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Calibration of a simple cone-penetration model for snow

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Abstract

Numerical studies using the Material Point Method (MPM) have been conducted recently to model snow penetration tests for fine-grained and coarse-grained snows using small cones with diameters ranging from 2.5 mm to 4 mm, and cone half-angles between 15° and 45°. Although numerical studies have gained physical insight of these tests, due to the lengthy computation time needed for the MPM simulations, it is not feasible to use these simulations to develop a stochastic model to assess the large variations of the mechanical properties of snow typically shown in tests. In this paper, we present a simple and efficient physics-based analytical model based on equilibrium and a cavity expansion solution upon which a stochastic model is built to obtain calibrated material parameters for a Drucker–Prager (DP) model such that prediction of the model can be made. Sensitivity analysis of the analytical model indicates that cohesion and interfacial shear (friction) factor contribute significantly to the penetration hardness whereas the friction angle has little contribution. The calibrated material parameters are similar to those estimated via the MPM simulations. The quality of the stochastic model, when compared with test data, was assessed using four interval-based validation metrics with good results.
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Keywords: Cone penetration; Snow; Drucker–Prager; Validation; Calibration; Sensitivity; Metrics; Hardness; Cavity expansion; Gaussian process

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1. Introduction

Indentation and cone-penetration tests are commonly used to estimate the mechanical properties of terrain materials – such as pressure-sinkage relationship (Lee, 2009; Wong and Irwin, 1992), cohesion and friction angle (Lee and Huang, 2012) – needed to model the interaction between a vehicle and the terrain. Small-diameter cone-penetration tests were developed in Schneebeli et al. (1999) to understand the effect of snow microstructure on snow properties. These small penetrometers were used recently for vehicle-snow interaction studies to characterize snow properties in the field (Lee et al., 2012; Lee and Huang, 2014). But similar to the work done in Schneebeli et al. (1999), the tests provide only a relative index of strength which is not related to material parameters in plasticity models such as the Drucker–Prager (DP) material model; in addition, only a single cone geometry was used such that its effect on material properties cannot be assessed.

Although indentation tests for snow have been systematically studied (Lee, 2009; Lee and Huang, 2012), cone-penetration tests for snow using a continuum mechanics approach have received little attention. Recently, penetration tests using small cones with diameters ranging from 2.5 mm to 4 mm, and cone half-angles between 15° and 45° were conducted (Lee and Huang, 2015) aiming at understanding the effect of cone geometry as well as the uncertainties of the mechanical properties of snow. Two types of snow, fine-grained snow with densities ranged from 148 to 170 kg/m^3, and coarse-grained snow with densities ranged from 200 to 230 kg/m^3 were used in the tests. Detailed numerical analysis of these cones was conducted

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Nomenclature

$\bar{\sigma}$	vonMises stress (Pa)
β	friction angle of Drucker–Prager criterion (deg)
$\hat{T}$	global sensitivity measure
$\mathbf{x}, \mathbf{x}_{calibrated}$	parameters, calibrated parameters of the analytical model
v	Poisson's ratio
Ω	covariance function of the statistical model
ϕ	friction angle of Mohr–Coulomb criterion (deg)
ψ	Mohr–Coulomb angle of dilation (deg)
τ	shear stress for Mohr–Coulomb yield criterion (Pa)
τ_{eff}	effective interfacial shear stress on the cone surface (Pa)
θ	cone half-angle (deg)
a	radius of the cavity and cone (m)
c	cohesion of Mohr–Coulomb criterion (Pa), radius of plastic zone of the cavity (m)
D	diameter of cone (m)
d	cohesion of Drucker–Prager criterion (Pa)
E	Young's modulus (Pa)
$f(\mathbf{x})$	target variable of the statistical model as a function of parameters $\mathbf{x}$
k	cylindrical ($k = 1$), spherical ($k = 2$)
M	total number of cone geometries studied
m	interfacial shear (friction) factor
N	number of replication of test data
p	hydrostatic pressure (compression positive) (Pa)
p_i	normal stress on the cone surface (Pa)
q	penetration hardness (Pa)
Y	test data in the statistical model
CI	confidence interval
DOE	design of experiments
DP, DPC	Drucker–Prager, Drucker–Prager model with a cap
LHS	Latin Hypercube Sampling
MC	Mohr–Coulomb yield criterion
MPF	maximum penetration force (N)
MPM	Material Point Method

(Lee and Huang, 2015), using a Drucker–Prager plasticity model with a cap (DPC) and the Material Point Method (MPM) (Sulsky et al., 1994), to understand the effect of cone diameter and cone half-angle on the penetration force-distance relationship. In addition, by comparing the simulation results of the maximum penetration force (MPF) with test data, ranges of material parameters of the DPC model were estimated.

The Material Point Method was used in Lee and Huang (2015) due to its versatility as a finite-element type of hybrid particle-continuum numerical method such that the behavior of the material as particles and/or continuum can be represented. Thus, transitions between particles and continuum such as the occurrence of fragmentation of materials, commonly seen in geotechnical applications, can be modeled using a single computational framework.

Due to its random heterogeneous nature, the mechanical properties of naturally-occurring snow typically exhibit large variations such that rigorous statistical model and analysis are desirable. Recently, using a flexible statistical framework (Bayarri et al., 2007), a series of studies have been conducted to model and characterize the uncertainties of snow (Lee and Huang, 2012), and its interactions with vehicle (Lee, 2013; Lee and Huang, 2014). These studies involve global sensitivity analysis, as well as the development, calibration, prediction and validation of stochastic models. In particular, following the recent development in the field of verification and validation (ANSI/ASME V& V 10-2006,; Oberkampf and Barone, 2006), various statistical validation metrics have been used to assess the quality of the stochastic models.

Although the prior MPM study (Lee and Huang, 2015) gained useful physical insight on the penetration process, due to the high computation cost of the numerical method, it is not feasible for the method to be used in a practical way for a stochastic model to be developed such that calibration, prediction and validation of the model can be carried out. Consequently, it is desirable to develop an analytical or semi-analytical model that is much more efficient for practicality but still captures the main aspects of the cone-penetration process enabling the development of a stochastic model such that rigorous statistical methods can be used to model the large variations of the mechanical properties of snow.

The approach we take in Lee and Huang (2015) and this paper for snow penetration is the same as that in our previous studies of snow indentation where a detailed numerical (finite element) analysis was first conducted to gain physical insight followed by the development of a simplified analytical model (Lee, 2009), and the subsequent detailed statistical modeling and analysis using the analytical model (Lee and Huang, 2012).

It is the purpose of this paper to present a simple analytical model, based on the model in Ladanyi and Johnston (1974), to be used in the stochastic modeling of cone penetration for calibration, prediction and validation of the stochastic model. The rest of the paper is organized as follows. The analytical model is first presented in Section 2. The statistical methods are discussed in Section 3. The results are presented in Section 4 followed by discussion and conclusions in Section 5. Comparison of the differences and similarities of the current model with those of the

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