Earthquake Engineering, Tenth World Conference © 1992 Balkema, Rotterdam. ISBN 90 5410 060 5

Preliminary results from a vertical array in Garner Valley, California

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ABSTRACT. A significant set of data (218 events of varying magnitudes and distances) has been recorded in southern California by means of a five-level vertical array installed in Garner Valley, near the reputed "Anza gap". Once the orientations of the instruments at depth had been determined and corrected for, transfer functions were computed which show good agreement with those derived from simple theoretical models. Lastly, a regression analysis linking the response spectrum with magnitude and distance was conducted, and results compared with those obtained for California at large and for Italy. A pronounced shift towards high frequencies is observed on the Garner Valley spectra, very probably indicating a high local stress drop.

1. INTRODUCTION

One of the objectives in engineering seismology is the prediction of strong ground motion at the site of a critical structure. The amplitude and duration of such motion is determined by the process of rupture at the source, but also is modified during its trajectory in the Earth's crust (path effect) and through surficial, low-velocity layers (site effect). The predominance of these latter, under certain conditions, was clearly demonstrated on the occasion of several recent major eathquakes, notably Mexico, Armenia, and Loma Prieta.

In order to gain a better understanding of site effects, with special attention devoted to non-linear soil response, and further to succeed in quantifying them, a downhole experiment was undertaken in Southern California as a cooperative Commissariat à l'Energie Atomique/U.S. Nuclear Regulatory Commission project (Murphy & Mohammadioun, 1989). *The object of the experiment is to collect* an extensive set of weak- and strong-motion data traversing a shallow soil column.

2. GARNER VALLEY DOWNHOLE ARRAY

The Garner Valley Downhole Array (GVDA) is installed in a seismically active zone some 7 km east of the San Jacinto fault, near a well-documented seismic gap (see Figure 1). It is comprised of five three-component accelerometric stations, with one at the surface and four at depths significant in terms of the site's soil profile: -6, -15, -22, and -220 meters. The network records ground acceleration digitally (with 500 samples per second) covering a wide dynamic range (between 3×10^{-6} and 2 g) and from 0 to 100 Hz.

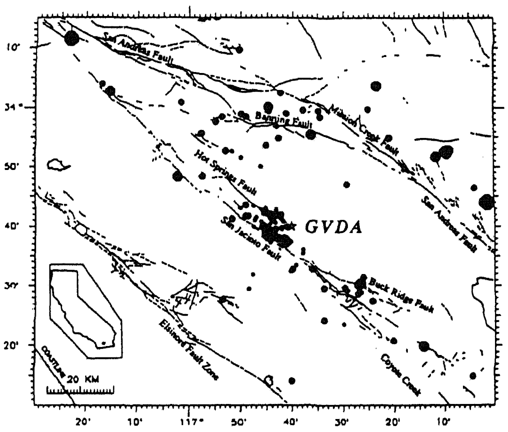

Figure 1. Seismotectonic setting of the Garner Valley Downhole Array site.

The site was selected notably because it offered a simple geological context, thus facilitating the interpretation of the data and limiting the number of parameters liable to influence ground motion.

The site is characterized by an alluvial layer 18 meters thick, directly overlying the bedrock. Refraction profiles and standard penetration tests have yielded a preliminary version of velocity structure as shown on Table 1 (Pecker & Mohammadioun, 1991).

Table 1. Veloctiy profile on the GVDA site.

Depth (m)	*Shear-wave velocity (m/s)*	*Mass density (t/m^3)*
0-1	90	1.95
1-2	130	1.95
2-4	165	2.0
4-6	190	2.0
6-8	215	2.0
8-11.5	240	2.0
11.5-15	260	2.0
15-18	280	2.05
18-22	600	2.2
>22	2000	2.4

