SITE CHARACTERIZATION AT THE LOCATION OF A VERTICAL ARRAY OF ACCELEROMETERS IN PATRAS, GREECE

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ABSTRACT

Earthquake recordings by a vertical array of accelerometers, installed in the central urban area of the city of Patras, Greece, are utilized to evaluate the $V_s$, $V_p$, and Poisson’s ratio, $\nu$, vs. depth profile at the site. The evaluation was based on computed values of cross-correlation functions between adjacent (in the vertical sense) pairs of accelerometers. A group of 50 seismic events were selected having magnitudes less than 3 and epicentral distances ranging from 3km to 40km. The data processing was performed assuming vertical propagation of waves between pairs of accelerometers. Parametric analyses showed that when the hypocentral angle of seismic waves (i.e. the angle between the horizontal direction and the direction of propagation) is less than 50° and the depth of event larger than 10km, the error in the estimated value of velocities remains lower than 5%. Estimated profiles of $V_s$, $V_p$, as well as Poisson’s ratio values are proposed for use in site response analyses at the location of the vertical array. A very good agreement was found to exist between the estimated values of shear waves velocity and the values obtained by surface wave measurement.

Keywords: vertical array; shear wave velocity; cross-correlation; surface waves measurements

1. INTRODUCTION

A vertical array of accelerometers is a field installation comprising a number of accelerometers, placed at the ground surface and at subsurface elevations, for recording the earthquake motion of soil or rock. The vertical arrays are valuable tools for (a) recording the actual seismic behavior of sites (effects of local soil conditions, dominant site periods, modal configurations, soil liquefaction) and (b) evaluating the in-situ dynamic soil properties (elastic and nonlinear), which are free of the effects of sample disturbance and of uncertainties regarding the in-situ stress state, the seismic loading history and the site stratigraphy/boundary conditions. In addition, the recordings of vertical arrays are utilized for the development, validation and calibration of stress-strain models and of numerical/analytical techniques for predicting the seismic site response.

The first applications of vertical arrays of accelerometers appeared in Japan (e.g. Shima, 1962) and USA (e.g. Seed and Idriss, 1970; Joyner et al., 1976). In the decades that followed (1980’s, 1990’s, and 2000’s) the number of vertical array installations increased dramatically and included installations incorporating pore water pressure sensors placed at subsurface elevations (e.g. Zeghal and Elgamal, 1994; Elgamal et al., 1995; Zeghal et al., 1995; Elgamal et al., 2001; Elgamal et al., 2004; Assimaki et al., 2006, 2008; Tsai and Hashash, 2009). Many recent publications have also demonstrated the great

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value of earthquake motion and pore water pressure recordings in vertical arrays, for advancing the
level of knowledge on seismic site response and on the in-situ values of dynamic soil properties (Kim
and Hashash, 2013; Yee et al., 2013; Groholski et al., 2014; Mercado et al., 2015; Han et al., 2015;
Chandra et al., 2015; Suwal et al., 2015; Mercado et al., 2017).

A dense urban accelerograph network (UPAN) has been installed in the central urban area of the
coastal city of Patras, Greece, comprising 8 three axis surface accelerographs (UP-1 to UP-8, models
either Etna or TSA-SMA) and a vertical array (VA-1) with 4 triaxial accelerometers (24 bit analysis,
synchronized through a GPS system) placed at the surface (model FBA ES-T) and at depths of 20m,
34m and 71.5m (model SBEPI and data acquisition PDAQ Premium) from ground surface (Batilas et
al., 2015). The vertical array is located in the central part of the city, at a distance of 1.5km from the
waterfront of the city. The locations of the 8 surface stations and of the downhole array are shown on
the Google Earth map of the area, Figure 1a.

The vertical array VA-1 comprises three force balance triaxial accelerometers installed in three
adjacent boreholes BH-1, BH-2, BH-3 with respective depths 71.5m, 20m, 34m, cased with plastic
inclinometer casing. The three boreholes -prior to installing the accelerometers- were utilized for
performing crosshole measurements, whereas their verticality was checked by conducting
inclinometer measurements. In addition, a surface triaxial force balance accelerometer has been
installed in close proximity to the boreholes (Pelekis et al., 2014, Theofilopoulou et al., 2014), Figure
1b.

Figure 1. (a) Location of VA-1 and surface accelerographs in Patras, Greece, (b) positions of boreholes BH-1,
BH-2, BH-3 and of surface receiver.

