SigProce: A computer program for signal processing, evaluation of seismic response in sites and buildings, and other engineering purposes

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Abstract

A computer program "SigProce" (Signal Processing) has been designed to evaluate seismic response in sites and buildings by multiple techniques, such as the H/V method and the reference site method, in simple, easy and efficient manner. The program has been written using Fortran language for Windows XP with Microsoft Developer Studio. It allows applying many methods of signal processing. So, programming these methods provides us a useful tool in application and education domains. The processing methods which can be applied are: calibration, shifting and trending correction, decimation, delete an interval, data windowing, integration and differentiation, signal rotation, filtering, convolution/deconvolution, correlation, and smoothing. Furthermore, the program has many graphical outputs for signals, spectra, spectral ratio, particle ground motion, polarigram and others.

Keywords: Signal processing, Seismic response, Earthquake engineering.

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SigProce: برنامج حاسوبي لمعالجة الإشارة الزلزالية وتقدير الاستجابة الزلزالية في المواقع والأبنية وأهداف هندسية أخرى

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الملخص

أُعدَّ البرنامج الحاسوبي (SigProce) لتقدير الاستجابة الزلزالية في المواقـع والأبنيــة باسـتخدام تقنيات متعددة مثل طريقة النسبة الطيفية والموقع المرجع وغيرهما بطريقــة بـسيطة ســهلة وفعَّالــة. استخدمت في إعداد هذا البرنــامج لغــة الفــورتران 90 وبيئــة التطــوير (Microsoft Developer Studio) بحيث يكون متوافقاً مع نظام التشغيل (Windows XP). يسمح هذا البرنامج بتطبيق العديـد من طرائق معالجة الإشارة، مما يجعله أداة مفيدة في المجالات التطبيقية والتعليمية. يمكن تطبيق طرائـق المعالجة الآتية: المعايرة، تصحيح الإزاحة والميل، إعادة التقطيع، حذف جزء مــن الإشـارة، الاشـتقاق والتكامل، تدوير مركبات التسجيل، التصفية، الثني والتـصفية العكـسية، الارتبــاط الـذاتي والمتـصالب والصقل. فضلاً عن ذلك، يسمح البرنامج بالحصول على نتائج المعالجة بيانيـاً ورقميــاً، مثـل الإشـارة، الأطياف، النسبة الطيفية، مساقط الحركة الجزيئية لسطح الأرض، عرض البولاري -غرام وغيرها.

الكلمات المفتاحية: معالجة الإشارة، الاستجابة الزلزالية، الهندسة الزلزالية.

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Introduction

It is well known and widely accepted that the effects of surface geology on seismic motion exist and can be large. The earthquake damage is generally larger over soft sediments than on firm bedrock outcrops (Aki, 1988, Sanchez-Sesma *et al.,* 1993, Haile *et al.,* 1997). This is particularly important, because most of urban settlements have occurred along river valleys. Over such young and soft surface deposits, a phenomenon of site effect is taking place (King and Tucker, 1984, Malagnini *et al.,* 1996). Ground-shaking site effect caused by an earthquake can vary significantly within a small distance (USGS, 2000). This is because at sites having soft soil and/or topographic and basement undulations, seismic energy gets trapped, leading to amplification of vibration to man-made structures (Navarro and Oliveira, 2006). Man-made structures with resonance frequency matching that of the site have the maximum likelihood of getting damaged (Navarro and Oliveira, 2006). Therefore, information about the site response is an integral part of the construction of seismically-safe structures and urban planning. One of the well known examples of such effects is Mexico City (Kramer, 1996). In Mexico City, there exist very soft clay deposits underneath the downtown area of the city. These led to very large amplifications which caused loss of life and structural damages during the distant Gurrero Michoacan earthquake of 1985 (Kramer, 1996). Site effects associated with local geological conditions constitute an important part of any seismic hazard assessment (Navarro and Oliveira, 2006). Many examples of catastrophic consequences of earthquakes have demonstrated the importance of reliable analyses procedures and techniques in earthquake hazard assessment and in earthquake risk mitigation strategies.

Detailed assessment of the site effects and the predominant frequencies on which significant amplification occurs can be obtained using empirical or analytical techniques, where many techniques have been proposed (Kudo, 1995). The main objective of this paper is, therefore, to develop a computer program for data analysis to allow performing the site effect assessment using multiple techniques. The program "SigProce" has been designed for signal processing, evaluation of seismic response in sites and buildings, and other engineering purposes.

General design of "SigProce"

"SigProce" has been developed in Fortran using Microsoft Developer Studio to provide a user-friendly graphical interface. The software operates in Windows environments where the minimum requirements are Windows 98, 128MB RAM (suggested configuration: Windows XP, 256MB RAM). The most basic functions on waveforms and the graphical representation of data are implemented. The program shows the repeated tests in separated windows (Figure 1) and the results can be saved in a text format file. Some of the Fortran subroutines have been written according to the "Numerical Recipes" (Press *et al.,* 1992). The main functionalities are integrated through a graphical user interface. There are basically four main modules: input data, signal preprocessing, main signal processing and post-processing. The user is guided through the dialogues boxes (i.e. graphical user interface, GUI) of the software to the input data selection, the signal preprocessing, the window selection, the processing and computation of the spectra, and spectral ratios. The display of the processing results has been designed to be visualized in proper windows in an easy and flexible way. These facilities are boosted up to make many manipulations such as filtering and to visually compare between their results.
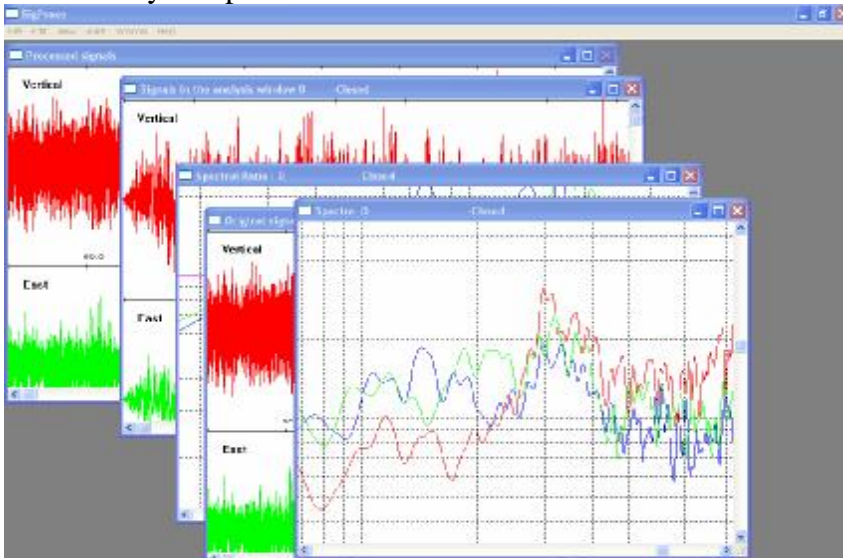

Figure 1: The graphical user interface of "SigProce".

