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Seasonal Variation of V_S at Shallow Depth and Nonlinear Behavior of Soil Based on the ARGONET Vertical Array Data

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Abstract. Ground acceleration time histories from earthquakes recorded by the ARGONET vertical array in Cephalonia, Greece, in the period from July 2016 to April 2022, are analyzed seeking evidence for nonlinear behavior of the shallow soil layers. Shear waves velocity, V_S, between the shallowest sensor pair of the vertical array, i.e., within the top 5.6 m of the soil column, is derived for each earthquake record using the method of interferometry by deconvolution. The temporal variation of V_S values is compared with indicators related to soil moisture and this leads to the identification of a clear difference in the level of the measured values between periods of intense rainfall and the dry summer months. Lower velocities, even lower than the level of V_S during rainy periods (7-13% of the annual average), are obtained based on the strongest records of the analyzed sample. These low velocities are considered as indicators of nonlinear soil behavior, the threshold onset of which is difficult to determine without prior correction for the seasonal variation. The applied method can provide a detailed description of V_S changes even during a single earthquake. Examples are provided on how nonlinear soil behavior may be manifested by a sudden V_S value drop at the arrival of the strongest seismic phases.

Keywords: shear-wave velocity, interferometry, soil response.

1 Introduction

The phenomenon of nonlinear soil behavior during strong seismic shaking has been recognized for decades, initially through laboratory experiments and later directly in seismic recordings (e.g. [1],[2],[3],[4],[5]). In seismic recordings, evidence of the phenomenon is usually sought through the comparative study of spectral ratios from recordings of strong and weaker earthquakes (e.g., a mainshock and its pre- and aftershocks) in the vicinity of a seismogenic fault. The nonlinear ground behavior is often imprinted as a "distortion" of the earthquake spectrum with energy shifting from higher to lower frequencies and a simultaneous reduction of spectral amplitudes in the natural frequency range of the ground column at the site (e.g. [6],[7]).

In the present study, the phenomenon of nonlinear soil behavior is investigated in changes of the shear wave velocity, V_S, in the shallowest meters of the soil column (upper 5.6 m) at the location of the ARGONET vertical accelerometer array in Argostoli, Cephalonia. The method applied is seismic interferometry by deconvolution and the aim is to identify unusually low V_S values that could be used as indicators for further analysis of the recordings in terms of their correlation with nonlinear soil behavior phenomena.

2 Data

2.1 The ARGONET Vertical Array of Accelerometers

The data set analyzed was obtained from the vertical accelerometer array of the ARGONET infrastructure in Argostoli, Cephalonia [8]. The array was installed in July 2015, initially comprising a surface accelerometer (CK00) mounted on a small concrete slab within a specially constructed wooden shelter and three borehole accelerometers at depths of 15.5, 40.1 and 83.4 m (CK15, CK40 and CK83, respectively). All accelerometers are of the Episensor Force Balance type from Kinemetrics. One year after the launching of the array (July 2016), another accelerometer was added in a 5.6 m deep borehole (CK06). Since their installation, the accelerometers have been continuously recording (with only short interruption intervals for individual instruments due to various technical problems) the ground motion at a rate of 200 samples per second. More information on the installation and geotechnical details of the site are provided in [8]. The ARGONET infrastructure database is open access and available through the website https://argonet-kefalonia.org/data/argonet_data/.

The data analyzed in this work are from the shallowest pair of accelerometers in the array, i.e. CK00 (0 m) and CK06 (5.6 m). Based on the available geological and geotechnical data, the medium between the two accelerometer locations consists of artificial fill (sandy-silty gravel, occasional large stones) to a depth of ~2 m, which overlies a ~6 m thick horizon of lake sediments (silty sand, sandy silt and clay). At greater depths, alternations of clay, silt and marl are encountered, which gradually transition to sandy-marly limestones, whereas at 83.5 m the Cretaceous limestone, considered the geotechnical bedrock of the area, occurs.

2.2 Description of Data – Initial Processing

The analyzed dataset includes 1524 horizontal ground acceleration component pairs (North-South and East-West directions, as available in the ARGONET database) corresponding to 762 earthquakes that occurred in the period July 2016 - April 2022, with local magnitude M_L=1.4-6.6 and epicentral distances R=2-180 km. Most records are of weak seismic motion, with only 5 of them exceeding 100 cm/s^2 at the surface station CK00. The main parameters of these recordings and the earthquakes that caused them are summarized in Table 1. The focal parameters of the examined earthquakes were taken from the catalogue of the Geodynamic Institute of the National Observatory of Athens (https://bbnet.gein.noa.gr/HL/databases/database).

