16th World Conference on Earthquake, 16WCEE 2017

Santiago Chile, January 9th to 13th 2017

Paper N° 24

Registration Code: S-R1461791639

Amplification behavior of vertical motion observed from downhole arrays

C.-C. Tsai[1], H.-W. Lui [2]

[1] *Associate Professor, National Chung Hsing University, tsaicc@nchu.edu.tw*
[2] *Master student, National Chung Hsing University, z20071997@hotmail.com.tw*

Abstract

Recently, very strong vertical ground motions have been recorded during several earthquakes and have been considered to be critical to structure designs. Similar to horizontal motions, vertical motions can be amplified with the local site condition. However, the amplification behavior of vertical motion is different from that of horizontal motion because of different propagation mechanisms. In this study, three component records of five downhole arrays, including different geological conditions, ground water tables, and intensity of motions, were analyzed to evaluate the differences of wave propagation in the vertical and horizontal directions. The amplification behaviors of two directions are characterized by the transfer function of the surface and downhole measurement. The findings are as follows: (1) the amplification of vertical motion is less significant than that of horizontal motion, (2) the amplification behavior of vertical motion is less dependent on the intensity of motion (i.e., soil nonlinearity) than that of horizontal motion, and (3) the amplification behavior of vertical motion is more sensitive to the location of ground water table than that of horizontal motion. These variances should be considered in the dynamic site response analysis.

Keywords: downhole array, vertical ground motion, soil nonlinearity, transfer function

1. Introduction

Vertical ground motions are often considered in the seismic designs of critical structures such as nuclear power plants and dams but not in those of standard structures. Therefore, the prediction for the vertical component of ground motions has received considerably less attention than that for the horizontal. However, recent studies suggest that the effect of the vertical ground-motion component can also be significant for the seismic response of ordinary highway bridges on sites located within about 15 km of major faults [1]. Therefore, an engineering need exists to predict vertical ground motions. For the same reason, the Pacific Earthquake Engineering (PEER) center organized a program to develop ground motion prediction equations (GMPEs) for the vertical component of ground motions as part of the NGA-West2 project [2].

Recent observations form earthquake records suggest that the commonly adopted vertical-to-horizontal (V/H) response spectral ratio of 2/3 [3] may be significantly exceeded at short periods in the near-source distance range. As an additional and important aspect, similarities and differences in the characteristics of the time histories between vertical and horizontal motions need to be examined. On the other hand, the evaluation of site response to earthquakes plays an important role in the seismic designs of engineering structures. Most site response analyses have concentrated on horizontal ground motion, in which site response is regarded as the consequence of the vertical propagation of shear waves in a horizontally layered system. Although the ground is simultaneously subjected to shaking in the horizontal and vertical directions during a real earthquake, the vertical ground motion has received less attention than its horizontal counterpart. As a result, knowledge on the characteristics of vertical ground motion, particularly on relating vertical and horizontal ground motions, is rather limited. The importance of earthquake vertical motion to structures and the inadequacy of related studies have motivated this study to further investigate the characteristics of vertical ground motions.

Elgmal and He [4] summarized the observation of vertical ground motions from downhole arrays around the world. Peak vertical acceleration (PVA) profiles from the TKS, KNK, SGK, Hualien, La Cienega, and Treasure Island downhole array sites show similar PVA amplification characteristics. Downhole array records show that PVA amplification mainly occurred within the top 20 m of the soil. At ground surface, PVA was amplified by a factor of 2–3. This amplification characteristic was barely affected by the level of shaking and remained the same before, during, and after strong shaking. The scarce downhole records show little variation with depth in spectral shape. The three-dimensional downhole array records found at the reclaimed Port Island in Kobe showed that while horizontal peak accelerations were reduced as seismic waves traveled from bottom to surface, vertical motion was significantly amplified at the surface, resulting in a ratio of peak vertical-to-horizontal acceleration as large as 1.5 to 2.0 [5]. Yang and Sato [5] found that the large vertical amplification was due to the incomplete saturation of surficial soils and suggested the importance of considering the saturation condition of soils associated with the change of water table.

Elgmal and He [4] pointed out that a simple one-dimensional (ID) vertical wave propagation model did not appear adequate for modeling the observed downhole array response. In using such a simplified model, very high viscous damping in the range of 15%–25% was needed to match the recorded downhole vertical response, even for small tremors. Elgamal and He [4] and Beresnev et al. [6] concluded that additional data and research are required for the development of a rational analysis procedure for vertical motion site response.

