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Philosophiae Doctor

Surface Wave Analysis and Inversion Application to the Bohemian Massif

by

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Analýza a inverze povrchových vln
Aplikace na Český masiv

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Contents

Abstract

English version

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An overview of surface wave analysis methods as well as of inversion techniques is given. Special attention is paid to the multiple filtering method for dispersion curve estimation, which is described by two different ways in detail. The isometric method is used for dispersion curve inversion and its description and tests are presented.

Described methods are further used in applications. The applications show examples of surface wave analysis and inversion for 1D and 2D crustal structure. The analysis of Love waves generated by quarry blasts and measured at short epicentral distances from 5 to 50 km and their inversion for uppermost crustal structure down to a depth of 3 km is given with results benchmarked by the synthetic waveform computation. An example of 2D surface wave tomography based on Rayleigh waves for Western Bohemia region is given in comparison to previous studies of the area. Phase velocities measured across the Bohemian Massif using the records of Aegean Sea earthquakes are presented with their inversion for crust and upper mantle 1D shear wave velocity distribution. A new method for estimating the true backazimuths of surface wave propagation for different wavelengths is presented.

The methods used in applications are compiled in a software newly developed during the author's PhD studies. The interactive SVAL program is a universal tool for surface wave dispersion estimation in an arbitrary frequency band and also for dispersion curve inversion to 1D structure. All functions of the program are described; all handlers and tools for filtering the records and for inverting the dispersion curves are discussed; examples are given and instructions for use are added. Color screenshots of the SVAL program windows help to understand the program functionality better. All input and output files are described and examples of them are given. For phase velocity estimation based on the results of the SVAL program analysis, the PhaseCorr program was developed and it is also described with all the necessary tools for estimating phase velocities between two stations at the same seismic profile.

Abstrakt

česká verze

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V práci je podán přehled metod analýzy povrchových vln a také přehled řešení obrácených úloh. Zvláštní pozornost je věnována metodě mnohokanálové filtrace pro určování disperzních křivek. Tato metoda je detailně popsána dvěma různými způsoby. Pro inverzi disperzních křivek je používána isometrická metoda, jejíž popis a testy jsou v práci uvedeny.

Popsané metody jsou dále použity v aplikacích. Tyto aplikace podávají příklady analýzy povrchových vln a inverze na 1D a 2D strukturu kůry. Je ukázána analýza Loveových vln generovaných lomovými odpaly a měřených v krátkých epicentrálních vzdálenostech od 5 do 50 km. Je provedena jejich inverze na strukturu svrchní kůry do hloubky 3 km. Výsledky jsou ověřeny výpočtem syntetických vlnových obrazů. Je uveden příklad 2D tomografie západních Čech založené na Rayleighových vlnách a provedeno srovnání s předešlými výzkumy této oblasti. Ukázány jsou také fázové rychlosti měřené v Českém masivu na záznamech zemětřesení z Egejského moře a jejich inverze na 1D rozložení rychlostí střižných vln v kůře a svrchním plášti. Je také uvedena nová metoda pro určování skutečných směrů příchodů povrchových vln pro různé vlnové délky.

Metody použité v aplikacích jsou zpracovány do nově vyvinutých programů sestavených během autorova doktorského studia. Je popsán interaktivní program SVAL, což je všestranný nástroj pro určování disperze povrchových vln v libovolném frekvenčním oboru a také pro inverzi disperzních křivek na 1D strukturu. Jsou popsány všechny funkce programu, všechna nastavení a nástroje pro filtraci záznamů a pro invertování disperzních křivek. Jsou uvedeny příklady a návod k použití. Barevné obrázky oken programu SVAL pomáhají lépe pochopit fungování programu. Jsou popsány všechny vstupní a výstupní soubory a uvedeny jejich příklady. Program PhaseCorr je sestaven pro určování fázových rychlostí. Pracuje s výsledky analýzy programu SVAL. Program PhaseCorr je také popsán se všemi potřebnými nástroji pro určování fázových rychlostí mezi dvěma stanicemi na jednom seismickém profilu.

Introduction

The abstract of the thesis follows the contents of the original work, keeping the numbering of chapters and sections according to the original thesis. Figures are taken from the thesis, their original numbering is given in respective captions. In this abstract, the original color figures are printed in black and white.

We give a short overview of three aspects of the thesis here in the *Introduction.* Section *Surface waves* gives a brief summary of the possible problems of surface wave analysis and inversion. Section *Motivation* contains the ideas and approaches to the work and section *Outline of the thesis* introduces the way how the thesis is built using the original papers, newly written parts, software and examples and how these elements are joined together to present compact work.

Surface waves

The fine deep internal structure of the Earth is often obtained from studies of seismic body waves. As opposed to that, surface waves can give us averaged information about the mean upper Earth structure between the source and our seismic stations, or between two or more seismic stations only. Presented thesis deals with surface wave structural seismology. All the theory, applications and software described in the thesis is particularly intended for the estimation of distribution of seismic velocities in the Earth crust and upper mantle. We present several methods of velocity distribution estimation from surface waves measurements, newly developed software and examples of applications. We use surface waves as a special tool for imaging the Earth interior.

As shown in the next chapters, we may find the surface waves of periods as long as hundreds of seconds and as short as 0.03 s ($\approx 30\,\mathrm{Hz}$). Estimating the dispersion of waves recorded at a distance of thousands of kilometers and using broadband instruments, we usually find the waves of periods as long as 200 s. From the records obtained by short-period geophones during shallow seismic refraction survey, we are able to detect surface waves in the range of 0.03 to 0.2 s. And there is no doubt that if we recorded high frequency records in the laboratory experiments, we would find surface waves of wavelengths even shorter.

The amplitudes of surface waves are diverse as well. Looking at the records of shallow Greek earthquakes at the distance of 1500 km, we see the surface waves to be of amplitudes much higher then the body waves at the first glance. Great epicentral distance, longer paths of body waves, higher attenuation of shorter frequencies and a good opportunity for surface waves to evolve, result in their dominance in the records. However, analyzing some of the records from quarry blasts, we do not see any surface waves at all. Close epicentral distance, high frequency content, small magnitude of the source, not enough time for waves to interfere and create the surface waves, complicated uppermost crust structure resulting in many reflections and conversions will make the records full of body waves. But it does not mean the surface waves disappear somewhere. They are in the records and using a proper technique, they may be found, their dispersion may be estimated and the velocity structure of their paths revealed.

We do not want to present the entire description of the surface waves theory here, but one thing to be kept in mind whenever talking about this phenomenon should be mentioned. Surface waves may be considered by two – at the first sight – completely different approaches. The first one considers the surface waves and their modes to be a result of interference of traveling waves, the second one regards the surface waves as a higher-frequency approximation of standing waves – the Earth normal modes. These approaches are, of course, valid also for body waves, but dealing with surface waves we are close to the opportunity to use both approaches together. Usually, when talking about surface waves, we do not specify which approach we use. And – of course – we use both approaches at the same time. When talking about higher modes of surface waves, we may have both the interference theory of superposition of body waves to let the higher modes evolve, or the finite proportions of the globe to explain the surface wave modes as higher modes of the free oscillations.

Surface waves are, as a complex phenomenon, influenced by many physical properties of the medium which they propagate through. The heterogeneity in vertical direction and the free surface are responsible for the dispersion of surface waves. The heterogeneity in horizontal direction is responsible for bending of the paths of the waves and for the occurrence of Love and Rayleigh waves on both radial and transverse components. Surface wave focus and defocus and their amplitudes are strongly influenced by heterogeneity along their paths. Anisotropy causes that both Love and Rayleigh waves are found at all three components of a record. It is also responsible for sometimes striking discrepancies between the velocities of Rayleigh waves measured at vertical and radial components. Joint inversion of both Love and Rayleigh waves in isotropic medium is usually impossible. Surface waves also reflect from sharp vertical discontinuities, they refract along faults and suture zones. Properties of waveforms are strongly influenced while the surface waves cross the oceanic/continental boundary. They interfere among themselves, they convert from one type to the other. Different wavelengths of the waves are sensitive not only to different depths, but also to different lateral extent – we talk about influence zones of the surface waves for given period. To distinguish between fundamental and higher mode is sometimes hard work and to estimate the number of higher modes is usually even impossible.

All these complexities of surface waves has lead to developing of many techniques of their measurement, analysis and inversion. The basic approach to measure surface waves is to look at records in the frequency and time domains at the same time. We have several techniques of frequency-time analysis, we may filter the records in time or frequency domain, we may use wavelet transforms, distributions and other techniques. Some of them have better resolution than others, but are more costly when using computers, some of them are more intuitive for use, some of them are outdated, but good for explaining the basic properties of the analysis. Using the frequency-time analysis, we always fight the uncertainty principle and we deal with all the problems of signal sampling, filtration, smoothing and truncating.

When inverting the information obtained by surface wave analysis, we have the possibility to make an inversion of the dispersion curve for 1D velocity distribution with depth, or to use the approaches of surface wave tomography to get 2D images for certain periods of surface waves in the target region. The final step is the three-stage approach, when artificially computed local dispersion curves are inverted for the 3D velocity distribution using 2D tomographic images for different wavelengths emerging as a result of 1D dispersion curve analysis.

Motivation

We would like to concentrate our effort to small datasets with detailed analysis and clear understanding of what had happened right in this record of the given event. We are limited by our station and computer equipment and our team dealing with surface waves is smaller compared to the foreign universities. We are not able to provide global or regional studies based on years of records from the stations from all over the world, which may seem to be a disadvantage disqualifying us from the latest trends. However, we try to keep the advantage of our research by providing detailed analysis of peculiar records from our stations with the aim to small scale research, short station distances and local events. We use reliable methods, broadband stations and we keep an eye on the latest proceedings in surface wave studies to help us concentrate the effort on problems which have not been solved yet.