Table 1. Basic parameters of the strongest strong ground motion records included in the analysis and of their causative earthquakes (in increasing PGA at the surface station CK00).

Date_Time	Lat	Lon	h(km)	M_L	R	PGA_CK00	PGA_CK06
20170501_110241	38.224	20.548	4.1	3.7	8	169.2	116.5
20181025_225449	37.341	20.512	9.9	6.6	91	149.7	107.4
20160919_035945	38.112	20.363	21.6	4.4	14	139.8	118.6
20200119_025209	38.168	20.748	6.9	4.8	21	119.4	58.1
20211119_132704	38.209	20.294	15.5	4.8	19	107.1	92.8

The set of horizontal recordings of stations CK00 and CK06 analyzed were corrected for base level and to remove possible linear trends over their entire duration. Then, a portion of each record with a duration up to the time when 75% of the Arias intensity is observed was automatically selected. In this way, part of the surface and coda waves were cut off, retaining most of the S waves [9], to avoid cases of highly energetic surface waves that could lead to surface wave velocity measurements instead of the requested V_S. Finally, a 2nd order Butterworth-type band-pass filter was applied in the frequency range 0.5-20 Hz, where the signal-to-noise ratio is sufficient to lead to reliable results even in the weaker recordings considered. The values of the signal-to-noise ratio in different frequency intervals are provided in the metadata file accompanying the recordings data (https://argonet-kefalonia.org/data/argonet_data/).

3 VS Velocity Using Interferometry by Deconvolution

3.1 Method

The method that was used to determine V_S within the top 5.6 m at the ARGONET site is the interferometry by deconvolution ([5],[10],[11],[12]). Through the deconvolution of the borehole seismic recording from the surface one, it is possible to determine the travel velocity of the seismic waves pulse in the between the two stations distance. This velocity corresponds to the dominating in terms of energy/amplitude seismic phase, which in the selected parts of the seismic recordings is expected to be the S-wave phase. The mathematical description of the result of the deconvolution of the recording at the location of a station *j* to that of a station *i* is:

$$D_{j-i}(t) = FT^{-1}\left\{\frac{A_j(\omega)}{max\left\{A_i(\omega),\ k\left(|A_i(\omega)|,\ \frac{A_i(\omega)}{|A_i(\omega)|}\right)_{max}\right\}}\right\} \quad (1)$$

where ω is the angular frequency, $A_j(\omega)$ the Fourier transform of the recording at station *j*, $A_i(\omega)$ the Fourier transform of the «reference» *i* station and *k* a parameter that stabilizes the deconvolution procedure in the frequency domain by defining a minimum frequency amplitude, which in our application was set to 10% of the mean spectral amplitude [13].

The result of the deconvolution through Equation (1) is the required pulse, which is then used, for example through its peak value, to measure its travel time from the location of accelerometer j to that of accelerometer i. Knowing the distance between the two accelerometers, the time measurement is converted into a measurement of the velocity V_S in the intervening material. To avoid cases of erroneous measurements due to e.g. double earthquakes or noisy interferograms, a quality criterion was set that the pulse peak should be at least 1.5 times larger than the next in amplitude peak appearing in the interferogram. In addition, all interferograms were visually inspected to ensure the quality of the measurements.

An example of the process of measuring the seismic wave pulse velocity is shown in Figure 1. In this example, the results have been obtained from the recordings of an M3.9 earthquake, the epicenter of which was located 45 km from the ARGONET location (01/02/2019, 05:02GMT). The bottom part of Figure 1 clearly shows the pulse of the waves propagating towards the surface (upward pulse; negative part of x-axis), but also that of the waves reflected at the ground surface and returning propagating downward (downward pulse; positive part of x-axis). The measurements in this study were based on the upward propagating waves and the points considered for measuring the pulse travel time are marked in the example in Figure 1 with red circular symbols.

