NEtwork of Research Infrastructures for European Seismology

Report on tests by third teams

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Contents

1. Introduction and objectives

It is well known that the properties of the shallower formations can greatly modify the seismic signal recorded at the surface. To adequately interpret the recorded signals it is necessary to properly characterize the ground mechanical properties near the surface. The knowledge of this information beneath accelerometric stations in the Euro-Med regions will allow improving the use of existing and future strong motion recordings obtained within Europe and therefore seismic attenuation, seismic hazard assessment and earthquake parameters characterization.

Reaching that objective requires a reliable geophysical or geotechnical characterization for each of the thousands of recording sites. While this information already exists for several tens of them, it is still unknown for the vast majority of the stations. Usual methods (e.g., drilling) presently appear too expensive to be considered for a systematic investigation campaign. The JRA4 is thus dedicated to investigating, developing and documenting prototype, reliable, low cost tools, which include a mixture of techniques, and optimize them for their systematic implementation by each country for its own strong motion network. The development of these tools partly relies on the results from the SESAME project dedicated to the use of ambient vibrations for site effect assessment (a FP5 project, n° EVG1-CT-2000-00026).

The objective of the JRA4 Task E was to test the Geopsy tools (Geopsy and Dinver) developed in Task B. The tests were made by teams who did not participate in the tool development (University of Lisbon (FFCUL) in Portugal and Résonance Ingénieurs-Conseils SA in Switzerland). There are indeed two goals in Task E: (*i*) to test a tool(s) for site characterization for national networks, and (*ii*) to test a tool(s) for EC8 classification for engineering purposes.

The tests were conducted on ambient vibration data recorded within the framework of the NERIES project. The University of Lisbon (FFCUL) participated to the measurements of three sites in Portugal; whereas Résonance made the tests on already recorded data in one site in Greece. In addition, ITSAK (Greece) and DPC (Italy) also provide some feedbacks on data acquisition and on the suitability of the Geopsy tools to provide subsoil structure information.

The structure of this report presents the different tests made to evaluate the feasibility of a practical use of the Geopsy tools to meet the objectives of the Task E:
  • chapter 2 describes the test of functionalities of the software developed in the Geopsy tools;
  • chapter 3 provides user feedbacks on the practical use of different acquisition systems to record ambient vibration data;
  • chapter 4 describes user feedbacks and improvements on data processing (computation of H/V ratio, array analysis: f-k and MSPAC techniques);
  • chapter 5 focuses on inversion strategy to determine the shear-wave velocity profile;

• chapter 6 discusses about result discriminations and site categorizations for engineering purposes;

• chapter 7 summarizes the main conclusions and recommendations.

2. Test of functionalities

2.1 Geopsy

The functionality test of Geopsy was performed with the help of GeopsyWiki and under Windows XP environment, using the default parameters. The version of Geopsy tested was 2.7.0-snapshot-20100221. The results of the test are presented in Table 1.

Table 1: Results of the functionality tests of Geopsy's modules.

Menu	Functional	User-friendly	Comments
File			
Open	yes	yes	
Save	yes	yes	
Save as	yes	no	The browser window has always the same directory by default ('My computer'). By default, the last directory should be opened
Close	yes	yes	
Imports signals	yes	yes	Only the 'File' option has been tested
Import headers	-	-	Not tested
Export	-	-	Not tested
Preferences	yes	yes	
Edit			
Lock table edition	yes	yes	
Sort	yes	yes	
Set headers	yes	yes	
Set receivers	yes	yes	
Set sources	yes	yes	
New group(s)	yes	yes	
View			
Table	yes	yes	
Graphic	yes	yes	
Map	yes	yes	
Chronogram	yes	yes	
Time	yes	yes	
Frequency (amplitude)	yes	yes	
Frequency (phase)	yes	yes	
Refresh now	-	-	Not tested
Set data fields	yes	yes	
Waveform			
Subtract value	yes	yes	
Subtract signals	yes	yes	
Multiply	yes	yes	
Filter	yes	yes	
AGC	-	-	Not tested
Whiten	yes	yes	
Clip	yes	yes	
Phase shift	yes	yes	
Over sample	yes	yes	
Taper	yes	yes	
Cut	yes	yes	
Merge	yes	yes	
Decimate amplitude	-	-	Not tested

Menu	Functional	User-friendly	Comments
Decimate time	yes	yes	
Wavelet transform STA/LTA	?	no	Do not understand the function
Rotate components	?	no	It seems to work, but it is not clear how we can get the results
Correlations	yes	yes	
Revert to original	yes	yes	Very useful
Tools			
Spectrum	yes/no	yes	Unable to load spectrum results without computing a spectra
H/V	yes/no	yes	unable to load H/V results without computing an H/V ratio
Spectrum rotate	yes/no	yes	Does not work when only two components are given
H/V rotate	yes	yes	
F-K	yes	yes	When the condition of velocity is too restrictive, the calculation should not start.
High resolution F-K	yes	yes	When the condition of velocity is too restrictive, the calculation should not start.
SPAC	yes	yes	
Linear F-K for active experiments	no	-	
Linear F-K for passive experiments	-	-	Not tested
Particle motion	yes	yes	
Time-frequency analysis	yes	yes	
Damping	yes	yes	
Noise reduction	-	-	Not tested
Refraction with NA	-	-	Not tested
Structure spectrum	-	-	Not tested

As general comments, almost all functionalities are user-friendly. The choice of the default parameters is suitable in most cases. For FK and HRFK computation, although the frequency range is arbitrary chosen, the warning at the beginning of the computation allows the user to change it easily. For the SPAC computation, a warning appears if the user forgot to define rings.

2.2 Dinver

The results of the functionality tests of Dinver are presented in Table 2.

Table 2: Results of the functionality tests of Dinver's modules.

