Review of doctoral thesis

Title: Seismic waves in inhomogeneous, weakly dissipative, anisotropic media

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Overall characteristics of the thesis

The thesis deals with various aspects of seismic wave propagation in dissipative media. It is based on 5 scientific peer-reviewed papers and 3 reports of the SW3D series in which the applicant is the first author or co-author. However, it does not take the form of a collection of these articles accompanied by an introductory commentary, as is common in such a situations, but takes the form of a single continuous text. However, the individual chapters generally reproduce some of these papers and are not very interrelated. The thesis thus appears thematically fragmented.

Chapters 1-3 contain the theory and synthetic data only. The analysis of real data measured in various regions is contained in chapters 4-6.

In Chapter 1, weak attenuation concept (WAC) is briefly introduced. The method is known for a long time (e.g., Gajewski & Pšenčík, 1992). It is based on the idea of small perturbations to an elastic medium, in which case standard real rays can be used, in some approximation, instead of complex ones. The applicant implemented the approach into the ANRAY program package, designed for laterally varying anisotropic media. He applied the modified ANRAY package in several synthetic examples demonstrating the WAC approach and various attenuation effects. It is a pity that the models are too simple (1D or even homogeneous) and far from exploiting the ANRAY potential. The calculations are performed in VTI models (i.e. anisotropic, but with a special symmetry) both with isotropic and anisotropic attenuation. The applicant also consider combined effects of anisotropic Q and directional source radiation, too bad he didn't do an inversion for source mechanism from synthetic data to demonstrate the influence of anisotropic attenuation on the result. At the end of the chapter the author briefly discussed also other than Futterman‘s attenuation models and attempted to investigate the applicability of WAC, unfortunately only in a homogeneous and moreover only isotropic structure.

The second chapter deals with reflected and transmitted SH waves in slightly dissipative isotropic media. The theory of the relevant plane-wave R/T coefficients is reproduced from the paper by Pšenčík et al. (2022), however, without explaining the weak attenuation concept in the R/T problem (small perturbations over elastic case). The calculation of the WAC R/T coefficients is implemented into the SEIS package, designed for isotropic structures. The author presents the SH R/T coefficients for few interface models, both for homogeneous and inhomogeneous incident wave. In the former case the coefficients are compared with an independent solution by Dahley and Krebes (2015). Synthetic seismograms are presented for some other single interface models and compared with full-wave solution. The same models are also used to demonstrate the influence of frequency dependent reflection SH coefficient in various attenuation models. At the end of the chapter, synthetics for a double interface model are calculated in a very simplified way (inhomogeneous character of the wave transmitted through the first interface is neglected) and those are again compared to full-wave seismograms.

Chapter 3 presents the so-called peak-frequency method, both the determination of peak frequencies and the possibility of using them to estimate the effective Q in regions offering sufficient amount of data (multiple sources and receivers). The relation of the peak frequency to the source-spectrum corner frequency is discussed. The method is suitable for microseismic studies, not only for lots of data usually available but also for higher frequency content in the data for which the attenuation effects are more pronounced. The chapter also contains a brief explanation of body-wave attenuation tomography, but without any citations of the basis of this method (e.g., Scherbaum, 1990; Liu et al., 2014, Bennington et al., 2008).

Chapter 4 is devoted to the geodynamically active region of West Bohemia, characterized by recurrent earthquake swarm occurrence and various post-volcanic phenomena. The author used data from the 2008 swarm (four selected separate days, M_L between 0 and 1) at seven selected Webnet stations and applied the peak-frequency method to investigate attenuation and its possible temporal changes. Also interesting is the discussion of the influence of the fluid saturation of rocks to their attenuation parameters. Data from NKC are moreover used to estimate Q in the focal zone. In the introduction of the chapter the author mentions previous attempts to determine Q in the given area (Bachura and Fischer, 2015; Mousavi et al., 2017), but unfortunately he does not compare his results with these studies.

In Chapter 5 the peak-frequency method is applied to 127 induced events with M_L between 0.3 and 1 recorded at four local stations in the vicinity of the oil field of High Agri Valley, Italy. Q_P was estimated at all four stations, Q_S at only two of them. Anomalous Q_P/Q_S ratio at the MOME station, the closest to the wastewater well, was interpreted as a consequence of rock saturation due to water injection. To support that hypothesis, the data set was extended by stronger events with the aim to reveal possible anomalies in the v_p/v_s ratio distribution Application of two independent methods resulted in detection of anomalous v_p/v_s at MOME.

