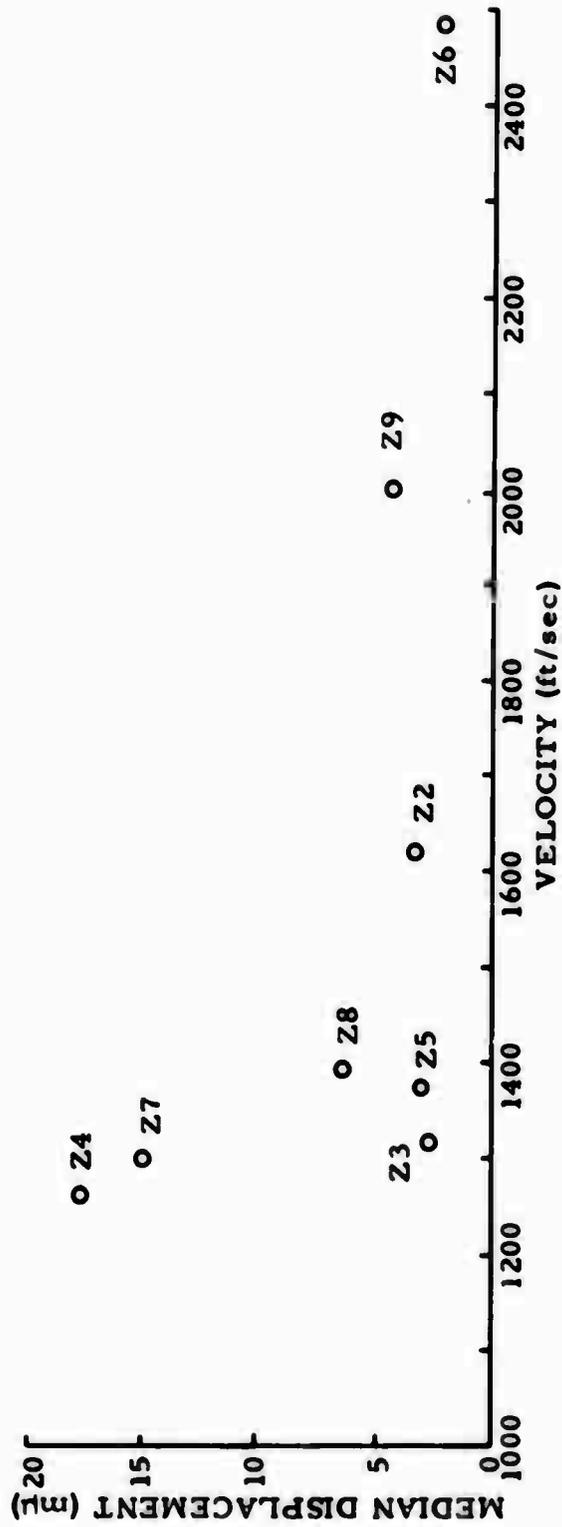
Figure 8. Plot of median ground displacement amplitudes vs velocities at vaults of WMSO during period of strong northerly winds on 7 April 1964

Noise Dispersion During Period of Strong Northerly Wind

So far, the central tendency of the noise has been discussed, but dispersion or scatter about the median has been mentioned just briefly. Yet some sites having about the same median noise have unlike dispersions. Thus, measures of the variability of noise, such as the interquartile range, were included along with median values of noise.

The relationship between wind protection number, median noise, and dispersion is shown in a three-dimensional plot (figure 9). The interquartile ranges in table 6 were halved and plotted as plus and minus values about the median values parallel to the Z axis. This plot shows an increase in noise variation as well as median noise as the site protection decreases during periods of strong winds. Hence, wind-noise variations and levels may be predicted and controlled if wind speeds, wind directions, and topographic setting of sites are known.

Bradford and others (1964) found that wind noise becomes significant when surface-wind speeds exceed 15 knots. Their investigations of a number of sites indicated that a surface pressure gradient of 2 mb/100 km was indicative of surface wind speeds above 15 knots. Thus, weather maps could be used to estimate critical surface wind speeds and wind directions associated with pressure systems that are moving toward a particular site or array.

