A FIELD INVESTIGATION OF THE INFLUENCE OF SITE CONDITIONS ON GROUND AND STRUCTURAL RESPONSE

by

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SYNOPSIS

This paper is intended as a contribution to the general problem of determining the effect of soil type on the seismic characteristics of the ground. It describes a controlled field investigation in which the ground surface response to artificial excitation was measured at two distinctly different soil sites. One of the sites was located on a firm rock outcrop, the other on a 20-ft clay deposit overlying bedrock. Artificial excitation of the ground was created by detonating 300-lb. depth charges on the ocean floor under 600-ft. of water. The sites selected for the study were situated within 1000-ft. of each other and at a distance of approximately 12 miles from the explosive source, such that both locations were simultaneously subjected to essentially the same disturbance.

An appraisal of the effect of ground condition on response is made by analyzing and characterizing the measured vibrations by means of power spectral density methods and response spectrum techniques. The main results are summarized by "response amplification spectra" which define the ratio of maximum structural response of soil to rock founded structures as a function of their natural period and damping. It is noted that experimental investigations similar to the one outlined above may provide useful data for seismic zoning and microzoning studies.

I. GENERAL

1.1 Introduction: It has long been recognized that local soil conditions and geology can have a significant effect on the destructiveness of earthquakes[1]. Many seismic countries recognize the importance of this fact by accounting for ground conditions in some qualitative manner in their building codes[2]. However, despite an active history of research in this area, the influence of site characteristics on earthquake motions remains one of the major uncertainties in earthquake engineering. Since earthquake ground motion characteristics play a strong role in governing the dynamic response of structures, a more accurate understanding of the dynamic behaviour of the ground is of utmost concern in the continuing development of rational earthquake resistant design procedures.

In general, investigations of dynamic site characteristics have taken

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three forms, namely (i) earthquake damage statistics, (ii) theoretical work, (iii) field and laboratory studies using large and small natural earthquakes, simulated earthquakes, explosive generated ground motions and microtremor measurements. Such studies have been pursued with special vigour by the Japanese[3], notably Kanai[4] and a number of his colleagues, and much significant progress on the overall problem has been made. In the U.S.S.R., Medvedev[5] and others[6] have developed methods for estimating the effect of surficial deposits on the intensity of earthquake motion for the purpose of seismic microzoning. Various phases of the problem have also been examined by numerous researchers in the U.S.A.[7,8,9]. In 1958 Duke[10] prepared a comprehensive listing of published material on the subject.

Information on the seismic behaviour of different ground deposits, which is obtainable from the measurements of ground response to real earthquakes, is limited for practical reasons because of the rarity of strong earthquakes. As a consequence, the direct experimental determination of in situ dynamic properties of soil and rock sites by artificial excitation of ground motion has been used to speed the production of data. This approach has obvious appeal; impact methods, explosive charges, quarry blasts and vibration generator techniques have been employed for this purpose in the past. In this paper underwater depth charges are utilized as the energy source for ground excitation in a pilot investigation for controlled field studies of site characteristics and their effects on structural response. This technique does not appear to have been exploited previously in earthquake engineering experiments.

1.2 Object and Scope of Investigation:

The work reported in this paper was originally undertaken to examine the feasibility of using depth charge blasts to supplement the data obtained from measurements of microtremors and small and large magnitude earthquakes. This information was desired for a proposed research program for evaluating the seismic characteristics of different ground sites. The first part of the paper is devoted to a description of the site conditions and instrumentation system. This is followed by a presentation of the ground motion measurements and an analysis of the data by means of response spectrum techniques and stochastic process reduction methods using power spectral density functions.

1.3 Ground Site Conditions:

Ground surface response to an underwater explosive charge was measured simultaneously on two distinctly different soil sites situated at the southern end of Vancouver Island, in the City of Victoria, off the west coast of British Columbia. A general schematic plan of the test area, showing site positions and shot point, is given in Fig.1. Appropriate seismic and subsoil profiles for the area are presented in Fig. 2; this information was gathered from existing surveys[11,12]. The Leech River fault, which is the main seismic feature in the immediate vicinity of the test, crosses the shot transmission line. An active seismic zone is found in the region lying west of Vancouver Island and there are indications that the Strait of Georgia-Puget Sound Trench is also a zone of major activity.

The artificial ground motions were generated by detonating a Mark VII

300-lb. T.N.T. depth charge on the ocean floor under 600-ft. of water in the Strait of Juan de Fuca, south-west of Race Rocks, at a point located approximately 12 miles from the measurement stations. As indicated by the seismic profile, Fig. 2(b), transmission from the shot point to the measuring stations was through bedrock.

