IMPORTANCE OF SURFACE WAVES IN STRONG GROUND MOTION IN THE PERIOD RANGE OF 1 TO 10 SECONDS

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by

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ABSTRACT

Analysis of the El Centro recordings of the 1968 Borrego Mountain, California, earthquake suggests that nearly all of the first 40 sec. of the largest motion in the 2 to 10 sec. period range can be described quite well by surface waves. In contrast to most engineering practice, it is this period range that is of particular concern in the design of offshore structures. The experience with the Borrego Mountain earthquake recordings suggests that surface waves will be an important component of the ground motion at the periods of interest to engineers and that existing techniques for computing surface wave characteristics can be applied to the prediction of ground motions in the offshore geologic environment, where data are not currently available. Synthesis of surface wave motion in crustal models similar to those which might be expected in a continental shelf suggest that the long period characteristics of motion are controlled not only by near surface soil characteristics, but also by the characteristics of the bedrock below. Differences in the bedrock structure with depth may result in differences in the ground response of possibly a factor of four or more. Gradients in seismic velocity with depth can amplify a wide period range. Sharp contrasts at depths as large as a few kilometers can cause strong resonances in the surface waves at particular periods. These results suggest that for long period design problems, one cannot assume that all rock structures are alike in response characteristics. More meaningful site classification may be in terms of regional geology or depth to basement, rather than surface lithology.

INTRODUCTION

Attention usually is restricted to seismic body waves in studies of effects of earthquakes on man-made structures. In most cases damage is limited to areas near the earthquake epicenter, and the majority of the ground motion appears to be a result of body waves, which seem to contain the bulk of the energy in the period ranges generally of interest for engineering purposes, less than 1 second. The response of a structure to incident body wave ground motion from below can be predicted fairly reliably. Not all ground motion from an earthquake, however, is due to body waves. Seismic surface waves (Love waves and Rayleigh waves) can contribute significantly to surface motion. Rayleigh waves can exist whenever a free surface is present. Love waves will be generated whenever shear velocities increase with depth. Even though surface waves are just superpositions of body waves, their characteristics are

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difficult to view with the same perspective as with body waves, and generally in seismic interpretation we differentiate between the two phenomena.

There are several practical reasons for limiting interest to body waves. As mentioned, body waves are thought to have the bulk of the energy near a source. The frequency content in surface waves is generally thought to be too low to be of engineering interest. Experience has shown that the high frequency characteristics of the motion observed are controlled by near surface layering very close to the site, implying that scattered waves and wave guides may be of little importance.

Despite these practical arguments, there are reasons which suggest that surface waves and surface wave-like phenomena may be important in certain circumstances. Many engineering structures of interest have relatively long resonant periods (1-10 sec.) including very tall buildings, offshore drilling platforms, and virtually any structure of large dimensions. At these periods, surface wave motion may be larger than body wave motion at intermediate distances (tens to hundreds of km.). Because of dispersion, the duration of shaking might be quite long, and lateral strains, often not accounted for in design, may be caused by surface waves propagating with relatively low horizontal velocities.

Throughout the data set of strong ground motion recordings there are a number of instances where surface wave-like effects are seen. Trifunac (1971) gave strong arguments for surface waves in the recordings of the 1940 Imperial Valley earthquake. Anderson (1974) showed that the largest accelerations in a few of the recordings of the 1966 Parkfield, Calif., earthquake, are in time intervals consistent with surface wave arrivals. The displacement recording at El Centro, Calif., from the 1968 Borrego Mountain earthquake is dominated by what appears to be well-dispersed surface-waves (Figure 1). Hanks (1975), using rotated displacement records, points out numerous cases of dispersed waves in the period range of 2-8 sec. for the 1971 San Fernando earthquake.

All of the observations mentioned above are based on qualitative analyses; though these observations seem to fit some characteristics of surface wave-like effects, no one has verified that this motion is consistent with our knowledge of what surface wave motion should be for the given source and media characteristics. This is important to verify, because if indeed these observations do fit classical theory, we can then apply classical theory to estimate potential design motion for site specific cases (Herrmann and Nuttli, 1975a,b). This is especially important in evaluating hazards in an offshore environment where we have no strong-motion data to rely on when choosing criteria for design motion.