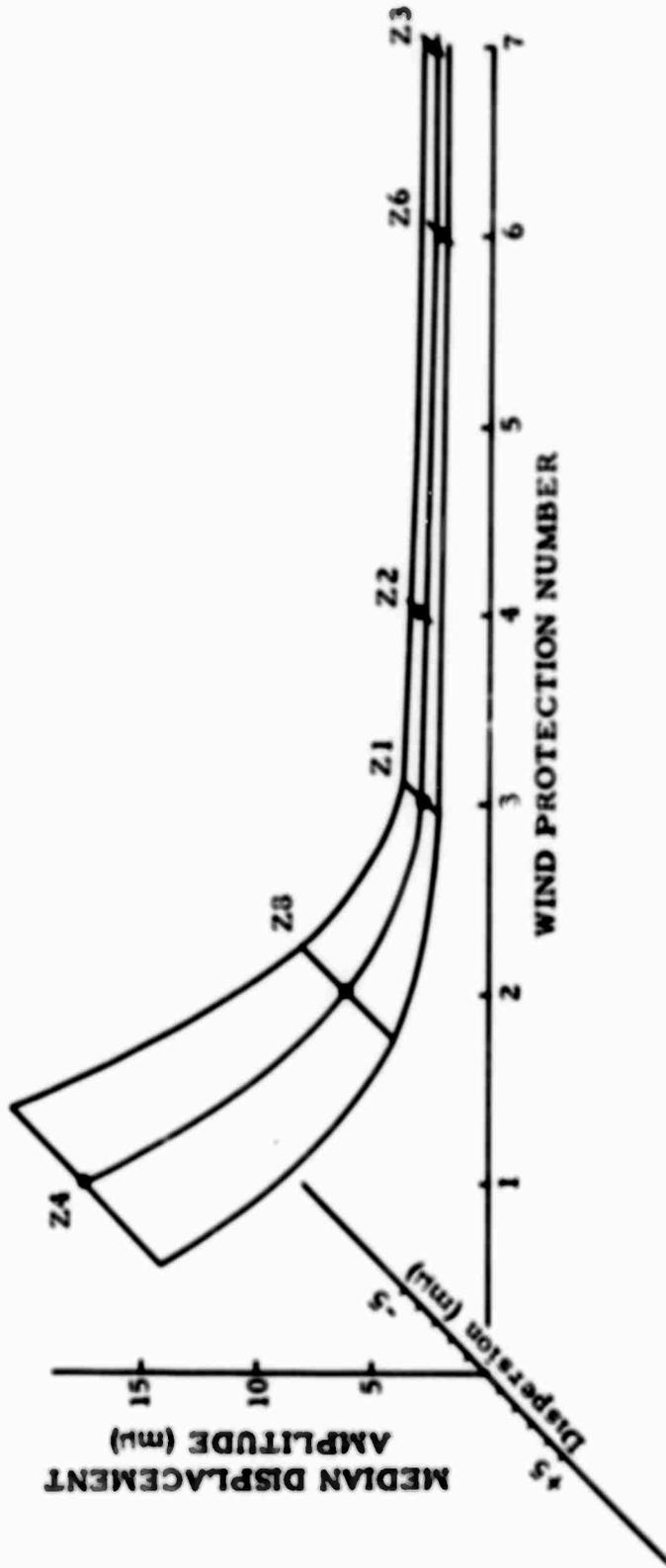TR 64-134   -24-

Figure 9. Plot showing wind protection number vs median displacement amplitude and dispersion for 30-mph northerly wind at WMSO array during 7 April 1964

Spectral Analysis of Noise Samples

Magnetic-tape records from vaults Z3, Z4, Z6, and Z7 were subjected to spectrum analysis, thereby giving additional data on the noisier (Z4 and Z7) and quieter (Z3 and Z6) vaults. Three-minute samples were taken on 27 September 1964 during a period when a northerly wind was blowing about 30 mph. Also, 3-min samples were taken from the same tape during a calm period. Figure 10 shows the power spectral energy density functions of the noise for windy and calm periods. Differences in power of ±3 db are significant at a 90 percent level of confidence. The wind energy at tank vaults Z3, Z4, and Z7 is shown by the significant increases in power at about 0.2 cps and in the band between about 0.5 to 3 cps. But for the walk-in vault Z6, the only significant increases in power are at about 0.2 and 1.0 cps. These spectral plots show a decrease in the wind contribution to noise with either topographic (Z3) or constructional (Z6) protection. Thus, they confirm previous findings on the effects of shielding. Moreover, spectral analyses of the noise at Z3 and Z6 show the topographic protection was not as effective as contructional protection in limiting wind noise at frequencies above about 0.7 cps.

