Random-Field Modeling of Subsurface Stratigraphy and Geo-properties: Applications in the Taipei Basin

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Abstract: Regional-scale characterization of subsurface uncertainty is essential for basin-wide seismic assessment, yet integrating stratigraphy and geo-properties in a single probabilistic model remains uncommon in practice. To address this gap, we adopt a stratigraphic-based geo-property random field (SGRF) framework that couples a stochastic Markov random field (SMRF) for categorical stratigraphy with a hidden Markov random field (HMRF) for continuous geo-properties (e.g. void ratio , unit weight). Fractional Brownian motion (FBM) captures scale-dependent variability, and parameters are inferred via Bayesian calibration. Applied to the Taipei Basin, the framework generates ensembles of stratigraphy and geo-property fields and propagates them to shear-wave velocity (V_S) and V_{S30} through soil-type-specific estimation functions. Stratigraphic uncertainty is quantified with information entropy, while geo-property uncertainty is summarized by ensemble moments. The resulting V_{S30} maps are geologically plausible and correspond well to an independent kriging baseline; where differences occur, they coincide with zones of elevated modeled uncertainty. Basin-wide analyses show that uncertainty in lithologic architecture is the dominant driver of dispersion in V_S and V_{S30}, with void-ratio variability contributing more than unit-weight variability. Overall, SGRF offers a computationally tractable route from heterogeneous geological data to probabilistic V_S/V_{S30} mapping at a regional scale and clarifies how uncertainty propagates from stratigraphy to engineering quantities, supporting targeted data acquisition and more robust seismic design decisions.

Keywords: ***Uncertainty, Stratigraphic random field modeling, Markov random fields, Seismic site characterization.***

Introduction

Regional-scale characterization of engineering-geological model uncertainty is increasingly necessary for basin-wide hazard assessment and infrastructure planning. Unlike site-specific studies, regional applications must account for vastly more subsurface elements and spatial heterogeneity. Therefore, scaling up site-level workflows is often computationally prohibitive and can obscure how uncertainty propagates from geology to engineering quantities (Juang et al., 2025).

To tackle this challenge, Lu et al. (2025) proposed a stratigraphic-based geo-property random field (SGRF) framework that couples categorical stratigraphy with continuous geo-properties (e.g., void ratio, unit weight) in a unified probabilistic model. SGRF integrates a stochastic Markov random field (SMRF) to simulate stratigraphic configurations and a hidden Markov random field (HMRF) to simulate geo-property fields, augmented with fractional Brownian motion (FBM) to capture scale-dependent variability. In this study, we adopt SGRF to perform regional uncertainty characterization in the Taipei Basin and demonstrate applications to seismic assessments. We quantify how stratigraphic uncertainty influences variability in geo-property fields and, in turn, affects shear-wave velocity (V_s) and V_{S30} (time-averaged Vs in the top 30 m), providing actionable guidance for regional modeling and seismic hazard assessments.

Methodology

We implement SGRF in three stages (workflow summarized in Figure 1), as outlined in Juang et al., 2025. First, foundational engineering-geological data are assembled (borehole logs, stratigraphic labels, geo-property statistics), including quality assurance/quality control screening. The borehole database is sourced from Taiwan's Geological Survey and Mining Management Agency (GSMM).

Second, stratigraphy is modeled as a categorical field using SMRF (Li et al., 2016b; Wei and Wang, 2022; Juang et al., 2025), with a Potts-type local energy and an ellipsoidal contextual constraint to encode anisotropy (stronger lateral than vertical correlation). Conditioning is enforced at borehole cells (hard data), and unknown voxels are sampled via Markov Chain Monte Carlo (MCMC) from local conditional probabilities (Li et al., 2016b; Wei and Wang, 2022).

Third, geo-properties are simulated with HMRF conditioned on the stratigraphic realization. FBM introduces Hurst parameter H to control scale-dependent roughness; class-dependent means/variances are used where measurements are sparse. Model parameters (spatial correlation, class statistics, H) are inferred via Bayesian calibration against observations. From joint realizations of stratigraphy, void ratio, and unit weight, we compute per-cell information entropy (stratigraphic uncertainty) and ensemble moments for geo-properties. Effective vertical stress σ_v' is obtained from unit weight and groundwater assumptions; soil-type-specific functions that correlate V_S to void ratio and σ_v' yield V_S profiles and V_{S30} by depth-averaging (Nicholas et al., 2025). Outputs include mean and standard-deviation maps of V_{S30} and correlation diagnostics linking geological uncertainty to velocity dispersion.

