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VERTICAL/HORIZONTAL RATIO
FOR STRONG GROUND MOTION IN THE NEAR FIELD AND SOIL NON-LINEARITY

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ABSTRACT

Strong-motion recordings obtained in the near field on the occasion of recent major earthquakes afford the opportunity of closely examining the relative importance of different ground-motion parameters (acceleration, velocity, displacement). One of the more remarkable observations is the presence of very large acceleration values on the vertical component as opposed to the horizontal components in certain contexts, notably sites with alluvial layers of weak mechanical resistance. These observations often appear in conjunction with disproportionately large horizontal velocities and displacements. A proposed explanation for this phenomenon presupposes the non-linear behavior of these soils, resulting in an anomalous reduction of horizontal accelerations.

KEYWORDS

Non-linearity, vertical component, horizontal component, site effect, ratio, Kobe, Imperial Valley, PGA, alluvia, near-field ground motion.

INTRODUCTION

Statistical analyses of strong-motion records commonly indicate that the ratio between maximum vertical and maximum horizontal accelerations is smaller than 1. Thus, for example, in the anti-seismic design of nuclear power plants, the vertical acceleration prescribed is quite often only two-thirds the horizontal value. However, in the aforementioned statistical analyses, very little near-source strong-motion data has been taken into account. Only in recent years, following major earthquakes in California: Imperial Valley (1979), Whittier Narrows (1987), Loma Prieta (1989), and Northridge (1994), and in Japan: Kobe (1995), has light begun to be thrown on the evolution of strong ground motion parameters in the near field. The Kobe event has been unusually instructive in that it has provided vertical-array data from a zone where soil liquefaction is known to have taken place.

The subject of ground motion parameter variation in the near field has already been addressed in a number of articles, including notably Bozorgnia & Niazi (1993), Bozorgnia, & *al.* (1994), Niazi & Bozorgnia (1991, 1992, 1994), and Nisar & Golesorkhi (1995). The results reported indicate that in the near field not only can the PGA_V/PGA_H ratio be 1 or higher, but also that it is frequency-variable. In the ensuing discussion, the variation of this ratio will be examined in the light of the data recently acquired, particularly for alluvial sites.

STRONG-MOTION DATA BASE

An extensive set of accelerometric data from California was divided into two categories according to site geology: soft sediment sites and hard rock sites (defined as those with V_S values of at least 700 m/s). Only the former category, consisting of 403 three-component records, was retained for the present study. Within this sub-set, two magnitude classes were defined: magnitudes of 5–6 and ones greater than 6, as well as three distance (to the fault) classes: smaller that 5 km; 5 to 10 km, and 10 to 50 km. The number of records comprising each of these groups is shown in Table 1, below.

Table 1. Number of sedimentary site records analyzed in different magnitude and fault-to-site distance categories.

	DISTANCE (KM)		
	<5	5–10	10–50
M = 5–6	3	19	42
M > 6	10	19	184

Response spectra (5% damping) were computed for all components of the above records. Within each class, the ratios of horizontal to vertical pseudo-relative velocity ($PSRV_H/PSRV_V$), r, were averaged for 96 frequencies (between 0.2 and 78 Hz).

A second data base, described in Table 2 and containing mostly recent near-field California data and data from the Kobe earthquake, was compiled to highlight the influence of non-linear soil behavior on ratios obtained from peak values of ground motion (acceleration and velocity).

RESULTS AND DISCUSSION

Figure 1a depicts the variation of ratio r versus frequency for the three distance classes at magnitudes greater than 6. The first observation, already mentioned by others, is that the ratio r diminishes as frequency increases. Between 0.2 and about 2 Hz, r is globally constant and takes on a value of 2 or 2.5 for all distance ranges. Beyond that, r decreases up to 10 Hz at least, but this decrease differs considerably according to the distances involved: at short distances it is quite drastic, falling off to a value of about 0.4. In the intermediate distance range, the minimum is substantially lower than 1, and at greater distance, it is slightly above. Beyond the minimum, r increases again, somewhat, in all instances.