EL CENTRO RECORDING OF THE BORREGO MOUNTAIN EARTHQUAKE

To determine whether surface wave methods are useful in strong motion problems, we examined the displacement recording at El Centro of the 1968 Borrego Mountain, California, earthquake (Swanger and Boore, 1978). The ground motion at El Centro was recorded simultaneously on a standard accelerograph and a Carder Displacement Meter with a resonant period of approximately 6 seconds. The displacement meter response showed considerable motion at the long periods for a duration of over one minute, and the characteristics of time history suggest that the majority of the motion may be due to surface waves. This is a particularly good test case for applying surface wave methods since the earth structure near the site is known quite well from seismic refraction work and the structure appears to be nearly plane-layered near the site.

Using a source model and layered earth model chosen from independent sources, synthetics were computed for comparison to the observed displacement motion. Figure 2 shows the observed and computed motion for varying source characteristics. The source model chosen for use has only two independent quantities, the rupture velocity and moment, and the moment was chosen to match the value of observed peak displacement. The fit is quite good, even for a wide range of source details. This suggests the overall character of the recording is controlled by the media response and only weakly determined by the source characteristics. It is important to note that the layered earth model chosen contained no near surface soils. Even though there are surficial soils at El Centro, they have almost no effect on the long-period character of the observed motion. The characteristics are controlled by surface waves resonating in the entire sedimentary basin.

MOTION ON A CONTINENTAL SHELF

The observations at El Centro suggest that surface waves are important in the long period response of sedimentary structures, and the comparison shown implies that surface wave methods work quite well at describing the response. Next we will show some examples of what type of response one might expect in a geologic structure for which we have no data: a continental shelf. The continental shelf has a number of structural features which may be conducive to the formation of surface waves. The sedimentary cover usually extends to depths in excess of 5 km. Seismic velocities in such material will generally increase significantly with depth. Such gradients in velocity can trap waves near surface. Sharp contrasts in velocity may exist within the sedimentary system where such units of different ages overlay one another. Continental shelf environments usually have rather deep soil cover as well. The details of the long period response will depend strongly on the detailed characteristic of the media. Here we can only give some examples of what general ground motion characteristics might be expected on a continental shelf, and how these characteristics might be different from those observed onshore.

First, we compare the long period response of a "typical" continental shelf to a "typical" onshore rock site. The continental shelf model chosen contains 100 m of soft soils with properties resembling San Francisco Bay mud and 8 km of sediments with seismic velocity with depth following Faust's law (Faust, 1951). The upper 8 km of the onshore models has velocities approximately that of granite. The layered model for the two structures were the same below 8 km. Love wave motion in each model was computed at various distances from equivalent sources. Enough modes were included to model all significant surface wave motion for periods greater than 1.5 sec. Figure 3 shows pseudo-velocity response spectra of computed transverse motion at 50 and 100 km from a source of approximate magnitude $M_S=7.5$. The peaks and troughs in the spectra are largely source effects rather than due to media response. The major feature in the comparison is that the overall amplitude of the longer periods is amplified on the shelf by a factor of 3 to 4.

One might assume that the controlling feature in the shelf model will be the 100 m of soft soil (with shear velocities on the order of 100 m/s). To check this, we computed the ground motion in the shelf model without any surface soils for comparison to the original motion. Figure 4 shows the ratio of pseudo-velocity spectra for motion on the shelf with and without surface soils. The variation seen here is much smaller than the factor of 3 or 4 shown in the previous comparison. At least for the period range where the calculations account for most of the ground motion periods greater than 2 sec., the shelf structure amplifies the motion considerably and amplification is controlled by the velocity below the rock-soil interface, not the soils.

It has been shown that the gradients in seismic velocity can amplify a large period band. We might expect that a sharp contrast at depth may cause resonance of a narrow period band. As an example, we computed motion for a model constructed from published refraction data off Kodiak Island, Alaska. The model contains a contrast at a depth of 1.9 km where shear and compressional velocity approximately double. No surface soils are included. Figure 5 shows computed horizontal and vertical Rayleigh wave motion at 40 km epicentral distance from an 8 km deep source. Note the peculiar character of the vertical component. The vertical motion is almost monochromatic and has its largest motion when the horizontal component is relatively quiet. The vertical pseudo-velocity response (Figure 6) reveals a strong resonance at about 4 or 5 sec. periods. Such peculiar time histories of motion may be important in the non-linear response of structures.