The observation points were situated in Beacon Hill Park, an area of Victoria which is relatively free of background (traffic, domestic, etc.) noise. Station R was located on an outcrop of dark, foliated metamorphic rock, which is cut by numerous dikes apparently related to a nearby granitoid intrusive body. Station S was on the alluvial fill in the rock basin shown in Fig. 1(b). These two stations were separated by a distance of approximately 1000-ft. The general characteristics of the subsoil conditions in the vicinity of Station S, as detected from available test borings originally taken in a drilling program for a sewer line construction project, are given in field log form in Fig. 2(a) and may be summarized as follows: The bedrock basin contains a widespread deposit of marine silty clay having a surface zone of weathered stiff brown clay underlain by an unweathered zone of very soft to firm impervious gray clay. The average depth of clay in the basin, whose surface area is approximately 1/3-sq. miles, is about 50-60 ft. and the maximum depth may be of the order of 100-ft. A mass of dense, heavily consolidated and impervious silty sandy gravel is located east and south of Station S, between the soft clay and bedrock, while to the north peaty swamp deposits underlain by water bearing silty sands are found on top of the marine clay. Miscellaneous fill, generally consisting of brown clay, sand and dumped rock are encountered at various locations. As indicated in Fig. 1(b), the boundaries of the extensive marine clay in this area are essentially enclosed by bedrock, with the exception of a ridge of relatively rigid glacial till found along the southern end of the basin. The depth to bedrock immediately below station S is estimated to be between 15-20 ft.

1.4 Instrumentation: A conventional seismic prospecting recording assembly, employing horizontal and vertical Electro Technical Laboratory 1-cps geophones, Models EV-17 and EV-17H, was used to measure the explosive activated ground motions at stations R and S. These transducers, which are of the electrodynamic movable core type, were damped to provide a flat velocity response over the frequency range 1 - 100+ cps at a sensitivity of 2.5 V/in/sec. The signals from the seismometers were fed though TGA-2 d.c. amplifiers, containing SIE input transformers and having high cut filters operating with an attenuation of 26 db per octave and a cut-off frequency of 26 cps, and transmitted to a 7 channel FM tape recorder and a multi-channel light beam oscillograph. The galvanometer records, which were obtained simultaneously with the tape recordings, permitted a running check to be kept on the vibration levels induced by the shock and the length of record affected by it.

Two components of ground motion were recorded at each measuring point, a horizontal component oriented radially toward the blast and the vertical component. A second, vertical geophone was situated within 100-ft. of each station for control and checking purposes. The locations of these units are subsequently referred to as stations R + 100' and S + 100' for the rock and soil sites respectively. Radio contact was maintained with the Royal Canadian Naval Tug "Clifton", from which the depth charges were dropped. This allowed the instrumentation system to be turned on just prior to detonation so that a complete velocity-time history of the event was obtained. Two preliminary shots were exploded initially in order to ensure appropriate gain settings of the amplifiers.

2. RESULTS OF INVESTIGATION

2.1 Ground Motion Records: Photographs of portions of the records of horizontal and vertical surface ground motion obtained at the alluvium and rock sites are reproduced in Fig.3. The arrival of the explosive generated waves is distinctly visible. The general character of the blast vibration is similar in appearance to typical earthquake records, but the time duration of the 'intense' motion is less than the corresponding durations normally associated with strong motion earthquakes. There is good correlation in the shape of the vibration records of the vertical component motions measured on rock, at and within 100-ft. of station R, Figs. 3(a) & 3(b). However, the peak amplitude readings of the appropriate seismometers differ by about 15%; this discrepancy may partly be due to instrumentation errors. In the case of the two vertical measurements on the alluvium, Fig.3(c) & 3(d), the difference reaches 24% and dissimilarities can be seen in the appearance of related graphs. This may be a reflection of the change in soil conditions within short distances, which is indicated by the variations in the bore hole logs for the general area.

At any one station the maximum amplitudes of the horizontal and vertical motions were approximately equal. The peak ground amplitude ratio of soil to rock at adjacent sites was found to be around 2.6. This soil amplification is in agreement with the general trend normally observed.

2.2. Data Preparation: Two methods were employed in the analysis of the ground motion records for the purpose of appraising the site conditions. These methods involved a frequency synthesis of the vibration signal in term of response spectra and power spectral density functions. For this purpose the transducer output voltages were used in both their original and in digital converted form.

The long seismic recordings were visually edited first to find the most significant portions of the record for analysis. Appropriate parts of the magnetic tape were then used directly as the input signal in a PACE 231-R electric analog computer and operated on to reveal the velocity response spectra. Calculations for the power spectral density functions were carried out on an IBM 7044 computer after digitizing selected segments of the analog tape at a sample rate of 0.0056-secs. The results of these analyses are given below.

2.3 Power Spectral Density Analyses: The power content of the vibration generated at the two measurement sites was characterized by a power spectral density analysis[13]. The resulting curves, which were obtained directly from a digital plotter and are reproduced in Figs. 4-6, give a measure of the average distribution of vibration energy per unit band width over the frequency spectrum for a selected length of recording. The power spectra were calculated by operating on a Fourier decomposition of the recorded signals; the signals had a duration of approximately 17-secs. and were defined by 3072 data points. The band width used was 0.15-cps.

Figs. 4 & 5(a) show the power distribution plots for horizontal and vertical vibrations in the bedrock. This material acts as the input source for the alluvial deposit. As might be expected, the two bedrock spectral graphs for vertical motion exhibit similar characteristics, with major peaking occurring at 5½-cps and a second, smaller concentration around 9-cps. These distinguishing frequencies are also present in the horizontal bedrock vibrations but in this case the 9-cps component provides the major energy level, with secondary contributions occurring at 5½-cps and 13½-cps.

