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Comment and Reply

Comment on "3D Site Effects: A Thorough Analysis of a High-Quality Dataset," by F. J. Chávez-García, J. Castillo, and W. R. Stephenson

by Roberto Paolucci and Ezio Faccioli

Introduction

Chávez-García *et al.* (2002) presented an analysis of 64 weak motion events recorded by a temporary digital seismometer array operating at Parkway Valley, New Zealand, from 1 August to mid-October 1995. The most significant record was obtained on 11 August, for a M_L 4.9 earthquake at 80-km epicentral distance, with a peak ground acceleration of 1 Gal and a peak ground velocity of 5 mm/sec.

The main indication of their analysis was that ground motion is dominated by surface waves, originating at the northern edge of the valley and propagating southward, mainly in the direction of the sloping base of the valley. They also gave much emphasis to a supposed contradiction between this result and the finding reported by Paolucci *et al.* (2000), that the ground motion in the frequency band around 1.6 Hz shows a clear pattern related to the 2D fundamental vibration mode of the valley.

Chávez-García *et al.* (2002) argued that Paolucci *et al.* (2000) were "deceived" by the simultaneous arrivals of surface waves at the stations along the different alignments considered (Fig. 1), the alignments being roughly perpendicular to the main direction of propagation of surface waves. According to the same authors, the error of Paolucci *et al.* (2000, p. 1950) was originated by considering only "groups of stations, instead of all of them together."

We will briefly recall the main considerations that lead us to the previous conclusions, including further results, to show that the contradiction is only apparent and that the occurrence of a 2D in-plane resonance pattern cannot be ruled out at all by the arguments of Chávez-García *et al.* (2002).

2D Resonance Pattern Inferred from Records

The displacement histories at three station alignments across the valley (Fig. 1) were considered for the 11 August 1995 earthquake mentioned previously. Referring to these alignments, the horizontal components were rotated into the in-plane (*SV*) and out-of-plane (*SH*) directions. To identify the possible resonance effect, the time traces were bandpass filtered between 1 and 1.8 Hz. The left side of Figure 2 illustrates the SV and vertical components of displacement for the different stations. As also shown by Chávez-García *et al.* (their figure 13), all horizontal components along a single alignment are practically in phase, at least in the strongest part of motion, while each horizontal component tends to be either in phase or out of phase with the corresponding vertical component.

In the right part of Figure 2, each plot shows the displacement at a single pair of stations. Each curve of the plot is obtained by taking on the horizontal axis the displacements at one station (say 03 for the top-left plot) and on the vertical axis the displacement at another station (say 04 in the same plot) for the time window indicated on the seismograms on the left. Thick lines are for the horizontal components, thin lines for the vertical ones. If the two signals are perfectly in phase, these "synoptic" curves should reduce to a straight line bisecting the first and third quadrants. If the signals are in perfect phase opposition, the line should bisect the second and fourth quadrants.

Along alignment 1 all pairs of stations have the horizontal component approximately in phase (synoptic curve in the first and third quadrants). As regards the vertical components, these are clearly in phase for the pairs of stations that lie on the same side of the valley (i.e., 03–04 and 05–

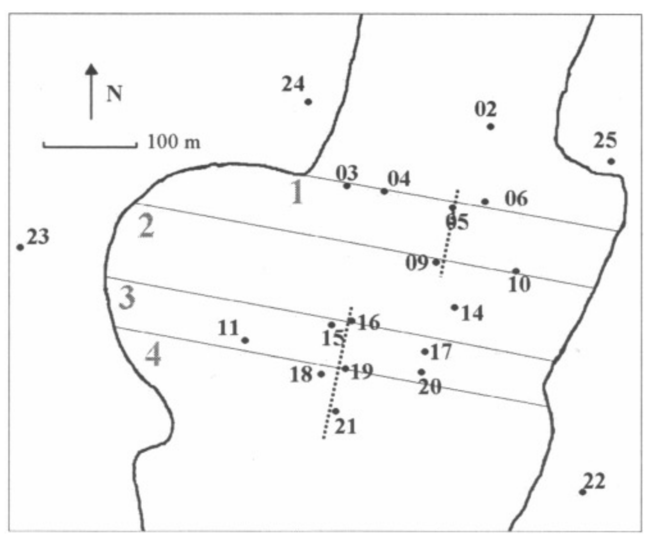

Figure 1. Detail of Parkway Valley with the station numbers and the alignments considered by Paolucci *et al.* (2000).