The SVAL program, described in this thesis, is intended to process the data record by record with interactive analyst intervention. There is also an option to process the data automatically. However, we are aware of the limits of automatic processing and we do not produce the dispersion curves automatically, since for the dispersion curve compilation, the seismologist personal work is unavoidable. We use the automatic procedures only to estimate the propagation times of surface wavegroups with no assumption where is the ”right” dispersion curve. For simple envelope maxima arrival time estimating, the analyst work may be spared since the computer is able to do the job properly.

Another goal of the methods developed and described in the presented thesis is to process any records from any source. Studies dealing with a priori assumptions and providing automatic estimation of dispersion curves are properly working when we process the records which the assumptions were made for.

The goal during my PhD studies was to develop a universal tool to process any records from earthquakes of any epicentral distance, the records of any sampling frequency, of any period range and from any instrument. We aimed to develop a procedure which is easily adjustable for all the options we may encounter.

One of the main advantages of presented software is that we get rid of the very restrictive assumption that surface waves have the highest amplitudes in the records. We are able to find surface waves also in records where they have much smaller amplitudes than body waves. We need to analyze records of such a different origin as are the $M = 8.3$ Kuril Islands earthquake measured by STS2 instrument at the distance of 8.500 km and with sampling frequency of 10 Hz or quarry blasts with magnitude less then 0.0, measured by 1 Hz Lennartz geophone at the distance of 15 km with the sampling frequency of 250 Hz. And the natural way to be able to do this is – to have NO a priori assumptions concerning the results at all.

All the above mentioned problems, goals, challenges and implications have their sense only when used with interesting datasets to resolve the structure of some appealing region. In our case, this is the Bohemian Massif, geologically diverse area of Variscan age in Central Europe. Bohemian Massif as a whole, or its parts such as the Western Bohemia region, have been of special interest of geologists and geophysicist for decades. Also surface wave measurements across the Bohemian Massif were provided in the past, but currently no systematic effort to study Bohemian Massif by surface waves is pursued. More than 20 permanent broadband stations are deployed in the Czech Republic and hence the opportunities for group velocity measurements and relative phase velocity estimation from regional and teleseismic events as well as smaller area investigation using quarry blasts are abundant. Surface wave measurements and studies can complement well the ongoing effort to understand the area's Earth crust and upper mantle as well as to estimate the origin of seismic swarms in the Western Bohemia region. Surface waves can provide better constrains for upper parts of the seismic velocity distributions. In case of the Bohemian Massif and teleseismic events, "upper" means crust and upper mantle. In case of quarry blasts, "upper" means the uppermost few kilometers below the surface.

Outline of the thesis

The thesis is written as a self-consistent text. Three generally basic segments of each seismological work – theory, software and measurements with results – are presented in three parts of the text. Part I (Chapters 1 and 2) – *Theory* – describes the theory of surface wave analysis and inversion. It is neither a complete list of procedures nor a detailed description of the techniques, however, the multiple filtering technique is described here closely. Part II (Chapters 3 – 5) – *Applications* – presents three papers with results of surface wave surveys made in the Bohemian Massif. Part III (Chapters 6 and 7) – *Software* – contains detailed descriptions of the SVAL and the PhaseCorr programs.

The thesis follows the way of surface wave studies from seismogram measurements to the velocity distribution estimation. It describes the theoretical background of the measurements and analysis of dispersion curves, the tools and software for processing and the inversion procedure implemented directly in the computer program. We are able to analyze the group velocity dispersion curve and determine the 1D velocity model of the structure. In addition to this, we can also provide phase velocity measurement using two stations. Having either group or phase velocity dispersion curves, we provide surface wave tomography. The application of Rayleigh wave tomography in Chapter 4 was done using the software provided by prof. Tatiana B. Yanovskaya.

The thesis is based on five papers:

- **Kolínský, P., 2004**: Surface wave dispersion curves of Eurasian earthquakes: the SVAL program, *Acta Geodyn. Geomater.*, 1 (134), 165–185.
- **Kolínský, P., 2005**: Seismic velocity model in the vicinity of Eger Rift from dispersion of surface waves, Final report about the Internal start project of the Grant Agency of the Academy of Sciences of the Czech Republic, *Acta Research Reports*, 14, 67–71.
- **Kolínský, P. and Brokešová, J., 2007**: The Western Bohemia uppermost crust shear wave velocities from Love wave dispersion, *Journal of Seismology*, 11, 101–120.
- **Kolínský, P. and Brokešová, J., 2008**: The Western Bohemia uppermost crust Rayleigh wave tomography, *Acta Geodyn. Geomater.*, 5 (149), 5–17.
- **Kolínský, P., Málek, J. and Brokešová, J., 2010**: Shear wave crustal velocity model of the western Bohemian Massif from Love wave phase velocity dispersion, *Journal of Seismology*, DOI 10.1007/s10950-010-9209-4.

I use two approaches how the papers are implemented in the thesis. Two of them (Kolínský, 2004 and Kolínský, 2005) are disjointed in the text of Part I (Chapters 1 and 2). We do not refer to these papers because the text of the thesis is just based on the previous work and almost no paragraphs or even sentences were kept unchanged from the original papers. Most of the text of Part I is written originally for the thesis.

Three remaining papers (Kolínský and Brokešová 2007, 2008 and Kolínský et al., 2010) are completely included in the thesis. Chapter 3 (Kolínský and Brokešová, 2007), Chapter 4 (Kolínský and Brokešová, 2008) and Chapter 5 (Kolínský et al., 2010) contain all the text, figures, tables and references of the respective papers. These three fully cited papers in Chapters 3 − 5 are supplemented by additional remarks and figures concerning some of the issues solved during the elaboration of the papers.

The paper by Kolínský and Brokešová (2007) (Chapter 3) has two parts. It concerns both methodology as well as real data processing. Theoretical sections describe the analysis of surface waves and inversion of dispersion curves. Both analysis and inversion techniques are supplemented by tests.

The paper by Kolínský and Brokešová (2008) (Chapter 4) concerns the analysis of surface waves from quarry blasts in Western Bohemia. The paper by Kolínský and Brokešová (2007) deals with Love waves, however, the paper by Kolínský and Brokešová (2008) is based on Rayleigh waves. The paper is supplemented by additional tests of resolution and other remarks.

The paper by Kolínský et al. (2010) (Chapter 5) has been accepted for publication in the Journal of Seismology.

Part III (Chapters 6 and 7) is written newly for the thesis. The topic of Chapter 6 is the same as the topic of Kolínský (2005), however, the description of the SVAL program is completely redesigned and expanded. Chapter 7 is a new description of the previously unpublished PhaseCorr program.

All the work with surface waves was accompanied by permanent development and debugging of the SVAL program (Chapter 6). In the last few years, the program has been tested and used by other colleagues from the Department of Seismology, Institute of Rock Structure and Mechanics, Academy of Sciences of the Czech Republic. This thesis should serve also as a detailed manual and tutorial to the SVAL program. Other smaller software pieces were also written and one of them – the PhaseCorr program – is also described in this thesis (Chapter 7).

Attached is a CD-ROM with the software executable files and also all source codes. Examples given in Chapter 6 are also copied at the disk with data files needed for practicing them. The disk contains also the text of the thesis in several formats as well as the LaTeX source file and all the figures in *.eps file format. The *readme.txt* file provides information about the disc arrangement.

This abstract of the thesis follows with a brief introduction to the seven chapters of the original thesis and gives the main results and conclusions.

1. Surface wave analysis

1.1 Background research of surface wave analysis methods

We give an overview of papers and studies concerning surface wave measurement and analysis. We do not consider this text to be complete in a manner that it includes all the works – there are hundreds of papers dealing with the problem and it is not possible to list them all. However, we present this overview to be complete in a way that it mentions all the features, physical properties and problems concerning surface wave generation, propagation, observation and analysis. We start with *Historical remarks (1885 – 1911)* mentioning the first observation and prediction of surface waves by Rayleigh and Love. Than we list few tens of papers of *Early surface wave observations (1934 – 1972)* concerning mainly the basic measurements and description of physical properties of the surface waves. Paragraph *Frequency-time representation and simple models (1969 – 2007)* describes the use of the techniques for estimating the dispersion curves by the Fourier transform. *Mode coupling in 3D anisotropic structures (1998 – 2007)* gives an overview of recent proceedings in the field of theoretical computations in complex media and *Surface waves, source mechanisms and nuclear explosions (1981 – 2006)* provides an insight into not so traditional use of surface waves. *Surface waves combined with other observables (2004 – 2010)* mentions the use of surface waves together with body waves, receiver functions and other geophysical measurements. Extensive paragraphs of *Surface wave tomography (1982 – 2009)* and *Surface wave array analysis (1993 – 2007)* list most important works of the corresponding fields. A recent method using the dispersion measurement without the earthquake records is referenced in *Ambient noise tomography (2003 – 2010)*. We concluded this section with a paragraph *Surface wave studies in the Bohemian Massif and neighboring regions (1977 — 2010)* covering the proceedings of the research made in the Czech Republic in the last 30 years.

1.2 Multiple filtering method

In the next paragraphs we explain why the multiple filtering method is a suitable tool for frequency-time analysis. We compare it with the technique of moving window.

Frequency-time representation is a 3D depiction of a distribution of energy in dependence both on time and frequency of the record. In this representation, frequency and time axis are theoretically equivalent. However, it does matter how the representation is computed. Two basic and equivalent methods of computing the frequency-time representation are “the technique of moving window” and “the multiple filtering technique”. Both are based on the Fourier transform and both work in similar manner in the respective domain.