The power functions of the output response, which corresponds to the vibration of the soil surface at station S, are shown in Figs. 5(b) & 6. These plots exhibit essentially the same peaking frequencies involved in the input functions, but the power distribution amongst the frequencies is different. A comparison of the horizontal input and output spectral functions, Figs. 5(a) & 5(b) respectively, suggests that the soil deposit tends to filter the higher frequency components noted in the horizontal input motion: this situation is in accordance with expectations. However, since the character of the measured signals and associated power functions for the two adjacent vertical recording points on the alluvium are in themselves dissimilar, a situation which may in part have been due to the rapid change in soil conditions encountered in the test area, it is difficult to assess, by means of the density plots, the filtering properties of the soil in the transmission of incoming vertical vibrations. In this respect, a frequency analysis employing power spectral density methods proved to be inconclusive.

2.4 <u>Response Spectrum Analyses</u>: The maximum relative velocity response spectra for the measured motions at each site are shown in Figs. 7 to 9. These curves reflect the general character of the ground motions and indicate the effects of such motions on the response of structures[14]. The calculations are based on record samples of approximately 25-secs. duration and were made for natural periods of vibration between 0.1 and 3.0-secs. and for damping values of 2.5, 5, and 15% of critical damping. About thirty different periods are used to define the individual curves; the associated maximum relative velocity values are joined by straight lines. The data are presented in conventional form in order to permit easy comparison with the majority of existing spectra found in the literature.

The curves exhibit two or three pronounced peaks, which is customary for spectra obtained from blast energy sources[15]. The locations of some of these spikes correlate with those found on the power spectral density plots. Significant peaking occurs even in the presence of relatively large damping values. This situation, which is contrary to the more pronounced smoothing influence of damping noted with the spectra of typical earthquakes, has also been observed in spectrum obtained for short duration earthquakes[16]. It is attributed to the relatively short time during which the damping forces are operative for energy dissipation in shock motions of this type.

It can be noted that all the spectrum curves approach constant values for periods greater than 1-sec. These values very nearly coincide with the measured peak ground velocities, Fig.3; the latter quantities are represented by short horizontal lines at the right edge of the velocity spectra curves. This agreement indicates that essentially all the period components of the ground motion fall within the 0 to 1-sec. period band.

Although the response spectra for the two vertical stations on bedrock bear a close resemblance to each other, significant variations in the general appearance of the two vertical spectra for the soil sites are apparent. This is related to the differences in measured ground motion for these locations, which was pointed out in section 2.1. It is disturbing that stations located on the same alluvial deposit and situated within 100-ft. of each other should appear to exhibit such different response properties. It has already been noted that local variations in soil conditions may have been a significant factor contributing to this situation.

2.5 Site Response Amplification Spectra: The main results of this investigation can be summarized in the form of the site response amplification spectra shown in Figs. 10 & 11. The site response amplification spectrum is here defined as a plot of the ratio of maximum structural response of soil to rock founded structures as a function of their natural period and damping. In this particular study the soil and rock refer to stations S and R respectively and the amplification factors are based on the maximum relative response spectrum values reported in section 2.4. In general, such curves provide an indication of the influence of local ground conditions on structural response in terms of some reference site. Because of the "pseudo relationships" which exist between the velocity, acceleration and displacement response spectra, the site response amplification spectrum has a generalized meaning.

From Fig. 10 it may be seen that the lateral response amplification factor for the test site reported in this paper oscillates between 1.5 and 4 in the low period range, and approaches a fairly constant level of about 2.5 in the long period range; this latter figure corresponds to the ratio of the peak ground velocities measured at the two sites. The transition period which differentiates the regional character of these amplification factors is 1.0-sec. The corresponding values for vertical vibration are 1.3 to 3.9 for short period amplification, 2.9 for long period amplification and 1.0-sec. for the transition period. The vertical amplification spectra, Fig. 11, are based on the average of the two sets of velocity response spectra obtained in the vicinity of each measuring station. In general, in the short period range of the spectrum increases in damping operate to reduce the upper bound amplification level and to increase slightly the lower bound amplification level. However, for different natural periods the spectrum is not necessarily maximized by the same value of damping.

The amplification spectrum serves to emphasize the importance of relating the dynamic properties of the foundation soil with those of the structure; the role played by the type of soil-structure combination in governing structural response and earthquake damage is clearly illustrated by these curves.

3. SUMMARY AND CONCLUDING REMARKS

The use of a single exploratory test for postulating broad conclusions on the effects of ground condition on earthquake motions is not justified. This danger is recognized here. However, certain general observations and remarks, which relate specifically to the present experiment, seem in order. The following statements are prefaced with a reminder that the ground motions measured in this investigation are of a considerably lower order of magnitude than those produced by strong motion earthquakes.

(1) The general character of the ground motion generated by the underwater blast bears some resemblance to the properties of vibration records obtained from earthquakes and other blast sources. The time duration of the 'intense' motion is, however, relatively shorter than that usually observed with typical earthquakes.

(2) The depth charge blast velocity response spectra exhibit fewer peaks than normal earthquake source spectra; the smoothing influence of the damping in reducing peak response is also noticeably smaller. These properties correlate with features noted in the spectra of short duration earthquakes and certain types of artificially excited vibration.