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The flow-chart of the "SigProce" software has been shown in Figure 2. The general configuration parameter settings are included as default values for different options of the software. The user has to check the default values, and (if not satisfied) he is then requested to change them with the desired values. Once the appropriate parameter values are chosen, they will be applied in the remaining computations. In the present version four waveform file formats are supported: zen (3 components ASCII Format), ufa (Universal File Format), sac (ASCII SAC Format), and CSV (Canmet file in the comma separated values file format). So, the extension of the input data file names is required to be one of these words (zen, ufa, sac-asc or cma).
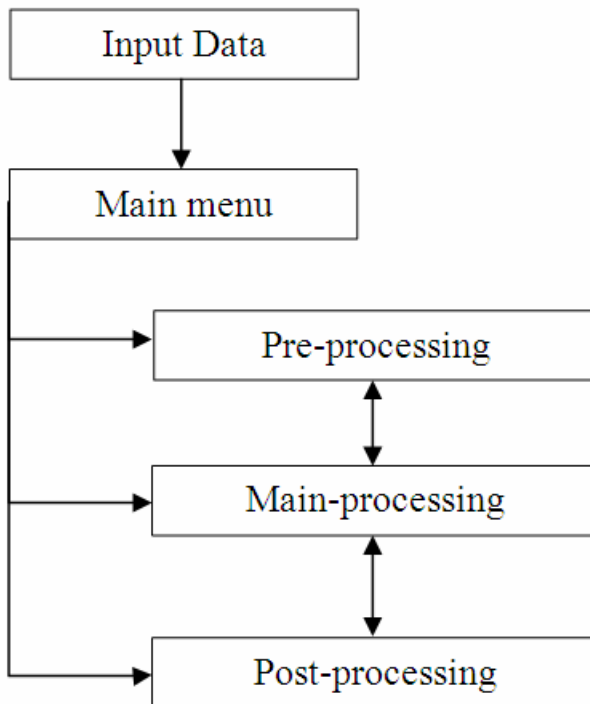

Figure 2: Flowchart of the basic structure of the software "SigProce".

After opening the input data file, the three components of waveform then are plotted for manual inspection. A message box shows some information about the record such as: station name, date and time of the record, record duration, sample rate (points/sec), type of record, amplitude unit, maximum frequency, minimum frequency and the maximum amplitude on the three components. Red color is used to represent the vertical component and all its graphical results. Green color is used to represent the EW component and all its graphical results, while the NS component and all its graphical results are represented using the blue color. The user can get all graphical windows by clicking the item menu <Edit> then "Select" and "Copy".

After the visual inspection, user can select an operation either "signal pre-processing" or "main processing and graphical output" or "plot and process previous results" using the main menu box. When the operation "main processing and graphical output" is selected, the user has to manually select a time-windows. The selected window is then processed to calculate spectra and spectral ratios as well as other options. The different outputs are displayed through a series of windows (Figure 1).

Pre-processing operations

The software "SigProce" provides in Pre-processing module a series of options for baseline processing and filtering of ground motion time series (Figure 3). Some of these options are suggested by Boore during his extensive research on ground motion data processing (Boore, 2005) and can be found in the references (Trifunac 2001) and (Kailath, 1985). Pre-processing operations allow to do the basic seismic waveform analysis and to improve the recorded signal through DC-offset removal, filtering, smoothing,…etc. The functionalities of the pre-processing module are cited below with their essential application goals:

- Calibration: to adjust the digital record unit (counts) into a physical unit such as accelerations or velocities.
- Shift correction: to remove the DC-offset and correct baseline.
- Trend correction: to remove linear trends by linear regression.
- Decimation: to reduce sampling rate if needed.

- Delete an interval: to remove spikes or transient noise.
- Data windowing (tapering): to reduce the effect of sharp cut at both temporal window edges.
- Signal integration or differentiation: to convert the signal into accelerations or velocities.
- Signal rotation: to redirect the three components of record.
- Filtering: to remove unwanted frequency components using Butterworth filters.
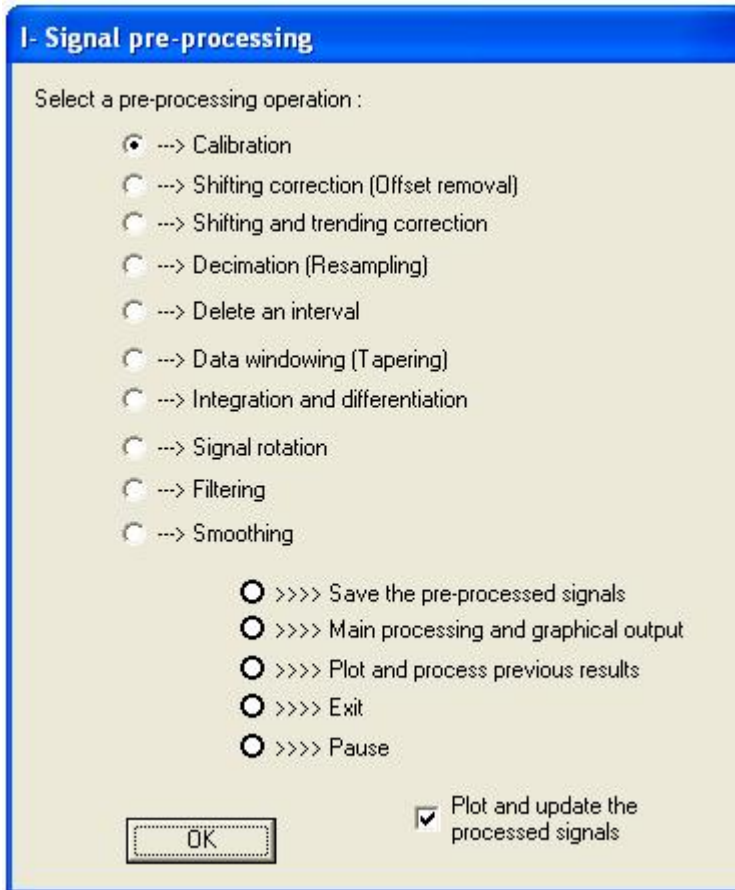- Smoothing: to reduce the effect of noise.