In the last chapter the peak frequency method is applied to extensive data set from a star-like surface array in a shale reservoir in North China to study effects of possible source directivity combined with attenuation. In the study, an induced event of M~1, related to hydraulic fracturing, was considered. Manually picked P-wave amplitudes were used to invert source mechanism. Measured peak frequencies display spatial distribution which can be caused by source directivity. This phenomenon is investigated by synthetic spectra calculated in a grid-search for various source parameters, including rupture direction and rupture velocity. Best misfit solutions indicate possible super-shear rupture, what is really interesting in the context of microseismicity. The source directivity seems to be confirmed also by amplitude distribution.

Since in five of the six chapters only isotropic media are considered and most of the calculations throughout the thesis are carried out in 1D or even homogeneous structures the title of the thesis may be somewhat misleading.

Topicality of the subject

Although WAC theory has been known for decades, its implementation into the sophisticated software package ANRAY is new and can extend the possibilities of theoretical modelling in complex dissipative structures, which is very relevant today.

The use of WAC the related determination of Q in the context of microseismic studies, either in regions with natural seismicity or in regions with induced/triggered seismicity related to, e.g., geothermal energy production or hydro-fracturing to extract oil or gas, is highly topical.

Methods applied

The work is based on the use of WAC both in theoretical forward modelling of synthetic wavefields and for the peak-frequency estimates applied to analyze real data measured in selected regions of interest with a focus on Q determination.

Results of the thesis and its specific contribution

The thesis has two types of outputs. First the program package ANRAY has been modified to include dissipative anisotropic models, i.e., models much closer to reality than it was possible up to now. Other outputs are interesting results of microseismic studies in three selected regions, aimed to retrieve spatial distribution of effective Q in the regions including possible time changes of the distribution. I also consider it interesting to study the source effects in dissipative media and the discovery of probable source directivity in the case of very weak earthquakes (M~1).

Clarity, formal editing and language level of the thesis

The thesis consists of several chapters that do not relate to each other, which makes it difficult to orient the reader in the text. It also contains many formal drawbacks, e.g. in the description of some figures or in the values of some quantities used for the model examples, etc. The level of English is very uneven, with some parts written in very good English but others where English is very poor and the text is difficult to understand.

General comments

No general conclusions about the applicability of WAC can be drawn from a single comparative calculation, moreover for such an extremely simplified model. The author presents comparison of a synthetic seismogram calculated by ray+WAC technique with full wave solution by Carcione (2014) at just one receiver (and one component only) in a homogeneous isotropic medium. More tests of WAC applicability should be presented, possibly collected from the existing literature on the subject, with focus on more complex media. Note that the problem of general conclusions based on a single very simplified synthetic example appears in several places in the thesis, e.g., negligible influence of attenuation to R/T coefficients outside the critical region, negligible frequency dependency of the coefficients for non-constant Q models, the possibility to ignore inhomogeneity of a transmitted wave incident to another interface in a layered model, etc..

In the thesis, a method of analytical calculation of the R/T coefficient in the frame of WAC in an isotropic dissipative medium is presented without explaining, however, in what actually the WAC in the case of the coefficient consists. What small perturbation of what compared to the elastic case does the author have in mind? What is the applicability of such an approximation with respect to Q and the degree of inhomogeneity of the incident/generated wave? Why does the author present the calculation of the coefficients in the dissipative model only for the SH component of S waves? Is there any principle problem in the calculation of the coefficients with more practical use, e.g. for P waves? In several places the author mentions as unphysical when the modulus of the reflection coefficient for the displacement exceeds 1. This in itself is not unphysical and we occasionally encounter this phenomenon in dissipative models (Brokešová, 2001). Note that the energy balance is preserved even in this case thanks to the interaction energy flux, as explained by Borcherdt 1977, Krebes1983, see also Borcherdt et al.1986 or Carcione1997. I have noticed that the results of the very extensive chapter 2 are not used anywhere else in the thesis.

In the thesis we find considerations on the combined effect of directional source radiation and anisotropic attenuation and its possible influence on the inversion for the source mechanism. It is a great pity that the author did not show any (cautionary) example of the inversion affected by the attenuation using synthetic data in receivers suitably distributed around the source, when all the tools for this were available: ANRAY modified for dissipative models and the method of source-mechanism inversion which he even applied on real data in Chapter 6. It would indeed be an extremely valuable theoretical result. Does the author intend to pursue this topic in the future?

Issues that can be discussed as part of the defense

Can anisotropic attenuation be introduced into isotropic models?

How reasonable is to consider homogeneous Q distribution in inhomogeneous velocity models (e.g., gradient models)?

Based on experience with real data, how much may differ peak frequencies determined from different components of the seismogram?

Minor comments and typing errors

Introduction:

„The strength of attenuation inside Earth crust is of magnitude that allows to consider attenuation as perturbation of elasticity.“ … this statement is not justified either by relevant argumentation in the text or, at least, by a proper citation.