(3) The predominant frequencies present in the ground motions generated at the measuring stations were found by power spectral density analysis to be 5½, 9, and 13½-cps. The two higher frequency components noted in the horizontal input vibration appeared to be filtered out during passage through the alluvial deposit. However, the analysis offers conflicting evidence of the tuning properties of the soil as regards the transmission of vertical vibration, so that the data obtained from the power spectral density functions are judged to be inconclusive.

(4) At the test site, the ground amplitudes on the alluvial deposits are higher than the amplitudes on the rock outcrop by a factor of 2.5 to 3.

(5) The response amplification spectrum exhibits marked oscillations with irregular sharp peaks in the low period range and approaches a fairly constant magnitude in the long period range. For the test site, the

maximum structural response amplification ratio of lightly damped, soil to bedrock founded structures is of the order of 4 : 1. The concept of site response amplification spectrum stresses the influence of the soil-structure relation on the dynamic structural response.

The possibility of using depth charge detonations as an energy source for artificial ground excitation has been demonstrated. This technique offers a means of supplementing data on site characteristics derived from microtremor measurements, weak and strong magnitude earthquakes and other explosive agents. It seems worthy of further exploration as an experimental tool for seismic zoning and micro-zoning studies, and as an aid in relating the results obtained from microtremor and weak magnitude earthquake measurements.

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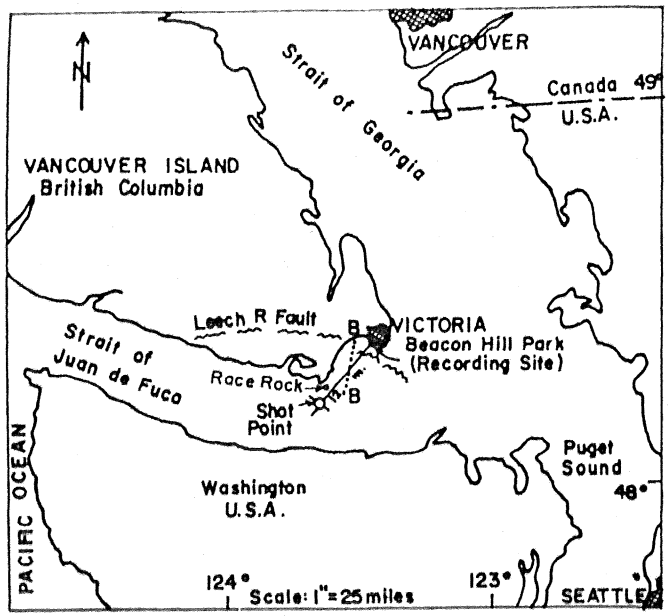
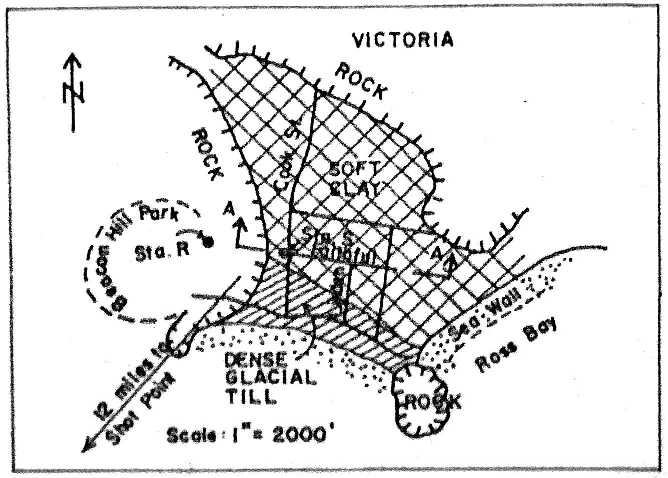
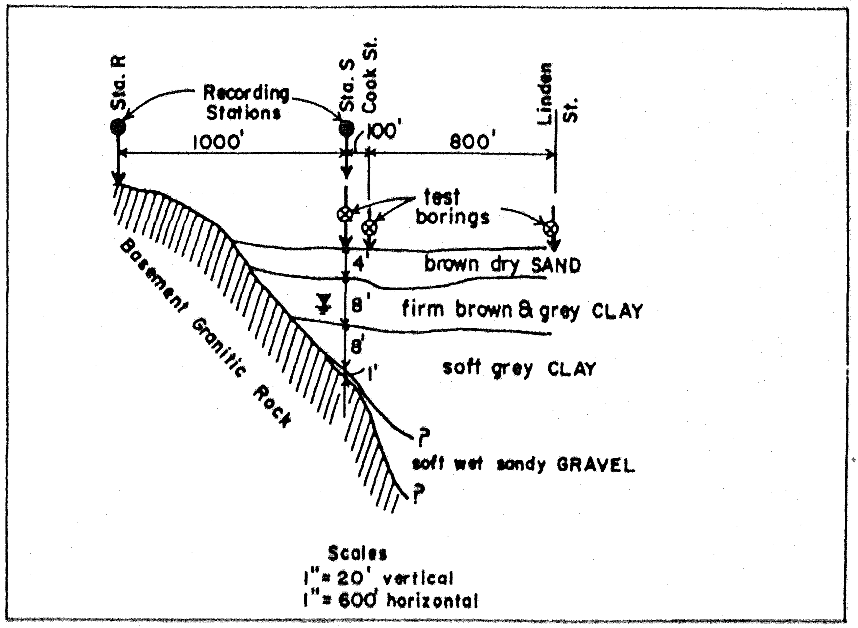


