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Adjoint tomography of 2D local surface sedimentary structures

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1. Introduction

Prediction of earthquake ground motion

Though the occurrence of earthquakes is extremely difficult to timely predict, it is extremely important to properly account for predicted earthquake ground motion during potential future earthquakes by an earthquake-hazard analysis – especially in densely populated areas and at sites of special importance.

Predicting of what can or will happen during a future earthquake is vital for land-use planning, designing new buildings and reinforcing existing ones. It is also extremely important for undertaking actions that could help mitigate losses during future earthquakes. Proximity to a seismogenic fault obviously poses an earthquake threat. Being atop sediment-filled basin or valley, i.e., a local surface sedimentary structure, can also considerably increase the earthquake hazard. This is because seismic wave interference and resonant phenomena in sediment-filled basins and valleys can produce anomalously large earthquake motion at the Earth’s surface and lead to the so-called “site effects”: characteristics of earthquake vibratory motion of the Earth’s surface can attain locally anomalous value.

Prediction of the earthquake ground motion for a given area or site might be based on an empirical approach if sufficient earthquake recordings at the site or physically relevant for the site are available. However, even in the earthquake most active regions of the world, the numerical modelling has clearly proven to be an irreplaceable tool in investigating physics of earthquake ground motion. In the regions with lower seismic activity, seismologists face a severe lack of data. Consequently, it is the theory and numerical simulations that have to be applied to “replace” non-existing earthquake recordings.

In recent international comparative numerical exercises on numerical prediction of earthquake ground motion in local surface sedimentary structures, ESG 2006 for Grenoble Valley, France (e.g., Chaljub et al. 2010), and E2VP for Mygdonian basin near Thessaloniki, Greece (e.g., Chaljub et al. 2015, Maufroy et al. 2015, Maufroy et al. 2016), teams with the most advanced numerical-modelling methods reached very good level of agreement among different methods (finite-difference, spectral element, discontinuous Galerkin, pseudospectral). The synthetics, however, were not sufficiently close to records of real earthquakes. It was concluded that improving forward modelling methods in not enough in order to obtain sufficient agreement between numerical prediction and records. Instead, the improvement of the available structural model is necessary.

To evaluate sensitivity of the recorded wavefield with respect to the available structural
model and sources, and thus to find origins of discrepancies between numerically simulated motion and records, an adjoint method can be used (Day et al. 2012). Thus dedicated measurements can constrain values of the most significant parameters. A seismic inversion can be used to find an improved structural model even in situations where the dedicated measurements do not provide satisfactory results.

**Full waveform inversion**

An inversion is a process of obtaining seismic parameters (sources and/or model of medium) using recorded seismic motion. Many inversions use only simple characteristics, e.g., arrival times of seismic phases. Full waveform inversion is an inversion using as much of recorded waveform data as reasonable.

The discrepancy between numerically simulated motion and true, recorded motion is quantified by misfit. It is natural to think of utilizing the misfit for improving the model of the local surface sedimentary structure.

In realistic configurations, no explicit formula for model or source as a function of seismic motion can be obtained. Instead, many inversion procedures relay on implicit approach. In these procedures, a set of preliminary, test models is firstly generated. The test models are evaluated and compared by calculating misfit using forward simulations. A simple trial-and-error approach needs to sample a large space of possible models to be successful. This is computationally intractable. For achieving a reasonable efficiency, we need a method capable of using a misfit to iteratively generate improved test models based on misfits calculated for the already evaluated models. An iterative minimization of a misfit value significantly reduces the number of models which have to be evaluated. Obviously, efficiency of the iterative inversion strongly depends on efficiency of the numerical-modelling method and the method of generation of models. An inversion solely imaging the structure, i.e., (parts of) the Earth’s interior, is called seismic tomography.

Adjoint tomography is seismic tomography that uses seismic records, numerical solution of the equation of motion and a mathematical tool – the adjoint method. The adjoint method gives a recipe for computing kernel – a gradient of the misfit (Fréchet derivative) with respect to material parameters. The gradient can be used for improvement of the model. The method was introduced to seismology by Bamberger et al. (1997), Lailly & Bednar (1983) and Tarantola (1984a) for acoustic waves, and implemented by Bamberger et al. (1979, 1982) and Gauthier et al. (1986). Theoretical background for inversions of elastic and anelastic waves was
developed by Tarantola (1987, 1988), and implemented by Crase et al. (1990). While the theoretical background was available, real-world applications had been hindered by insufficient computational capacity for full waveform simulations. Only high-frequency approximations were used for inversions. The finite-frequency theory was based on the fact that the wave propagation is affected also by the structure in the vicinity of the ray (Yomogida 1992). Material parameters in the “banana-doughnut” shaped influence zone were iteratively changed to minimize the misfit (e.g., Marquering et al. 1998, 1999, Friederich 1999, Dahlen et al. 2000). The finite-frequency approach had been successfully applied both in the global surface-wave (e.g., Zhou et al. 2006) and body-wave (e.g., Montelli et al. 2004) tomography, and in the regional tomography (e.g., Friederich 2003).

