2023 DRAGON 5 3rd YEAR RESULTS SYMPOSIUM

YOUNG SCIENTISTS POSTER SESSION

12 SEPTEMBER 2023

Geodetic Monitoring of Surface Deformation in Shale Gas Blocks and as Constraints on Oil and Gas Production (Dragon Project 59308)

中国地震局地质研究所
Institute of Geology, China Earthquake Administration

Zhaoyang Zhang[1], Jianbao Sun[1]

State Key Lab. of Earthquake Dynamics, Institute of Geology, China Earthquake Administration, Beijing, China

zhangzhaoyang527@163.com(Zhaoyang Zhang); sunjianbao@ies.ac.cn(Jianbao Sun)

Abstract: With fast shale gas exploitation in Sichuan basin in China in recent years, numerous micro-seismicities and even some medium-sized earthquakes occurred. Some studies show that shale gas exploitations can generate detectable surface deformation. We used ALOS-2 InSAR data to measure the surface deformation over the Changning shale gas block and find significant ground deformation that may be caused by massive shale gas production. Meanwhile, we also did time-series analysis of Sentinel-1 satellite radar data to measure the surface deformation of the Sichuan basin during the active periods of shale gas exploitation, which shows strong correlations between the surface deformation and three major shale gas blocks, namely the Changning, Weiyuan, and Fulin blocks. So the observed InSAR deformation in the tectonic-stable Sichuan basin is probably caused by hydraulic fracturing for shale gas production. Some speculations on deformation sources could be made based on such deformation patterns. Firstly, the surface deformation could be caused by long-term fluid injection or pumping which lasted several months in a poroelasticity medium. Secondly, such deformation may be due to multiple induced seismicities or fault creeping caused by pore pressure diffusion or fluid migration to vulnerable faults. Thirdly, the long-term shale gas development in the Sichuan basin could change the underground fluid mass. Injection or pumping of fluids into the crust would change upper crustal gravity and produce the elastic response of the crust, called the mass loading effect. We test these hypotheses based on numerical analysis of surface deformation patterns from InSAR data. To quantitatively interpret the surface deformation with shale gas production, we model the deformation sources as multiple fluid injection and pumping processes in a poroelasticity layer by spatiotemporal Green's function method, rather than the simple elastic volcanic-like sources, which may misinterpret the physical parameters of the shale gas production. Then we invert for the production parameters in a least-squares solution and compare our results with limited open production data as a verification.

Introduction: Since the beginning of the 21st century, with the maturity of China's shale gas extraction technology, substantial shale gas extraction has taken place in regions rich in shale gas content. Starting from 2010, the focus of shale gas extraction in China shifted to the Sichuan Basin and its surrounding areas. Companies like PetroChina and Sinopec successively developed shale gas extraction areas in places like Fuling, Changning, and Weiyuan. As shale gas extraction progressed, a series of minor earthquakes gradually occurred. Notably, in the Changning area of Sichuan, a magnitude 6.0 earthquake occurred on June 17, 2019, and in Weiyuan, a magnitude 5.4 earthquake occurred on September 8, 2019. These earthquakes resulted in multiple casualties and significant structural damage. Through geodetic measurements, we observed surface deformations ranging from centimeters to tens of centimeters during the shale gas extraction period. All this evidence points to significant geophysical changes underground in shale gas extraction areas.