CONCLUSIONS

It has been shown that surface wave contributions to ground motion may be a controlling feature in determining amplitudes of long period strong ground motion. Calculations indicate that the long period motion may be enhanced in sedimentary geologies where gradients in velocity with depth are present. Sharp contrasts in velocity with depth can cause resonances similar in nature to those in near-surface soils. Ground motion at the long periods is due to waves with wavelengths so long that often near-surface soil will not influence their characteristics.

Specific considerations may be required in specifying design motion for long period structures. If existing data are to be used for specifying rock motion characteristics, it may be inportant to use only observations made in a geologic environment similar to the site on a regional scale. For off-shore design, the most useful information will come from onshore observations in deep sedimentary basins like the Los Angeles Basin or the California Central Valley.

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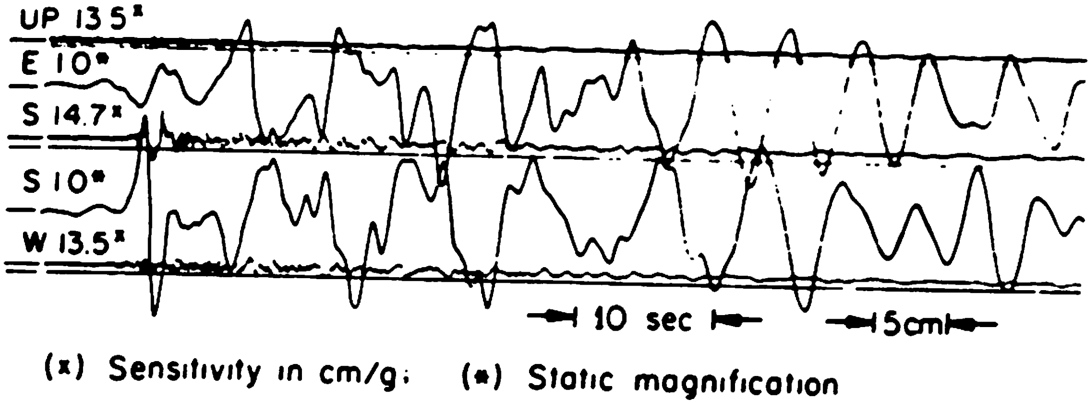

Figure 1.-El Centro recording of the 1968 Borrego Mountain earthquake on accelerograph (traces 1, 3, and 5) and Carder displacement meter. The amplitude scale can be derived from the listed sensitivities and the peak amplitudes of 120 cm/sec^2 and 5.7 cm on the S acceleration and displacement traces (U.S. Earthquakes, Dept. of Commerce, 1968).