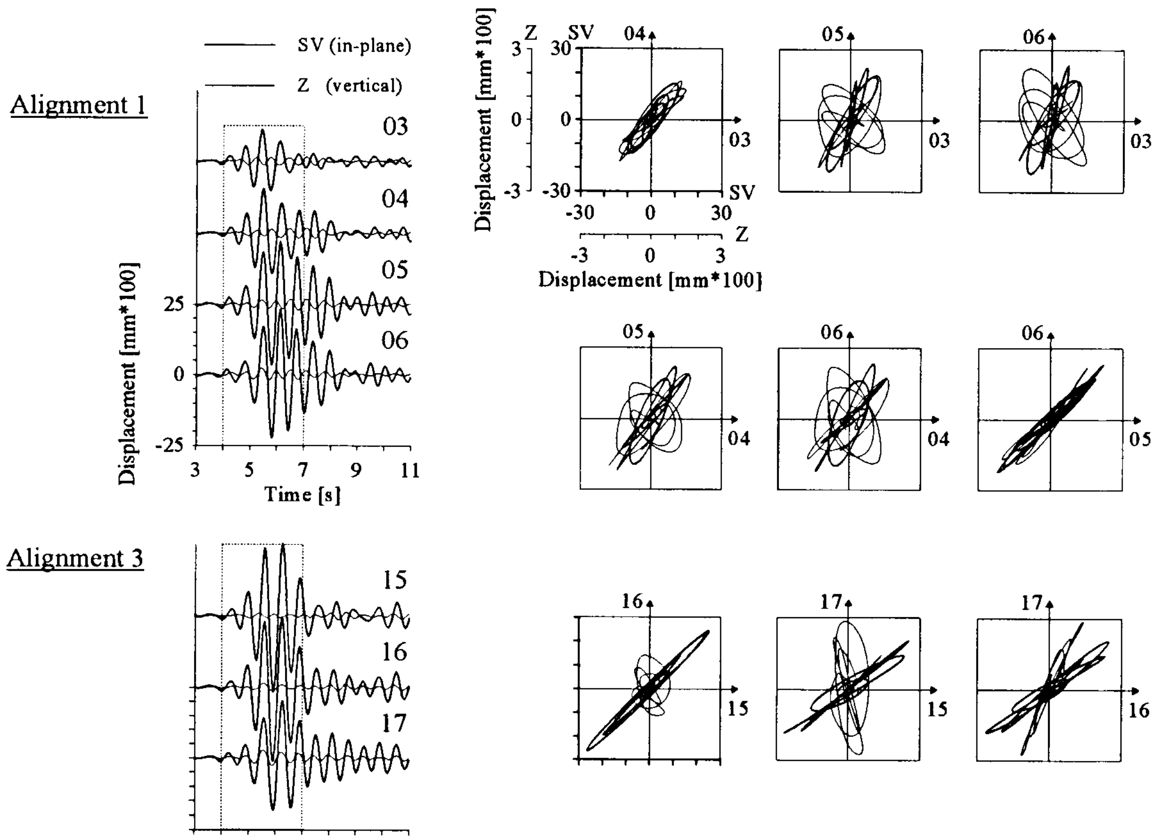

Figure 2. Left: Seismograms recorded during the 11 August 1995 event along alignments 1 and 3 (see Fig. 1). Right: "Synoptic" displacement plots at pairs of station along alignements 1 and 3. Thick lines and thin lines are for horizontal and vertical displacements, respectively. From Paolucci *et al.* (2000).

06), while the other pairs (i.e., 03–05, 03–06, 04–05, and 04–06) show the out-of-phase behavior (synoptic curve in the second and fourth quadrants). The position of the middle line of each alignment is indicated in Figure 1 by a dashed line. The same indications also apply for the pairs of stations of the other two alignments, although for brevity the results of alignment 4 in Figure 1 have been omitted. Therefore, while all the horizontal components along the valley, within the selected frequency band, tend to move in phase, the vertical components move in phase only if they lie within the same side of the valley; otherwise they move out of phase.

