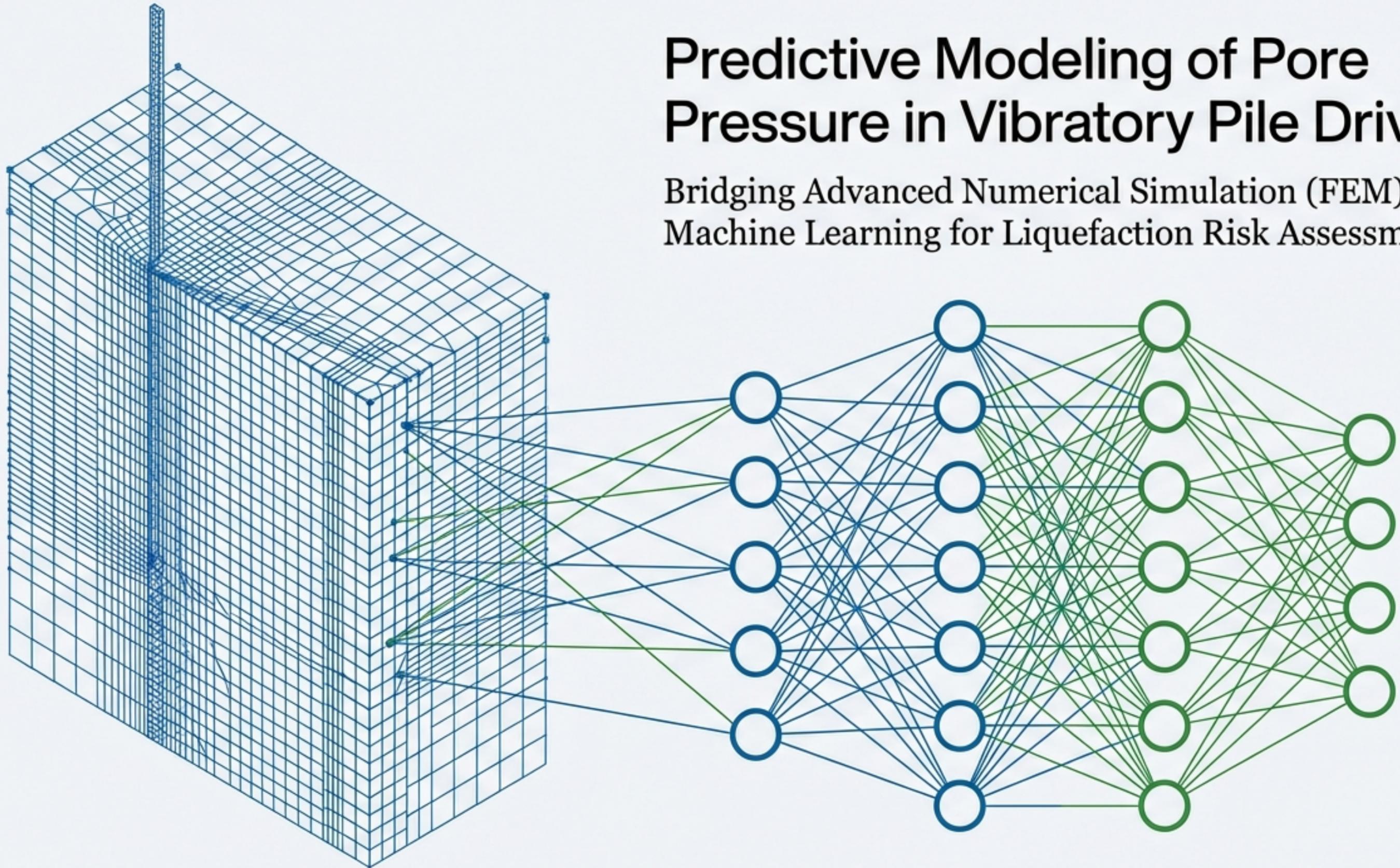


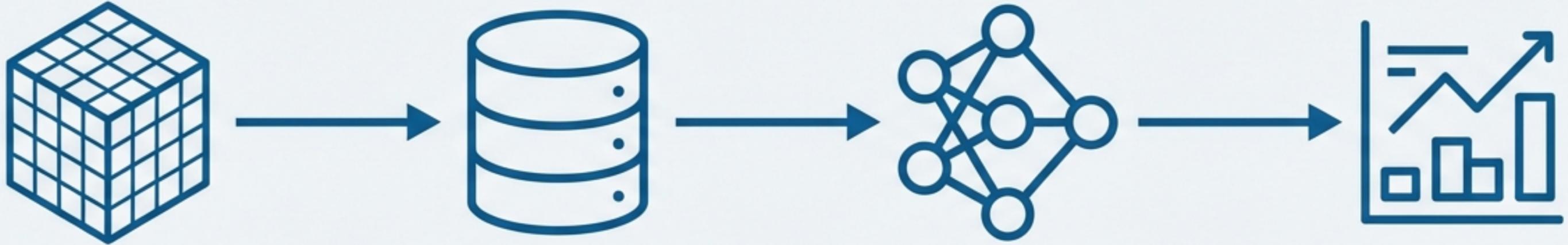
Predictive Modeling of Pore Pressure in Vibratory Pile Driving

Bridging Advanced Numerical Simulation (FEM) with Machine Learning for Liquefaction Risk Assessment



Research Framework: Midas GTS NX • UBCSAND Constitutive Model • Symbolic Regression

