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SEISMIC MOMENT TENSOR AND FOCAL MECHANISM OF THE OCTOBER 9, 2023 EARTHQUAKE IN EASTERN SLOVAKIA

The accuracy of the focal mechanism solution mainly depends on the number of stations used and becomes problematic especially in the case of weak earthquakes and sparse networks. In our study, we retrieve the seismic moment tensor of the M=5 earthquake on 9 October 2023 (18:23:09 UTC, 21.783°E, 49.086°N, depth 11.5 km) in Eastern Slovakia from its records at only four seismic stations. Our seismic moment tensor inversion is based on the point source approach and the use of only direct waves calculated by the matrix method. Displacements on the surface of an elastic, horizontally-layered medium are generated using the frequency-wavenumber integration technique. The advantage of using only direct P- and S- waves in our inversion method is that they are less sensitive to path effects compared to reflected and converted waves, which reduces the impact of an inaccurate velocity structure and improves the accuracy and reliability of the result. Based on the forward modeling, a numerical technique was developed for the inversion of the observed waveforms for the components of the moment tensor M(t) using the generalized inversion solution. Before applying our method to the earthquake of October 9, 2023, it was also tested on the April 23, 2020 earthquake (23:18:26.42 UTC, 21.945°E, 48.781°N, magnitude M=5, depth 9 km), also in Eastern Slovakia, using data from only three stations. The resulting versions of the mechanism compare well with a very reliable version previously determined from the polarities of the first P-waves at a much larger number of stations, which only confirms the reliability of our inversion method and the very possibility of obtaining useful results from data of only limited number of stations.

Key words: focal mechanism, waveform inversion, seismic moment tensor, direct waves, seismic stations, earthquakes.

Introduction

Determining the mechanism of an earthquake is, perhaps, one of the most difficult problems of seismological research today. Originally, the source mechanisms were determined from the polarities of the first P-waves at the stations [Aki & Richards, 1980]. To calculate the angles of the emergence of the first P-waves, it also was necessary to know the accurate location of the source, as well as an adequate velocity model between the source and the stations. Usually, a sufficient number of reliable polarities was only available for large (M>4) earthquakes, occurring in areas with dense seismological networks [Dziewonski et al., 1981; Herrmann, 2002, 2008; Herrmann et al., 2008; Zhu et al., 2006]. In contrast to polarities, waveforms contain much more information about the source, which enables to alleviate the above limitations, use fewer stations, and determine the mechanisms of smaller earthquakes [Dreger & Helmberger, 1993; Malytskyy, 2010, 2016; Malytskyy & Amico, 2015]. This is especially valuable in regions with low to moderate seismic activity and a sparse station network, such as Eastern Slovakia.

In the current study, we determine the source time function (STF) and the moment tensor of the event with a reported magnitude of M5, which occurred on October 9, 2023 (18:23:09 UTC, 21.783°E, 49.086°E, depth 11.5 km) in Eastern Slovakia. A method for the moment tensor inversion of only direct P- and S-waves is used, which is less sensitive to path effects than reflected and converted waves [Malytskyy 2010, 2016; Malytskyy & Amico, 2015]. The use of only direct waves significantly improves the accuracy and reliability of the inversion. For direct modeling, i.e., calculation of synthetic seismograms, the matrix method was used, since it enables to analytically isolate only direct waves. To test the reliability of our inversion method, we first applied it to the earthquake on April 23, 2020 (23:18:26.42 UTC, 21.945°E, 48.781°N, depth 9 km) in Eastern Slovakia using data from three stations and compared the results with the mechanism determined using the polarities of the first P-waves at a much larger number of stations.

Inversion method

The inversion scheme consists of two steps. The first one is forward modeling. We consider the propagation of seismic waves in a horizontally layered medium and calculate synthetic seismograms on its upper surface. The point source is located inside a layer and is represented by seismic moment tensor **M**(t). The displacements on the upper surface **U** are presented in matrix form in frequency and wave number domain, separately for far-field and near-field [Malytskyy, 2016]. Further, only the far-field displacements are considered, and the wave-field from only direct P- and S-waves is isolated with the application of eigenvector analysis reducing the problem to a system of linear equations [Malytskyy, 2016].