A MEANS OF RELATING WIND PROTECTION NUMBERS TO TOPOGRAPHIC SETTING

In an effort to relate wind protection numbers to something measureable, the following assumption was made. If wind protection numbers are a function
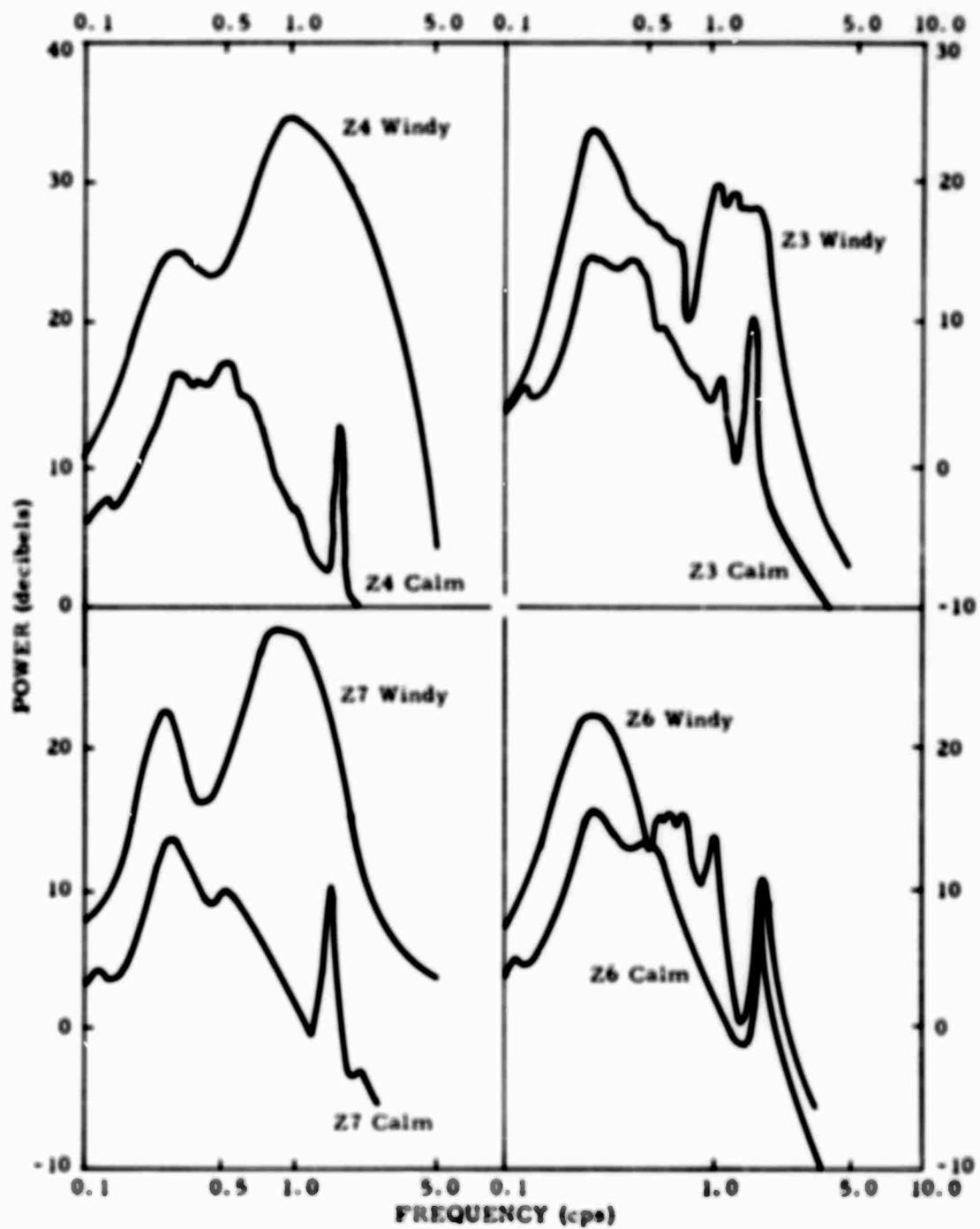
Figure 10. Power spectral density functions of the noise for windy and calm samples taken at Z3, Z4, Z6, and Z7. Note: 0db = $1(m\mu/sec)^2/cps$

