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Poroelastic Modeling of Soap Hole Formation

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Summary

Soap holes were first identified >50 years ago by Toth (1966, 1971) as areas of localized surface weakness characterized by a thin and fragile crust covering sand, silt, clay, and water. It was hypothesized that they form where groundwater is moving upward to the ground surface through unconsolidated sediment. Soap holes are ubiquitous across the prairies and manifest as either mounds or flat exteriors underlain by liquefied mud. They range in diameter from less than 1-m to several meters and can reach up to several meters in depth, posing a risk to farming activities and livestock. Previous work has provided hydrological and geochemical constraints to create a conceptual model for soap hole formation. In this conceptual model, pressurized water from a confined aquifer travels upward through preferential flow paths in glacial till to a lacustrine deposit at the ground surface. There, the combined effects of increased fluid pressure and clay dispersion cause the soil to liquefy and form a soap hole. This study tests the conceptual model for soap hole formation by determining which parameters and processes impact the extent and volume of liquefaction in a 3 dimensional model using a steady state solution in COMSOL Multiphysics. In COMSOL, we employ Darcy's Law, solid mechanics, and poroelasticity to successfully approximate a simplified version of the observed field data. Variations in hydraulic, elastic, and geometric parameters were explored to determine their impact on the volume of liquefaction in the model. The results provide insight into the conditions required for soap hole formation, and serve to verify the conceptual model developed through field studies.

Method

The model requires several physical, hydraulic, and geometric parameters, many of which are well constrained by the field data collected by Woods (2019), Shatar (2020), and Cunningham (in progress). Parameters that are unconstrained by the field data are collected from literature for a range of values for lacustrine deposits and glacial till in Alberta. An initial model is created and compared to the field data to determine the model's accuracy in recreating the observed field phenomena. The results are displayed in Figure 1.

The 3-dimensional model consists of a volume 100 m by 100 m by 12 m in the x-, y-, and z-directions, respectively. The top 2 m of the model is defined as a lacustrine deposit, and the bottom 10 m is defined as a glacial till. A fracture of 2 cm by 2 cm by 10 m in the x-, y-, and z-directions, respectively, extends from the base of the model up to the interface between the lacustrine deposit and the glacial till. Fluid flow in the lacustrine deposit is governed by Richards' Equation for variably saturated media, and the rest of the model is governed by Darcy's Law. Stress and deformation are governed by the stiffness tensor in the relationship between stress and strain, assuming a homogeneous, isotropic, and linearly elastic material. The model sensitivity is analyzed to examine which parameters affect the model results. A range of possible values for hydraulic, elastic, and geometric parameters were collected from the field data, or from a literature review if no field data were available. The volume of liquefaction is calculated for each simulation to determine the sensitivity of soap hole formation to each parameter using an effective stress less than or equal to zero as a proxy for liquefaction.

Conclusions

The hypotheses developed to test the conceptual model for soap hole formation were either supported or partially supported. Firstly, Darcy's Law and Richards' Equations can approximate the observed field phenomena to a degree given the initial assumptions of the model. Heterogeneity and/or anisotropy would need to be added to reproduce the field observations. Secondly, a preferential flow path with a confining layer is essential to soap hole formation, but the relative hydraulic conductivities play less of a role. Thirdly, variations in Young's Modulus, Poisson's Ratio, density, and the Biot-Willis Coefficient resulted in changes in the volume of liquefaction. Fourthly, a flow path with high transmissivity due to either a fracture with a high hydraulic conductivity or a large fracture width result in a larger volume of liquefaction. Finally, an increase in either the lacustrine or glacial till unit's thickness results in a decrease in the volume of liquefaction. Future work includes incorporating heterogeneity and/or anisotropy to the model units and including temporal variations to reproduce the seasonal variability of soap holes observed in the field data.

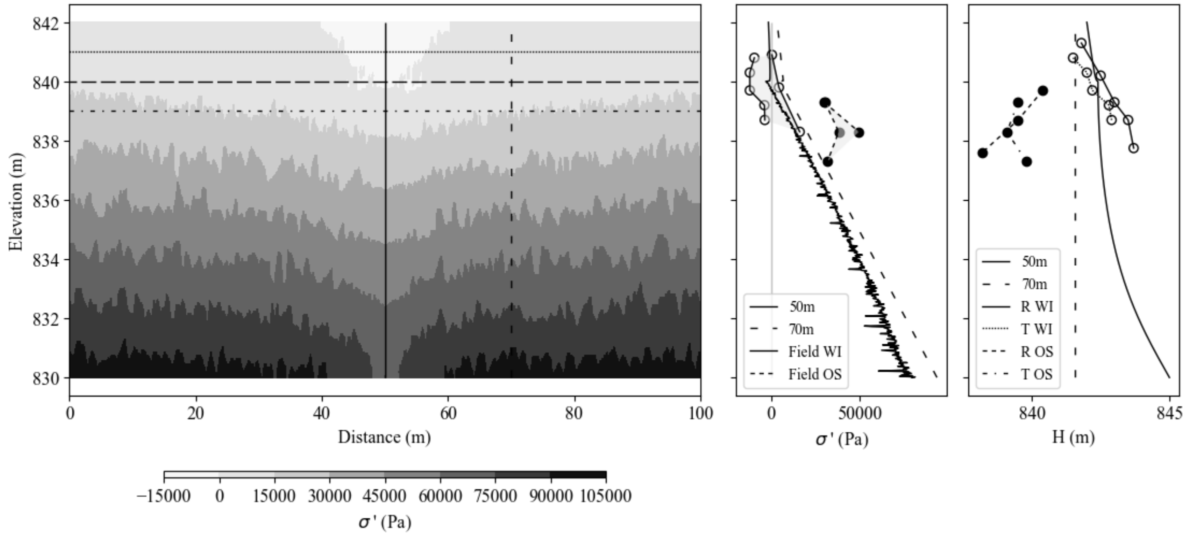

Figure 1. The base model results for a vertical cross section of the model contoured for effective stress (left panel). The results are compared to the effective stress and hydraulic head observed at two field sites (middle and right panels).

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