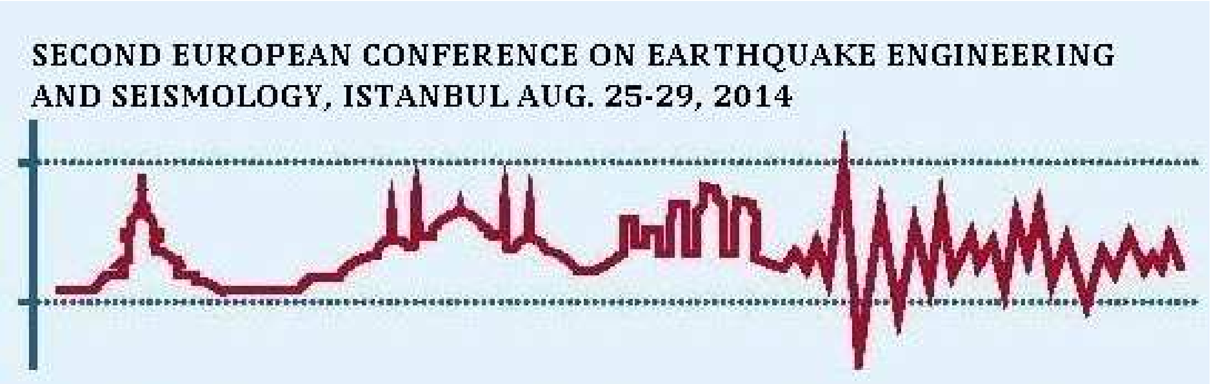

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ENGINEERING APPROACHES TO SITE SPECIFIC PROPAGATION OF VERTICAL GROUND MOTION FOR SEISMIC DESIGN

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Despite both field and analytical observations have shown the damaging effect of vertical earthquake motion on structures (Papazoglou and Elnashai, 1996), vertical site response analysis remains a research topic (Matasovic and Hashash, 2012) and normally in professional practice even when carrying out 3D time history structural analysis for seismic design of large structures only horizontal ground motion propagation analyses are carried out. The main reasons for this have to do with several peculiar aspects that would require special consideration: back analysis of propagation of vertical ground motion as found in the literature (e.g. Mok et al., 1998) requires extensive geophysical field measurements such as downhole arrays which are not always available; both analytical evidences (Yang et al., 1996) and comparison with predicted response to site measurements (Mok et al. 1998) have shown that even a slight decrease from complete saturation can lead to a substantial influence on vertical motion; measurements off the coast of southern California (Boore and Smith, 1999) have shown that vertical to horizontal spectra ratio is influenced by water depth in the high frequency range for which the influence of P waves is more relevant.

The purpose of this paper is to provide a synthetic overview of the main methods available at date for engineering evaluation of vertical ground motion in the most common case when rock outcrop defined motions are prescribed and to show their application to one hypothetical practical example which could be applicable to seismic design. In such example the results obtained by two vertical propagation analyses, one based on the methodology proposed by Mok et al. (1998) and one based on the methodology proposed by Beresnev et al. (2002) are compared to the results obtained by considering the simplified methods based on the estimation of spectral ratio of vertical to horizontal motion proposed by Gülerce and Abrahamson (2011) and Poggi et al. (2012).

INTRODUCTION

The importance that vertical ground motion can have on seismic performance is a known issue for structures such as buildings and bridges. Analytical considerations (e.g. Paulay and Priestley, 1992) prove that the increase in compressive forces reduces the rotational ductility of columns/piers and that under reduced compression the contribution of concrete to shear resistance is eroded. Field observations show that failure can occur in vertically bearing elements such as walls and columns in buildings structures but also in bridge piers. Particularly for bridge piers (Papazoglou and Elnashai, 1996) damage was observed as a result of high vertical accelerations where detailing was poor and at locations along the bridge where amplification of vertical response was higher. A more special case is in wind tower structures, where the vertical seismic acceleration combined with wind can also cause disturbance of the fine-tuned machinery inside the nacelle.

In the near source region of large earthquakes observations of vertical motions prove that vertical to horizontal V/H spectral ratio (e.g. Niazi and Bozorgnia, 1991) can exceed unity and that the adoption of a constant ration V/H over all periods (Newmark and Hall, 1978) maybe unconservative.

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The ration V/H at close distance and or for short spectral periods is in general lower for rock sites where vertical motion can exceed horizontal motion by a moderate amount (in average 20%), while at soil sites vertical motion may exceed horizontal motions by a factor of two (Silva, 1997).

