egusphere-2025-4768 Manuscript Review

Journal: The Cryosphere

"Experimental Investigation of the Direct Shear Strength Parameters of Compacted Snow"

Summary:

This manuscript presents methods, datasets, and results from a laboratory experiment related to the shear strength of compressed snow cylinders, where snow samples were obtained from an artificially created snowpack. The findings of this study could have significance for cold regions structural engineering applications, where infrastructure is built from compressed snow, and therefore stability of said infrastructure is highly dependent upon shear and normal strength of various snowpack types. Methods from the study include both an empirical approach involving laboratory testing, as well as a modeling approach, using a neural prediction network. Results of the two approaches include an observational dataset, as well as simulated model output, respectively.

The model was calibrated and validated via partitioning of the empirically derived data. Four parameters were varied and tested in different combinations, using an applied horizontal shear force held constant for each variation of the other parameters. The varied parameters included initial compaction density, applied normal force, snow crystal sintering time, and sintering temperature. Internal friction angle and cohesion of the various samples were calculated using a previously established algorithm from the literature.

The approach and results of this study are interesting and a valuable contribution to snow physics and mechanics, although the overall novelty of this experiment is limited. If the methods presented here can be replicated in future experiments, results from multiple studies could eventually provide a statistically significant body of evidence for establishing numerical thresholds for these snow shear strength parameters. Such thresholds would be valuable for practical use in snow engineering.

Overall Comments:

Shear Stress vs Shear Strength: The authors use these words somewhat interchangeably; however, these are not really the same thing. Conceptually related, but distinct, shear stress is the internal force per unit area acting within a material due to external loads, while strength is the maximum stress said material can withstand before failure (plastic deformation). For this study, stress is the demand placed on each snow sample, while strength is the capacity of each sample. A material fails when the applied stress equals or exceeds its strength.

This is commonly a grey area within the field of snow mechanics, because shear stress is a quantifiable variable with established units of measurement, while shear strength is more nebulous. Previous studies offer approaches for defining snow strength, but it is overall still more of a concept than it is a specific quantity. While sometimes perplexing, defining snow strength is still an open field of research with much opportunity for creativity.

Generally, I understand and agree with the authors' good approach of defining shear strength as the yield stress of the snow samples, i.e. the quantity of applied shear force at which plastic deformation of the snow begins. However, this needs to be stated more clearly near the beginning of the paper. Refer to the line-by-line comments below, where I've identified sections of the paper that need this clarification.

Abstract: Add a little more context (a couple sentences here) and briefly describe the conditions of the experiment. It would be easier to understand the summary of results and what the paper is about, with a simple description of the experiment set up, i.e., "experiments were conducted in a cold lab with environmental controls, using an instrument that does…." Which parameters were measured vs. calculated vs. modeled? Specify which parameters are the "essential strength parameters".

Introduction: I don't fully agree with the first part of the last paragraph in this section. I'm not sure that most previous studies within the snow engineering field of research are, in fact, focused on low density snow. I'd say the opposite is true. Most engineering related snow research actually does focus on compacted/altered snow, while avalanche research typically explores unaltered/natural, in-situ snowpacks. Either way, citations of studies on low density snow strength for snow engineering purposes should be provided. Or consider removing this section.

The novelty of this paper is not that it explores compacted snow. This study still has value in terms of contributing quantifiable results that could support (or not support) conclusions made by related studies. The results of this study could also be used in the future for establishing thresholds for certain snow parameters for engineering applications. The value is more practical than novel, which is fine.

Neural network and prediction modeling: The agreement between the measured data and the modeled data from the neural network looks a little too good. The level of validation is sky high. I'm wondering if the model is overfit, considering 80% of the empirical dataset was used for calibration. Also, I'm not a neural network expert by any means, but isn't this a ton of computation power for predicting only four variables? I still think having a prediction model for these parameters is very valuable, but this looks like over-fitting to me.

Discussion Section: This section needs a lot of work and major revision and improvements. It seems like the authors ran out of steam by the time they got to this part of the manuscript. Discussions are often the most difficult section to craft, yet the most important part of most papers. Organizing this section by snow parameter seems like a good way to start, but there are actually zero conclusions drawn from the results of the study. Each parameter listed in this section is accompanied only by some literature citations.

The authors need to clearly communicate conclusions drawn from conducting the experiment, supported by the study outcomes. The overall messages that the authors wish for the readers to take away need to be stated, using specific examples from the results section as evidence for conclusions drawn. Refer to the results presented, including the empirical measurements, results from calculations, figures etc., and the modeled output. The conclusion also needs more work and should be tied back into how this study is valuable for snow structural engineering.

Organization: This paper is generally very well written, however, several sections seem out of order to me, including components of the results section that should be moved to earlier in the manuscript, as part of the methods (see line by line comments below).

Gramar: The paper is, for the most part, easy to read and understand. However, there are several areas that need to be rewritten for clarity (see line by line comments). Several sections mix present and past tense, as well as first and third persons, which is a little confusing for the reader.

Line-by-Line Comments:

L30: Deeper snow layers, especially at the base of the snowpack, do not always get stronger over time from compaction of overlying snow layers. Changes in the temperature gradient from top to bottom of the snow profile often cause faceting and weakening of the basal layer crystal bonds. Qualify this sentence by specifying under what conditions at a snow construction site would base layers of the snowpack be strongly bonded and not faceted.