I- Signal pre-processing

Select a pre-processing operation :

- ⦿ ---> Calibration
- ○ ---> Shifting correction (Offset removal)
- ○ ---> Shifting and trending correction
- ○ ---> Decimation (Resampling)
- ○ ---> Delete an interval
- ○ ---> Data windowing (Tapering)
- ○ ---> Integration and differentiation
- ○ ---> Signal rotation
- ○ ---> Filtering
- ○ ---> Smoothing

  - ○ >>>> Save the pre-processed signals
  - ○ >>>> Main processing and graphical output
  - ○ >>>> Plot and process previous results
  - ○ >>>> Exit
  - ○ >>>> Pause

☑ Plot and update the processed signals

[OK]

Figure 3: The pre-processing dialogue box in "SigProce".

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In case of transients, or other existing problems in the data such as spikes, there are filtering options (Figure 4), where the user can apply either low-pass, high-pass or band-pass filter using Butterworth filters which can be recursive or non-recursive. Filter parameters are optional and can be changed. The filtered traces are then displayed in new window "Pre-processed signals". This window is updated for each further preprocessing operations. In the pre-processing module, a visual comparison can be made between the preprocessed and the original signals windows, for example, between filtered and unfiltered trace. The user can save the pre-processed signals in a new file for further processing or continue through the "Main-processing" module. The smoothing operation, mentioned above, can be applied either on signals in time domain or on spectra in frequency domain. Several functions of smoothing, commonly used in seismology, can be applied in "SigProce" (Figure 5). The user can easily test the smoothing functions and choose graphically the adequate function (Figure 6).
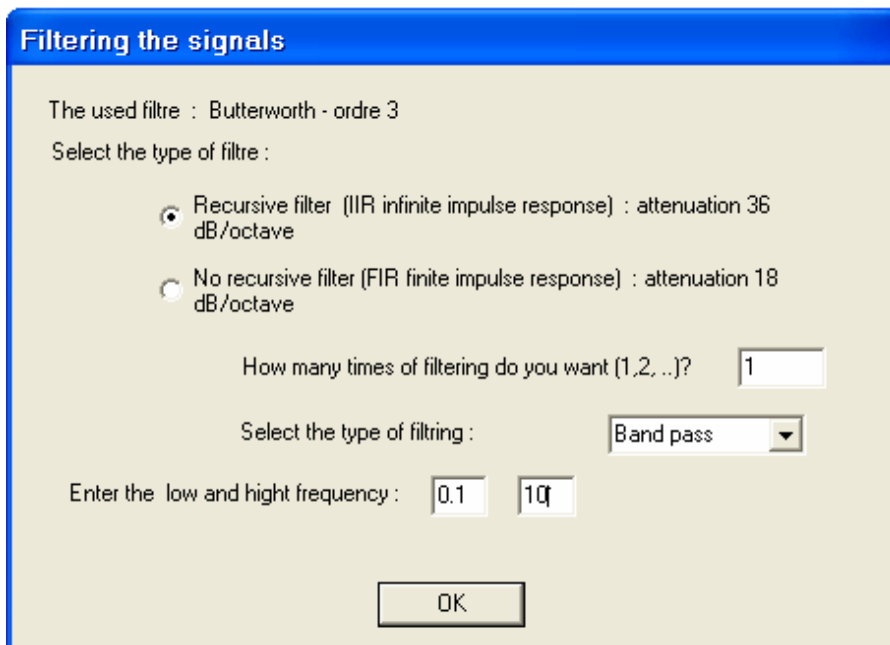

Figure 4: The filtering dialogue box in "SigProce".

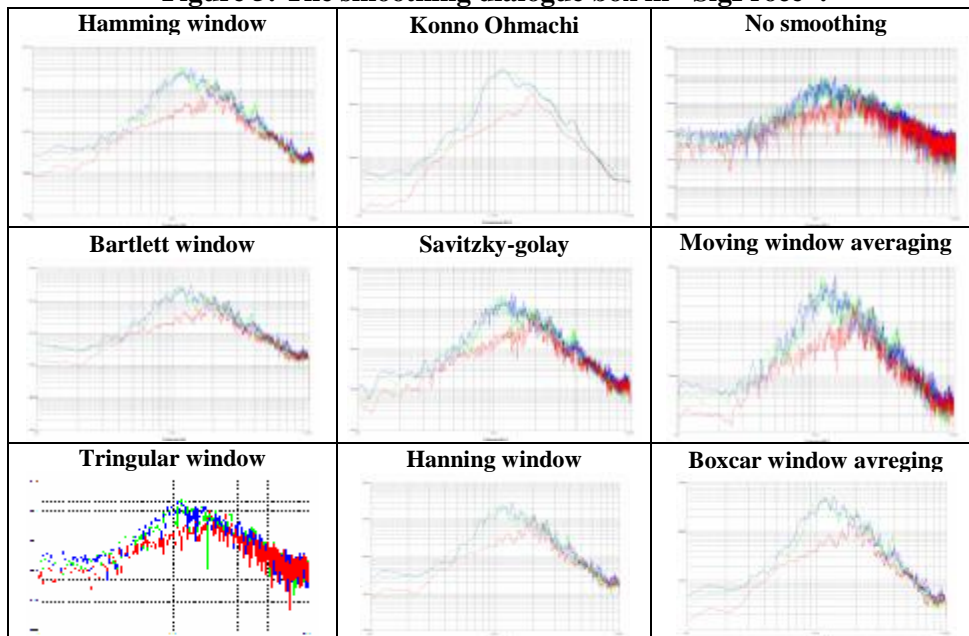**Figure 5: The smoothing dialogue box in "SigProce".**

Figure 6: A comparison between the results of applying several smoothing methods.

Main processing

This module requires selecting a limited time window (Figure 7) using some criteria. For example, in Nakamura (1989) method, the criteria is to keep the most stationery parts of noise and to avoid the transients often associated with specific sources (pedestrians, close traffic, etc.). The time window is used to study a selected portion of the signal and to investigate time variations such as the frequency content. A cosine tapering with a length of 5% will be applied on both sides of the selected time Window.
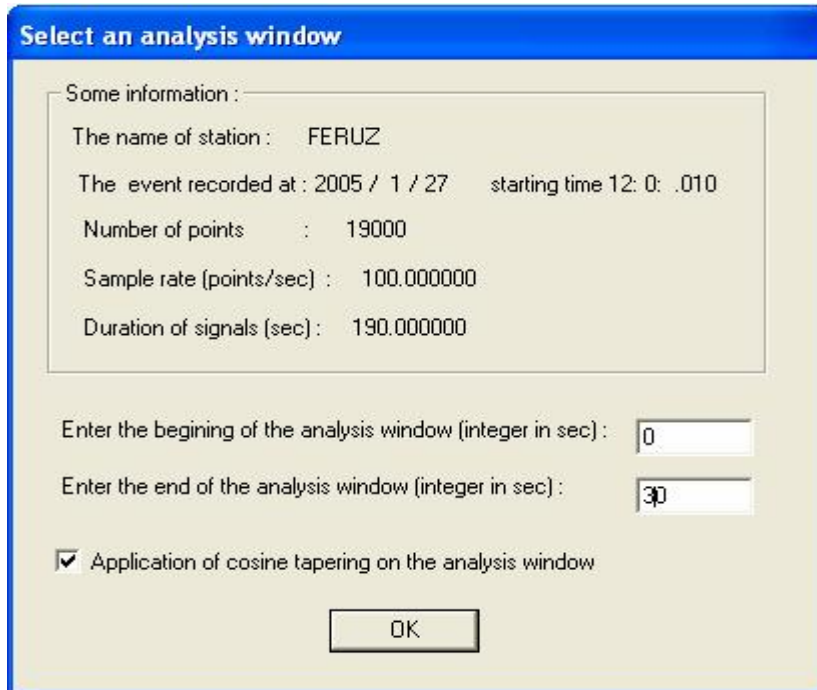
Figure 7: The "Select an analysis window" dialogue box in "SigProce".

