Poroelastic modeling of soap hole formation

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What is a soap hole?

Soap holes manifest as circular or elongated areas of localized weakness with a thin, fragile crust overlaying sand, silt, clay, and water. Toth (1966, 1971) interpreted soap holes as geomorphic features formed during groundwater discharge to the surface.

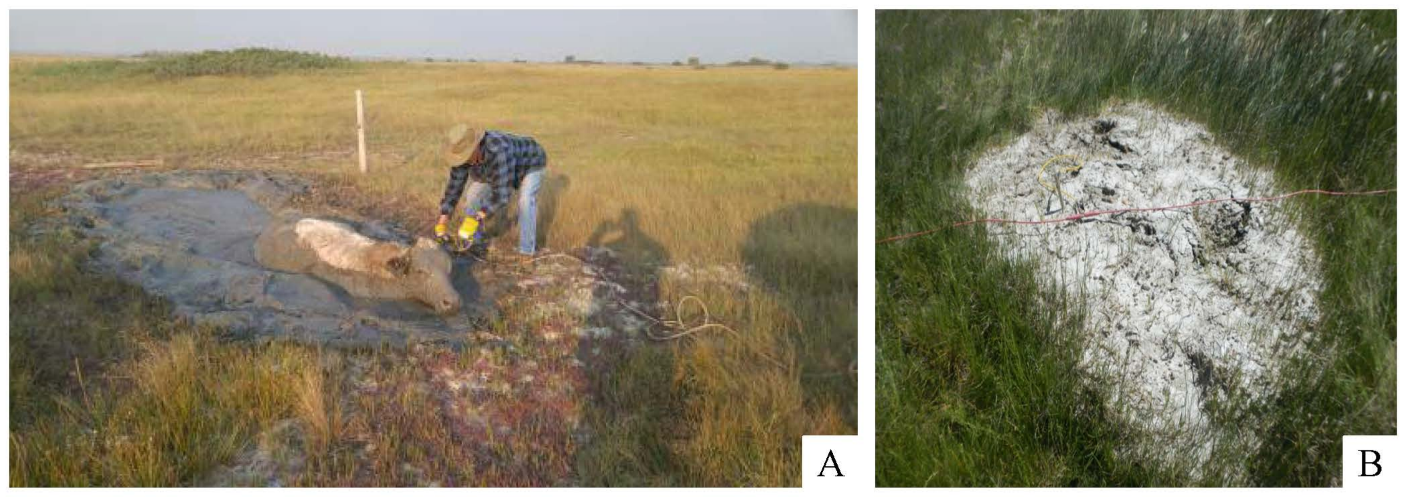

Figure 1. Two examples of soap holes in Alberta. A) A farmer helps a cow out of a hole-type soap hole. B) A small mound-type soap hole, ~1 m in diameter.

Background

Woods (2019) conducted the first major hydraulic, geophysical, and geochemical study of soap holes at two field sites to develop the first conceptual model for soap hole formation.

Figure 2. The instrumentation at the Torrington field site. The white dashed line indicates the edge of the soap hole.