The Methodology: A “Virtual Laboratory” Workflow



3D FEM Modeling

Midas GTS NX + UBCSAND

Parametric Study

2,700 Unique Cases

Machine Learning

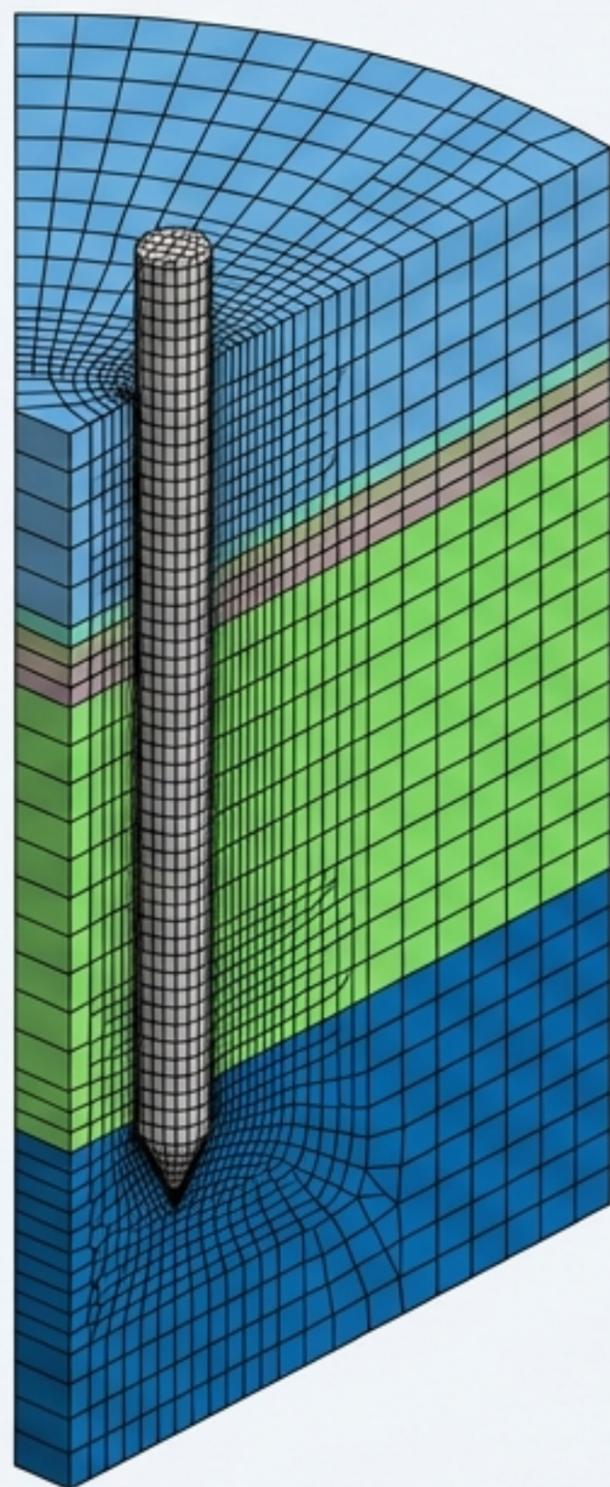
ANN & Symbolic Regression

Practitioner Tools

Design Charts & Formulas

We generated a massive synthetic dataset (2,700 simulations) to train models that predict liquefaction probability with >98% accuracy.

Rigorous Numerical Setup: Midas GTS NX



Constitutive Model: UBCSAND
(Captures sand plasticity & liquefaction)

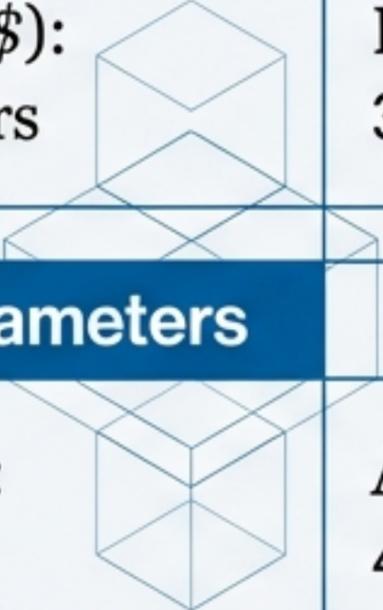
Geometry: Axis-symmetric 10° slice
with 60° conical tip

Pile Material: Linear elastic steel
(Non-rigid deformation)

Boundaries: Absorbing boundaries
(Rayleigh damping 7.5%–17.5%) to prevent
wave reflection

