DOI 10.4430/bgta0210

The possible effect of vertical ground motion on the horizontal seismic response at the surface of a sedimentary structure

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(Received: August 23, 2017; accepted: November 21, 2017)

ABSTRACT Numerical modelling is considered to evaluate the possible effect of vertical ground motion components of input motion on the horizontal seismic response at the surface of a stack of homogenous sedimentary layers. This analysis has been made at four Italian sites where the local *Vs* profile was available down to the reference bedrock. Computations show that the effect of vertical components on horizontal ground seismic response is frequency dependent and changes as a function of the local *Vs* profile and accelerometric time history. These outcomes suggest that the common practice of considering only horizontal components of input motion to compute horizontal seismic response may provide biased results, particularly when local hazard is dominated by seismic events that are relatively close to the site of interest. In these cases, vertical component of input motion cannot be neglected and should be considered in seismic response analysis.

Key words: Seismic response, seismic hazard, seismic risk, numerical modelling.

1. Introduction

In the current practice of anti-seismic design, horizontal components of seismic ground motion are considered of major interest. This because most existing structures prove to be weakest under horizontal inertial loads and thus more vulnerable to these ground motion components. Despite the fact that recent experiences [see, for instance, Grimaz and Malisan (2014)] indicate the importance of vertical ground motion components in intensifying the damage to many structures (masonry buildings, churches, industrial warehouses, etc.), current seismic codes mainly focus on horizontal seismic motion. Furthermore, vertical components are generally considered just a fraction (2/3) of the horizontal ones (e.g., Newmark and Hall, 1982).

The above-cited pieces of evidence explain the general use of simplified one-dimensional models for computing local seismic response of soft soils under the effect of seismic loads. In these models, eventual amplification effects are considered the results of interfering upward and downward SH-waves propagating inside a stack of plane uniform layers (e.g., Kramer, 1996). The eventual presence of P-wave components (responsible for the vertical ground motion) is modelled separately, being considered entirely decoupled from S-wave components. This is acceptable for vertically uprising body waves when a significant delay exists between P and S phases and waves propagate vertically. However, this is not always the case and a body of experimental evidence (e.g., Takahashi *et al.*, 1992; Parolai and Richwalski, 2004; Parolai *et al.*, 2009) shows the existence of possible P/S waves conversion phenomena and the contribution of converted S waves to the vertical seismic response. This could be the effect of wave trains characterized by oblique incidence or of the partial overlapping of S and P phases in the near field condition. In these situations, one might also expect that vertical P-wave components may occasionally contribute to the horizontal seismic response: in such cases, neglecting vertical components of the input ground motion, when the horizontal seismic response is of concern, may give biased results. On the other hand, the boundary between near- and far-field conditions cannot easily be defined being dependent on the hypocentral depth, on the focal mechanism and on the local crustal structure. This problem is generally neglected in current professional practice: earthquakes that are representative of the input ground motion are selected by fitting reference response spectra deduced from regional hazard studies and deaggregation analyses (e.g., Iervolino *et al.*, 2009), with no reference to the eventual near-field or far-field conditions for the specific earthquake. In order to explore the possible impact of this practice, horizontal seismic response has been numerically estimated at a set of four sites in Italy, by respectively neglecting and considering the role of vertical ground motion components of input motion in computing the horizontal seismic response.

2. Input data

Four sites have been selected for the analysis (Fig. 1), whose subsoil configuration (Table 1) was assessed by independent studies (Lunedei and Albarello, 2015; Albarello *et al.*, 2016).

Fig. 1 - Position of the 4 Italian sites considered for this study: Cascia, Castel Viscardo, Gildone and Mirandola.

Table 1 - Seismic layering at the sites considered for the numerical analysis (Fig. 1).

