Univerzita Karlova v Praze

Matematicko-fyzikální fakulta

Autoreferát dizertační práce

Petra Adamová

Modely zemětřesného ohniska

Katedra geofyziky

Vedoucí dizertační práce: RNDr. Jan Šílený, CSc.

Studijní program: Fyzika

Studijní obor: Geofyzika

Praha 2013

Charles University in Prague

Faculty of Mathematics and Physics

Summary of doctoral thesis

Petra Adamová

Earthquake source models

Department of Geophysics

Supervisor of the doctoral thesis: RNDr. Jan Šílený, CSc.

Study programme: Physics

Specialization: Geophysics

Prague 2013

Dizertace byla vypracována na základě výsledků získaných v letech 2006-2013 během doktorandského studia na katedře geofyziky MFF UK a v Geofyzikálním ústavu AV ČR.

Doktorand:
RNDr. Petra Adamová
Geofyzikální ústav AV ČR
Boční II 1401,141 31 Praha 4
Katedra geofyziky MFF UK
V Holešovičkách 2,180 00 Praha 8
adamova@ig.cas.cz
http://www.ig.cas.cz/en/personal-pages/petra-adamova/

Obor studia:
4F7: Geofyzika

Školitel:
RNDr. Jan Šílený, CSc.
Geofyzikální ústav AV ČR
Boční II 1401/1a, 141 31 Praha 4

Oponenti:
RNDr. František Gallovič, PhD.
Katedra geofyziky MFF UK
V Holešovičkách 2, 180 00 Praha 8

doc. RNDr. Tomáš Fischer, PhD.
Ústav hydrogeologie, inženýrské geologie a geofyziky PřF UK
Albertov 6, 128 43 Praha 2

Předseda oborové rady:
Doc. RNDr. Hana Čížková, PhD.
Katedra geofyziky MFF UK
V Holešovičkách 2, 180 00 Praha 8

Autoreferát byl rozeslán dne:

Obhajoba se koná dne 25.11.2013 v 10:00 hod. před komisí pro obhajoby disertačních prací v oboru 4F7 Geofyzika na Matematicko-fyzikální fakultě Univerzity Karlovy v Praze, Ke Karlovu 3, v místnosti 105 (252).
S dizertací je možno se seznámit v PGS MFF UK, Ke Karlovu 3, Praha 2.

Contents

Abstrakt

Zemětřesné ohnisko je standardně popisováno pomocí momentového tenzoru. V mnoha případech potřebujeme více informací o seismickém zdroji, a proto se zabýváme vyššími momenty. Tento přístup nám umožňuje odhadnout nebodové veličiny včetně některých dynamických parametrů (geometrie zdroje, trvání zdrojového procesu, průměrný skluz na zlomu, prostorový a časový centroid a průměrnou rychlost rozrušování) z aproximace bodovým zdrojem. Tento popis zahrnuje celkem 20 parametrů: 6 pro standardní momentový tenzor a 14 pro momenty druhého řádu. Nejdříve aplikujeme metodu na syntetická data. Mnoho velkých zemětřesení na výrazných zlomech vykazuje falešnou nesmykovou složkou, která může být způsobena aproximací konečného zdroje zdrojem bodovým. Tato hypotéza byla ověřena na případu jednostranně se šířící trhliny kde klasický momentový tenzor obsahoval více než 20 % nesmykových složek a po odečtení vyšších momentů tato složka klesla na 6 %. V další části byla metoda aplikovaná na reálná data. Vybrali jsme velké jevy (Mw>6) s výraznou nesmykovou složkou. Určili jsme pro ně vyšší momenty a potvrdili falešné nesmykové složky způsobené konečností zdroje. V poslední části jsme aplikovali metodu na důlní data a určili rovinu zlomu.

Abstract

The earthquake source is routinely modeled by moment tensor description. In many cases we need more information about the source process and for that reason we occupy with higher degree moments. This approach allows us to estimate non-point characteristics (including some dynamic parameters): geometry of the source, duration of the source process, average slip on the fault, spatial and temporal centroid and rupture velocity vector within the point source approach. This description includes 20 parameters – 6 parameters for standard moment tensor (MT) and 14 parameters for second degree moments (SDM). First, we studied synthetic tests. Large amount of significant earthquakes contains false non-DC component which can be caused by approximation finite source by point source. This hypothesis was proved on the case of unilateral rupture. Standard MT contains more than 20 % non-DC components which was reduced to 6 %. In the second part we applied this procedure to real data. We chose large earthquakes (Mw>6) with large non-DC component. We estimated second degree mo-

ments for them and compared them with previous studies. Moreover we restitute higher degree moments from data and proved that false non-DC component were caused by source finiteness. In the last part we applied this method to mining data and identified the fault plane.

1 Introduction

Earthquake source modelling is a broad topic with different applications. These applications range from the earthquake mechanism retrievals mostly for needs of geologists inferring tectonics and its evolution in time, through modelling of fault slip history during significant and well monitored earthquakes, to investigation of the earthquake physics. In such a way it is possible to study the dynamics of rupture process in complexities of non-elastic rheology and examine constitutive laws ruling the phenomena on the crack edges and on the fault surface.

In our study we aimed at applications of the earthquake mechanism retrievals dealing with the mechanism of a seismic event but in a generalized way. This approach allowed us to extend the concept of the mechanism from a point source quantity towards the finite extent sources. The finiteness is treated in a simplified way, of course, aiming to keep the applicability of the method to events with a limited amount of data which excludes the reconstruction of slip history. The source finiteness in our approach means the determination of several integral parameters over the focus which provide rough information on its orientation, shape, average rupture velocity etc. When these parameters have been obtained, an implicit benefit can be seen in the identification of the fault plane from the couple of the nodal planes. Decreasing the ambiguity in the fault plane solution may be a major help for geologists who use seismic investigation and represent a bridge towards tectonic interpretations.