Model behavior validated against experimental data from Fadaei and Hamidi

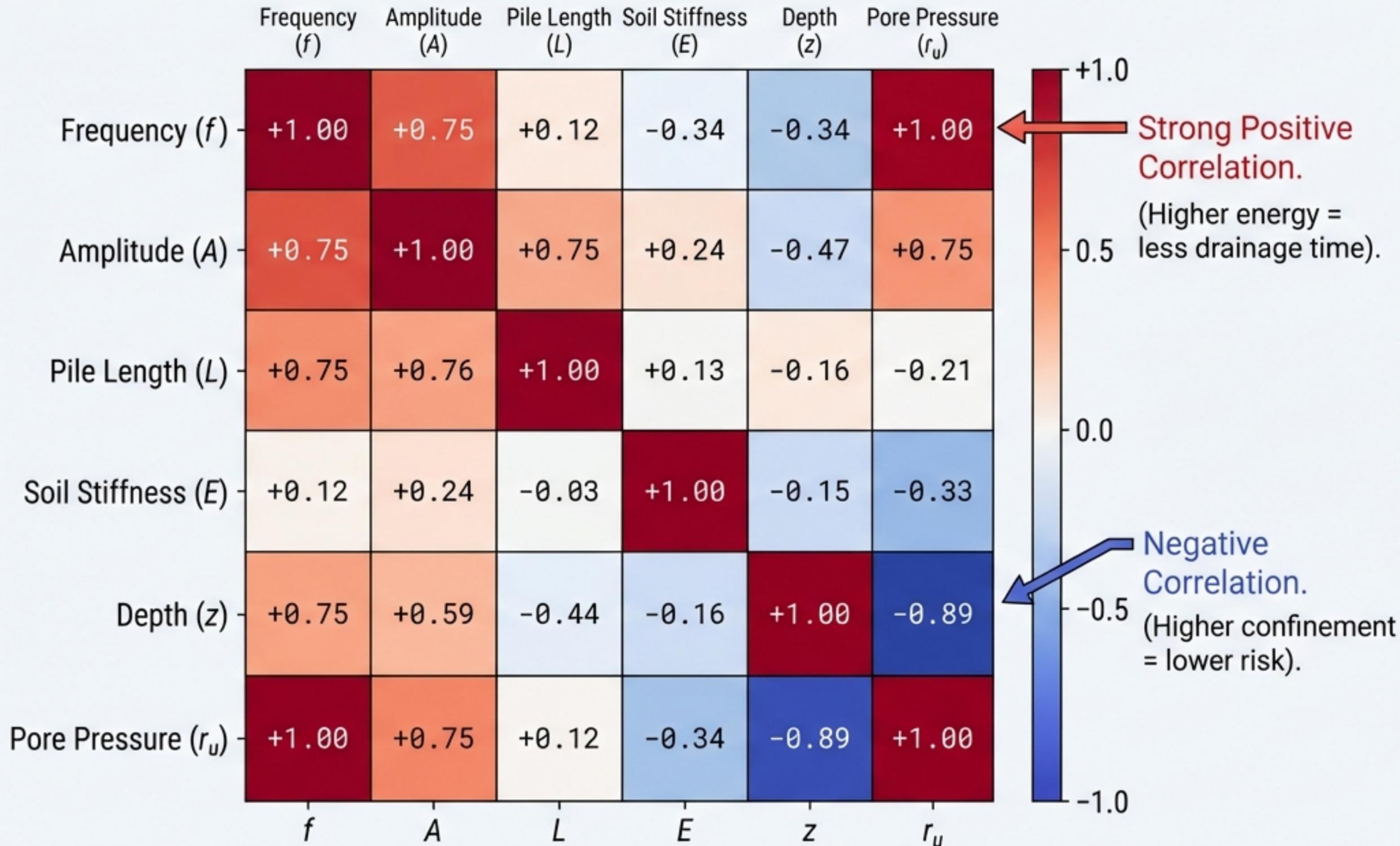
The Dataset: 2,700 Simulated Scenarios

1	Pile Geometry	
	Pile Length (L): 12 – 24 meters	Length-to-Diameter (L/D): 30 – 50 (Slender to Stout)
2	Vibration Parameters	
	Frequency (f): 23 – 38 Hz	Amplitude (A): 435 – 10,748 kN
3	Soil Properties	
	Soil Stiffness (E): 10.5 – 22.5 MPa	

2,700
Data Points

Covering the transition from safe drainage to rapid pressure buildup.

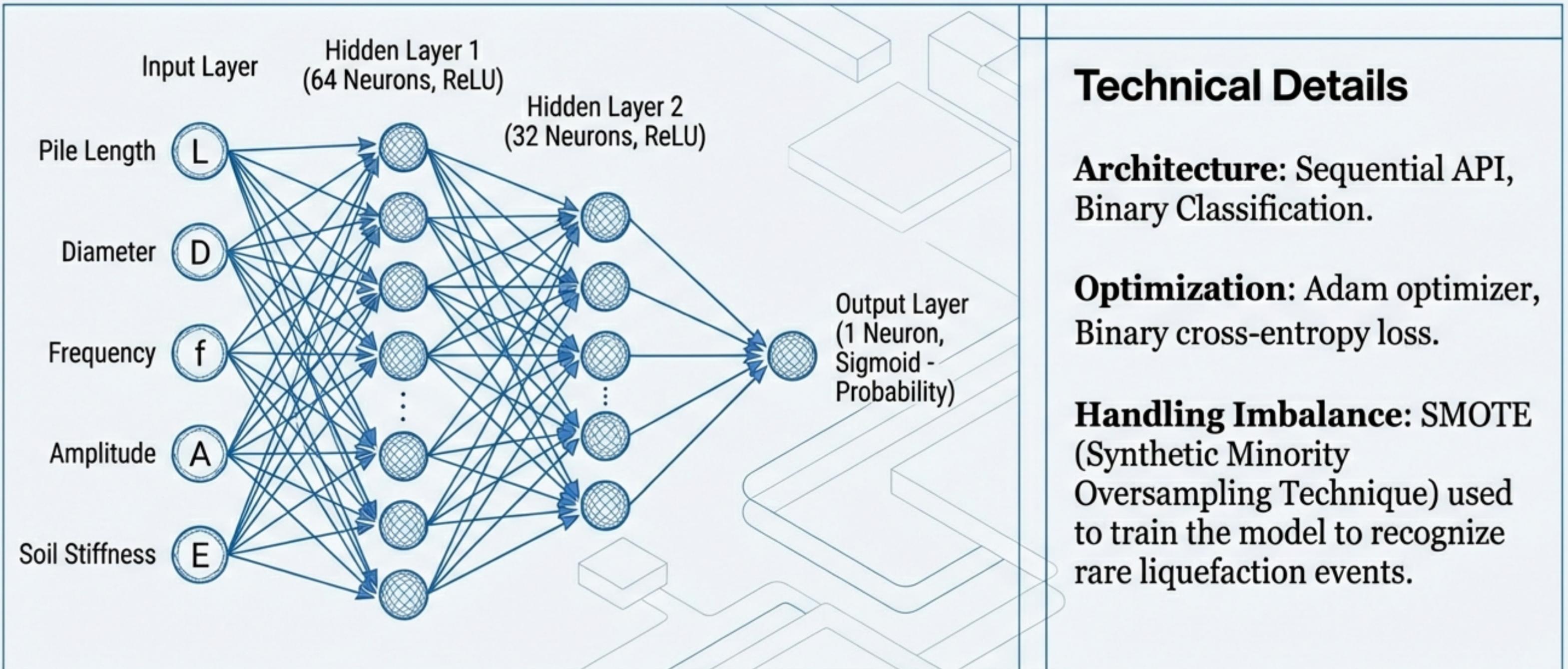
Physics Validation: Correlations & Heatmap