As an additional and important aspect, similarities and differences in the characteristics of the time histories between vertical and horizontal motions need to be examined. In this study, three component records of five downhole arrays, including different geological conditions, ground water tables, and intensity of motions, were analyzed to evaluate the differences of wave propagation in the vertical and horizontal directions. The amplification behaviors of two directions are characterized by the transfer functions of surface and downhole measurements. The objectives of this study are the following: (1) to compare the amplification of vertical motion and that of horizontal motion, (2) to determine dependency of the amplification behavior of vertical motion on the intensity of motion (i.e., soil nonlinearity), and (3) to evaluate the ground water table on the effect of amplification behavior of vertical motion. The identified behavior should be considered in the dynamic site response analysis.

2. Downhole array

Geotechnical strong-motion downhole arrays consist of strong-motion accelerometers distributed vertically throughout a site. They offer engineers and seismologists important data for identifying the dynamic response of a site as waves propagate through the subsurface. Typically, the data gathered from these arrays can be used to assess the effectiveness of site response methods in capturing the response of a site during earthquake shaking. In addition, the downhole measurements also provide information to characterize the underlying soil behavior and wave propagation behavior. In this study, downhole measurements are used to enhance the understanding of vertical motion propagation.

The arrays adopted here satisfy the criteria of adequate geological data, multiple recorded events, and high recorded surface accelerations. A total of five arrays are used, described in greater detail in the following.

2.1 Lotung Array

In the early 1980s, the US Electric Power Research Institute (EPRI) in cooperation with the Taiwan Power Company (TPC) conducted a large-scale seismic test (LSST) at a site near Lotung within the southwestern quadrant of the SMART1 array [7]. A 1/4 scale containment structure modeling a nuclear power plant was instrumented. The sensors installed on the structure and below the ground surface provided recordings for the study of soil—structure interaction. Many earthquakes were recorded between 1985 and 1986. Sensors containing three-component accelerometers oriented in the east–west (EW), north–south (NS), and updown (UD) directions were installed at 0, 6, 11, 17, and 47 m below the surface. DHA is located 3 m from the 1/4 scale structure, and DHB is located 47 m from the structure. Only DHB downhole array recordings are used in this study because recorded motions more closely reflect free-field site responses.

The area consists of a recent alluvium layer 40–50 m thick overlying a Pleistocene formation that varies from 150 m to 500 m in thickness [7]. Soil profile consists of interlayered silty sand and sandy silt with some gravel, over clayey silt, and silty clay. Groundwater level is about 1 m below ground surface. The Vs and Vp profiles developed from geophysical test results [7] are shown in Fig. 1. Eighteen earthquakes were recorded between 1985 and 1986, including three moderate events (about 0.2 g peak horizontal surface acceleration). Listed in Table 1 are 10 events selected for analysis.

Table 1. Arrays and records used for analysis

Array	No. of Event	Used measurement	PGA range (H)	PGA range (V)
Lotung	10	0 m, 17 m	0.08g-0.3g	0.02g-0.2g
La Cienega	14	0 m, 18 m	0.003g-0.49g	0.002g-0.082g
Wildlife Array	11	0 m, 7.7 m	0.003g-0.096g	0.001g-0.039g
Corona Array	2	0 m, 8 m	0.029g-0.16g	0.01g-0.12g
Turkey Flat Array	6	0 m,23 m	0.005g-0.346g	0.008g-0.089g

2.2 La Cienega Array

In 1989, the California Strong Motion Instrumentation Program (CSMIP) began instrumenting boreholes with strong-motion accelerometers, including the La Cienega array, to study site amplification effects. The array is located near the section of the Santa Monica freeway (I-10) at La Cienega that collapsed during the Northridge earthquake. Accelerometers are installed at the ground surface and at depths of 18 m, 100 m, and 252 m. The geological profile consists of recent fluvial deposits of about 30 m in thickness over marine deposits (sands, silts, clays, and gravels). P-wave and S-wave velocity surveys were performed by Caltrans (suspension logging method) and the US Geological Survey (averaging along the geologic layers). The Vs and Vp profiles of the upper 18 m are shown in Fig. 1(b) [8]. The ground water table is around 9 m below the ground surface.

Nineteen earthquakes with magnitudes 1.9 < M < 7.1 have been recorded at this site, at the surface, and at depths of 18 m and 100 m. The latest few events, including the M7.1 Hector Mine and its M5.8 aftershock, were also recorded at the recently instrumented deepest hole (252 m). However, the epicenters of these events were distant from the La Cienega site, and consequently the recorded motions at the site were not strong enough to induce significant nonlinear soil behavior. Only three events produced high accelerations at the sites. Listed in Table 1 are 14 events selected for analysis.

2.3 Wildlife Array

The Wildlife Liquefaction Array was established in 1982 on a floodplain in the Imperial Valley of Southern California, where sand boils developed during the 1981 Westmorland earthquake. This site was selected and instrumented to study the liquefaction process during seismic events.

