Understanding the mechanical stability of tunnels using machine learning

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CS229 course project

Motivation

We try to understand the various components affecting the stability of tunneling and wellbore operations. We use a series of advanced finite element (FE) simulations to obtain a dataset which contains the stress response of the soil during drilling operations as a function of 12 input parameters. Using Multivariate Adaptive Regression Splines (MARS), we create a simplified model of the simulations (meta-model) and test its accuracy. Furthermore, we perform Sobol sensitivity analysis and study the most important variables and interactions.

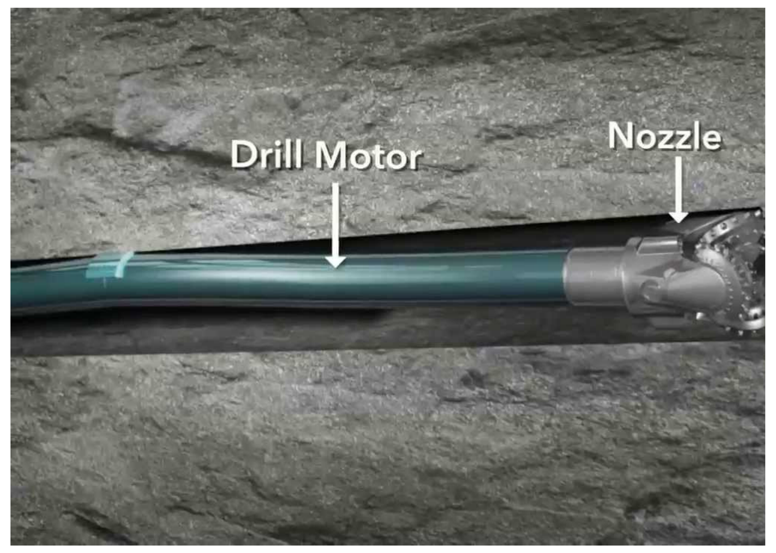

Figure 1: Horizontal drilling

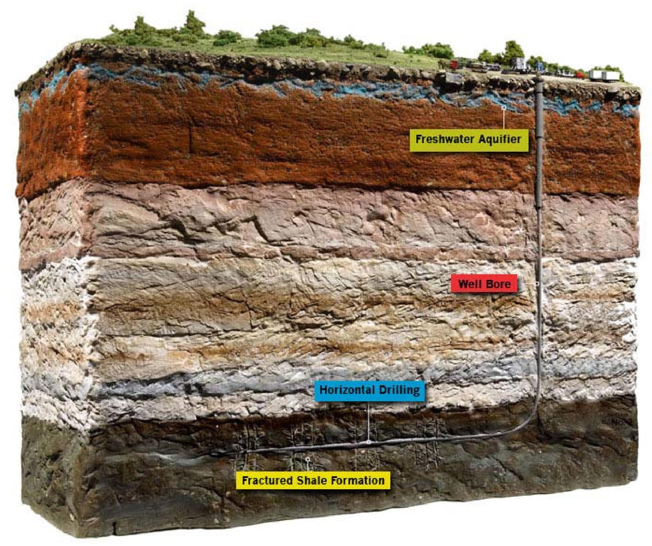

Figure 2: Horizontal wells for hydraulic fracturing

Data

We use accurate Finite element simulation create a database of will 2000 records. For each data point, a geometry is created and a finite element mesh is obtained, then the mechanical PDE is solved and a number of mechanical outputs are extracted through the post-processing step. The input data is uniformly distributed and it is sampled through Latin Hypercube sampling.