The main processing operations (Figure 8) conduct many computations such as H/V spectral ratio and the other associated processing such as smoothing, merging of horizontal components, etc., on the selected time windows. The results of each process are plotted separately in proper window framework and can be saved in text output file or copied as an image. The window frameworks are

numerated to distinct between repeated processing operations. The functionalities of the main processing module are cited below:

- Plotting signals in the selected time window.
- Calculate the spectra using Fast Fourier Transform and plot the smoothed spectra on normal or logarithmic scale.
- Calculate and plot the spectral ratios (H/V) by Nakamura (1989) method (Microtremor Spectral Ratios).
- Calculate and plot the spectral ratios (H/V) by reference site method (Standard Spectral Ratios).
- Calculate and plot the spectral energy per mass unit.
- Calculate and plot the response spectra.
- Plot the square of ground motion amplitude.
- Plot the projection of ground motion (Particle motion viewer).
- Plot the Polarigram (Particle motion viewer). The Polarigram can be used to determine the polarization direction of particle ground motion (Bouin, 1994).
- Calculate and plot the convolution/deconvolution of signals with a given response.
- Calculate and plot the correlation of signals (Auto-correlation and Cross-correlation).The Auto-correlation of ambient noise can be used in the building seismic response assessment (Safak, 2007).
- Calculate and plot the polarization analysis of the three components records.

Regarding the principal goal of this paper, a brief description of two methods which are now universally used in the assessment of the site effect, is done below.

Microtremor spectral ratios

Among the empirical techniques, the H/V spectral ratio of the ambient vibrations (microtremors) has been widely used in microzonation studies due to its cost-effective nature (Bard, 1998, Stephenson, 2003, Bonnefoy-Claudet, 2004). Microtremors, also called ambient/cultural/seismic noise, are short-period vibrations that result from wind-structure interaction, traffic, trains, construction, factories, etc. (Field *et al.,* 1990, Bard *et al.,* 2004). To estimate the local amplification factor of seismic waves it is prevalent to use the H/V-Method according to Nakamura (Nakamura, 1989) due to the fact that it is a very simple and user-friendly practice. The method is convenient for almost every region in the world, because it was successfully accomplished in countries with moderate seismicity

where no strong motion data was available. Therefore, the input for the H/V-computation can also consist of transient or even ambient excited signals. Nevertheless, in case of the amplification factor it is more beneficial to use ambient excitation, because the large number of samples which are needed for statistical evaluation would, in case of transient excitation, lead to unacceptable disruption for occupants.

The ambient vibration technology for seismic microzonation was effectively applied in former projects, see e.g. the SESAME-project (SESAME European research project, 2004). With the Nakamura method the following local soil parameters can be defined:
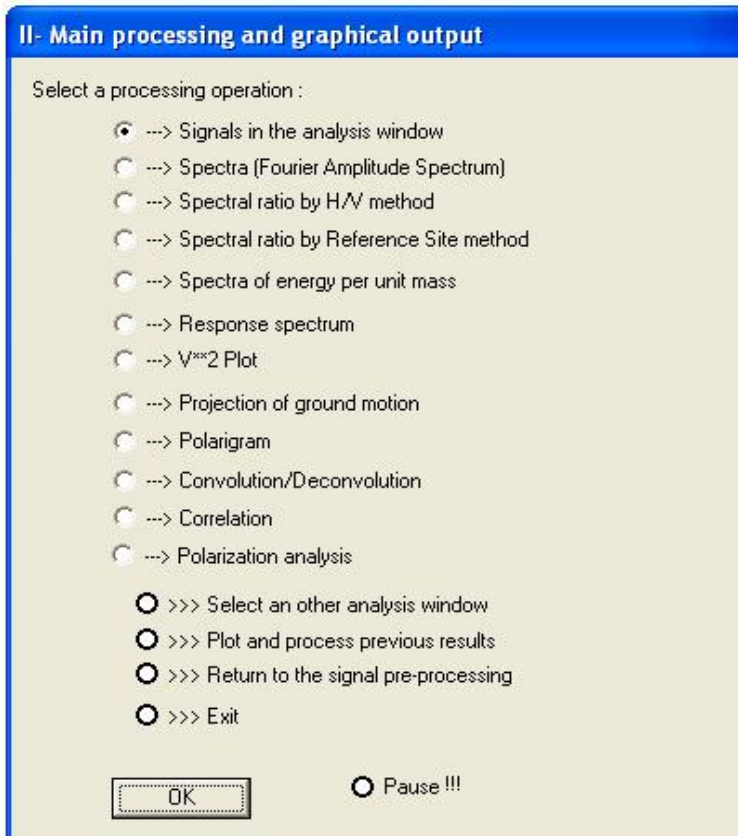- Basic natural frequency of the subsoil.
- Amplification factor.

Figure 8: The "Main processing" dialogue box in "SigProce".

Standard spectral ratios

This method compares the seismic activity recorded simultaneously on a rocky reference and on sedimentary sites (Lanston, 1984, Malagnini *et al.,* 1996, Moya *et al.,* 2000). In theory, the signal recorded on the rocky reference is supposed not to be affected by the subsurface geology and is the same one arriving from the deep bedrock (Borcherdt, 1970). The site to bedrock spectral ratio gives a good assessment of the transfer function, then of the site response in the spectral domain, if background noise remains negligible with regard to the signal on the site and on the reference (Bard and Thomas, 2000).