„Without great efforts, a similar procedure as used for the calculation of SH-SH coefficients can be applied to … anisotropic media.“ – I do not understand the point as in anisotropic media the R/T coefficients are evaluated numerically while the author consider an analytical expression for SH-SH coefficient.

Chap. 1

Page 8 - **u(x,t)**, boldface should be used for vectors, so not for time t

- The term ‘ray velocity’ is misleading, use ‘group velocity’ instead.

Fig. 1.1. – The model is not sufficiently described. While 13 receivers are considered in the computations, we see only 7 receivers in the figure. There are no coordinates introduced despite the coordinates are used later, e.g. in Fig. 1.12. It would be worth plotting the rays from the source to the receiver array to see how curved they are in the given gradient model. What is the prevailing wavelength compared to the source-receiver and surface-receiver distances? A plot of the input signal and its spectrum would be very useful with respect to the considerations of frequency-dependent attenuation models.

Page 12 – „…the maximum amplitude of the radial component … is 2.7 times smaller …“This concerns probably the vertical and not radial component.

Figs. 1.2 – 1.5 – missing amplitude scaling factors

Fig. 1.3 and 1.5 – Why the vertical component at the depth of 1 km vanishes? Rays are curved in gradient models.

Fig. 1.6 – When normalizing amplitudes the scaling factors should be given.

Fig. 1.7 – Axes are not described (components)

- Where the reference isotropic Q values come from? (also in Page 17)

Figs. 1.8 – 1.11 – missing amplitude scaling factors

Figs. 1.10 -1.11 - as in Fig. 1.10., i.e., vertical component is not shown.

Figs. 1.12-1.14 – coordinate axes not defined (it is not clear how they are related to the source-receiver configuration)

Figs. 1.13-1.14 – It would be extremely interesting to show combined effects of anisotropic radiation and anisotropic attenuation (only explosion in anisotropically atteanuative medium and DC in isotropically attenuative medium are shown).

Fig. 1.15. Travel time instead of depth on the horizontal axes makes the reader's orientation difficult.

Page 24 – For the sake of formal consistency, formula for phase velocity in the Futterman‘s model should also be given when it is compared with other models (only group velocity is written on page 9).

Page 25 and Fig.1.17 – the parameters of the structure and source position with respect to the receivers are not specified.

Page 27 - The Ricker signal used is not sufficiently specified. A plot of the input signal should be shown.

- Structure is not sufficiently specified. Explosive source generates P waves but only S-wave velocity is specified.

Fig. 1.18-Amplitude scaling factors should be given when the seismograms are normalized.

-Why only one component shown? Which component? What is the wave type, P?

Chap. 2

Page 31 – Condition a) should be written in the form of simple formula, condition b) ditto

Eq. 2.4., 2.5, 2.6 - It is not explained that slowness is approximated in the frame of WAC

Eq. 2.5 and further – Is β_1 and b_2 real- or complex-valued. Not explained.

Page33 – The formulas for the SH R/T coefficients in WAC should be written explicitly.

- Formula (2.3) is always appropriate as it is general (no WAC approximation in it)
- The third criterion (R coefficients exceeding 1) is not correct as itself. The displacement coefficients may exceed 1. The problem would be with energy flux coefficients exceeding 1. (the same argumentation holds for the statement about a failure of WAC in Page 50)
- The correspondence principle may be ok, but WAC may not be applicable in some cases.
- I miss the discussion of the applicability of the R/T coefficient under WAC (allowable Q, γ, D values)

Fig. 2.2. – Caption: the critical angle is 53 deg (not 44, that seems to be the Brewster angle)

- Please comment the fact that γ=90 deg in overcritical region. Is it a general rule following from the theory?

Page 42 – “…we can expect that, in general, attenuation should not be a limiting factor for using the ray method with WAC.“ The statement is derived based on limited number of very simple examples for SH waves only. General conclusions cannot be drawn from so few specific examples. (The same in Page 50, top)

Tab. 2.2. - The test would be more informative if the model was based on the BC2. Why a completely different model is considered here?

Fig. 2.10. a) and b) mentioned in the caption are not in the figure itself

Figs. 2.11 – 2.14 – The coefficients are calculated for models proposed in Brokešová & Červený (1998). So it would be worth comparing the coefficients with those published in that paper (namely for γ=+/- 30 deg). Those coefficients are more general, no WAC is used to derive them, and so such a comparison could shed more light on the applicability of WAC R/T coefficients.