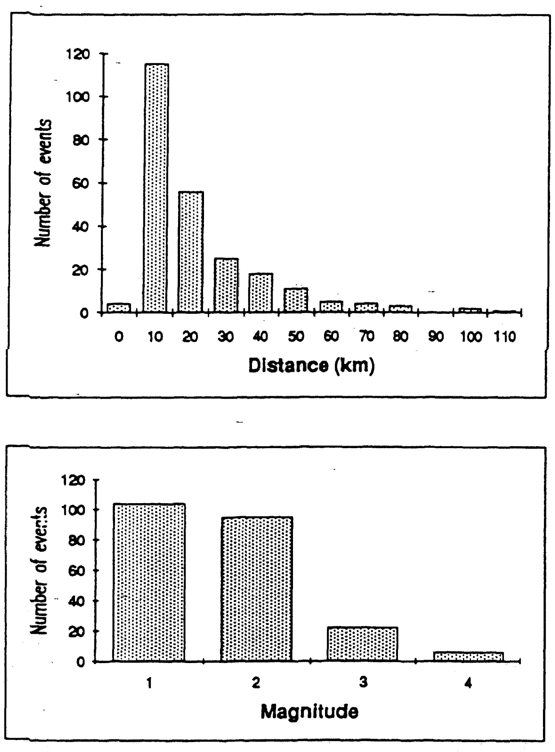

Figure 2. Histograms depicting.the GVDA data population distribution with respect to focal distance and magnitude.

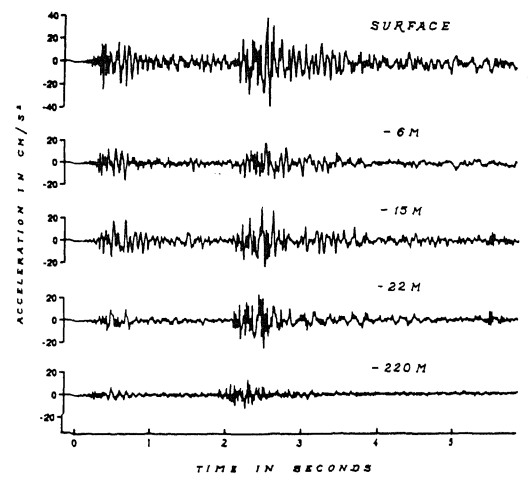

Figure 3. Time histories, horizontal component, recorded at all five levels of GVDA (0, -6 m, -15 m, -22 m, and -220 m) for the magnitude 4.2 event on December 2, 1989 at 23:16.

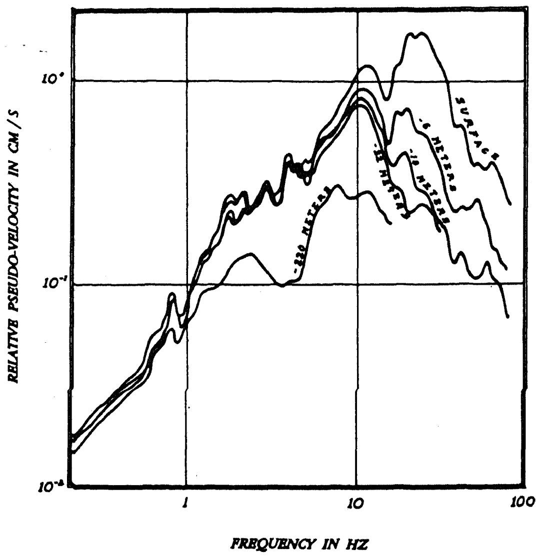

Figure 4. Response spectra at 5% damping, vertical component, recorded at the Five levels instrumented at GVDA; event on December 2, 1989 at 23:16.

Since the network began operation in July, 1989, over 218 events have been recorded. Magnitudes range from 1.0 to 4.7 and focal distances from 8 to 110 km, as seen on Figure 2. The level of acceleration has so far not exceeded 0.04 g; time histories at all five levels for this largest recorded event are shown on Figure 3. Most events have depths of at least 10 km.