METHODS BASED ON GROUND MOTION PREDICTIVE EQUATIONS

The type of assessment of vertical ground motion at a site can be subdivided into two main groups: it can either be based on the use of ground motion predictive equations (GMPE) or it can be based on propagation analysis of the vertical motion along the soil column. The application of two GMPE based methods is described in this paragraph.

The method recently proposed by Gülerce and Abrahamson (2011) allows to derive the V/H spectrum consistently with the probabilistic seismic hazard assessment of horizontal ground motion and the functional form used by Abrahamson and Silva (2008) accounting for the effects of distance, magnitude and standard deviations for the ground motions as well as non linear site effects. The dataset used for the regression analysis is similar to that used by Abrahamson and Silva (2008) and consists in recordings from 127 earthquakes and site conditions that are classified using $V_{s30.}$ The model for the median ground motion in the Abrahamson and Silva (2008) method is given by an equation of the form of equation 1. The function f_1 accounts for the magnitude and style of faulting effects and is adopted without a change from Abrahamson and Silva (2008) while the function f_5 takes into account the site response dependency of the V/H ratio described in detail in Walling et al. (2008) and Abrahamson and Silva (2008). M is the moment magnitude, R_{rup} is the rupture distance, F_{RV} and F_{NM} are flags for normal or reverse faulting, PGA_{1100} is the mediam peak horizontal acceleration for V_{s30}=1100 m/s, a_6 and a_7 are period dependent coefficients determined by regression analysis:

$$\ln(V/H) = f_1(M, R_{rup}) + a_6 \cdot F_{RV} + a_7 \cdot F_{NM} + f_5 \cdot (V_{s30}, PGA_{1100}) \tag{1}$$

To estimate the spectral ratio V/H at ground level the method developed by Poggi et al. (2012) is used. This methodology extends that from Edwards et al. (2011) to account for the amplifications effects due to resonance phenomena and the increased presence of surface waves for sites with soft sediments and particularly those with large impedance contrast at depth. As pointed out by Silva (1997) and later by other researchers, a transition between inclined shear waves (SV) into more vertical compression waves is observed for large contrast in shear wave velocity at rock soil interface and at short distances to seismic sources, causing high amplitude, high frequency vertical accelerations. In this method the quarter wavelength seismic impedance contrast (IC^{qwl}) is introduced. As shown in equation 2 this is defined as the ratio between two quarter wavelength average velocities to a depth $Z_1 = \lambda_1/4$ (nominator) and $Z_1 + Z_2$ where $Z_2 = \lambda_2/4$

$$IC^{qwl}(f) = \frac{V_{S1}^{QWL}(f, \lambda_1/4)}{V_{S2}^{QWL}(f, \lambda_2/4)} \tag{2}$$

The quarter wavelength average velocities to a depth *Z* is such that for a specific frequency the following two equations hold (Poggi et al., 2012b):

$$\arg\min_{z(f)} \left| z(f) - \frac{V_S^{QWL}(z(f))}{4f} \right| \tag{3}$$

$$V_S^{QWL}(z(f)) = z(f) \cdot \left(\int \frac{1}{Vs(z(f))} \cdot dz(f) \right)^{-1} \tag{4}$$

The functional form proposed for a simplified frequency dependent model takes the form shown in equation 5, where the coefficients a, b and c are obtained by minimization of the residuals between predicted and observed V/H data from the Japanese Kik-net strong motion network dataset.

$$\ln(\frac{V}{H}(f)) = a \cdot \ln(V_s^{qwl}) - b \cdot \exp(-IC^{qwl}) + c \qquad (5)$$

In order to account for magnitude (M_{JMA}) and (hypocentral) distance (R_{hyp}) dependency and to extend the prediction to higher frequencies a regression analysis of the residual misfit (δ) to the above (frequency independent) model is carried out assuming the following functional form valid in the range 0.5 to 100 Hz.

$$\delta = \ln\left[\frac{(V/H)_{obs}}{(V/H)_{\text{mod}}}\right](f) = d_1(f) + d_2(f) \cdot M_{JMA} + \cdot d_3(f) \cdot \ln(R_{hyp}) \qquad (6)$$

Where d_1, d_2 and d_3 are frequency dependent function including nine parameters values (e_0 to e_8) determined by a non linear least square regression analysis.

