Differentiable Model for Muon Transport and Two-Phase Flow in Porous Media with applications to Subsurface Pollution Monitoring

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Overview

Various industrial processes in geological formations could present safety and environmental risks including groundwater contamination. Non-aqueous phase liquids such as chlorinated hydrocarbons and oil, but also super-critical CO_2 and other compressed gas have low solubility in brine. Their migration, especially due to external forces, must be thoroughly monitored in order to avoid long-time pollution of freshwater aquifers in the subsurface. In the case of geological storage sites, any leaks would be also detrimental for the performance of the capture system itself.

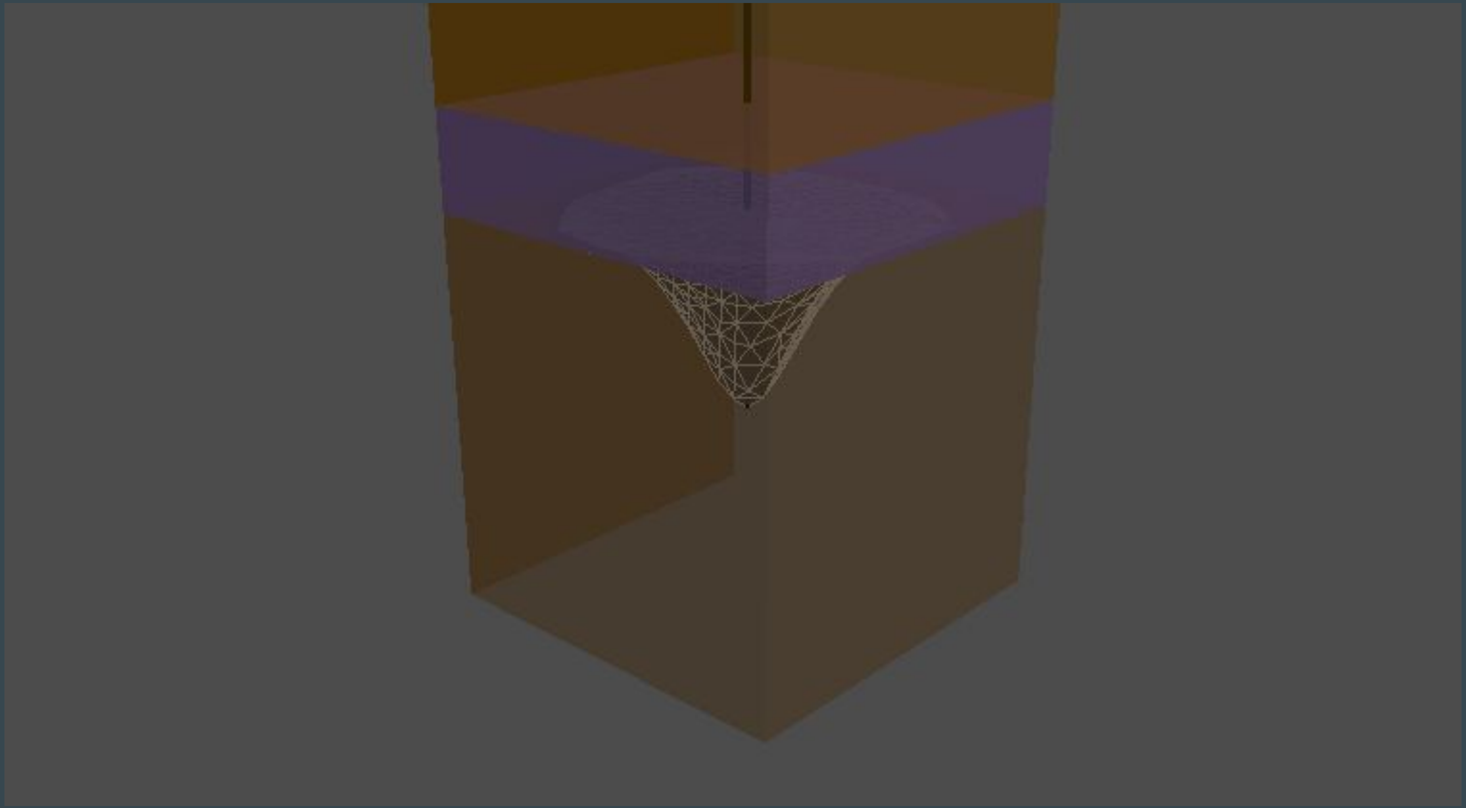
We have developed a realistic 3D evolution model for such leakage incidents, and propose a detection technique and quantitative assessment for them based on muography.