Menu	Functional	User-friendly	Comments
File			
New	yes	yes	
Open	yes	yes	
Save	yes	yes	
Save as	yes	yes	
Import targets	yes	yes	
Export targets	yes	yes	
Import parameterization	yes	yes	
Export parameterization	yes	yes	
Quit	yes	yes	

View			
Parameter space	yes	yes	
Ground profile	yes	yes	
Dispersion	yes	yes	
Autocorrelation	yes	yes	
Ellipticity	yes	yes	
Refraction Vp	-	-	not tested
Refraction Vs	-	-	not tested
Runs			
Add	yes	yes	
Remove	yes	yes	
Start	yes	yes	
Stop	yes	yes	
Clear	yes	yes	
Show	?		Working?
Import models	?		Working?
Tools			
Status	yes	yes	
Parameters	yes	yes	
Runs	yes	yes	
Log	yes	yes	
Targets	yes	yes	

As general comment, almost all functionalities are user-friendly. However, if the computer has not enough memory and the processor is not enough fast, Dinver program may crash very often. It is better to give technical requirements for the computer on which Geopsy is installed (RAM, processor, etc.).

3. Data acquisition

Different acquisition systems were used during several experiments performed in four countries by different teams.

• During the first experiment performed in Portugal (by University of Lisbon) the equipment developed in the University of Potsdam was used. It consisted of eight Lennartz 5 second, three component sensors, connected to EarthData digitizers. At each station, a MeshCube Linux System managed recording and communication between stations. Each station was powered by a 12Volts battery. Data were transmitted in quasi-real time via WiFi. The WiFi connections needed line-of-sight between any single station and at least one other station. However no central unit was needed to contact all stations directly, because each station acted as a transmitter and a recorder. Data package could consecutively be transferred between stations until they reached the WiFi receiver (omnidirectirectional 18 dB antenna) which was connected to the field PC. Recordings were done with a sampling rate of 100Hz and a sensitivity of 2.5 µV/bit. GPS receivers were included in each station to synchronise the clock of the recorders. The precise position of each station, as needed for array analysis methods, was performed by the use of different GPS measurements, carried out with a Leica GPS 1200 system, as a reference station, and another Leica GPS 1200 as a Rover. This combination leads to a relative accuracy in the centimetre range for stations locations.
Data acquisition was performed using quasi-circular arrays, constrained by the terrain conditions, with increasing radius, varying from 5 meters to 200 meters, and with one central station. In each site, 3 to 5 arrays were recorded. In the

field PC, all arriving data were archived via seed link and can be processed in near-real time allowing a first evaluation of the data. Pre-processing was carried out with Geopsy software (Wathelet, 2005, www.geopsy.org) for near-real time calculations of spectra and H/V ratios and with a command-line based subroutine of CAP (Ohrnberger et al, 2004) for near-real time frequency-wave number (f-k) array analysis of the vertical component signals and calculation of Rayleigh waves dispersion curves. These curves were displayed and checked in the field with the max2curve feature of Geopsy.

   • A second experiment was performed in Portugal using a set of 15 RefTek 125A Miniature seismic recorder (Texan) equipped with Geo Space geophones, GS-11D, with natural frequency of 4.5Hz. These instruments had only vertical component. No WiFi transmission existed so there was not possible to check in the field if the equipment was working properly and it was not possible to perform any data processing in quasi-real time. GPS receivers were included in each station, to synchronise the clock of the recorders, and the recordings were done with a sampling rate of 250Hz. The relative position of the stations was computed using a Leica TC307 Total Station, which needed line-of-sight with all stations. The advantage of this equipment was that it enables accuracy in the centimetre range for stations distances, which was very important for the smaller array apertures. For the absolute location of the array a Leica GS15 GNSS receptor was used.
Data was acquired using quasi-circular arrays, constrained by the terrain conditions. The first array was composed by one central station, 7 stations distributed along a circumference with 5 meters radius (approximately), and 7 stations distributed along a circumference with, approximately, 10 meters radius; ambient vibrations were recorded during 1 hour. The second array was performed with a similar geometry, for 20 meters and 40 meters of radius; ambient vibrations were recorded during almost 2 hours. To compute the H/V ratio, a Cityshark (LEAS) seismic station was used, equipped with a Lennartz LE3D-5s seismometer. During the first array, this 3 component equipment recorded near the central point of the array; during the second array, 15 minutes records were performed in each station of the 40 meters circumference.

   • In the framework of the L'Aquila area Microzonation project, organized and coordinated by the Italian Civil Protection Department (DPC), the research unit of Siena University (Coordinator: Prof. D. Albarello) acquired ambient vibration data by array of sensors in order to retrieve Vs profiles at different depths and in different subsoil conditions. Acquisition settings and field operations were conditioned by the short-term aims of the Project. In fact field measurements were conducted quickly and often in "blind conditions" in a very wide area, with no opportunity to repeat measurements. Two datasets, acquired in the villages of Fagnano Alto-Vallecupa and San Demetrio nei Vestini (L'Aquila province), were re-processed using Geopsy software package.
The same acquisition system and methodology were used during the two experiments. Data were collected by means of vertical geophones (4.5 Hz natural frequency) connected by cables (50 m length) to 16 channels 24 bit portable ADC/recording system Soilspy. Signals were recorded at a sampling rate of 128 Hz for a total duration of 20 minutes. The 2D array was designed in

the field with cross-configuration (Figure 1). The sensors were deployed along two perpendicular alignments and inter-station distances were not fixed in order to sample different wavelengths; these distances were estimated by measuring tapes. Due to the available space and cables lengths, the two arrays reached dimension of 44.0 x 37.0 m in Fagnano Alto-Vallecupa and 55.0 x 50.5 m in San Demetrio.
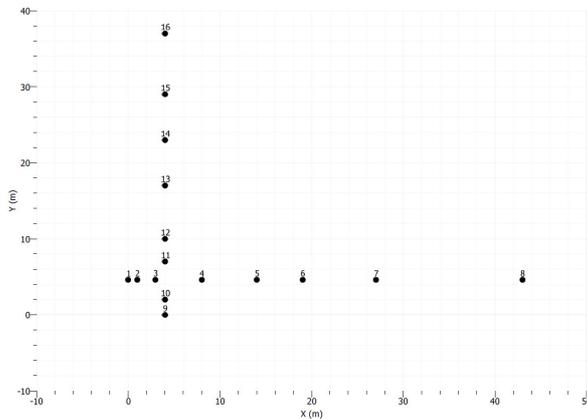