(a) Shot Point and Recording Site

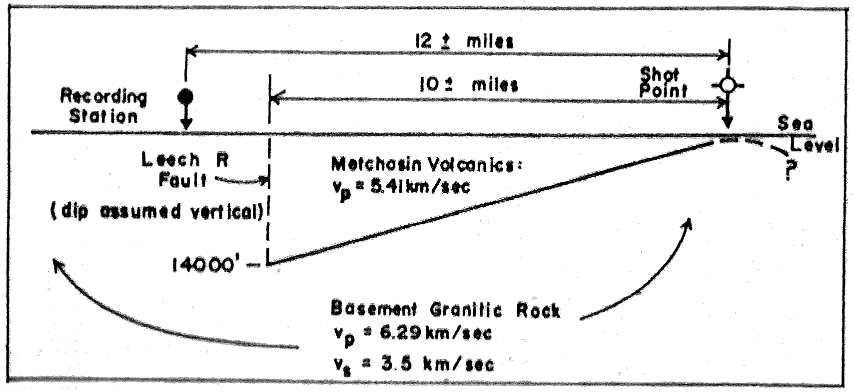


(b) Enlarged View of Recording Site

FIG. I. GENERAL PLAN OF TEST AREA

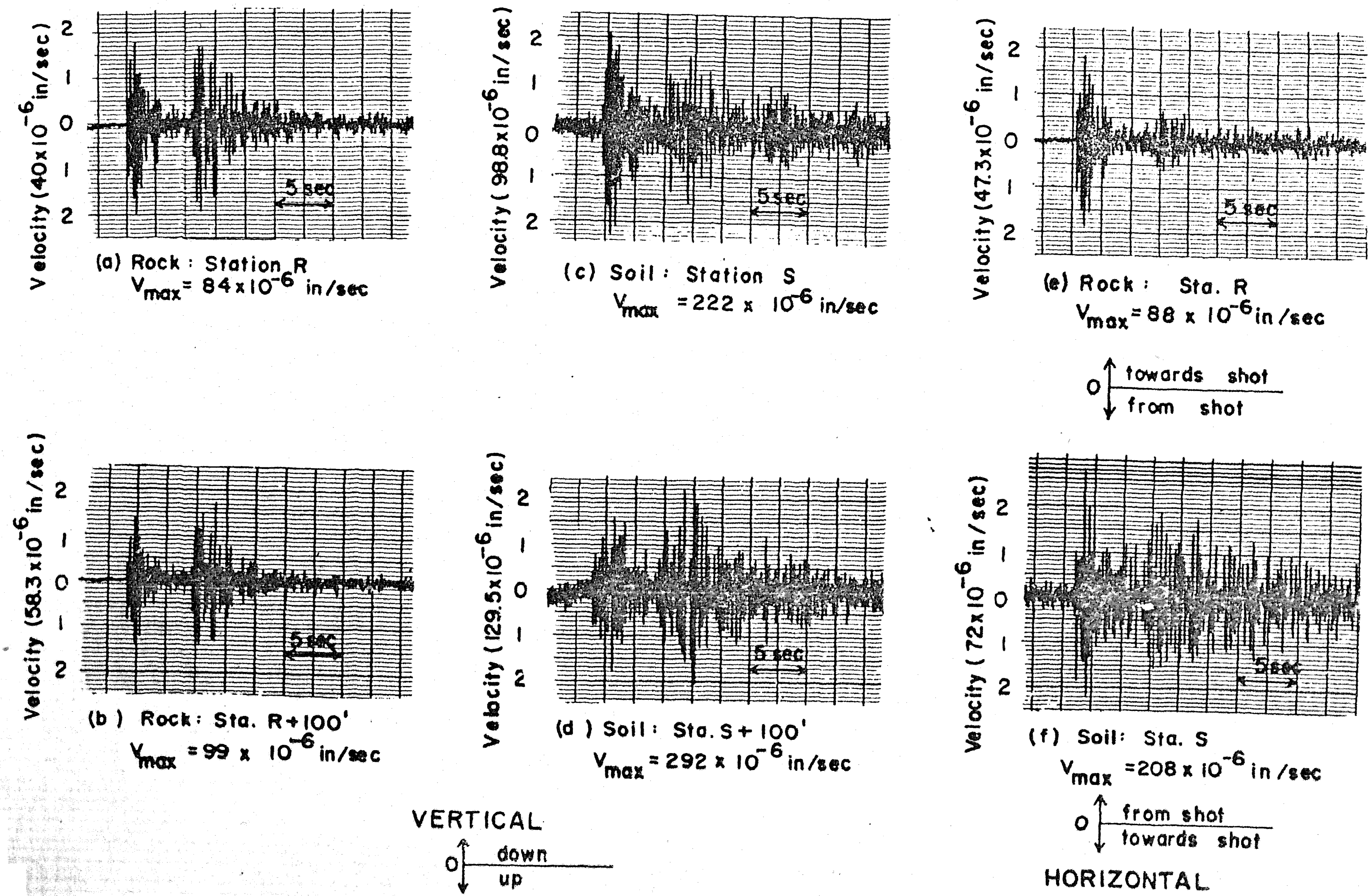


(a) Subsoil Profile Along Faithful St. (from Ref. 11)
(see Section A-A , Fig. 1(b))