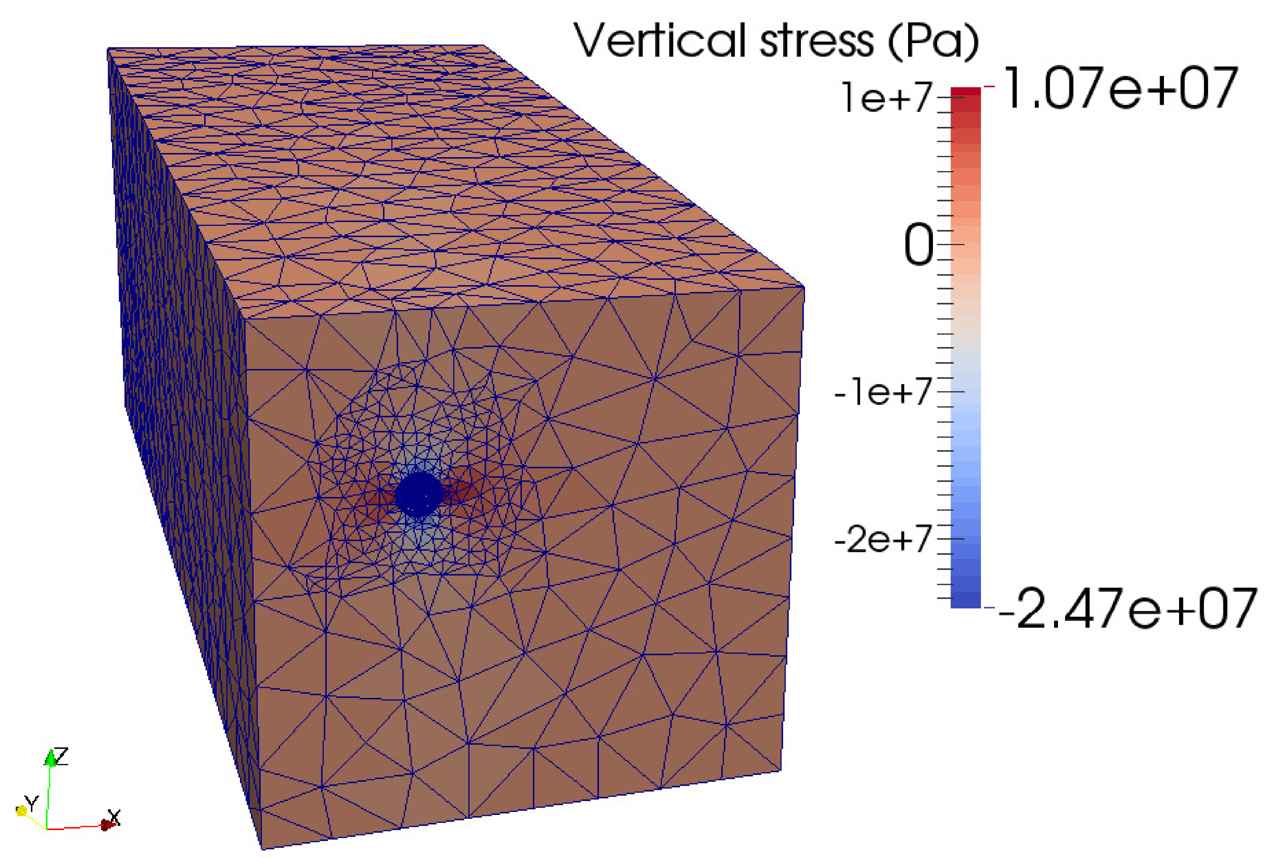

Figure 3: Finite element simulation result (vertical stress contour)

Features

There are 12 input parameters (features) that describe each simulation.

- **Geometry** (3 features): Radius of the tunnel, the horizontal and vertical inclination angle of the tunnel.
- **In-situ conditions** (4 features): Vertical stress, two horizontal stress coefficients in two directions, and the mud-pressure used in the dilling operations.
- **Material properties of the soil** (5 features): Elastic modulus (E), Poisson's ratio (ν), cohesion (c0), friction angle (ϕ), dilatation angle (ϕ')

In addition to these features, a very large number of hinge functions and their combinations are included while calibrating the MARS model (see next section). A simple hinge function has the form $\max(0, x_j - c)$ or $\max(0, c - x_j)$

Models

We use the Multivariate Adaptive Regression Splines (MARS) model to create a meta model from the simulated data points. MARS preforms regression on a large feature set containing a combination of linear and hinge functions. These features are added selectively one-by-one until reasonable accuracy on the training set is obtained. Later, some of the features are selectively removed from the model to simplify the model and avoid overfitting. Two important hyper-parameters are available with this algorithm.

- The maximum degree of interaction.
- The regularization coefficient that penalizes large number of features.