For the smaller-magnitude events seen on Fig. 1b, the general tendency is similar, but the variation not nearly as pronounced. At low frequency, r has nearly the same value as in the previous example, but the minimum reached is 1 or slightly higher, and little variation is observed with distance.

A number of factors likely to influence near-field motion might be proposed to explain the variation of horizontal-to-vertical ratio just described. Some, of a seismological nature, could be linked to the proximity of the fault, and more particularly to its mechanism. However, such factors might logically be expected to differ significantly from one earthquake to another, possibly cancelling each other out when treated statistically, and this does not appear to have been the case here.

Actually the choice of records principally from alluvial sites was effected in order to ascertain whether the instances of unusually high vertical accelerations (or energy in high frequencies) could be the consequence of a non-linear behavior of the soils. Indeed, quite often, due to a sharp velocity gradient with depth, seismic waves emerge at the station practically vertically. Accordingly, the vertical component records consist primarily of compressional waves, whereas, on the horizontal components, shear waves predominate. Under such circumstances, in the event of very strong ground motion, for the most part near the fault, horizontal (shear-wave) accelerations tend to saturate when soils behave non-linearly: the

Table 2. Description of data used in the peak ground motion ratio analysis. Distances are to the fault unless marked with an asterisk, in which case they are epicentral.

EARTHQUAKE	DATE	MAGNITUDE	STATION	DISTANCE	EARTHQUAKE	DATE	MAGNITUDE	STATION	DISTANCE
Kobe	Jan. 17, 1995	6.8	Kobe Univ.	2.2	Westmorland	Apr. 26, 1981	6.0	Westmorland	8.1
			Tadaoka	29	Coyote Lake	Aug. 6, 1979	5.7	San Martin	4.6
			Sakai	25				Gilroy #2	8.4
			Fukushima	16				Gilroy #3	6.8
			Abeno	23				Gilroy #4	5.5
			Morikawachi	24	Loma Prieta	Oct. 17, 1989	7.1	Corralitos	1.4
			Yae	28				Saratoga	3.5
			Chihaya	48				Gilroy Com. Bldg.	4.5
			Oosakayama	56				Gilroy #2	6.2
			Kusatsu Obs.	64				Gavilian College	5.4
			Kuzukawa	70				Lexington Dam	3.0
			Mizukuchi Obs.	81	Northridge	Jan. 17, 1994	6.8	Rinaldi Rec. St.	10*
			Imazu Obs.	96				Sylmar Conv. Sta.	12*
			Torahime Obs.	113				Sylmar Conv. St. E.	13*
			Nishiakashi Sta.	10				Sylmar Co. Hosp.	16*
			Takatori Sta.	0.5	Imperial Valley	Oct. 15, 1979	6.9	Array #1	21.
			Kakogawa Sta.	25				Array #2	15.2
			Takaraduka Sta.	6.8				Array #3	12.1
			Shin Osaka Sta.	17				Array #4	6.6
			Shin Osaka (SS)	18				Array #5	3.9
			Kobe JMA	0.5				Array #6	1.3
			Osaka JMA	20				Array #7	0.8
			Maiduru JMA	76				Array #8	3.7
			Okayama JMA	93				Array #9	5.8
			Tottori JMA	122				Array #10	8.2
			Hikone JMA	102				Array #11	12.8
			Fukui JMA	165				Array #12	17.4
			Taisho	19				Array #13	20.2
			Sumiyoshi	24				Bonds Corner	3.0
			Port Island	2.1				Brawley	8.3
			Vert. Array surf.	2				Holtville	8.7
			Vert. Array -16m	2				Calexico	10.5
			Vert. Array -32m	2				Parachute Test	13.4
			Vert. Array -83m	2				Plaster City	23
Whittier Narrows	Oct. 1, 1987	5.8	Bright Ave.	6.0				Calipatria	24
			Norwalk	9,4				Superstition Mtn.	25
			Alhambra	9.8				Meloland Overp.	1.1