Example: Geological Carbon Storage

Parameter	Symbol	Value	Units
Brine density	ρ_w	1100	kg m^{-3}
Supercritical CO_2 density	ρ_n	720	kg m^{-3}
Rock density	ρ_s	2670	kg m^{-3}
Rock matrix porosity	η_1	0.2	–
Rock fract. porosity	η_2	0.05	–
Reservoir intrinsic permeability	κ^I	10^{-13}	m^2
Caprock intrinsic permeability	κ_1^{II}	10^{-15}	m^2
Caprock fract. permeability	κ_2^{II}	10^{-11}	m^2
Brine residual saturation	S_{rw}	0.4438	–
Well injection depth	W	680	m
Reservoir height	H	170	m
Detector depth	D	800	m
CO_2 mass injection rate	M_n	20	kg s^{-1}

Other examples include enhanced oil recovery, well disposal, subsurface renewable energy storage for hydrogen, methane or compressed air, as well as geothermal energy and mountain hydrology.

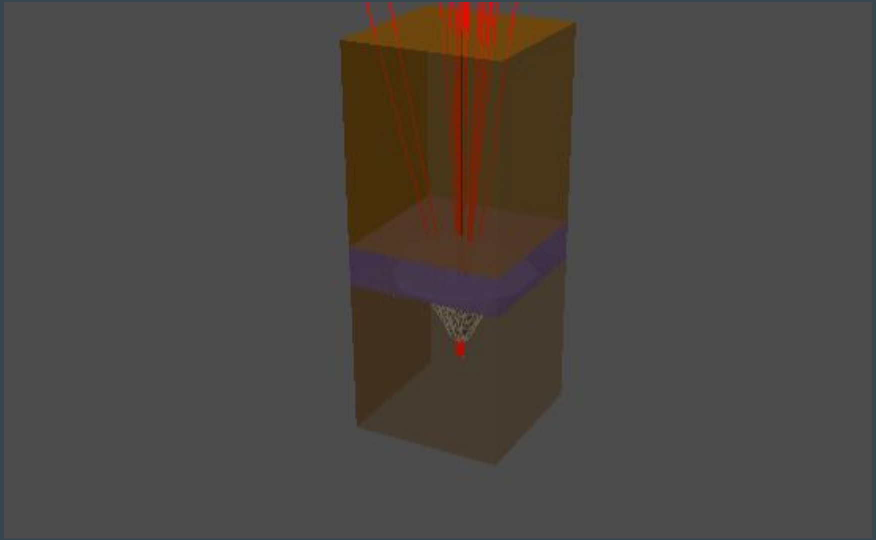
MHFEM scheme for two-phase flow in porous media