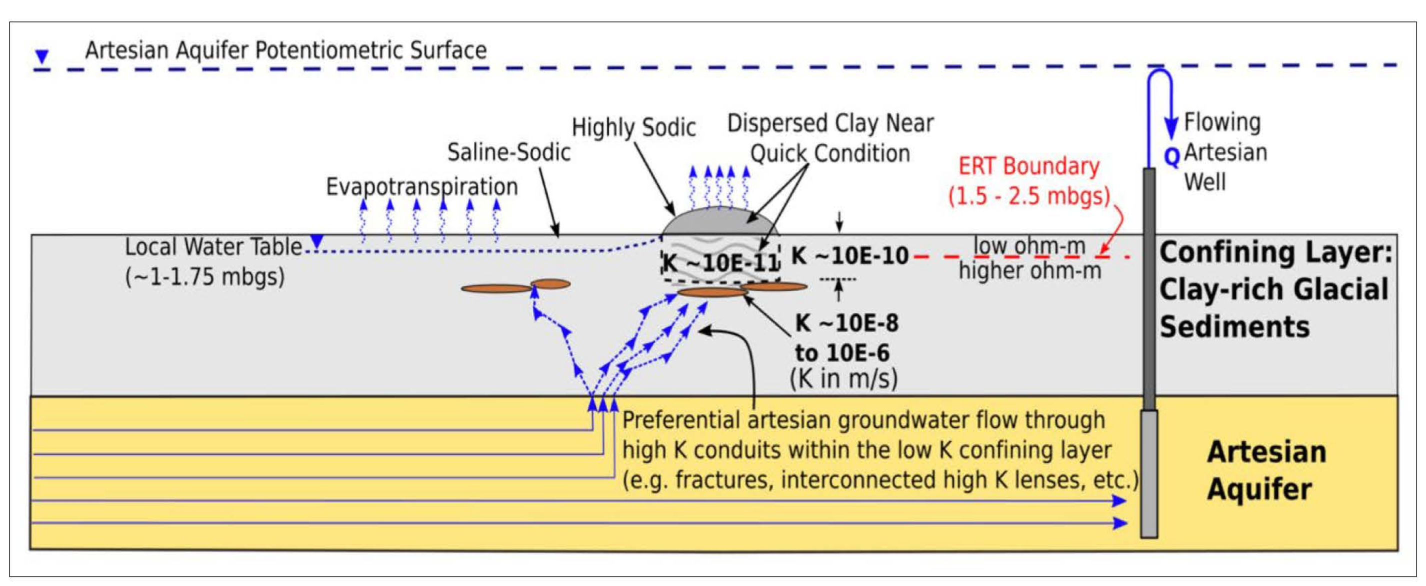

Figure 3. The conceptual model for soap hole formation by Woods (2019). Pressurized water from an artesian aquifer travels upwards through preferential flow paths in the glacial till to a confining lacustrine deposit at the ground surface. There, the combined effects of increased fluid pressure and clay dispersion cause to soil to liquefy and create a soap hole.

Hypotheses

1. Darcy's Law and poroelastic theory can accurately approximate the observed field phenomena,
2. The combination of high flow path permeability and low lacustrine deposit permeability are essential to soap hole formation,
3. Changes in elastic parameters will change the effective stress of the soil and soap hole formation,
4. A flow path with high transmissivity will result in a more developed soap hole, and
5. The thickness of the lacustrine deposit and glacial till above the pressurized aquifer will affect the extent of liquefaction and soap hole formation.

Methods

To test the conceptual model of soap hole formation, a 3D steady state model is created in COMSOL Multiphysics (COMSOL, 1998−2019).

$$\rho_f S \frac{\partial p_f}{\partial t} + \nabla \cdot \left(\rho_f \vec{u}\right) = -\rho_f \alpha_B \frac{\partial}{\partial t} e_{vol},$$