L35: which snow layer? Or referring to snow in general?

L46: awkward wording, "shear rate strongly influences snow strength and failure modes……"

L47: awkward wording, do you mean "strength initially increases, then subsequently decreases rapidly with the transition from ductile to brittle"?

L50: I think I understand the concept here, but the sentence needs rewording for clarity.

L56: Name the three instruments described and invented in 2016, 2010, and 2013.

L61: What is a "variation pattern"? This seems vague to me. Are you referring to snow strength spatial variability across a landscape? Or snow strength variations temporally over a winter season or variations in the snowpack profile?

L65-69: The specific study objectives need to be clarified here.

L75-84: Clarify which of these steps described in the methods are for the initial snow making process and which are the subsequent sample collection and preparation steps.

L80: Where was this done? In a cold lab?

L82: the snow crystals were plate-like, not the snow samples

L89: were the uniform snowflakes spread inside the ring before sealing with the membrane? It sounds like the opposite, i.e. the snowflakes were added after applying the membrane.

L96: I think you mean "snow sample shearing process, using the equipment", not "equipment shearing process".

L100: This is confusing. How would one pre-define the shearing plane? The samples will shear where the two boxes meet, correct?

Sections 2.2 and 2.3: Be more consistent and accurate when referring to shear force (force per unit area) vs. shear rate (displacement over time). Also be consistent and clear on the difference between the applied shear stress vs. how this study reasonably decided to define shear strength (amount of applied stress required for plastic deformation, or measured shear stress at 4 mm displacement when plastic deformation does not occur).

Figure 4: The x-axis label needs to include the units.

L106-108: This sentence is very confusing. What is increasing initially and then shows a decreasing trend? Strength or strain? Also the relationship here is stated as shear strain rate vs. strength, but the axes in figure 4 are labeled as strain rate vs. stress. Be consistent.

L115: Clarify what is meant by "patterns in failure modes and strength variations".

L127: Is this really data processing or data collection?

L135: provide a citation for the 400 kg/m3 threshold or where does this quantity come from? This sentence also needs to be written more clearly. What is meant by interparticle friction impeding density? Do you mean that 700 kg/m3 is as dense as snow can get before turning to glacier ice or firn? Refer to Cuffey and Patterson, 2010, for density ranges for snow, firn, and ice.

Table 1: The Serial # column could use a description of why the various experiment trials were labeled D-1 vs t-1 vs T-1, etc. It's somewhat obvious, but only after reading well past the table and then referring back to it. The way multiple trials are listed on one line totally makes sense and is easy to understand, but I don't get the numbering in the first column, i.e., the first line (D-1) is really tests 1 through 20, and the second line (D-2) is for tests 21 through 40; the fourth line is for tests 61-72, I think. Lastly, it was stated earlier that there were 69 test conditions, but this table shows many more parameter combinations and tests than that.

L144-145: This needs to be stated at the beginning of the paper, i.e. "In our study, we define shear strength as the peak shear stress right before plastic deformation or critical displacement", or a similar statement should be in the introduction and/or methods sections.

Figure 7: The idea of representing the shear stress – displacement curves in this alternative way seems creative and intuitive to me. I really like this figure. However, I wondering if I don't understand how to read it correctly. Maybe a sentence or two in the text on how to read this figure would help. Because I thought I got it, but to me, it looks like in graph (a), at 25 Kpa normal force, density of 650 Kg/m3, t=5 days, Temp = -10 deg C, the peak shear displacement is roughly 2,000 mm, but in graph (b) the same combination of parameters shows the peak shear displacement as more like 3,000 mm.

Equation (1) and the process of calculating internal friction angle and cohesion needs to be added in the methods section. One or two sentences in the methods should be fine.

L173: Which author are you referring to here? At first I thought this was in reference to the authors of the citations provided for equation (1), but then it says the "advance shear tests up to 350 Kpa" were done in the experiments from this paper? This is a whole new aspect/component of the experiment not described

previously in the methods section. This needs to be added as the first step, or one of the first steps, in the methods.

L174: what is a "partial test"?

Section 3.2.2: I enjoyed looking at the data and results in this section, but there is nothing that new here. It more or less just shows how snow crystal sintering over time increases bonding up to a certain point, but with continued aging of the snowpack, there is mass loss and bond weaking due to sublimation. This can be seen in the experiment's laboratory generated snowpack, as evidenced by the graphs in this section. Also, shows evidence to support that warmer temperatures lead to stronger bonding, which is well known. I suggest moving this section into an appendix. It's neat to look at but makes the paper longer than necessary.

L249: define "back propagation".

Section 4.1 belongs in the methods.

L255: Where did the 276 points come from? This is the first its mentioned in the paper and might be the number of tests in Table 1? How do these relate to the 69 test conditions?

Section 4.1.3 needs to be much expanded. This whole component of the study, the neural network, is not explained in any detail.

Figure 18 is very good.

Figure 19: Do the serial numbers on these x-axes relate to Table 1 somehow? The way the trials/tests are numbered needs improvement and more consistency throughout the paper.

Figure 19(a): The agreement between the measured data and the modeled data from the neural network looks a little too good. The level of validation is sky high. I'm wondering if the model is overfit, considering 80% of the empirical dataset was used for calibration. Also, I'm not a neural network expert by any means, but isn't this a ton of computation for predicting only four variables?

L289: What is the "Connection Weights Method"? I don't see this mentioned anywhere else in the study.