The standard spectral ratios are computed by dividing the site Fourier spectra by the reference bedrock Fourier spectrum of an earthquake (Borcherdt, 1970). The method is applicable if the distances between sites and the reference are small compared to the distance to the earthquake epicenter, such that source and travel path effects between sites are common (Bard and Thomas, 2000). The standard spectral ratios method has two major inconveniences: need a rocky reference and waiting for a seismic event to occur (Steidl *et al.,* 1996). The record must be consequent of good signal-to-noise ratio which may be difficult if the level of the background noise is important. However, the Nakamura's technique uses the microtremors and does not need any rocky reference (Field *et al.,* 1990, Bard *et al.,* 2004). Steidl et al. (1996) pointed out that the choice of the reference site might be critical, since rock sites might have their own site response.

Post-Processing

This module allows plotting previous results which is important to compare with the results of an actual opened waveform file. The output of the data main-processing in n-windows can be accumulated and saved in one text output file. This file is required in the post-processing module. Some of the previous results, such as spectra and spectral ratios, can be statistically processed. The saved results can be averaged over the number of windows in order to consider the experimental and numerical uncertainties. The statistical standard deviation can be calculated and finally the averaged H/V-Ratio can be

calculated and displayed. The functionalities of the post-processing module are cited below (Figure 9) and detailed in the case study:

- Plot the spectra of Fast Fourier Transform on logarithmic scale. Calculate and plot the spectral ratios (H/V) by Nakamura (1989) method (Microtremor Spectral Ratios)
- Plot the spectral ratios (H/V) by Nakamura (1989) method (Microtremor Spectral Ratios) for all directions, or for one direction. Calculate merging of horizontal components, the average spectral ratio and the standard deviation.
- Plot the spectral ratios (H/V) by reference site method (Standard Spectral Ratios) for all directions, or for one direction. Calculate merging of horizontal components, the average spectral ratio and the standard deviation.
- Plot the spectral energy per mass unit.
- Plot the response spectra.
- Plot the convolution/deconvolution of signals.
- Plot the correlation of signals (Auto-correlation and Cross-correlation).
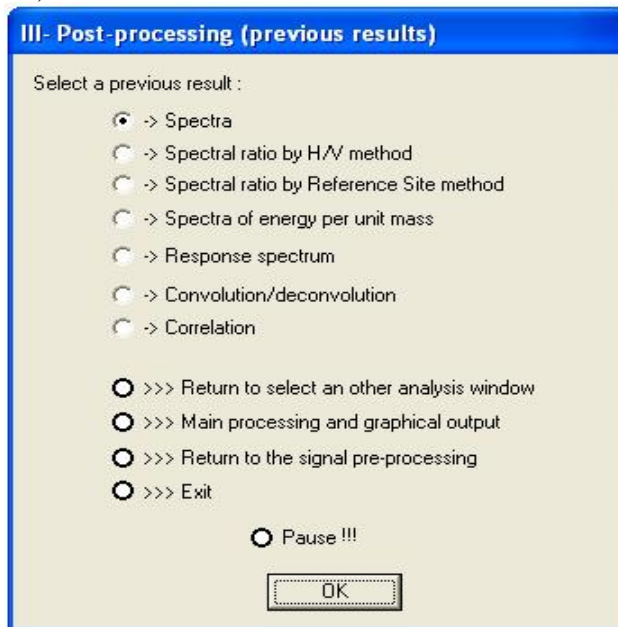

Figure 9: The "Post-processing" dialogue box in "SigProce".

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Case study

Before using "SigProce" in real applications, it has been tested on several types of data: synthetic signals, micro-earthquakes records and the ambient vibrations (micro-tremors) measurements. Let us examine some of the main features of "SigProce" in a practical example. We will consider the case of ambient vibrations measurements realized in Aqaba city (Jordan) during the RELEMR meeting (2004). This meeting, organized by UNESCO & USGS, was essentially concentrated on "Site Response and Building Response". The measurements of Aqaba have been chosen as "a case study" because they have published in final scientific report of specialist meeting (RELEMR, 2004) and in the paper of (Al-Qaryouti and Al-Tarazi, 2007). In both works, the measurements were processed by "SEISPECT" software. This fact allows to compare the results of applying "SigProce" with other software.

In Aqaba city, the sediments sequence is relatively thick. The outcrops of sedimentary rocks of the area are of Quaternary age and consist mainly of alluvium, sand dunes, sandstones, clay, conglomerate and reef coastal deposits, and ancient dunes. The seismometers used are sensitive velocity transducers with a natural frequency of 1.0 Hz. All seismometers are wired directly to the recording site. Digital recordings with a sampling rate of 100 samples per second have been obtained using a 0.2–25 Hz band-pass filter. The micro-tremors measurements were made during the daytime, when the contaminating effects of traffic and industrial noise were significant.

The three-component seismometers were set up by the workshop participants in a large vacant lot adjacent to the Aqaba Gulf Hotel to measure site effects. The data were collected for 1.5 hours. Although the data collection time and analysis time during the workshop were insufficient to make a definitive determination, some of the data windows appear to show an amplification (site effect) of 2.5 at 1.5 Hz (RELEMR meeting 2004). The data files were converted into zen format, recognized by "SigProce", and made one file: 20040127-09231455.zen (Figure 10). A time window duration of 60 seconds has been selected according to the recommendations of European project: SESAME (Site EffectS assessement using Ambient Excitations (Atakan