METHODS BASED ON GROUND MOTION PROPAGATION ANALYSIS

Two different ground motion propagation methodologies are considered. The methodology proposed by Mok et al. (1998) assumes that the vertical motion is due to propagation of compressional (P) body waves only and replaces the more conventional soil columns small shear wave velocity with the small strain compressional wave velocity. Based on back analysis of measurements from two downhole arrays in Lotung, Taiwan and Port Island, Japan, and on the estimated value of compressional waves velocity in the upper meters of (unsaturated) soil, it is established that a reduction to the measured velocity maybe necessary when these measurements are below the compressional velocities of water. Moreover while it is found that the stiffness degradation curves should be kept unchanged from those applicable to vertical shear wave propogation analysis, the damping is found to be lower, it should be based on the level of shear strain estimated from the analysis of vertically propagating shear waves and, in all cases, should not exceed 10%.

An alternative propagation methodology considered in this study is that proposed by Beresnev et al. (2002). Based on results of field measurements this methods assumes that the vertical response up to 10 Hz is dominated by non vertically propagating shear waves (SV waves) while above such frequency the compressional (P) waves dominate the response. For this reason for frequencies below 10 Hz conventional equivalent linear 1D propagation analyses are carried out and then to convert the simulated SH waves into SV motion at a desired depth and thus account for the inclined path, depth specific correction factors are applied. Such correction factors (Darragh et al., 1999) are expressed as ratios between V/H at depth to V/H ratio at surface. Moreover by studying the amplification of P waves at variable amplitude levels and the resonance frequency shift, Beresnev et al. (2002) conclude that the compressional wave non linearity is similar to non linearity induced by shear waves.

EXAMPLE APPLICATION

A hypothetical ground motion with a peak ground acceleration of 0.34 g on rock, magnitude 7.5 at a distance from site between 5 and 10 km and a reverse and strike slip type of fault is considered, V_{s30} for soil is equal to 120-250 m/s.

The median spectral ratio V/H resulting from the application of the Gülerce and Abrahamson (2011) method is plotted in Figure 1. As expected for near source the ratio is above unity for short spectral periods.

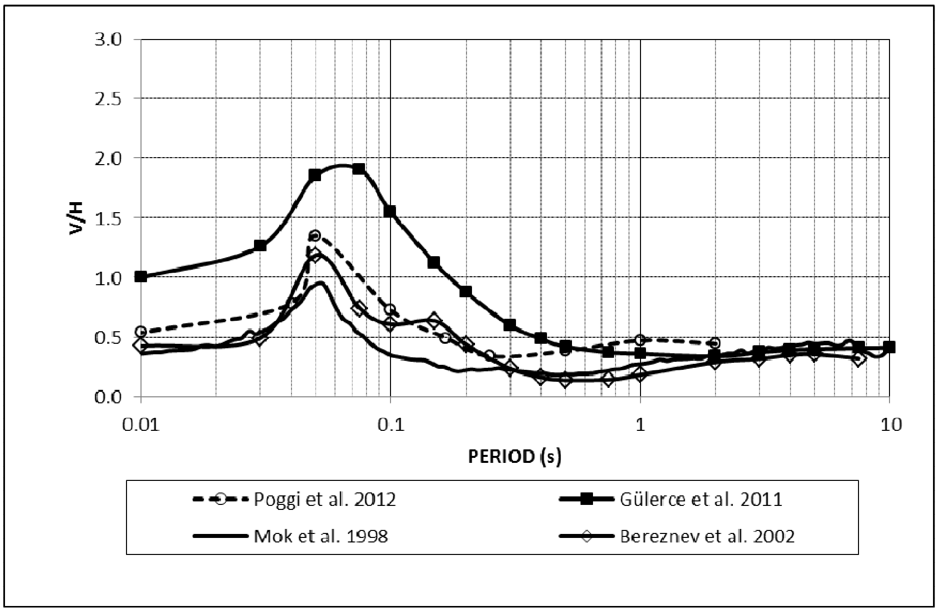

Figure 1. Comparison between vertical to horizontal spectral ratio according to methods based on GMPE and to methods based on propagation of vertical ground motion.

The second GMPE based methodology considered (Poggi et al., 2012) requires the knowledge of the shear wave velocity profile in order to calculate the quarter wavelength shear wave velocity (equation 4) and the quarter wavelength seismic impedance contrast (equation 2) plotted in Figure 2 and Figure 3 respectively. In Figure 3 it is possible to observe the frequency of resonance of the stratum estimated using the velocity profile and the impedance contrast.