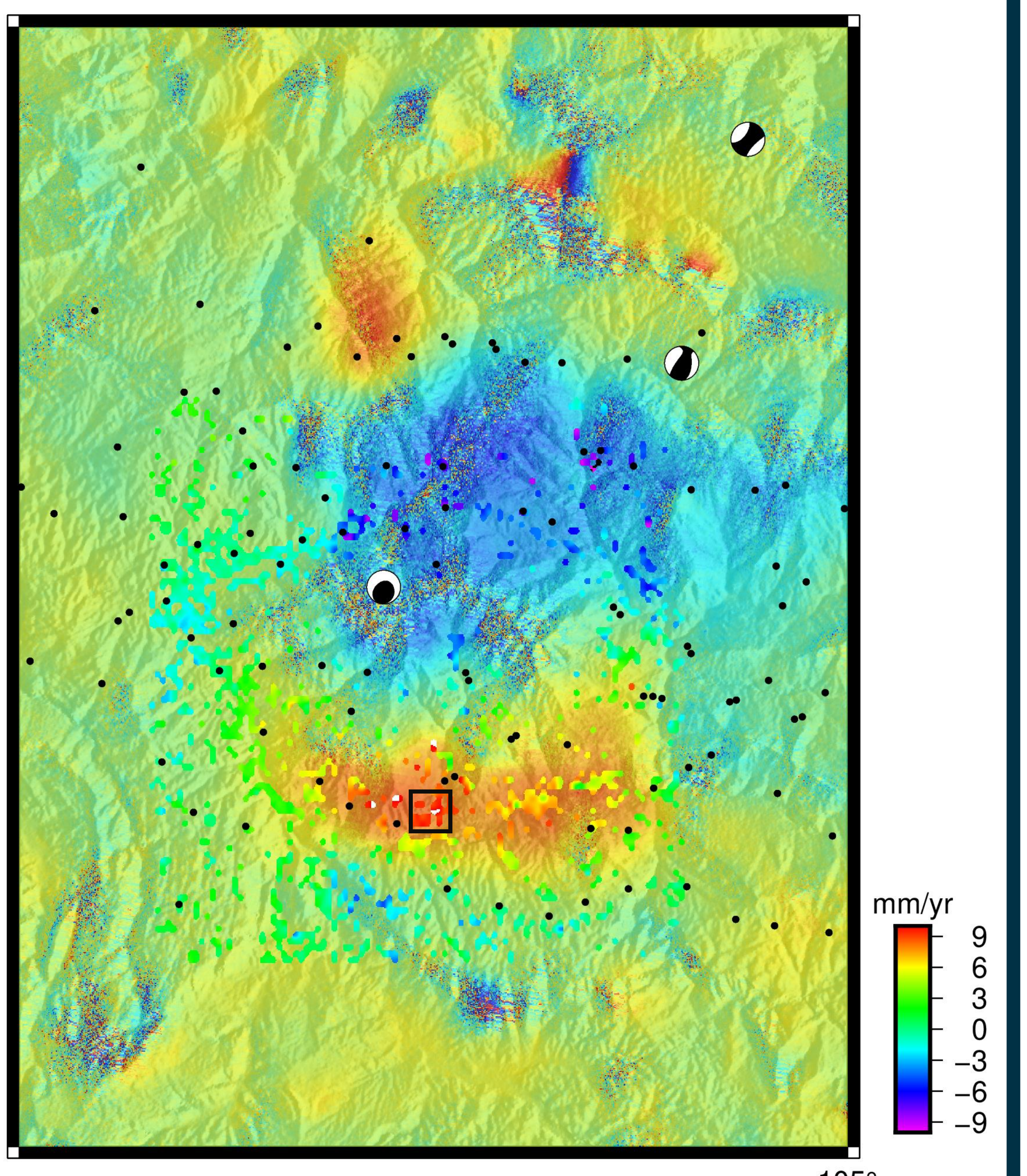

Fig 1a

We analyzed Sentinel-1 satellite data from 2015 to 2019 in the Changning region of Sichuan. Throughout the shale gas extraction process, we observed successive surface deformations. Figure 1a presents the surface deformation rates in the Line-of-Sight (LOS) direction. In the southern section of the shale gas extraction area, surface uplift predominates (the red area in the figure). Conversely, in the northern region, surface subsidence prevails (the blue area in the figure). Figure 1b specifically showcases surface deformations within the black-bordered area, where the maximum surface deformation rate can reach up to 20 mm/year. Given the varying activity levels of shale gas extraction across different times and locations, deformation patterns and rates also exhibit variability.