	Depth (m)	Vs (m/s)	Vp (m/s)	Geological unit	Unit weight (kN/m^3)
Cascia	0	512	1066	Scaglia Cinerea (shale)	21
	3	668	1391		
	8	684	1424		
	10	692	1441		
	11	714	1486		
	13	1032	2148	Bedrock	22
Castel Viscardo	0	230	479	Alluvium	18.5
	2	342	712		
	3	385	801		
	7	420	874		
	8	450	937		
	10	470	978		
	12	510	1062		
	16	530	1103		
	19	560	1166		
	22	630	1311		
	24	700	1457		
	29	730	1520		
	32	760	1582		
	40	760	1582		19
	76	760	1582		
	106	950	1978	Bedrock	22
Gildone	0	220	458	Argille del Fortore (flysch/shale)	20.5
	2	360	749		
	5	440	916		
	9	475	989		
	17	500	1041		
	20	570	1187		
	22	605	1259		
	24	660	1374		
	29	740	1540		
	40	755	1572		
	46	1140	2373	Bedrock	22
Mirandola	0	230	703	Silt	18
	4	270	1135	Clay	
	10	320	1632	Sand	
	25	350	1785	Coarse sand	19
	36	350	1785	Alluvial deposits	
	50	370	1887		
	60	360	1836		
	65	375	1912		
	75	375	1912		20
	94	390	2785		
	114	570	2906		
	120	1000	3300	Bedrock	22

For each site, seven accelerometric records measured at reference soil conditions ('Type A' by following the Italian Building Code (2008), which corresponds to a stiff soil characterized by *Vs*>800 m/s) were considered as input for computations (Table 2). These natural three-directional accelerograms were selected from the European strong-motion data set (Ambraseys *et al.,* 2000, 2002, 2004a, 2004b) by using the code Rexel (Iervolino *et al.*, 2009). This code allows selecting time histories (eventually rescaled) by ensuring their average compatibility with:

- the relevant uniform hazard spectra provided for each ground motion component by the reference seismic hazard map of Italy (Stucchi *et al.*, 2011; http://esse1.mi.ingv.it/);
- magnitude and epicentral distances deduced from a disaggregation analysis relative to the site.

[for details, see Iervolino *et al.* (2009)]. An example of response spectra relative to a set of selected accelerograms is reported in Fig. 2. For each earthquake, a single horizontal component has been considered by selecting the one characterized by the highest PGA. As one can see, all the selected earthquakes are relatively close to the site (in the range 5-20 km) and this suggests that near-field conditions may occur at all the sites.

Table 2 - Accelerograms selected for seismic response analysis at the sites in Fig. 1. ID number refers to the European strong-motion data set (Ambraseys *et al*., 2000, 2002, 2004a, 2004b).

	Epicentral Area	Date	Mw	Fault Mechanism	Epicentral Distance [km]	Waveform ID
Cascia	Bingol	01/05/2003	6.3	strike slip	14	7142
	Friuli (aftershock)	13/05/1976	4.5	thrust	20	72
	South Iceland	17/06/2000	6.5	strike slip	13	4675
	Mt. Hengill Area	04/06/1998	5.4	strike slip	18	5090
	Umbria Marche (aftershock)	06/10/1997	5.5	normal	5	651
	South Iceland (aftershock)	21/06/2000	6.4	strike slip	15	6335
	South Iceland	17/06/2000	6.5	strike slip	5	4674
Castel Viscardo	Friuli (aftershock)	11/05/1976	4.9	thrust	14	706
	Friuli (aftershock)	13/05/1976	4.5	thrust	20	72
	Mt. Hengill Area	04/06/1998	5.4	strike slip	18	5090
	Near NE coast of Rodos island	25/10/1987	5.1	?	19	1960
	Umbria Marche (aftershock)	06/10/1997	5.5	normal	5	651
	Friuli (aftershock)	16/09/1977	5.4	thrust	11	981
	Mt. Hengill Area	04/06/1998	5.4	strike slip	15	5085
Gildone	Bingol	01/05/2003	6.3	strike slip	14	7142
	South Iceland	17/06/2000	6.5	strike slip	13	4675
	Mt. Hengill Area	04/06/1998	5.4	strike slip	18	5090
	Izmit (aftershock)	13/09/1999	5.8	oblique	15	1243
	South Iceland	17/06/2000	6.5	strike slip	5	4674
	Friuli (aftershock)	16/09/1977	5.4	thrust	11	981
	Mt. Hengill Area	04/06/1998	5.4	strike slip	15	5085
Mirandola	Friuli (aftershock)	11/05/1976	4.9	thrust	14	706
	NE of Banja Luka	13/08/1981	5.7	oblique	10	5655
	Friuli (aftershock)	13/05/1976	4.5	thrust	20	72
	Umbria Marche (aftershock)	06/10/1997	5.5	normal	5	651
	Mt. Hengill Area	04/06/1998	5.4	strike slip	18	5090
	Umbria Marche (aftershock)	06/10/1997	5.5	normal	20	670
	Mt. Hengill Area	04/06/1998	5.4	strike slip	15	5085