Moving window technique filters the signal in the time domain. The time signal is weighted and only a part of it is selected in a close vicinity of given central time. Then this small part of the whole signal is transformed to the frequency domain. This selecting procedure is repeated for many central times, many Fourier transforms are made and many spectra are obtained. Then the spectra are aligned side by side one to another along the time axis representing the central times. We use 2D frequency-time base of the plot while the spectral amplitudes are shown in the third dimension along the third axis. In fact, instead of the complex spectra, the modulus of the spectra is depicted (amplitude spectra), what represents the energy carried by the signal at each time for each frequency. Such a 3D representation is called “spectrogram”.

In case of the multiple filtering method, all the steps are done in the other domain. First, the Fourier spectrum of the whole record is computed. Then for many central frequencies, only limited part of the spectrum close to the given frequency is selected. These weighted spectra are transformed back to the time domain and a set of harmonic signals is obtained. They are plotted side by side along the frequency axis of the frequency-time representation. Instead of harmonic signals itself, their envelopes (moduli of analytical signals corresponding to these harmonic signals) are used. Envelopes directly represent the energy carried by the respective harmonic signal.

Spectrograms created by moving window and multiple filtering techniques are equivalent. However, there are some peculiarities showing us that the multiple filtering method is more suitable for analyzing dispersed surface wave records.

In my opinion, there is not a strong need to use more complicated methods of frequency-time analysis then the multiple filtering technique. The most difficult aim and the main goal are not to reach high resolution of frequency-time representation but to interpret the ridges and to draw the continuous dispersion curves. I encounter many problems with the dispersion curve estimation, higher modes identification, dispersion splitting due to multipathing and recognizing other dispersion curve related phenomena and I was never limited by the resolution of the spectrograms. The difficulties with the inversion of dispersion curves also mitigate the need for higher resolution of the analysis. I would not be able to use any more precisely determined dispersion curves in my inversion anyway. Hence I think that the multiple filtering method has a good use for its simplicity, easy controlling and suitable comparison of filtered harmonic signals in the time domain.

1.3 Illustrative description of the method

In this section, a description of the multiple filtering method is given. As an intention, we do not use any equations, expressions or mathematical symbols to introduce the technique. This is just to propose the basic idea how the multiple filtering works.

Here we give and overview of the whole process. Consider a particular component of an earthquake record. First of all the complex Fourier spectrum of the record is computed. After that the complex spectrum is filtered. It means that both real and imaginary parts of the spectrum are multiplied by a set of weighting functions. For weighting, smooth Gaussian functions are used. Toward higher frequencies, the width of the filters in the frequency domain broadens to ensure more accurate resolution in the time domain, which is needed to represent narrower signals of shorter periods. This filtering is done for selected central frequencies (periods). By the weighting, we obtain many spectra. All these filtered spectra are transformed back to the time domain. We obtain a set of nearly monochromatic time functions – for each period of filtering we get one corresponding signal in the time domain. Envelopes of each of the signals are computed.

Than we use a procedure for selecting the proper wavegroup from each signal. Local maxima of each envelope are found and according to the mutual relationships of arrival times of these maxima, one of the local maxima at each signal is selected to represent a point at a smooth curve linking all the selected times. Such a curve representing the arrival times of the wavegroups depending on period is the *dispersion curve* and the procedure for its selecting is using a *criterion of continuity*. The criterion of continuity works in such a way that at first, we find the proper wavegroup for longer periods. Then, we proceed filter by filter toward shorter periods and we look for the local maximum of the next signal to be as close in time to the maximum of the preceding signal as possible regardless of its amplitude. For longer periods, the fundamental wavegroups are found as the highest maxima of each signal.

After selecting the dispersion curve, we truncate all signals around the selected maxima to keep only the desired wavegroups. We truncate also the corresponding envelopes of these wavegroups.

The original whole envelopes are used to create the complete spectrogram. Ordering one envelope side by side according to the periods of corresponding time signals, we obtain a 3D depiction of the energy contained in the original record with respect both to time and frequency.

Truncated harmonic signals may be used for creating the separated dispersed wavegroup. This dispersed wavegroup is a product of the analysis and is used to compare the mode corre-

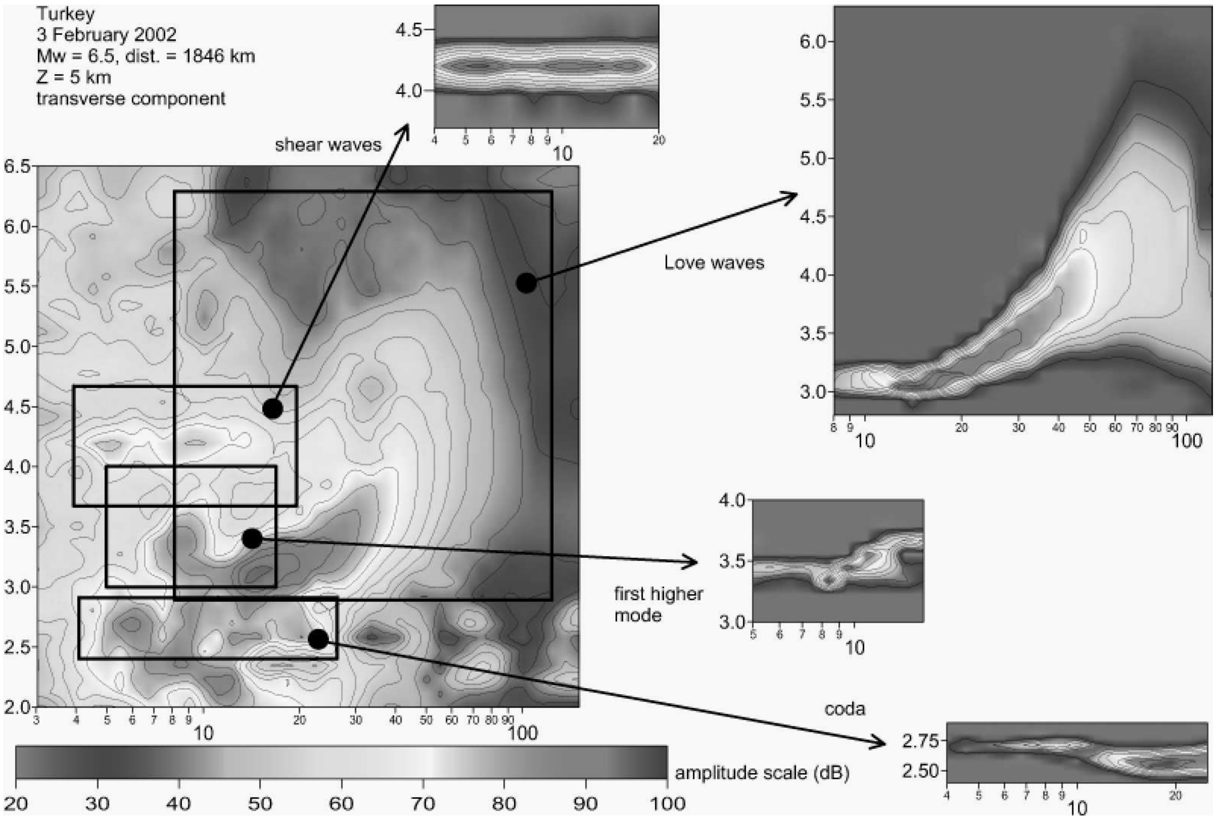


Figure 1: (*Fig. 6 in Kolínský, 2004; modified; Fig. 1.11 in the thesis*) Spectrogram of the transverse component of the Turkish earthquake record is shown. The four rectangles represent a selection of three dispersive surface wave modes (L_0, L_1 and coda) and one non-dispersive ridge of body S-wave. The energy contours spacing is 5 dB for the whole spectrogram and 10 dB for the four separated spectrograms.

sponding to the found dispersion curve with the original seismogram. The truncated harmonic components are simply summed up.

Fig. 1 presents a schematic view of selecting the desired modes from the spectrogram.

1.4 Formally exact description of the method

After the illustrative characterization of the method from the previous section, we now introduce a formal description of the multiple filtering. We follow the general explanation given in Kolínský (2004). We describe a theoretical approach to the multiple filtering as well as to the moving window technique and frequency-time representations in general. For the most complete and formal description of the multiple filtering technique, refer to Chapter 3, where the paper Kolínský and Brokešová (2007) is cited.

1.5 Instrumental time correction

When processing any seismic data, instrumental transfer function has to be applied to obtain the proper amplitude and phase independent of the instrument used. For surface wave analysis, the instrumental characteristic is a crucial tool to reveal the true properties of records. Each instrument distorts different periods by different way and since the properties of the signal changing with period is exactly the matter we are dealing with when processing dispersed surface wave records, we need to know the characteristic of the instrument to correct the records. The transfer function is given in spectral domain by poles and zeros and its application is straightforward – we divide the spectrum of the measured record by the transfer function of the used instrument and we get corrected spectrum which corresponds to the signal as if it was measured with the instrument not influencing the record in any way.

The influence of the phase characteristic on the group velocity is not straightforward. Group velocities are estimated using the envelopes of the harmonic components and the quantity which the phase characteristic is concerning is the phase of the underlying (carrying) wave beneath that envelope. Generally, the instrument cause a shift of the phase of the harmonic component. It looks like the whole harmonic signal is shifted in time by certain time interval. But together with the phases, which are shifted, the amplitudes are also restored. It causes that the envelope of the "shifted" harmonic signal does not shift in the same manner. It can be shifted less, more and even in the opposite direction. It is not possible to use the time shifts given by the phase correction for restoration of the group velocities.

1.6 Seismograms, velocigrams or accelerograms?

Estimating the group velocity dispersion curve from any type of record gives the same results. Using the multiple filtering technique, we look for maxima of the envelopes of harmonic components of the original signal. These components are obtained using inverse Fourier transform of a filtered spectrum, which is filtered by the Gaussian filter. The envelope of the signal in the time domain is thus also a Gaussian-like. Such a signal is called Gabor's signal – the sinusoidal carrier wave is modulated by the Gaussian function. The Gaussian-like shape of the harmonic components of surface waves in the time domain is, however, not artificially caused by the filtration. It is a natural property of the waveforms. Hence we may represent our harmonic components of dispersed surface wave by the Gabor's signals.

