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# AN ANALYSIS OF SOIL EFFECTS ON EARTHQUAKE BED-ROCK MOTION: A COOPERATIVE NRC/IPSN DOWNHOLE EXPERIMENT AT GARNER VALLEY (CALIFORNIA)

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## ABSTRACT

This paper provides an overview of a multi-phase experiment being conducted jointly by the US Nuclear Regulatory Commission and the French Institut de Protection et de Sûreté Nucléaire (IPSN). The objective of the experiment is to collect a comprehensive set of data on the propagation of earthquake ground motion through a shallow soil column. The Garner Valley downhole array (GVDA) in southern California is a five-element array of three-component, dual-gain force-balance accelerometers that are capable of measuring acceleration from $3x10^{-6}$ to 2g over a frequency range of 0 to 100 Hz. The analysis of an extensive data set accumulated since 1989 has enabled several of the available seismological and engineering computer codes for modeling earthquake ground motion to be validated. The analysis of weak motions, recorded so far by GVDA shows that the computed ground surface motions, assuming a one-dimensional wave propagation analysis, are in very good agreement with actual recorded surface motions.

## KEYWORDS

Site effect; vertical downhole array; non-linearity; ground motion; soil deposits.

## INTRODUCTION

The anti-seismic design of critical structures, such as nuclear power plants, presupposes a precise determination of the vibratory ground motion which these facilities may be subjected to during a strong earthquake. Seismic monitoring in highly active zones has produced a large number of strong motion records from epicentral areas, but records from the immediate vicinity of faults, which are necessary for the characterization and the determination of certain source and propagation parameters in the near-field, are still rare. Recourse may be had to theoretical developments. Recent headway in the area of the simulation of earthquake sources and wave propagation has, in many instances, been made possible on the strength of the aforementioned strong ground motion records. Usually, these data, however, likewise hear the imprint of the superficial soil layers at the recording site. Thus, two scales of wave propagation, namely tens of kilometers for the seismologist and tens of meters for geotechnical engineers, must be addressed. These two scales also correspond to contrasting ranges in frequency : while basic seismology is mainly preoccupied with frequencies under 1 Hz, engineering seismology must operate in the realm of high frequencies, from 1 up to 30 Hz (small-scale features). In the field of engineering seismology, the behavior of superficial soil deposits and soft-rocks is of particular concern because it is responsible for a preponderant proportion of the damage incurred during major earthquakes (Mexico, 1985; Loma-Prieta, 1989; Kobe, 1995). Local site geology consisting of soft-soil overlying hard-rock supports two opposing phenomena : amplification in the case of weak motion (linear behavior) or in the case of strong motion, attenuation and transfer of seismic energy towards low frequencies (Fig. 1) due to strain-dependent behavior (Mohammadioun and Pecker, 1984). Quantifying the relative contribution of these competing factors is the basic purpose of the Garner Valley, California, downhole array. By giving access to seismic sources capable of generating ground motion both strong and weak, over an extensive range of frequencies, both aforementioned aspects should be able to be investigated.