The area mainly consists of relatively young saturated Holocene floodplain sediments approximately 7 m-thick overlying denser sedimentary deposits. The upper 2.5 m consists of lean clay to silt, with the water table typically located at depth of 1–2 m. From depths of 2.5–6.8 m, the deposits transition from sandy silt to silty sand, which comprises the liquefiable layer. The Vs and Vp profiles based on the Spectral Analysis of Surface Waves are shown in Fig. 1(c) [9].

The instrumentation of the site consists of accelerometers installed at the surface and beneath the liquefiable layer and piezometers installed throughout the soil profile and radially located approximately 4.6 m from the accelerometers. Two three-component force-balanced accelerometers oriented in the EW, NS, and UD directions were installed at the surface and approximately 7.5 m below the surface.

In November 1987, the WLA recorded the Moment Magnitude M_w 6.2 Elmore Ranch earthquake followed by the M_w 6.6 Superstition Hills earthquake approximately 10 h later. The surface accelerometer recorded peak ground acceleration (PGA) of 0.128g for the NS and EW components. No significant buildup of excess pore pressures was observed during the Elmore Ranch event. The Superstition Hills earthquake occurred along the Superstition Hills fault at an epicentral distance of approximately 31 km. The surface accelerometer recorded PGAs of 0.205g and 0.183g for the NS and EW components, respectively. During the Superstition Hills event, significant excess pore pressures were generated, and the site eventually liquefied.

2.2 Corona Array

Corona Array is located at the interaction of I15 and Hwy 91 in Riverside County, California. Three three-component force-balanced accelerometers oriented in the EW, NS, and UD directions were installed at the surface and at 7.5 m, 21.6 m, and 41.8 m below the surface. The area primarily consists of sandy soil. The ground water table is approximately 13 m below the ground surface, where the Vp profile suddenly increases to greater than 1000m/s, as indicated in Fig. 1. The average Vs of the top 30 m at the site is 349 m/s, which belongs to NEHRP site class D.

Only two records are available at Corona Array. One is a small event (PGA = 0.035g), and the other is a moderate event (PGA = 0.16g). In this study, only the measurements of the surface and 7.5 m below the ground surface are analyzed. Therefore, the influence of ground water is eliminated.

2.4 Turkey Flat Array

The Turkey Flat test area was established 20 years ago to help determine the state of practice in estimating the effects of surface geology on earthquake ground motion. The California Geological Survey (CGS) joined the IASPEI/IAEE working group on the effects of surface geology on ground motion to promote the installation of strong motion arrays specifically designed to study the site-effects phenomena. CGS's Strong-Motion

Instrumentation Program (CSMIP) established the Turkey Flat test area in 1987 near the town of Parkfield in the central California Coast Ranges.

The site-characterization program categorized the Turkey Flat test area as a shallow 25 m deep stiff-soil site with a depth-to-half-width ratio of 1:40 and with unsaturated clayey sand and sandy clays derived from the mountain slopes along the eastern edge of the valley. Repeated measurements during the wet and dry seasons show that the water table generally remains below the sediment bedrock interface.

The Turkey Flat test area instrument array is composed of four recording sites: Rock South (R1), Valley Center (V1), Valley North (V2), and Rock North (R2), with downhole sensors at Rock South (D1) at 24 m depth and Valley Center at 10 m depth in sediments (D2) and at 24 m depth in bedrock (D3). Each sensor location consists of three-component forced-balance accelerometers. The Vp and Vs profiles of the valley center are shown in Fig. 1(e). Except for the 2004 Parkfield Earthquake used for the blind test, six other events are also adopted for analysis.