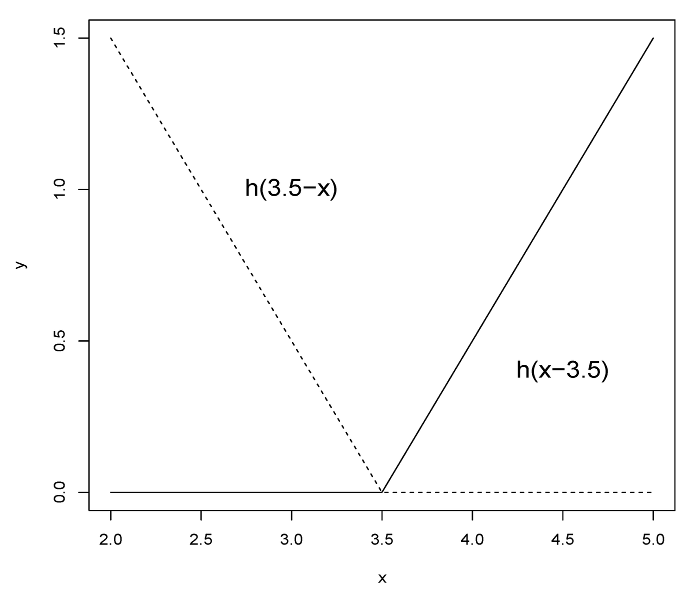

Figure 4: Hinge function examples

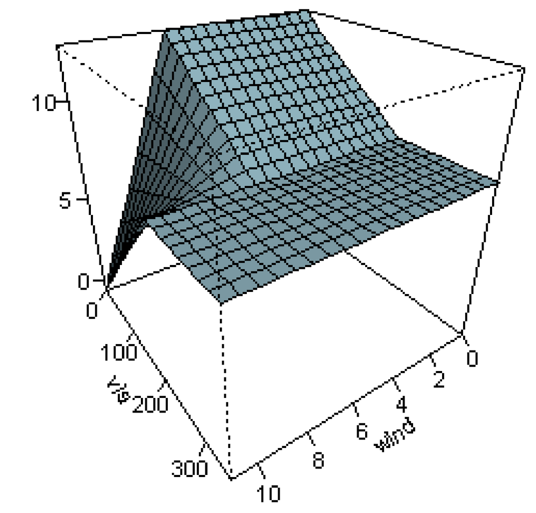

Figure 5: MARS regression example for 2D input space

Results

We perform 5-fold cross-validation on 490 data points and measure the mean square error (MSE) of the data. The inputs and outputs are normalized by their average value.

Output var.	Max. degree	Penalty coef.	MSE training	MSE dev	performance
Max. stress Z	1	3.0	0.014	0.020	High Bias
	2	3.0	0.004	0.022	High Variance
	2	40.0	0.015	0.019	Good
Max. stress X	1	3.0	0.011	0.016	High Bias
	2	3.0	0.003	0.011	Good
Max. mises stress	1	3.0	0.021	0.032	High Bias
	2	3.0	0.008	0.137	Very high Variance
	2	40.0	0.026	0.027	Acceptable

Table 1: Performance of the learning model with various hyper parameters

Parameter name	Cohesion (c0)	Mud Pressure	Friction angle (ϕ)	Radius
Sobol sensitivity index S1	0.441	0.193	0.044	0.024
Sobol total sensitivity index ST	0.507	0.357	0.120	0.092

Table 2: Sobol sensitivity analysis

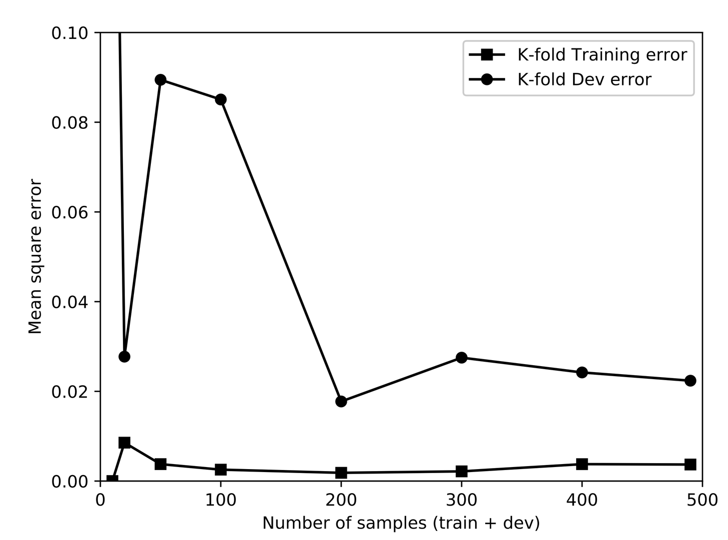

Figure 6: Learning curve of Max. stress Z for Max. degree = 2 and Penalty = 3.0

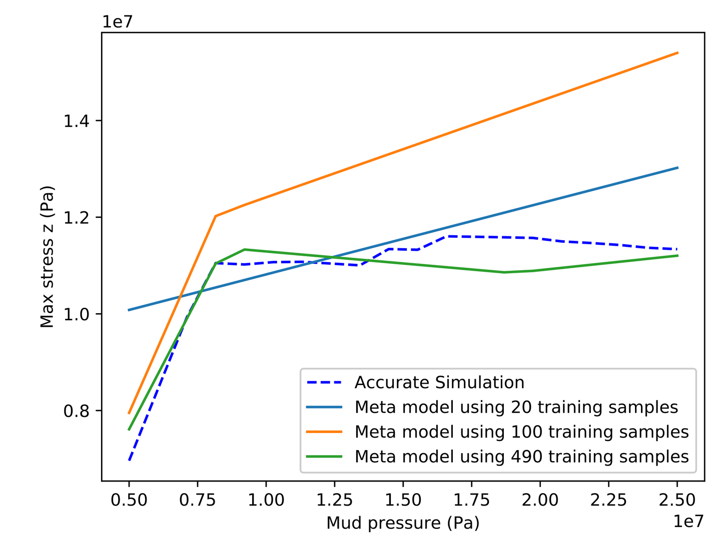

Figure 7: Prediction of Max. stress Z as a function of the mud pressure for Max.degree = 2 and Penalty = 3.0

Discussion

This project shows that simplified models can be an efficient and relatively accurate way to simplify complex numerical simulations, especially in the case of tunneling operations. This simplified model, which can give us answers more than 1000 times faster than the FE simulation, enables us to run big monte-carlo simulations, analyse the sensitivity of the model, or perform optimizations. Furthermore, we show that MARS algorithm is a very effective method of generating accurate meta-models. It can handle complex models and it can easily prevent overfitting.

References

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