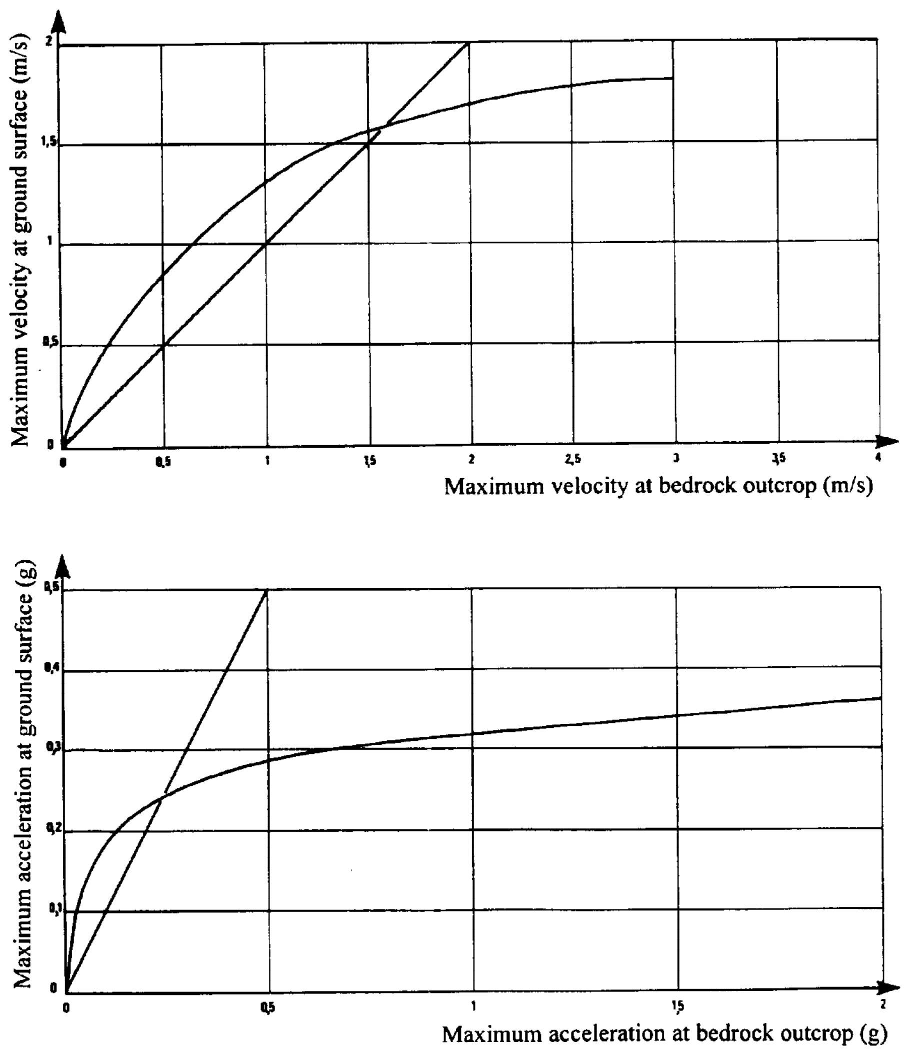


Fig. 1. Variation of maximum acceleration and velocity at the ground surface (from Mohammadioun and Pecker, 1984).

EXPERIMENT SET-UP

The site was selected with three basic criteria in mind. First, it had to be in a seismically active area, then it had to be in an area with good coverage by local and regional seismic networks for the location of earthquakes and lastly, the site had to be situated on soil. These criteria were satisfied at Garner Valley (Fig. 2), 7 km east of the San Jacinto fault and close to a well-documented seismic gap. The instrumentation comprises six three-component accelerometric stations, one of which is at the surface and the five others have been positioned at depths meaningful in terms of the site's soil profile : -6, -15, -22, -55 and -220 meters this last being set well within an unaltered granitic bedrock. Soft soil accounts for the uppermost 18 meters on this site. Instrumentation of an additional 520 meter deep hole is currently in progress, including the same seismic equipment as in the other holes, with piezometers, in addition, in order to measure water pressure. A surface array was installed by the Electric Power Research Institute (EPRI). The final configuration of the surface array has five surface accelerometers in a linear array spanning 244 meters (Fig. 3). The network records ground acceleration digitally between 0 and 100 Hz (at 500 samples per second); the dynamic range is wide : 3 10-6 to 2g (Archuleta *et al.*, 1992). The GVDA site is in a shallow valley within the southern California igneous batholith. Approximately 900 meters of geophysical lines were conducted around the designated site. Both surface refraction and shear wave tests were performed. These tests yielded preliminary estimates of wave velocities. At the site, Standard Penetration Tests (SPT) were conducted, and triaxial compression and extension tests were performed in soil samples representative of three depths, namely 3m, 10.5 m and 15.5 m (Pecker, 1995). The uppermost 18 m of soil has been analyzed in detail using geotechnical methods which yielded a velocity structure material (Pecker and Mohammadioun, 1991). The tests, carried out at the Waterways Experiment Station, are intended to be used for the determination of the constitutive relationship of the alluvial deposits.