The second step is inverse modeling. It consists in determining the parameters of the source under the condition that its location and velocity structure are known in advance [Malytskyy, 2010, 2016]. Mathematically, the solution of the inverse problem is reduced to the inversion of matrix **G**, which relates the source parameters **M**(t) to the observed field **U**(t). The components of the seismic tensor can be obtained using the solution of generalized inversion (Eq. 1) and transformed to the time domain by applying the inverse Fourier transform [Malytskyy 2010, 2016; Malytskyy & Amico, 2015; Malytskyy & Gnyp, 2023]:

$$\mathbf{M} = (\tilde{\mathbf{G}}^{*}\mathbf{G})^{-1}\tilde{\mathbf{G}}^{*}\mathbf{U}, \qquad (1)$$

in which $\mathbf{U} = \left(U_x,\ U_y, U_z\right)^{T}$ consists of displacement components of direct P- or S-waves, $\mathbf{M} = \left(M_{xz}, M_{yz}, M_{zz}, M_{xx}, M_{yy}, M_{xy}\right)^{T}$ consists of components of seismic moment tensor, **G** is the matrix relating the source parameters **M**(t) to the observed field **U**, and $(\tilde{\mathbf{G}}^{*}\mathbf{G})^{-1}\tilde{\mathbf{G}}^{*}$ is the generalized inverse of **G**.

Calculation of seismic moment tensor and focal mechanism

First, we apply our inversion method to the event on April 23, 2020 (23:18:26.42 UTC, 21.945°E, 48.781°N, depth 9 km) in Eastern Slovakia. Its mechanism (Fig. 1) was previously determined using polarities of direct P-waves.

Fig. 1. Location of seismic stations used in the inversions, the epicenter of the April 23, 2020 earthquake (white star) and its focal mechanism determined using polarities of the direct P-waves at nearly 40 stations, the epicenter of the October 9, 2023 (gray star) earthquake and its mechanism from the IRIS website, https://earthquake.usgs.gov/earthquakes/eventpage/us6000lec2/moment-tensor.

The waveforms were recorded at three stations: SK22A (21.721°E, 48.619°N), SK21A (21.997°E, 49.013°N), and TRPA (22.539°E, 48.130°N). The records at the SK22A are shown in Fig. 2. After conversion to displacements the waveforms were band-pass filtered in the frequency range from 0.1 to 10 Hz. Next, the portions of records containing only direct P- and S-waves were identified visually, considering the travel times and the source depth. Versions of the focal mechanism corresponding to the seismic moment tensors calculated using waveforms from only three stations together with the version obtained from the polarities of the first P-wave at almost 40 stations are shown in Fig. 3. The 1D crustal model used in the inversions is listed in Table.

1D crustal model used in the inversions

h_S, km	V_P, km/s	V_S, km/s	ρ, g/cm^3
1.0	2.5	1.445	2.2
3.0	3.7	2.139	2.44
3.0	5.2	3.006	2.74
10	5.9	3.41	2.88
3	6.4	3.699	2.98
4	6.75	3.902	3.05
	8.0	4.624	3.3