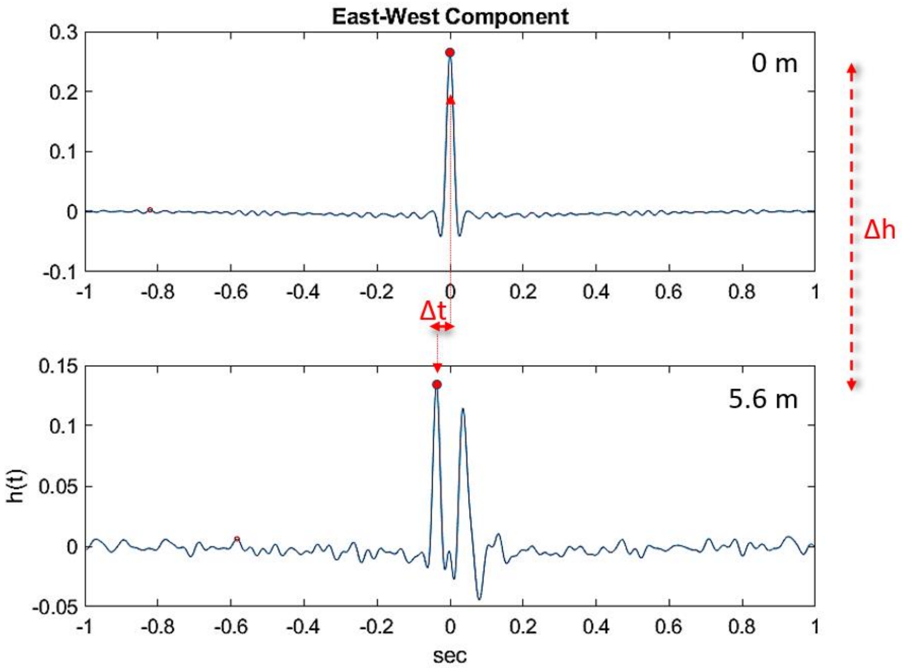


Fig. 1. Example results of the interferometry by deconvolution method using the recordings of a M3.9 earthquake (February 01, 2019, 05:02GMT) at epicentral distance of 45 km from the ARGONET site. Red circular symbols denote the pulse peaks that have been used to measure the travel velocity of the seismic waves pulse, *Δt*, for the distance *Δh* and ultimately of V_S.

3.2 Application and Results

Of the total 1524 pairs of records examined, 1318, corresponding to 659 earthquakes, met the quality criteria mentioned in the previous section. These values, as calculated for the East-West component are presented in Figure 2. The results for the North-South component are not presented for reasons of space economy, but it has been checked and confirmed that they lead to the same conclusions as described below.

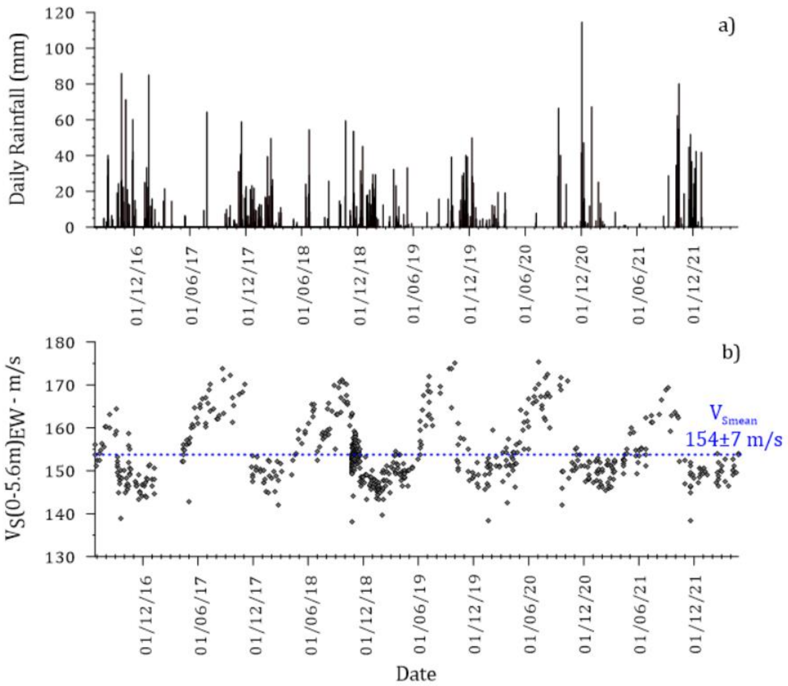


Fig. 2. Temporal variation of a) the daily precipitation height at a station of the Hellenic National Meteorological Service in Argostoli and b) the V_S values measured by seismic interferometry. The dotted blue line indicates the average V_S value calculated for the location of the ARGONET array.