Results

The SGRF ensemble yields geologically plausible V_{S30} surfaces; the mean V_{S30} map (Figure 2a) captures expected low-velocity zones within fine-grained depocenters and higher values toward coarser margins. The standard-deviation map (Figure 2b) delineates uncertainty “hotspots.” Pixel-wise analyses reveal that dispersion in V_S and V_{S30} are governed primarily by uncertainty in stratigraphic architecture. Figure 3demonstrates that basin-wide, the average entropy at 30 m depth ($I_{E,30}$) exhibits a clear positive association with V_{S30} standard deviation (Juang et al., 2025). Additionally, it was found that void ratio played a larger role than unit-weight variability to the standard deviation of V_{S30} (Juang et al., 2025). Hold-out comparisons at reserved boreholes (not shown) indicate low bias and residuals consistent with ensemble-derived uncertainty envelopes, supporting both central estimates and credibility intervals.

Conclusion

The SGRF framework provides a coherent, computationally feasible route from heterogeneous borehole data to regional-scale uncertainty maps for stratigraphy and geo-properties, and onward to probabilistic V_S and V_{S30}. In the Taipei Basin application, mean V_{S30} fields align with an independent kriging baseline, and analyses confirm that stratigraphic uncertainty is the dominant source of dispersion in V_S and V_{S30} (Juang et al., 2025). By pinpointing where geological ambiguity is greatest, the approach supports targeted data acquisition and more defensible basin-scale seismic hazard and design decisions. Future extensions will incorporate geophysical constraints, refined groundwater models, and site-specific transformation functions to further reduce uncertainty in priority zones.