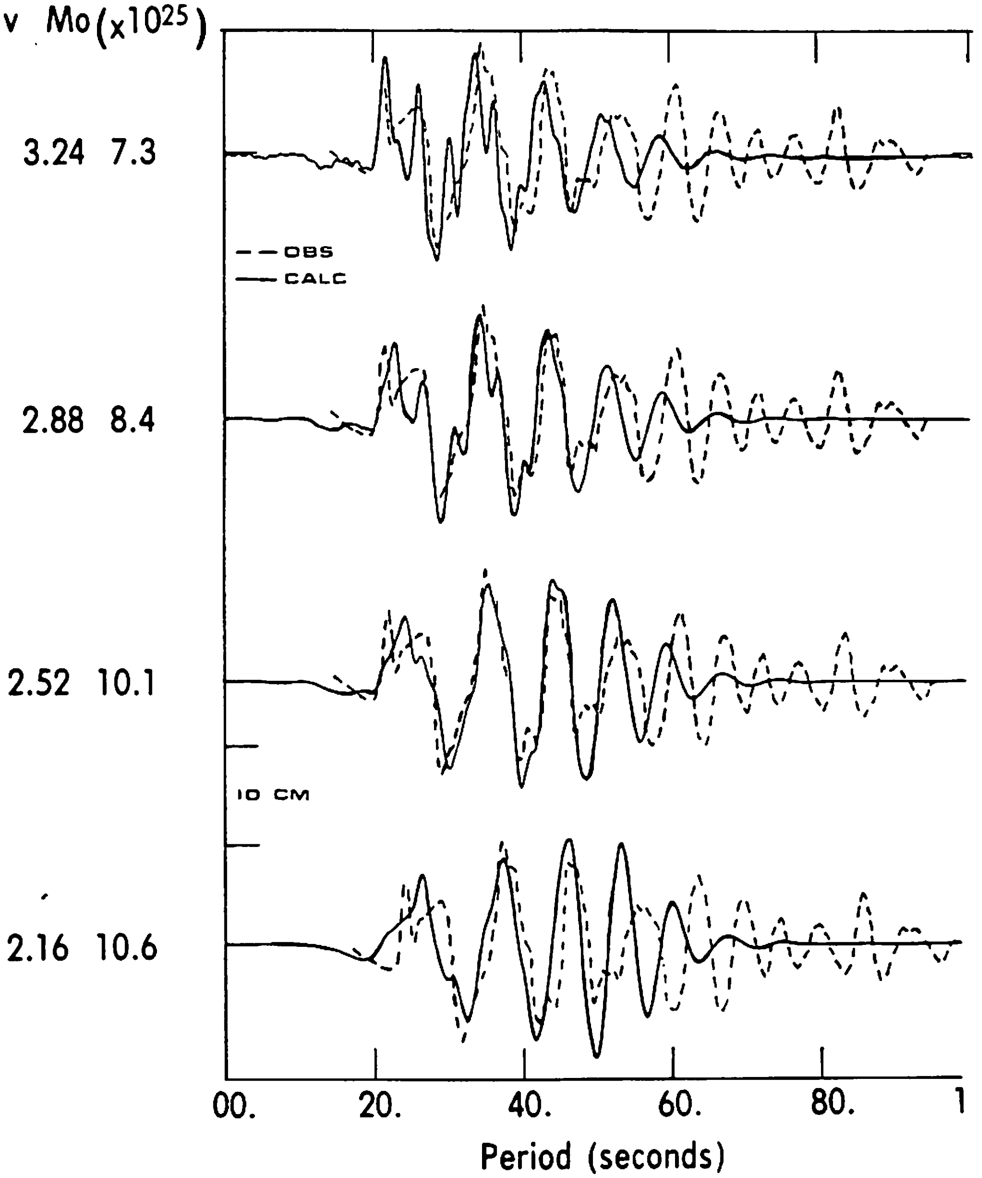

Figure 2.-Observed and calculated waves for a series of rupture velocities (in km/s) and seismic moments (in dyne-cm).

