Title: Hyperbolic Hydro-mechanical Model for Seismic Compression Prediction of Unsaturated Soils in the Funicular Regime

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Motivation: During cyclic or seismic shearing of unsaturated soils, a reduction in total volume of the soil may occur as the particles rearrange into a tighter configuration and the void space is decreased, a phenomenon referred to as seismic compression. Seismic compression is defined as the accrual of permanent contractive volumetric strains in soils during earthquakes and has been recognized as a major cause of seismically-induced damage in earth structures. The current state of the practice in prediction of seismic compression during earthquakes is to empirically relate vertical strain profiles with depth to the shear strain induced in a soil layer as part of a site response analysis. This is a practical approach as it builds upon analyses performed for the earthquake site response but does not necessarily consider hydro-mechanical coupling observed in laboratory experiments. There is also inconsistency in the expected trends in seismic compression with the initial degree of saturation from different experimental techniques having different pore fluid drainage conditions. Accordingly, a mechanistic framework is needed to confirm the trends in seismic compression in unsaturated soils.

Objectives: The objective of this study is to develop a constitutive model that can represent the hydro-mechanical coupling expected in unsaturated soils undergoing seismic compression during cyclic or seismic shearing, with focus on the funicular regime of the soil-water retention curve (SWRC), where undrained cyclic simple shear test data is available for calibration and validation. The greatest amount of seismic compression is expected in the funicular regime due to the presence of both air and water. This constitutive model is intended to be simple so that properties can be calibrated with non-specialized laboratory tests and to facilitate implementation into software packages used in geotechnical earthquake engineering (OpenSees, FLAC, etc.).

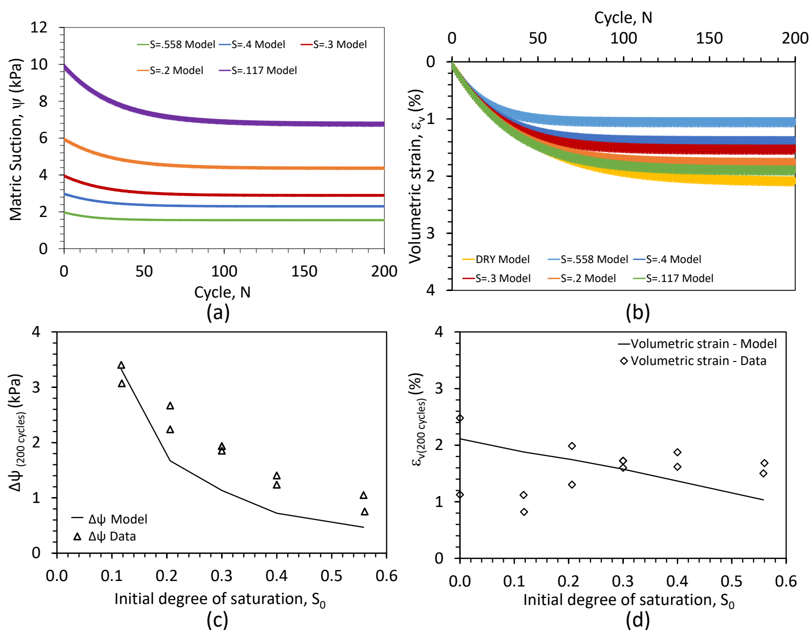
Methodology: A semi-empirical elasto-plastic constitutive model with a hyperbolic stress-strain curve was developed with the goal of predicting the seismic compression of unsaturated sands in the funicular regime of the SWRC during undrained cyclic shearing. Using a flow rule derived from energy considerations, the evolution in plastic volumetric strain (seismic compression) was predicted from the plastic shear strains of the hysteretic hyperbolic stress-strain curve. The plastic volumetric strains were used to predict the changes in degree of saturation from phase relationships and changes in pore air pressure from Boyle's and Henry's laws. The degree of saturation was used to estimate changes in matric suction from the transient scanning paths of the SWRC, which was a novel approach that permits independent prediction of the pore water and air pressures. Changes in small-strain shear modulus, estimated from changes in mean effective stress computed from the constant total stress and changes in pore air pressure, degree of saturation and matric suction, in turn affect the hyperbolic stress-strain curve's shape and the evolution in plastic volumetric strain. The model was calibrated using experimental shear stress-strain backbone curves from drained cyclic simple shear tests and transient SWRC scanning path measurements from undrained cyclic simple shear tests. Then the model predictions were validated using experimental data from undrained cyclic simple shear tests on unsaturated sand specimens with different initial degrees of saturation in the funicular regime.

Results: While the model captured the coupled evolution in hydromechanical variables (pore air pressure, pore water pressure, matric suction, degree of saturation, volumetric strain, effective stress, shear modulus) well over the first 15 cycles of shearing, the predictions did not match the data after 200 cycles of shearing. After 200 cycles of undrained shearing, a linear decreasing trend between seismic compression and initial degree of saturation was predicted from the model while a nonlinear increasing-decreasing trend was observed in the cyclic simple shear data. This discrepancy may be due to issues with capturing all mechanisms of seismic compression, calibration of model parameters, or drift in the position of the experimental hysteretic shear-stress strain curves. Nonetheless, the predicted trends from the model are consistent with those from previously developed empirical models in the funicular regime of the SWRC.

Conclusions: The new mechanistic model is useful for studying the evolution in seismic compression for different initial conditions as a function of cycles of shearing and will play a key role in the development of a holistic model for predicting seismic compression across all SWRC regimes. The new model can be used by engineers to predict site-specific seismic compression values for unsaturated soil layers and can help identify possible soil improvement techniques.

Future directions/References: Future developments may focus on improving the equation for changes in slope of the transient SWRC scanning paths, which plays a key role in predicting changes in matric suction and pore water pressure. The model should be also calibrated against experiments with different vertical total stresses, relative densities, and degrees of saturation.

Keywords: Seismic Compression; Unsaturated Soils; Coupled Processes; Cyclic Simple Shear; Constitutive Modeling



Typical results from the new model: (a) Evolution in matric suction during cyclic shearing; (b) Evolution in volumetric strain or seismic compression during cyclic shearing; (c) Predicted and measured trends in matric suction after 200 cycles of shearing; (d) Predicted and measured trends in volumetric strain or seismic compression after 200 cycles of shearing