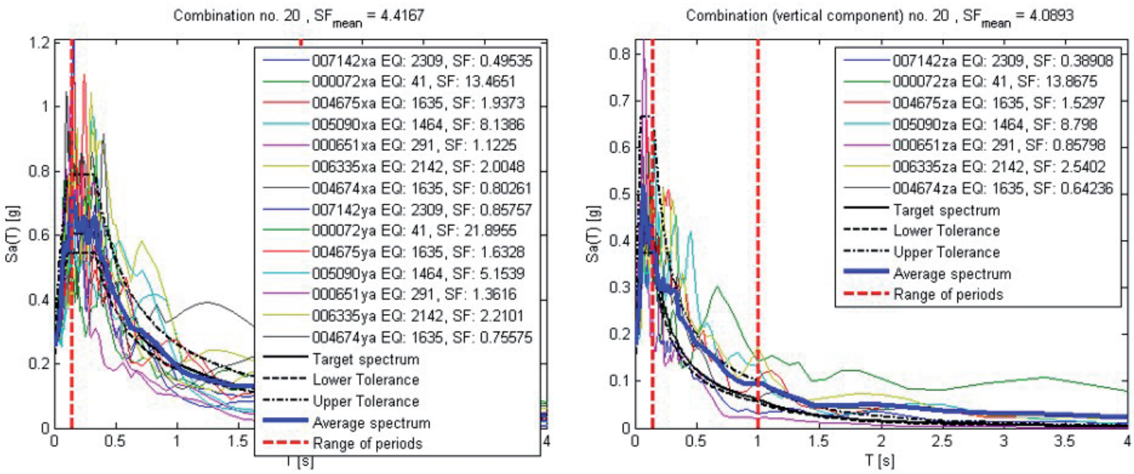

Fig. 2 - Response spectra of the accelerograms selected for the Cascia site (Fig. 1). Data have been extracted from the European strong-motion data set (Ambraseys *et al.*, 2000, 2002, 2004a, 2004b). Spectra relative to horizontal and vertical components are reported in the left and right panels respectively. In each panel, the scaling factors (SF) considered so that the average response spectrum fits the target spectrum (i.e., uniform hazard spectra provided for each ground motion component by the reference seismic hazard map of Italy) are also reported along with tolerance boundaries [for details, see Iervolino *et al.* (2009)].

3. Numerical tools

A standard linear-equivalent approach (e.g., Kramer, 1996) was used to compute the horizontal response spectrum at each site (with 5% damping). Computations performed by using the standard procedure (i.e., by just considering the horizontal component of the ground motion as input) were carried out by using the software STRATA (Rathje and Kotke, 2013). Since this software does not allow managing vertical components of input motion, a different code was used to evaluate the effect of this element in computing horizontal response spectrum at the surface of the layered soft soil. To this end, computer code LSR-2D provided by Stacec s.r.l. (http://stacec.it/Prodotto/92/lsr-2d) was applied which implements the 2D finite element approach described by Hudson *et al*. (1993). The 1D configuration was simulated by a rectangular box with horizontal dimensions ten times the thickness of the sedimentary structure above the seismic bedrock in question. Input motion was applied at the bottom of the box while dampers were applied to the lateral boundaries. Effectiveness of this 2D configuration in simulating the 1D approach of the code STRATA was tested by taking into account the same horizontal input motion for both the codes. A typical outcome of this check is reported in Fig. 3. In all the cases, outcomes of 2D (LSR2D) and 1D (STRATA) codes perfectly overlap in the range 0.01-2.00 s. This last interval is the one considered in the following analysis.

4. Numerical results

In order to evaluate the possible effect of vertical component of input motion on the horizontal response spectrum, the ratio HV/H was computed between the 5% response spectra (Sa) obtained at the Earth surface by respectively considering (LSR-2D code) and discarding