Validation: The dataset reflects physical reality.

Frequent peak r_u values $> 80\%$ confirm the simulation captures liquefaction events.

The Prediction Engine: Artificial Neural Network (ANN)



Technical Details

Architecture: Sequential API, Binary Classification.

Optimization: Adam optimizer, Binary cross-entropy loss.

Handling Imbalance: SMOTE (Synthetic Minority Oversampling Technique) used to train the model to recognize rare liquefaction events.

Interpretable AI: Symbolic Regression

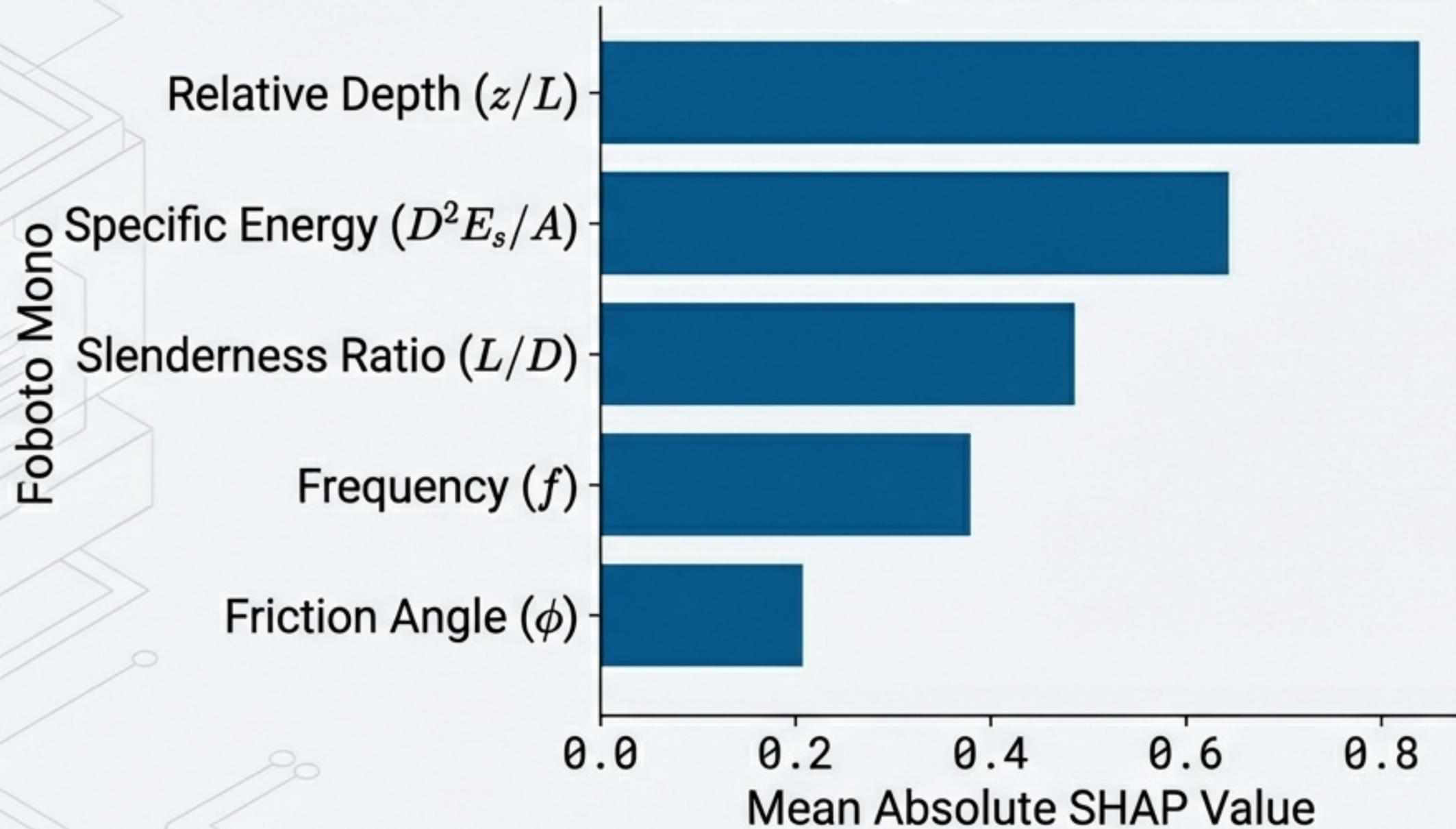
$$r_u = f\left(f_n, \frac{z}{L}, \frac{D^2 E_s}{A}, \tan \phi, \dots\right)$$

Methodology	Type	AUC Score	Pros
ANN	Black Box	0.981	Highest Accuracy
Symbolic Regression	White Box	0.951	Human-Readable Formula

Symbolic Regression evolves an explicit mathematical formula to fit the data, offering transparency at the cost of slight precision.