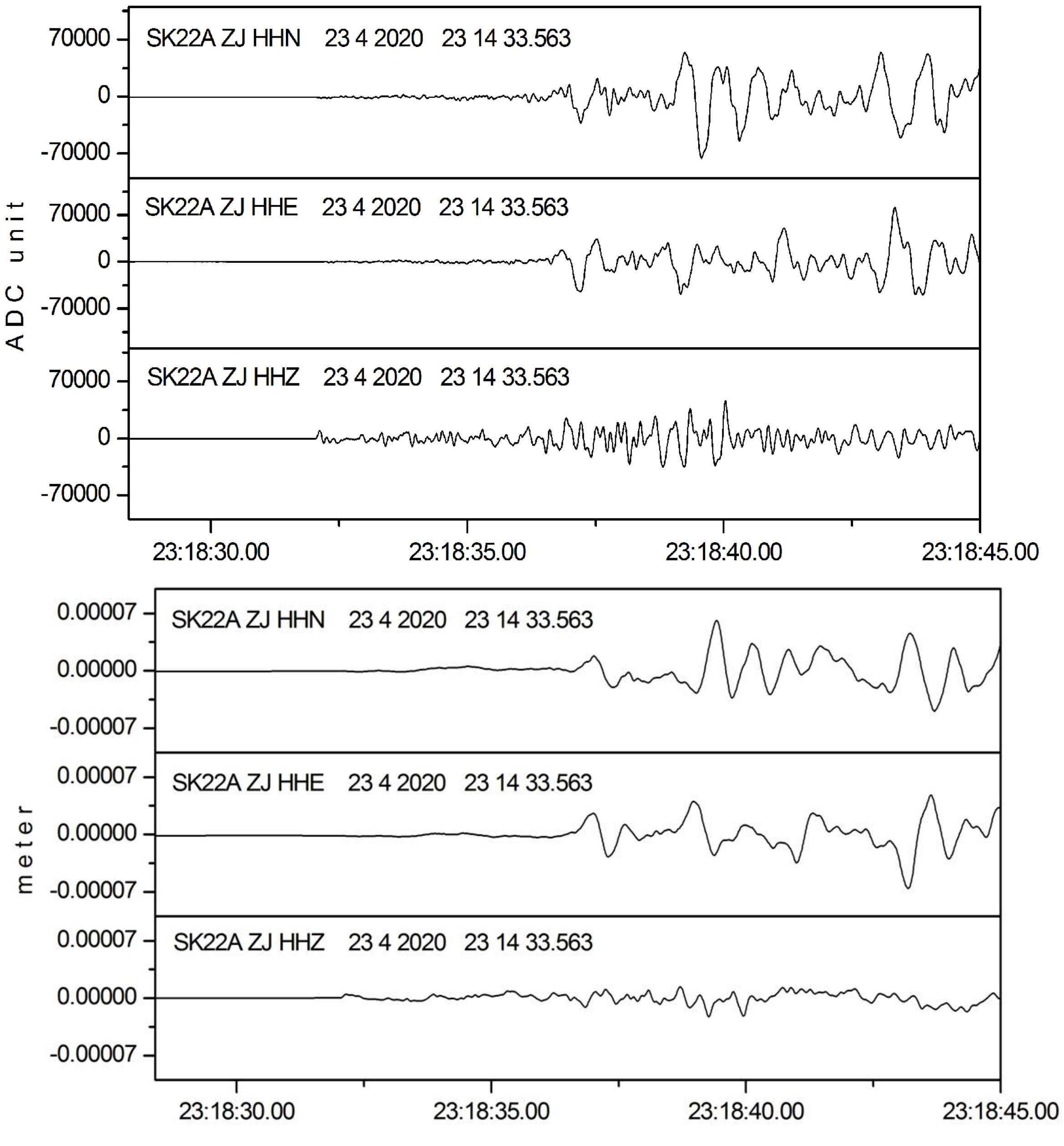
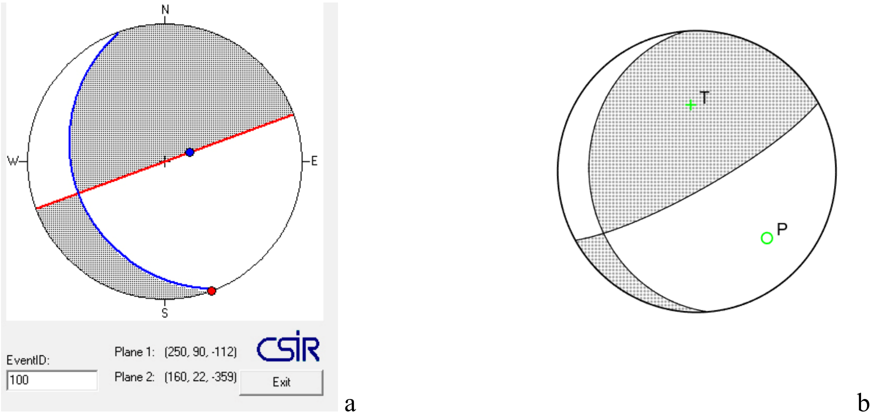


Fig. 2. Raw records of the April 23, 2020 earthquake at the station SK22A (top); the records converted to displacements (bottom).



EventID: 100

Plane 1: (250, 90, -112)

Plane 2: (160, 22, -359)

Fig. 3. A version of the focal mechanism of the April 23, 2020 earthquake corresponding to seismic moment tensor obtained by the inversion of waveforms at only SK22A, SK21A and TRPA stations (a). A version of the mechanism determined using the polarity of the first P-waves at almost 40 stations (b).