The soil stratigraphy at the location of VA-1 was determined by a geotechnical investigation and
comprises cohesive formations interlayered with sands and gravels, as is shown in Figure 2a, whereas
the blow count depth profile is shown in Figure 2b. The $V_s$ profile at the location of VA-1 was
evaluated by performing surface waves measurements using both active and passive sources of
vibration. Electromechanical vibrators (with a frequency range of 2Hz to 200Hz) and drop weights
(25kg from a height of 2m) were used as active sources of vibration at the ground surface; these
sources of vibration allowed the evaluation of $V_s$ vs. depth profile up to a depth of 50m, using the
SASW technique. Furthermore, by performing microtremor measurements (using the ReMi method
with 180m length linear array of geophones with geophones separation 8m) $V_s$-depth profiles were
established to a depth of 100m from ground surface. The $V_s$ profile obtained from the surface wave
measurements is shown in Figure 2c.

As mentioned above, the three cased boreholes BH-1, BH-2 and BH-3 were utilized for performing
crosshole measurements prior to installing the subsurface accelerometers. The results of measurements
are included in Figure 2c, indicating the good agreement between surface waves and crosshole
measurements.

In the present study the earthquake recordings in the VA-1 vertical array are utilized for estimating the
Figure 2. (a) Soil stratigraphy at the location of VA-1, (b) N_SPT profile, (c) \( V_s \) profiles at the location of VA-1 obtained by surface waves and crosshole measurements.

\( V_s \), \( V_p \) and \( \nu \) (Poisson’s ratio) profiles at the location of the array. The evaluation is based on computing the cross-correlation function between pairs of simultaneous recordings (obtained for a particular earthquake event) at different depths, i.e., between 0m and -20m, between -20m and -34m, and between -34m and -71.5m. Average values of wave velocities were estimated based on calculations for 50 events recorded by the vertical array.

**2. CALCULATION OF CROSS-CORRELATION FUNCTIONS**

The cross-correlation between pairs of accelerometer recordings in a vertical array for estimating the average propagation velocity of P-waves and S-waves has been used in the past by Zeghal and Elgamal, 1993 and Gunturi et al., 1997. It has also been used in a reverse algorithm to determine the elastic soil properties and to create a wave propagation model (Chiu & Huang, 2003; Assimaki et al., 2006), as well as for estimating the deviation of the orientation of the installed accelerometers (Chiu and Huang, 2003; Ktenidou, 2010). The processing of the recorded time histories involved baseline correction and highpass filtering (0.05sec to \( f_{\text{max}} \)) performed by the data acquisition unit.

The cross-correlation function is computed for two time histories \( f_1(t) \) and \( f_2(t) \) recorded by stations 1 and 2, respectively, and can be expressed by the following equation (Bendat and Piersol, 1980):

\[
R_f = \frac{\sum_i (f_1(t) - f_{m1}) \ast (f_2(i + j) - f_{m2})}{\sqrt{\sum_i (f_1(t) - f_{m1})^2} \sqrt{\sum_j (f_2(i) - f_{m2})^2}} \quad i = 1, 2, 3...n \quad j=1, 2, 3...n
\]

where \( R_f \) is the cross-correlation value, \( f_1(t) \), \( f_2(t) \) are the two time histories, and \( f_{m1}, f_{m2} \) are the averages of the respective time histories.

The cross-correlation value is maximized at the time corresponding to the time lag, \( \tau_d \), of the wave \( f_2 \) in relation to \( f_1 \), and for a given receivers distance it allows the estimation of the wave propagation velocity.
2.1 Orientation of accelerometers in VA-1

During processing of earthquake recordings low values of cross-correlation were found for particular pairs of accelerometers, a fact that is usually caused by non-uniform orientation of the accelerometers. For this reason the methodology reported by Yamazaki et al., 1992 was applied to identify the actual (i.e. as installed) orientations of the accelerometers of VA-1. According to this methodology, if the distance between two receivers (one of them considered as reference receiver with known orientation) is small it can be assumed that the waves between the receivers are correlated. Thus, the angle of rotation of the receiver with unknown orientation relatively to the orientation of the reference receiver will be the one leading to the highest value of cross-correlation function. By applying the above method and using the surface accelerometer as the reference receiver, the orientation of each of the three downhole accelerometers was estimated as shown in Figure 3.