of topographic setting, then the numbers must be a function of: (1) vertical distance from a projection to the site elevation, (2) horizontal distance from a projection to the site, and (3) the arctan of the angle between the horizontal and vertical. The vertical distance was chosen to be 10 ft, the contour interval on the topographic map (figure 5). The horizontal distance was the distance windward to the next highest contour. Figure 11 is a plot of the arctan versus median noise during the period of strong northerly wind. Each station is shown with its respective wind protection number. Wind numbers one and two that are related to the noisier sites follow in sequence except for Z7. The high noise level along the ridge at Z7, which is leeward of a small hill, may be due to either (1) wind direction a little east of north or (2) vortex motion (Prandtl and Tietjens, 1934, p. 139-223, figs 154-157; and Davidson, 1963, p. 463-472). The remaining numbers do not follow in sequence, but they do relate to the quieter sites. Thus, referring to table 4, "hilltop or ridge" and "unprotected slope" appear valid for numbers one and two, respectively. Because Z2 is the noisier of the quieter sites, "unprotected lowland" should be three. And the "slightly protected" and "protected" sites should be lumped as four. Figure 12 is a plot of the revised wind protection numbers versus horizontal distance. Distance rather than arctan was used in the plot to increase the order to magnitude of numbers of the ordinate. The plot shows a linear functional relationship. Thus, horizontal distances could be used instead of wind numbers as in figure 13. If the prevailing directions
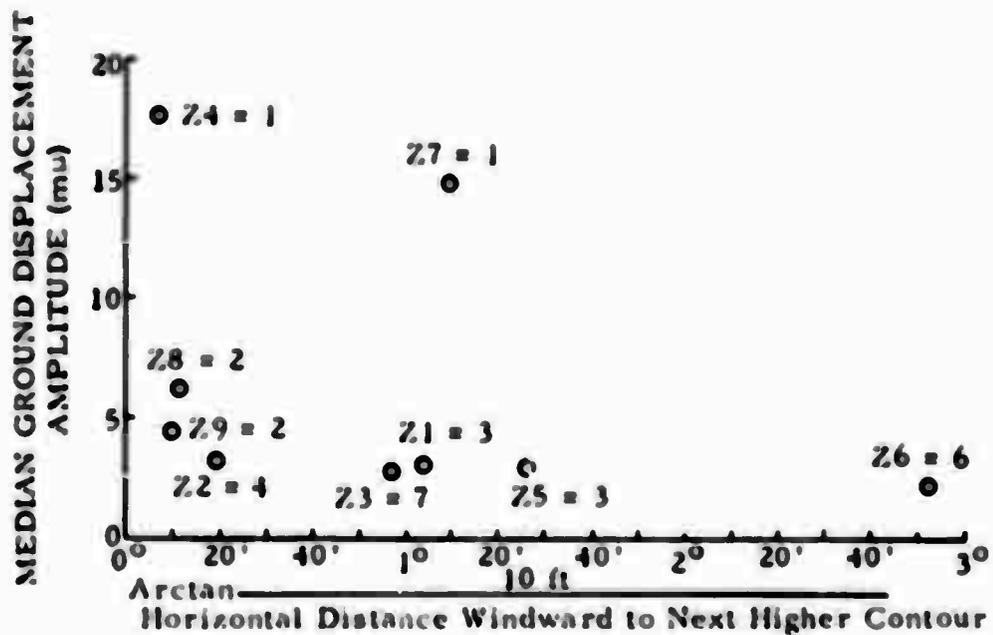
Figure 11. Plot of "protection angle" vs noise for WMSO
array during period of strong northerly wind on
7 April 1964. Numbers following equal
sign are wind protection numbers
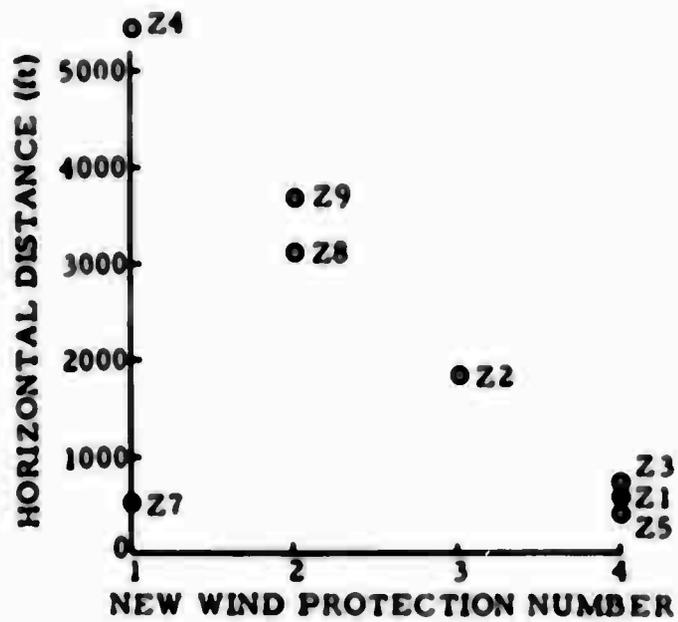
Figure 12. Plot of new wind protection numbers vs horizontal distance windward to next higher contour
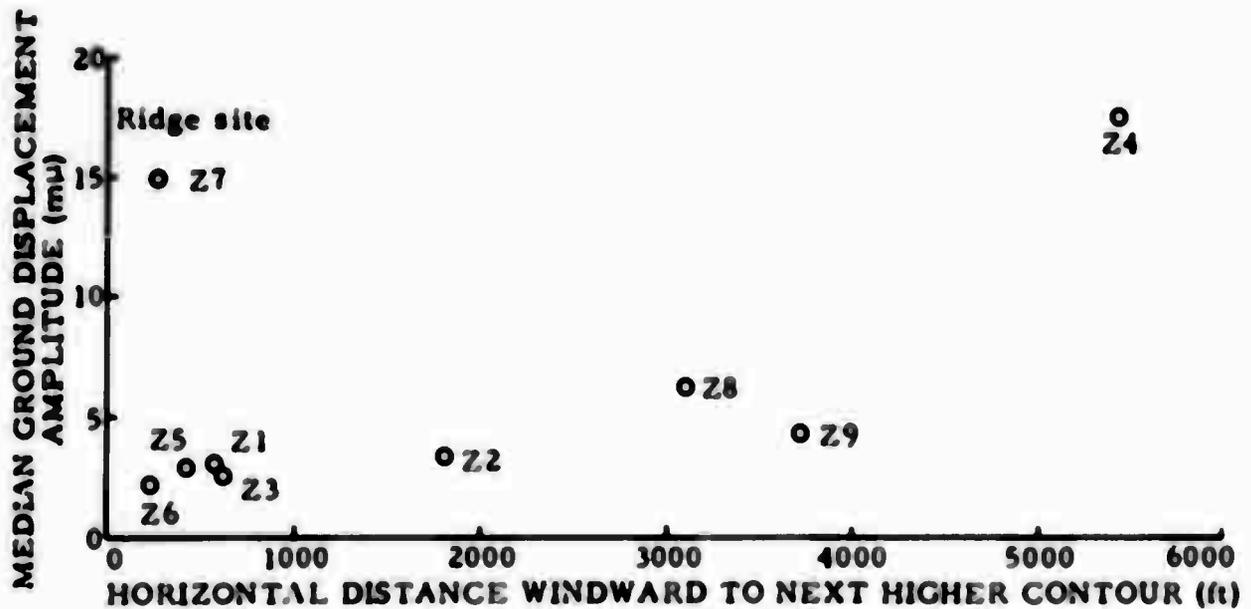
Figure 13. Plot of horizontal distance windward to next higher contour vs noise

