ABSTRACT

Integration of Interferometric Synthetic Aperture Radar methods with the geophysical description of induced seismic phenomena

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Understanding the mechanisms of seismic phenomena, including those induced or triggered by human activity, requires an analysis of both processes occurring within the Earth's crust and the associated surface displacements. Traditional seismic methods provide information on source parameters but do not fully capture the spatial characteristics of surface deformation. This study focuses on the potential of satellite imagery acquired using Synthetic Aperture Radar (SAR), using various methods of Interferometric Synthetic Aperture Radar (InSAR), to identify ground displacements caused by induced seismic events and to integrate these data with a geophysical description of the phenomenon.

Six induced seismic tremors with moment magnitudes ranging from $M_w4.7$ to $M_w7.4$ were analyzed. The events were located in areas with different types of mining operations (gas extraction and fluid injection, groundwater extraction, quarrying, and hydraulic fracturing) and varied in terms of land cover, terrain morphology, and recorded seismic activity.

In the interferometric part of the study, short-term surface displacements in the satellite line-of-sight (LOS) direction were determined using Differential InSAR (DInSAR), with tropospheric correction based on the GACOS model. Vertical and horizontal (east–west) components of surface motion were derived through LOS displacement decomposition, based on SAR imagery acquired from two satellite orbits (ascending and descending). Long-term displacements were estimated using the Small Baseline Subset (SBAS) method, applied to 8-month time series (4 months before and after the seismic event). Small-scale surface ruptures were identified based on averaged phase gradients, while the direction of movement along deformation zones was determined using the averaged interferometric phase enhanced with a high-pass Gaussian filter.

In the seismological part of the study, short-term surface displacements derived from two satellite orbits were used as observational data for seismic source analysis based on probabilistic inversion theory. The seismic source was modeled as a finite, rectangular fault surface with uniform slip, following the classical Okada model. The inverse problem was solved in two stages: in the first stage, a simplified model of the Earth's crust was used in the form of an elastic, homogeneous, and isotropic half-space, with a wide parameter search range. In the second stage, a more detailed layered model was applied, accounting for vertical variations in seismic wave velocity, while narrowing the parameter search space.

The conducted research enabled a comprehensive analysis of the impact of induced seismicity on surface deformation, both in qualitative and quantitative terms. The obtained results allowed for the identification of characteristic features of short- and long-term deformation, the determination of displacement trends associated with processes occurring before and after the mainshock, estimation of the seismic source geometry, and evaluation of the influence of factors such as land cover and event magnitude on the surface response to seismic activity. The collected research material represents a significant contribution to forecasting and monitoring in areas affected by mining activity.

Key words: induced seismicity, inversion theory, fault plane, Okada model, ground surface displacement, Interferometric Synthetic Aperture Radar (InSAR), mining operation

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