Figure 1 - Geometry of the 2D array in Fagnano Alto-Vallecupa

• During the NERIES project ITSAK performed several ambient vibration array surveys at different sites. All experiments are described in detail in Appendix 1. The first experiment was performed in seven selected sites for which geophysical and geotechnical data were available. The equipment used was the same as in the first experiment described for Portugal, which was developed by University of Potsdam, and the procedure was similar. Measurements were performed during the day, independently of the market timetable, and dispersion curves were obtained in situ. A group of five to six persons per site were dedicated for the accomplishment of the field work. The biggest advantage of that experiment was the real time estimation of the dispersion curve in the examined site.

• The second set of experiments, performed by ITSAK, consisted on measurement performed in 14 sites, all close to accelerograph stations of the national strong motion network. The site selection was mainly based on the number of strong motion recordings already available for these stations. The equipment used was composed by 13 autonomous velocimeters (Guralp CMG-6TD, 24 bits digitizer, coupled with CMG 30sec sensors) with their own acquisition system (including GPS). Measurements were performed during the day, independently of the market timetable. A group of three to four persons per site were dedicated for the accomplishment of the field work. The typical array geometry was a central point and 2 circles of 5 sensors each, with radius r and 2*r with a shift of 36 degree between the small and large arrays (Figure 2). The recording duration was between 30 minutes (for the small array radii) to one hour (for the large array radii). For accurate sensor positions a differential GPS units was used during the array deployment only for the large array radiuses. Positioning of the medium and small arrays (r<30m) was done with measuring tape.
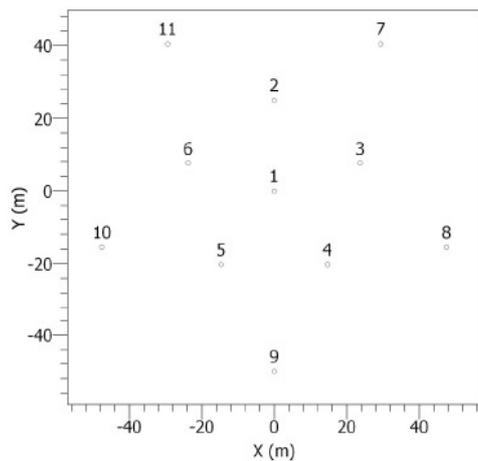
Figure 2 – Typical array geometry

• In collaboration with another European project (Transfer of Knowledge, ITSAK_GR), two ambient noise arrays were deployed close to respective accelerograph sites in the city of Patras, Greece. In fact, the aim of this experiment, that took place during summer 2009, was the comparison of the dispersion curves as well as the shear wave velocity profiles deduced from three different scientific groups and different methods (USGS: 2 persons; University of Patras: 5 persons; NERIES_JRA4: 5 persons). The NERIES-JRA4 group deployed arrays for ambient noise measurement, the USGS team performed SASW method and the University of Patras team used REMI and SASW methods. All measurements took place during the morning and afternoon, in different time windows for active and passive methods. For accurate sensor positions a differential GPS unit was used few hours before the array deployment only for the large array radii. Positioning of the medium and small arrays (r<30m) was done with measuring tape. The equipment was the same as used in the former experiment (13 Guralp CMG-6TD coupled with CMG 30sec sensors). The radius of each array varied from 9 m to 93 m, for the PAT3 accelerographic station site and from 8 m to 50 m for the PHOS station site.

• Finally, during the NERIES-JRA4 project, also in collaboration with another European project (Transfer of Knowledge, ITSAK_GR), one ambient noise array was deployed in the EUROSEISTEST area close to the accelerometric station FRM. This array was deployed during the day and for accurate sensor positions a differential GPS unit was used during the array deployment. Three persons were occupied with the deployment and data acquisition using the wireless WARAN system developed within the NERIES-JRA4 project. Around station FRM a very large array with 7 stations (CMG6TD) was installed and was recording for a time interval of 9 hours. In addition, eight WARAN stations (coupled with Le/5s sensors) were used to record shorter wavelength of the ambient vibration wavefield. These stations were moved all the time in order to cover the surface of approximately 800x400 m lying between the stations of the large array (Figure 3).