Knowledge of a mechanism of seismic wave generation is important because it provides the first insight into source physics and the processes inside. The process of rupturing of geological material is obviously very complex. Its study is indirect, from data which are necessarily limited due to technical aspects of data collection, and needs prior simplification. It means that we cannot study the physics of the process in a straightforward way as physicists do in their labs, but we are constrained to a phenomenological description of the source.

The moment tensor is the general dipole source (Backus and Mulcahy 1976a, b). It is the second-rank tensor, which describes a superposition of nine elementary dipoles: the diagonal components correspond to linear dipoles without torque, and the non-diagonal elements correspond to force couples. For the sake of interpretation it is usually decomposed into several "elementary mechanisms". Apart from the separation of the isotropic part

(ISO), the decomposition is not unique. The most common decomposition is separating the deviatoric part into the double couple (DC) and compensated linear vector dipole (CLVD) with the same P or T axis. Usually the moment tensor (MT) is not retrieved in the full complexity, but for the sake of increasing the stability of the waveform inversion, it is assumed to be deviatoric, i.e. without the ISO part.

Non-DC components (CLVD and ISO) have been widely studied during last years. Their occurrence can have many reasons (Julian et al., 1998; Miller et al., 1998). Let's note the following: 1. Complex shear faulting: multiple shear events, volcanic ring faults or Ortlepp shear fault (Ortlepp, 1984); 2. Tensile faulting: opening tensile faults, effects of fluids, combined tensile and shear faulting; 4. shear faulting in an anisotropic or heterogeneous medium.

The higher degree moment tensor representation was suggested by Backus (1977a, b). His formalism initiated the effort to determine finite extent source parameters described by higher degree moments from the inverse problem. Doornbos (1982) designed the source model based on second degree moments consisting of 20 parameters, which he related to Haskell (1964) and Savage (1966) finite extent fault models. Stump and Johnson (1982) related higher-degree moments with 19 parameters of plane rectangular shear source where the rupture propagates unilaterally with constant velocity and rise time. They found the convergence of the moment series to be frequency dependent with the higher frequencies being emphasized in the higher degree moment tensors. The convergence is also a function of azimuth and fault model. Das and Kostrov (1997) formulated the inverse problem of determining the temporal and spatial power moments of the seismic source moment rate density distribution. In numerical experiments, they demonstrated the necessity of the positivity constraints (in their formalism the absence of back-slip on the fault), which they enforced through a set of linear equations. They suggested to proceed from low degree moments (zero and first degree moments specifying the size and duration) retrieved from long periods to higher degree moments estimated from high frequencies. They stress the necessity to subdivide the source region to achieve a low approximation error of the Green's functions. Similarly, Dahm and Krüger (1999) pointed out that for inversion of seismic waves with periods and wavelengths in the range of the rupture duration and spatial extent of the fault, respectively, a single centroid is not sufficient for the Green's function approximation to be accurate enough. Therefore, they developed a method to estimate the extended source parameters by using higher degree moments at 27 centroid locations (3 along the time duration of the rupture and 9 centroids covering the rupture area). They developed an iterative scheme to estimate the higher degree moments related to uni- and bi-directional finite source model of Haskell, and showed that the rupture model can be distinguished, fault and auxiliary plane resolved and the rupture direction estimated. The higher degree moments approach has particular importance if applied to studying the foci of deep earthquakes because these seismic events usually have few aftershocks, from which extension of active fault area is usually estimated (the couple of papers listed above; Gusev and Pavlov 1986, 1988). However, it has been used to study the spatial-temporal characteristics of sources of shallow earthquakes as well (e.g., Silver and Masuda 1985, Bukchin et al. 1992).

From all the approaches listed we focused on the representation by Doornbos (1982) for its clarity and straightforward relation of its parameters to quantities describing the rupturing along a simple finite-extent fault.

Higher degree moments represent an advantageous formalism for description of the temporal and geometrical characteristics of extended seismic source from the point source approximation. It means that it is not necessary to specify ad hoc a finite extent focus (e.g., the fault plane orientation and size) and solve for the rupture propagation in a tomographic inverse problem. Of course, these two approaches are not equivalent: higher degree moments provide averaged parameters only while computing rupture propagation is performed to obtain a detailed insight into the kinematics of the rupturing. However, the approach of higher degree moments is less laborious and can be applied even when only low period data are available in a particular site. Thus, it is anticipated to be a next step following the standard retrievals of the seismic moment tensor. Then, we may ask a similar question which is vital in the routine of the MT determination, namely how reliably it is reconstructed when the response of the earth structure, the Green's function, is not known accurately. Apart from the global studies where extremely long waves are used, in local and frequently also regional studies, we rarely know the medium sufficiently well to model successfully the details of the waveforms. The poor knowledge about the medium in this frequency band is rather a rule than the exception. Therefore, it is important to investigate how the resolution of the parameters of the finite extent source, described by the higher-degree moments, is limited by the unfamiliarity with the medium. In configurations of several case studies, we intend to simulate mislocation of the hypocenter and mismodeling of the structure of the earth crust/mantle and test how successfully the finite source parameters are reconstructed.

We will apply this methodology to two applications. First, we apply second degree moments to large non-DC earthquake and show that these non-DC components can be caused by neglecting source finiteness. Second application will be determination of second degree moments for mining events where we can identify the fault plane from two nodal planes.