The main conclusion from observing the results in Figure 2 is that the measured quantity (V_S) in the upper 5.6 m of the soil column in ARGONET shows significant variation with time. The mapped values vary between 138 and 175 m/s, around the mean value of 154 m/s. The temporal variation is not random but shows repeatability with a period of one year. In a previous work [12], a correlation of these discrete periods with precipitation and indirectly with the moisture content of the shallow subsurface was found. In Figure 2 we contrast the V_S results with daily precipitation data provided by the Hellenic National Meteorological Service (http://www.hnms.gr) for its permanent station in the Argostoli area. The comparison of the two distributions confirms over almost 6 hydrological cycles the existence of the previously mentioned correlation, with the lowest V_S values occurring abruptly after the onset of intensive rainfall of each hydrological cycle, and the highest during the dry summer months.

The observation of the correlation between the variations of V_S values and the hydrological cycle led to the decision to reinforce the ARGONET infrastructure with a meteorological station and a soil moisture meter. The ARGONET meteorological station, installed at the Ionian University premises, at ~1 km from the vertical accelerometer array, and the soil moisture meter (type SoilVUE10 - 1 m, Campbell Scientific), installed at the vertical array site, have been operating with continuous recording since July 2021. Figure 3 compares the V_S values corresponding to earthquakes in the period July 2021-April 2022, the rainfall data from the ARGONET meteorological station (hourly measurements) and the soil moisture measurements (% of volume) at 0.75 m depth for the corresponding period. The vertical dashed line marks the abrupt change in the level of measured V_S values, which coincides with a sharp increase in soil moisture after the first heavy rainfall in October 2021.

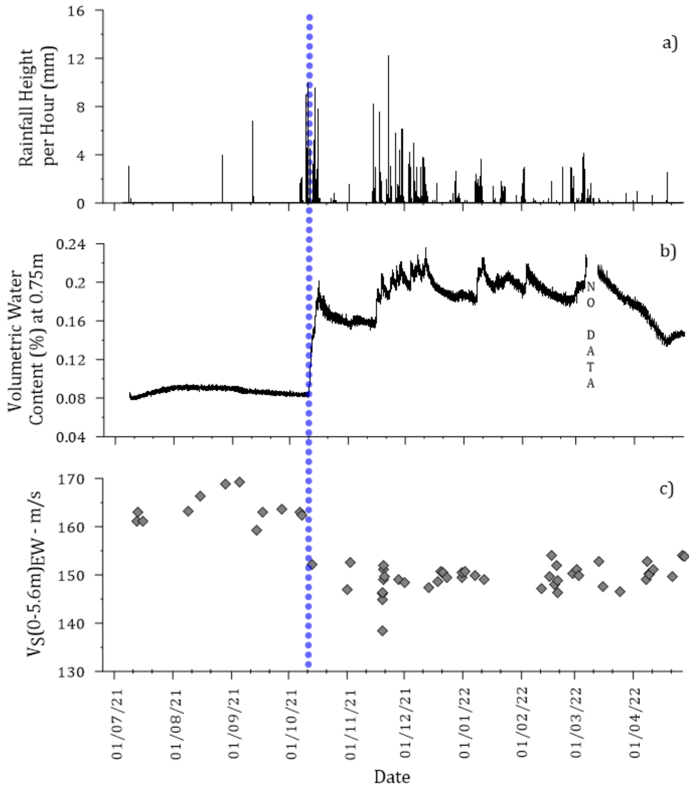


Fig. 3. Comparison of a) the precipitation height (hourly measurements) recorded at the newly installed ARGONET meteorological station, at ~1 km from the location of the accelerometer array, with b) soil moisture measurements at the ARGONET site at 0.75 m depth and c) the temporal variation of V_S values calculated from earthquake data in the period July 2021 - April 2022. The vertical dashed line marks the time of the abrupt change in the level of measured V_S values, which coincides with the onset of the strong and prolonged rainfall of the hydrological cycle and the consequent increase in soil moisture.