We present an analytical derivation of the evidence, that the time of the maximum of the signal envelope does not depend on the derivation of the signal. Hence it does not make any difference if we estimate the group propagation time from the record of ground displacement or from the record of ground velocity when the ground displacement is represented by the Gabor's signal.

These results are demonstrated using a synthetic example. We consider a 1D velocity model of uppermost crust down to the depth of 3 km, which was determined from short period surface wave measurement at station Trojmezí in the Western Bohemia region from the record of blast in quarry Libá, see Chapter 3. Synthetic records were computed using the discrete wavenumber method (DWN). For the single structural model, synthetic ground displacement, velocity and acceleration were computed. All three synthetics were used for surface wave dispersion curve determination using the multiple filtering technique. We show that all three curves are the same regardless of the fact they were estimated from three various records.

Another test of the dispersion curve invariance with respect to the record type is given using the transverse component of the Aegean Sea earthquake measured at station Háje (HAJ). This second test is given here to verify the idea of group velocity dispersion curve invariance using completely different type of record in comparison with the first test. In contrast to the first test which was based on synthetic records, this second test uses real measured data.

1.7 Tests of the multiple filtering method

For the test of any technique, the particular implementation of the method has to be used. For the frequency time analysis, we use the SVAL program. During the SVAL program development, many tests of its function and of the multiple filtering technique were performed. We present three of them here. The first and the second test verifies the ability of the SVAL program to determine the proper group velocity dispersion curve, the third test also benchmarks the ability of the PhaseCorr program to determine the phase velocity dispersion curve using the two-station method. The idea of the first and the second test is based on using a signal with analytically known dispersion. The first test was introduced by Kolínský (2003). We process a synthetic signal by the multiple filtering technique and then we compare the result with the synthetic analytically derived dispersion. Modifications of the second and third test are further developed in the papers by Kolínský and Brokešová (2007) and Kolínský et al. (2010), respectively.

All tests concluded that the method, implemented in the SVAL and PhaseCorr programs, is reliable and able to determine the group and phase velocity with sufficient accuracy.

2. Dispersion curve inversion

2.1 Overview of the inversion methods

Similarly as in the previous chapter, we reference methods for inversion. We concern on the inversion of dispersion curves in the paragraph *Dispersion curve inversion (1962 – 2009)* and we proceed with *Inversion used for advanced measurement techniques (1982 – 2009)* where inversion of other surface wave observables are described.

2.2 Isometric method description

Isometric method is an inversion algorithm developed by Jiří Málek at the Department of Seismology, Institute of Rock Structure and Mechanics, Academy of Sciences of the Czech Republic, see Málek et al. (2005 and 2007). The isometric method (IM) is a fast algorithm for solving weakly non-linear inverse problems with many parameters. It combines several advantages of standard methods such as simulated annealing, Newton's least-squares method and the simplex method (see Tarantola, 1987), and others. It employs linearization of the forward problem similar to Newton's least-squares method.

2.3 Application of the isometric method for dispersion curve inversion

When inverting the dispersion curves by the isometric method, we have several options. We can invert Love wave dispersion only, Rayleigh wave dispersion only or both Love and Rayleigh wave dispersion curves together. For each of these three options, we can invert also the densities or we can keep them constant. We can also keep the shear wave velocity in the first layer constant or we can let it to be found as well as the velocities for other layers. All these options are applicable for inversion of both group and phase dispersion curves and for all these options we can choose if the low velocity zone should be found or if we force the inversion to look only for monotonously increasing velocity with depth.

During the inversion, the modeled dispersion curve is compared with the measured one. For the velocity (density) distribution found in each iteration, the dispersion curve is computed and the misfit with respect to the measured dispersion is estimated.

2.4 Inversion tests

In this section, we present a test of the inversion process. We use the implementation of the isometric method in the SVAL program for inversion of group velocity dispersion curves, as described above. Modification of this test is also given in the paper by Kolínský and Brokešová (2007). A test of the phase velocity inversion is given in the paper by Kolínský et al. (2010).

For the tests, three shear wave velocity models are set and synthetic group or phase velocity dispersion curves are computed. Then, only some of the points from each of the dispersion curves are selected to resemble the real measurement. Such dispersion curves are inverted and the resultant structures are compared with the original tested ones. Synthetic seismograms are also computed by the modal summation method and compared for the tested and resultant structures. The synthetics do not play any role in the inversion and are shown only for comparison to determine the reliability of the inversion with respect to the real measurements – in case of the inversion of real records, the synthetics are also used for comparison after the inversion of the dispersion curves.

3. Application A: Uppermost crust shear wave velocities

3.1 Dealing with the topic

We started to analyze the records of quarry blasts in 2005. Not only the analysis itself was the main reason – we also tuned many details of our procedures, programs and methods while looking for the short-period surface waves in the Western Bohemia region. This project was the one which moved the developing of the SVAL program into a universal tool for analysis of the surface waves of all wavelengths, different sampling frequency and arbitrary record lengths. Until this moment, the SVAL program was mainly used for the analysis of teleseismic event records with surface waves of period >10 s. During the project, many tests of the surface wave analysis were made with the aim to use the multiple filtering method in the best way possible. We created synthetic records with analytically known dispersion and we compared this dispersion to the dispersion determined by the SVAL program to check the reliability of the method and the program. Similar tests were made during my Master studies a few years ago and both sets of tests were successful and proved that the SVAL program may be used for any kind of surface wave measurement.

When we were satisfied with the short-period surface wave measurement, we tried to develop also the inversion procedures to obtain the velocity distribution of uppermost crust of the target region. We implemented the isometric method, developed by Jiří Málek (Málek et al., 2005 and 2007), into the SVAL program and we inverted results of the analysis for the 1-D shear wave velocity distributions. We also computed synthetic dispersion curves for known structural models and then we inverted the dispersion curves to see if we got the same models in order to check the reliability of the isometric method and its implementation for the dispersion curve inversion in the SVAL program.

This chapter consists of the paper Kolínský and Brokešová (2007) which has been published in the Journal of Seismology. Not all the tests and examples have been introduced in the paper. We cite the complete paper in the thesis and we add some additional remarks at the end of the chapter. Some of the sections of the paper complement the methodology sections from Part I – *Theory* of the thesis, because the paper is aimed at both methodological description of the procedures and also at the data processing and structural results.

3.2 The Western Bohemia uppermost crust shear wave velocities from Love wave dispersion

Petr Kolínský and Johana Brokešová, 2007, Journal of Seismology, Vol. 11, p. 101–120

The original text of the paper is cited in the thesis. We present the Abstract of the paper here. Fig. 2 shows the resultant shear wave velocity distributions for three profiles in the Western Bohemia region.

Abstract

We present a detailed study of Western Bohemia Love waves generated by blasts with an intention to estimate the uppermost crust structure for a more detailed layer distribution than the

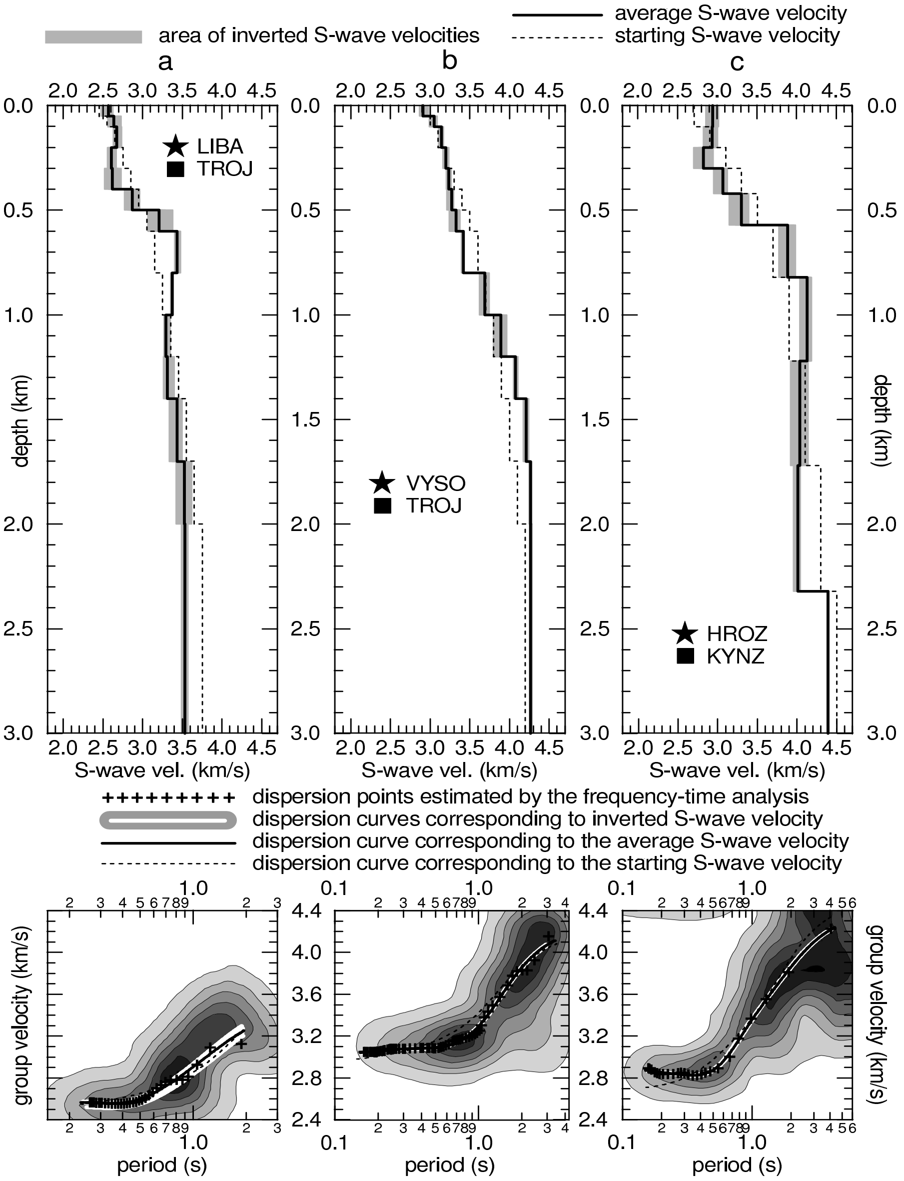


Figure 2: (*Fig. 7 in Kolínský and Brokešová, 2007; Fig. 3.7 in the thesis*) Results for LIBA – TROJ, VYSO – TROJ and HROZ – KYNZ paths. Top panels (for each path): six inverted velocity distributions (gray areas), average velocity distribution (bold solid line) and starting models (thin dashed lines) are shown. Bottom panels (for each path): measured dispersion points (crosses), six dispersion curves corresponding to the six inverted S-wave velocity distribution (white lines), dispersion curve corresponding to the resultant average S-wave velocity distribution (black solid line) and starting dispersion curve (thin dashed line) are depicted. Truncated spectrogram amplitude contours are also drawn.