Tromp et al. (2005) showed that the adjoint method is closely related to the finite-frequency “banana-doughnut” theory. 3D kernels using real data have been computed both on the regional and global scales (Zhao et al. 2005, Liu & Tromp 2006, 2008). In their article, Zhao et al. (2005) also formulated an alternative to adjoint method, the scattering integral method. The scattering integral method and adjoint method are closely related (Chen et al. 2007a). The first application of the 3D full waveform tomography using real data in structural seismology was done by Chen et al. (2007b). Soon other studies followed. For example, Fichtner et al. (2009b, 2010) investigated the upper-mantle beneath Australia, Tape et al. (2009, 2010), Lee et al. (2014), Lee & Chen (2016) the crustal structure in southern California, Zhu et al. (2012, 2013), Zhu & Tromp (2013) and Fichtner et al. (2013) in Europe, Rickers et al. (2013) in North Atlantic, and Chen et al. (2015) in East Asia. While the resolution of the main structural features is convincing, smaller details can be still ambiguous due to the inherent non-uniqueness of the inverse methods (see, e.g., Hosseini & Pezeshk 2015). Anisotropy still poses a challenge, mostly due to its trade-off with isotropic heterogeneity (Liu & Gu 2012).

Because full 3D waveform inversions are computationally very demanding, hybrid approaches based on perturbation theory developed by Li & Romanowicz (1996) were used to obtain global upper-mantle (Lekic & Romanowicz 2011) and whole-mantle (French et al. 2013, French & Romanowicz 2015) structure.

Recently, full 3D waveform inversions were applied for improving previous Earth models – e.g., PREM (Dziewonski & Anderson 1981), Crust2.0 (Bassin et al. 2000), Crust1.0 (Laske et al. 2013), S362ANI (Kustowski et al. 2008) and S40RTS (Ritsema et al. 2011). As a result, new models have been developed – crust and upper mantle model EU60 (Zhu et al. 2015), First-generation global tomographic model (Bozdag et al. 2016) and collaborative Earth model (Afanasieiev et al. 2015).

2. Goals

Even with well enough constrained source, the principal difficulty in utilizing numerical prediction of earthquake ground motion based on forward modelling is an insufficient knowledge of the structural model beneath the site of interest. The reason is that dedicated measurements, possibly leading to sufficiently determined structural model in the entire frequency range of interest, are very expensive, and technologically and methodologically far from trivial. Numerical methods must be involved.

Therefore, the goal of dissertation is to develop a methodology for an improvement of a poorly determined structural model of a local 2D surface sedimentary structure using available seismic records so that the improved model can be used for a sufficiently accurate numerical prediction of earthquake ground motion at the site.

Only a small number of recordings, that can be expected to be available for a given site of interest, are to be used. However, to be useful for numerical prediction the inverted model should not only fit the provided data, but should be sufficiently accurate for additional sources and receivers.

This work should provide a solid basis for elaborating methodology for 3D local surface sedimentary structures using real data in the follow-up studies.

3. Contents and results

To fulfil the goals we have chosen to develop a methodology based on adjoint tomography. The adjoint tomography is an iterative gradient method used to find an inverted model of an unknown structure using seismic records at receivers. In the iterative method, the inverted model is found using a sequence of models. The models in the sequence lead to decreasing values of misfit between the numerical simulations for these models and records. The gradient of misfit with respect to the model parameters is calculated according to adjoint method.

During the development of methodology for the adjoint tomography of local surface sedimentary structures we had to respect the specific aspects of these structures. The development was based on results of numerous tests on various canonical local surface
sedimentary structures. The result is the presented procedure for the full waveform adjoint tomography in local surface sedimentary structures.

In order to verify the developed inversion procedure, we used a blind test. The blind test was an inversion of an undisclosed structure using the obtained seismic records. As a result of the inversion, we have obtained an inverted model for which the simulated seismograms are very close to the records as shown in Fig. 1.