A second observation with respect to Figure 2 is the presence of some V_S values at levels even lower than the lowest of seasonal variation. These values are found to be associated with the strongest (in terms of PGA) records of the analysed sample. In

Figure 4, the V_S values obtained from the five waveforms of the sample with PGA at the surface stations CK00 >100 cm/s^2 are marked with red triangular symbols. The correlation of these V_S values with the intensity of ground vibration indicates a decrease in V_S due to non-linear soil behavior.

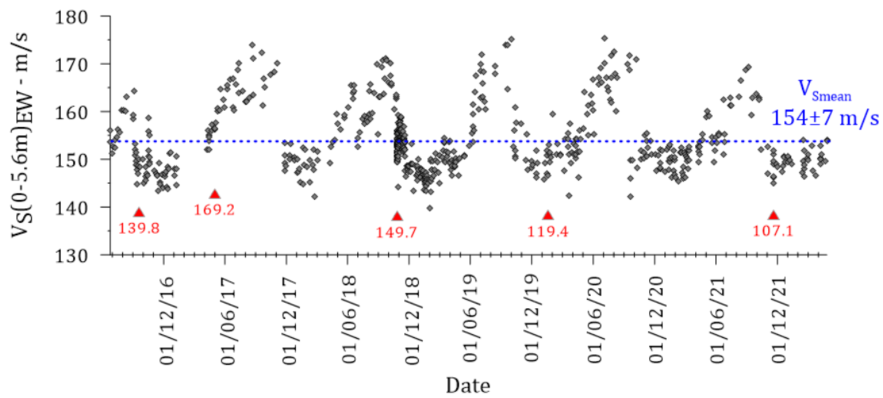
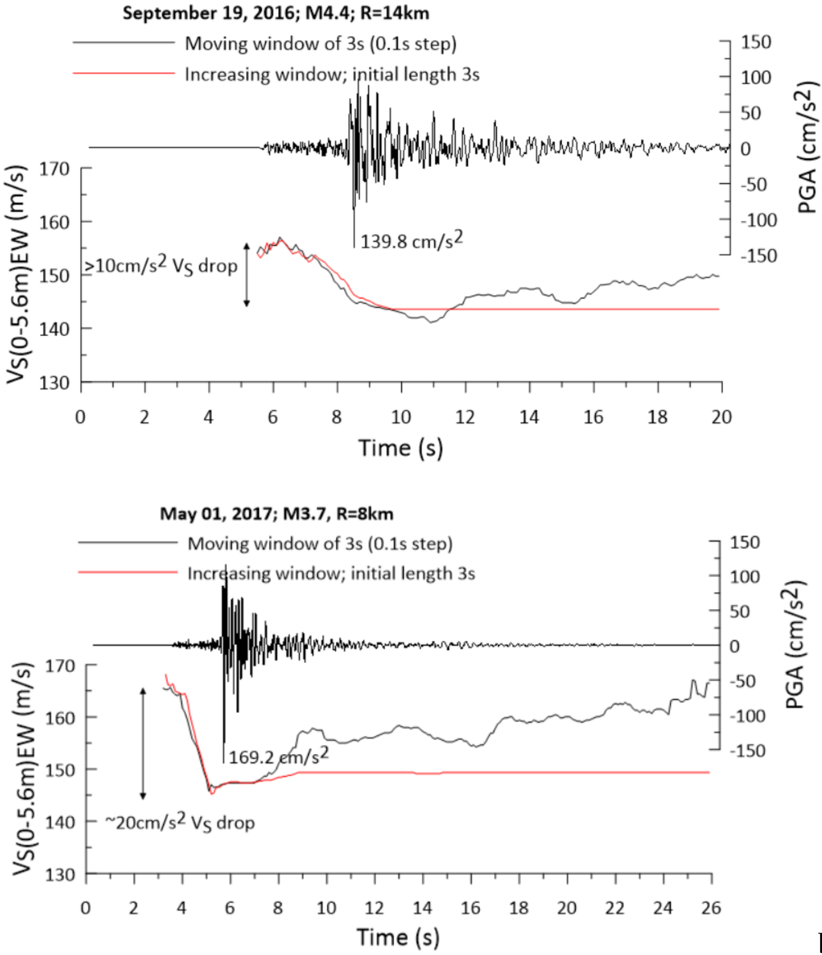


Fig. 4. Temporal variation of V_S calculated by the interferometry method (as in Figure 2b) where red triangular symbols indicate the values obtained based on the 5 strongest records of the studied dataset (Table 1, PGA at surface station CK00 > 100 cm/s^2). The corresponding PGA value at station CK00 (in cm/s^2) is noted below the individual symbols.