• Complementary measures performed by ITSAK are presented in the Appendix 1.
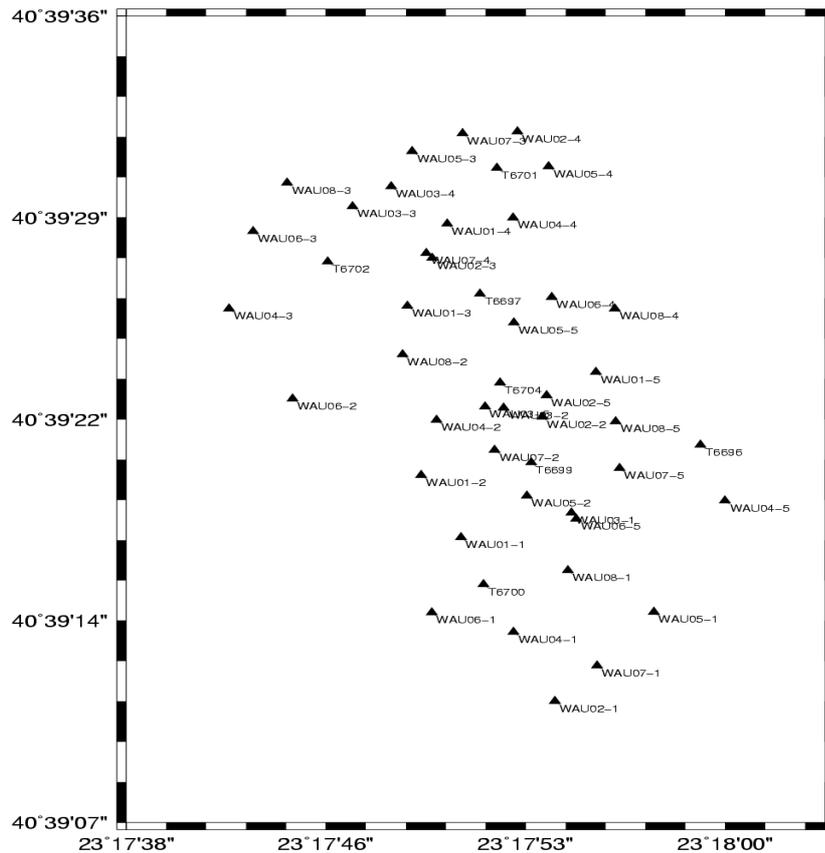
Figure 3 - Deployment configuration of the ambient noise array close to the FRM station

Comments:
 • In the field, we must first select the sites, for the sensors installation, and the array geometry. This could be constrained by the use of cables that limits the array dimension and, as consequence, the retrieving of information for low frequency bands. Also, the use of cables limits the applicability of array analysis in proximity of infrastructures or other building structures. Equipment without cables enables more freedom on the array geometry and it is easier to deploy in the field. However, the check of an appropriate place, for instance an open area large enough for the aperture of the planed arrays, is not easy. If possible, a visit to the site must be done in advance.
 • When installing the sensors we must follow the recommendations from the Sesame European Project EVG1-CT-2000-00026 reports (Sesame, 2003; 2004). For instance, it is absolutely necessary to protect the sensor against wind and/or rain; a bucket was used, by different teams, with that aim.
 • The type of sensors limits the analysis of the array data. The use of single component sensors does not allow H/V analysis. In this case, we must use, at least, one three component sensor to characterize the H/V value of the site. The cut-off frequency of sensors (1 Hz or 4.5 Hz) is a limitation for retrieving information at low frequency range. This type of sensors must only be used

when the site presents H/V values higher, or close, to the natural frequency of the sensors.

• However, the use of very simple equipment (1D sensors) allows to perform 2D array ambient vibration analysis by standard active seismic with a relatively cheap cost instrumentation. This equipment is very easy to use in the field and it is not affected by the problem of GPS communication which could be difficult in closed or urbanized areas. Of course, we must be aware for the frequency range analysis.

• If each station has its own GPS for time synchronization there is no need to use cables and to look for open spaces. Then, measurements can be performed inside an urban area. However, GPS needs a good communication with satellites that may be difficult to obtain in closed area.

• The use of a GPS total station can be very useful for the stations inter-distance computation. In general, this type of instrumentation gives less error than the GPS included in the acquisition systems, allowing a better accuracy on station locations. For the smaller arrays it is possible to use a tape but, for the larger arrays, if we want accuracy in the centimetre range, it is better to use a good GPS receiver.

• Without pseudo-real time data transmission, we perform like a "blind" experiment. We cannot be sure about the good performance of the instruments, and the recording duration of each array has to be longer to be sure that our time window is enough to perform the data analysis. It is necessary to compute the array transfer function in the lab, before going to the field but, if some unexpected obstacles are present, we will know the array transfer function only after the field experiment. Another option is to select the location of the stations in advance. This implies an increase of one or half- day duration for the experiment. If we did not take the good (blind) options, or if the equipment is not working properly, we must be forced to repeat the experiment, which will took one or more days longer.

• Data transmission by WiFi allows a quick and comparatively easy deployment of quite large arrays, even in an urban environment, enabling the check of the performance of all the equipment. The computation of H/V in the field gives valuable information of the site characteristics, in particular, gives an indication about the complexity of the structure (1D or 2D/3D). The theoretical array transfer function computed in the field, enables the modification of the location of one or more stations. This is particularly important when the array is not quasi-circular due to buildings, vegetation, urban or country obstacles. The computation of the dispersion curve in the field gives an idea of the quality of the results (in what concerns the site characterization), allows a good estimate of the recording duration for each array and helps on the decision for performing, or not, a larger array, saving much time.

4.   *Data processing with Geopsy*

Data processing using Geopsy was performed by independent users that did not participate in the software development. The use of Geopsy was made with the support of the documentation available in the wiki (http://www.geopsy.org/wiki/index.php/Main_Page). We will present the users feedback, as well as some suggestions for future improvements.

4.1 Computing H/V

The H/V tool works quite well with no difficulties.

However, it is absolutely necessary to read the SESAME guidelines for the processing of the H/V spectral ratio technique on ambient vibrations (SESAME, 2004), in order to correctly compute and interpret the H/V results.

For instance, before performing any analysis, the three criteria for the reliability of the H/V curve must be fulfilled:

1) $f_0 > 10 / l_w$
2) $n_c > 200$
3) $\sigma_A(f) < 2$ for $0.5\ f_0 < f < 2\ f_0$ if $f_0 > 0.5$ Hz or
   $\sigma_A(f) < 3$ for $0.5\ f_0 < f < 2\ f_0$ if $f_0 < 0.5$ Hz

Where:

• f_0 = H/V peak frequency;
• l_w = window length;
• n_c = lw * nw* f_0 = number of significant cycles;
• n_w = number of windows selected for the average H/V curve;
• $\sigma_A(f)$ = standard deviation of $A_{H/V}(f)$, $\sigma_A(f)$ is factor by which the mean $A_{H/V}(f)$ curve should be multiplied or divided;
• f = current frequency.