Although time histories are in themselves useful elements, the analyses that were to be undertaken in the present paper called for data to be in spectral form. Response spectra with different levels of damping were computed for the entire set of GVDA records, with 96 frequencies between 0.2 and 78 Hz. This type of spectrum was chosen in preference to the Fourier spectrum because its relatively smooth shape readily lends itself to such operations as divisio nor averaging. Figure 4 thus presents response spectra at 5% damping for the event in Figure 3, vertical component.

3. COMPONENT ORIENTATION

Experience has shown that difficulties may be encountered when attempting to interpret downhole data because of potential instrument rotation at depth (c.f. Pecker & Mohammadioun, 1989): it is effectively impossible to control instrument orientation during installation under such conditions. To determine actual instrument orientation, so as to be able to correct for it and obtain comparable components at all levels in the array, it is first necessary to work from very accurately located seismic sources, whether these be natural or man-made. Various techniques of wave-form analysis can then be applied to the time histories at depth in order to deduce the actual component orientation with respect to the source.

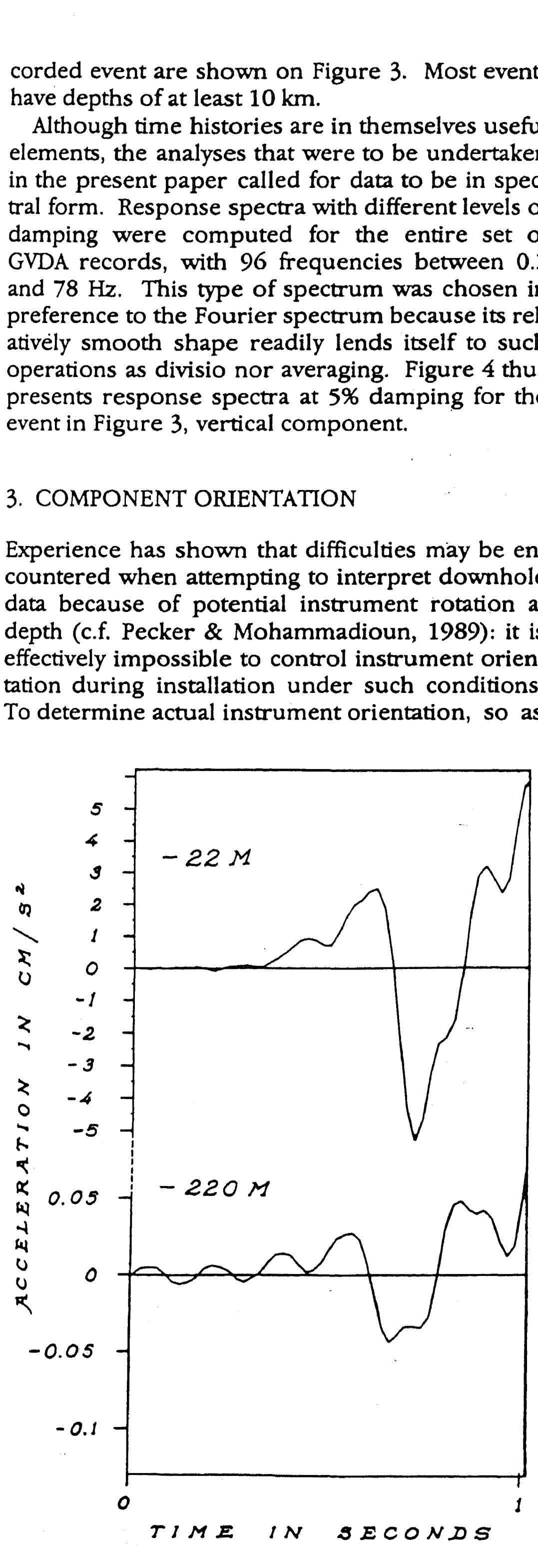

Figure 5. Reoriented radial components of GVDA records for the December 2, 1989 event at -22 and -220 m (325° and 15°, respectively).