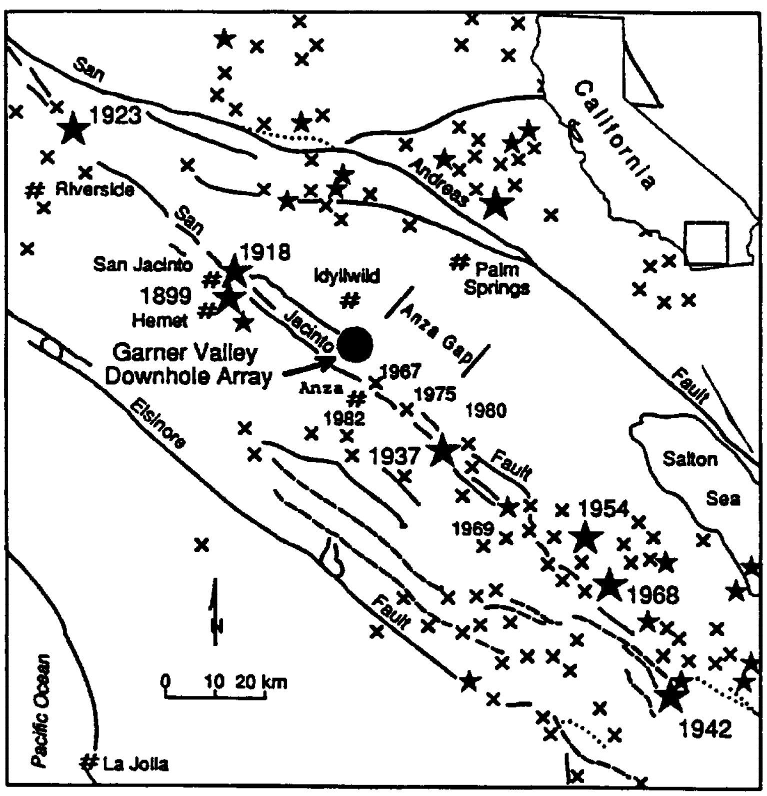


Fig. 2. Location of Garner Valley Downhole Array (GVDA) site. Seismicity (1932 to 1982) for magnitudes greater than 4.0 and main faults in the GVDA region are shown (from Archuleta *et al.*, 1992).