2 Second degree moments

If we have enough data available for the detailed modeling of the rupture history along the fault, we can use the second degree moment approach and obtain at least average values of parameters of the fault like geometry, orientation, slip velocity, etc. we can use second degree moment tensor. The standard moment tensor does not contain spatial information, and cannot be related to finite-extent source parameters like fault geometry, average velocity at the fault, etc. The information on geometry of the focus and simplified insight into the dynamics of the source process are contained in quantities called second degree moments (SDM). We follow the approach developed by Doornbos (1982). In his approach he starts from the relation of the displacement with moment tensor density

$$u_i(\mathbf{x},t) = \int_{-\infty}^{t} \int_V \partial\xi_k G_{ij}(\boldsymbol{\xi}, t-\tau) m_{jk}(\boldsymbol{\xi},\tau) dV d\tau \tag{1}$$

derived from the representation theorem. The elementary source substituted by the $m_{jk}(\xi,\tau)$ is applied at position $\boldsymbol{\xi}$ and in time τ; G_{ij} is Green's function tensor. In the following text (from the equation 2.2) we use notation $\partial\xi_k G_{ij} \equiv G_{ij,k}$. Equation (1) can be replaced by a point source representation by expanding $G_{ij,k}$ about a reference source point $\boldsymbol{\xi_0}$ using Taylor expansion up to degree two. The expansion of the Green's function can be written as

$$G_{ij,k}(\mathbf{x},\boldsymbol{\xi},t,\tau) = G_{ij,k}(\mathbf{x},\boldsymbol{\xi}_0,t,\tau) + G_{ij,kl}(\mathbf{x},\boldsymbol{\xi}_0,t,\tau)(\xi_l - \xi_l^0) \tag{2}$$

$$+\frac{1}{2}G_{ij,klm}(\mathbf{x},\boldsymbol{\xi}_0,t,\tau)(\xi_l-\xi_l^0)(\xi_m-\xi_m^0)$$

We neglect terms of degree three and higher. The displacement can be now written as

$$u_i(\mathbf{x},t) = G_{ij,k}(\boldsymbol{\xi_o},\mathbf{x},t,\tau) * M_{jk}(t) + G_{ij,kl}(\boldsymbol{\xi_0},\mathbf{x},t,\tau) * M_{jk,l}(\boldsymbol{\xi_0},t) + \\ +G_{ij,klm}(\boldsymbol{\xi_0},\mathbf{x},t,\tau) * M_{jk,lm}(\boldsymbol{\xi_0},t) \quad (3)$$

where

$$M_{jk}(t) = \int_V m_{jk}(\boldsymbol{\xi},\tau)dV \quad (4)$$

$$M_{jk,l}(\boldsymbol{\xi_0},t) = \int_V (\xi_l-\xi_l^0)m_{jk}(\boldsymbol{\xi},\tau)dV \quad (5)$$

$$M_{jk,lm}(\boldsymbol{\xi_0},t) = \int_V (\xi_l-\xi_l^0)(\xi_m-\xi_m^0)m_{jk}(\boldsymbol{\xi},\tau)dV \quad (6)$$

We expand the convolution into series of time moments of degree less than three (Doornbos, 1981)

$$u(t) = G(t)*\dot{F}(t) = G(t-\tau_0)F^{(0)} - \dot{G}(t-\tau_0)F^{(1)}(\tau_0) + \frac{1}{2}\ddot{G}(t-\tau_0)F^{(2)}(\tau_0) + \ldots \quad (7)$$

where $F^{(n)}(\tau_0)$ is n-th moment of the function F aroundτ_0

$$F^{(n)}(\tau_0) = \int_{-\infty}^{\infty}(t-\tau_0)^n\dot{F}(\tau)d\tau \quad (8)$$

When we use terms up to degree 2 only, we obtain the following formula:

$$
\begin{aligned}
\dot{u}_i(\mathbf{x},t) = {} & G_{ij,k}(\boldsymbol{\xi_0},\mathbf{x},t-\tau_0)\int_{-\infty}^{\infty}\dot{M}_{jk}(\tau)d\tau- \\
& -\dot{G}_{ij,k}(\boldsymbol{\xi_0},\mathbf{x},t-\tau_0)\int_{-\infty}^{\infty}(\tau-\tau_0)\dot{M}_{jk}(\tau)d\tau+ \\
& +\frac{1}{2}\ddot{G}_{ij,k}(\boldsymbol{\xi_0},\mathbf{x},t-\tau_0)\int_{-\infty}^{\infty}(\tau-\tau_0)^2\dot{M}_{jk}(\tau)d\tau+ \\
& +G_{ij,kl}(\boldsymbol{\xi_0},\mathbf{x},t-\tau_0)M_{jk,l}(\boldsymbol{\xi_0})- \\
& -\dot{G}_{ij,kl}(\boldsymbol{\xi_0},\mathbf{x},t-\tau_0)\int_{-\infty}^{\infty}\int_V(\tau-\tau_0)(\xi_l-\xi_l^0)\dot{m}_{jk}(\boldsymbol{\xi},\tau)dVd\tau+ \\
& +\frac{1}{2}G_{ij,klm}(\boldsymbol{\xi_0},\mathbf{x},t-\tau_0)M_{jk,lm}(\boldsymbol{\xi_0})
\end{aligned} \tag{9}
$$

For brevity we use term 'second degree moments' for all moments of degree 1 and 2, some authors use different terminology: 'first degree moments' for parameters with first GF derivative and 'second degree moments' for parameters with second GF derivative. Here, we introduce the second degree moments (SDM)

$$M_{jk}^{(n)}(\tau_0) = \int_{-\infty}^{\infty}(\tau-\tau_0)^n\dot{M}_{jk}(\tau)d\tau$$

$$M_{jk,l}^{(1)}(\boldsymbol{\xi_0},\tau_0) = \int_{-\infty}^{\infty}\int_V(\tau-\tau_0)(\xi_l-\xi_l^0)\dot{m}_{jk}(\boldsymbol{\xi},\tau)dVd\tau$$