$$\sigma'_{ij} = c_{ijkl} e_{kl} - \alpha_B p \delta_{ij}.$$

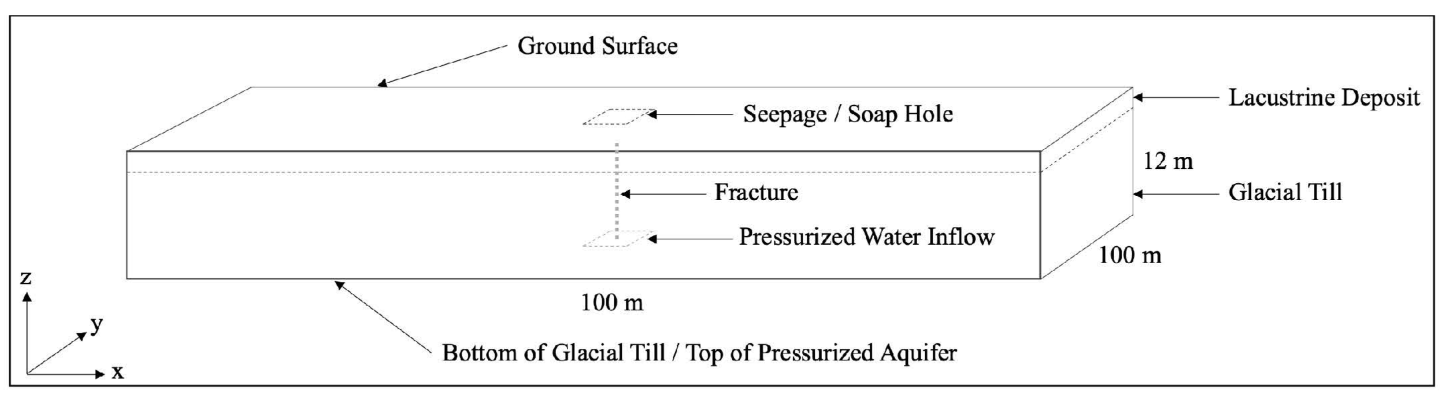

Figure 4. The geometry and boundary conditions of the 3D model.