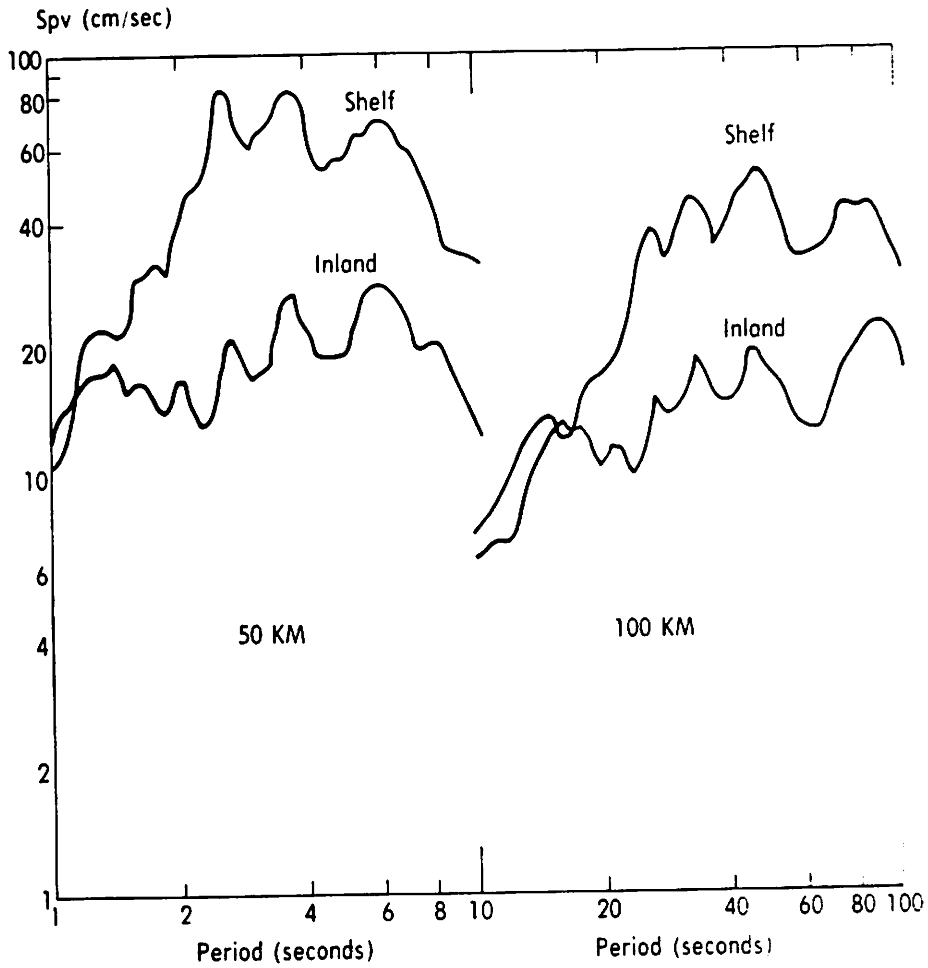

Figure 3.-Pseudo-relative velocity response (S_{pv}) at 5% damping for surface wave motions recorded at 50 and 100 km for propagation across different geologic structures.

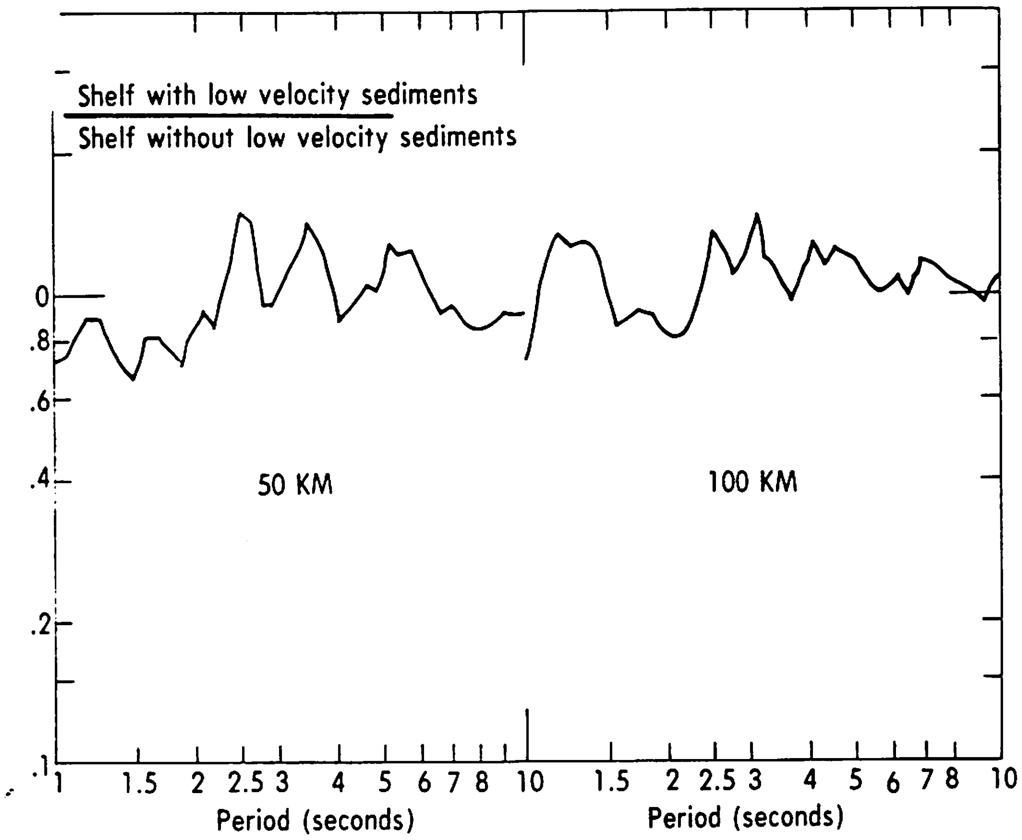

Figure 4.-Ratio of 5% damped S_{pv} at 50 and 100 km for a shelf with and without a surface layer.