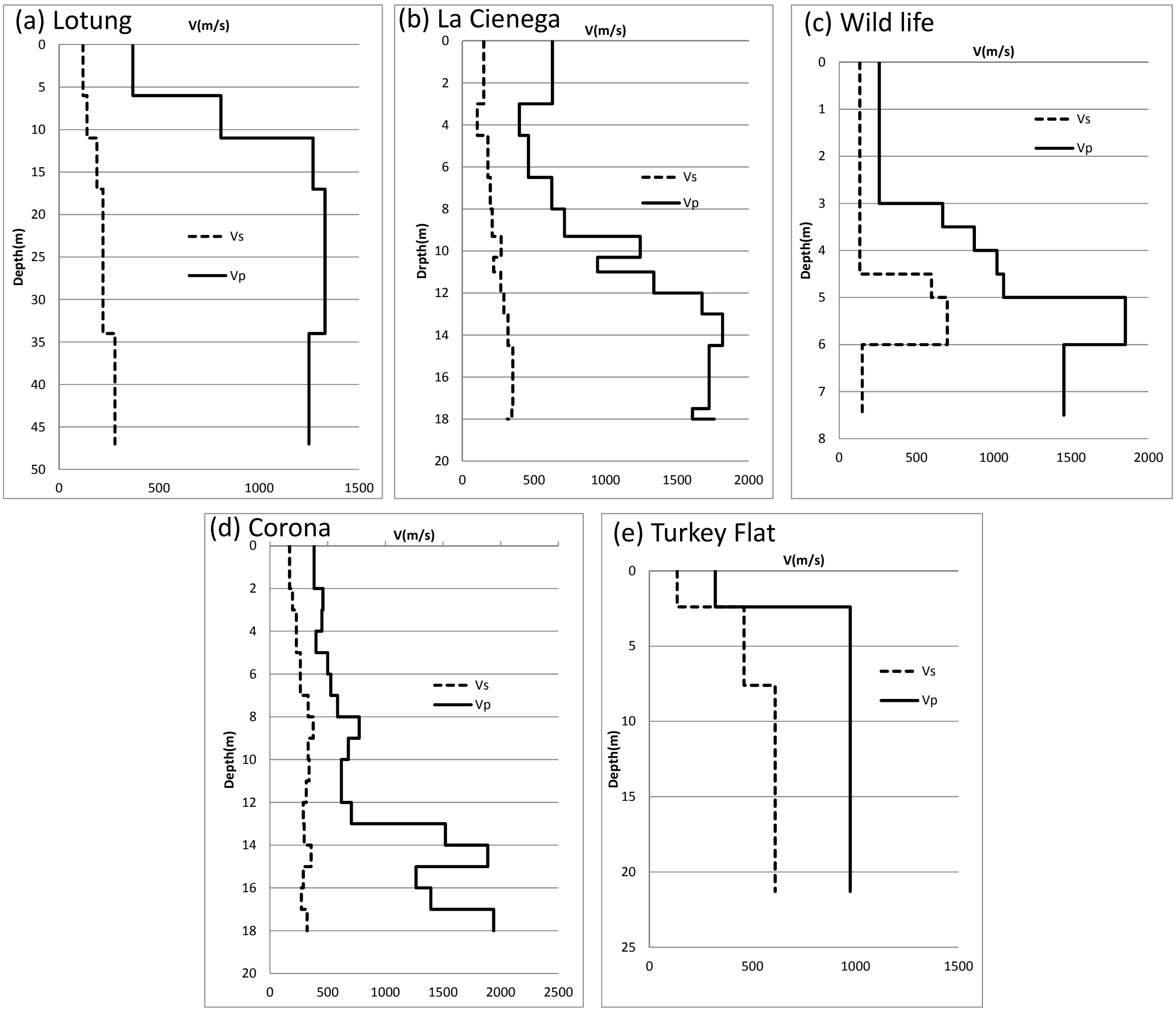

Fig. 1. Vs and Vp profiles

Based on the subsurface condition, these arrays can be divided into two main groups. The first group, including Turkey flat and Corona Array, is the unsaturated condition, in which the ground water table is lower than the bottom or the analyzed measurements of the downhole array. Therefore, the influence of ground water is delimited in these arrays. The second group, including Lotung, La Cienega, and Wildlife Array, is the saturated condition so that the influence of ground water can be evaluated.

3. Analysis procedure

3.1 Transfer function

In treating the measured acceleration time-history as any two locations of downhole arrays (i.e., x(t), y(t)), a transfer function (TF) was calculated. The measured motions were converted from time domain to frequency domain (i.e., X(f) and Y(f)). Thereafter, the TF was calculated as the ratio of the amplitude of the motions at two locations (i.e., |Y(f)|/|X(f)|). The TF shows the amplification or de-amplification of the motion through the soil layer between two locations because of the dynamic excitation at different frequencies.

The TF is theoretically a function of the Vs and damping ratio of soil (ξ). For instance, for a single soil layer, the theoretical TF can be expressed as

$$\mathrm{TF}(f) = \frac{1}{\cos(\frac{2\pi f}{V_d} h)} \quad (1),$$

where h is the distance between two locations, and

$$V_d = V_s(1 + i\xi) \quad (2),$$

Where Vs is shear wave velocity. Therefore, the peak value of TF and its corresponding frequency (predominant frequency) depend on the Vs and the damping of soil. As the Vs is lower, the predominant frequency is lower; as the damping is higher, the peak value is lower. A higher peak value implies a more significant amplification between two measurements. When a ground shaking intensity is higher, the soil becomes more nonlinear. Thus, the Vs is reduced, and more damping is induced. As a result, the amplitude of TF and the predominant frequency decrease. Through a comparison of the TFs between weak and strong events, the degrees of underlying soil nonlinearity can be determined.