Comments / suggestions:

• It should be suitable to clear indicate how to decompress the provided example files in the wiki page. We know that for windows it is recommended to use 7zip for decompressing but this information is available in some pages but not in the H/V page. It can cause some difficulties for windows environment users.

• There is no indication on how to save the results in a file. This is not very important, because the user can find this alone but, compared with the information available in other Geopsy tools, maybe it should be suitable to add this information in the wiki page.

• The only no user-friendly feature is when we want to save a different database (or if we want to change the database name, using "save as"), or saving some figure (in page format or using "export image", for instance). In these cases, the browser window opens always the same directory by default ('My computer'). It should be suitable to open the last accessed directory.

4.2 Dispersion curves determination - FK technique

Two tools are available, in Geopsy, to retrieve the dispersion curves using frequency-wavenumber analysis: the conventional frequency-wave number technique (FK) and the high resolution frequency wavenumber algorithm (HRFK), implemented following the ideas of Capon (1969).

For both tools the processing flow is exactly equivalent to the conventional technique and the corresponding toolboxes are nearly equivalent. The only difference concerns the High resolution matrix parameter that is included in the processing tab of the HRFK toolbox. As the calculation for the HRFK algorithm involves the inversion of the cross spectral matrix estimate from the data, it may sometimes be necessary to stabilize the cross spectral matrix before inverting.

Before performing the frequency-wave number analysis (and maybe, even before going to the field) it could be recommended to run the WaranGPS program to obtain the theoretical array transfer function. This program will provide an estimation of the minimum and maximum wavenumbers (k_{min} and k_{max}) that can be analyzed, according to the array geometry and the minimum propagation velocity. These values are needed to estimate the computation parameters (*grid_step* and *grid_size*) to perform FK and/or HRFK analysis. Note that these values are automatically updated in f-k toolbox.

We computed the frequency-wavenumber analysis with both tools (FK and HRFK). Advantages or disadvantages of using one of these techniques are not discussed here. More details on this topic can be found in the GeopsyWiki or in the literature.

The f-k analysis was performed using only the vertical components of the signals and following GeopsyWiki directives, which are very useful and simplified the computation. f-k analysis was performed using the pre-processed database from the H/V analysis. Further processing was made concerning grouping the vertical components of the signals and loading and saving the coordinates from all the stations for each array.

To estimate the computing parameters GeopsyWiki gives clear directives. For instance (using HRFK tool):

> • T = 20 -50 seconds (and even more !);
> • bad sample threshold (variable);
> • Anti-triggering on raw signal;
> • grid_step < k_{min}/20*;
> • grid_size > k_{max}/2 (up to 2 kmax)*.

(*) Besides, the values for grid_step and grid_size are computed automatically, taking into consideration the minimum physical propagation velocity which is set, by default, to 100 m/s. This is a very useful utility that enables the user to process the HRFK method without further calculations, but still allowing the introducing of further constrains, depending on the knowledge about the site conditions.

Another extremely useful tool is the Test button which opens a frequency wavenumber window browser that allows the user to explore the f-k analysis for individual time windows and different frequency bands. This enables checking the parameter settings and controlling the data quality interactively.

Comments / suggestions:
  • The f-k tool works quite well with no difficulties. The default parameters and the warning system (ex. upon the choice of a wrong frequency range) make it,

in general, a user-friendly application, especially when performed with the support of the GeopsyWiki, which is very clear and well-documented.

• Since the processing time of the FK and HRFK tools is relatively long, it would be useful to have estimation on the computing time or on the remaining time for the program to provide the results.

• It should be suitable to have some indications about how to specify the minimum and maximum frequencies for processing. Indeed, adjusting the frequency range to the target dataset should save computing time. It is clear that no general rules can be defined for achieving this purpose; however the user would appreciate to have some keys. For instance, the minimum frequency could be defined as the H/V peak frequency. These guidelines may be included in the GeopsyWiki.

4.2.1 Visualisation and Interpretation of the FK results

To view the results from the FK (or HRFK) processing we used the *Max2curve* graphical tool available within the Geopsy package. It is easier to use it with the help of the GeopsyWiki. The provided default parameters seem to be adequate for most site conditions.

Max2curve presents in its main window (right panel) the slowness histograms (probability density functions) displayed as a color image for a log frequency scaling. By default Max2curve computes the sample mean and sample standard deviation for each frequency histogram; those values are stored in the curve browser, on the left panel.

After running the WaranGPS, which gives the theoretical array transfer function, we can import the wavenumber curves of k_{min} / 2, k_{min}, k_{max} / 2, k_{max}, presented in frequency vs. slowness, which provide information on the capabilities of the array in terms of resolution and expected aliasing features. These curves can be overlaid to the display of f-k analysis results in Max2curve.

It should be pointed out that outside these wavenumber limits the results may exhibit strong bias. So, to estimate the reliable frequency range for analysis the user must take into account the wavenumber limit curves.

After the analysis of the displayed histograms (that can be "cleaned" using the *grid statistics*) the user has two choices for selecting the dispersion curve. It can be done either manually (by picking the most reliable dispersion curve) or automatically from the remaining statistics (by computing the mean or the median of the estimates). The identification of this curve is not an easy task. It could be not clear or it can be "contaminated" by higher modes, which are also very difficult to identify. This is a relatively common situation, which can lead to wrong velocity estimations and consequently direct to an unrealistic model.