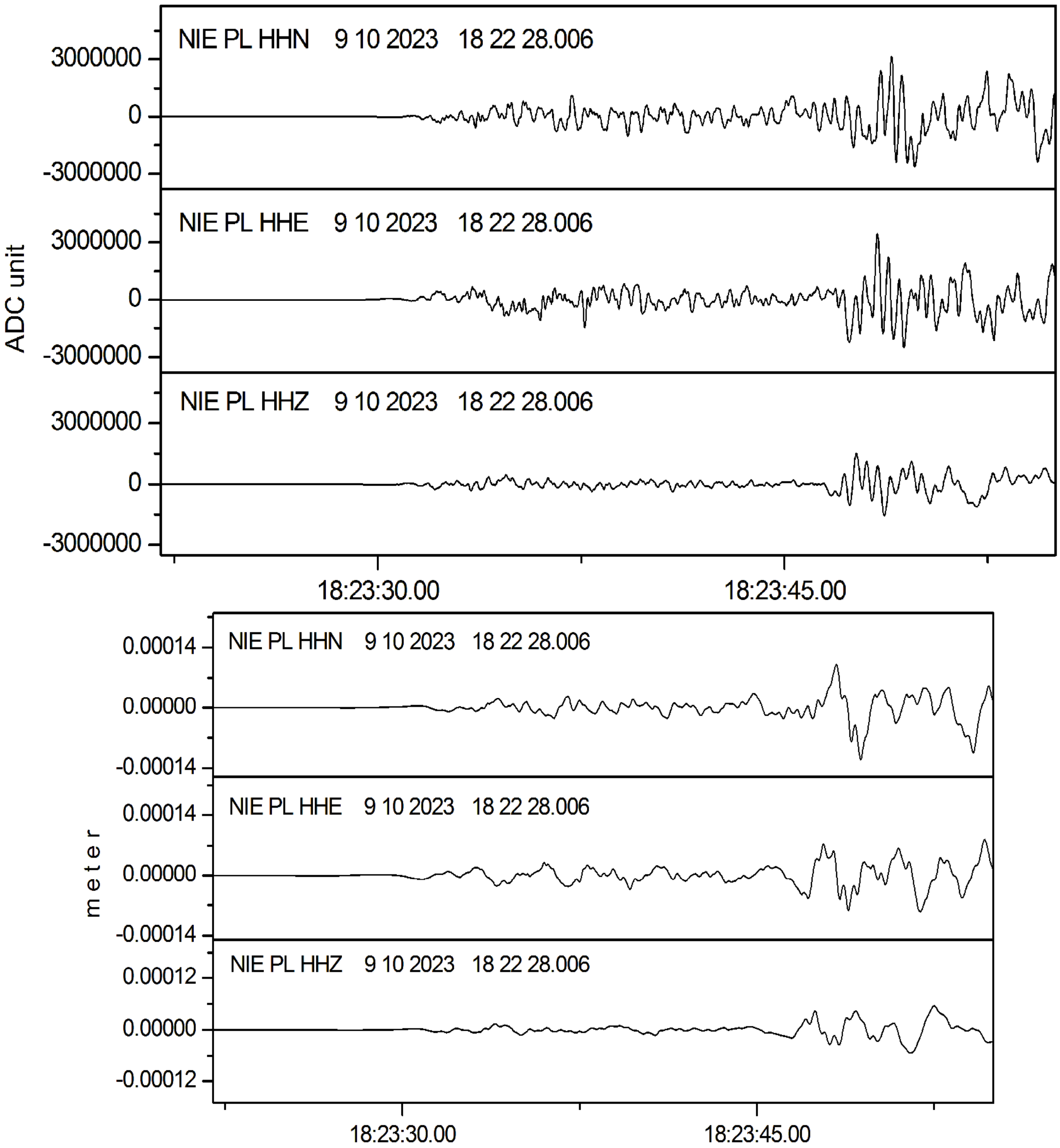