et. al. 2003, 2004)) in order to detect all frequencies from 0.1 to 10 Hz. To fulfill the SESAME conditions, the minimum number of windows has to be at least 10 windows and the total recording duration has to be at least 30 minutes, 20 windows have been used to calculate Fourier spectra and spectral ratio. Figure 11 shows an example of individual Fourier spectra calculated in a time window started at 60s and ended at 120s from the Aqaba record. The spectra were smoothed using Haning method which was used in RELEMR meeting 2004 in order to compare the results of "SigProce" with those issued in the meeting. After spectra smoothing, and in order to obtain spectral ratios (Nakamura method), the spectra of an E-W and N-S channel were divided by the spectrum of the vertical channel (Figure 12).
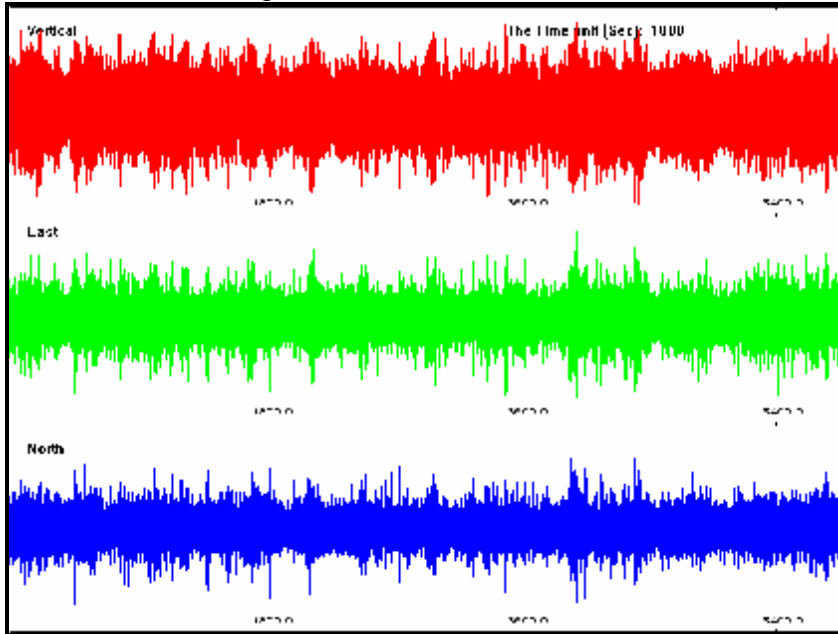
Figure 10: "SigProce" view of the three components record of microtremors measured in a large vacant lot adjacent to the Aqaba Gulf Hotel for 1.5 hours. The time unit is second. The three components are represented as: the vertical in red color, the east-west in light green color and the north-south in blue color.
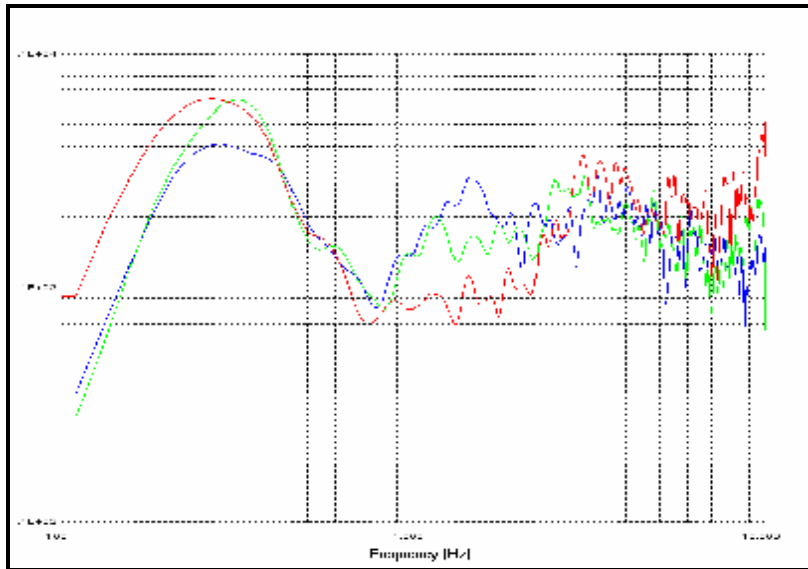
Figure 11: "SigProce" view of individual Fourier spectra of time window started at 60s and ended at 120s from the Aqaba record.
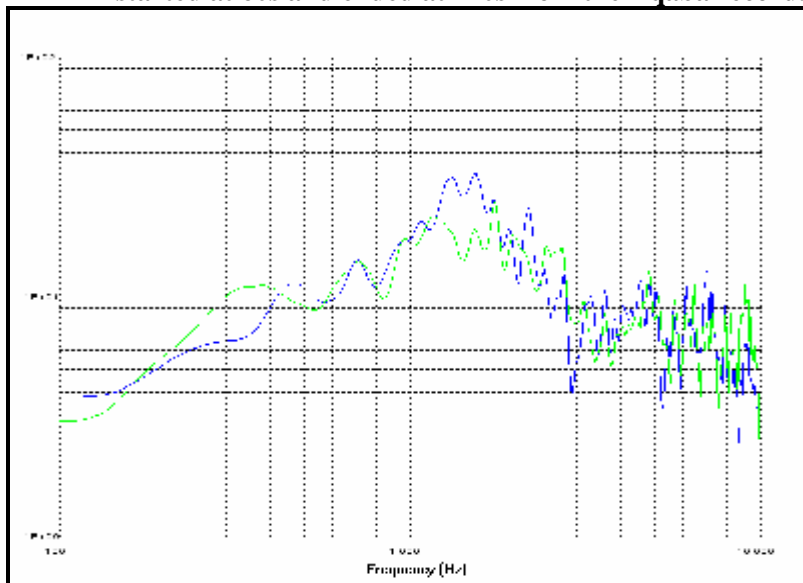

Figure 12: "SigProce" view of the horizontal-to-vertical spectral ratios of the directions: east-west in light green color and north-south in blue color.

The Procedure in "SigProce", which can be applied to compute the spectral ratios in the case of ambient vibrations (micro-tremors) measurements realized during the RELEMR meeting (2004), can be summarized in the following points:

Pre-Processing: The most important is to apply "shifting and trending correction".

Main-Processing: Hence the three different components of the signal were considered separately. The following operations of "Main-processing" can be repeated for every time window:

1. Selecting a time Window of the signal (in our case only the ambient parts are of interest, observe, in case of transient excitation only the transient parts of the time response are of interest). A cosine tapering with a length of 5% will be applied on both sides of the selected time Window.

2. Fast Fourier Transformation (FFT) is applied to obtain the spectral amplitudes of the three components.

3. Smoothing of the three spectral amplitudes with a bandwidth factor of 20 points.

4. Ploting the spectra on logarithmic or normal scale and save the spectra in an output text file, where the spectra of several windows can be accumulated together and saved in the same text file.

5. The spectral ratios are obtained by the division the spectra of an E-W and N-S channel by the spectrum of the vertical channel.

6. Ploting the spectral ratios on logarithmic scale and saving the spectral ratios in an output text file. The spectral ratios of several windows can be accumulated together and saved in the same text file.

Post-Processing: The output of the data main-processing of many time windows is accumulated and averaged over the number of these windows. In this case study, there are two possibilities: the accumulated spectra and the accumulated spectral ratios.