Comments/ suggestions:

• It is common to use several array apertures to estimate the dispersion curves. It should be suitable to have the possibility to load more than one .max file (associated to different arrays) in the Max2curve program, in order to be able to view all of them together.

• Also the possibility to remove the added theoretical aliasing curves (kmin, kmax) should be easily achieved.

• The graphical windows should not open linked to a scale. They should open with the minimum and maximum values of the variables, in both axis, and the total length of the axis. This happens, not only, in *warangps*, but also in other Geopsy applications.

• Overall, the *Max2curve* graphical tool works properly. The use of GeopsyWiki is very helpful on choosing input parameters which must be done wisely because otherwise the results may not be reliable.

• The most difficulty lies with the identification of higher modes.

• It should be absolutely necessary to have some theoretical background to analyse and interpret the results and, consequently, to select the most adequate computing parameters (for instance, it should be suitable to attend a training course).

4.3　　Determination of autocorrelation curves - MSPAC technique

The Modified Spatial Autocorrelation (MSPAC), implemented in Geopsy according to the work of Bettig et al. (2001), is a modification of the SPAC method first presented by Aki (1957). It allows computing average spatial autocorrelation coefficients for any arbitrary array configuration.

The MSPAC is implemented under the SPAC button (available in the Geopsy main screen), which can cause some confusion, for less attentive users.

We use only the vertical component of our signals. After loading the data we must select the rings. However, prior to specifying the inner and outer circles of each ring it is suitable to analyze the co-array map. For designing the rings we took into account the number and the azimuthal distribution of the pairs of sensors displayed in the co-array map. Defining the rings is an easy procedure following GeopsyWiki.

Comments / suggestions:
• The MSPAC tool works quite well with no difficulties, when performed with the support of the GeopsyWiki.

• The name of the button is SPAC and not MSPAC. This can cause some confusion. Maybe it could be changed.

• There is no indication on how to select the most adequate computing parameters (number of sensor pairs per ring, the minimum and maximum center frequencies for processing, etc.). The example parameters, presented in the GeopsyWiki, are specific for the provided database.

• Again, the graphical windows should not open linked to a scale. They should open with the minimum and maximum values of the variables, in both axis, and the total length of the axis. It happens in the array station locations and the co-array stations location maps.

4.3.1 Visualisation of the autocorrelation curves

To view the results from the MSPAC processing we use the graphical tool *Spac2disp*, available within Geopsy package. We use it with the help of GeopsyWiki.

MSPAC gives reliable estimates of the dispersion characteristics within larger frequency band, and allows additionally an easier recognition of the presence of higher modes from the unexpected occurrence of oscillations in the autocorrelation curves.

Comments / suggestions:
- *Spac2disp* is easy to use with the help of the GeopsyWiki.
- It is useful for checking the relation between autocorrelation coefficient and phase slowness, for each frequency and each ring, using the *Frequency* and *Radius* scroll bars.
- It is easy to select the kmin and kmax values. Between these two wavenumbers the spatial autocorrelation coefficients contribute for the definition of the dispersion curve. However, we must take into consideration that these kmin and kmax values have no relation with the kmin and kmax values used in the f-k analysis.
- When starting, *Spac2disp* must show its three windows equally distributed in space. Sometimes the spatial autocorrelation curves window is almost missing (it is reduced to a thin column)

5. Determination of Vs profiles using Dinver

The Dinver program runs with no difficulties on a computer with sufficient RAM and a rapid processor. However, minimum requirements information for the software to run properly must be provided to the users because with less rapid processors several problems occurred (very, very slow processing and the program crashes very often).
All the panels/ tools are easy to fill/ understand with the help of GeopsyWiki.

The most difficult part is to define the parameterization. We can follow what is indicated in GeopsyWiki (uniform layers over half-space); it must work for a large number of cases. However, we will never know if this simple structure is close to the real one, or not. If we have a more complex structure there is no indication about what strategy we should follow.

Another problem is related with the misfit. We already know that the model with the minimum misfit is not, probably, the best. How can we choose the best (or a set of "best") model? What should be the maximum acceptable misfit? We should take into consideration the models with misfit up to 1, or other value? When the minimum misfit is 0.01, does it make sense to take all models up to misfit equal to 1? Is it possible to derive a "best mean" soil profile with a standard deviation that covers the physical acceptable uncertainties?

These are some of the questions that the users would like to have answers to, or at least, an indication on how to take into consideration the minimum misfit.

The panel to view the results works quite well, with no problems, but the misfit default scale is not very suitable (for instance, if we choose to see all the models with misfit less than 1.0, the scale ends at 0.6; but for the parameter space, it goes up to 1.0!...). And after choosing the scale limits, usually they are not shown in the plot (the values are cut). In the "Parameter space" plot, it is not possible to reduce the length of the misfit scale. It should be suitable that the default scale of the misfit value be the same for all viewing plots/ results.

Outside Dinver, and after computing a large amount of soil profiles (for instance, 20 000), with misfit less than a maximum value defined by the user, it is possible to compute the V_{S30} for all profiles and computing the mean and the standard deviation. This is useful information.

Comments / suggestions:
   • Dinver runs quite well with no problems.
   • It is should be nice if it would be possible to provide some inversion strategies, or some test to check the validity of our final model
   • Indication on how to interpret and use the misfit value should be provided
   • Is it possible to derive a "best mean" soil profile with a standard deviation?
   • In the graphical window, to see the results the default misfit scale should be the same for all viewing/ plots, with well defined limits.
   • V_{S30} is very useful information, but maybe also V_{S10} and V_{S20} would be useful for some sites. This will be discussed in the next section.

Results obtained by different teams are presented in the Appendixes 2, 3, 4 and 5.