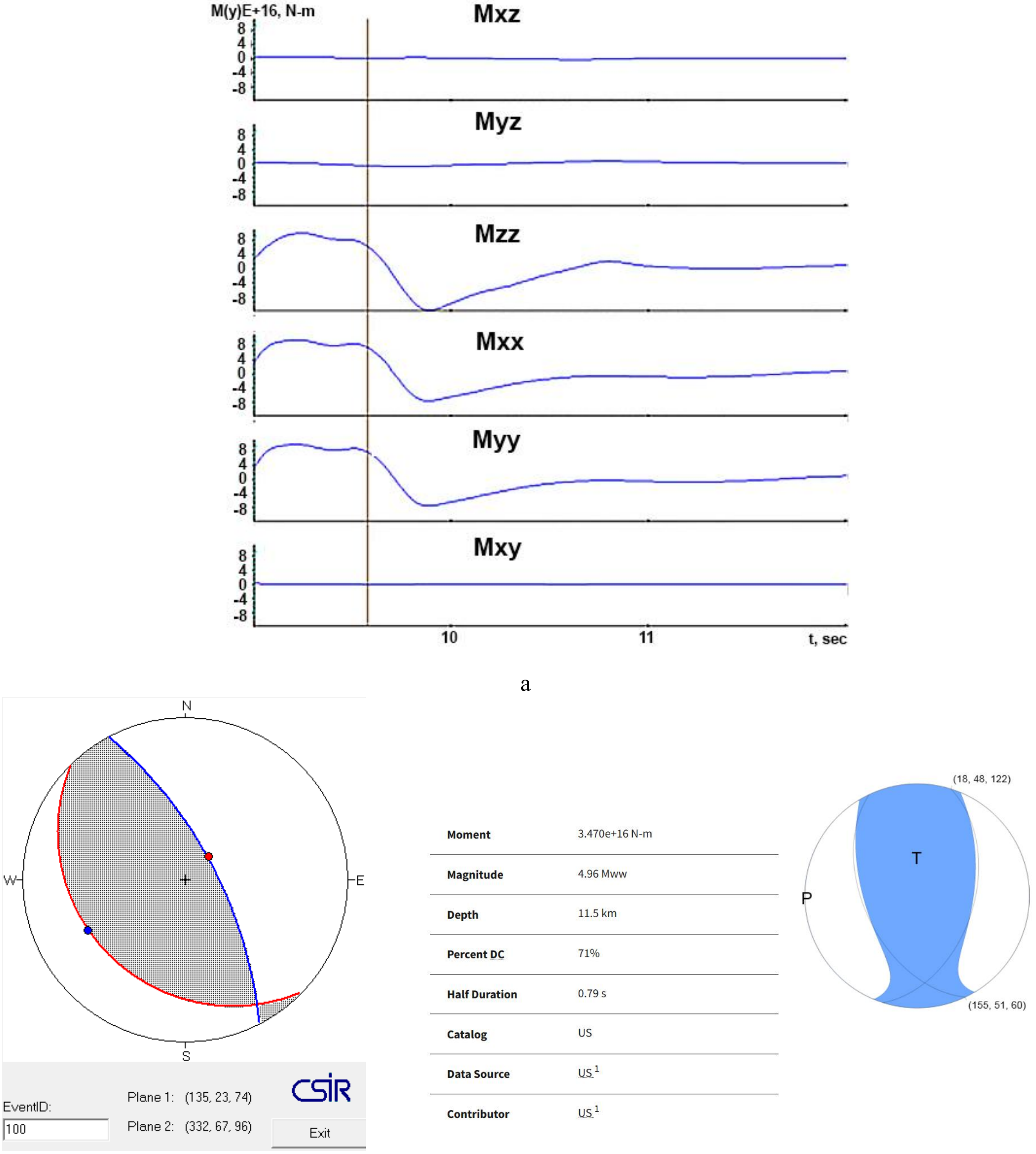