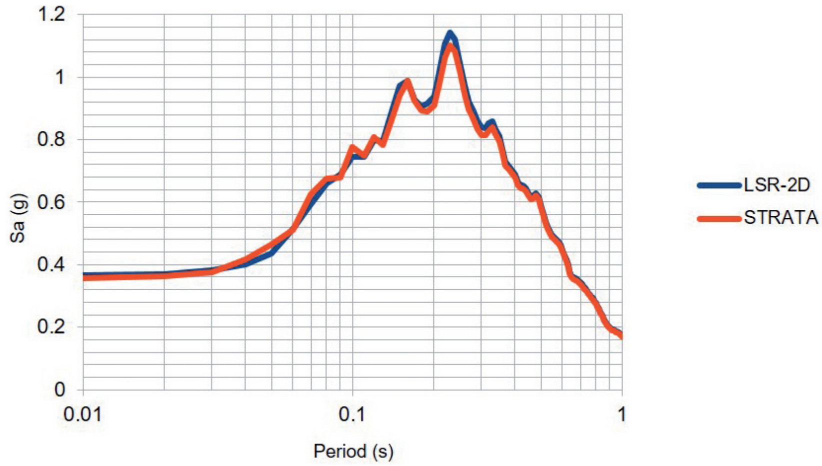

Fig. 3 - Comparison between outcomes of STRATA and LSR-2D codes for the same subsoil configuration. In the plot, average elastic response spectra (Sa) obtained for the same horizontal input motion by the two codes LSR-2D and STRATA by considering the 7 accelerograms at the Gildone site (Fig. 1).

(STRATA) the vertical component of the input motion at the four sites. For this elaboration, the input motions reported in Table 2 were used. The results obtained at each site are outlined briefly here.

4.1. Cascia

The site of Cascia is characterized by a thin and relatively stiff sedimentary cover overlying the rigid bedrock. In this case, a purely linear behaviour (Kevin-Voight) has been assumed with a constant 2% damping coefficient. The Poisson coefficient was assumed as constant (0.35). In the Finite Element modelling, the size of the triangular elements was 2 m, which was reduced to 1 m close to the point at the surface where horizontal response spectra have been computed.

Outcomes relative to computations performed by considering the accelerometric records in Table 2 and the seismic parameterization in Table 1 are reported in Fig. 4. As it can be seen, no systematic effect is revealed (the median is close to 1 almost in the whole range of periods here considered). However, variations up to 20% are revealed between horizontal acceleration response spectra obtained by including or not the vertical input motion component for the single accelerograms. This suggests that, at this site, polarization of ground motion relative to the single time histories may play a significant role but only in the very short period range, i.e., shorter than those of major interest to civil engineering.

4.2. Castel Viscardo

At this site, a relatively thick (about 80 m) alluvial sedimentary cover overlies the seismic bedrock (Table 1). *Vs* velocities are relatively high and gradually increase with depth by reducing the seismic impedance contrast at the contact between sediments and bedrock. G/Go decay and damping curves relative to the shallow alluvial sediments have been obtained in laboratory tests carried on in the same formation. As concerns deeper sediments (depth larger than 30 m), literature data have been considered (EPRI, 1993). Seismic bedrock has been modelled as a Kevin-Voight solid with a constant damping value (2%). Also for this case, in

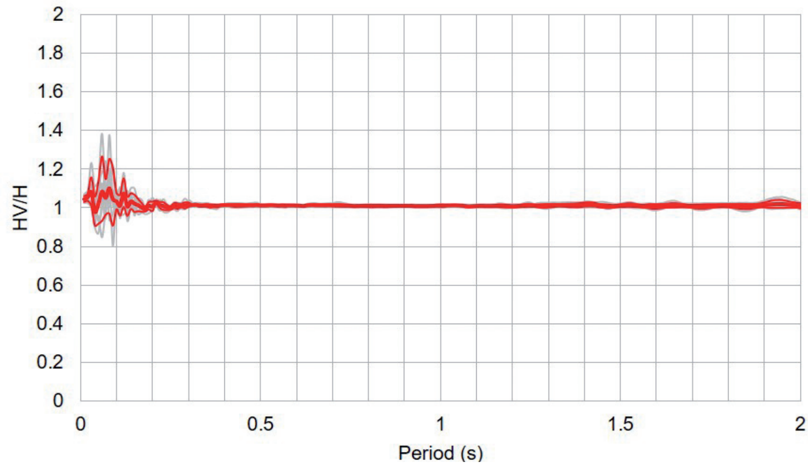

Fig. 4 - HV/H ratios at the site of Cascia (Fig. 1). Grey lines indicate HV/H ratios relative to each single accelerometric time history. Continuous thick red line represents the median of the HV/H ratios and the two thin red lines respectively represent 84th and 16th percentiles.

the lack of direct data concerning the *Vp* profile, a constant Poisson coefficient (0.35) has been assumed. In the Finite Element modelling, the size of the triangular elements was 4 m that was reduced to 2 m close to the point at the surface where horizontal response spectra have been computed. Outcomes relative to computations performed by considering the accelerometric records in Table 2 and the seismic parameterization in Table 1 are reported in Fig. 5. Unlike the case of Cascia in Fig. 3, systematic effects are observed in the range of potential engineering interest. In particular, a strong effect of vertical component of input motion on the horizontal output at the surface is obtained around 0.3 s. This effect is nearly independent from input motion, is above 30% in most cases and may reach 60%.