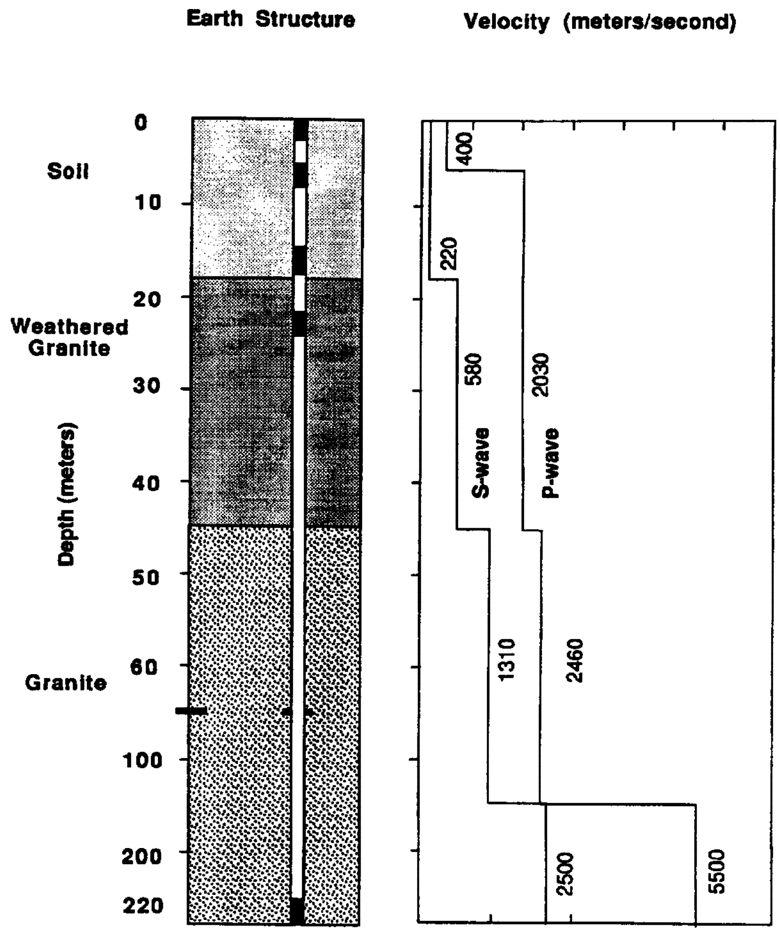


Fig. 3. Lithology and velocity structure at GVDA. Velocities are based on logs to a depth of 100 m (from Archuleta *et al.*, 1992).

## RESULTS AND DISCUSSION

The analysis of 218 weak motions collected during the period 1989-1991 enabled the elastic (small strain) mechanical soil characteristics to be validated, that had been assessed before processing data from aforementioned geotechnical survey (Pecker, 1995). The computed transfer functions are compared to the measured ones in Fig. 4. A very good agreement has been obtained as to the natural frequencies of vibration of the soil column at all three depth measurements; since these frequencies only depend on the shear wave velocity profile, it can be concluded that the velocity structure derived on the basis of the geotechnical survey alone is correct. Ground surface response spectra computed assuming a one-dimensional shear-wave propagation analysis are in very good agreement with those computed from the recorded surface motion. Finally, in the realm of soil dynamics studies, the hypothesis of a rate-dependent damping value for the soil layers produces a better agreement between recorded and computed transfer functions, especially at the fundamental frequency of the soil column. A Q factor proportional to the power 0.68 of the frequency has been obtained, yielding values between 13 and 33 in the frequency range of interest. In basic seismology, a preliminary analysis of the data set allowed certain hypotheses on source and wave propagation to be verified.