![Fig. 1 Seismograms at receivers 1-8 simulated for the final inverted model (in red) compared with records (in black). Event 1: seismograms simulated for source 1, event 2: seismograms simulated for source 2.](image)

The verification of the procedure continued with the final inverted model fixed. We have calculated seismograms for additional sources and receivers to see whether the inverted model fits only the data used in the inversion or the misfit is reduced also for this additional data. Fig. 2 demonstrates that L2-norm, envelope, and phase misfits are reduced both for seismograms used in inversion and for additional seismograms added later. This indicates that no overfitting of data happens.
Using the final inverted model we demonstrate the potential usefulness of the adjoint tomography as a tool for the earthquake ground motion prediction for local surface sedimentary structures. In Fig. 3 we show that calculated GOFs for chosen characteristics of earthquake ground motion for the final inverted model are, on average, in excellent agreement with the records. These values are calculated for records which have not been used in inversion, i.e., excellent agreement can be expected for any future earthquake originating in the considered domain.

Finally, we compare the final inverted model with the disclosed structure and we can see a similarity between the models.
4. Conclusions

Based on extensive numerical modelling and testing we have developed a procedure for adjoint tomography for 2D local surface sedimentary structures. The procedure comprises:

- Waveform misfit. The waveform misfit is calculated for given source, receiver and component. We use the L2-norm misfit because it provides better results than a phase, envelope or time-shift misfits.
- Kernel. For updating model we use kernel as a sum of all source-receiver kernels, and name this kernel the aggregate kernel.
- Kernel computation. We use an efficient space-time accuracy-adaptive integration.
- Kernel preconditioning. We use a spatially-dependent normalization by maximal absolute values and anisotropic smoothing. We apply a spatial mask for restricting a region of inversion. The mask is rectangular and kernel is nullified at the mask left, right, and bottom boundaries.
- Inversion model parameter. In the inversion, we directly calculate the shear-modulus (µ) component of kernel. This component is used for updating values of model. Afterwards, the Lamé elastic parameter λ is calculated from the chosen empirical relation between λ and µ.
- Misfit minimization. For updating model, we minimize the aggregate misfit – the sum of all waveform misfits at all receivers.
- Selection of an optimal step for updating model. We use a robust and efficient algorithm for finding an approximation of the optimal step with a small number of (computationally expensive) trial steps.
- Adaptive multiscale approach. We apply an inversion using a sequence of frequency ranges (scales). A subsequent frequency range is an extension of the current frequency range towards higher frequencies. Frequency ranges are calculated at the beginning of the inversion from the available records. Energies (in filtered records) corresponding to the sequence of the frequency ranges are logarithmically equidistantly distributed.
- Set of scenarios. We call a complete multiscale inversion using one set of values of inversion parameters a scenario. Because the best set of values of the inversion parameters cannot be determined at the beginning of the inversion process, it is necessary to try a set of different scenarios.
- Repetitive multiscale inversion. The best inverted model from all scenarios is used as a starting model for another set of scenarios.
We verified the procedure in a blind test. A third party provided

- seismograms numerically simulated for an undisclosed true structure,
- source parameters,
- material parameters of the bedrock.

As the initial model we assumed the simplest possible model – a homogeneous halfspace with parameters of the bedrock. We evaluated quality of the obtained inverted models using direct comparison of seismograms, waveform misfits (L2-norm, envelope and phase misfits), waveform goodness-of-fit (time-frequency envelope, time-frequency phase, single valued envelope and single-valued phase) and goodness-of-fit for selected earthquake ground motion characteristics (peak ground acceleration, peak ground velocity, peak ground displacement, spectrum intensity, cumulative absolute velocity, Arias intensity and root-mean-square acceleration). We also verified the inverted models for other source-receiver configurations not used in the inversion. Eventually we visually compared the inverted models with the disclosed true model.

We have developed and verified the procedure for 2D structures because development including extensive numerical modelling and testing for 3D would be computationally too heavy. We assume that the procedure can be in principle applied to 3D structures after some refinements due to 3D spatial distribution of sources and receivers.
Abstract

