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# Numerical Modeling of Anisotropic Elastic-Wave Sensitivity Propagation for Optimal Design of Time-Lapse Seismic Surveys

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**Abstract.** Reliable subsurface time-lapse seismic monitoring is crucial for many geophysical applications, such as enhanced geothermal system characterization, geologic carbon utilization and storage, and conventional and unconventional oil/gas reservoir characterization, etc. We develop an elastic-wave sensitivity propagation method for optimal design of cost-effective time-lapse seismic surveys considering the fact that most of subsurface geologic layers and fractured reservoirs are anisotropic instead of isotropic. For anisotropic media, we define monitoring criteria using qP- and qS-wave sensitivity energies after decomposing qP- and qS-wave components from the total elastic-wave sensitivity wavefield using a hybrid time- and frequency-domain approach. Geophones should therefore be placed at locations with significant qP- and qS-wave sensitivity energies for cost-effective time-lapse seismic monitoring in an anisotropic geology setting. Our numerical modeling results for a modified anisotropic Hess model demonstrate that, compared with the isotropic case, subsurface anisotropy changes the spatial distributions of elastic-wave sensitivity energies. Consequently, it is necessary to consider subsurface anisotropies when designing the spatial distribution of geophones for cost-effective time-lapse seismic monitoring. This finding suggests that it is essential to use our new anisotropic elastic-wave sensitivity modeling method for optimal design of time-lapse seismic surveys to reliably monitor the changes in subsurface reservoirs, fracture zones or target monitoring regions.

**AMS subject classifications**: (or PACs) To be provided by authors
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## 1 Introduction

The goal of time-lapse seismic monitoring is to reveal the temporal media property changes of subsurface target regions, such as fracture zones/fault zones in geologic car-

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bon storage reservoirs, geothermal reservoirs and fractured reservoirs. This goal is usually achieved by subtracting the imaging or inversion results of the target monitoring regions before and after a certain time interval, using the same source-receiver geometry configuration. However, the accuracy of this approach can be degraded by numerous factors, such as random environmental noises, petrophysical environment changes beyond the detection of existing techniques, data acquisition repeatability, and changes in data processing flows across time-lapse surveys. To reduce the influence of unpredictable factors and accurately extract changes in target monitoring regions, it is necessary to design a seismic source-receiver network to cost-effectively capture the most significant seismic signals from time-lapse changes in target monitoring regions.

Time-lapse seismic monitoring becomes more complicated when subsurface geologic layers and the target monitoring region are anisotropic media, such as thin layers and fracture/fault zones. Naturally occurring cracks and fractures usually exhibit preferentially spatial alignment, resulting in significant velocity and permeability anisotropies [8–10,12,14–17,19,20]. For example, a set of rotationally invariant fractures sharing a common symmetry axis could result in transverse isotropy along the symmetry axis, which may lie horizontally [20], and orthogonally aligned fractures may result in orthotropic anisotropy [20,24]. Because seismic signals reflected/scattered from these fractures significantly complicate both data acquisition and subsequent data processing flow, we cannot determine the media properties of fracture zones as reliably as those of simple geology. In addition, most sedimentary layers are anisotropic media. Time-lapse seismic monitoring is crucial for many applications, such as geologic carbon utilization and storage (including potential $CO_2$ leakage through fracture/fault zones), geothermal energy production, conventional/unconventional oil and gas production, waste water injection, and waste repository, etc. Therefore, the optimal design of time-lapse seismic surveys is essential for reliable and cost-effective monitoring of subsurface changes.

Conventional time-lapse seismic surveys are usually based on seismic wavefield illumination [5, 11], employing ray-based methods [2, 13] and wave-equation based methods [1, 25]. However, complex geology limits the practical applications of these methods. [6] designed optimal time-lapse seismic surveys based on elastic-wave sensitivity modeling, that is, numerically propagating the sensitivity of an elastic wavefield with respect to medium parameters such as P-wave velocity $V_P$ or mass density $\rho$. This approach has a significant advantage that the spatial distributions of the elastic-wave sensitivity energies indicates how much significant information of the time-lapse changes of reservoirs can be acquired using a given geophone distribution. This approach has been applied to monitoring $CO_2$ leakage through faults [21]. However, present elastic-wave sensitivity methods are limited to isotropic media, which can be simply described by the density $\rho$, P-wave velocity $V_P$, S-wave velocity $V_S$, and certain derived petrophysical parameters such as the ratio of fluid saturation. However, additional parameters are needed to characterize anisotropic properties in fracture/fault zones such as elasticity parameters $c_{ijkl}$, excess compliance $\Delta s_{ijkl}$ contributed from fractures [8,17] and Thomsen parameters along with a reference velocity [23, 24].