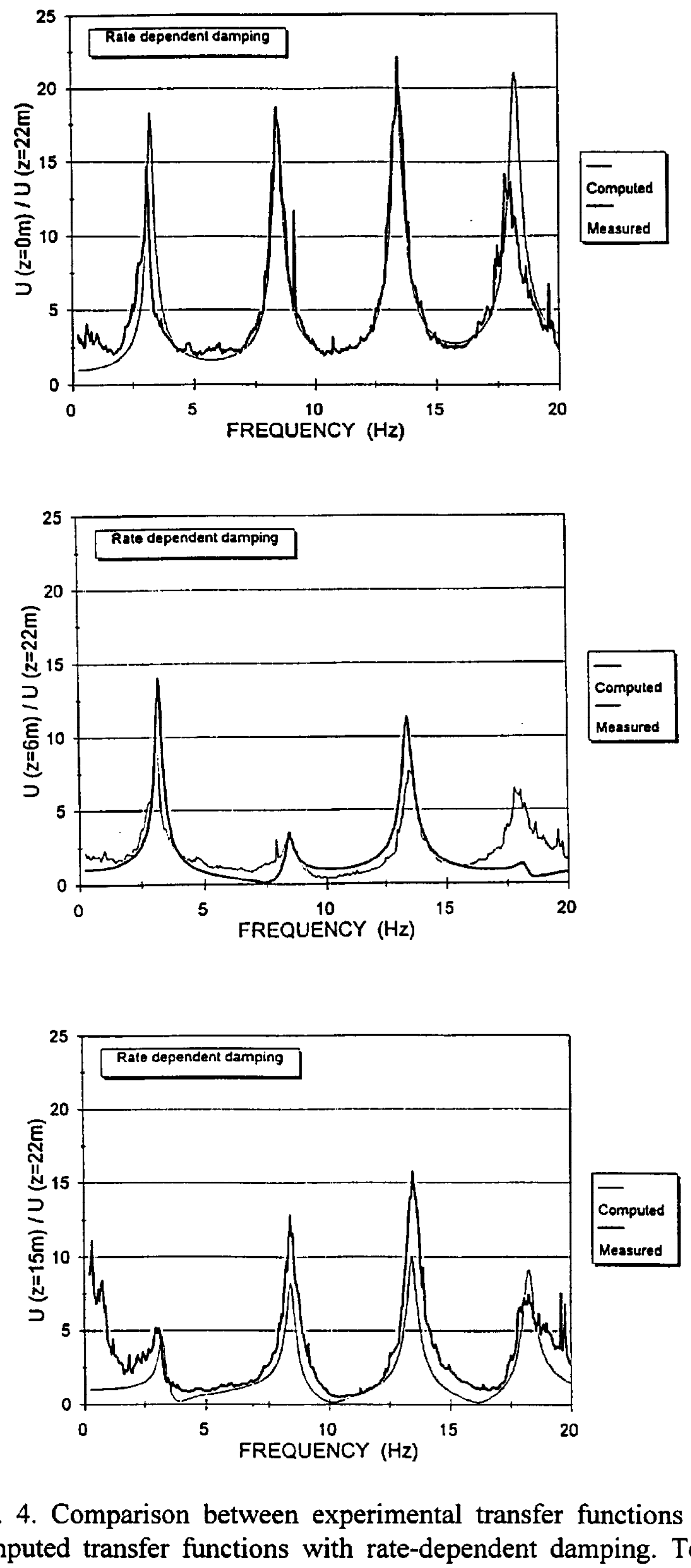


Fig. 4. Comparison between experimental transfer functions and computed transfer functions with rate-dependent damping. Top : between 0 m and 22 m; middle : between 6 m and 22 m; bottom : between 15 m and 22 m (from Pecker, 1995).

To quantify the influence of local geological conditions at different depths, spectral ratios have been computed between surface records and those obtained at two of the subsurface levels (Fig. 5). Corresponding synthetic seismograms over a frequency range of 0 to 50 Hz were calculated at these depths using the site velocity model and the discrete wave number method (Bouchon, 1981). Excellent agreement was generally found between observed and calculated motions, indicating that the chosen velocity structure, monodimensional model and the hypothesis of linear behavior are suitable for these weak motions. A word of caution is nevertheless in order, for the largest acceleration recorded to date (0.1g at the surface, for the 1992 Joshua Tree earthquake) could hardly be expected to elicit nonlinear behavior (Mohammadioun and Gariel, 1994). Similar investigations have been carried out by Bouchon and Kelner (1994) based on data from GVDA. This study is oriented towards investigating the variation of " $f_{max}$ " (the high-frequency limit of spectral acceleration). This study shows that $f_{max}$ depends notably on the epicentral distance of the records considered. The evolution of $f_{max}$ versus instrument depths on the vertical array shows that anelastic attenuation is more pronounced in weathered granite. According to this investigation, attenuation due to scattering effects in a heterogeneous medium seems not to be significant. An important study by Steidl *et al.* (1995) highlights the difficulties inherent in the estimation of site response when using the so-called " reference rock site ". Importantly, data collected in this study demonstrate that surface rock sites can have a site response of their own which could lead to an underestimation of the seismic hazard when these sites are used as a " reference site ".