previous studies have used. The use of short-period (4 s and shorter) Love waves represents a new approach in the studied region. Properties of multiple filtering as a tool of frequency-time analysis are discussed. A new method of selecting the dispersion ridges is introduced. Tests of filtering are provided by analyzing signals with analytically known dispersion. The isometric algorithm for the inversion problem is applied, the problem of non-uniqueness is discussed and tests of reliability of the inversion are presented. During the inversion, the forward problem is solved by use of the matrix method. Six records of blasts from the Western Bohemia region are analyzed to separate the fundamental modes of Love wavegroups, and shear wave velocity distributions down to a depth of 3.0 km are inferred. Modal summation is used to compute synthetic velocigrams, which are compared to measured ones. The lateral heterogeneity of the region is discussed and the presented models are compared to those of previous studies and to the geological setting of the region.

3.3 Additional remarks to the paper

The paper is complemented by a graphical flow chart with detailed description of the computational process. Comments on the instrumental corrections used in the paper are also given with a remarks that a new method of applying these characteristic was implemented after the paper was published.

4. Application B: Rayleigh wave tomography

4.1 Dealing with the topic

As we have prepared the paper concerning 1-D structural models of the Western Bohemia region (Chapter 3), the idea of surface wave tomography seemed to be a natural continuation of our work.

For surface wave tomography, we use a program developed by prof. Tatiana B. Yanovskaya with her permission. The program computes 2D group velocity maps in a plane and it has all the advantages we looked for – it is easy to use, it is designed for areas with linear distance smaller than 100 km, it can deal with uneven distribution of rays, it has variable number of grid nodes where the velocity values are estimated and it gives not only the velocity distribution,

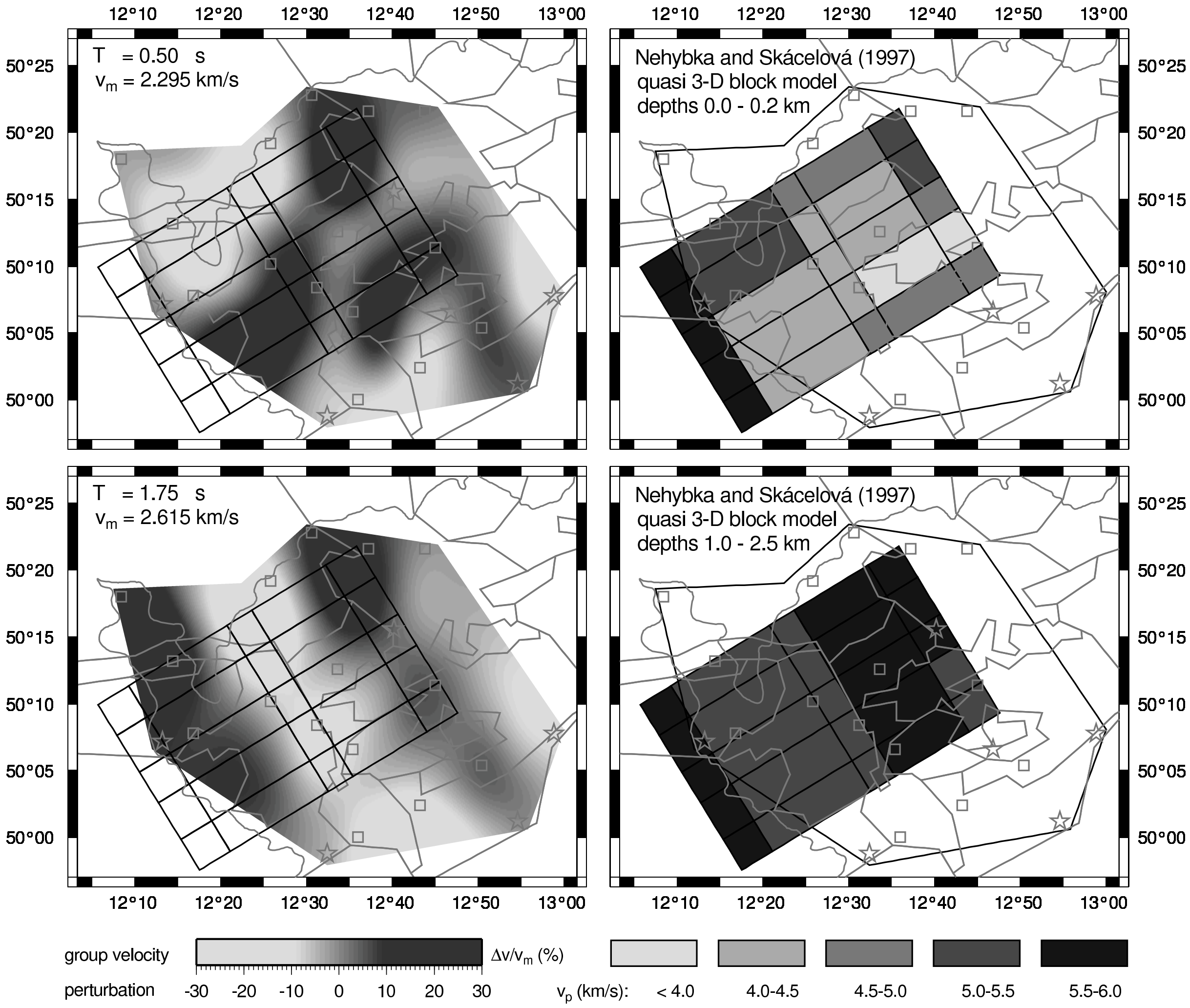


Figure 3: (*Fig. 7 in Kolínský and Brokešová, 2008; Fig. 4.9 in the thesis*) Comparison of 2-D tomography maps for periods 0.5 and 1.75 s with the quasi 3-D block models of Nehybka and Skácelová (1997) for the depths of 0.0 – 0.2 km and 1.0 – 2.5 km respectively. Block edges are imagined in the left maps and tomography map borders in the right ones for better comparison.

but it also allows to see the averaging area for each grid node. This averaging area corresponds to the resolution of the method in given node and we can easily compare the results and their reliability for different smoothing parameters and different grid node distributions.

Instead of Love waves, we use the Rayleigh waves for the paper dealing with surface wave tomography in the Western Bohemia region.

4.2 The Western Bohemia uppermost crust Rayleigh wave tomography

Petr Kolínský and Johana Brokešová, 2008, Acta Geodyn. Geomater., Vol. 5, No. 1(149), p. 5–17

The paper is completely cited in the thesis. We present the Abstract here. Fig. 3 shows the comparison of our results with results previously published.

Abstract

We apply a traditional method of surface wave tomography as a new approach to investigate the uppermost crust velocities in the Western Bohemia region (Czech Republic). It enables us to look for velocity distribution in a small scale of tens of kilometers. We measure Rayleigh wave group velocity dispersion curves in a period range $0.25-2.0\,\mathrm{s}$ along paths crossing the region of interest. We use modified multiple filtering method for frequency-time analysis. We compute 2-D tomography maps of group velocity distribution in the region for eight selected periods using the standard methods and programs described in literature. We discuss the velocity distribution with respect to results of former study by Nehybka and Skácelová (1997). We present a set of local dispersion curves which may be further inverted to obtain a 3-D shear wave velocity image of the area.

Reference

Nehybka, V. and Skácelová, Z., 1997: Seismological study of the Kraslice/Vogtland-Oberpfalz region, in: Vrána, S. and Štědrá, V. (eds.): *Geological model of Western Bohemia related to the KTB borehole in Germany*, Czech Geological Survey, Prague, 186–190.

4.3 Smoothing and resolution of the tomography

Comments on defining the smoothing parameter and discussion of the resolution is added as well as two more figures of tomography maps computed using different smoothing parameters are presented. These examples are shown to explain in detail how we set the regularization parameters in the paper to obtain realistic perturbations and reliable resolution of the Rayleigh wave group velocity tomographic maps.

5. Application C: Phase velocity and crustal structure

5.1 Dealing with the topic

This chapter is based on the paper by Kolínský et al. (2010). We tested several methods of phase velocity measurement. The primary goal of the paper was to find out the differences between the short profiles and to compare the crust structure between the eastern and western part of the profile TBR-NKC. Then we concern ourselves not only to the structure estimation, but mainly to the surface wave propagation paths and true backazimuth correction.