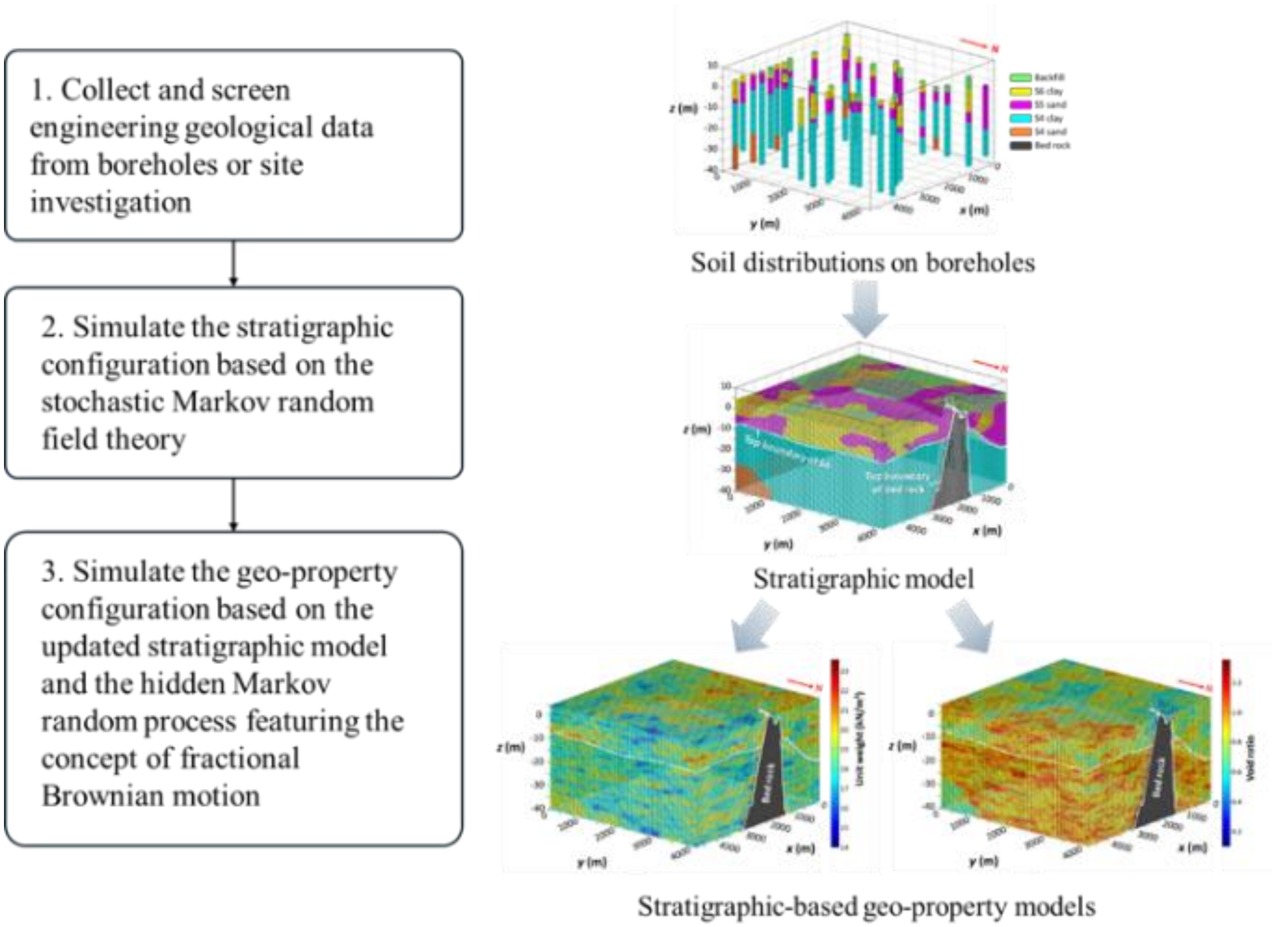

Figure 1, Procedures for implementing the stratigraphic-based geo-property random field (SGRF) (modified from Lu et al., 2023; reproduced from Juang et al., 2025).

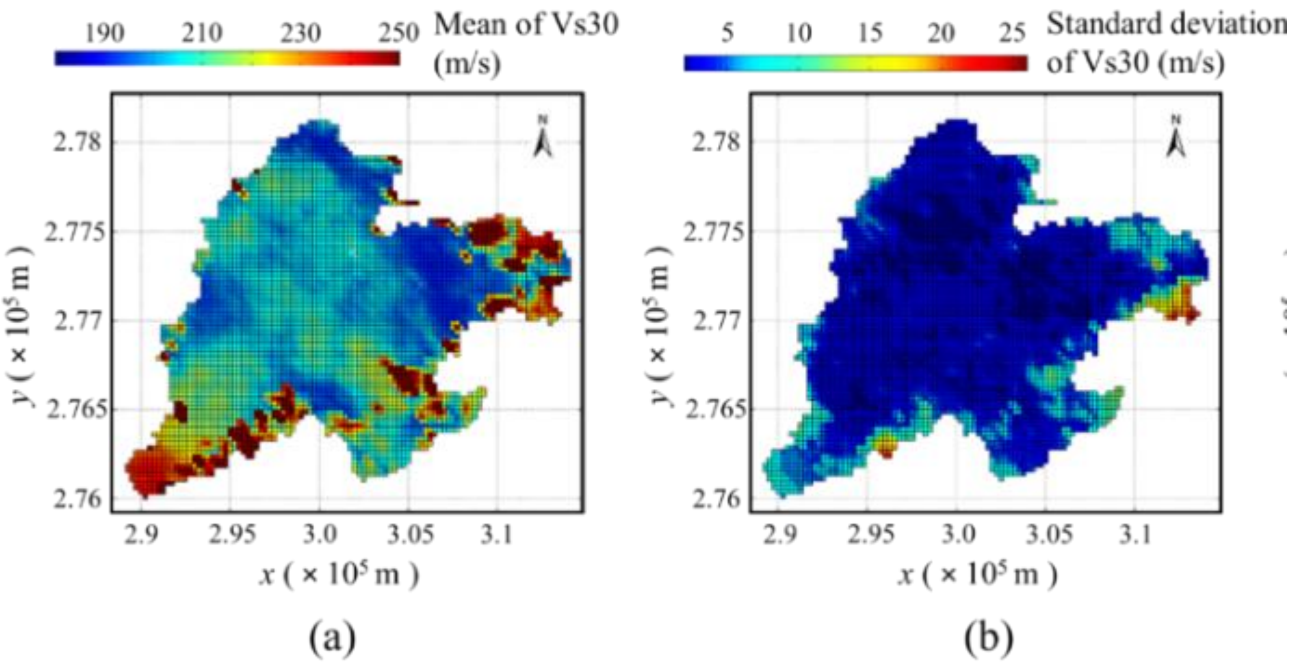

Figure 2, The probabilistic V_{S30} mapping results in the Taipei Basin: (a) Mean of V_{S30}; (b) Standard deviation of V_{S30}. Reproduced from Juang et al. (2025).