Then, the formula for the velocity can be written as

$$\dot{u}_i(\mathbf{x},t) = G_{ij,k}M_{jk} - \dot{G}_{ij,k}M_{jk}^{(1)}(\tau_0) + G_{ij,kl}M_{jk,l}(\boldsymbol{\xi_0}) + \frac{1}{2}\ddot{G}_{ij,k}M_{jk}^{(2)}(\tau_0) - \tag{10}$$

$$-\dot{G}_{ij,kl}M_{jk,l}^{(1)}(\boldsymbol{\xi_0},\tau_0) + \frac{1}{2}G_{ij,klm}M_{jk,lm}(\boldsymbol{\xi_0})$$

This formula describes multipole expansion up to degree two of the velocity expression for point source. In general case this formulation contains 90 parameters. To reduce number of parameters we make assumption that all the components of the moment tensor have the same spatial and temporal history. In that case we simplify relations for second degree moments and reduce number of parameters to 20. For instance, for the SDM which corresponds to temporal centroid we can write

$$M_{jk}^{(1)}(\tau_0) = M_{jk}\Delta\tau$$

And analogicaly for the other SDM:

$$M_{jk}^{(2)}(\tau_0) = M_{jk}\Delta(\tau^2)$$

$$M_{jk,l}^{(1)}(\boldsymbol{\xi_0}, \tau_0) = M_{jk}\Delta(\tau\xi_l)$$

$$M_{jk,l}(\boldsymbol{\xi_0}, \tau_0) = M_{jk}\Delta\xi_l$$

$$M_{jk,lm}(\boldsymbol{\xi_0}, \tau_0) = M_{jk}\Delta(\xi_l\xi_m)$$

where

$$\Delta\tau = \int_{-\infty}^{\infty} (\tau - \tau_0)\, f_1(\tau) d\tau$$

$$\Delta\xi_l = \int_V \left(\xi_l - \xi_l^0\right) f_2\left(\boldsymbol{\xi}\right) dV$$

$$\Delta(\tau\xi_l) = \int_{-\infty}^{\infty}\int_V (\tau - \tau_0)(\xi_l - \xi_l^0) f_3(\boldsymbol{\xi}, \tau) dV d\tau$$

$$\Delta(\tau^2) = \int_{-\infty}^{\infty} (\tau - \tau_0)\, f_1(\tau) d\tau$$

$$\Delta(\xi_l\xi_m) = \int_V \left(\xi_l - \xi_l^0\right)\left(\xi_m - \xi_m^0\right) f_2\left(\boldsymbol{\xi}\right) dV \tag{11}$$

are SDM. Functions f_i are normalized functions which are defined by the following relations:

$$f_1\left(\tau\right) = \frac{\dot{M}_{jk}(\tau)}{M_{jk}}$$

$$f_2(\boldsymbol{\xi}) = \frac{m_{jk}(\boldsymbol{\xi})}{M_{jk}}$$

$$f_3(\boldsymbol{\xi}, \tau) = \frac{\dot{m}_{jk}(\boldsymbol{\xi}, \tau)}{M_{jk}}.$$

Then, the representation in equation (10) results in

$$\dot{u}_i(\mathbf{x},t) = M_{jk}[G_{ij,k} - \dot{G}_{ij,k}\Delta\tau + G_{ij,kl}\Delta\xi_l + \frac{1}{2}\ddot{G}_{ij,k}\Delta\left(\tau^2\right) - \tag{12}$$

$$-\dot{G}_{ij,kl}\Delta\left(\tau\xi_l\right) + \frac{1}{2}G_{ij,klm}\Delta\left(\xi_l\xi_m\right) + \ldots]$$

where x and ξ are respectively the point of observation and point on the fault, $u_i(x,t)$ is the velocity record, M_{jk} is the zero degree moment (6 parameters) - standard moment tensor describing the mechanism of a "point source", the others are 2nd degree moments: temporal centroid $\Delta\tau$, spatial centroid $\Delta\xi_l$, spatial-temporal moment $\Delta\left(\tau\xi_l\right)$, second temporal moment $\Delta\left(\tau^2\right)$, and second spatial moment $\Delta\left(\xi_l\xi_m\right)$. Second degree moments can be interpreted in terms of the parameters related to the finite extent of the focus: (a) temporal centroid (1 parameter) specifying the origin time of the finite-extent source estimate; (b) spatial centroid (3 parameters) – specifies the position of a point source substituting the finite-extent focus; (c) spatial-temporal moment (3 parameters): after division by second degree temporal moment it estimates the rupture propagation, i.e. both its direction and speed; (d) second temporal moment (1 parameter) – squared estimate of the source process duration; (e) second spatial moment (6 parameters) – geometrical characteristics of the source: it specifies an ellipsoid (hereinafter the source ellipsoid), the orientation of its major axis indicates the direction of the extension of the focus.

3 Application to strong earthquakes

We selected five strong tectonic events with large non-DC components in the Global CMT solution: Kobe earthquake (16/01/1995 at 20:46:59.4,M_w 6.9), Izmit earthquake (17/08/1999 at 0:1:50.1,M_w 7.6), Solomon earthquake (12/06/2003 at 8:59:23.9, M_w 6.2), Tohoku aftershock (07/04/2011 at 14:32:51.4, M_w 7.1), Bolivia earthquake (17/11/2005 at 19:27:0.0, M_w 6.8). Global CMTs are retrieved from long-period waves ranging about 125 - 350 s, while our MT are determined from low-pass filtered regional records in the range 20 - 50 s. Therefore, the MT solution and its non-DC content in particular, need not be necessarily the same. Nomination of eligible candidates was not completely straightforward due to several criteria which we demanded to be fulfilled with the aim of a prospective retrieval of the SDM. First, we need events from the last roughly 15 years because earlier the station distribution was frequently sparse, excluding retrieval of ”second-order” source characteristics. Second, we search among large events with magnitude above approximately 6.5 capable to be seen in regional distances, which is the range of available data. Moreover, we prefer to treat events associated clearly to a distinct geological fault, just to be able to verify resulting source parameters. And finally we concentrate on events with large non-DC components expressed in Global CMT and USGS solutions.