Results – Base Model

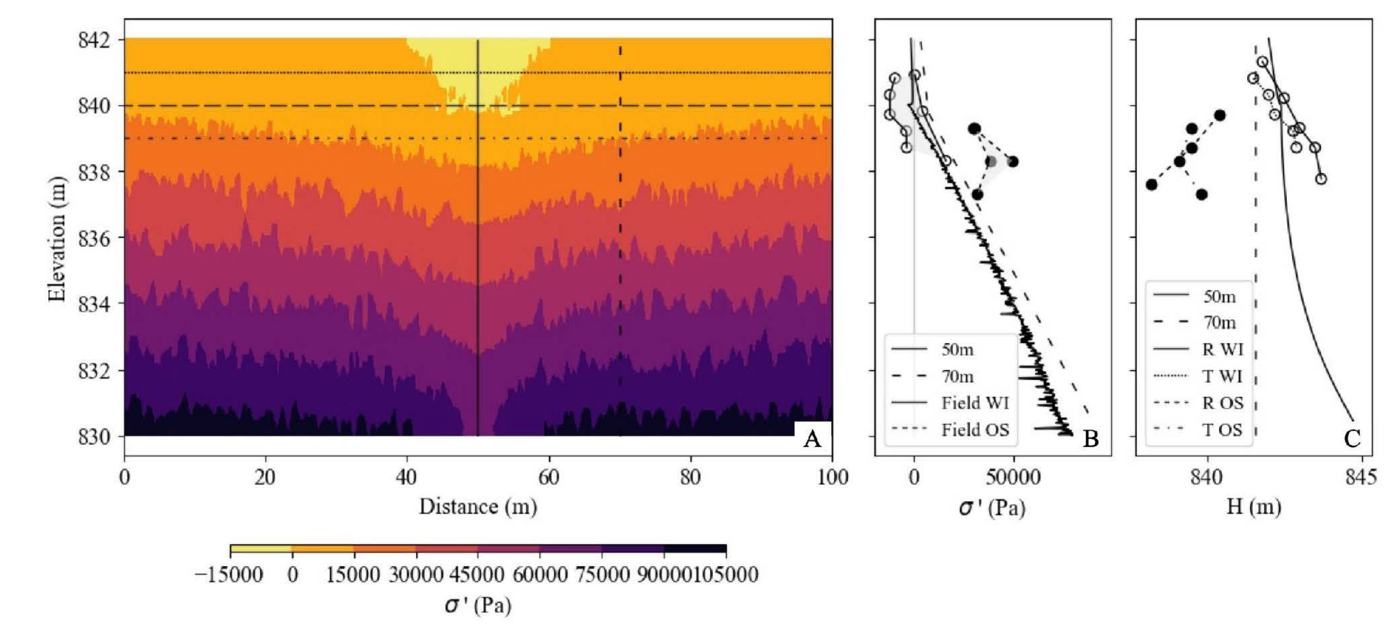

Figure 5. The base model results. A) A vertical cross section taken at y = 50 m. The contours are for effective stress, where purple is high effective stress and yellow is low effective stress. An effective stress less than or equal to zero represents an area of liquefaction. B) Cut lines at 50 m and 70 m along the cross section are compared to field effective stress within (WI) and outside (OS) the soap holes at the field sites. C) The hydraulic conductivity in the model for the same cut lines are compared to the Rumsey (R) and Torrington (T) field sites.

Results – Sensitivity Analysis

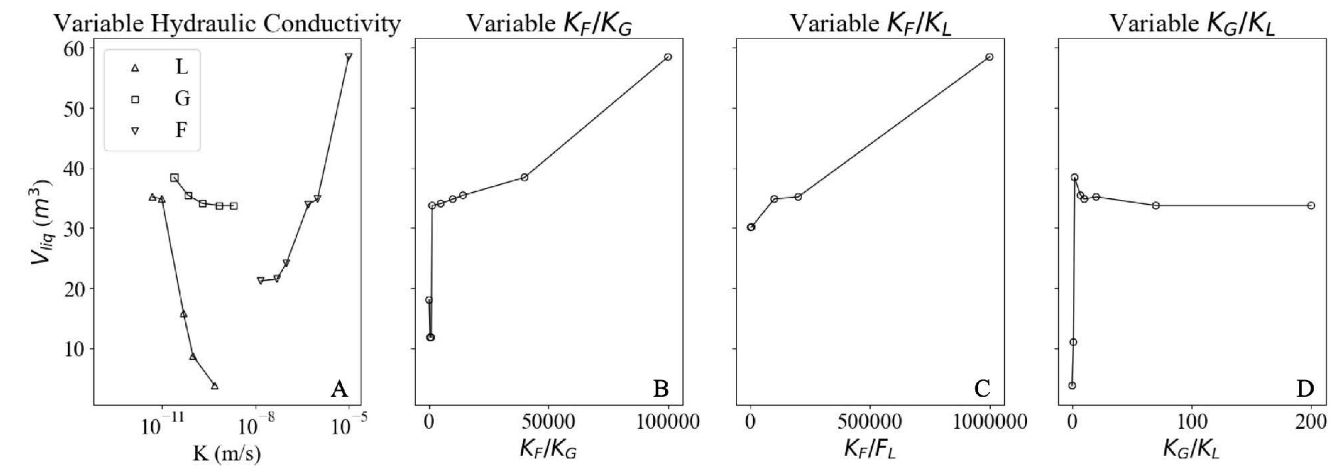

Figure 6. The volume of liquefaction for variations in, A) lacustrine deposit, glacial till, and fracture hydraulic conductivity, B) the ratio of fracture to glacial till hydraulic conductivity, C) the ratio of fracture to lacustrine deposit hydraulic conductivity, and D) the ratio of glacial till to lacustrine deposit hydraulic conductivity.