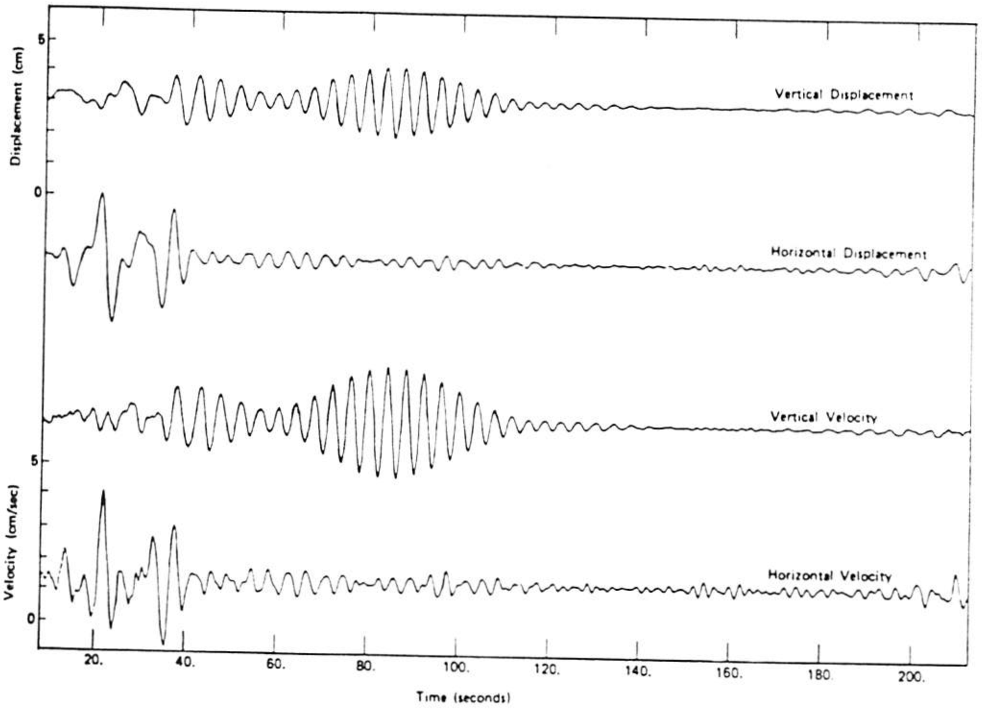

Figure 5.-Rayleigh wave displacement and velocity at 40 km for a source at 8 km depth.