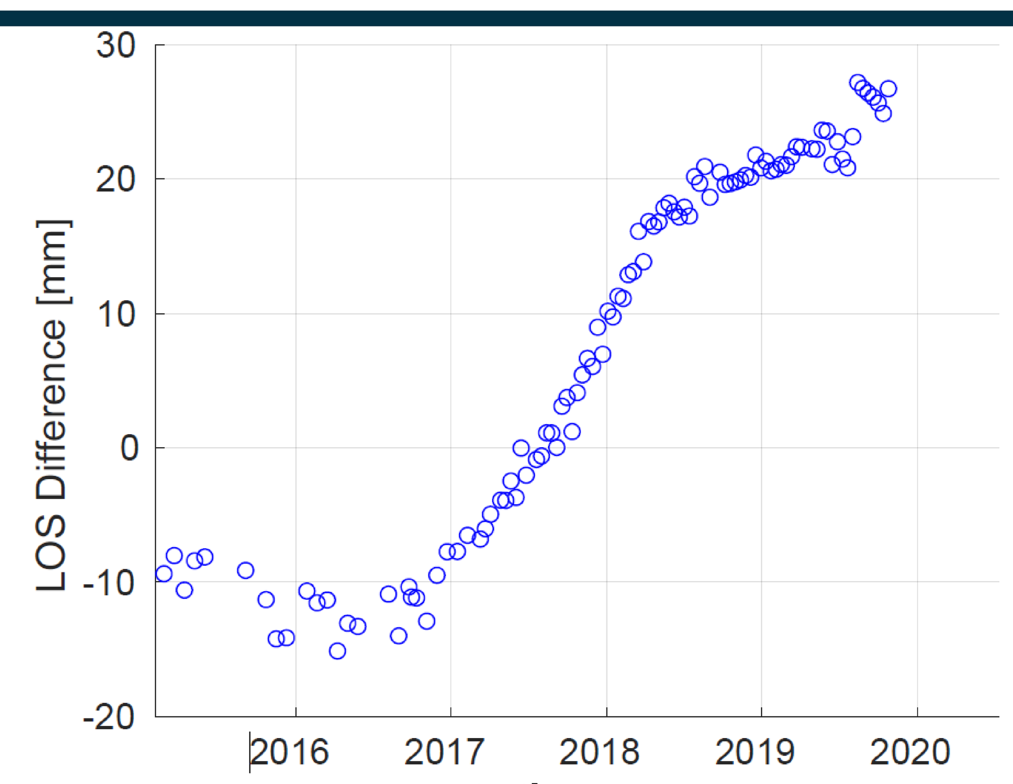

Fig 1b

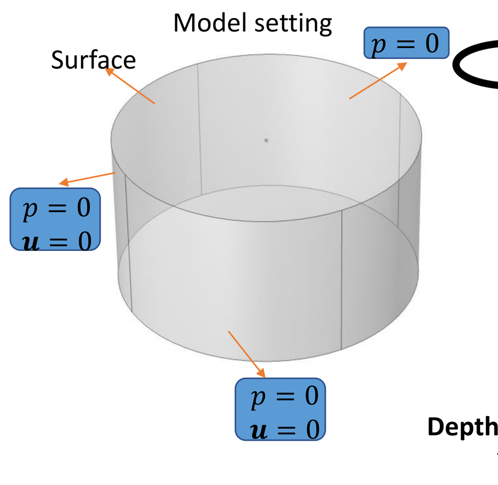

Fig 2a

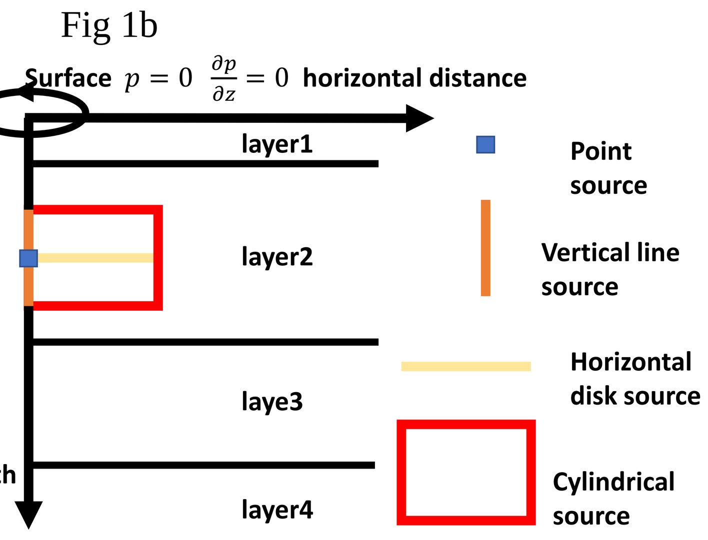

Fig 2b

We conducted a comparative analysis between numerical simulations and the semi-analytical solution POEL to derive pore elasticity parameters. Figure 2a illustrates the conceptual diagram of the numerical simulation model, while Figure 2b presents the schematic diagram of the semi-analytical solution POEL model.