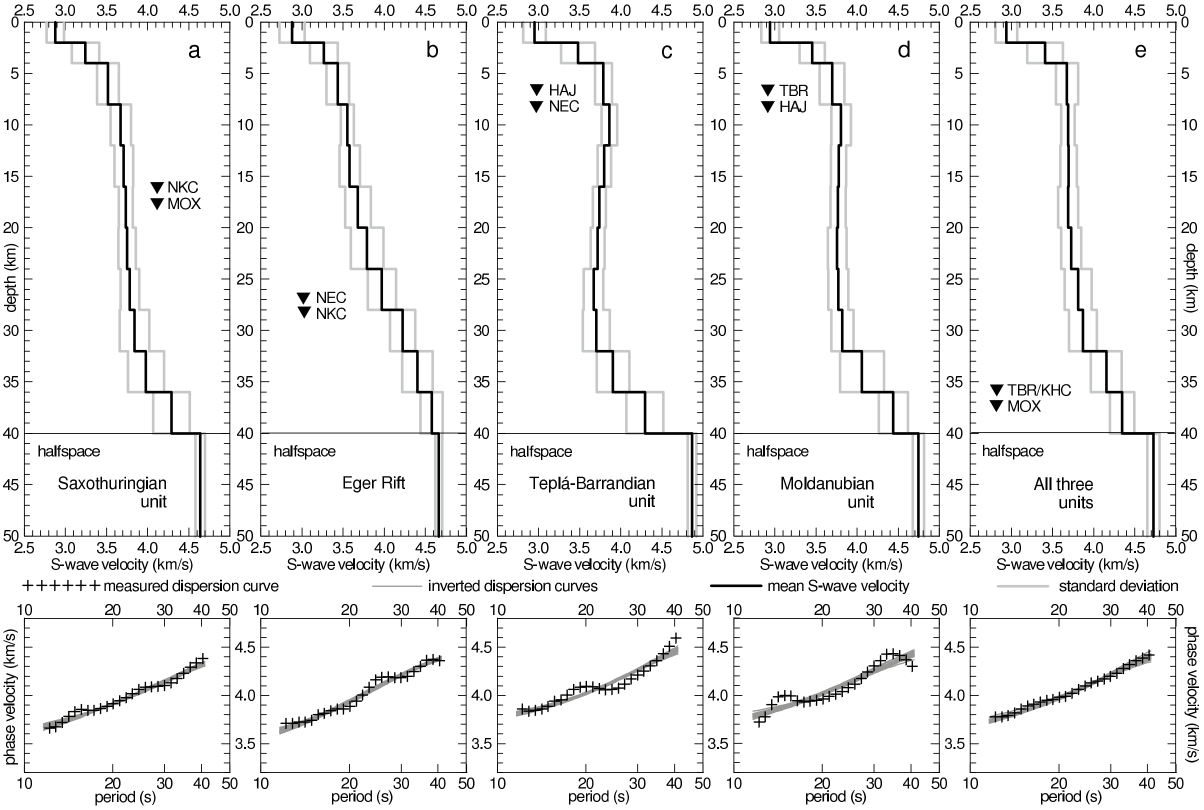


Figure 4: (*Fig. 14 in Kolínský et al., 2010; Fig. 5.14 in the thesis*) Determined v_S structures: (**a**–**d**) four short sub-profiles and (**e**) TBR/KHC-MOX long profile. Standard deviations (gray lines) of mean S-wave velocities (bold black line) from the twenty found models are presented. Crosses in the lower panels represent the backazimuth-corrected dispersion curves entering the inversion. Twenty dispersion curves found by the inversion are shown as dark gray lines.

As it is shown at the end of this chapter, we applied several methods of phase velocity measurements and we selected the time shift measurement as the most suitable one. We do not argue that there are not new methods of phase velocity measurement, however, the goal of this project was not to develop or test new methods, our aim was to contribute to the crust structure estimation efforts of the Bohemian Massif. The other goal was to develop a unique technique to estimate the true backazimuths of propagation of surface wave of different wavelengths.

The paper has been accepted for publication in the Journal of Seismology.

5.2 Shear wave crustal velocity model of the Western Bohemian Massif from Love wave phase velocity dispersion

Petr Kolínský, Johana Brokešová and Jiří Málek, 2010, Journal of Seismology,
DOI 10.1007/s10950-010-9209-4

The paper is completely cited in the thesis. We present the Abstract here. Fig. 4 shows the resultant shear wave velocity distributions for the profiles across the three geological units of the Bohemian Massif.

Abstract

We propose a new quantitative determination of shear wave velocities for distinct geological units in the Bohemian Massif, Czech Republic (Central Europe). The phase velocities of fundamental Love wave modes are measured along two long profiles (≈ 200 km)) crossing three major geological units and one rift-like structure of the studied region. We have developed a modified version of the classical multiple filtering technique for the frequency-time analysis and

we apply it to two-station phase velocity estimation. Tests of both the analysis and inversion are provided. Seismograms of three Aegean Sea earthquakes are analyzed. One of the two profiles is further divided into four shorter sub-profiles. The long profiles yield smooth dispersion curves; while the curves of the sub-profiles have complicated shapes. Dispersion curve undulations are interpreted as period-dependent apparent velocity anomalies caused both by different backazimuths of surface wave propagation and by surface wave mode coupling. An appropriate backazimuth of propagation is found for each period, and the dispersion curves are corrected for this true propagation direction. Both the curves for the long and short profiles are inverted for a 1D shear wave velocity model of the crust. Subsurface shear wave velocities are found to be around 2.9 km/s for all four studied sub-profiles. Two of the profiles crossing the older Moldanubian and Teplá-Barrandian units are characterized by higher velocities of 3.8 km/s in the upper crust while for the Saxothuringian unit we find the velocity slightly lower, around 3.6 km/s at the same depths. We obtain an indication of a shear wave low velocity zone above Moho in the Moldanubian and Teplá-Barrandian units. The area of the Eger Rift (Teplá-Barrandian – Saxothuringian unit contact) is significantly different from all other three units. Low upper crust velocities suggest sedimentary and volcanic filling of the rift as well as fluid activity causing the earthquake swarms. Higher velocities in the lower crust together with weak or even missing Moho implies the upper mantle updoming.

5.3 What is not included in the paper

While preparing the manuscript, we proposed another comparison with studies dealing with P-wave velocities. By the same method as described in the paper, we determined also the shear wave velocity distribution between stations TBR and NKC, since several $\mathrm{v_p}$ studies were made along nearly the same profile. We included this comparison in the thesis to show alternative approach to the study of the crust.

When preparing the manuscript, we started our phase velocity measurement by computing the differences of record phases in the spectral domain. We add some details about this method and examples, how it works. At first, we tried to compute the phases using spectra of the raw records, what gave us very unstable results. Raw record contains noise, body waves and higher surface wave modes, their shape is complicated and the phase estimation is hence not well constrained. We propose another approach – to provide the spectral phase measurement using only the separated fundamental modes of the desired surface wavegroup. This approach, however it is used often in literature, gave us reliable results only in limited period range. To avoid the uncertainty, we decided to measure the phase velocity in the time domain.

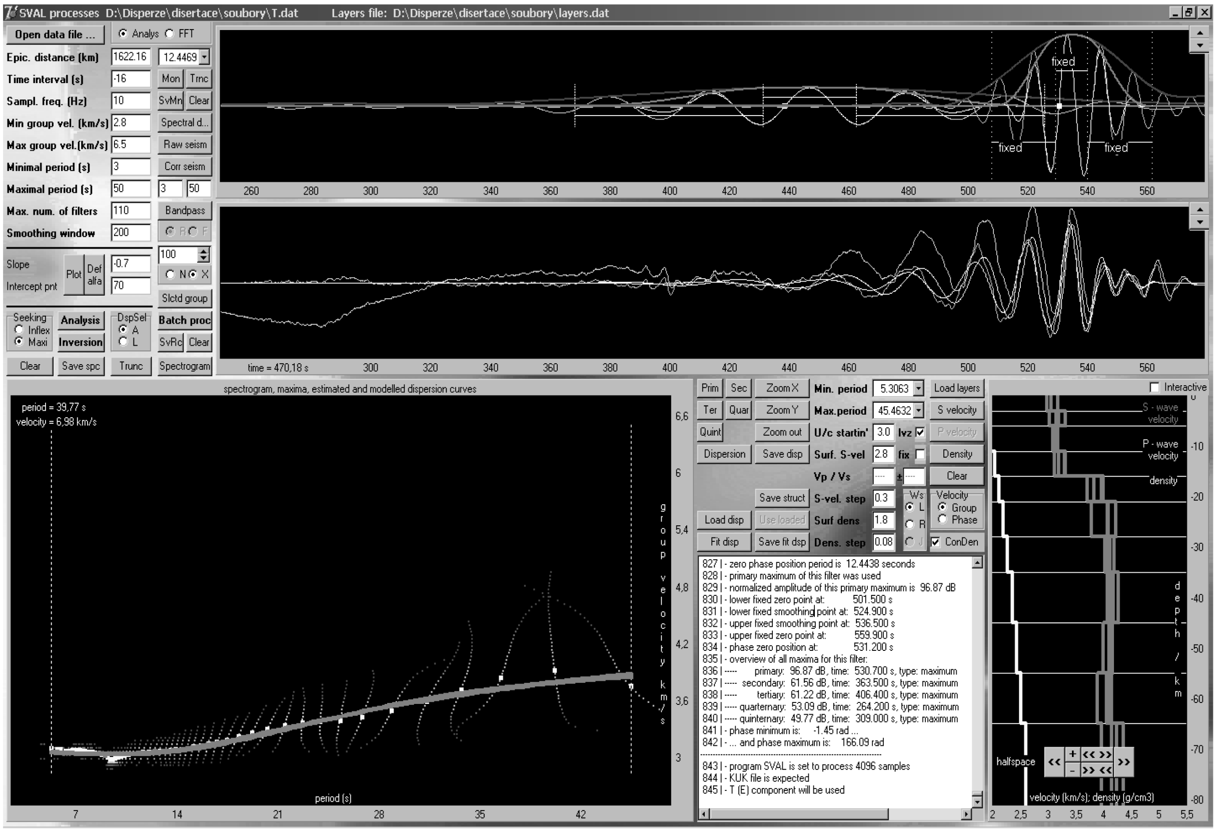
6. The SVAL program

We present a detailed description of the SVAL program. The SVAL program is an interactive software for frequency-time analysis of dispersed signals of any dynamic and frequency range. It also enables to make an inversion of measured dispersion curves for 1-D velocity structure.