ot probable strong winds are known, then wind-noise medians, dispersions, and spectra can be estimated from simple map or field measurements.

CONCLUSIONS

Plots of median ground displacement amplitude versus wave propagation velocity showed considerable scatter. However, plots of median ground displacement amplitude versus wind protection number indicated a functional relationship between topography and wind noise. Thus, topography rather than lithology was the principal factor affecting short-period wind noise at the Pole Mountain array and the WMSO array.

The walk-in vault at WMSO, located high on the south slope of a hill, had lower dispersions than all tank vaults and lower median displacement amplitudes than tank vaults in similar topographic settings. Also, spectral plots showed that wind energy at Z6 was less than that at Z3. Hence, vault construction was a major factor affecting wind noise.

ACKNOWLEDGEMENTS

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APPENDIX

The following equation was used to obtain ground velocity Z for a noise
pulse.

$$Z = \frac{C \times L \times S_s}{K \times D \times S_c \times F_T \times W} \times 10^{-6} \text{ cm/sec/mm}$$

where

    S_s = channel sensitivity for noise playout

    S_c = channel sensitivity for calibration playout

    C = calibration pulse in microvolts

    D = mean deflection of trace in millimeters for calibration pulse

    L = insertion loss of playback filter

    W = operational sensitivity of seismometer

    F_T = frequency response factor of Willmore

The factor K represents the attenuation of the calibration pulse C because of line capacitance effects.   Values for K are as follows.

