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Modeling and testing of snow penetration

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Abstract

Penetration by a cone into snow is commonly used to characterize snow properties. However, the effects of the diameter and half-angle of the cone on the mechanical properties of snow have not been systematically studied. In addition, no estimation of material parameters in a physically-based model has been made such that the results from penetration provide only an index of snow properties. In this paper, modeling and experimental methods are used to examine the effects of cone geometry on the maximum penetration force and associated hardness, with penetrometers ranging from 2.5 to 4 mm in diameter, 15° to 45° in cone half-angle, and testing both fine-grained and coarse-grained snows. The material point method, in conjunction with the Drucker–Prager cap plasticity model, was used to obtain the theoretical penetration force-distance relationship. Global sensitivity studies were conducted that indicate that the cohesion accounts for 86% of the penetration force, followed distantly by friction angle which accounts for 27%. A general trend, for the simulation results was established: for a given half-angle, the penetration force increases with the increase of diameter which holds for most of the test data as well; for a given diameter, the penetration force decreases with the increase of half-angle, which holds for some of the test data. In addition, for a given half-angle, the hardness decreases with the increase of diameter; for a given diameter, the hardness decreases with the increase of half-angle. To take into consideration the uncertainty of test data, a simple interval-based metric was used to compare test data with simulation results; the comparison was satisfactory. The material parameters from the simulations can thus be considered as calibrated ones for the snow studied.

Keywords: Micropenetrometer; Cone diameter; Cone half-angle; Snow; Drucker–Prager cap; Calibration; Global sensitivity; Size effect; Material point method

1. Introduction

Indentation and penetration of terrain materials using indenters and cone penetrometers are common methods of obtaining pressure-sinkage relationships for vehicle-terrain interaction studies. In materials science, indentation and penetration tests are usually grouped into a single category, and are just called indentations with indenters of different geometry. These tests, providing only load-penetration distance information, usually aim to provide an index of the hardness of the materials such that material properties, such as cohesion and friction angle, cannot be obtained directly from the tests but must be estimated through a model. These tests are in contrast with the test methods for geomechanical or porous materials such as the triaxial tests which are direct tests to find material properties.

Whereas cone penetrometers for soils have been well developed, those for snows are still under active research. For vehicle-snow interaction studies, the rammsonde (Mellor, 1974), used by dropping a weight onto the back of a cone where the cone face area is on the order of 10's of cm^2, has been used in Wong and Irwin (1992), Lee and Wang (2009). And the Snow MicroPenetrometer (Schneebeli et al., 1999; Marshall and Johnson, 2009)

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Nomenclature

$\bar{P}_E$	elastic limit pressure (compression positive) (Pa)
$\bar{\epsilon}_v^p$	volumetric plastic strain (compression positive)
$\bar{\sigma}$	von Mises stress (Pa)
β	friction angle of Drucker–Prager criterion (deg)
$\hat{T}$	global sensitivity measure
ρ	density (kg/m^3)
d	cohesion of Drucker–Prager criterion (Pa)
p	hydrostatic pressure (compression positive) (Pa)
p_0, p_1, p_3	material constants for the hardening of Drucker–Prager criterion (p_0 in Pa, p_1 in 1/MPa, p_3 dimensionless)
p_a	current hydrostatic stress on Drucker–Prager yield surface (Pa)
p_b	location of the cap on the hydrostatic axis of Drucker–Prager criterion (Pa)
R	shape of the cap of Drucker–Prager criterion
s_0	initial slope of the porosity versus pressure curve (1/MPa)
DOE	Design of Experiments
DP, DPC	Drucker–Prager, Drucker–Prager model with a cap
GIMP	Generalized Interpolation Material Point Method
LHS	Latin Hypercube Sampling
MPF	maximum penetration force
MPM	Material Point Method
SMP	Snow MicroPenetrometer

(SMP), with a tip area of 20 mm^2, has been used in Lee et al. (2012), Lee and Huang (2014). It should be noted that the rammsonde and micropenetrometer – interrogating larger and smaller areas of snow, respectively – are developed by geophysicists mainly to classify the types of snow while providing an index of the hardness of snow without connecting the measurement to material parameters in physically-based models such as plasticity models typically needed to model vehicle-snow interaction. For flat indenters, such a connection has been made in the calibration and validation studies in Lee and Huang (2012), Lee (2009) where the pressure-sinkage data were used to calibrate the material parameters in a simple pressure-sensitive plasticity model.

One of the motivations to develop a micropenetrometer (Schneebeli et al., 1999) is to better assess the effect of microstructure on snow properties. Due to the random heterogeneous nature of snow properties, this effect has been rarely studied (Lee et al., 2009; Yuan et al., 2010). Since the plasticity models used for vehicle-snow interactions so far have all been continuum mechanics models without considering microstructural parameters, it is desirable to understand the snow penetration process by assuming that the snow being studied can be considered as a continuum. The effectiveness of such an approach can be evaluated by a comparison between model and test data.

A cone penetrometer is characterized by its diameter and half-angle as shown in Fig. 1, unlike a flat indenter where the geometry is defined by diameter only. In materials science, the effects of indenter geometry, defined as *size effect* in this paper, are often studied to gain a more comprehensive understanding of the material properties obtained through the indentation/penetration process (Flores-Johnson and Li, 2010; Huang and Lee, 2013). However, The micropenetrometer in Schneebeli et al. (1999) uses a cone with a single half-angle (30°) and diameter (5 mm) only.

The purpose of this paper is then to study, using experimental (Huang and Lee, 2011; Huang, 2013) and numerical methods, the effects micropenetrometer geometry on penetration force and hardness, and to infer the material parameters of a simple continuum-mechanics pressure-sensitive plasticity model by comparing experimental data with numerical results; for simplicity, only the maximum penetration force (MPF) is used in the comparison. It should be noted that inference of material properties is also called inversion or calibration of the numerical model. In addition, due to the typical large variations of snow properties, the uncertainties in the test data when compared with numerical results are also assessed and quantified by a simple *percentage*-based metric (cf. Section 5.3.4).

The rest of the paper is organized as follows. Section 2 presents the experimental procedure. Section 3 discusses the numerical model including the numerical method, the material model, as well as the modeling and simulation of snow penetration. In order to gain insight on the relative contribution of the parameters of the material model, as well as to guide the selection of these parameters for snow penetration simulation, sensitivity studies are discussed in Section 4. Results are presented in Section 5, followed by discussion and conclusions in Section 6.

2. Experimental procedure

Snow falls in many different types, depending on atmospheric and ground conditions (Fierz et al., 2009). However, in the cold, dry, windless conditions of Fairbanks winters, once it lands, it metamorphoses within a few weeks to one of a few stable snow types. For this study, two different snow types were selected. The first was snow that had fallen a few weeks to a few months prior, which will be called fine-grained snow. The other was snow that had fallen over a few months prior, and had been insulated under layers of fresher snow. These conditions lead to the