This chapter also contains practical examples of surface wave analysis and inversion. The SVAL program is based on methods mentioned in the previous chapters assembled in a software which is easy to understand and friendly to use.

I have been developing the SVAL program for seven years. The first version was made during my diploma thesis elaboration in 2003 and hence for the basic procedures refer also to my work Kolínský (2003). The source code has been under permanent development.

The SVAL program is to be used for frequency-time analysis of seismic records. It is possible to estimate the dispersion curve of selected mode and to make an inversion for 1D layered velocity and density model. In theory, no limitation is made for analysis of fundamental modes as well



SVAL processes D:\Disperze\disertace\soubory\T.dat Layers file: D:\Disperze\disertace\soubory\layers.dat

● Analys ○ FFT
Epic. distance (km) 1622.16 12.4469
Time interval (s) -16
Sampl. freq. (Hz) 10
Min group vel. (km/s) 2.8
Max group vel.(km/s) 6.5
Minimal period (s) 3
Maximal period (s) 50 3 50
Max. num. of filters 110
Smoothing window 200
Slope -0.7
Intercept pnt 70
100
○ N ● X
Seeking ○ Inflex ● Maxi
DspSel ● A ○ L

Min. period 5.3063
Max.period 45.4632
U/c startin' 3.0 lvz ☑
Surf. S-vel 2.8 fix ☐
Vp / Vs ---- ± ----
S-vel. step 0.3
Surf dens 1.8
Dens. step 0.08
Ws ● L ○ R ○ J
Velocity ● Group ○ Phase
☑ ConDen
☐ Interactive

```
827 | - zero phase position period is  12.4438 seconds
828 | - primary maximum of this filter was used
829 | - normalized amplitude of this primary maximum is  96.87 dB
830 | - lower fixed zero point at:          501.500 s
831 | - lower fixed smoothing point at:  524.900 s
832 | - upper fixed smoothing point at:  536.500 s
833 | - upper fixed zero point at:          559.900 s
834 | - phase zero position at:             531.200 s
835 | - overview of all maxima for this filter:
836 | -----       primary:  96.87 dB, time:  530.700 s, type: maximum
837 | -----  secondary:  61.56 dB, time:  363.500 s, type: maximum
838 | -----        tertiary:  61.22 dB, time:  406.400 s, type: maximum
839 | ----- quarternary:  53.09 dB, time:  264.200 s, type: maximum
840 | ----- quinternary:  49.77 dB, time:  309.000 s, type: maximum
841 | - phase minimum is:     -1.45 rad ...
842 | - ... and phase maximum is:    166.09 rad
-------------------------------------------------------------------
843 | - program SVAL is set to process 4096 samples
844 | - KUK file is expected
845 | - T (E) component will be used
```

Figure 5: (*Fig. 6.2 in the thesis*) The main SVAL window. Time domain signals, frequency-time representations and inversion results are located here as well as most of the controlling buttons.

as higher modes of surface waves. Records of lengths up to 32768 samples may be processed and two types of input data files are supported. Any surface wave modes and also body waves can be extracted, properties of the signal in time and frequency domains can be determined, automatic procedure for compiling the dispersion curve as well as manual selection of the dispersion points is available. Manual mode for processing of one record with detailed investigation of all its properties as well as batch processing mode for extracting the group travel times from hundreds of records automatically is enabled.

At current time we provide the program version which can invert Love wave dispersion for 1D shear wave velocity and density model, Rayleigh wave dispersion for 1D longitudinal and shear wave velocity and density model and both Love and Rayleigh wave dispersion curves for longitudinal and shear wave velocity and density model. The density values may be optionally kept constant during the inversion and only velocities are found. The velocity value in the first layer may be optionally kept constant during the inversion.

The time domain basic window, Fig. 5, is used for setting all the parameters and for checking the results in the time domain and in the group velocity-period plane. The result of inversion is also displayed in this window.

For estimating the group velocity dispersion curve, only one record is needed – this is exactly what the SVAL program does. For estimating phase velocity between the two stations, we need to analyze the two records separately by the SVAL program, save the information about the harmonic components at each station, and then load the two files into the PhaseCorr program to estimate the phase shifts between the harmonic components. After the phase velocity dispersion curve is estimated and saved by the PhaseCorr program, we may load it into the SVAL program to provide the inversion.

As the SVAL program uses graphical interface it is possible to check all the computational steps both in time and frequency domains. It is possible to change the parameters of analysis and inversion to obtain the results by requested and reliable way. It is designed to repeat selected portions of the analysis with different parameters to ensure the proper filtration and dispersion curve compilation.

We use the multiple filtering technique for the frequency-time analysis (programmed by Petr Kolínský), the isometric method for inversion (developed and programmed by Jiří Málek) and the matrix method for forward modeling (developed and programmed by Oldřich Novotný). As the SVAL program computation is divided into separated procedures, it is possible to go through only a part of the task. It is possible, for example, to make only the analysis of the record or to make only the inversion of the previously estimated dispersion curves.

The source code is written in PASCAL using Delphi environment (Borland, version 7.0). It is possible to distribute and execute the SVAL program using one *.exe file (3.2 MB). The SVAL program is a freeware and users are supposed to cite the respective papers. All the source files and other working materials needed to compile the executable file are attached to this thesis on the CD ROM as well as is also the executable SVAL file itself. The executable file is also provided at the web page: http://www.irsm.cas.cz/˜ kolinsky/.

There are two basic, one auxiliary and one inversion windows to be displayed at the monitor while the program is running. Many dialog and message boxes appears during the data processing.

In the thesis, we describe all the functions and handling options of the SVAL program. We give and overview of all input and output file format options. We also give a detailed cook-book for the use of the program as well as several examples with exact instruction how to process the data, which are included on the CD-ROM. The same applies for the inversion of the dispersion curves – all the features are described, working manual is given and examples included. All steps are documented by program screenshots.

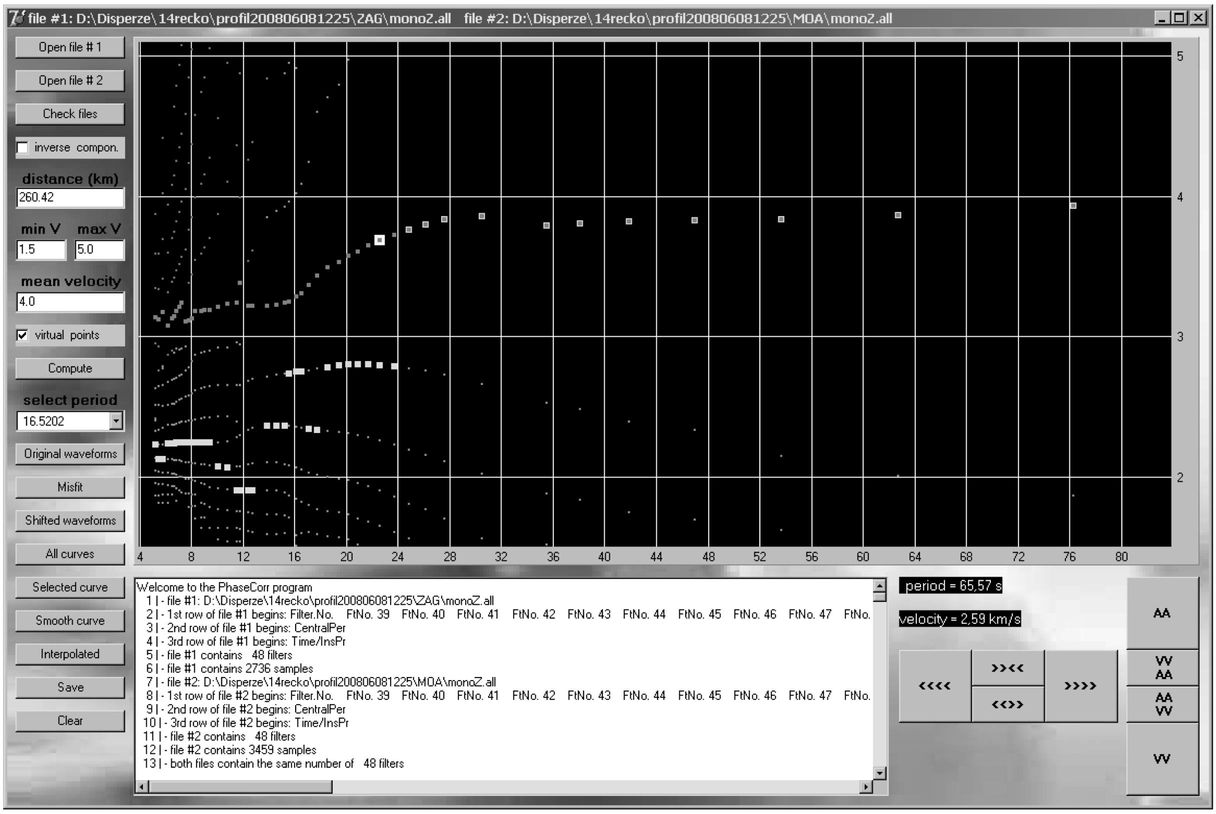
The main feature differing the SVAL program from other software for filtration is its extensive graphical interface. All steps of computation can be viewed. The user is able to check all the parameters and their influence on the record, spectrogram, harmonic components and dispersion curve. It is possible to use trial approach to the processing – when viewing the results, one can directly change the parameters to achieve desired resolution in time or frequency domain, to compile the dispersion curve by one of the two automatic procedures or to compile it manually selecting point by point by mouse-clicking. It is possible to check selected wavegroups at each harmonic components filter by filter and to adjust the truncating in the time domain. Using the spectral domain window, the user is able to check and adjust the width of the filters, to see the influence of the filters at the corresponding part of the spectrum and to observe the influence of the instrumental transfer function.