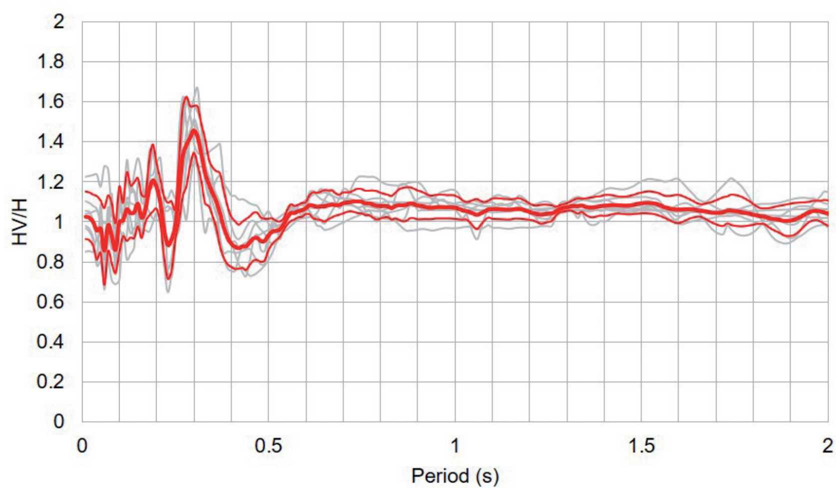

Fig. 5 - HV/H ratios at the site of Castel Viscardo (Fig. 1). For the caption see Fig. 4.

4.3. Gildone

In this case, there is a relatively sharp seismic impedance contrast at the bottom of a 40 m sedimentary layer, characterized by *Vs* velocities gradually increasing with depth (Table 1). G/Go decay and damping curves have been deduced by analysis made by the Italian National Seismic Service for the seismic microzonation of San Giuliano di Puglia (Baranello *et al.*, 2003) for the shallower sediments (depth less than 30 m) and from the literature for the deeper layers (EPRI, 1993). Seismic bedrock has been modelled as a Kevin-Voight solid with a constant damping value (2%). In the Finite Element modelling, the size of the triangular elements was 2 m that was reduced to 1 m close to the point at the surface where horizontal response spectra have been computed. Again, lacking direct data concerning the *Vp* profile, a constant Poisson coefficient (0.35) has been assumed. Outcomes relative to computations performed by considering the accelerometric records in Table 2 and the seismic parameterization in Table 1 are reported in Fig. 6 and show that slight systematic effects (about 10%) fall in the range 0.1-0.3 s. These appear erratic in that both lower and higher seismic response occur at different periods when vertical ground motion at the bedrock is also considered. Occasionally, due to the specific time history, larger effects can be observed (up to 20%) in the range 0.1-0.2 s.

4.4. Mirandola

The situation of Mirandola is somewhat similar to the case of Castel Viscardo due to the presence of a relatively thick sedimentary cover (about 120 m). In this case, however, the impedance contrast at the top of the seismic bedrock is sharp. Owing to the lack of direct laboratory data, G/Go decay and damping curves have been deduced from the literature (Idriss, 1990; EPRI, 1993). In the Finite Element modelling, the size of the triangular elements was 5 m, which was reduced to 2 m close to the point at the surface where horizontal response spectra have been computed. Numerical outcomes relative to computations performed by considering the accelerometric records in Table 2 and the seismic parameterization in Table 1 are reported in Fig. 7. They show systematic effects around two period ranges: below 0.2 s and around 1 s. A higher seismic response (of about 20%) occurs in the period of engineering interest (around 1 s), when vertical ground motion at the bedrock is also considered. The reverse occurs in the short period range.