In the first case, after opening the output file of accumulated spectra (Figure 13), the average spectra are calculated for each component. Then, the spectral ratios are obtained by the division of the average spectrum of an E-W and the average spectrum of N-S channel by the average spectrum of the vertical channel (Figure 14).
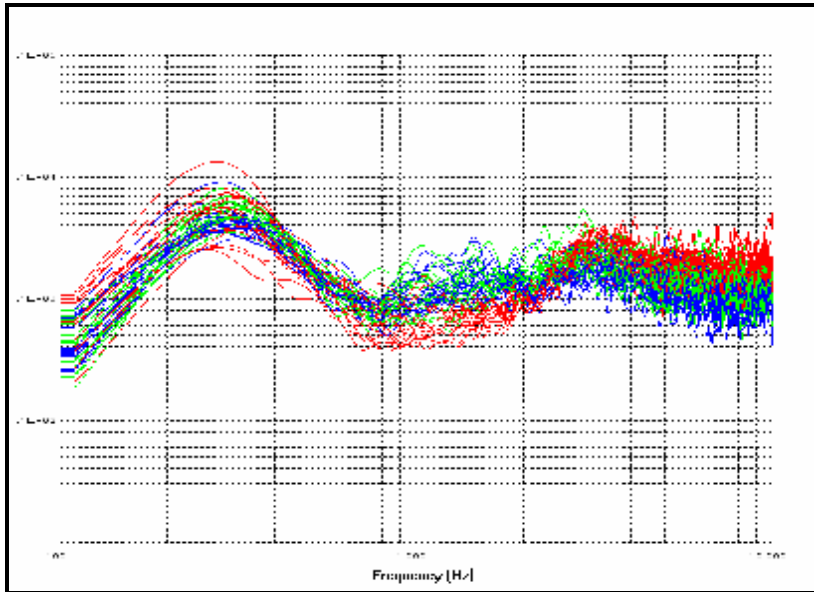
Figure 13: "SigProce" view of Fourier spectra calculated for 20 selected time windows of 60s from the Aqaba record.
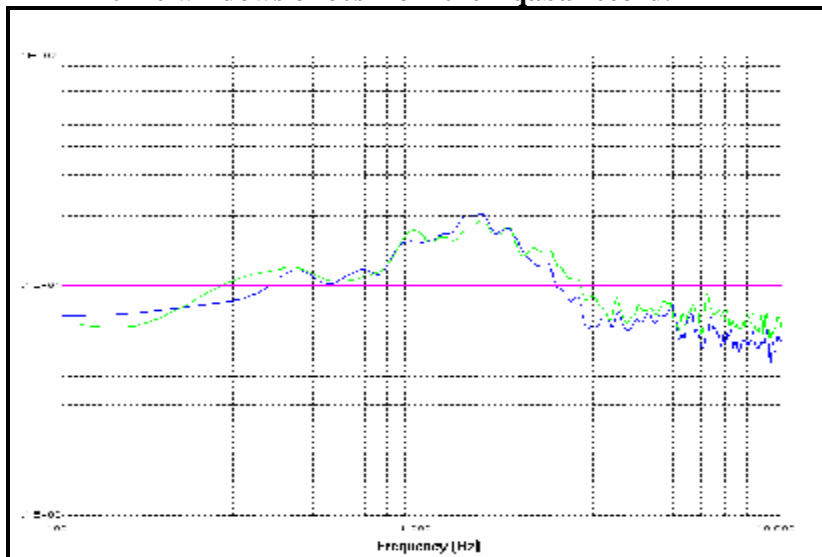

Figure 14: "SigProce" view of the average horizontal-to-vertical spectral ratios calculated from the average spectra of 20 selected time windows in the figure (13).

The second case is more sophisticated and several options are available:

- The two horizontal components can be separately considered in order to estimate the seismic response in function to direction (Figures 15 and 16). This option allows studying the directional response in some particular situation (e.g. some geological structures or buildings and manmade structures). "SigProce" calculates the average spectral ratio and the standard deviation for the selected horizontal component. The average spectral ratio in the North-South direction appears to show an amplification of 2.1 at 1.45 Hz. However, it shows an amplification of 1.9 at 1.46 Hz in the East-West direction. It is obvious that the seismic response is not directional in the case study of Aqaba. Therefore, the spectra of the North-South and East-West components can be merged into one horizontal spectrum in each time window.
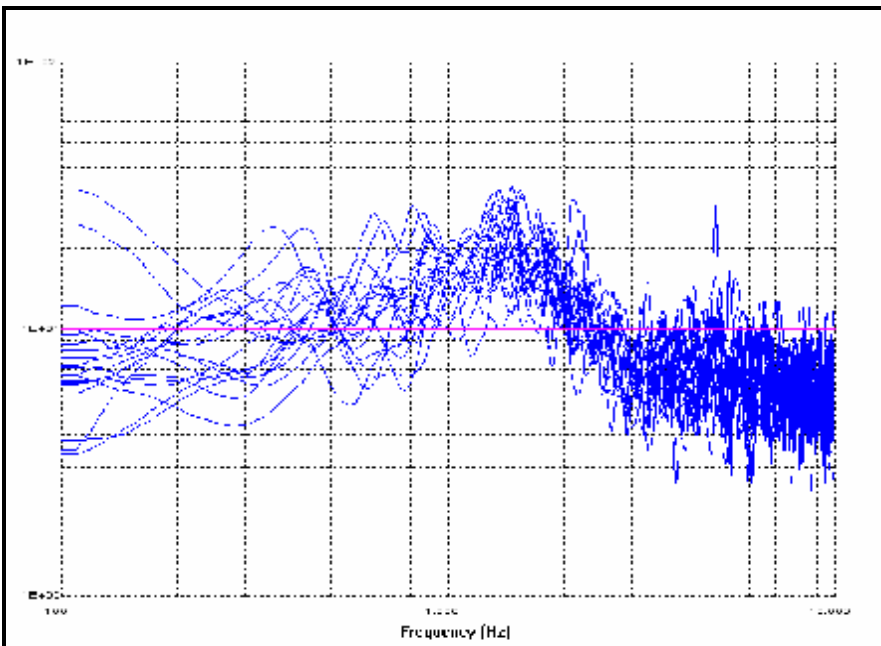

Figure 15: "SigProce" view of horizontal-to-vertical spectral ratios calculated for 20 selected time windows of 60s from the Aqaba record in north-south direction.
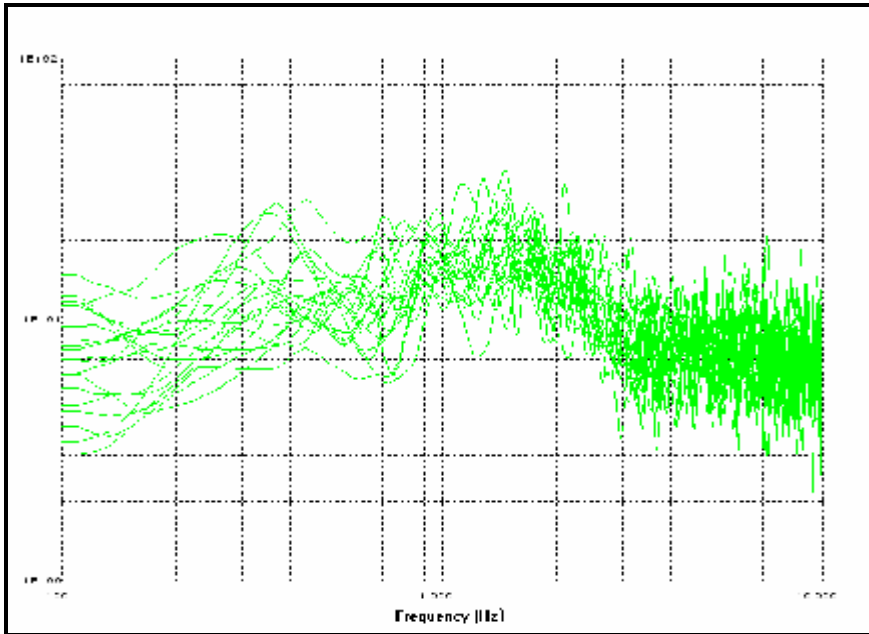
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Figure 16: "SigProce" view of horizontal-to-vertical spectral ratios calculated for 20 selected time windows of 60s from the Aqaba record in east-west direction.

