Coupled thermo-geophysical inversion for permafrost monitoring

This dissertation summarizes results of 5 years of field, laboratory and modeling studies of permafrost properties in Ilulissat, West Greenland. Ilulissat town and airport are located in an area of frost-susceptible, ice-rich marine sediments with residual salinity content in pore water, which effectively lowers the freezing point of the soil. Consequently, these sediments have strength properties similar to thawed ground in spite of ground temperatures well below 0 °C. In the view of increasing pressure on infrastructure development, better knowledge of such permafrost types, distribution, thermal and geotechnical properties is needed for informing sound and sustainable design choices.

Monitoring approaches using geophysical methods have become more widespread in permafrost studies, as they are indicative of spatial variation and in-situ processes rather than isolated properties in time and space. However, they only provide indirect information about the properties in question. To enable quantitative interpretation of in terms of thermal properties and ground ice changes, there is a need for extensive calibration and validation data.

In this project, we experimented with use of time lapse geoelectrical data for calibration of thermal model simulating heat transfer in active layer and permafrost. To acquire necessary calibration/validation data, we built a station for monitoring of ground temperature, electrical resistivity and soil moisture regimes. Automated resistivity measuring system was optimized for time lapse acquisitions in this environment characterized by extremely variable electrode grounding conditions between thawed vs. frozen season. Dense data series collected over three years provided insight into relationships between soil petro-physical parameters. We observed that temperature-dependent ground physical properties depend strongly on history of freeze-thaw cycles. Magnitudes of observed water content and resistivity hysteresis respectively have implications for thermal modeling and interpretation of resistivity changes in terms of temperature and ground ice content changes.

Thermal regime of the ground at the site can be simulated by one-dimensional model of conductive heat transfer in saturated porous medium. Sensitive thermal parameters were calibrated in an automated optimization scheme using gradient-search algorithm. When calibrated on borehole temperature data, the model reproduced training ground temperature dataset within ±0.55 °C, provided that the freeze-thaw water content hysteresis was accounted for. The calibrated model predicted the temperature variation in two testing datasets within ±0.32 to ±0.62 °C, depending on length of the testing timeseries.

The coupled inversion approach showed that the time lapse resistivity data contain information that constrains the optimization of thermal parameters of the heat model. In spite of not fully appropriate resistivity model, the thermal calibration was useful and reproduced the training dataset within ±0.65 °C, which is comparable to calibration on borehole temperatures. Thermal parameters optimized in coupled inversion predicted the temperature variation in the two testing datasets within ±0 °C to 0 °C.

A number of possibilities and paths for improvement of both coupled and uncoupled optimization approaches has been identified and identification of these bottlenecks is considered one of the contributions of this thesis.

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