The five earthquakes corresponding to the red symbols in Figure 4 were further analysed through seismic interferometry, performing calculations in different time windows in order to obtain the time history of the VS variation during the individual events. The calculations were initially performed with a time window of 3s duration, starting at the beginning of each recording. In subsequent steps, the duration of the window was gradually increased (with a step of 0.1s) until the duration of the strong ground motion was exceeded. The results of this analysis are mapped as red curves in Figure 5 for 2 example events. The top of each plot shows the accelerogram at station CK00. The black curves in the plot of VS values with time correspond to the results obtained when instead of a time window of steadily increasing duration, a window of constant duration (3s) was used, which, however, was shifted with a constant step (0.1s) to the right of the time axis. The results of the two approaches in the plots in Figure 5 are comparable up to the region where VS takes the lowest values (~10s in 5a and at 5-7s in 5b). From there on, the increasing duration window maintains the low value, which proves that the effect of the applied method is modulated by the more active seismic phase. In contrast, the shifting but constant-duration window gradually enters the region of the coda waves and the level of the measured VS starts to rise, indicating the return of the ground behavior to the linear region. The VS drop for the 5 earthquakes studied was found to be of the order of 10-20 cm/s2 for the sediment thickness (5.6 m) studied, i.e. ~7-13% of the annual average VS value.



a)

b)

Fig. 5. Examples of V_S variation analysis during individual earthquakes, namely a) the M4.4 earthquake that occurred at a distance of ~14 km from ARGONET on 19/09/2016 and b) the M3.7 earthquake that occurred at a distance of ~8 km on 01/05/2017. The top panel maps the time history of the ground acceleration in the East-West component of CK00, whereas the bottom panel maps the V_S variation with time. The interferometry was applied to individual time windows that either gradually increased in duration starting from a minimum duration of 3s at the beginning of the record and including a progressively longer part of it (red curves), or were of fixed duration (3s) but moving at steps of 0.1s to the right (black curves).

4 Conclusions

In this paper, the ground acceleration records of 659 earthquakes obtained at the surface and the 5.6m-deep borehole station of the ARGONET vertical array in Argostoli, Cephalonia, during the period July 2016 - April 2017 were analysed. The aim was to apply the seismic interferometry by deconvolution method to calculate the shear wave velocities in the upper 5.6 m of the soil column at the recording site and to investigate possible velocity variations that could indicate non-linear soil behaviour. The analysis revealed a significant seasonal variation in the measured values, clearly correlated with the variation in rainfall and soil moisture. At least 5 cases of V_S values at a level lower than even the lower limit of the seasonal variation were identified in the analysed data set. These values correspond to the 5 strongest records in the sample (PGA = 107.1-169.2 cm/s2), which were further studied in terms of VS variation over their duration. A detailed analysis of the V_S time history reveals a clear decrease in its value during the passage of the strongest shear waves, which in the analysed data reached up to 13% of the annual average V_S value at the ARGONET site. This drop is attributed to effects of non-linear soil behaviour.

In the international literature one can find several different estimates of the value of PGA that defines the onset of non-linear soil behaviour. Indicative values are 100-200 cm/s^2 [6], ~60 cm/s^2 [14], 50 cm/s^2 [4], 35 cm/s^2 [3]. The results of the present study highlight the need to understand and correct the effect of the seasonal variation of V_S in order to establish the true threshold of the onset of nonlinear soil behaviour. Although at the strongest records the effect is strong enough to be detected, at lower levels of ground shaking it may be obscured by the effect of seasonal variation of V_S and become undetectable. In addition, it is of interest to investigate the role of V_S level at the onset of nonlinear behavior, e.g., if the margin for nonlinear behavior is greater during dry months, when V_S levels are at their maximum.

The aim of future research is the physical interpretation of the phenomenon of seasonal variation in VS, and the study of its effects on the amplitudes and frequency content of ground motion. By removing the seasonal variation from the measured values, it is expected to better highlight the low VS values that, according to this work, indicate non-linear soil behaviour. With the continued operation of the ARGONET infrastructure and the ongoing recording of numerous data, it will be possible to quantify the phenomenon even at low levels of ground vibration.

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