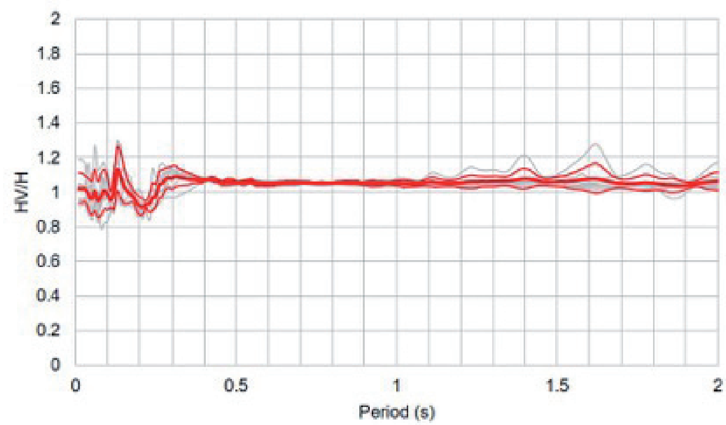

Fig. 6 - HV/H ratios at the site of Gildone (Fig. 1). For the caption see Fig. 4.

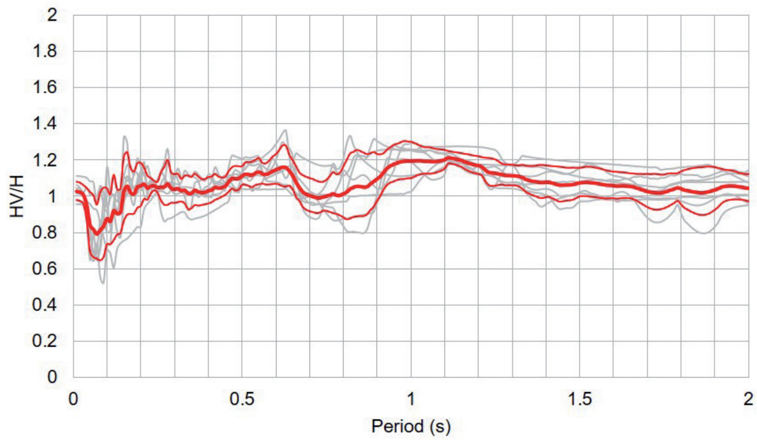

Fig. 7 - HV/H ratios at the site of Mirandola (Fig. 1). For the caption see Fig. 4.

5. Considerations on the results

A numerical test has been performed to evaluate the possible role of input motion vertical components in evaluating horizontal seismic response at a number of sites. Outcomes suggest that the assumption of a complete decoupling between vertical and horizontal propagation effects may be unfeasible in a number of rather common situations. Four real situations found in Italy have been explored by considering 1D structures characterized by thick and thin sedimentary covers, relatively high and low impedance contrasts at the top of the seismic bedrock and relatively soft and stiff sediments. At each of the four sites, the standard approach for selecting hazard compatible input motion has been applied. At these sites, horizontal seismic response (in acceleration) has been computed by respectively including and disregarding the vertical component of input motion. Outcomes of this analysis, far from being exhaustive, indicate that biases (in the order of 20% or more) may be introduced when the vertical components of input motion are neglected. To some extent, the observed effects depend on the input seismic history (in particular when the bedrock is shallower) and seismic response may result biased for single earthquakes but, on average, unbiased. However, in some cases, there seems to be a systematic effect which is independent of the input motion. These effects are frequency dependent and appear stronger for deeper seismic bedrock (for example the sites of Castel Viscardo and Mirandola) and stiffer geological sedimentary covers (Castel Viscardo). Differences are less relevant when the geological covers are thinner, such as in the site of Cascia. Observed effects occur at periods that are lower if the seismic bedrock is shallower and higher if it is deeper. More in general, the above outcomes, along with experimental observations from other authors suggest that vertical input motion components could, in some cases, significantly modify the horizontal seismic response. When the analysis is performed by considering the most commonly used numerical tools (e.g., STRATA), the eventual bias could be reduced if input motion is carefully selected to avoid near-field conditions or oblique incidence, in particular when deeper sedimentary coverages are of concern. However, in many cases, local hazard is dominated by relatively close seismic sources and thus near-field conditions cannot be avoided. In these cases, vertical components of input motion should not been neglected in the analysis of the horizontal seismic response.

Acknowledgements. Many thanks are due to the two anonymous referees, whose constructive comments helped us improve the paper. The English manuscript was checked by Stephen Conway.

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