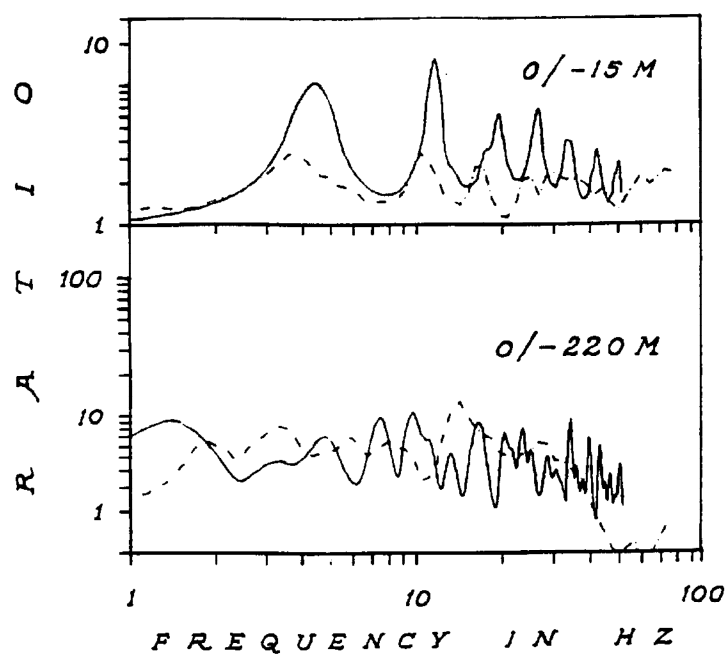


Fig. 5. Comparison between average spectral ratios (dashed and dotted lines) and those computed from the velocity model (solid lines) for two depths (from Mohammadioun *et al.*, 1992).

Although these various theoretical developments in basic seismology do throw some light on the factors that cause seismic motion to vary, and notably on site effects, the engineer requires, for his anti-seismic design relationships that are simple to apply and most, often, highly simplified methods are called upon, wherein the source is represented by the earthquake's magnitude and the path effects by a function depending on the distance separating the source from the observation point (so-called *attenuation law*). Such a local attenuation relationship linking the response spectrum (5% damping) to the magnitude and distance has been determined on the basis of GVDA data so far collected. The calculated response spectrum for a magnitude 4.5 event is compared (Fig. 6) with the results of two predictions based on Californian data at large and on Italian data. A pronounced shift towards high-frequencies is observed in the case of GVDA prediction (Mohammadioun *et al.*, 1992), which could reflect a high local stress-drop.

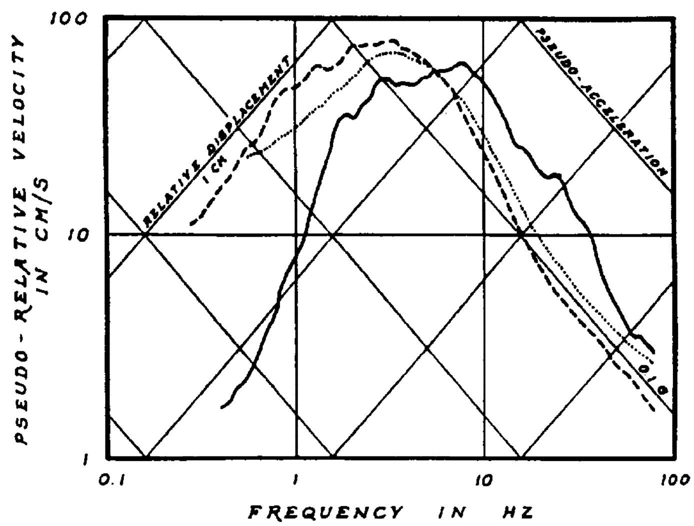


Fig. 6. Synthetic response spectrum (5% damping) computed for a magnitude 4.5 and a focal distance of 20 km with coefficients obtained through regression analysis of GVDA data (solid line); comparable synthetic response spectra derived from a varied set of California data (dashed line) and from Italian data (dotted line) (from Mohammadioun *et al.*, 1992).

## CONCLUSION

The influence of superficial soil layers on bedrock ground motion is one of the generic topics of worldwide importance. Since any number of parameters may modify this motion, topography and lateral heterogenousness among others, the GVDA site was selected with a view to limiting these, the better to isolate soil behavior effects under intense seismic loading. First of all, this site presents what is basically a single alluvial layer, overlying the granitic bedrock and without lateral disturbances. Furthermore, in the experiment, parameters have been painstakingly controlled, particularly in the matter of soil sampling and laboratory testing of the various formations penetrated by the boreholes, so as to ensure a precise knowledge of their mechanical characteristics. The set-up lies in the immediate vicinity of a highly active fault system, liable to produce events over a wide dynamic range both amplitude and frequency-wise. Activity in the area is monitored by a number of seismic networks (USGS, CDMG,...), thus the characteristics of the events recorded can be accurately determined. Lastly, this experiment is unique in that the various communities, notably seismologists and geotechnical engineers, cooperate in order to understand the complex phenomena involved. All these factors should make it possible to follow the evolution of soil behavior versus increasing levels of seismic loading.

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