Seeing the Unseen: From Sparse Observations to Cognitive Subsurface Modelling

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Subsurface characterization is fundamentally constrained by sparse and heterogeneous data. This lecture presents a unified data-intelligent modelling framework that integrates data acquisition, spatial modelling, and inference to enable robust subsurface models under data scarcity. To capture complex stratigraphy and spatial variability, the framework introduces a boundary dictionary learning method that guides machine learning with geologically meaningful interface constraints. This is complemented by multi-source fusion that produces more reliable subsurface profiles by integrating sparse, high-precision intrusive tests with wide-coverage geophysical data. To overcome data scarcity in structural characterization, the framework combines deep-learning-based vectorized search retrieving knowledge from historical databases, intelligent acquisition methods rapidly extracting discontinuity orientations and traces from images and point clouds, and diffusion-based generative models expanding these sparse field observations into diverse, geologically plausible fracture scenarios. These augmented observations further enable inference of internal fracture networks and their spatiotemporal evolution, bridging the gap to inaccessible subsurface conditions. Building upon these components, an AI agent-based cognitive system orchestrates specialized models and tools, performing expert-level interpretation, consistency checking, and automated report generation. Together, these developments represent a paradigm shift from empirical practice to principled, data-intelligent subsurface modelling that substantially enhances reliability and decision-making in tunnels, slopes, foundations, and underground space development.