Page 49 – It would be extremely interesting to show the propagation and attenuation vectors for selected angles of incidence of the inhomogeneous wave (in analogy to Fig. 2.2)

Tab. 2.3. - The test would be more informative if the model was based on the BC2 (or, at least, one of the models listed in Tab. 2.2). Why a completely different model is considered here?

Page 50 –„ In Figure 2.30…“ It is definitely incorrect number. (Fig 2.11 or 2.12?)

Fig. 2.16. – What is the type of the incident wave? (homogeneous or inhomogeneous).

Page 54 – „For offsets larger than 0.9 km, the head wave starts to separate from the reflected wave …“It is visible even for the offset of 0.8.

Fig. 2.19 – Why the ‚low-frequency‘ head wave (integral) is affected more than the ‚high-frequency‘ reflected wave?

Page 56 – „Specifically, one can observe increase of ray amplitudes to infinity….“ Only finite maximum values are seen in Figs. 2.20.-2.22

Page 62 – „…seismograms with frequency-dependent reflection coefficients…“ How are they calculated? It should be explained in more detail. How wide is the source time function spectrum?

Figs. 2.27-2.29 – The differences between the red and black seismograms are too small to be seen. Difference plots should be provided.

Tab. 2.4. - The test would be more informative if the model was based on the BC2 (or, at least, one of the models listed in Tab. 2.2). Why a completely different model of the first two layers is considered here? Why so small densities below the second interface?

Fig. 2.35 – I do not see the reason why the figure for inappropriate R/T coefficients is involved?

Chap. 3

Eq. 3.1. – Valid for smooth media, otherwise it should involve the product of R/T coefficients along the ray path.

Page 84 – It should be noted that the method is applicable under the assumption of homogeneous or only slightly inhomogeneous medium.

Eq. 3.16 – $\Delta t_{2,1}$ undefined

Chap. 4

Fig. 4.1 – a) the solid black line not described in the figure caption (the same in Fig. 4.4)

b) Missing horizontal coordinates

Fig. 4.3 – What components are shown? Does the evaluated f_{peak} differ for different components?

Page 88-89 – What is the total number of the processed events and how many P- and S-waveforms are used?

Fig. 4.5. – For the sake of credibility, the same test should be shown also for the VAC station that is at similar distance to the foci cluster. Are results for VAC worse in some sense?

Fig. 4.7. – It would be worth indicating centroids of the considered events in the map.

Page 94 – For the sake of consistency with chapter 3, the Q factor in the focal zone should be denoted as Q_{source}.

Chap. 5

Fig. 5.2. – Wave types and components not specified.

Fig. 5.3 – Where are the Q values used to plot the theoretical f_{peak} as a function of travel time taken from?

- In the caption there should be eq. (3.7) instead of (3.6).

Fig. 5.4 - Peak frequency of what type of wave (P or S) is shown?

- For the sake of credibility, analogous figures should be shown for the three remaining stations as well.

Fig. 5.6 – The data time range is by one year longer that the time interval mentioned on page 104

Tab. 5.3. - Both the 1D and 3D model should be specified. Only the existence of two layers (without details) is mentioned in the text on page 113.

Chap. 6

Tab 6.1. On which of the two nodal planes is the rupture direction of the best-misfit solutions in the table?

Fig 6.9 – The picture is too small, individual symbols are not distinguishable.

- What angle is α ? In the figure caption it is described as the angle „between the rupture direction and the ray take-off angle“ while in the text (p. 130) it is the rupture direction measured from the vertical in the fault plane.

Fig. 6.10. – For the sake of formal consistency with the text, V_{RU} should be used instead of V_R

Page 134 and Fig. 6.11 – Unclear meaning of the angle α. Is it the same as in Figs. 6.9 and 6.10a?

- How are the synthetic amplitudes calculated? Are rays traced through the isotropic structure in Fig.6.2? Is the WAC approach implemented to ANRAY (or SEIS) used? What is the value of Q? What is the source time function? More details on computation of the synthetics should be presented. Examples of synthetic vs. observed seismograms would be very useful.

Page 135 – A picture showing „observed-to-synthetic amplitude ratios as a function of α" with the linear regression fit mentioned in the text is missing. It should definitely be shown, especially when the regression coefficients serve to correct amplitudes for source mechanism retrieval.

Summary

An important part of the work is the implementation of WAC into the ANRAY software package, which can be a great contribution to synthetic seismology. The investigation of attenuation in microseismic studies offers a wide range of interesting applications.

Despite a lot of formal deficiencies mentioned above, the thesis contains significant novel results. The applicant has demonstrated a good knowledge of the relevant scientific literature, skills in programming and he has proved the ability to carry on scientific research. I therefore recommend that the thesis, after successful defense, is accepted and that the applicant is awarded PhD degree.

Prague, October 9, 2023

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