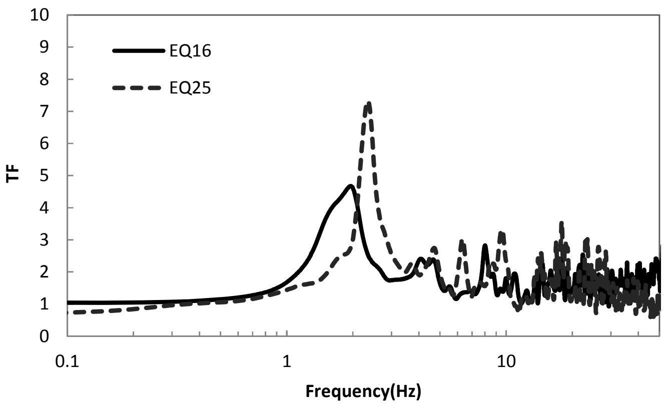

Fig. 2. TF of LLST EQ16 and EQ25

3.2 Example

Fig. 2 shows an example of TFs between the surface and at a depth of 17 m of Lotung array. EQ16 is a strong event (PGA = 0.25g), and EQ25 is a weak event (PGA = 0.1g). Therefore, the predominant frequency of EQ16 (2.0 Hz) is lower than that of EQ25 (2.5 Hz) because of soil nonlinearity. Moreover, the peak value of EQ16 is lower than that of EQ25 because of the higher damping. Similarly, the amplitude of the peak and the predominant frequency of all events are identified. Thereafter, these values are plotted against the PGV to determine nonlinearity, as shown in Fig. 3. PGV is used instead of PGA because it is proportional to the excited strain theoretically. As the PGV is higher (i.e., a larger strain), the peak value and the predominant frequency in horizontal direction decrease significantly because the soil is nonlinear at higher strains. However, such nonlinear behavior is not shown in the vertical component because no clear decreasing trend against PGV is observed. The reason for this finding will be discussed in detail later.

4. Results

Fig. 3 to Fig. 7 show the amplitude of the peak and the predominant frequency against the PGV for the other downhole arrays. Overall, the peak value of the horizontal direction is higher than that of the vertical direction, especially for the saturated sites such as Lotung and La Cienega arrays. The finding implies that the vertical direction shows less amplification compared to the horizontal direction. The result of such observation may be due to the coupling effect of fluids and solids that induce additional damping when propagating vertical motion. For the predominant frequency, the vertical direction is three to four times larger than the horizontal direction for the wet arrays, whereas this difference is about two for the dry arrays. The difference between the predominant frequencies of the horizontal and vertical directions is attributed to the difference of Vs and Vp.

As the PGV increases, the peak value and the predominant frequency decrease in the horizontal direction for all arrays because of soil nonlinearity. However, the decreasing trends are not shown in the vertical direction for most of arrays. The Turkey flat and Corona array show a decreasing tend in the vertical direction similar to that in the horizontal direction, but the rest of the arrays show almost no change against the PGV. Ideally, the nonlinear behavior shown in the horizontal direction should also exhibit in the vertical direction.

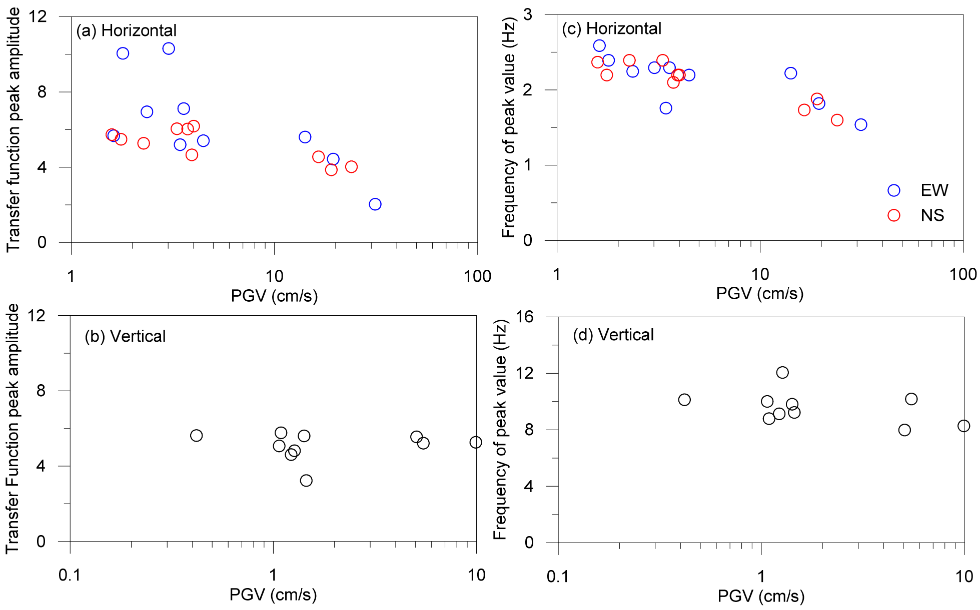

Fig. 3. Peak value (left column) and the corresponding frequency (right column) against PGV at Lotung Array