(b) Seismic Survey Along Line B-B (from Ref. 12)
(see Fig. 1(a))

FIG. 2 SUBSOIL AND SEISMIC PROFILES



(a) Rock : Station R $V_{max} = 84 \times 10^{-6}$ in/sec

(b) Rock: Sta. R+100' $V_{max} = 99 \times 10^{-6}$ in/sec

(c) Soil : Station S $V_{max} = 222 \times 10^{-6}$ in/sec

(d) Soil: Sta. S+100' $V_{max} = 292 \times 10^{-6}$ in/sec

(e) Rock : Sta. R $V_{max} = 88 \times 10^{-6}$ in/sec

(f) Soil: Sta. S $V_{max} = 208 \times 10^{-6}$ in/sec

VERTICAL

HORIZONTAL

FIG. 3. GROUND MOTION RECORDS FOR DEPTH CHARGE EXPLOSION

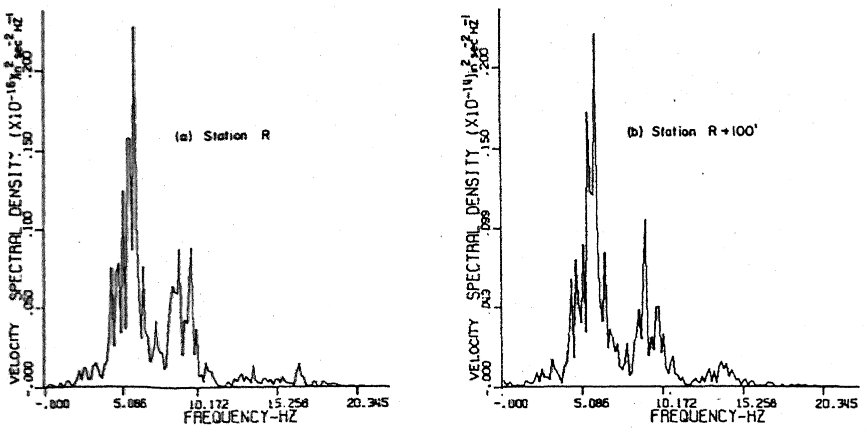


FIG. 4. POWER SPECTRAL DENSITY ANALYSIS : VERTICAL MOTION : BEDROCK

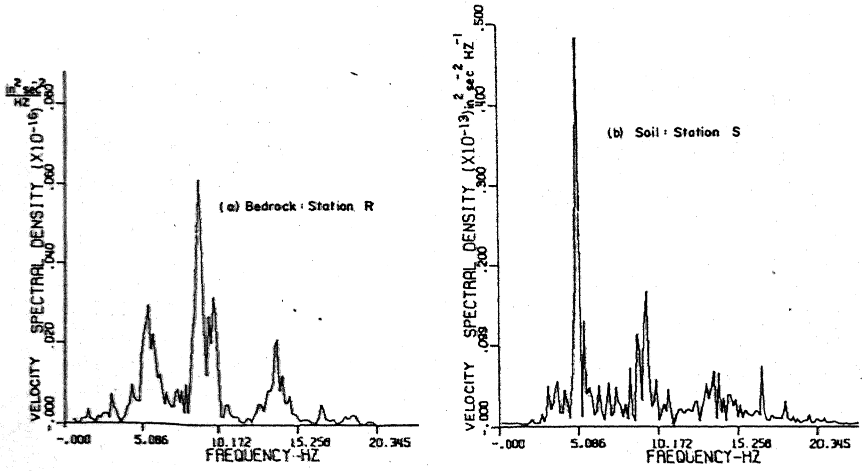


FIG. 5 POWER SPECTRAL DENSITY ANALYSIS: HORIZONTAL MOTION: SOIL AND BEDROCK

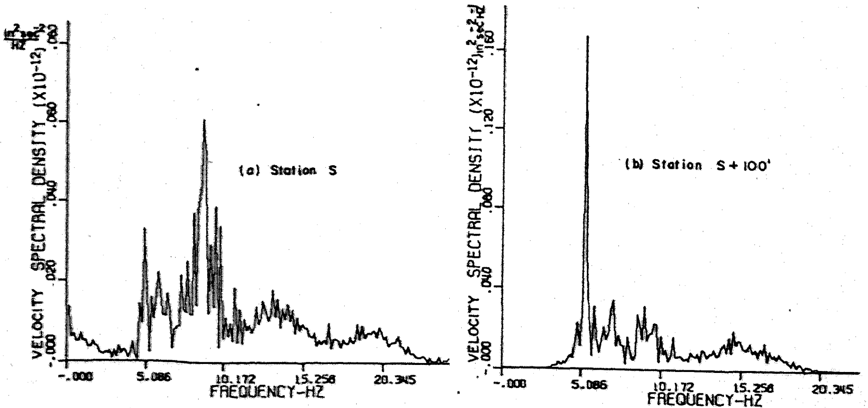


FIG. 6 POWER SPECTRAL DENSITY ANALYSIS : VERTICAL MOTION : SOIL

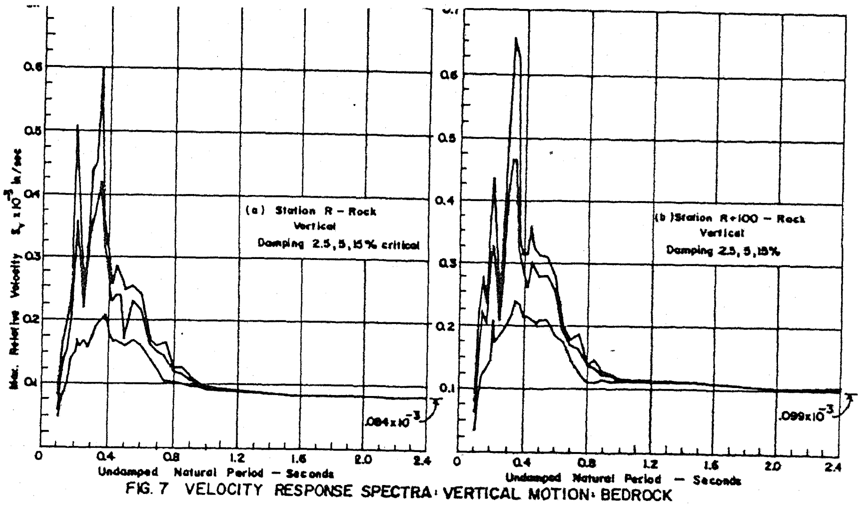