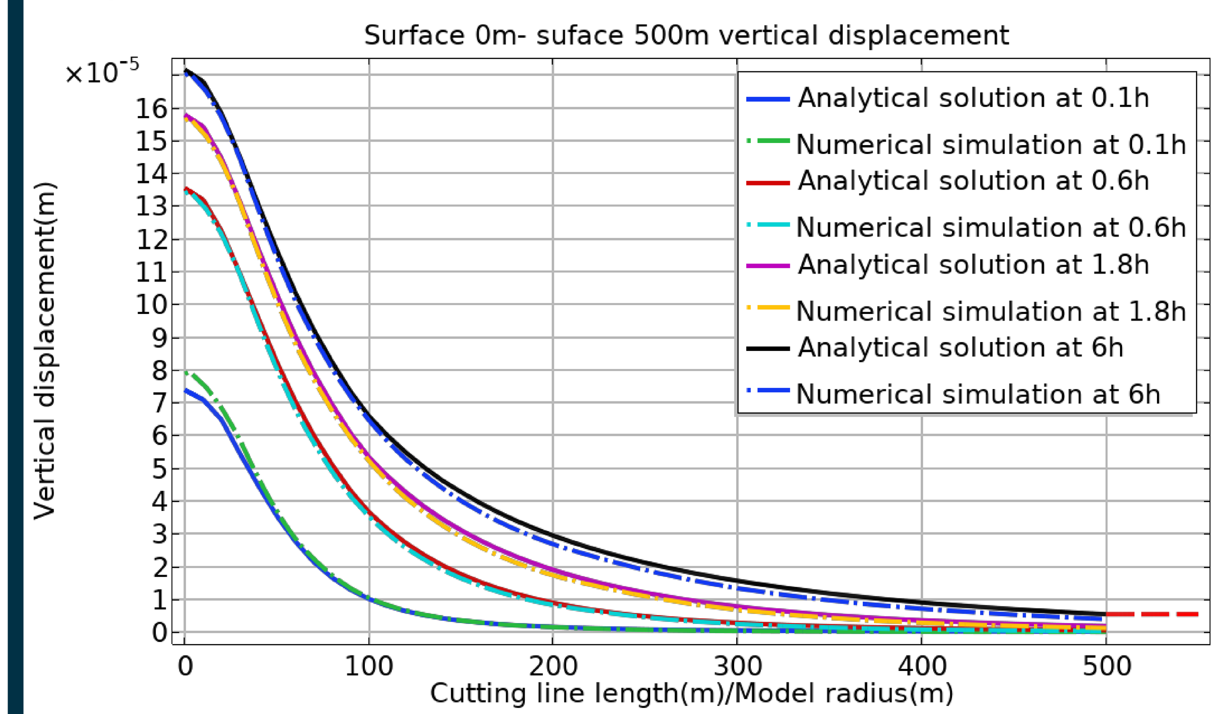

Fig 3a

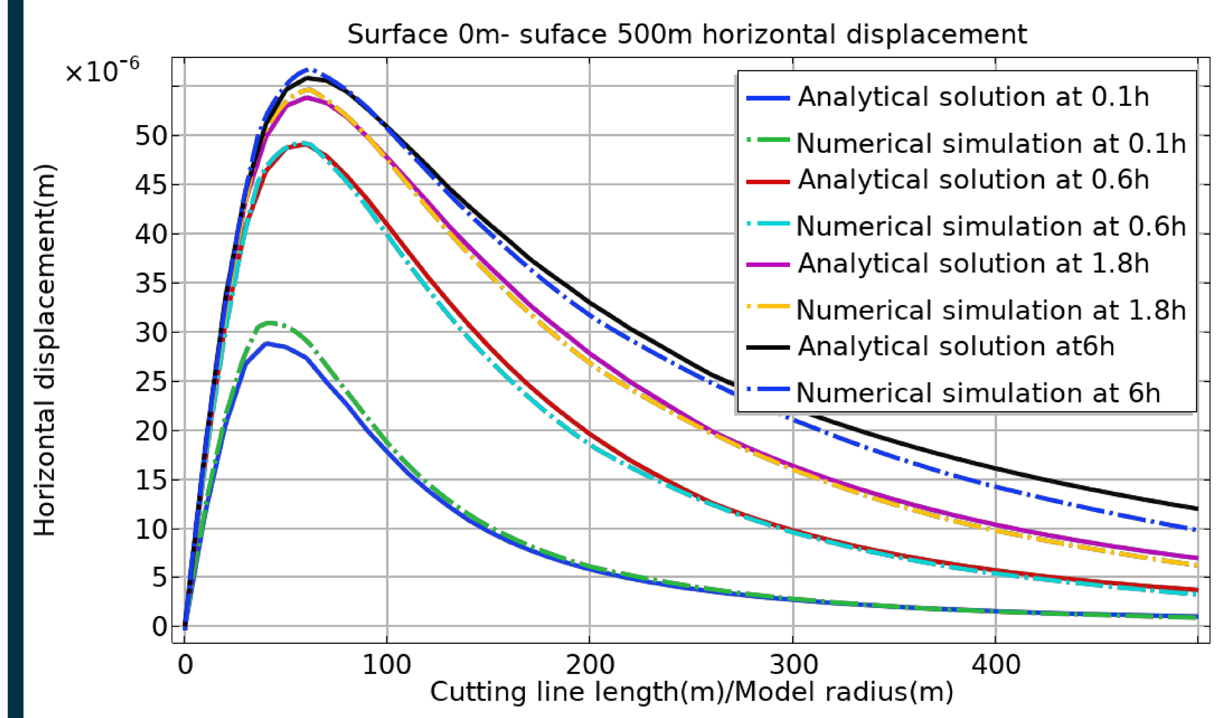

Fig 3b

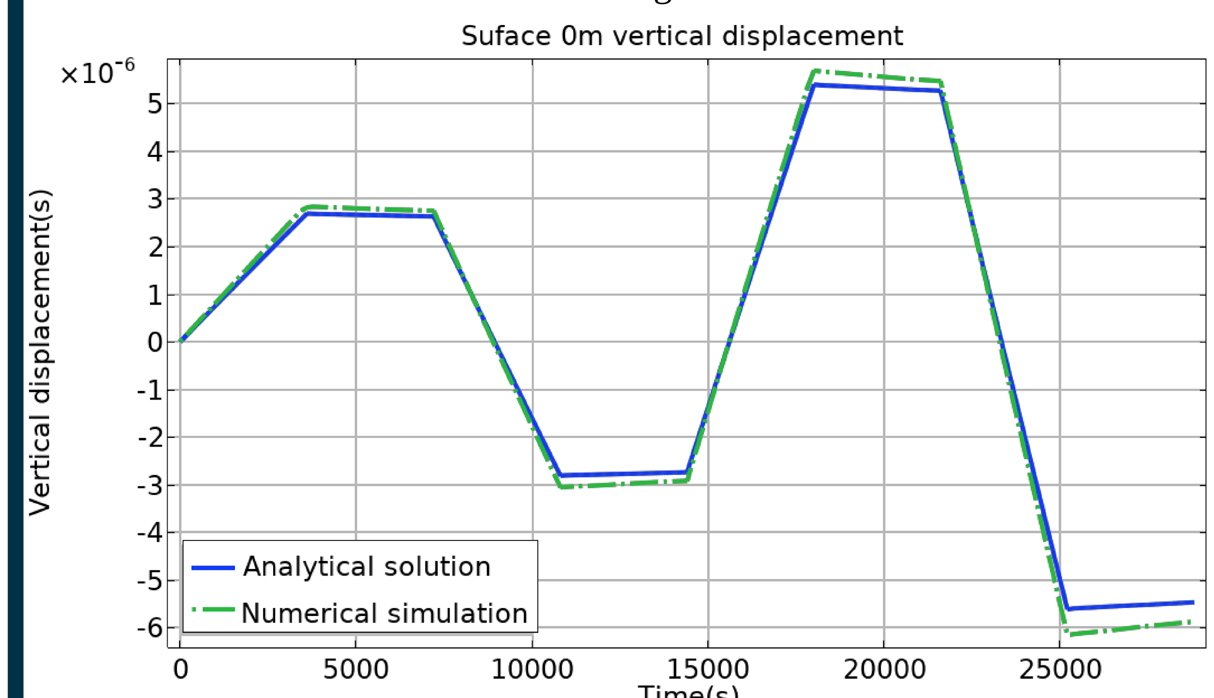

Fig 3c

Figure 3a illustrates the horizontal displacement of the surface for the 50-meter depth source model, while Figure 3b showcases the vertical displacement of the surface for the same model. Both 3a and 3b represent the simplest single-layer models. Figure 3c displays a more complex scenario involving a three-layer porous elastic medium model at a depth of 1000 meters, where the source action varies over time. This model includes both injection and extraction of fluids.

Result: Poroelasticity behavior of the crust may be one of the major factors responsible for the observed deformation in shale gas fields induced by anthropogenic activities. As a frequently occurred geophysical phenomena in shallow parts of the crust, poroelasticity behavior is high-profile in coal mining and underground water injection at a depth of hundreds of meters in the last century. In recent years, lots of geophysicists speculate that surface deformation may be also caused by the injection or extraction of fracturing fluid. Based on the assumption, we study the poroelasticity response of the curst to fluid migrations and apply the theory to shale gas production applications. Poroelasticity theory was raised by Biot as early as 1941 and was developed by the further generations' experimentation. At present, the poroelasticity theory become a mature geophysical knowledge. It includes many more parameters than the pure elastic models. These parameters describe the basic physical properties of underground poroelastic layers. A popular and simplified solution is the half-space multi-layered semi-analytical solution for poroelastic calculations by Wang et al., 2003. The program uses five poroelastic parameters for calculation of surface deformation and is accepted by geophysicists. However, the numerical simulation of poroelasticity needs seven parameters for a calculation as provided by COMSOL Multiphysics software. The seven parameters in COMSOL are different from the POEL program's parameters. So the deduction of parameters will be given in the following. By referring to the semi-analytical solution program we build a more realistic finite element numerical model to describe the poroelasticity behaviors of the curst. The solutions of both approaches in the similar physical situations indicate the correctness of these parameters' deduction.