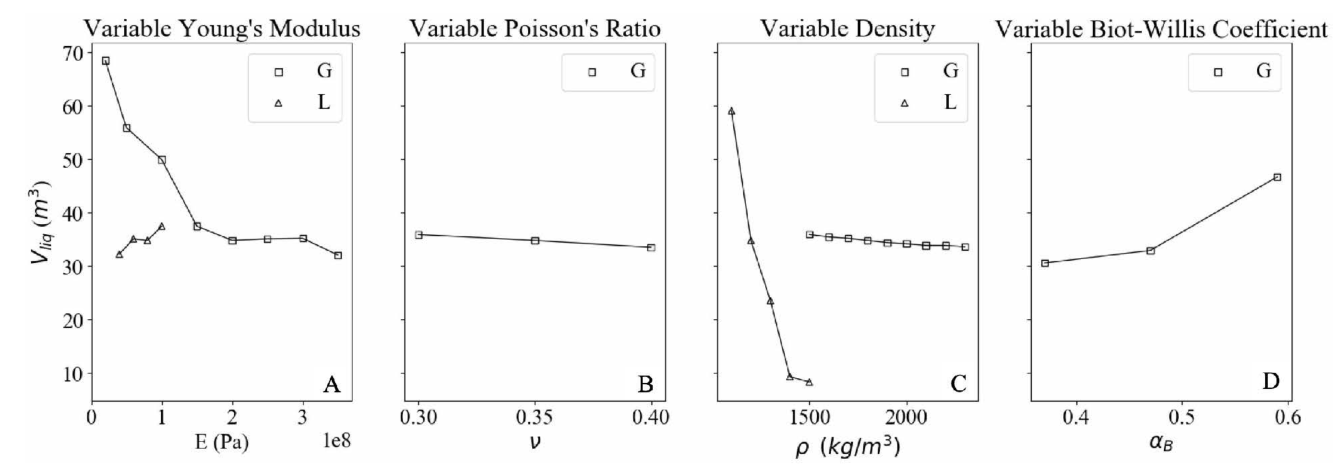

Figure 7. The volume of liquefaction for variations in, A) lacustrine deposit and glacial till Young's Modulus, B) glacial till Poisson's Ratio, C) lacustrine deposit and glacial till density, and D) glacial till Biot-Willis Coefficient.

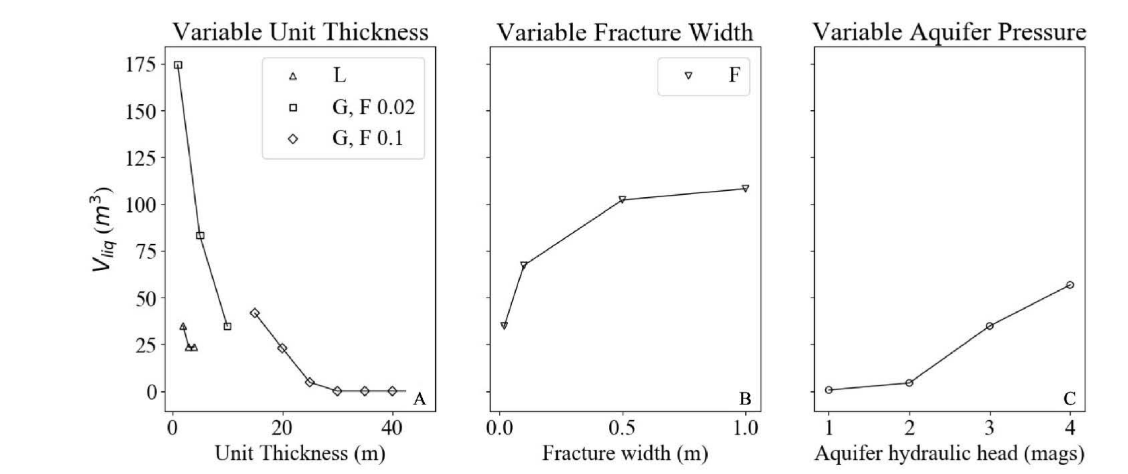

Figure 8. The volume of liquefaction for variations in, A) unit thickness, B) fracture width, and C) the aquifer potentiometric surface.

Conclusions

1. Heterogeneity and/or anisotropy are needed to recreate the field data more accurately.
2. A preferential flow path with a confining layer is essential to soap hole formation, but the relative hydraulic conductivities are less important.
3. Variations in elastic parameters result in changes in the volume of liquefaction.
4. Large fracture hydraulic conductivity and fracture width result in a greater volume of liquefaction.
5. An increase in either unit's thickness results in a decrease in the volume of liquefaction.

References

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