The main reason for the differences in behavior among these arrays is the present of shallow ground water table. Turkey flat and Corona array are two dry sites where the ground water table is lower than the bottom or analyzed measurement, whereas other array sites have ground water tables near the ground surface. The water can only take the compression but cannot take the shear. Therefore, it induces different behaviors when propagating shear waves (horizontal direction) and compression waves (vertical direction). In the horizontal direction, shear waves are propagated by the solid medium (i.e., skeleton of soil) and is not affected by the water unless excess pore water pressure is generated during the shaking. By contrast, compression waves are propagated by both the soil and water in the vertical direction. The vertical wave propagation is dominated by the water because of its higher bulk modulus compared to the soil. As a result, even if the horizontal direction exhibits nonlinear behavior caused by the soil, the vertical direction still behaves linearly. A good example can be illustrated by the Wildlife array, where liquefaction occurs and induces a significant nonlinearity. Although the wave propagation shows significant nonlinearity (i.e., substantial reductions of the predominant frequency) in the horizontal direction because of liquefaction, it still exhibits a linear behavior (i.e., no change of the predominant frequency) in the vertical direction. However, for the Turkey flat and the Corona array, the nonlinearity shown in the horizontal direction is also presented in the vertical direction because the sites are dry and are not affected by the water.

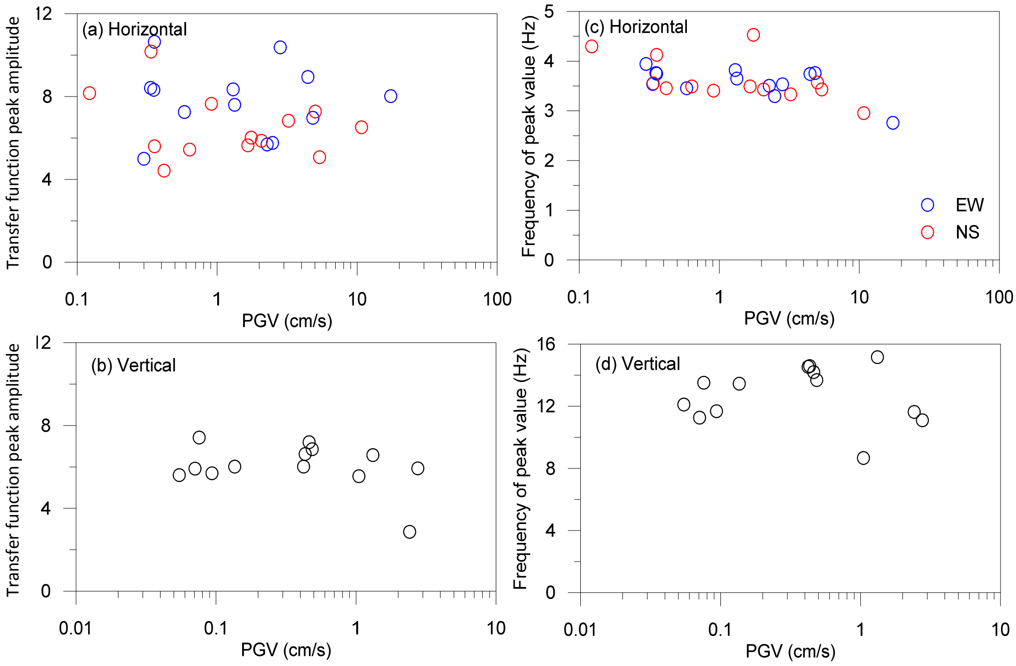

Fig. 4. Peak value (left column) and the corresponding frequency (right column) against PGV at La Cienega Array