Feature Importance: What Drives Liquefaction?

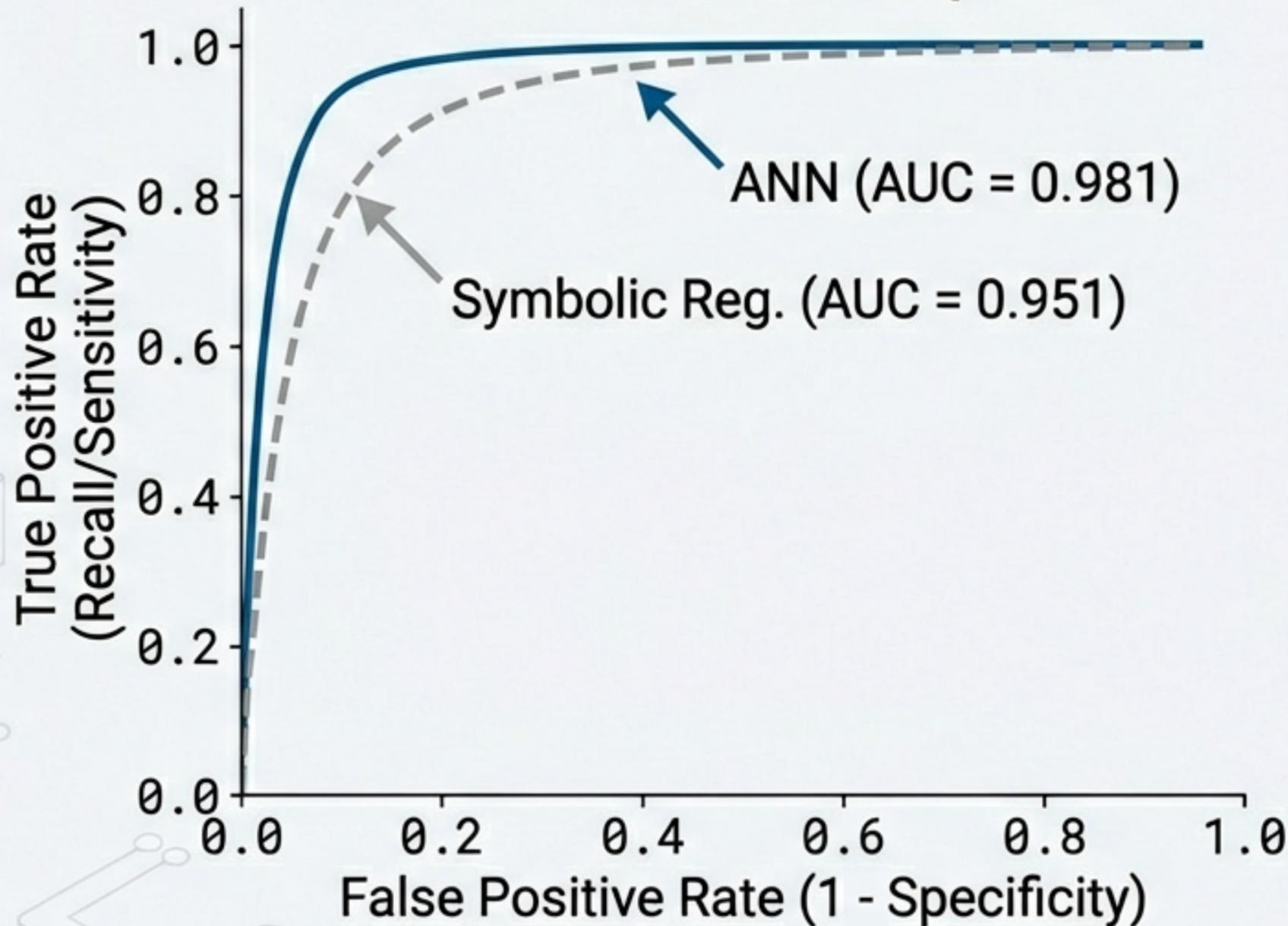
SHAP Value Magnitude (Feature Importance)



SHAP Analysis reveals that geometry (z/L) and energy input are the dominant drivers. Notably, Soil Stiffness (E_s) outweighs Friction Angle in vibratory scenarios.