BE 2	2. 1
BW 1	1. 4
BW 4	1. 6
RS 1	1. 7
GN 1	2. 2
GN 2	2. 4
GN 4	2. 9
BW 3	1. 3

APPENDIX 3 to TECHNICAL REPORT NO. 65-2

**TECHNICAL REPORT NO. 64-132, SPECIAL ORIENTATION
PROGRAM, PHASE I**

TECHNICAL REPORT NO. 64-132

SPECIAL ORIENTATION PROGRAM, PHASE I

THE GEOTECHNICAL CORPORATION
3401 Shiloh Road
Garland, Texas

15 December 1964

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CONTENTS

ILLUSTRATIONS

SPECIAL ORIENTATION PROGRAM

1. INTRODUCTION

In June 1964, the Air Force Technical Applications Center (AFTAC) announced plans to transfer several Long-Range Seismic Measurements (LRSM) mobile seismological observatories to other United States Government agencies and to several foreign agencies. Three fully-equipped vans were scheduled for transfer to the Office of Scientific Research (OSR). This agency, in turn announced its plan to present one of these vans to each of three foreign governments - Bolivia, Germany, and Norway. The Advanced Research Projects Agency (ARPA) also scheduled the transfer of six vans to the United States Coast and Geodetic Survey (USC&GS), and four vans to the United States Geological Survey (USGS). All transfers were scheduled to take place early in 1965.

In order for this equipment to be efficiently transferred, a special orientation program was requested by OSR. Its objective was to qualify the new station researchers to operate these seismological laboratories.

A proposal to conduct the orientation program (P-323) written by The Geotechnical Corporation (Geotech) outlined a five-point program, as follows:

1. Preparation;

2 Formal classroom instruction on equipment operation;

3. System setup exercises;

4. On-site visits, after the transfers have taken place to inspect the sites, modify and/or repair equipment, and instruct site operators on newly developed analysis techniques, station operations, etc.

5. Publication of a Signal Atlas of earthquake signals recorded at LRSM sites in Bolivia, Germany, and Norway.

Phase I of this proposal contained points 1, 2, and 3. Phase II contained points 4 and 5.

On 1 October 1964, Geotech was assigned the task of organizing and conducting this technical orientation program. All instruction was patterned after the operations established for the Long-Range Seismic Measurements Program (LRSM), Project VELA T/4051, Contract AF 33(657)-12145. Instructors were selected on the basis of their technical familiarity with LRSM field equipment and operations. An LRSM van was brought into Garland, Texas to complement the program.

The formal instruction phase of this program began on 19 October 1964 and was concluded on 25 November 1964.

This report summarizes Phase I, the preparation, classroom lecture, and station setup tasks of the Special Orientation Program. A final report will be submitted within 45 days after the completion of Phase II. This work is being conducted under Project 8652, Contract No. AF 49(638)-1150, Supplemental Agreement No. 3 (65-103), dated 1 October 1964.

2. PROGRAM PREPARATION

Instructors were assigned to teach specific subjects based on their technical competence and experience. Several conferences were held for the instructors to outline areas of responsibility, to gather material, and to prepare lecture outlines. Close coordination between the instructors was maintained to avoid duplication in the instruction outlines while assuring continuity between each course. Because of his broad experience in all phases of LRSM equipment and operation, Mr. Robert D. Wolfe was asked to serve as the Instructor Coordinator during the preparation phase.

The classroom area consisted of a two-building complex near the Geotech home office in Garland, Texas. One building contained three classrooms and a refreshment area; the second building contained one classroom and a large open area, suitably arranged for equipment demonstrations. These facilities were well suited to the program's needs.

LRSM requirements precluded the assignment of a mobile laboratory to the orientation program until the second week of the course. Such a condition was anticipated in advance and steps were taken to assure that needed equipment was available. Further, two seismograph systems were installed and

operating in the equipment demonstration building for use by the instructors.

3. PROGRAM INSTRUCTION

3.1 GENERAL

Thirteen students were expected for the orientation program, but only ten students attended. The following tabulation shows the agencies and countries represented at the program and the job category of each student.

No. of students	Representing	Category
2	USC&GS	Technicians
3	USGS	Technicians
1	Federal Republic of Germany	Physicist
1	Norway	Electrical Engineer
2	Bolivia	Electrical Engineer/Technician
1	Geotech	Technician
Total 10		

In addition, Father Luis Fernandez, St. Louis University, Missouri attended the site-setup phase of the program. He was in attendance from 20 November through 27 November.

All courses were taught in the English language. The technical terminology used in the classroom was not familiar to the Bolivian students, so an interpreter was in attendance at all classes and during the site-setup demonstration.

3.2 SCHEDULE

Prior to developing the schedule of classes, the following concepts were established:

   a. Classes were limited to three or four students to insure optimum class participation.