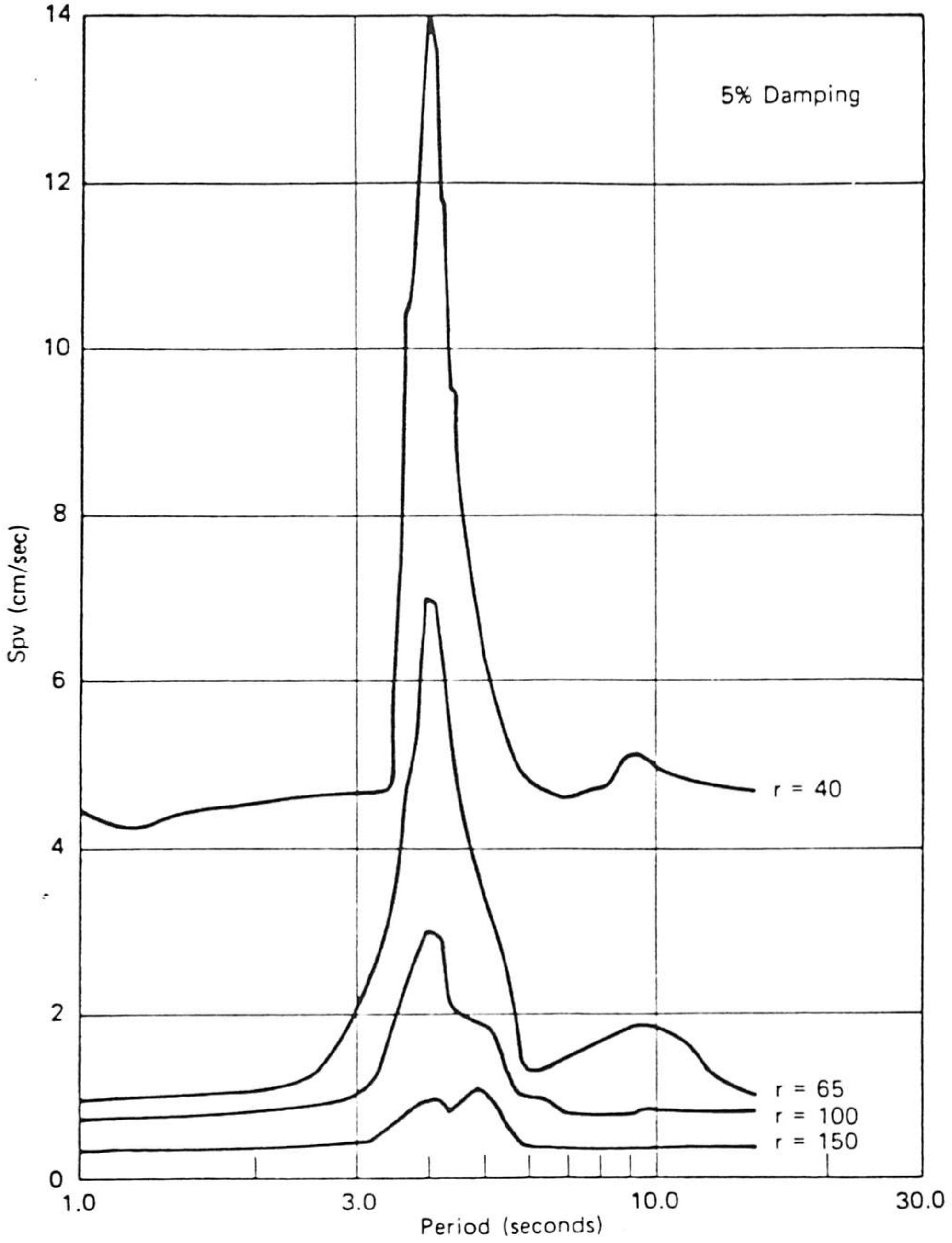

Figure 6.-S_{PV} for vertical component of Rayleigh waves, at various distances with the source and geologic model used in Figure 5. Note the narrow-band resonance due to the sharp change in geologic properties with depth.

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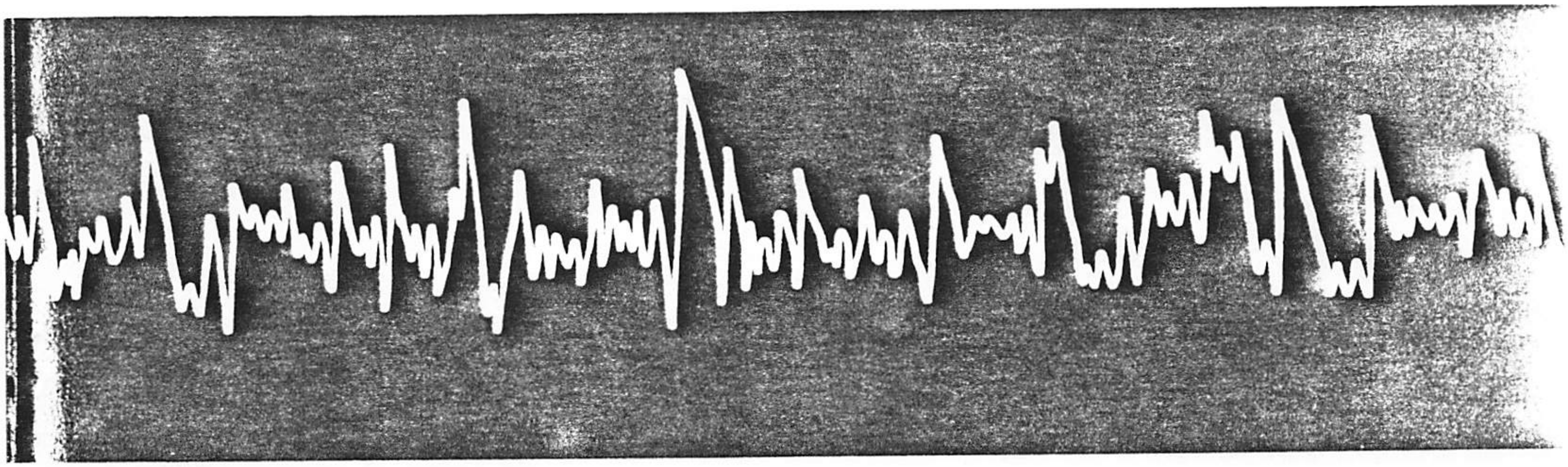

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