An extremely simple technique was applied to the event depicted on Figure 3 (December 2, 1989). It consists in rotating the two horizontal components (by 5° steps, for the sake of convenience) until a maximum value is reached for the first impetus peak (the sample number being defined on the basis of the vertical component). The component thus derived is considered to be radial with respect to the source (see two examples on Figure 5). Once this component is obtained, it can in turn be combined with the vertical in the same manner in order to ascertain the incident angle, as illustrated in Figure 6. Table 2, below, shows the results derived from this procedure.

One might be inclined at first thought to believe that the very high frequencies present at the signal onset (often approaching 40 Hz) would not prove to be a reliable indicator for such purposes, the circumstances being rendered yet more unfavorable by the fact that, in the uppermost layers at least, a nearly vertical incidence is to be expected. In actuality, at the surface, where the horizontal components are known to be oriented north and east respectively, the result obtained corresponded precisely to the earthquake's epicentral location, even though the incident angle was only 3°, and the value was determined without previous knowledge of this position.

Table 2. Position of the source of the December 2, 1989 event with respect to the different GVDA instruments.

Depth (m)	*Azimuth (degrees)*	*Incident angle (degrees)*
Surface	235	3
-6	20	5
-15	325	7
-22	325	9
-220	10-20	15-20

Further corroboration of these results comes from work done (at the Universities of Joseph Fourier-Grenoble and Santa Barbara, personal communication) using other wave-form analysis techniques based on both P and S-waves and applied to a larger number of events.

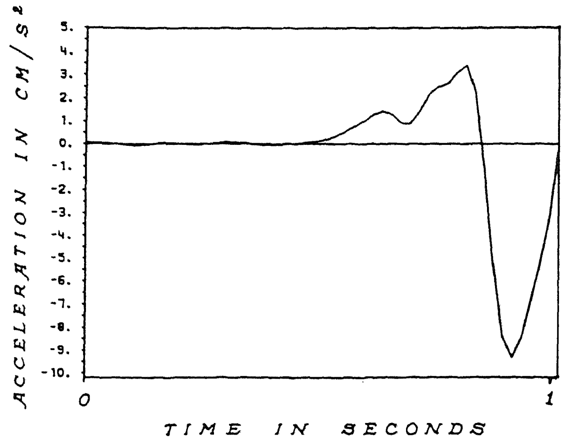

Figure 6. Surface record from GVDA for the December 2, 1989 event, reoriented in the direction of propagation (235°, 3° incident angle).

4. TRANSFER FUNCTIONS

In order to quantify the influence of the local geological conditions at different depths, spectral ratios have been computed between records at the surface and those from the four subsurface levels. The calculation was carried out in two stages. Firstly, for the 218 events and for each horizontal component, the ratio was computed between the surface response spectrum at 0% damping and the corresponding spectra at depth. Secondly, averages were obtained for each surface/subsurface couple (combining all horizontal components, for a total of 436). This process enabled us to gloss over possible azimuth and distance effects, so as to enhance those actually due to the mechanical properties of the geological formations present at the site. Figure 7 depicts the average spectral ratios obtained for the four depths. It will be noted that: 1) For the 0/-6 m ratio, two rather narrow amplification spikes are observed at 9 and at 26 Hz; amplifications attain about 5.5 to 8.5; 2) For the 0/-15 m ratio, the spikes shift to 3.5, 10.5, and 15 Hz and present amplification values of around 3; 3) For the 0/-22 m ratio, the spikes are located as for -15m, but amplifications double (≃ 6); and 4) For the 0/-220 m ratio, aside from a peak amplification of about 12 near 14 Hz, no other outstanding spikes are visible; an average amplification of 4 to 5 is displayed over the 1 to 30 Hz range. Globally speaking, it will be noted that, with the exception of the 0/-220 m ratio, the average transfer functions obtained are characterized by the narrow and clearly defined amplification spikes typical of monodimensional resonances.