2.2 Selected earthquake events

The 50 earthquake recordings utilized in the present study are events relatively close to the vertical array; these events were selected on the basis of clarity of wave (P and S) arrival times and their magnitude was M<3. The mean focal distance of the events is less than 12km, whereas the average hypocentral depth, H, is generally greater than 20km. The hypocentral angle (i.e. the angle between the horizontal direction and the direction of propagation) of these seismic events range from 50° to 82°. The above data were derived from the database of the Geodynamic Institute of the National Observatory of Athens, Greece (http://bbnet.gein.noa.gr/HL/database), Figure 4.

Figure 3. Rotated directions of the downhole accelerometers of the vertical array.

Figure 4. Locations and associated depths of the seismic events used in the present study.
Figure 5. Hypocentral angle of seismic event and incident angle of refracted wave.

2.3 Calculations

The accuracy of velocity estimations (based on the time lag, \( \tau_d \), between the receivers) depends on the ratio \( \tau_d/\Delta t \), where \( \Delta t \) is the sampling interval. In the present study the sampling frequency was \( f_{\text{max}}=100\text{Hz} \) \( [\Delta t=1/(1/2)f_{\text{max}}] \), whereas the sampling interval was kept constant and equal to \( \Delta t=0.005\text{sec} \). The expected error in determining the seismic velocities -based on the mean values of the computed time lags between the receivers- can be obtained as shown in Table 1. The average value of error in estimated values of wave velocities was calculated by using Equation 2.

\[
\frac{\Delta V}{V} (\%) = \frac{1}{2} \left( 1 - \frac{\tau_d}{\tau_d \pm \Delta t} \right)
\]

The results indicate that for the depth interval from -34m to -71.5m the error in the values of V\(_S\) and V\(_P\) is 12.5% and 51.4%, respectively. In order to reduce the magnitude of the above errors the sampling time was reduced 8 times (i.e. \( \Delta t/8 \)) by using linear interpolation in the original data. Using this method of data processing the error was significantly reduced, as shown in Table 1.

In Section 2.1 the deviations of orientation between the accelerographs of VA-1 were estimated by identifying the rotation angle that maximizes the value of cross-correlation function between the signals of two receivers. In the process of above calculations, it was found that the difference of orientation between a pair of receivers results in a decrease of the value of cross-correlation function; however, the time lag between the two signals remains unchanged. Based on the above observation, it became apparent that there was no need for aligning the recorded signals to the N-S and E-W directions. In the case of Receiver 3- characterized by the greatest deviation- the cross-correlation functions were estimated between the receivers X\(_4\)-Y\(_3\), Y\(_4\)-X\(_3\) for the V\(_S3\) calculation and the receivers X\(_4\)-X\(_1\), Y\(_4\)-Y\(_1\) for the calculation of V\(_S1\). Given the large deviation of the orientation of the Receiver 3 relatively to the Receiver 2, the velocity V\(_S2\) was calculated indirectly as follows:

\[
\tau_{d,3-2} = \tau_{d,4-1} + \tau_{d,2-1} - \tau_{d,4-3}
\]

\[
V_{s2} = \frac{\Delta z_{3-2}}{\tau_{d,3-2}}
\]

where \( \Delta z_{3-2} \) is the thickness of the second layer and \( \tau_{d,ij} \) is the time lag between stations i, j.
Table 1. Dependence of accuracy of calculated seismic velocities on sampling rate.

<table>
<thead>
<tr>
<th>Depth (m)</th>
<th>Average Time lag $\tau_{d, \text{sec}}$</th>
<th>$\Delta V/V$ (%)</th>
<th>$\Delta t = 0.005 \text{ sec}$</th>
<th>$\Delta t = 0.000625 \text{ sec}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>S-wave</td>
<td>P-wave</td>
<td>S-wave</td>
<td>P-wave</td>
</tr>
<tr>
<td>0.0-20.0</td>
<td>0.0769</td>
<td>0.0232</td>
<td>6.5</td>
<td>21.5</td>
</tr>
<tr>
<td>20.0-34.0</td>
<td>0.0400</td>
<td>0.0097</td>
<td>12.5</td>
<td>54.1</td>
</tr>
<tr>
<td>34.0-71.5</td>
<td>0.0688</td>
<td>0.0171</td>
<td>7.3</td>
<td>29.3</td>
</tr>
</tbody>
</table>

It is noted that the velocity values of the longitudinal waves were determined directly since they are not affected by the orientation of the receivers.

For the calculation of S-wave time lags both horizontal components of motion were used for each seismic event, taking into account the value of the correlation coefficient as follows:

$$\tau_{d,xy} = \frac{R_x \cdot \tau_{d,x} + R_y \cdot \tau_{d,y}}{R_x + R_y}$$

where $R_x$, $R_y$ are the correlation coefficients for the two components and $\tau_{d,x}$, $\tau_{d,y}$ are the time lags for the two components.