Model Validation: Performance Metrics

ROC Curves: Model Comparison



Key Metrics at 0.6 Threshold

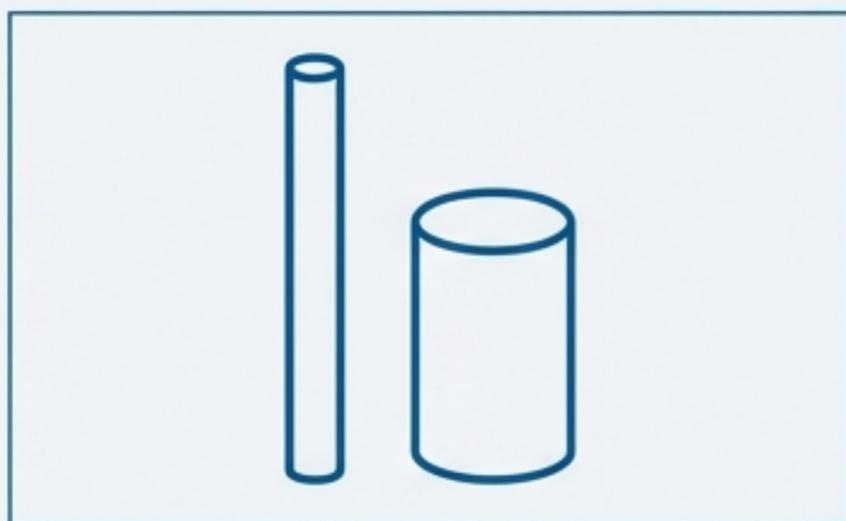
Recall (Sensitivity):
~94%
(at 0.6 threshold)

Implication:
The model successfully identifies the vast majority of dangerous liquefaction cases.

Practical Heuristics for Site Engineers

Geometry

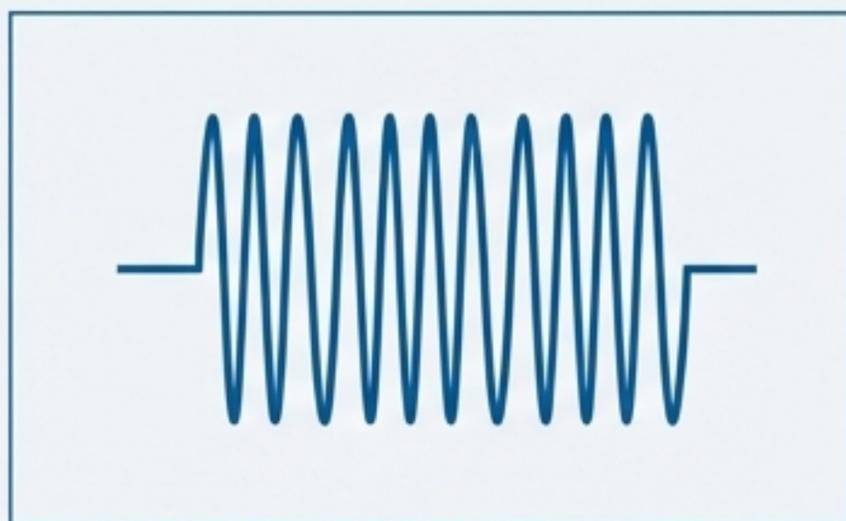
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Slender Piles (High L/D):
Generate lower pore
pressure buildup.  **Safer.**

Frequency

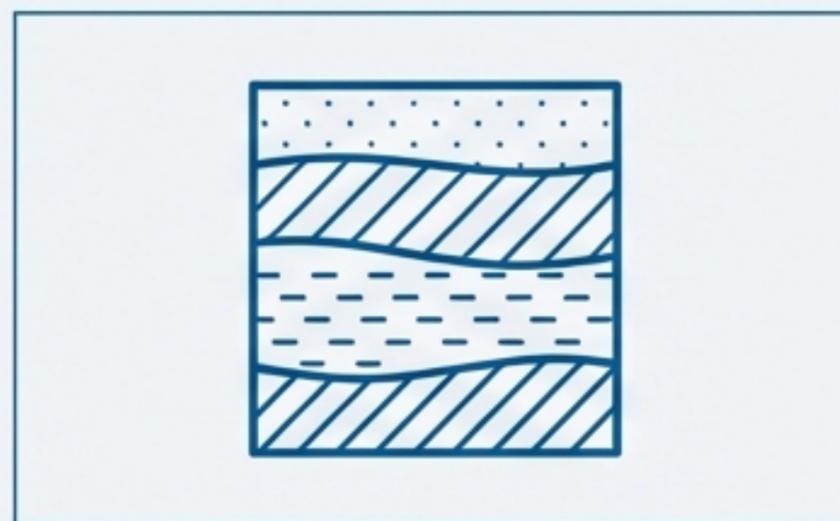
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High Frequency:
High Frequency: Leads to
extensive liquefaction zones. 
Low frequency confines risk
to the pile mid-section.