Fig. 4. The raw records of the 9 October, 2023 earthquake at the station NIE (top); the records converted to displacements (bottom).

Next, we apply our inversion method to the M5 earthquake on 9 October, 2023 (18:23:09 UTC, 21.78 N, 49.09 E, depth 11.5 km) in Eastern Slovakia. We use records from the four stations: NIE (20.313°E, 49.419°N), KWP (22.708°E, 49.631°N), KOLS (22.273°E, 48.933°N), and PSZ (19.894°E, 47.918°N) (Fig. 1). The 1D crustal model used in the inversion of waveforms is listed in Table 1. The source is located at a depth of 11.5 km, inside the fourth layer. The raw records of the earthquake at the station NIE and the displacements corresponding to them are shown in Fig. 4. After conversion to displacements the waveforms were band-pass filtered in the frequency range from 0.22 to 50 Hz. Seismic moment tensor components M(t) and focal mechanism versions calculated for a source depth of 11.5 km by inverting the waveforms recorded at different station configurations together with the preliminary version reported on the IRIS website (https://earthquake.usgs.gov/earthquakes/eventpage/us6000lec2/moment-tensor) are shown in Figs. 5 and 6.



a

Plane 1: (135, 23, 74)

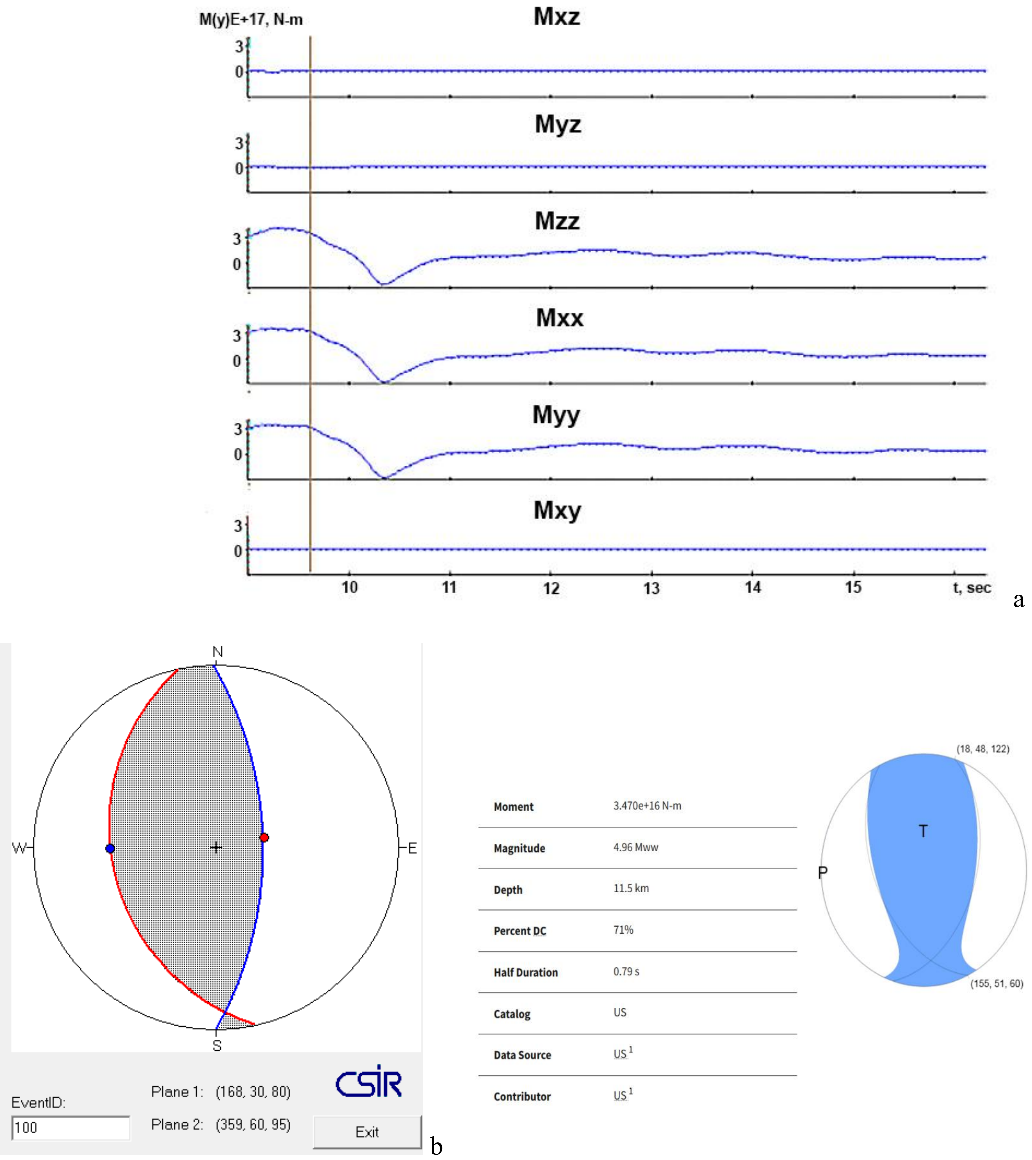
Plane 2: (332, 67, 96)

Moment	3.470e+16 N-m
Magnitude	4.96 Mww
Depth	11.5 km
Percent DC	71%
Half Duration	0.79 s
Catalog	US
Data Source	US[1]
Contributor	US[1]

b

c

Fig. 5. The components of the seismic moment tensor **M**(t) obtained for the earthquake of 9 October, 2023 by inversion of its waveforms at the stations KOLS, KWP, NIE (a); the focal mechanism corresponding to the tensor (b); the mechanism from the IRIS site https://earthquake.usgs.gov/earthquakes/eventpage/us6000lec2/moment-tensor (c).