In recent international numerical exercises on numerical prediction of earthquake ground motion in local surface sedimentary structures (ESG 2006 for Grenoble Valley, France, and E2VP for Mygdonian basin, Greece) teams with the most advanced numerical-modelling methods reached very good level of agreement among different methods (finite-difference, spectral element, discontinuous Galerkin, pseudospectral). The synthetics, however, were not sufficiently close to records of real earthquakes. It was concluded that improvement of the available structural model is necessary. In this thesis we present a procedure for adjoint tomography for 2D local (small-scale) surface sedimentary structures. The problem of the local structure is specific in terms of relatively small amount of data, large initial waveform misfit, and low frequencies with respect to the size of the structure. These specific features are reflected in choice of misfit, definition, computation and preconditioning of kernel, selection of inversion model parameter, misfit minimization, selection of an optimal step for updating model, adaptive multiscale approach, set of scenarios and repetitive multiscale inversion. We verified the procedure in a blind test. A third party provided a) seismograms numerically simulated for an undisclosed true structure, b) source parameters and c) material parameters of the bedrock. We assumed a homogeneous halfspace as the initial model. We demonstrated quality of the inverted model up to the target frequency 4.5Hz using direct comparison of seismograms, waveform misfits, waveform goodness-of-fit, and goodness-of-fit for selected earthquake ground motion characteristics. We also verified the inverted model for other source-receiver configurations not used in the inversion. Eventually we compared the inverted model with the disclosed true model. We have developed and verified the procedure for 2D structures because the entire development (including extensive numerical modelling and testing) directly for 3D would be computationally too heavy. We assume that the procedure can be in principle applied to 3D structures after slight refinements due to 3D spatial distribution of sources and receivers.

KEYWORDS: ADJOINT TOMOGRAPHY, FINITE DIFFERENCE METHOD, EARTHQUAKE GROUND MOTION, LOCAL SURFACE SEDIMENTARY STRUCTURE
Abstrakt

V nedávnych medzinárodných testoch numerického predpovedania seizmického pohybu v lokálnych povrchových sedimentárných štruktúrach (ESG 2006 pre údolie Grenoblu, Francúzsko, a E2VP pre Mygdónsky bazén, Grécko) dosiahli tímy numerického modelovania veľmi dobrú vzájomnú zhodu pre rôzne metódy (konečné diferencie, spektrálne prvky, nespojitá Galerkinova metóda, pseudospektrálna metóda). Syntetické seismogramy však neboli dostatočne blízke záznamom skutočných zemetrasení. Účastníci testov sa zhodili na potrebe zlepšenia dostupných štrukturálnych modelov. V tejto práci prezentujeme procedúru adjungovanej tomografie pre 2D lokálne (malorozmerné) povrchové sedimentárne štruktúry. Probleém inverzií v takýchto štruktúrach je špecifický relatívnym nedostatkom dát, veľkým počiatkočným nesúladom a nízkymi frekvenciami vzhľadom na charakteristické rozmery štruktúry. Tieto špecifiká sú zohľadnené použitím misfitom, definiciou, výpočtom a úpravami kernelov, výberom invertovaných modelových parametrov, spôsobom minimalizácie misfitu, výberom optimálneho kroku pre zmenu modelu, použitím adaptívneho multiškálového prístupu, množinou scenárov a opakovanou inverziou. Procedúru sme verifikovali pomocou slepého testu. Mali sme k dispozícii a) seismogramy numericky simulované pre nás neznámu štruktúru, b) parametre zdrojov a c) parametre skalného podložia. Ako štartovací model sme uvažovali homogénny polpriestor. Kvalitu invertovaného modelu v rozsahu do 4.5Hz sme demonštrovali priamym porovnaním seismogramov, misfitov a kvantitatívnymi charakteristikami zhody hodnôt charakterístik seizmického pohybu. Invertovaný model sme verifikovali aj pre aditívne konfigurácie zdrojov a prijímačov. Nakoniec sme porovnali invertovaný model s odtajneným správnym modelom štruktúry. Vývoj a verifikácia procedúry sme realizovali pre 2D problém, pretože vývoj pre 3D problém by nebol v dostupných výpočtových podmienkach realizovateľný. Predpokladáme, že vyvinutá procedúra môže byť aplikovaná aj v 3D po zohľadnení 3D priestorového rozloženia zdrojov a prijímačov.

KLĹЎĽOVÉ SLOVÁ: ADJUNGOVANÁ TOMOGRAFIA, METÓDA KONEĽŇČÝCH DIFERENCIÍ, SEIZMICKÝ POHYB, LOKÁĽNE POVRCHOVÉ SEDIMENTÁRNE ŠTRUKTÚRY
List of publications

**AFG Abstracts for contributions in international scientific conferences**

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AFH01 Kubina, Filip [UKOMFKAFZMd] (40%) - Moczo, Peter [UKOMFKAFZM] (35%) - Kristek, Jozef [UKOMFKAFZM] (25%): Investigation of the use of the adjoint-tomography inversion to the small-scale surface sedimentary structure: the case of the Mygdonian basin, Greece
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