In the following, we describe shortly results for the selected earthquakes:

- Kobe 1995 earthquake

The Kobe earthquake (M_w= 6.9) occurred on 16th January 1995 in western Japan at the depth of 14 km. The mechanism is a strike slip with a small thrust component (Ide et al, 1996). We obtained very good agreement between the orientation of the source ellipsoid and its shape on one hand, and the aftershock distribution by Ide et al. (1996), on the other: aftershocks are sharply concentrated along a steeply dipping plane striking NE, the source ellipsoid in map view is narrow and stretched in the same azimuth. Rupture velocity vector, if drawn from the Harvard hypocenter, points towards the high-slip area, the estimated velocity is 2.8 km/s, see Fig. 1.

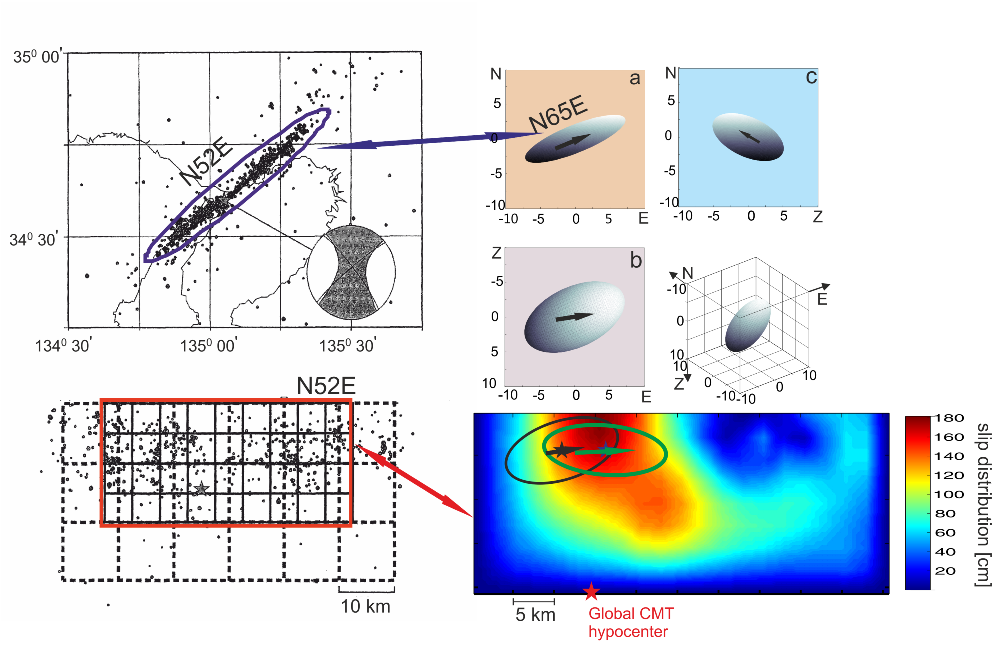

Figure 1: Second degree moments for Kobe earthquake. Left part shows aftershock distribution plotted by Ide et al. (1996). We compared this distribution with source ellipsoid on the right hand side of the figure. Right bottom part illustrate comparison between slip distribution and velocity vector.

- Izmit 1999 earthquake

A very strong earthquake (M_w= 7.6) occurred in 1999 on the Northern Anatolian fault in Turkey near the town Izmit. The centroid moment tensor (CMT) reported by agencies contains large amount of the CLVD. Slip distribution of this event was studied by several authors from high frequency data recorded near the fault. Clévédé et al. (2004) analyzed teleseismic surface waves in the periods 50-100 s and were the first who determined second degree moments of this earthquake. In detail they compared their integral parameters with those derived from slip distributions obtained by several authors from high frequency data recorded near the fault on one hand, and from GPS, SAR and tectonic observations on the other. They showed that although these slip distributions differ a lot, some of the integral characteristics are similar and can be compared with their long-period solution. Then, by evaluating parameters of 'equivalent models', i.e. constrained simplified models of slip distribution on the assumed fault plane, they arrived with conclusions which parameters rule the integral characteristics they decided to compare. We obtained the source ellipsoid well similar in both the shape and size with their study regardless rather different frequencies involved in the data being processed in the two approaches: we inverted low-pass filtered records, while Clevede et al. (2004) evaluated the source ellipsoid from the slip distributions obtained from high frequency data. The average velocity of rupturing was estimated as 2.6 km/s.

- Solomon 2003 earthquake

The Solomon earthquake (M_w= 6.2) occurred on 12th June 2003 in the Pacific area near Solomon's islands at a depth of 185 km. Source ellipsoid is very slim and elongated in a single direction. This indicates a nearly linear source, where the rupture propagates either unilaterally or bilaterally. The reasonable value of the average rupture velocity derived from the retrieved SDM suggests that the former option is probable.

- Aftershock of Tohoku-oki earthquake

The aftershock of the large Tohoku-oki earthquake (11 March 2011, M_w= 9.1) occurred on 7 April 2011 at a depth of 53 km about 60 km to the west from the main shock. We compare our MT solution with Global CMT and obtained very similar solution, the only difference is in the non-DC part. In the second step we inverted for the SDM. The parameters obtained are summarized in Table 2 and Fig. 8 in P2.