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b. All instruction contained these elements: Introduction, Component Theory and Operational Characteristics, Practical Demonstrations and Setup Exercises.

c. Instructors utilized visual aids to the greatest extent possible.

d. Classes began at 8:15 a.m. and normally were concluded at 4:45 p.m. Appropriate breaks were taken for lunch and coffee.

Figure 1 shows the original schedule for the classroom instruction. The nine students and one Geotech employee were divided into the three groups, A, B, and C as shown. Each group's schedule can be traced horizontally across the figure. Figure 2 is an expanded and modified schedule of the second-half of the classroom session (30 October through 17 November). Classes were rearranged to allow two days of system setup exercises for the USGS and USC&GS students. The program was concluded for these students on 17 November. The program continued for the foreign students through 25 November. This schedule of training is shown in figure 3.

3.3 TECHNICAL INSTRUCTION

Three diverse groups emerged as a result of separating the students into small classes.

The USGS students formed Group A. At their request, each course was adjusted to assure major emphasis be placed on equipment demonstration and setup exercises, and equipment maintenance procedures.

Group B was formed by the Bolivian students, one USC&GS student and one Geotech technician (from the LRSM team in Bolivia) acting as interpreter. This group desired a balance between theory and practical demonstration. An occasional language barrier slackened the pace of each lecture; however, this fact caused few problems in either program timing or in the students' ability to learn and retain the material.

The students from Norway and Germany and one student from USC&GS comprised Group C. Because of the relatively high educational backgrounds of these students, their interest lay primarily with the theory and operational characteristics of the equipment under review. Accordingly, instructors placed considerable emphasis in this area.

	19 Oct. 1 Day	20-21 Oct. 2 Days	22-23 Oct. 2 Days	26-27 Oct. 2 Days	28-29 Oct. 2 Days	30-Oct.-3 Nov 3 Days	4-6 Nov. 3 Days	9-11 Nov. 3 Days	12-16 Nov. 3 Days
		FIRST-HALF SCHEDULE					**SECOND-HALF SCHEDULE**		
Group A	INTRODUCTION	Site preparation and field wiring	Phototube amplifiers	Calibrations	Power	Seismometers	Tape system	Recorders (4 hours unscheduled)	Timing systems (4 hours unscheduled)
Group B	INTRODUCTION	Power	Site preparation and field wiring	Phototube amplifiers	Calibrations	Timing systems (4 hours unscheduled)	Seismometers	Tape system	Recorders (4 hours unscheduled)
Group C	INTRODUCTION	Calibrations	Power	Site preparation and field wiring	Phototube amplifiers	Recorders (4 hours unscheduled)	Timing systems (4 hours unscheduled)	Seismometers	Tape system

Figure 1. Original schedule for classroom instruction, Special Orientation Program

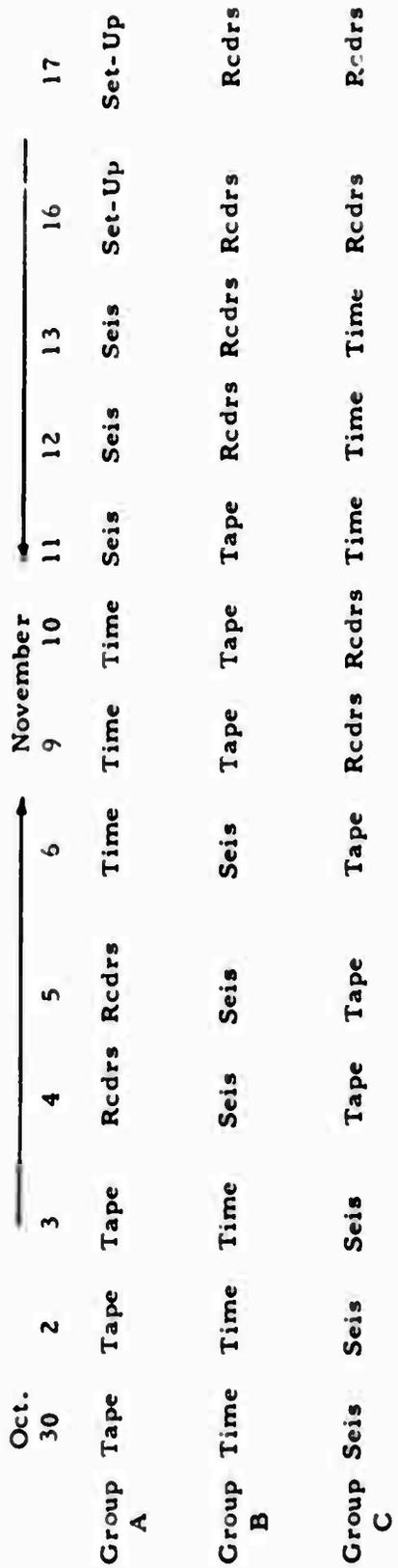| Group	Oct. 30	2	3	4	5	6	November 9	10	11	12	13	16	17
Group A	Tape	Tape	Tape	Rcdrs	Rcdrs	Time	Time	Time	Seis	Seis	Seis	Set-Up	Set-Up
Group B	Time	Time	Time	Seis	Seis	Seis	Tape	Tape	Tape	Rcdrs	Rcdrs	Rcdrs	Rcdrs
Group C	Seis	Seis	Seis	Tape	Tape	Tape	Rcdrs	Rcdrs	Time	Time	Time	Rcdrs	Rcdrs