This pattern is essentially the same (Fig. 3a) as the well-known 2D in-plane first vibration mode analyzed by Bard and Bouchon (1985). To further highlight the similarity, we have plotted the in-plane trajectories of motion along alignment 4 for the three available stations (Fig. 3b) and connected the peaks. The striking resemblance of the curves of Figure 3a, b has led us to assert with little doubt that ground motion in the frequency band around 1.6 Hz is strongly affected by a 2D in-plane resonance frequency of the whole valley. Note that this is far from saying, as Chávez-García *et al.* (p. 1948) claim that we did, that "ground motion for this event consists mainly of 2D resonance modes," whatever the last part of their statement means.

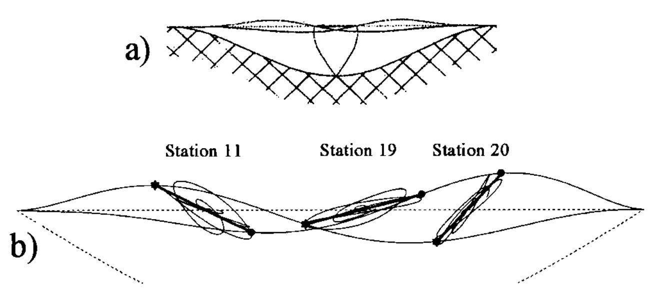

Figure 3. 2D in-plane vibration mode of an alluvial valley according to (a) Bard and Bouchon (1985) and (b) Paolucci *et al.* (2000).

2D Numerical Results

Based on recent site investigations (W. R. Stephenson, personal comm., 2001) and on a spectral analysis of surface waves velocity profile (Sutherland and Logan, 1998), a representative geological cross section of Parkway Valley was modeled using a spatial discretization based on spectral elements, a recently introduced numerical approach for the accurate and efficient simulation of elastic wave propagation in earth media (Faccioli *et al.*, 1997).

The geological cross section is depicted in Figure 4, with the dynamic soil properties summarized in Table 1. The numerical model was subjected to the vertical incidence of an in-plane shear wave, with a Ricker-type time dependence, having a peak frequency at 1.7 Hz and exciting frequencies up to 5 Hz. The numerical 2D transfer function was then obtained at selected receivers on the valley surface by computing the spectral ratio of surface response versus ground motion at outcropping bedrock.

In Figure 5 we show such transfer functions for receivers A and B (see location in Fig. 4), corresponding to the valley center (top of figure) and to the half-distance of center from the edge (bottom of figure), respectively. For each case we have also plotted the corresponding 1D transfer function and the "observed" spectral ratio for the August 11 event, calculated as the average between spectral ratios for various representative stations with respect to station 23, on outcropping bedrock. Namely, stations 15, 16, 19, and 21 are representative of the response at the valley center (receiver A in Fig. 4) and stations 10, 11, 17, and 20 of the response at half-distance from the valley edge (receiver B in Fig. 4). For this purpose, the east–west and north–south components of ground motion were rotated to provide the in-plane component. Figure 5 deserves the following comments:

- The first two peaks of the observed spectral ratios, around 1.6 and 2.4 Hz, respectively, both at locations A and B, are reproduced rather accurately by the 2D numerical results.
- The 1D transfer functions fail to predict both the peak frequencies and the amplification levels, which are generally underestimated, as pointed out in previous studies for other 2D valley configurations (Faccioli, 2002); note that the discrepancy between 1D predictions and observations is notable especially at half-distance from the valley edge.
- Although the 2D numerical model is inadequate to capture the 3D features of the valley response, such as the southward propagation of surface waves from the northern edge of the valley, detected by Chávez-García *et al.* (2002), it clearly provides results reasonably close to observations, which would appear adequate for many engineering applications.
- These results strongly support the previous conclusion by Paolucci *et al.* (2000), that is, during the August 11 event a 2D in-plane vibration mode was excited, corresponding to the fundamental resonance frequency of the valley.

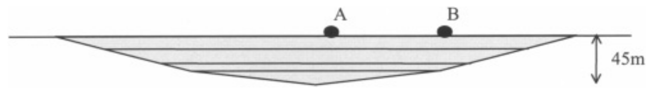

Figure 4. Representative geological cross section of Parkway Valley next to alignment 3. Layer properties are given in Table 1. The model was kindly provided by W. R. Stephenson (personal comm., 2001).

Table 1
Dynamic Soil Properties of the Numerical Model of a Representative Cross Section of Parkway Valley

V_P (m/sec)	V_S (m/sec)	Density (kg m^{-3})	Thickness (m)
1650	155	1800	11.5
1650	345	1800	13.5
1650	133	1800	7
2400	1200	2000	13
3500	1750	2600	Bedrock

Layers are reported from top to bottom.