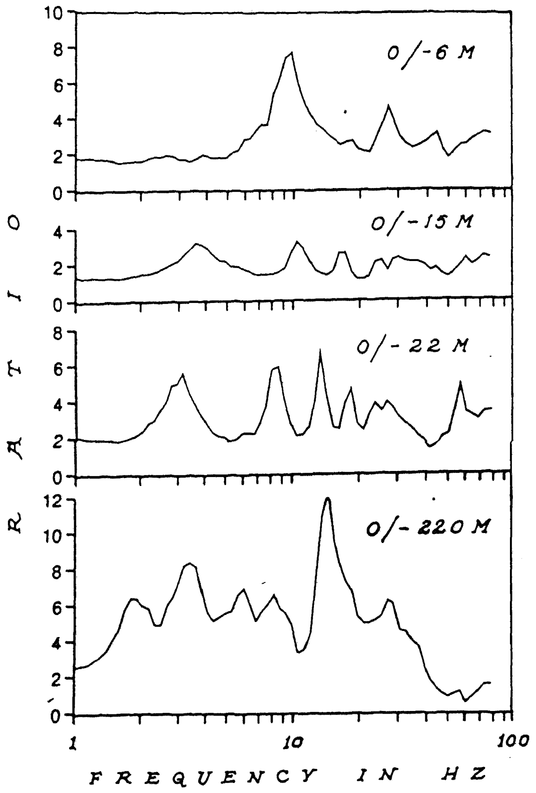

Figure 7. Average spectral ratio, horizontal component, for the four depths at GVDA versus the surface.

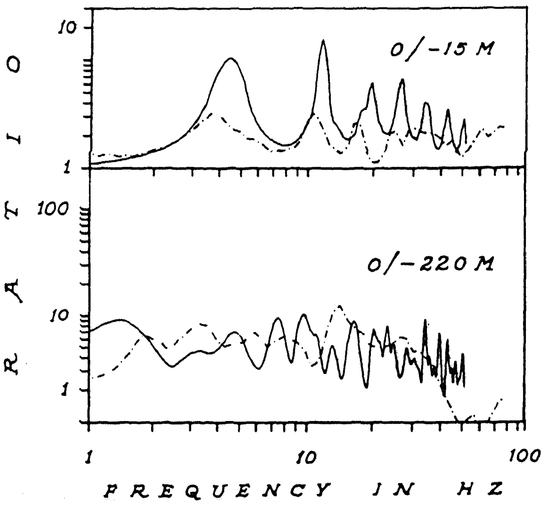

Figure 8. Comparison between average spectral ratios (dashed and dotted lines) and those computed from the velocity model (solid lines) for two depths.

In order to test this hypothesis, synthetic seismograms were computed at various depths using the velocity model proposed by Pecker & Mohammadioun (1991) and the discrete wave number method (Bouchon, 1981) over a frequency range of 0 to 50 Hz. A point-source has been considered at a depth of 5 km, directly beneath the site. Spectral ratios were then calculated for seismograms (SH component) for the surface and for the different depths. These ratios were smoothed with a triangular moving window, 1 Hz wide. Figure 8 presents the comparison between the average (experimental) and the synthetic ratios for the depths of -15 and -220 m.

At -15 m, an excellent agreement was obtained between observed and calculated spikes, indicating the adequacy of the velocity model and the fact that, for the site in question, a monodimentional model is quite sufficient. The amplitudes, on the other hand, are overestimated by the model, which may result from the choice of two of the input parameters: 1) A source directly beneath the site was selected, whereas the actual events were situated at distances of ten to several tens of kilometers from the site. One might accordingly expect the wave incidence beneath the site to have been sub-vertical, resulting in lower amplification levels; 2) In the absence of information about the quality factor in the superficial layer, a uniform Q_S value, independent of frequency, of 20 was assigned between 0 and 20 m. Obviously, a smaller value and/or a frequency-dependent one would affect both the absolute and the relative values of the various amplification spikes.

At -220 m, however, the agreement is not nearly so good, although the average amplification over 1 to 20 Hz is comparable. This discrepancy between observed and synthetic may be caused by an improper knowledge of the velocity law in the uppermost meters of the granitic formation, for the formation is characterized by a weathered layer extending down from -20 to -40 m that has not been taken into account in the velocity model (a constant velocity was supposed where a decreasing velocity from bottom to top would normally be expected.