Figure 2. Second-half schedule for classroom instruction,
Special Orientation Program, as modified
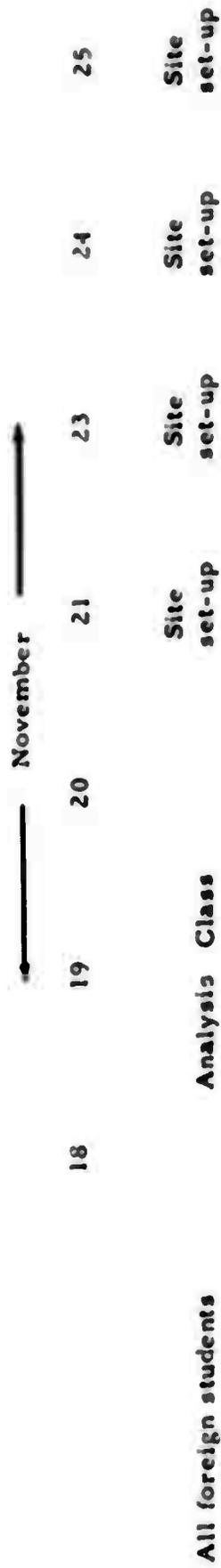
Figure 3. Schedule for analysis and system setup exercises

	18	19	20	21	23	24	25
			November				
All foreign students		Analysis Class					
				Site set-up	Site set-up	Site set-up	Site set-up

3.4 ANALYSIS INSTRUCTION

It was originally planned that one week of the orientation program be devoted to lectures on the basic interpretation of seismic records. The decision to provide two days' site setup experience for the USGS and USC&GS students, and additional recorder lectures for the foreign students, altered the analysis schedule. These two days were provided by reducing the analysis lectures to three days.

During the three-day analysis course, emphasis was placed on the proper preparation of USC&GS data messages. Additional lectures included an introduction to data processing techniques applicable to the Seismological Bulletin, as well as an introduction to analysis of 35-mm film seismograms.

4. CONCLUSIONS

a. The basic objective of the orientation program to assure that all students were qualified to perform the fundamental operations of a mobile seismological laboratory was achieved;

b. The limited time allowed in the contract for an equipment packing and moving demonstration and site setup exercises restricted the students' proficiency in these areas. It should be expected that these men will encounter some difficulty in their efforts to move and setup the first time. If possible, qualified Geotech technicians should be made available to assist with any moves that might be planned;

c. The students' attitude towards studying and their apparent eagerness to learn were commendable;

d. Operation and maintenance manuals were not available for all equipment components. In these cases, corrected schematic diagrams, memoranda and other pertinent material were offered to the students;

e. The concept of limiting the size of each class was justified as evidenced by the personal attention required by and given to each student.

5. RECOMMENDATIONS

a. During the planning stage of future similar orientation programs, classes should be scheduled to cover the following time periods:

Course	Recommended period (days)	Special orientation program schedule (days)
Site setup	1-1/2	2
Calibrations	2	2
Power	1-1/2	2
Phototube amplifiers (PTA)	2-1/2	2
Timing systems	4	3
Magnetic-tape systems	3	3
Seismometers	3	3
Recorders	2	3

b. Some value in each class is lost if an LRSM van and equipment is not readily available for the purpose of demonstrations. Site setup, phototube amplifier and calibration lectures can be taught without the use of the van if sufficient planning precedes each lecture. Other classes should not be taught unless the van and its equipment are available.

c. Consideration should be given to combining the seismometer and calibration lectures into a single course. Considerable overlapping of topics was evident in these lectures.

d. Future orientation programs should allow three weeks in which to conduct a site-move and setup course.

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