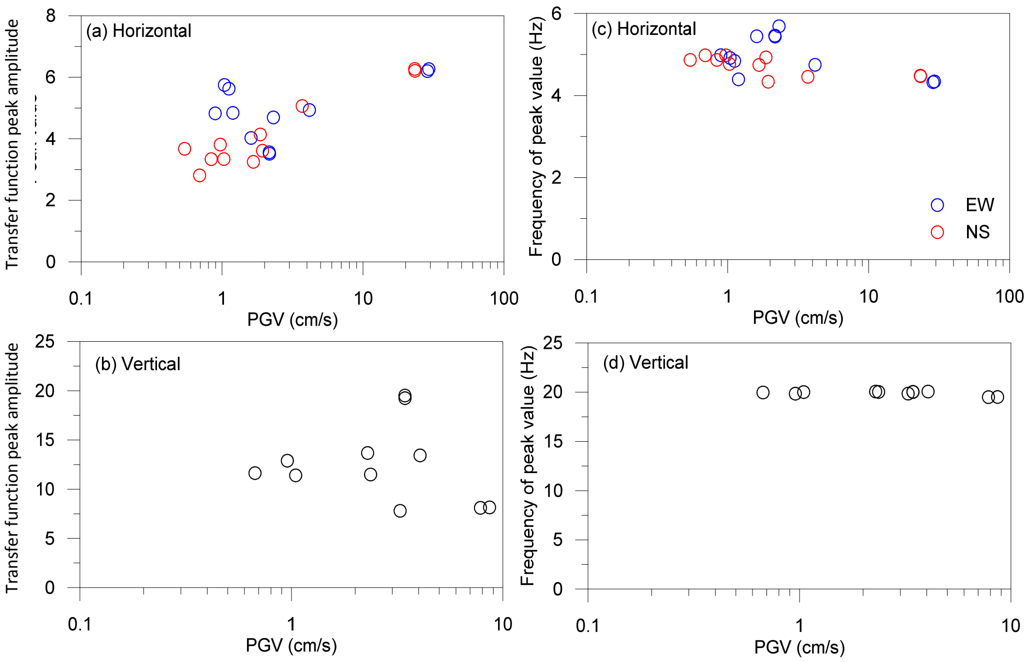

Fig. 5. Peak value (left column) and the corresponding frequency (right column) against PGV at Wildlife Array

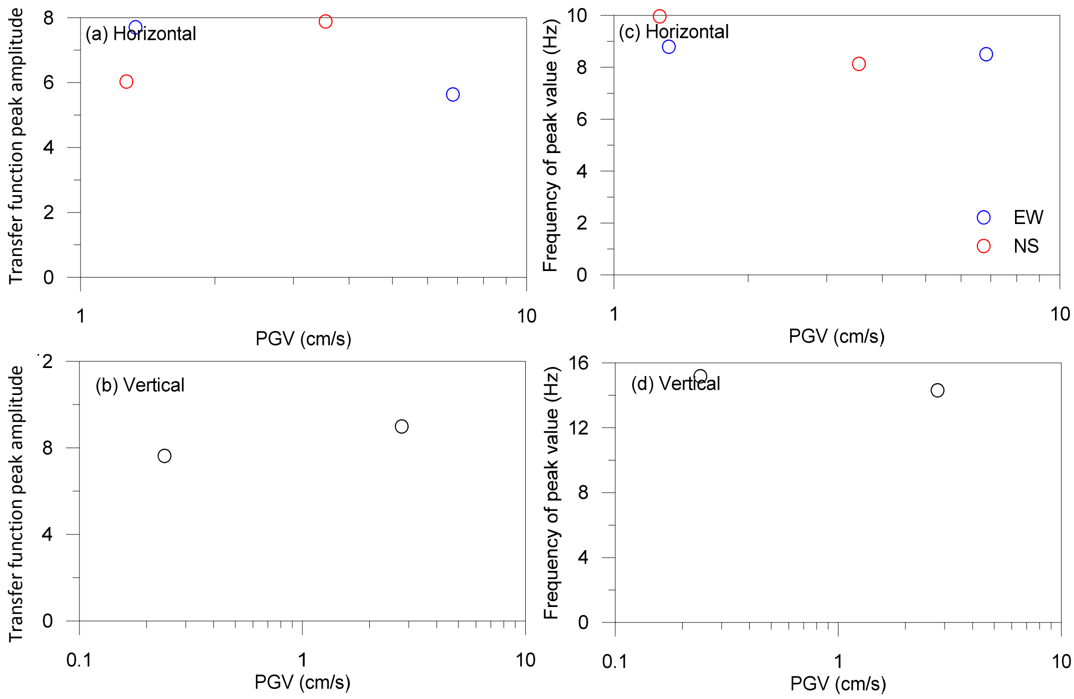

Fig. 6. Peak value (left column) and the corresponding frequency (right column) against PGV at Corona Array