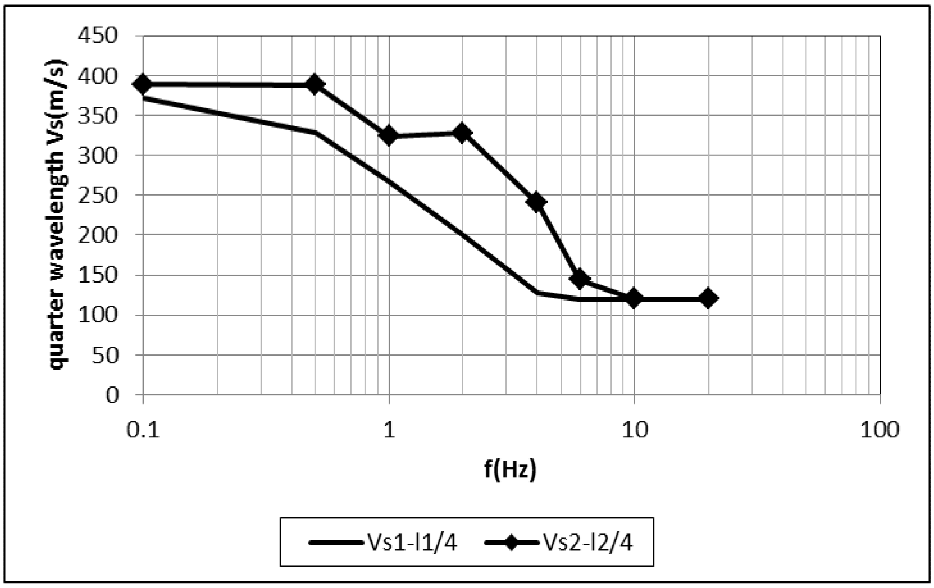

Figure 2. Quarter wavelength average velocity (V_s^{QWL}).

In order to carry out the propagation of the vertical motion from the rock through the soil column as P waves (Mok et al., 1998) or SH/SV waves (Beresnev et al. 2002) the software Deepsoil (Hashash et al., 2009) was used. In the latter methodology the conversion from SH to SV was carried out at 10 m depth below mudline by multiplying the V/H ratio estimated using the vertical motion by mean of the Mok et al. (1998) method by the correction factors by Darragh et al. (1999).

The resulting V/H spectra are shown in Figure 1 for all four methodologies. A good agreement can be noticed between all methodologies except the Gülerce and Abrahamson (2011).

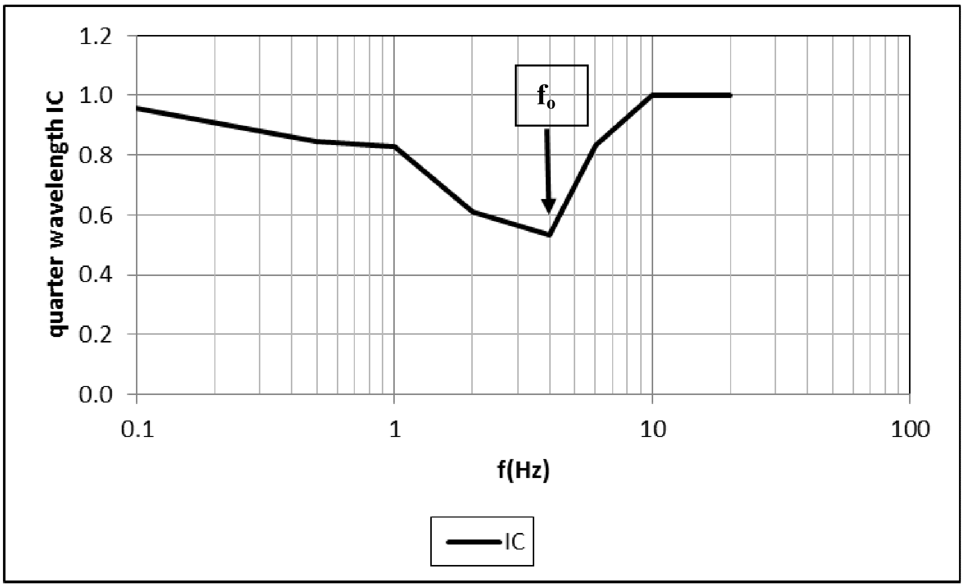

Figure 3. Quarter wavelength impedance contrast (IC).

CONCLUSIONS

Despite the importance that vertical ground motion can have on seismic performance of structures, estimation of vertical ground motion by site specific propagation is still a research topic. Several methodologies for estimation of vertical ground motion at ground surface have been described along with an application to a specific hypothetical example. It is assumed that the horizontal ground motion is known at all depth so the results obtained from the application of four different methods have been shown in terms of H/V spectral ratio. Despite the difference in the nature of the approaches considered it appears that the methods lead to comparable results except the GMPE based method proposed by Gülerce and Abrahamson (2011).

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