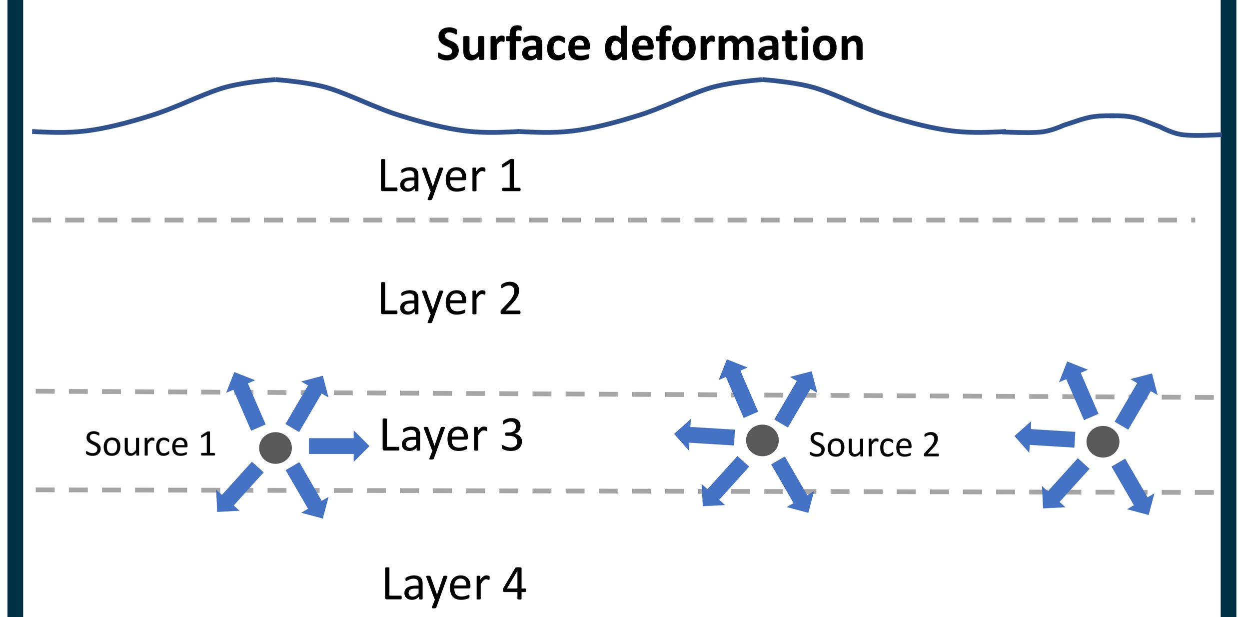

Fig 4

Figure 4 depicts a spatiotemporal Green's function multi-source superposition model, primarily derived through the secondary development of POEL. This model computes the integrated well process for multiple injection wells and achieves inversion through algorithmic implementation. The inversion outcomes can effectively constrain the essential parameters of subsurface well processes and the poroelastic medium.

Based on the analytical solutions for poroelastic injection sources, Rongjiang Wang developed the POEL software through propagation matrices and half-space treatments. Equations for poroelasticity injection sources are expressed using spatiotemporal Green's functions, which are combined in both time and space domains. This combination creates a model of poroelasticity for a semi-infinite space with multiple sources. This semi-analytical model for multiple-source poroelasticity differs from numerical simulations and enables inversion algorithms to be implemented. This model allows for the inversion of subsurface well processes constrained by the deformation field over time.

Discussion and Conclusion: Utilizing long-term geodetic measurements to constrain shale gas extraction activities is crucial. Long-time series InSAR observations are challenging to process and offer an opportunity to develop new InSAR algorithms. Investigating the mechanisms and quantitatively studying surface deformations induced by shale gas extraction are essential challenges in seismology, crustal deformation studies, and geodynamics. This effort also provides a chance to reexamine the geological structures of shale gas development areas and supplement elastic and poroelasticity parameters of geological formations. Our ongoing efforts involve using various numerical and analytical methods to test and establish geophysical models and, when necessary, develop new geophysical inversion algorithms.

Studying the principles behind surface deformations caused by shale gas extraction and constraining the shale gas extraction process has the potential to provide a quantitative foundation and evidence for studying induced seismicity. This research contributes to understanding the comprehensive interplay of factors influencing earthquakes and allows for the integration of various geophysical parameters alongside velocity structures. Investigating the physical mechanisms of shale gas extraction also involves exploring elastic loading and unloading of the crust, poroelasticity-induced surface deformations, and volume changes leading to compaction or filling due to shale gas extraction.

From investigating surface deformations caused by shale gas extraction, estimating shale gas production, understanding the well injection processes, to studying fluid diffusion and induced seismicity through quantitative well injection processes—each step has practical significance. This comprehensive approach contributes to the understanding of crustal structures, tectonic stresses, and the processes of seismicity, providing valuable insights for seismic hazard assessment and disaster prevention.