EventID: 100

Plane 1: (168, 30, 80)

Plane 2: (359, 60, 95)

Moment	3.470e+16 N-m
Magnitude	4.96 Mww
Depth	11.5 km
Percent DC	71%
Half Duration	0.79 s
Catalog	US
Data Source	US 1
Contributor	US 1

Fig. 6. The components of the seismic moment tensor **M**(t) for the earthquake of 9 October, 2023 calculated by inversion of its waveforms at the stations KOLS, KWP, NIE and PSZ (a). The focal mechanism corresponding to the tensor (b); the focal mechanism from the IRIS site https://earthquake.usgs.gov/earthquakes/eventpage/us6000lec2/moment-tensor (c).

It can be concluded from Figs. 5 and 6 that the best result is obtained by using records from four stations more or less evenly distributed around the epicenter of the earthquake.

Discussion and conclusion

Addressing the problem of determining the earthquake mechanism, we have chosen to invert only direct P- and S-waves instead of the full field. An advantage of the direct waves consists in their much lesser distortion, if compared to reflected and converted waves, by inaccurate modeling of velocity contrasts. Therefore, the direct waves carry a much less obscured imprint of the source. An advantage, in this connection, of the matrix method used by us for the calculation of the wave field consists in its ability to analytically isolate only the direct waves from the full field. Versions of the seismic moment tensor **M**(t) and the corresponding focal mechanisms calculated for the earthquake of 9 October, 2023 in Eastern Slovakia by inversion of waveforms recorded at only three and four seismic stations turned out to be quite similar in terms of the mechanism type (Fig. 5–6), which indicates the correctness of our approach and the very possibility of determining the focal mechanism from waveforms recorded only at a limited number of seismic stations.

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ТЕНЗОР СЕЙСМІЧНОГО МОМЕНТУ ТА МЕХАНІЗМ ВОГНИЩА ЗЕМЛЕТРУСУ У СХІДНІЙ СЛОВАЧЧИНІ 9 ЖОВТНЯ 2023 РОКУ

Точність визначення фокального механізму залежить передусім від кількості використовуваних станцій. Досягти точності проблематично, особливо у разі слабких землетрусів та мереж з недостатнім покриттям. У цій роботі ми визначили тензор сейсмічного моменту землетрусу із магнітудою M=5 9 жовтня 2023 року (18:23:09 UTC, 21,783°E, 49,086°N, глибина 11,5 км) у Східній Словаччині за записами лише на чотирьох сейсмічних станціях. Обернена задача щодо тензора сейсмічного моменту ґрунтується на точковій моделі вогнища та використанні лише прямих хвиль, обчислених матричним методом. Переміщення на поверхні пружного горизонтально-шаруватого середовища згенеровано за допомогою інтегрування у смузі частот та хвильових чисел. Перевага використання лише прямих P- та S-хвиль у нашому методі полягає у їх набагато меншому спотворенні на шляху поширення, порівняно з відбитими та конвертованими хвилями, що зменшує вплив неточності швидкісної моделі та підвищує точність і надійність результату. На основі прямого моделювання розроблено числову методику обернення спостережених хвильових форм до компонент тензора моменту M(t) з використанням узагальненого оберненого розв'язку. Перед застосуванням нашого методу до землетрусу 9 жовтня 2023 року його тестували і на землетрусі 23 квітня 2020 року (23:18:26.42 UTC, 21,945°E, 48,781°N, магнітуда M=5, глибина 9 км), теж у Східній Словаччині, з використанням даних лише трьох станцій. Отримані версії механізму добре узгоджуються з механізмом, дуже надійно визначеним раніше за полярностями перших P-хвиль на набагато більшій кількості станцій, що лише підтверджує надійність нашого методу та саму можливість отримання корисного результату за даними обмеженої кількості станцій.

Ключові слова: механізм вогнища; обернення хвильових форм; тензор сейсмічного моменту; прямі хвилі; сейсмічні станції; землетруси.

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