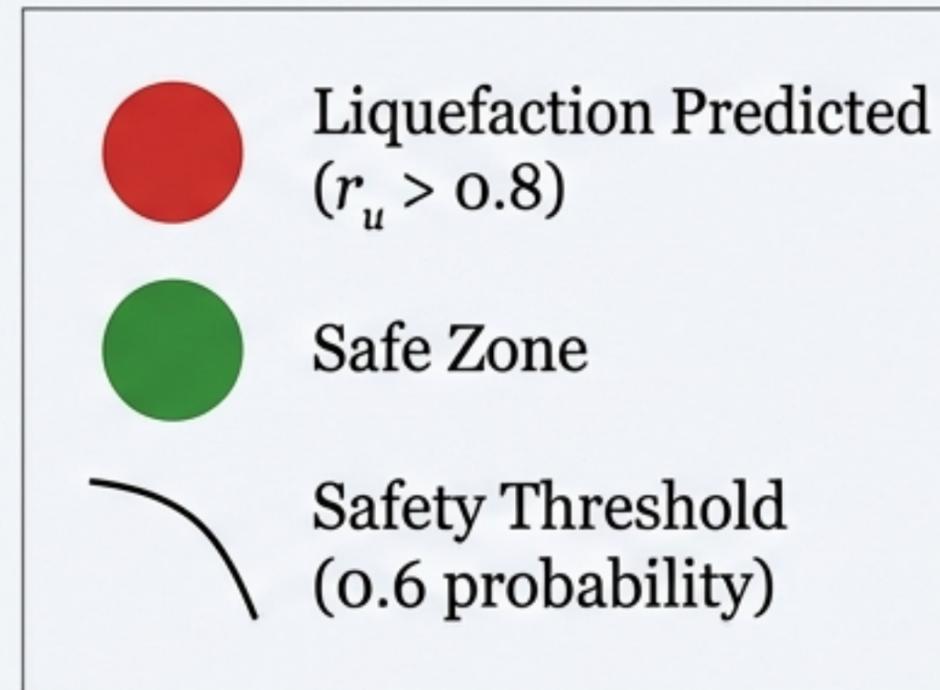
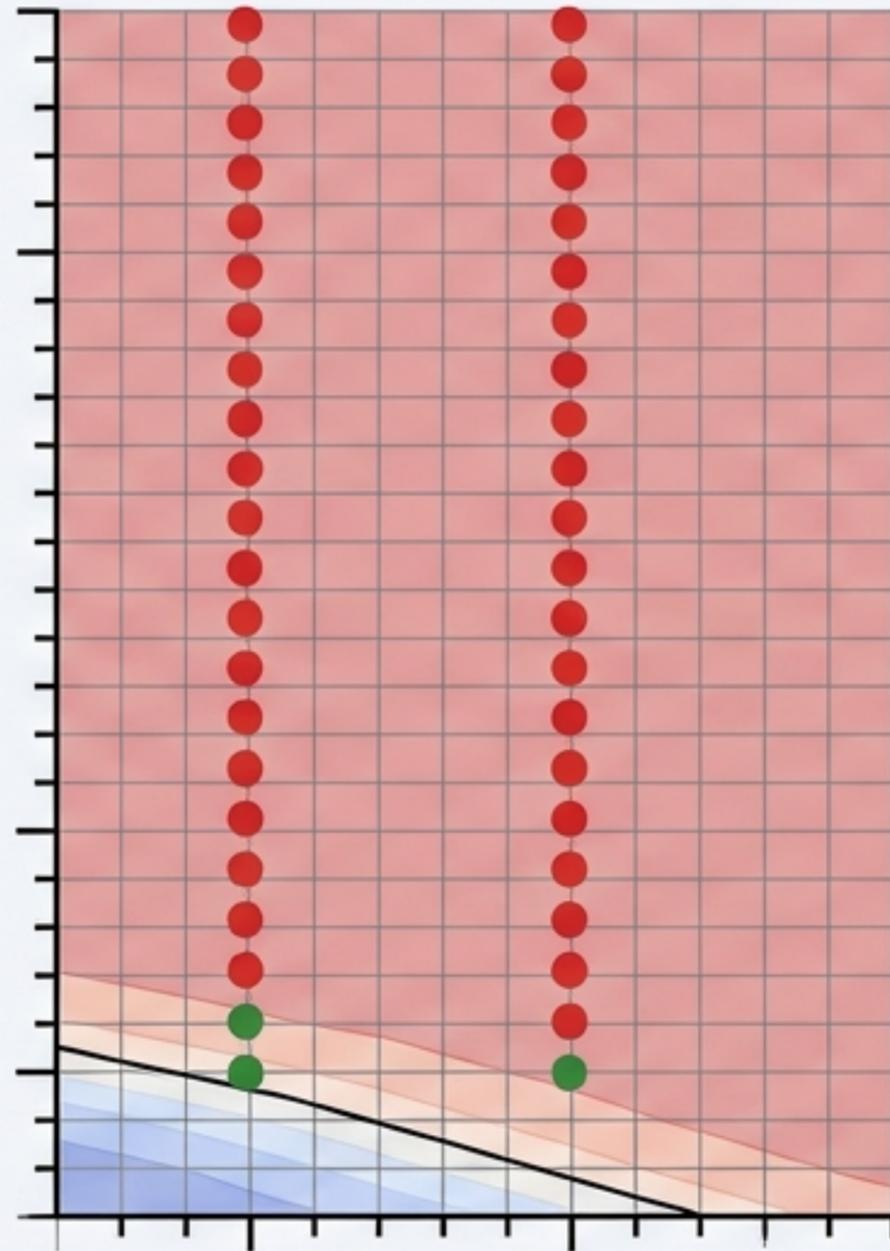
Soil