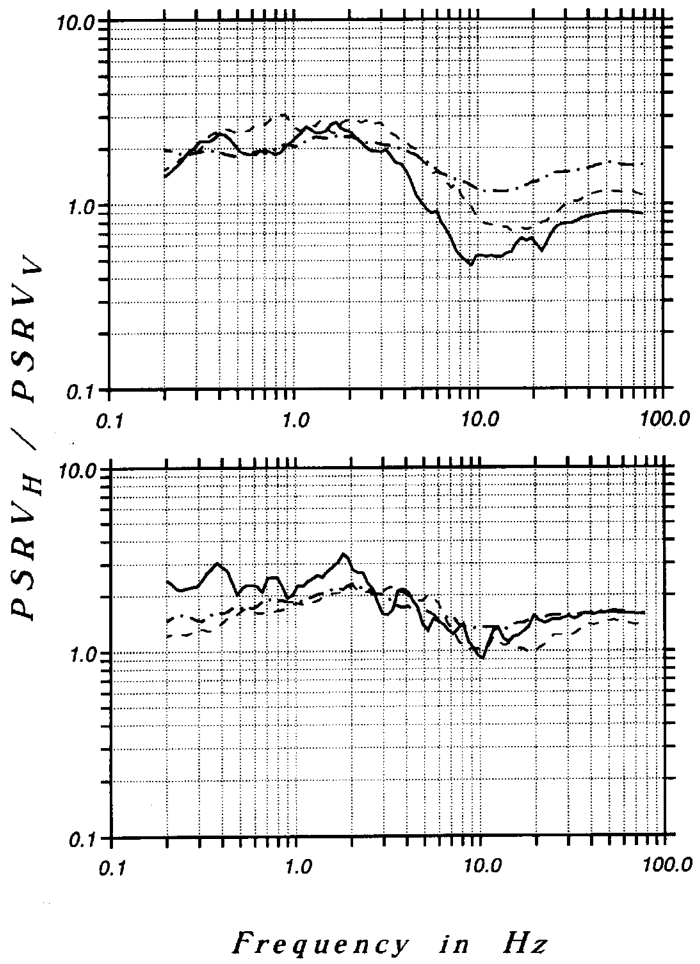

Fig. 1. Average horizontal/vertical response spectrum (*PSRV*) ratios for strong-motion records divided into three distance ranges: <5 km (*solid lines*); 5-10 km (*dashed lines*), and 10-50 km (*dashed and dotted lines*). Magnitudes greater than 6, above (*a*) and 5-6, below (*b*).

saturation threshold might commonly be on an order of 0.45–0.5 g (cf. Mohammadioun & Pecker, 1984 and Mohammadioun, 1986). By contrast, the vertical component, containing mainly compressional waves, is unaffected by this behavior (Fujii & *al.*, 1992; Akao & *al.*, 1992), and in fact may even be enhanced in the event of strong non-linearities (Aubry & Modaressi, 1992). Figures 1a and 1b clearly bear out this hypothesis, in that the variation observed is more pronouced at high as opposed to more moderate magnitudes and at short distances as opposed to longer ones. In both cases, the ground is subject to high levels of strain.

The second set of data (cf. Table 2), for which only peak values of ground motion are analyzed, includes a number of events from sites evidencing soil non-linearities, notably the Imperial Valley earthquake, in 1979, recorded in many close-in stations with the dense El Centro array (which perpendicularly transects the fault) and the recent major earthquakes of Northridge and of Kobe in Japan (Irikura & Fukushima, 1995), including data from a vertical array on Port Island operated by the municipal services of Kobe and instrumenting depths of 16, 32, and 83 m (cf. Aguirre & Irikura, 1995). Here the evolution of peak ground acceleration is very significant versus depth. Indeed, for horizontal components, an average value of 0.6 g is observed at depth in comparison with only 0.3 g at the surface. Acceleration has thus visibly saturated as it reached the uppermost soil layers. The vertical component of ground acceleration, on the other hand, is actually amplified by the superficial layers: 0.2 g at depth and 0.55 g at the surface, i.e. a vertical-to-horizontal ratio of about 2.7.