Discussion and Conclusions

We have presented some solid arguments to support our contention that during the 11 August 1995 earthquake the fundamental in-plane vibration mode of Parkway Valley, around 1.6 Hz, was excited significantly enough to be detected by a careful analysis of ground motion. In their argument against this conclusion, Chávez-García *et al.* (2002) failed to explain the out-of-phase vertical motion of the two sides of the valley that, on the contrary, is a typical feature of an in-plane vibration mode (Bard and Bouchon, 1985).

However, as stated by Chávez-García *et al.* (2002), southward propagation of surface waves does occur inside the valley. Where is the contradiction? The correct answer, in our view, is that there is no contradiction. Why should we exclude that two key physical phenomena in the seismic response of an alluvial valley, such as its response at resonance and the generation of surface waves by diffraction at the valley edge, can occur simultaneously? Why rule out that observed ground motion is just the superposition of both effects (and of course of additional ones)? The superposition of valley resonance and laterally propagating surface waves has been observed in a number of cases, among which probably the most deeply investigated is that of the Valley of Mexico during the 19 September 1985 Michoacán earthquake (see, e.g., Fäh *et al.*, 1994).

The problem is not whether the system responded at its fundamental resonance frequency. Obviously it did, as any dynamic system does, when subjected to an excitation at such frequency. The true problem is to assess the relative contribution of resonance and lateral propagation of surface waves. According to the well-known diagram presented by Bard and Bouchon (1985) to discriminate between the predominance of 2D resonance or 1D plus lateral surface-wave propagation, in the case of Parkway Valley the second effect would be prevailing. But this does not exclude at all the occurrence of the first one, which would be nonsense from the point of view of system dynamics. Note also that Bard and Bouchon's diagram refers to out-of-plane (*SH*) wave propagation, while in the in-plane case the domain of 2D resonance would be enlarged. Anyway, a quantitative an-

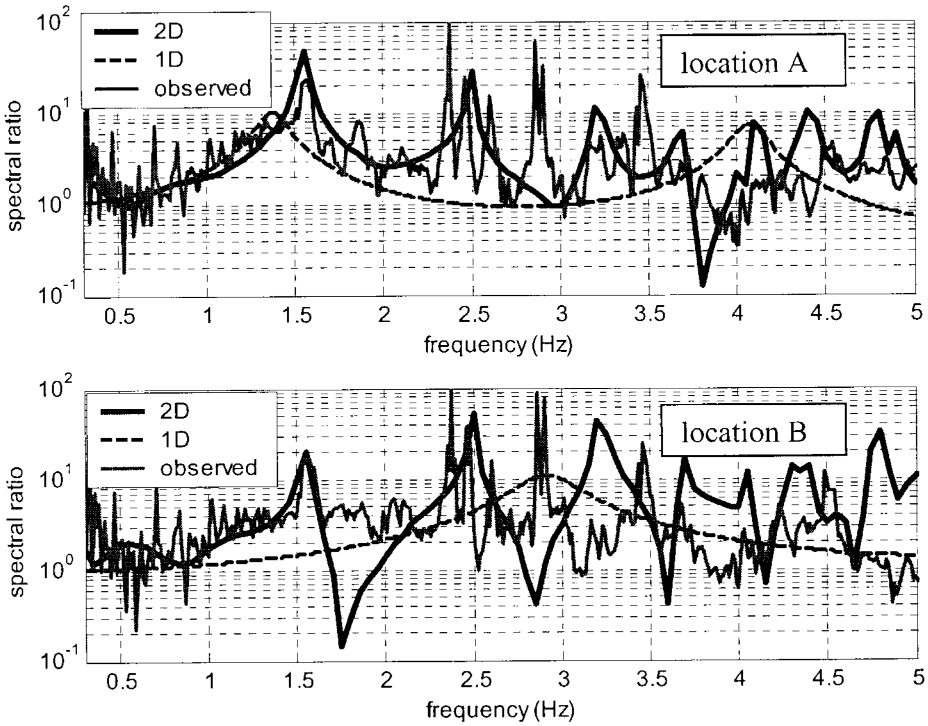

Figure 5. Comparison of 2D and 1D numerical transfer functions for vertically propagating *S* waves and the spectral ratios calculated for stations at valley center (location A in Fig. 4) and half-distance from the valley edge (location B in Fig. 4), with respect to reference station 23.

swer to this question would require a careful investigation through a 3D numerical model.