6.   Output for engineers

6.1   Suitable outputs / Choice of the best model

The final goal for engineers is to draw the design spectra accounting for soil conditions. There is no need for high precision, but an estimation of variability is required. Indeed, in most cases, only a few design spectra are provided for a whole area. Therefore, the spectra must be wide enough to cover some spatial variation.

Site specific design spectra are computed with software determining the seismic soil responses (e.g., Shake or Cyberquake for 1D-cases). Such softwares need as input, among other parameters, the shear wave velocity profile. Depending on the engineer practice, only the mean best estimate Vs profile, if possible, associated to uncertainty limits, are taken for the computation. The methods commonly used to determine the Vs profiles are a combination of all available geophysical (H/V single point, SASW, etc.), geotechnical (boreholes, SPT, etc.)

and geological information. Unlike commonly used methods, the ambient vibration array processing techniques, as implemented in Geopsy, has the advantage of producing, not a single Vs profile, but a set of models that equally fits the data. This would introduce uncertainties based on physical background in the computation of site specific design spectra. On the other hand, the occurrence of many solutions raises the question of the selection of the mean best Vs profile and the associated uncertainty.

The determination of the mean best Vs profile is a key point for engineers. The best procedure would be to keep all Vs profiles determined by the inversion procedure and having a misfit less than one, for computing the design spectra. However, this is not a realistic task, mainly because many inputs have to be introduced by hand in softwares that compute soil seismic response. Therefore it would be required to define a procedure to select – or help to estimate – at least three Vs profiles that describe the variability of the solutions:
   • the best mean Vs profile,
   • the min and max profiles that cover the physical acceptable uncertainties.

If no strategy is proposed for the determination of the mean best Vs profile, there is a danger that the engineer takes only the Vs profile with the minimum misfit without any further considerations.

6.2   Site categorization

In the Eurocode 8, the shape of the design spectra is defined as a function of the site classes. The soil classification is mainly based on the value of the average shear wave velocity down to 30 m (Vs30) and on the thickness of the soft layers down to 30 m. It is possible, with the aid of *Gpec8*, a tool of Geopsy, to determine the EC8 category of a site for horizontally layered models. The definition of EC8 site classes computed here are based on the Vs30 values.

Figure 4 shows the distribution of Vs30 computed for all inverted Vs profiles of each of the 7 soil models computed for the AIGIO site in Greece (see Appendix 4). The distribution of Vs30 is rather homogenous between the 7 models (although the structure of each model is different) and leads to a site class B for more than 99% of the Vs profiles (see Figure 10 in Appendix 4). Although, in this case study, the attribution of the site class seems to be robust, the result slightly differs from the true site categorization (site B/C).

Besides, the distribution of Vs30 computed at the site RELVÃO in Portugal (see Appendix 3), from inverted soil profiles computed with different techniques (HRFK and SPAC) by two users, points out two separates classes of Vs30 values: below or higher than 400 m/s (see Figure 5). The result, in this specific case is that the soil class evaluated by the two users is not consistent. Depending on the user, the site has a class B or C.
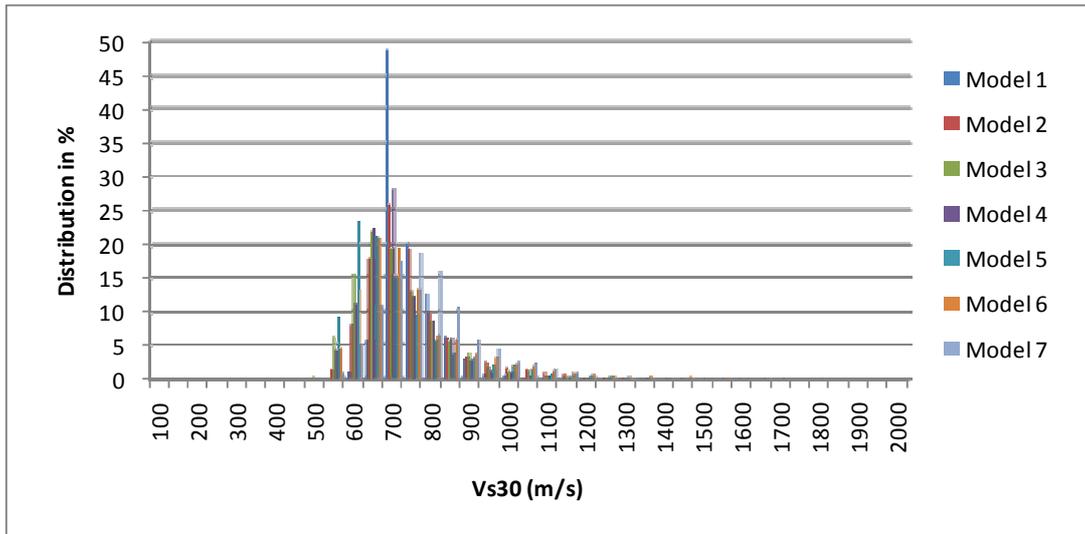
Figure 4: Distribution of the values of Vs30 computed from all inverted Vs profiles of each of the 7 soil models for the AIGIO site (Greece). See Appendix 4 from more details.
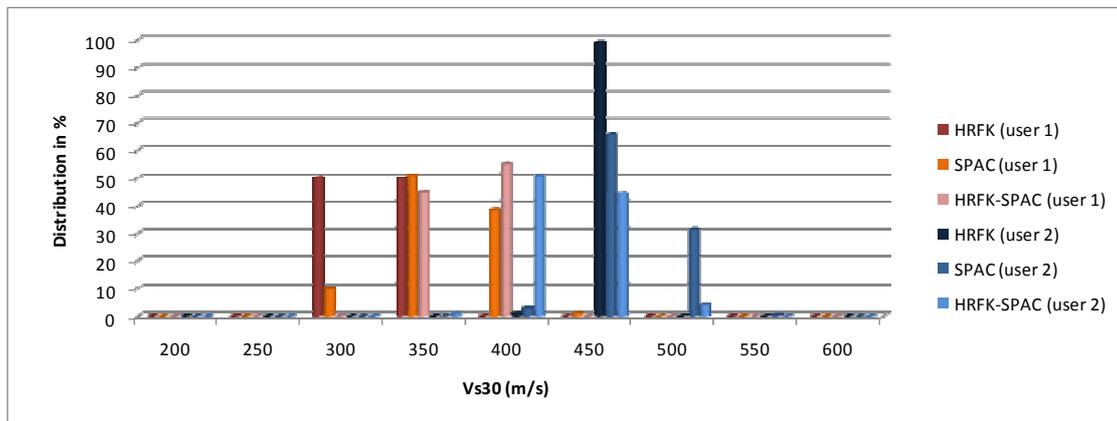