5. THE PREDICTION OF SEISMIC MOTION

In linear elasticiy, vibratory ground motion is the convolution of a source function (slip function) and of a function representative of the path effect (Green's function). Considerable headway has been made over the past ten years or so in simulating these two aspects. However, most often, highly simplified methods are called upon when predicting seismic motion for engineering purposes, wherein the source is represented by the earthquake's magnitude and the propagation, by a function depending on the distance separating the source from the observation point. In the present study, the equation relating the response spectrum PSV (f) for a given level of damping (in the present case, five levels of damping, 0%, 2%, 5%, 10%, and 20% were considered) to the magnitude M and the focal distance R is expressed as follows:

$$\log PSV(f) = K(f) + \alpha(f) \times M + n(f) \log R \qquad (1)$$

where K (f), α (f), and n (f) are frequency-dependent correlation coefficients.

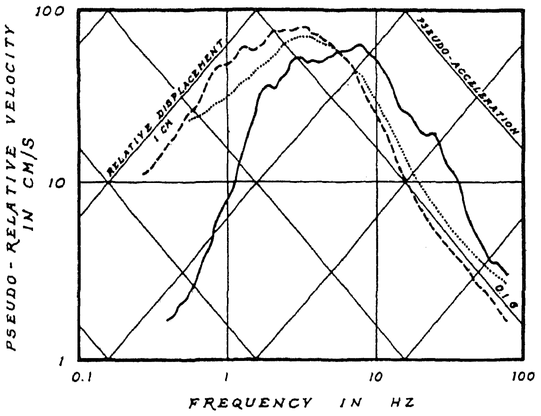

Figure 9. Synthetic response spectrum (5% damping) computed for a magnitude of 4.5 and a focal distance of 20 km with coeffficients obtained through regression analysis of GVDA data (solid line); comparable synthetic response spectra derived from a varied set of California data (dashed line) and from Italian data (dotted line).

Regression analyses on the basis of equation (1) have been carried out on a wide range of California data through 1989, as well as on a set of Italian data and the data obtained with the Garner Valley array. Figure 9 shows the synthetic spectra computed with coefficients derived from these three data sets for a damping value of 5%, a magnitude of 4.5 and a distance of 20 km. The Italian data spectrum is seen to shift somewhat towards the higher frequencies in comparison with the general California spectrum. This effect is even more striking where the Garner Valley data spectrum is concerned. One possible explanation for these differences could be the influence of the stress drop parameter (Mohammadioun, 1991). Italian earthquakes, arising in an intracontinental context, may well be characterized by a higher level of stress drop than those originating at plate margins. According to Fletcher et al. (1987), stress drops prevailing on the San Jacinto fault are substantially higher (≃200 bars) than those encountered on the central, creeping section of the San Andreas fault, where stress drops of 10 bars or less have been estimated.

CONCLUSION

A preliminary analysis of the extensive data set acquired to date on the Garner Valley Downhole Array has already made it possible to verify certain hypotheses and to highlight some specificities of seismic motion from this site.

The statistical study of transfer functions for surface/depth couples has made it possible to demonstrate that, even for a population of earthquakes that is heterogeneous with respect to magnitude and distance, spectral ratios are relatively stable; furthermore, a simple monodimensional model, with no provision made for non-linearities, suffices to explain the average transfer functions observed. It must, however, be borne in mind that the level of motion was in all cases modest (well under 0.1 g). The experiment is scheduled to continue for a number of years: the possibility of occurrence of a major earthquake in the vicinity is considered to be relatively high, due to the proximity of the "Anza gap," and other lesser, although significant, events may very reasonably be expected within a radius of 30 or so kilometers. Such additional data should allow one to define a threshold of motion above which the behavior of the more superficial layers becomes non-linear.

Statistical studies conducted with data from all parts of California, from Italy, and from GVDA show the enhancement of high frequencies for these latter. A reasonable assumption would be that this variation is linked with the higher stress drops attested to in the literature.

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