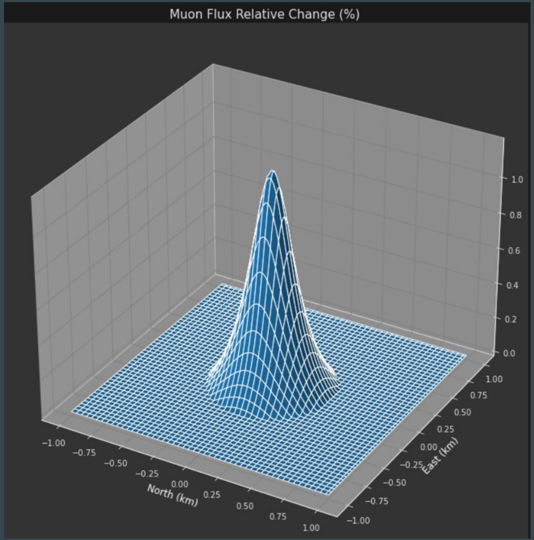


BMC scheme for muon transport

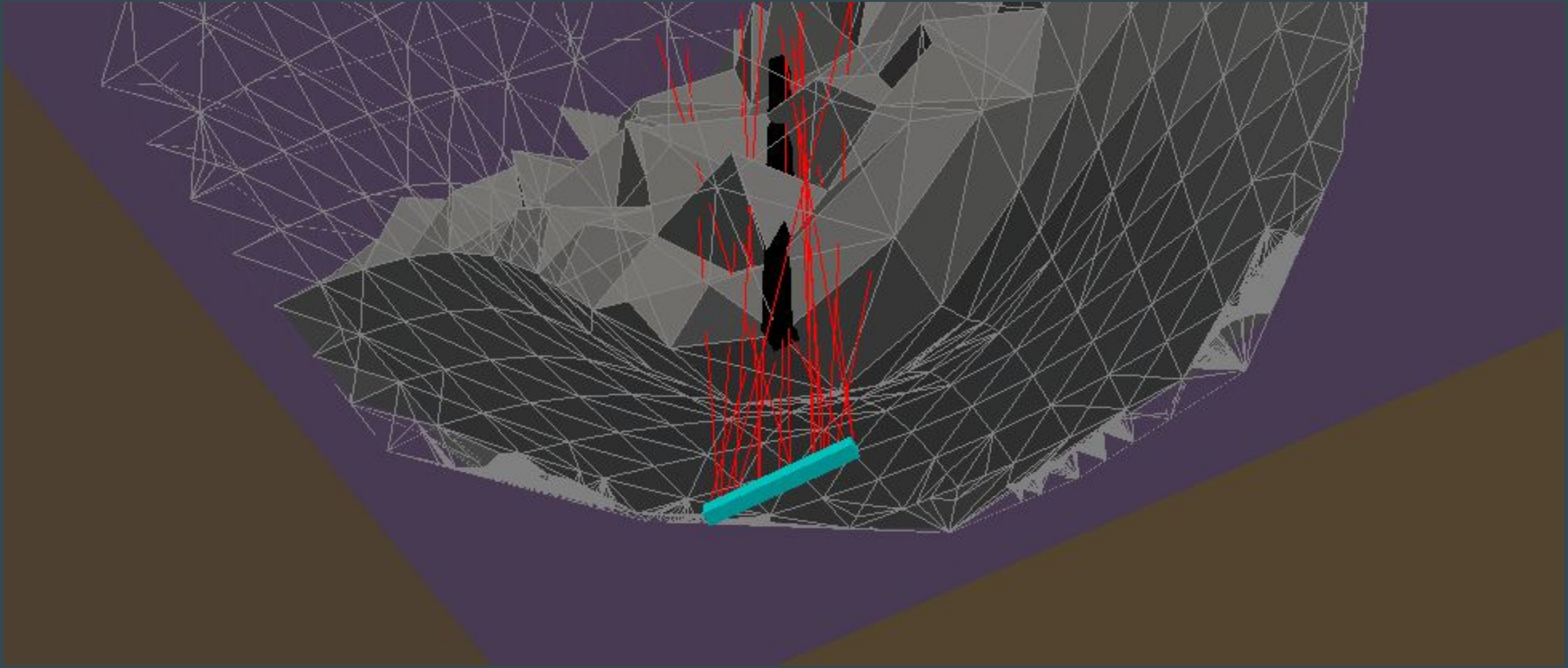
Cosmic-ray muon flux in atmosphere:

$$\frac{d\phi}{dE} = 0.14\left[E \cdot \left(1 + \frac{3.64}{E \cdot (\cos\theta^*)^{1.29}}\right)\right]^{-2.7} \left(\frac{1}{1 + \frac{1.1E\cos\theta^*}{115}} + \frac{0.054}{1 + \frac{1.1E\cos\theta^*}{850}}\right)$$





Adjoint sensitivity analysis for the coupled muon + fluid transport



Main outcomes

Modelling of substances migration in porous media with low solubility in water has been addressed by a vast literature. The use of atmospheric muons to monitor underground fluid saturation levels has been also studied, specifically for the case of carbon sequestration. However, the low-contrast and possibly noisy muon flux measurements require accurate and realistic modelling of the main physical processes for the inverse problem behind monitoring. Moreover, first order sensitivity information for control parameters is needed to improve the analysis, as was demonstrated using approximate and simplified dynamics for both the CO2 plume evolution and the muon flux computation.

We address those issues by incorporating a differentiable programming paradigm into the implementation of the physics with detailed simulations.