During recent California earthquakes (Lew, 1992), notably Loma Prieta and Northridge, a number of instances of non-linear soil behavior have been reported (cf. Aki & *al.*, 1993). For Northridge, the *PGA* vertical/*PGA* horizontal ratio varies between 0.5 at the hard rock site station and 0.8 at the station closest to the source (Iwan, 1994). It is interesting to see to what extent the other earthquakes listed in Table 2 display the same tendency as to the vertical/horizontal ratio.

The parameters chosen in this analysis are the maximum acceleration values measured in each station (horizontal and vertical components) and the corresponding peak velocities. The analysis of this data set has been restricted to peak values principally because the Kobe data was not available at the time in such a form as to allow spectra to be computed. It should likewise be mentioned that for many of the stations, site geology was not known (these have been supposed to be alluvial in this study).

It is generally acknowledged that when non-linearities occur, horizontal acceleration saturates, as mentioned earlier, and also that the energy is transferred towards lower frequencies, causing an increase in peak velocities and displacements. The A_H/V_H ratio (Sawada & *al.*) might accordingly be expected to be an effective indicator, accompanied by an increase in the PGA_V/PGA_H ratio. Figure 3 shows the variation of these two ratios versus each other for all the records listed on Table 2. This figure can be viewed as consisting of two zones. In the first, where the PGA_V/PGA_H ratio is less than 0.75, values of A_H/V_H display a considerable degree of scatter. Most PGA_V/PGA_H values lie between 0.5 and the cut-off value of 0.75. The scatter may be due to a wide variety of site conditions, but also to such specifically near-field factors as source mechanism, radiation model, and directivity. A number of points in this zone, notably ones for which PGA_V/PGA_H is less than 0.5, correspond to more distant stations ($R > 50$ km) included in the set of Kobe data. In the second zone, A_H/V_H falls off sharply as PGA_V/PGA_H increases to 1; it continues to decrease beyond that point. These two zones can be construed as corresponding to the linear and non-linear portions of the variation, respectively. This interpretation is supported by the data from the Kobe array, insofar as the two uppermost level records, where soil is known to have behaved non-linearly, are situated in zone 2, whereas the lower ones are in zone 1.