- Afterwards the resulting horizontal component is evaluated on the quadratic average of the North-South and East-West components, the H/V-spectral ratio is calculated from the resulting horizontal component spectra and the vertical component spectrum in each window. The final spectral ratio is averaged on all time windows. To consider the experimental and numerical uncertainties, the statistical standard deviation is calculated. The user can display all spectral ratios with the average spectral ratio and the standard deviation (Figure 17), or only the average spectral ratio and the standard deviation (Figure 18).

The final result can be deduced from the average spectral ratio (Figure 18), which appear to show an amplification (site effect) of 2 at 1.5 Hz according to Nakamura method. This result is very close to the obtained result during the RELEMR meeting in 2004. Furthermore, similar results were found by (Al_Qaryouti and Al_Tarazi, 2007)

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when they have studied the site effect using ambient vibration measurements at Aqaba city. The use of "SigProce" program in real applications can be validated through comparison with the results of previous works (RELEMR, 2004, Al_Qaryouti and Al_Tarazi, 2007), where a good agreement can be found.
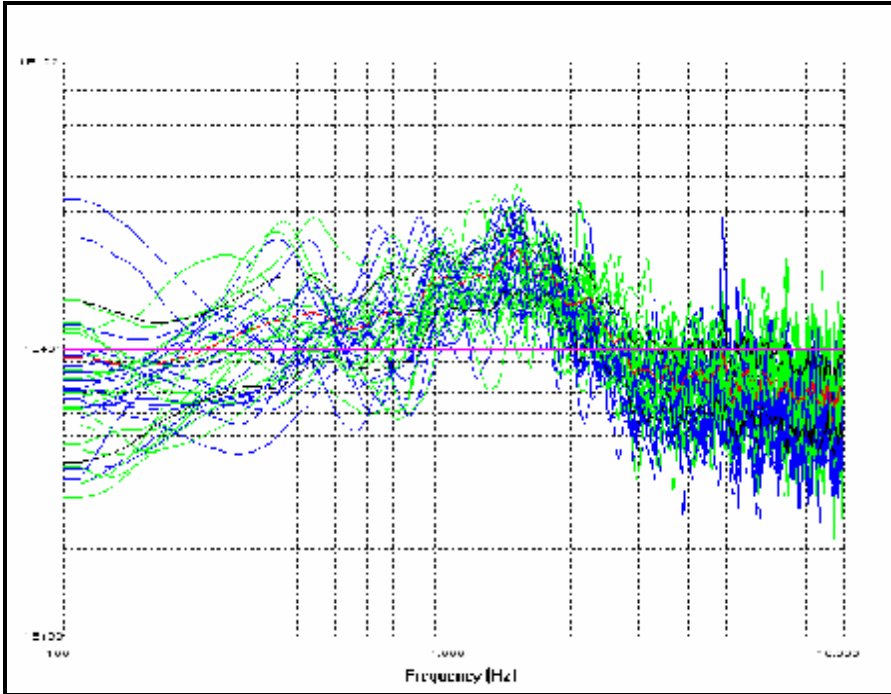

Figure 17: "SigProce" view of horizontal-to-vertical spectral ratios calculated for 20 selected time windows of 60s from the Aqaba record in east-west and north-south directions. The red curve represents the average spectral ratio after merging the two horizontal components of the 20 selected time windows.
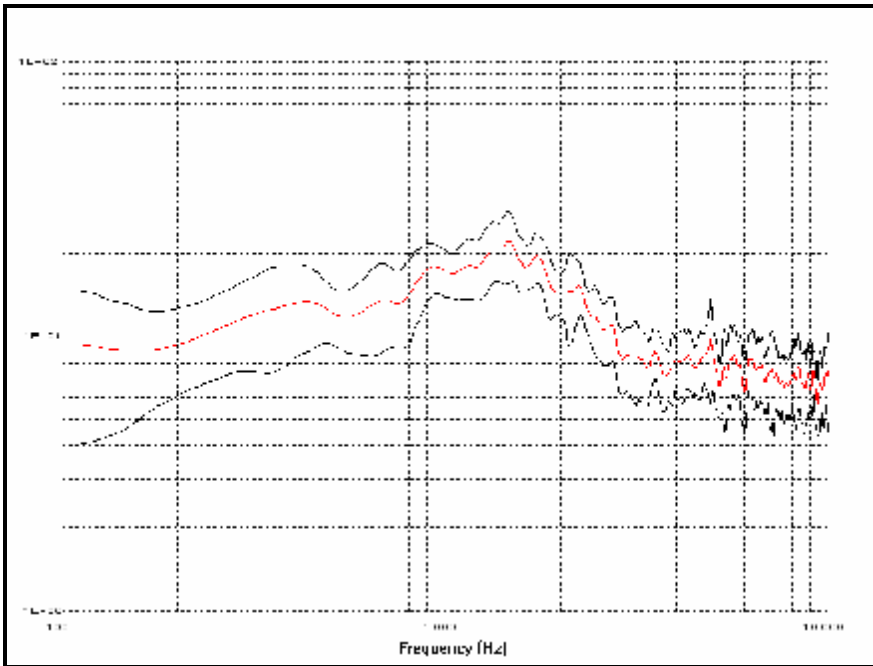
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Figure 18: "SigProce" view of the average spectral ratio after merging the two horizontal components of the 20 selected time windows (the red curve). The black curves represent the average spectral ratio + and – the standard deviation.

Conclusion

Although the program presented in this work does not perform particularly original or complex computations, we believe that it can be very useful to geophysical investigator and geotechnical engineers to process three components seismic measurements in order to estimate the seismic response. It can be very useful also to the students to manipulate several methods of signal processing. The "SigProce" software is self-contained very easy to use. So, we have not prepared a detailed write up or a user's guide. All functions are made easy by the visual context of the system.

The massive use of "SigProce" is to assess the seismic response in site and building through calculating spectra and spectral ratios. "SigProce" can be used for other engineering purpose, where many algorithms for the study of particle motion in 2D and 3D are implemented. The case study of Aqaba has allowed to validate the use of "SigProce" in the site effect assessment according to Nakamura method.

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