- Bolivia earthquake

A magnitude 6.8 earthquake occurred on the Bolivia and northern Chile border on 17 November 2005 at a depth of 155 km. The earthquake was centered 110 kilometers east of Calama, Chile, in the Potosi region of Bolivia. In comparison of our MT with Global CMT solution, a good similarity of the fault plane solution can be seen, but there is a small difference in non-DC part of the MT solution. As to the SDM, the results seem to be fairly realistic taken into account the scheme of the subduction process, but we cannot compare it in detail with any previous study. The parameters obtained are summarized in Table 2 and in Fig. 9. in P2.

More detailed results (mainly figures for MT and SDM and comparison with the previous studies) are summarized in paper **P2**.

4 Application to the mining tremors

Finite sources in mines are rarely investigated by seismologists. Foci of mining tremors are usually treated in the point source approximation and inverted for the moment tensor solution (usually an amplitude MT inversion) which yield basic information about the seismic source. In this chapter, we apply second degree moments method, recently tested on synthetic data (Adamová and Šílený, 2010) and on large tectonic events (Adamová and Šílený, 2013), to mining induced data.

Monitoring of mining induced events underground frequently has an additional advantage compared to recording seismograms of natural earthquakes: stations are not constrained to a single level - the Earth surface, so they are situated both above and below the focus of the event. Also the azimuthal distribution is often better in mines than for events in global seismology. Additionally, identification of phases is significantly simplified, as often only the direct P and S body wave arrivals need to be considered-due to the simplicity of the velocity model.

For this purpose, we tested the method on local records from the deep-level gold mine Ridgeway in East Australia. Ridgeway Mine, situated in the Cadia Valley province in New South Wales, Australia, is a block-cave mine operated by Newcrest Mining. It is one of the largest underground operations in Australia but it will be surpassed by the nearby Cadia East (also Newcrest Mining). The ore body has the shape of an inverted teardrop and is situated 500 m below surface.

A significant advantage of the data set from Ridgeway mine is that it has been processed on a routine basis by the Institute of Mine Seismology (IMS). The Institute provides seismic service for this mine; they manually picked thousands of events and located them. Only part of these events can then be used for the source inversion: they process data with magnitude larger than zero using spectral amplitude inversion method. Their results provide basic information about the source while our solution yields more detailed information of seismic source including its size and shape.

We selected five events from the Ridgeway data set mainly according magnitude and directivity in the data: we need larger events (approximately above magnitude 1.0) with pronounced directivity because it is an indication of the source finiteness, which we intend to study by means of the second degree moments. Generally we require good signal to noise ratio and no instrumentally destroyed data.

Second degree moments

Benefits of evaluation of the second degree moments are twofold. Mining tremors frequently exhibit significant non-DC mechanisms, which reflects the complex mining environment (caves, tunnels, etc.) and ambient stress field. The SDM method allows for making the estimate of the non-DC contents more precise than for the large non-DC components described in the previous section. The other advantage provided by the SDM technique is the hint about the fault plane, which is particularly beneficial in the mining environment, where knowledge about small scale tectonics is frequently scarce. Large faults within the mine are regularly mapped by mine geologists by in situ observation.

We apply the same methodology as for large earthquakes. We choose frequencies slightly above corner frequency for estimation of SDM. A careful trade-off needs to be made here, as on the one hand the effects of a finite source need to be preserved in the seismograms, whilst simultaneously the seismograms should be simple enough to allow for successful inversion. A simple indication of the finiteness of the source is the observation of directivity effects in the records, namely distinct pulse widths at different azimuths. We found that the SDM parameters involving time are much more stable than those containing spatial information - temporal parameters converge to their final value faster than the spatial ones. The less stable parameter is the source ellipsoid because it contains the second order spatial derivative. Moreover, the temporal and spatial centroid are determined more easily (i.e. parameters connected with the Green's function's first derivative) than the other second order moments - it needs much less iterations during the numerical procedure. This is not surprising, as the centroids are related to the Green's function derivatives of lower order than for the other SDM parameters. A very important description of a finite-size focus is the average velocity of rupture propagation. It can be determined as a ratio of two parameters from the SDM set (for unilateral rupture it is defined as the ratio of the term containing combination of spatial and temporal derivative and term with second temporal derivative - for details see the Theory section). For all events we obtain a rupture velocity of around 2 km/s.

Removing ambiguity of the fault plane

The source ellipsoid is a characteristics of the focus which is of extreme importance, as it can help to eliminate the ambiguity involved in the fault-plane solution, thus to identify the correct fault plane from the couple of nodal planes that are indistinguishable from the radiation pattern in the classical DC solution. The source ellipsoid (as symmetric 3×3 matrix) is defined by the six SDM parameters. By evaluating its eigenvalues and eigenvectors we can determine the directions and lengths of its principal axes. For all the events considered, the source ellipsoids display a large eccentricity, i.e. they are stretched in a single particular direction. This is an important feature, as they can be used as a hint to discern the fault from the two nodal planes determined by the DC part of the MT solution: the fault should be identified with that plane which contains the major axis of the source ellipsoid. In this way, for Events 1, 3, 4 and 5 the fault was determined clearly, while for Event 2 the ellipsoid lies very near to intersection of fault and auxiliary plane.

Comparing our fault plane solutions with the known geological faults at Ridgeway Mine, we find generally a good agreement. Our solutions (in the form of the source ellipsoids) as well as the 3D representation of the faults are shown at Figure 2 for comparison.