Inversion is to be adjusted in a similar manner – starting models including shear and longitudinal wave velocity in each layer as well as density and possible ranges of their resulting values can be set. The SVAL program is able to invert Love or Rayleigh wave phase or group dispersion curves or even both Love and Rayleigh wave dispersion curves together.

7. The PhaseCorr program

Unlike SVAL, the PhaseCorr program is a small program with only one purpose – to estimate the phase velocity dispersion curve between two seismic stations. The PhaseCorr program is an extension of the SVAL program. It uses the file outputs of SVAL and without the analysis of the records by the SVAL program, one would not be able to estimate the phase velocities by the PhaseCorr program itself.

The reason, why the functions of the PhaseCorr program are not included directly in the SVAL program is, that in the SVAL program, only one record is analyzed at one moment. In contrast to that, PhaseCorr needs two records from two different stations in the same time to read and to compare. It seemed to us easier to prepare independent program instead of adding next procedures into SVAL.



```
file #1: D:\Disperze\14recko\profil200806081225\ZAG\monoZ.all   file #2: D:\Disperze\14recko\profil200806081225\MOA\monoZ.all
```

☐ inverse compon.

distance (km) 260.42

min V 1.5 max V 5.0

mean velocity 4.0

☑ virtual points

select period 16.5202

period = 65.57 s

velocity = 2.59 km/s

```
Welcome to the PhaseCorr program
  1 | - file #1: D:\Disperze\14recko\profil200806081225\ZAG\monoZ.all
  2 | - 1st row of file #1 begins: Filter.No.   FtNo. 39   FtNo. 40   FtNo. 41   FtNo. 42   FtNo. 43   FtNo. 44   FtNo. 45   FtNo. 46   FtNo. 47   FtNo.
  3 | - 2nd row of file #1 begins: CentralPer
  4 | - 3rd row of file #1 begins: Time/InsPr
  5 | - file #1 contains   48 filters
  6 | - file #1 contains 2736 samples
  7 | - file #2: D:\Disperze\14recko\profil200806081225\MOA\monoZ.all
  8 | - 1st row of file #2 begins: Filter.No.   FtNo. 39   FtNo. 40   FtNo. 41   FtNo. 42   FtNo. 43   FtNo. 44   FtNo. 45   FtNo. 46   FtNo. 47   FtNo.
  9 | - 2nd row of file #2 begins: CentralPer
 10 | - 3rd row of file #2 begins: Time/InsPr
 11 | - file #2 contains   48 filters
 12 | - file #2 contains 3459 samples
 13 | - both files contain the same number of   48 filters
```

Figure 6: (*Fig. 7.1 in the thesis*) The PhaseCorr program window includes all setting edit boxes and all controlling buttons.

Estimating the phase velocities, we may use both programs simultaneously. Sometimes it is required, after estimating the phase velocities by the PhaseCorr, to prepare new versions of input files for PhaseCorr by the SVAL program. We may save new files by SVAL and open them by PhaseCorr to see what happens if the width of filters is changed in the frequency domain or if more filters are included, if an instrument transfer function is used and so on.

In the thesis, we introduce the features of the PhaseCorr program. All phase velocity dispersion curves in Chapter 5 were estimated by this program. Besides that, many other profiles of two and more stations were analyzed by PhaseCorr for other projects and measurements.

The PhaseCorr program has only one window, see Fig. 6. Almost all what is needed for successful phase velocity computation is contained in the two *.all files produced by the SVAL program. This is the reason, why PhaseCorr has almost no analyzing tools and only a few parameters to be controlled. The PhaseCorr program just takes these two files and correlate corresponding quasimonochromatic signals to obtain the time shift between them. The only information needed for the phase velocity estimation is the distance of the two stations. We use not the actual distance between the two stations in a geographical sense, instead of it we simply compute the difference of the two epicentral distances from the source to the respective stations. The meaning of such an approach is that we would like to measure the phase velocity of the plane wave propagating from the source across the first station and then to the second station. In other words, we create a projection of the first station location perpendicularly to the ray path of the wave propagating to the second station.

All buttons and edit boxes in the PhaseCorr program window are designed in such an order that the easiest way how to process the data using the program is to simply use all the buttons and boxes on the left hand side of the window from the top to the bottom.

As in the case of the SVAL program, we present not only an overview of the function of the PhaseCorr program. We also introduce input/output files and a manual how to work with PhaseCorr with examples of real record processing.

Conclusion

Resume

In the thesis, I have presented a complete set of tools for the analysis of dispersed records and for inversion of the dispersion curves for 1D layered velocity models. A comprehensive overview of papers and books concerning the surface wave phenomena has been given and ordered chronologically with pointing out the most important technique inventions both in terms of analysis and inversion. The multiple filtering technique has been introduced as a tool for surface wave analysis with no limitations for any period and velocity ranges and with sufficient resolution in time or frequency domains. Tests of both analysis and inversion have been presented; some of them have been included in the original papers written by the author and his supervisor and consultant, others solely prepared for the thesis. A new evidence of the dispersion curve determination independence of the record type (seismogram, velocigram and accelerogram) has been made and included.

An original SVAL program based on the multiple filtering method with interactive tools for controlling all the steps of the analysis and with parameter setting directly in the working environment by the user has been developed and described in detail. The program includes the isometric method (Málek et al., 2005 and 2007) for inversion of currently estimated or previously saved and uploaded dispersion curves and the matrix method for forward computation of dispersion curves (developed by Oldřich Novotný).

Additional tools for preprocessing of the records as a bandpass filtering and instrumental transfer function application are also available. Parameters of the multiple filtering, as a velocity and period ranges, width of the filters, number of filters and many others can be adjusted directly during the processing. Options for dispersion curve compilation and separated mode waveform computation are included. All features of the program has been mentioned and demonstrated on selected examples.

Another original software called PhaseCorr for phase velocity estimation has been introduced, tested and described with examples, too. It uses the results of the SVAL program – it reads the set of harmonic components from two stations analyzed and separated by the SVAL program and it provides a correlation between the two corresponding harmonic components to estimate the time difference and to compute the phase velocity for each period of the surface waves.

Applications of the method and the software for real structural parameters estimation have been given in three papers dealing both with Love and Rayleigh waves. The works concerning both short period dispersed wavegroups from local measurements as well as regional long period surface waves have been included. Upper crust as well as whole crust shear wave velocities have been estimated. Both group and phase velocity curves have been measured and inverted. Both 1D models and 2D tomographic velocity maps have been figured out. These three papers have been complemented with comments, additional remarks and notes to the problems which emerged when dealing with the respective topics.

Outlooks

Several other projects concerning the surface wave analysis and inversion have been provided during the author's PhD studies. It has not been possible to include all of them in the thesis. The author would like to proceed in further studies with some of the topics to reveal velocity distributions of other parts of the Bohemian Massif.

One of the other projects has concerned especially the estimation of the average 1D anisotropic model of the Bohemian Massif using the phase velocities of earthquakes with good azimuthal distribution around Central Europe. This project is ongoing; the events have already been selected and difficulties with advanced phase velocity estimations are solved continuously. Using both Love (T component) and Rayleigh waves (both Z and R components), we would like to estimate the anisotropy of the crust and upper mantle. Preliminary results of the study have already been presented at conferences using the phase velocities of all three components from Kurile Islands earthquakes from November 2006 and January 2007.

Close cooperation between the Institute of Rock Structure and Mechanics, Academy of Sciences of the Czech Republic, and the Geophysical Institute, Bulgarian Academy of Sciences, started in 2008. Bulgarian broadband seismic station Provadia, near to the Black Sea, was equipped with Czech small aperture array and data between both Institutes are extensively exchanged. Phase velocity measurements between Bulgaria and the Bohemian Massif are provided using all three components of records from earthquakes from Turkey and Greece as well as from the North Atlantic Ridge and Iceland to confirm the dispersion curve determination using the surface waves propagating from both directions.

Other study has also turned our interest to the large amount of data processing. We have selected records of 8 earthquakes which had occurred in Greece from nearly 200 broadband stations from all around the Europe. For this project, the automatic batch processing has been implemented in the SVAL program. We have analyzed long time windows of the records to reveal not only the fundamental modes, but also surface wave reflection and converted modes which come after the fundamental mode. This study is at its final stage with developing a software to select among different surface wavegroups at 200 stations around the continent to found smooth propagation isochrones of fundamental, higher and reflected modes. Colleagues from the Department of Seismology, Institute of Rock Structure and Mechanics, are working with the data using the SVAL and PhaseCorr programs developed and described in the presented thesis.

Epilogue

I have shown that surface waves have various applications. Different sources, distances and wavelengths have been studied. Methods for analysis and inversion have been developed and used. New methodology advances are being implemented what will continue in the future work. Multipathing, reflection, refraction, mode conversion, finite wavelength effects and anisotropy have to be incorporated to increase the accuracy, lower the errors and reveal the structure with more details. Surface wave studies as a branch of seismology are continuously evolving and their applications are to be utilized henceforward.

This thesis, built up using the papers written by the author and his supervisor and consultant, offers not only a simple compilation of the published works. It introduces the papers in a comprehensive framework of theoretical background and software tools. Besides that, different topics of the papers enable different views at the single surface wave phenomenon. The papers are consistently joined in a standalone work which results in, as I hope, not only giving a sum of the results of the original papers. I have written the thesis to present the synergy of the particular topics, which enables close look at the surface wave theory, software, actual measurements and results.

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