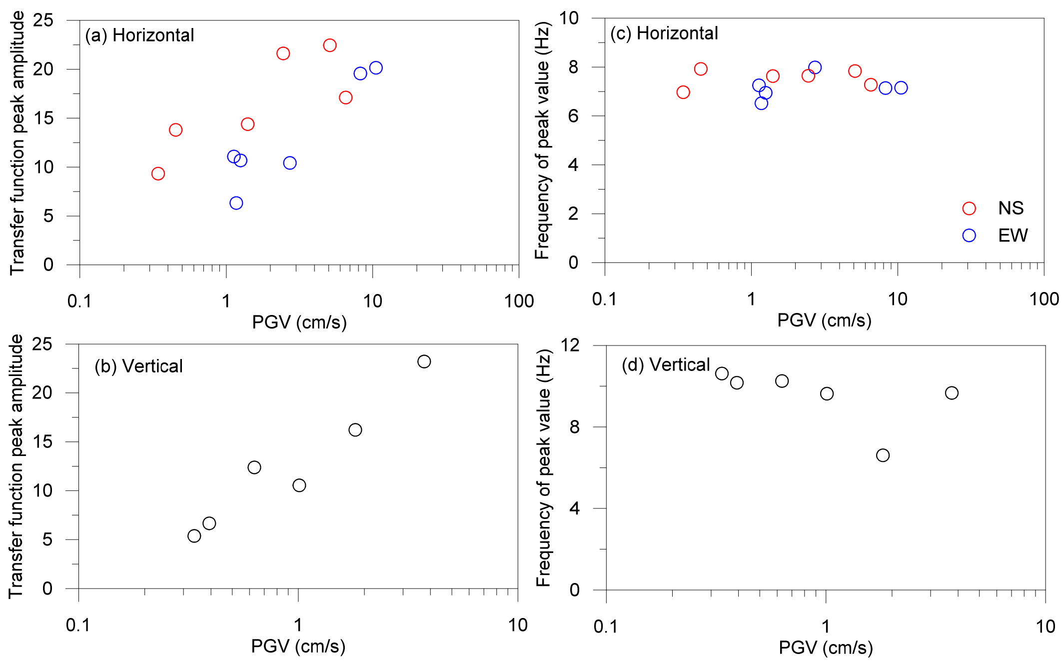

Fig. 7. Peak value (left column) and the corresponding frequency (right column) against PGV at Turkey flat Array

5. Conclusions

Three component records of five downhole arrays are analyzed to evaluate the differences of wave propagation in the vertical and horizontal directions. The amplification behaviors of two directions are characterized by the transfer function of surface and downhole measurement. The following are found. (1) The amplification of vertical motion is less significant than that of horizontal motion. (2) The amplification behavior of vertical motion is less dependent on the intensity of motion (i.e., exhibiting less soil nonlinearity). Finally, (3) the abovementioned nonlinear amplification behavior of vertical motion is highly dependent on the location of ground water table. These observations indicate that the amplification behaviors in the vertical and horizontal directions are quite different. These variances should be considered in the dynamic site response analysis and the building code.

5. References

[1] Gülerce Z, Abrahamson NA (2010): Vector-valued probabilistic seismic hazard assessment for the effects of vertical ground motions on the seismic response of highway bridges, *Earthquake Spectra*, 26, 999-1016.

[2] Bozorgnia Y, Abrahamson NA, Al Atik L, Ancheta TD, Atkinson GM, Baker JW (2014): NGA-West2 research project, *Earthquake Spectra*, 92, 3152-64.

[3] Newmark NM, Hall WJ (1978): Seismic Design Criteria for Pipelines and Facilities. *Journal of the Technical Councils of ASCE*, 104(1), 91-107.

[4] Elgamal A, He LC (2004): Vertical earthquake ground motion records: An overview. *Journal of Earthquake Engineering*, 8(5):663-97.

[5] Yang J, Sato T. (2000): Interpretation of seismic vertical amplification observed at an array site, *Bulletin of the Seismological Society of America*. 90(2):275-85.

[6] Beresnev IA, Nightingale, M. A, Silva WJ. (2002): Properties of vertical ground motions, *Bull Seismol Soc Am.* 89(1):260-274.

[7] Tang HT (1987): Large-scale soil structure interaction. Palo Alto, California: Electric Power Research Institute.

[8] Darragh R, Graizer V, Shakal A (1997): Site Characterization and Site Response Effects at CSMIP Stations: Tarzana and La Cienega Near the Santa Monica Freeway (I-10). Calif. Div. Mines and Geology, p. 262.

[9] Bierschwale JG, Stokoe KHI. (1984): Analytical evaluation of liquefaction potential of sands subjected to the 1981 Westmorland earthquake. . Geotechnical engineering report GR 84-15: University of Texas, Austin.