FIG. 7 VELOCITY RESPONSE SPECTRA: VERTICAL MOTION: BEDROCK

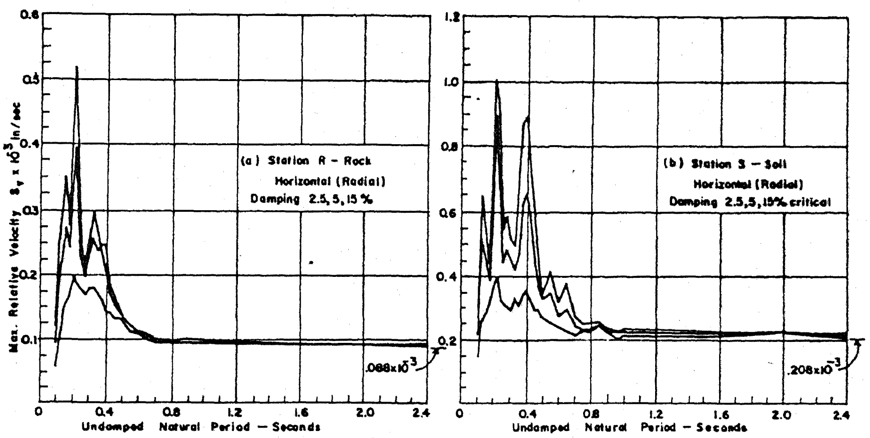


FIG. 8. VELOCITY RESPONSE SPECTRA: HORIZONTAL MOTION: SOIL AND BEDROCK

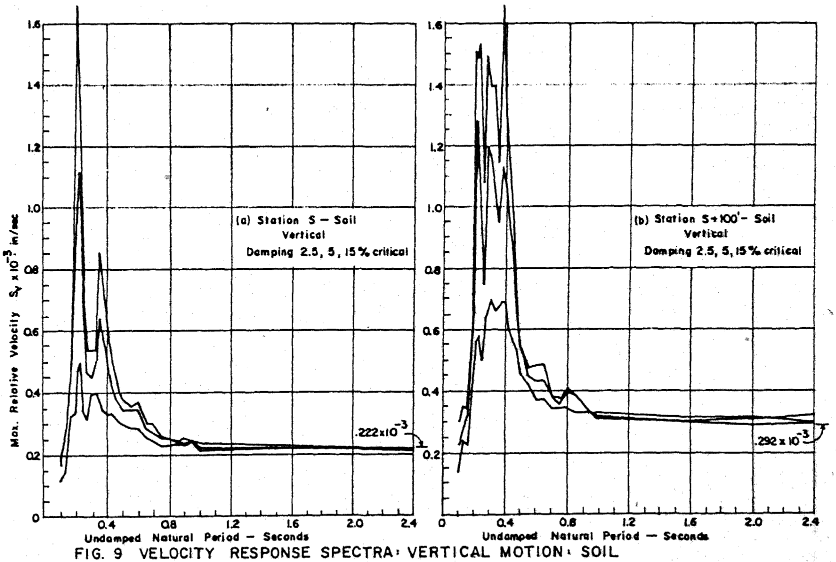


FIG. 9 VELOCITY RESPONSE SPECTRA: VERTICAL MOTION: SOIL

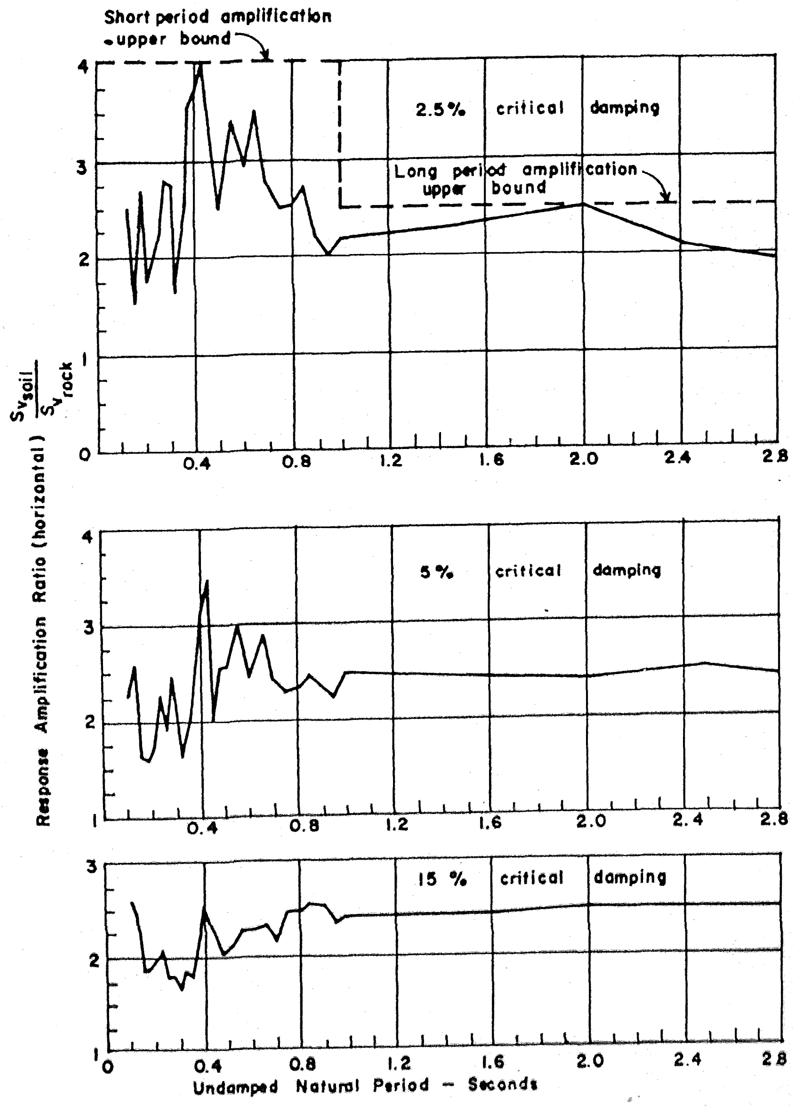


FIG. 10. SITE RESPONSE AMPLIFICATION SPECTRUM: HORIZONTAL MOTION

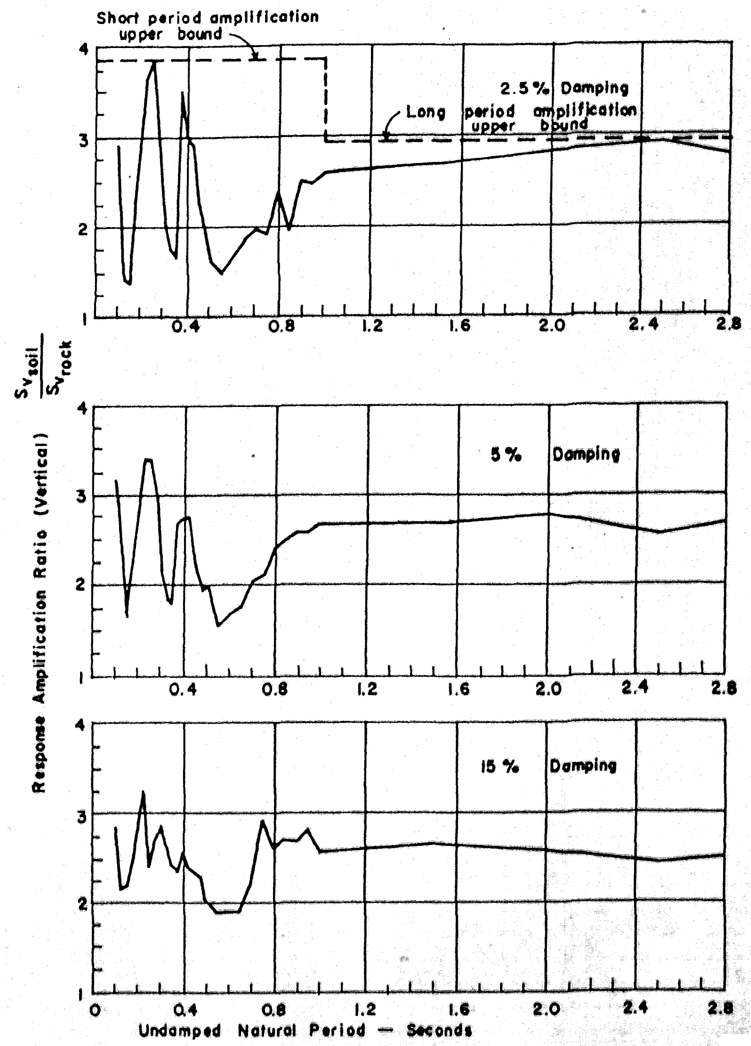


FIG. 11. SITE RESPONSE AMPLIFICATION SPECTRUM: VERTICAL MOTION.