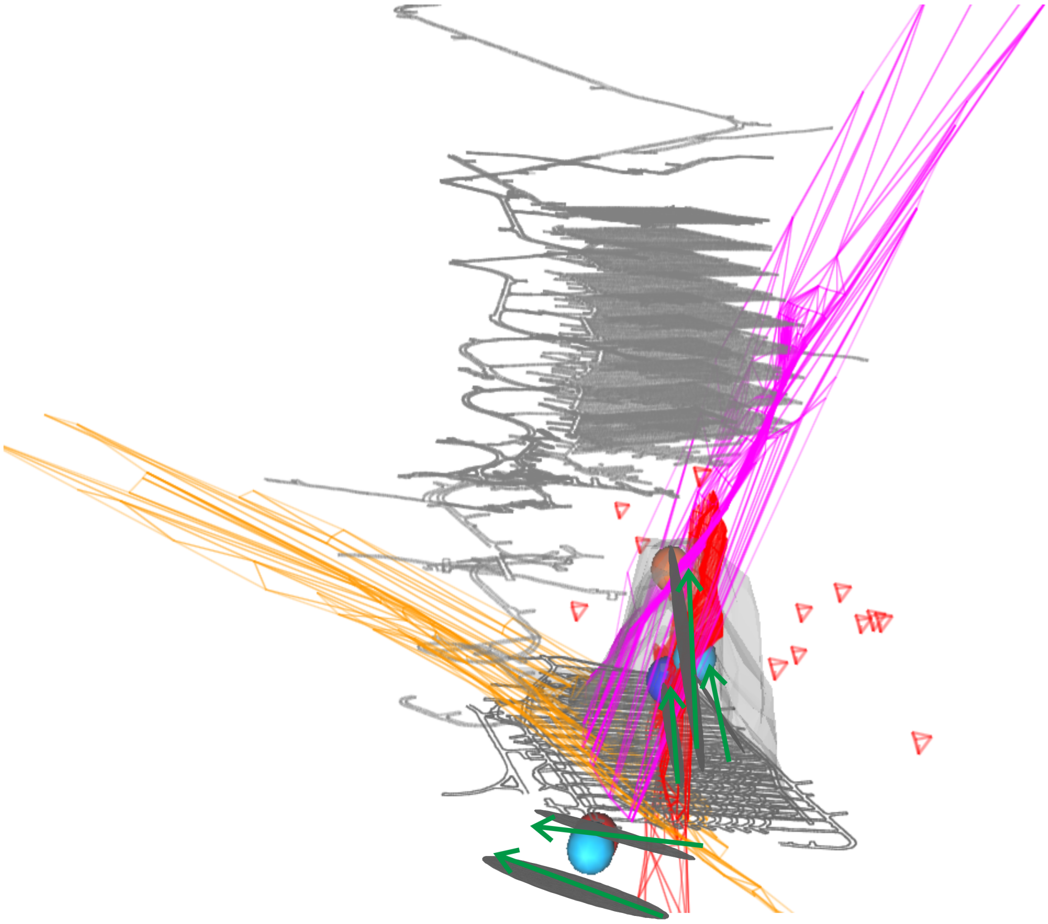

Figure 2: Location of all events with source ellipsoids in view looking east. Geological faults in Ridgeway mine are plotted in the same figure: orange, red and purple planes. Source ellipsoids are slightly shifted from their right positions to see them clearly.

5 Discussion and conclusion

The second degree moment approach beneficially provides additional information to standard MT: geometry of the source, duration of the source process, spatial and temporal centroid and rupture velocity vector. In addition to the usefulness of them for gaining more insight about the source, the SDM can help to obtain a more accurate estimate of the mechanism, especially concerning its DC vs. non-DC contents. To do that, we proceed in an iterative loop, where we determine the zero degree MT from the data filtered below the corner frequency, use it to estimate the second degree moments from the data keeping the information from the frequency range reaching beyond the corner frequency, subtract their effects from the records, and invert them subsequently for the zero degree MT. In this way we have demonstrated the following:

• Neglect of source finiteness, the effects of which remain in the data even after excessive low-pass filtering, yields spurious non-DC components in the reconstructed MT;

• The orientation of the mechanism, that is, the position of the fault plane solution is, however, almost unbiased;

• Correcting the data for source finiteness by subtracting the contribution of the second degree moments reduces spurious non-DC components substantially.

With the skill to reduce spurious non-DC component of the mechanism, we have a good chance to reconstruct the genuine non-DC originated by the source process itself, in particular, to decide between DC and non-DC events.

With this aim we studied five events with large non-DC component using SDM approach (Kobe 1995, Izmit 1999, Solomon 2003, Bolivia 2005 and aftershock of Tohoku-oki 2011). For all 5 events we determined standard MT and estimated the SDM. For Kobe and Izmit earthquake we performed the jack-knife test which demonstrated the robustness of the results. We compared the SDM obtained for Kobe and Izmit earthquakes with previous studies and found our results largely in agreement with them. Then, we removed the SDM contribution from the data and recomputed the standard MT by using the data without the SDM effects. We demonstrated that the large non-DC component was probably the effect of the source finiteness, which remained in the data even after the low-pass filtering.

The second application was to mining tremors, where we studied five events from the large Ridgeway data set. The MT solutions are similar to that obtained by IMS from the spectral amplitude inversion.

Unfortunately, the Ridgeway SDM cannot be compared with any previous study because our evaluation is the first application of the methodology to mining tremor data. The major benefit for the practice is foreseen in the capability of the approach to remove the ambiguity of the two nodal planes within the traditional MT solution, i.e. to identify the genuine fault plane. We demonstrated this advantage clearly on the sample events. As a completely novel approach, the IMS company is interested to implement it into their processing package as an advanced extension of the existing routine procedures.

6 References

Adamová P. (2006). Earthquake source process and its complexity. Master thesis, Charles University, Prague.