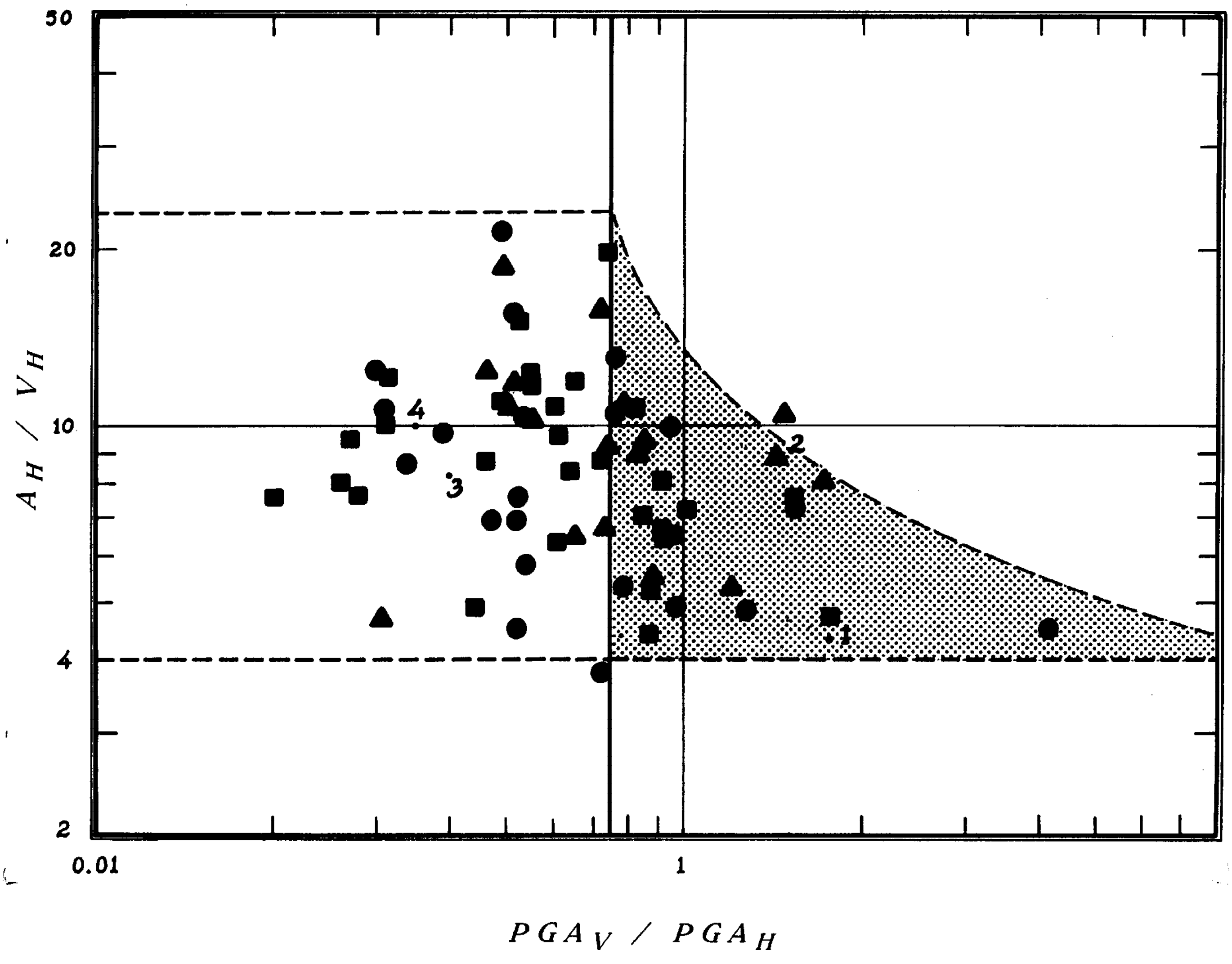

Fig. 2. Variation of the A_H/V_H ratio versus PGA_V/PGA_H for the data set described in Table 2. *Dots* represent data from Imperial Valley, *squares*, those from Kobe, and *triangles*, miscelleaneous California data. Results from the Port Island downhole array (Kobe) are numbered 1 to 4 in descending order. The shaded area indicates a zone of suspected soil non-linearities.

It should be noted that A_H/V_H has a frequency dimension ($2\pi f$), thus the passage from zone 1 to zone 2 on Fig. 3 reflects an overall lowering of frequency, which, from about 1 to 3 Hz in zone 1, evolves towards about 0.1 in zone 2. What actually seems to be taking place is a progressive disappearance of the highest frequency values, for although low A_H/V_H ratios do indeed appear in both zone 2 and zone 1, no high ones are to be found in zone 2, as indicated by the dashed upper limit. Plotting these ratios might offer a fairly quick and convenient way to detect, within a data set where soil conditions are not readily available, those records for which non-linearities could be suspected.

CONCLUSION

In this contribution, the high values of ground motion acceleration displayed by the vertical component on the records of some major earthquakes from the near field and in alluvial settings can in large part be explained by non-linear soil effect. Superficial layers of materials with poor mechanical resistance do have a determining influence on the incident bedrock motion. It is of prime importance that the global, and so commonly used, term *amplification* be refined in such a way as to specify the parameter of motion intended, i.e. displacement, velocity, or acceleration. Test sites, including vertical arrays (such as the Garner Valley Downhole Seismic Array – see contribution to this conference elsewhere) conducted under carefully controlled conditions, can reasonably be expected to clarify, in the future, our understanding of the phenomena described above. If the near-field ground motion parameters discussed above are indeed level dependent, transfer functions derived from weak earthquake motions will not be applicable to large earthquakes. This deduction is in fact borne out by observation, since in the case of the Loma Prieta earthquake, small magnitude aftershocks displayed large amplifications while for the main event, values were found to be only 1.5 to 2. It is accordingly strongly recommended that circumspection be exercised when relying on transfer functions computed from small earthquakes, as is common practice in microzonation studies, particularly when determining amplification levels (sometimes found to be 10 or more).

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