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Probabilistic risk assessment for CO_2 storage in geological formations: robust design and support for decision making under uncertainty

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CO_2 storage in geological formations is currently being discussed intensively as a technology for mitigating CO_2 emissions. However, any large-scale application requires a thorough analysis of the potential risks. Current numerical simulation models are too expensive for probabilistic risk analysis and for stochastic approaches based on brute-force repeated simulation. Even single deterministic simulations may require parallel high-performance computing. The multiphase flow processes involved are too non-linear for quasi-linear error propagation and other simplified stochastic tools. As an alternative approach, we propose a massive stochastic model reduction based on the probabilistic collocation method. The model response is projected onto a orthogonal basis of higher-order polynomials to approximate dependence on uncertain parameters (porosity, permeability etc.) and design parameters (injection rate, depth etc.). This allows for a non-linear propagation of model uncertainty affecting the predicted risk, ensures fast computation and provides a powerful tool for combining design variables and uncertain variables into one approach based on an integrative response surface. Thus, the design task of finding optimal injection regimes explicitly includes uncertainty, which leads to robust designs of the non-linear system that minimize failure probability and provide valuable support for risk-informed management decisions. We validate our proposed stochastic approach by Monte Carlo simulation using a common 3D benchmark problem (Class et al. Computational Geosciences 13, 2009). A reasonable compromise between computational efforts and precision was reached already with second-order polynomials. In our case study, the proposed approach yields a significant computational speedup by a factor of 100 compared to Monte Carlo simulation. We demonstrate that, due to the non-linearity of the flow and transport processes during CO_2 injection, including uncertainty in the analysis leads to a systematic and significant shift of predicted leakage rates towards higher values compared with deterministic simulations, affecting both risk estimates and the design of injection scenarios. This implies that, neglecting uncertainty can be a strong simplification for modeling CO_2 injection, and the consequences can be stronger than when neglecting several physical phenomena (e.g. phase transition, convective mixing, capillary forces etc.).

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