Adamová P., Šílený J. (2010). Non-double-couple earthquake mechanism as an artifact of the point source approach applied to a finite-extent focus, *Bull. Seis. Soc. Am.*, **100**(2), 447-457

Backus, G.(1977a). Interpreting the seismic glut moments of total degree two or less, *Geophys. J. R. astr. Soc.*, **51**, 1-25.

Backus, G., 1977b. Seismic sources with observable glut moments of spatial degree two, *Geophys. J. R. astr. Soc.*, **51**, 27-45.

Bouchon, M., Coutant O. (1994). Calculation of synthetic seismograms in a laterally varying medium by the boundary-element discrete wavenumber method, *Bull. Seismol. Soc. Am.* **84**, no. 6, 1869–1881.

Bukchin, B.G., Levshin, A.L., Ratnikova, L.I., Dost, B., Nolet, G. (1992). Estimation of spatio-temporal source parameters from the 1988 Spitak, Armenia, earthquake from broadband surface wave records, *Comp. Seismol. Geodyn.*, **2**, 156-161.

Bulut, F., Bohnhoff M., Aktar M., Dresen G. (2007). Characterization of aftershock-fault plane orientations of the 1999 Izmit (Turkey) earthquake using high-resolution aftershock locations, *Geophys. Res. Lett.* **34**, L20306.

Clevede, E., Bouin M.-P., Bukchin B., Mostinskiy M., Patau G. (2004). New constraints on the rupture process of the 1999 August 17 Izmit earthquake deduced from estimates of stress glut rate moments, *Geophys. J. Int.* **159**, 931-942.

Dahm, T., Krüger, F.(1999). Higher-degree moment tensor inversion using far-field broad-band recordings: theory and evaluation of the method with application to the 1994 Bolivia deep earthquake, *Geophys. J. Int.*, **137**, 35-50.

Das, S., Kostrov, B.V. (1997). Determination of the polynomial moments of the seismic moment rate density distribution with positivity constraints, *Geophys. J. Int.*, **131**, 115-126.

Doornbos, D. J. (1982). Seismic moment tensors and kinematic source parameters, *Geophys. J. R. Astr. Soc.* **69**, 235–251.

Dufumier H., Rivera L. (1997). On the resolution of the isotropic component in moment tensor inversion, *Geophys. J. Int.* 131(3), 595-606.

Goldberg D. E. (1989). Genetic Algorithms in Search, Optimization, and Machine Learning, Addison-Wesley, Reading, Massachusetts, 412 pp.

Gusev A.A., Pavlov V.M. (1986). Detailed study of the focus of a deep earthquake (Fiji, Feb. 15, 1971) as a radiator of elastic waves, II. Calculation of the first- and second-order power moments, *Volc. Seism.*, **8**, 929-954.

Gusev A.A., Pavlov V.M. (1988). Determination of space-time structure of a deep earthquake source by means of power moments, *Tectonophysics*, **152**, 319-334.

Ide S., Takeo M., Yoshida Y. (1996). Source process of the 1995 Kobe earthquake: determination of spatio-temporal distribution by bayesian modeling, *Bull. Seismol. Soc. Am.* **86**(3), 547-566.
Julian, B.R, Miller A. M., Foulgar G.R. (1998). Non-double-couple earthquakes 1. Theory, *Reviews of Geophysics* 36(4), 525-549.
McGuire J. J., Zhao L., Jordan T.H. (2001). Teleseismic inversion for the second-degree moments of earthquake space-time distribution, *Geophys. J. Int.* **145**, 661–678.
McGuire, J. J., Zhao L., Jordan T.H. (2002). Predominance of unilateral rupture for a global catalog of large earthquakes, *Bull. Seismol. Soc. Am.* **92**, no. 8, 3308–3317.
Miller A.M., Foulgar G.R., Julian B.R. (1998). Non-double-couple earthquakes 2. Observations, *Reviews of Geophysics* **36**(4), 551-568.
Ozalaybey S., Ergin M., Aktar M., Tapırdamaz C., Bicmen F., Yoruk A. (2002). The 1999 Izmit Earthquake Sequence in Turkey: Seismological and Tectonic Aspects. *Bull. Seis. Soc. Am.* , **92**(1), 376-386.
Silver P., Jordan T.H. (1983). Total moment spectra of fourteen large earthquakes, *J. geophys. Res.*, **88**, 3273-3293.
Silver P., Masuda T. (1985). A source extent analysis of the Imperial Valley earthquake of October 15, 1979 and the Victoria earthquake of June 9, 1980, *J. Geophys. Res.*, **90**, 7639-7651.
Stump B.W., Johnson L.R. (1982). Higher-degree moment tensors – the importance of source finiteness and rupture propagation on seismograms, *Geophys. J. R. astr. Soc.*, **69**, 721-743.
Vavryčuk V. (2001). Inversion for parameters of tensile earthquakes, *J. geophys. Res.*, 106(B8), 16339-16355.
Zahradník, J., Plešinger A. (2005). Long-period pulses in broadband records of near earthquake, Bull. Seis. Soc. Am. 95, 1928-1939.

List of publications

1. Adamová P., Sokos E., Zahradník J. (2009). Problematic non-double-couple mechanism of the 2002 Amfilochia M(w)5 earthquake, Western Greece, Journal of Seismology 13(1),1-12

2. Adamová P., Šílený J. (2013). Disputable non-double-couple mechanism of several strong earthquakes - second degree moment approach, Bulletin of the Seismological Society of America, 103(2), 2836-2849

3. Adamová P., Šílený J. (2010). Non-Double-Couple Earthquake Mechanism as an Artifact of the Point-Source Approach Applied to a Finite-Extent Focus, Bulletin of the Seismological Society of America, 100(2), 447-457