In their reply to this comment, Chávez-García and Stephenson (2003, see their "Discussion") present additional results to support their conviction that "no indication of 2D resonance was observed" in the data of Parkway Valley and ground motion is dominated by southward-propagating surface waves. We have no objection as to the dominance of southward-propagating surface waves on ground motion: they are very clear on the seismograms. However, it is far from clear how the authors can explain with that type of waves the out-of-phase vertical motion observed on the two sides of the valley.

Furthermore, we stress that the transient response of a dynamic system is a superposition of different effects, which cannot be clearly and easily separated. Consider for example figure 6 of Chávez-García and Stephenson (2003), where laterally propagating surface waves are quite clear. However, it is also clear, especially in the vertical motion plot and in the frequency window between 1.25 and 2 sec, that the central portion of the valley tends to move perfectly out of phase with respect to the north–south axis; this is a hint of the contribution (not of the dominance, of course) of the in-plane resonance mode. To throw further light on this important aspect, we have excited our 2D numerical model of Parkway Valley with a sinusoidal plane wave with frequency $f = 1.55$ Hz, coinciding with the resonance peak of the transfer function of Figure 5. The resulting synthetic seismograms of Figure 6 clearly display, after an initial transient, the in-plane resonant mode, with the whole valley vibrating in phase for the horizontal component and out of phase for the vertical one. Obviously, when the valley is excited by a broader-band input signal, this resonance mode is partially or totally concealed by other effects, such as depicted in figure 6 of Chávez-García and Stephenson (2003). Only in the case of an excitation with negligible energy at the fundamental resonance frequency of the valley would the resonance mode not be excited. But this is not the case for the Parkway Valley ground motion, for which the peak of the Fourier spectrum of rock motion lies precisely between 1 and 2 Hz.

We are perfectly aware that this resonance mode would have dominated the response only for deeper valleys, but we never claimed that the response of Parkway Valley is dominated by 2D resonance. Indeed, only after a filtering operation could we clearly detect the in-plane fundamental resonance mode of the valley, both on real records and on our numerical simulations.

Finally, we believe that the arguments brought by Chávez-García *et al.* (2002) and Chávez-García and Stephenson (2003) against our conclusion completely fail to refute it.

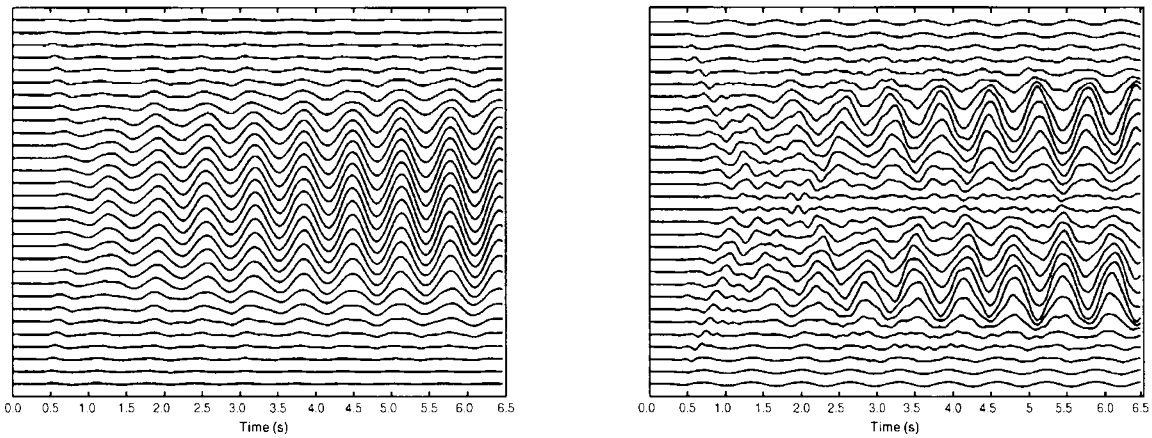

Figure 6. Synthetic seismograms calculated at the valley surface, using a sine excitation with frequency $f = 1.55$ Hz, coinciding with the fundamental resonance peak of the transfer function of Figure 5. Left: horizontal component; right: vertical component.

Acknowledgments

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Department of Structural Engineering
Politecnico di Milano
Piazza L. da Vinci 32
I-20133 Milano Italy

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