Figure 5: Distribution of the values of Vs30 computed at the site RELVÃO (Portugal), from the inverted Vs profiles determined by different techniques (HRFK, SPAC and a combination of the two methods), by two different users.
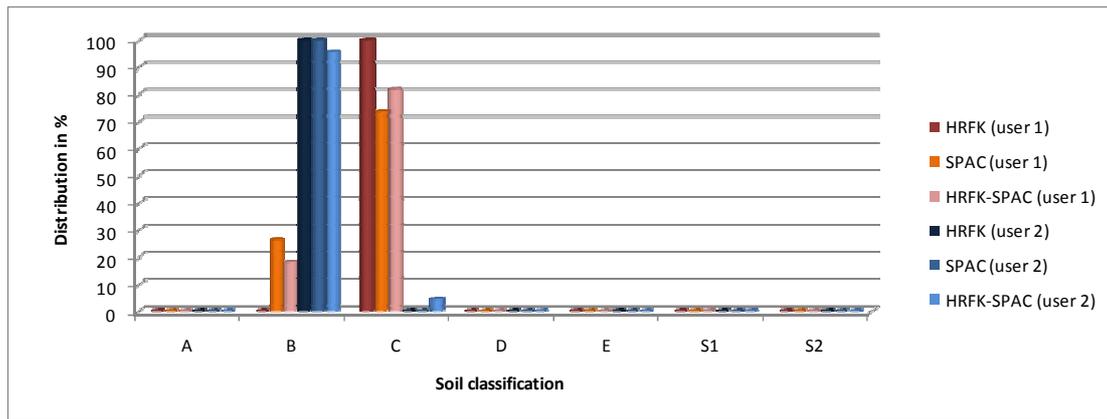
Figure 6: Distribution of the site classes determined mainly from the results shown in Figure 5.

These two examples show that a general rule cannot be given for the robustness of the array ambient vibration analysis to attribute the class at a given site. Although the rough value of Vs30 and the site class given by the software may be of interest for engineers, it is recommended to check the robustness of the results with available site information before providing any recommendations.

Moreover, it would be also useful to have the possibility to compute not only average shear wave velocity down to 30 m (Vs30), but also the average shear wave velocity down to a depth defined by the user (for instance Vs5, Vs10, Vs20 to the bedrock, etc.).

7.   *Concluding remarks*

The field measurements have the advantage of being of easy implementation on the field. The versatility of the method that allows the use of pre-existing acquisition systems and equipment, the use of 'natural' noise sources, the versatility of layout and the comparatively less time and energy spent contribute to make Geopsy a user friendly, effective and low cost tool. Real time communication with the acquisition system implies an additional cost, but the advantages concerning the quality control and the time spent to perform the experimental acquisition are a benefit. Disadvantages at the field are not found if compared with traditional methods.

The Geopsy package is a powerful tool that accepts several file formats (avoiding format conversions) and has several pre-processing tools, allowing all the processing steps to be done within the same software. Minor difficulties maybe rose when the computer has limited performances. Clear directives about the minimum acceptable computer capabilities (memory and processor) must be furnished. The computation of surface wave dispersion curves, using f-k or MSPAC techniques implemented in Geopsy, is easy to handle. However, some difficulties in the identification of higher modes may arise in some cases.

In such cases, users who have not so much experience do not have any guidelines or at least information on how to deal with higher modes.

The inversion of surface wave dispersion curves to determine the shear-wave velocity profile at the site under study is the most problematic part of the processing. Clear directives on the inversion strategy must be provided to help the user (three or four initial parameterizations must be available: uniform layers over half-space, linear increase over half-space, etc). The most delicate part is the selection of the best profile. Whatever the objectives for the ambient vibration array analysis – site characterization for national networks or engineering purposes – the user always face the same problem: which soil profile should be derived from the inversion? It would be very useful to provide a strategy to define a best mean soil profile with a standard deviation (minimum and maximum curves) that covers the physical acceptable uncertainties. If no strategy is proposed, there is a danger that the user takes only the Vs profile with the minimum misfit without any further considerations.

As a general remark, because the ambient vibration array techniques are not suitable for inhomogeneous environments at the array scale, specific information on this purpose should be given to the user prior to the processing. This should be perhaps clarified in the online documentation (GeopsyWiki) or a warning should pop-up when launching f-k or MSPAC toolboxes.

Finally, The Geopsy and Dinver packages are valuable tools for engineers. They provide a rough estimate of the site conditions (bedrock depth, Vs30 and site class). However, it is strongly recommended to use all available information on the site conditions to constraint and validate the results. The attribution of a site class can not be performed from the sole array processing without any further check. If so, one has to be aware that this is only a rough estimation.

It is worth concluding by emphasizing that the Geopsy package is a very powerful tool and very helpful if properly used. It should be very useful, and recommended, to attend a training course. Also, users are strongly encouraged to refer to the documentation available on GeopsWiki before and during the processing.

8.   References

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