The size of the time windows was selected to include only the initial pulses of the P-waves and S-waves to avoid passive reflections. In processing the data it was found that weak events ($M<3$) and intermediate focal depths $>20\text{km}$ produced high values for the cross-correlation function, especially for the case of S-waves, which is free of P-coda waves due to the short time of seismic rupture.

Typical results of data processing are shown in Figure 6 for an event having magnitude $M_l = 2.5$, hypocentral distance $R=6.5\text{km}$, focal depth $H=36\text{km}$ and hypocentral angle $\alpha=79^\circ$. The results of correlation calculations for this particular event are shown in Figure 7. The values of cross-correlation function, $R$, and the starting time of processed interval of recordings, $T_0$, are also included in Figure 7.

3. RESULTS

The results of cross-correlation analyses for 50 near field seismic events are shown in the diagrams of Figure 8. The diagrams indicate that for the depth interval -3.4m to -71.5m the calculated values of wave velocities ($V_{S3}$ and $V_{P3}$) increase with increasing hypocentral angle. This effect reflects the error introduced in the calculation due to the erroneous assumption of vertical propagation of seismic waves. The change of the apparent wave velocity caused by the non vertical propagation of seismic waves can be estimated as:

$$V_{ap,i} = V_i / \cos \theta_i$$

where $V_{ap,i}$ is the apparent velocity value considering vertical propagation, $V_i$ is the actual velocity in layer $i$ and $\theta_i$ is the refraction angle in layer $i$.

Thus, it is possible to estimate the value of refraction angle $\theta_i$, which according to the results shown in Figure 8 varies from $0^\circ$ to $13^\circ$, for hypocentral angles ranging from $90^\circ$ to $50^\circ$, respectively. By applying the Snell’s law (Richart et al., 1970) for a layered soil it becomes possible to estimate the value of refraction angle in all layers, Figure 5. Based on the diagrams of Figure 8 it is observed that the value of $\theta = 13^\circ$ results in an overestimation of $V_{S3}$ and $V_{P3}$ by 2.6%, whereas for layers 1 and 2 the deviation is less than 1%.
An evaluation of the results of all analyses indicates that the wave velocity values estimated in the present study deviate less than 10% from the corresponding mean values. In the diagram of Figure 9 the values of estimated wave velocities and Poisson's ratios are plotted as a function of depth. The estimated shear wave velocities are also compared to the measured velocities from the surface wave measurements indicating the existence of a very good agreement. The Poisson’s ratio values were estimated from Equation 7.

\[
\frac{V_p}{V_s} = \sqrt{\frac{2(1-v)}{1+2v}}
\]  

(7)

4. CONCLUSIONS

Based on the results of analyses performed in the present study the following conclusions can be drawn:

(1) The use of cross-correlation method for evaluation of seismic ground velocities is associated with an error proportional to the ratio of sampling rate to the time delay between the pairs of receivers. In the present study the sampling rate was increased 8 times by interpolation and this resulted in deviations in the computed velocity values less than 5%.
Figure 7. Recordings for the event #290 and corresponding cross-correlation functions.

(2) For low magnitude (M<3) and intermediate focal depth events the time window of S-waves is characterized by clarity and a high value if cross-correlation coefficient.

(3) Seismic events with hypocentral angles ranging from 90° to 40° are associated to refraction angles (at the bottom of the vertical array) equal to 0° to 18°. For refraction angles less than 18° the error in estimating the wave velocities remains less than 5%.
Figure 8. Variation of computed seismic wave velocities with hypocentral and incident angles.
The values of shear wave velocities estimated in the present study on the basis of earthquake recordings by the vertical array VA-1 are in very good agreement with the results of surface wave measurements. The proposed values that can be adopted in response analyses are:

- Depth 0.0m-20m: \( V_{S1} = 260\text{m/sec}, V_{P1} = 860\text{m/sec}, \; v_1 = 0.45 \)
- Depth 20.0m-34.0m: \( V_{S2} = 350\text{m/sec}, V_{P2} = 1440\text{m/sec}, \; v_2 = 0.47 \)
- Depth 34.0m-71.5m: \( V_{S3} = 545\text{m/sec}, V_{P3} = 2200\text{m/sec}, \; v_3 = 0.47 \)

The estimated values of Poisson’s ratio indicate the presence of saturated soil formations at the site of vertical array.

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6. REFERENCES


Cambridge, UK.