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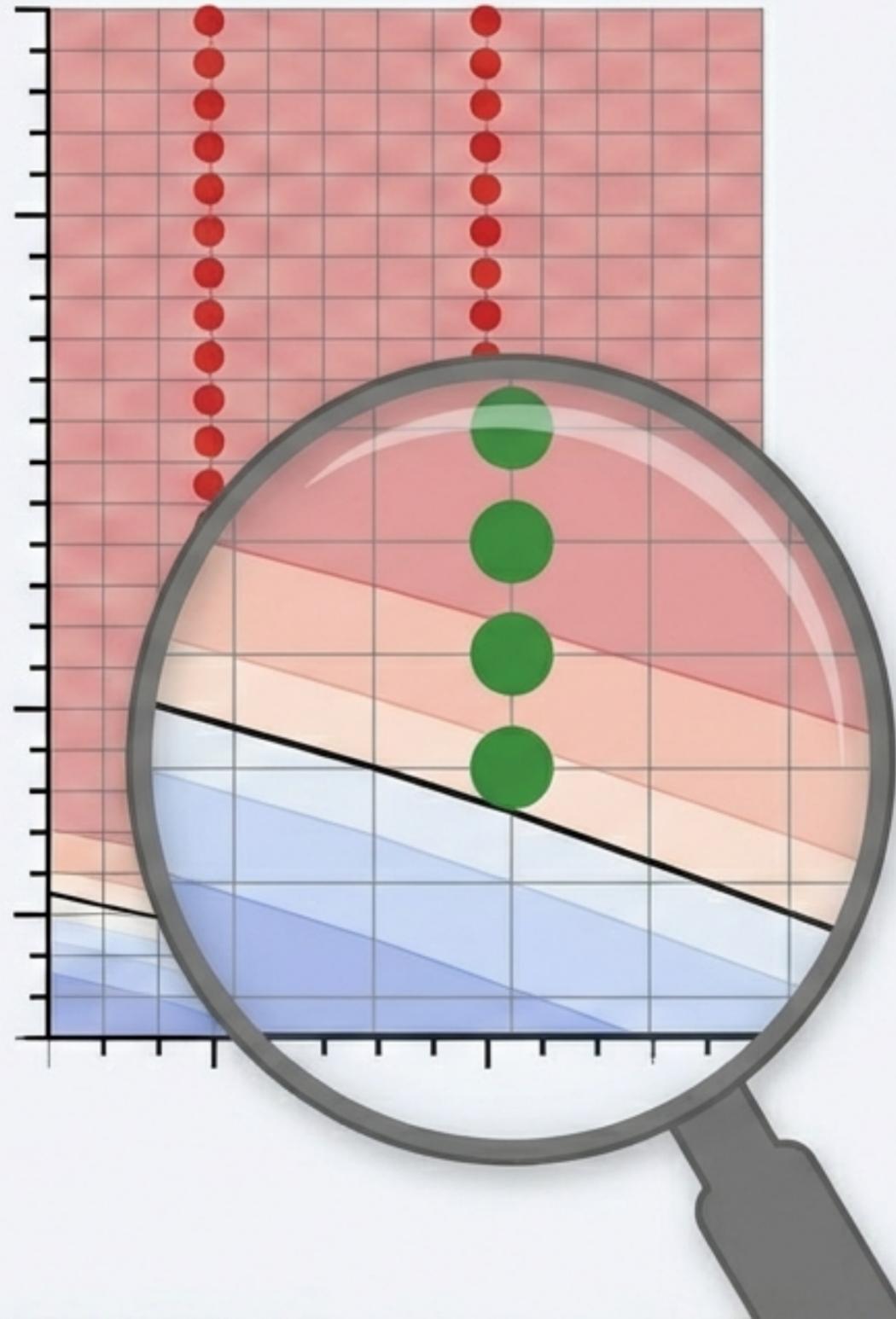
Stiffness Matters:
Stiffness Matters: Soil
Stiffness (E_s) is a stronger
predictor than Friction Angle
in this context.

The Practitioner's Tool: Design Charts (Part 1)



Instant feasibility check: Locate your pile depth and vibration frequency to determine safety without simulation.

Design Charts: Safety Margins & Conservatism



-  Liquefaction Predicted ($r_u > 0.8$)
-  Safe Zone
-  Safety Threshold (0.6 probability)

Conservative Bias: The model occasionally classifies safe cases (**Green**) as risks (above line). In geotechnical safety, false positives are preferable to missed failures.

Limitations & Scope

- ⚠ **Soil Type:** Model valid only for saturated sandy soils (UBCSAND constitutive law).
- ⚠ **Conservatism:** Approx. 6% misclassification of safe cases as risks (prioritizing safety).
- ⚠ **Frequency Range:** Validated for 23–38 Hz; extrapolation requires caution.
- ⚠ **Future Work:** Integration of field data required to refine margins.

Summary: From Computation to Instant Insight

SAFETY

Early identification of liquefaction zones before equipment mobilization.

EFFICIENCY

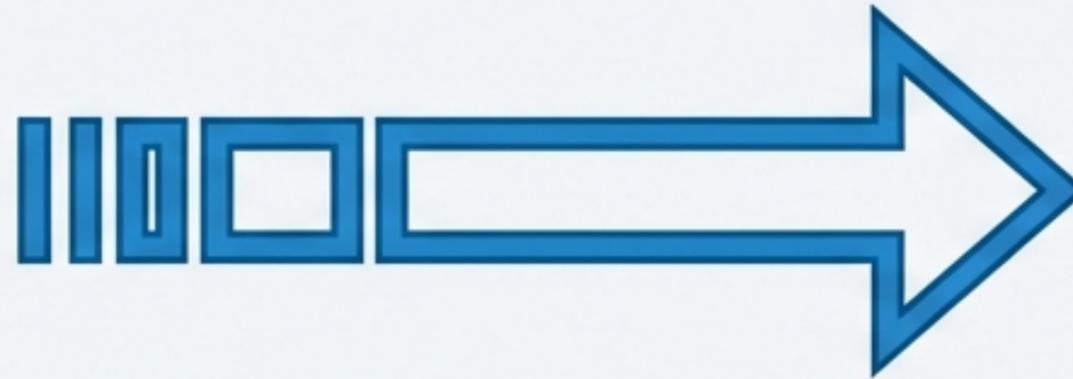
Replaces days of numerical calculation with millisecond ML predictions.

ACCESSIBILITY

Democratizes advanced geophysics via simple Design Charts.



FEM Data



Safe Design