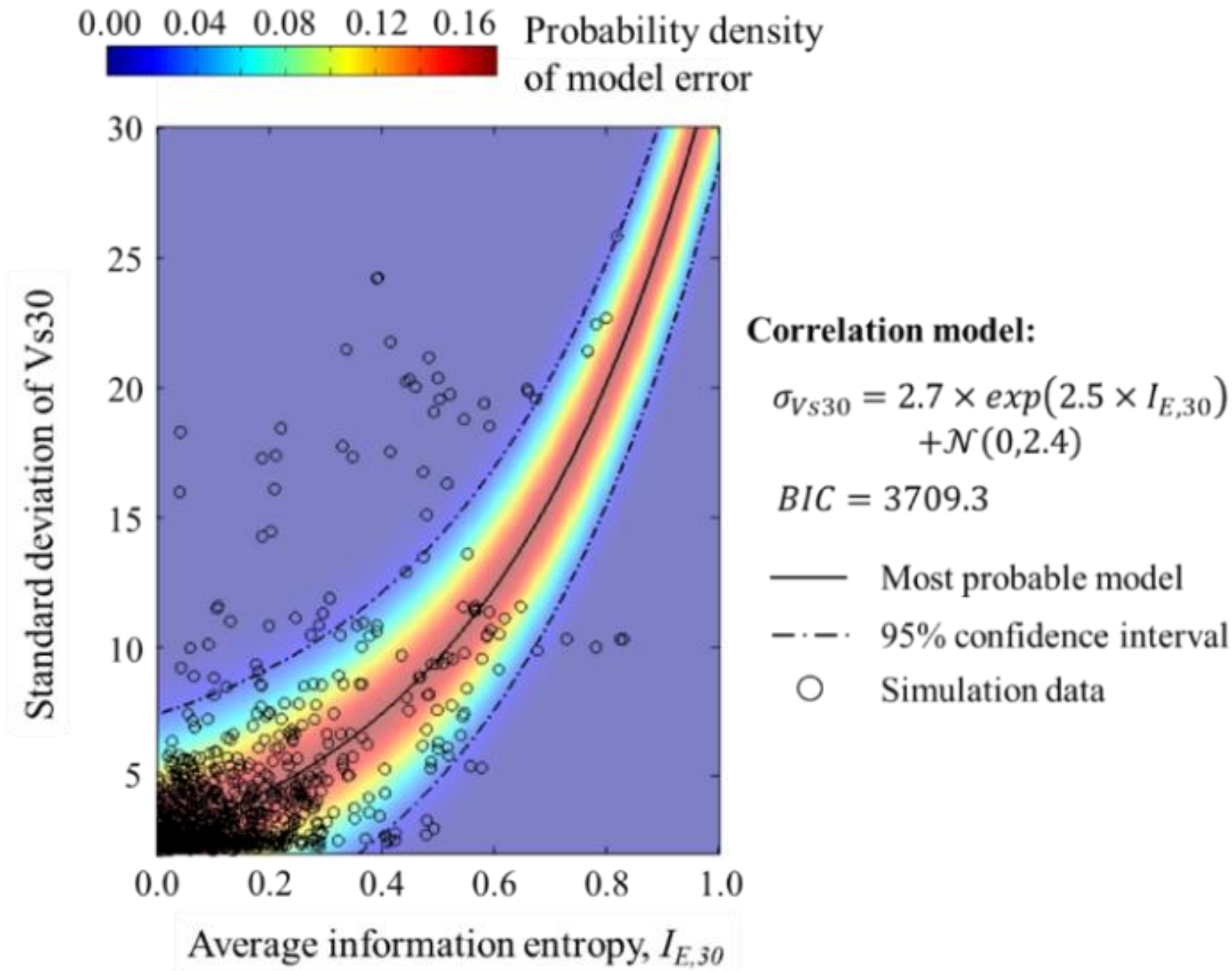

Figure 3, Probabilistic correlation between the average information entropy under the depth of 30m from the ground (IE,30) and the standard deviation of VS30. Reproduced from Juang et al. (2025).

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