State-of-practice for synthesizing climate modelling data and risk-based estimation of geotechnical properties: a literature review

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Short Statement

There exists increasing need for improved understanding of thawing permafrost behaviour in the Arctic due to demand for infrastructure adaptation to climate change, anthropogenic impacts, and population growth. We review the literature and state-of-practice for geotechnical characterization in Arctic regions including consideration of climate change effects on environmental variables such as temperature, precipitation, and wind speed. The review consists of three main components: 1) review of current climate models including methods for stochastic generation of forward-looking synthetic data, 2) geotechnical models for changes to soil properties resulting from changes to climate and ground temperature profile, 3) state-of-practice for incorporating climate impacts into geotechnical design and analysis to assist in developing mitigation and adaptation solutions. We conclude by summarising and synthesizing information from the literature on climate change models and their influence on geotechnical properties, to suggest key areas of focus for future research and improvement to design practices for sustainable and resilient infrastructure.

Permafrost is ground, composed of any combination of soil, rock, peat, ice, and water, that remains below 0°C for at least two consecutive years (Andersland and Ladanyi, 2004). The Arctic is an

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important socio-economic zone that hosts communities that rely on linear infrastructure such as highways, railways, pipelines, and airports. The Arctic is also a vital region for industrial and energy sectors such as mines, hydropower stations, and forestry, as well as growing sectors such as tourism. The Intergovernmental Panel on Climate Change (IPCC) advises that climate change impacts the Arctic more immediately and more severely compared to other regions (Meredith et al., 2019). The mean ground temperature increased over the past several decades negatively impacting the Arctic environment, municipal, transportation, and industrial centres (Hjort et al., 2018). Thawing permafrost leads to reduced ground strength (Buteau et al., 2010), thaw settlement (Hong et al., 2014), ground instability (Daanen et al., 2012), frozen ground creep (Aldaeef and Rayhani, 2017), increased runoff and flooding (Zheng et al., 2019), increased forest fires (Teufel and Sushama, 2019) and undesirable impacts on socio-economic aspects of local communities and the environment (French, 2017; Harris, 2010). Anthropogenic impacts of soil disturbance and climate change should be incorporated in engineering design for the resilience of structures on underlying permafrost (Hayley, 2004).

Hazard assessment in the Arctic requires an advanced understanding of how environmental conditions influence and change the engineering properties of frozen ground (Arenson et al., 2015). Site characterization through in situ investigation in the Arctic is complex due to limited access and data, high cost, and heterogeneity of the ground (Gruber, 2012). The distribution and volume of ice-rich permafrost may significantly impact the stability of infrastructure and increase maintenance and operation cost considering the impact of climate change and anthropogenic interference with the ground over the life expectancy of the structure (Streletskiy et al., 2012). The complexity of designing and maintaining sustainable infrastructure in permafrost for the future arises from a limited understanding of how climate change affects geomorphology and geotechnical properties as thawing occurs. Uncertainty also plays a role in estimating the magnitude of climate effects over the life expectancy of infrastructure.

Recent advancements in geophysical tools such as electrical resistivity tomography (ERT) combined with borehole log data can assist in the mapping of ice-rich permafrost (Lewkowicz et al., 2011). However, ERT modelling, inversion techniques, and parameter estimation for site characterization have inherent uncertainties that must be understood to properly incorporate this information into geotechnical analysis for improved risk analysis. Since none of the geotechnical and geomorphological data is exact there is a benefit of a probabilistic approach to model geotechnical properties. This is especially important when site characterization is not well understood, and the geotechnical analysis will require the incorporation of climate change scenarios. Instead of describing a process which can only evolve in one way as a deterministic approach (as in the case, for example, of solutions of an ordinary differential equation), in a stochastic, or random process, there is some indeterminacy: even if the initial condition (or starting point) is known, there are several (often infinitely many) directions in which the process may evolve. The stochastic approach for engineering design should incorporate a time sequence representing the change of geomechanical variables that are subjected to random variation from climate and anthropogenic impacts.

Key words:

1. Climate change
2. Arctic Infrastructure
3. Northern geohazards
4. Thawing permafrost

5. Adaptation and mitigation
6. Sustainable design
7. Socio-economic growth
8. Northern communities
9. Probabilistic modelling
10. Geotechnical engineering

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