An experimental and computational investigation of the compressed snow-tire interaction

Yogesh Surkutwar[1] Mohit N. Shenvi[2] Corina Sandu[2]

Costin Untaroiu [1]

[1]Department of Biomed. Eng. and Applied Mechanics, [2]Department of Mechanical Engineering

Virginia Tech, Blacksburg, Virginia, USA

Motivation of the compressed snow-tire interaction study: <u>ASTM F1805-20 Standard</u>

- Testing of winter tires for 'severe snow use' certification commonly known as the 'mountain snowflake symbol' is performed according to ASTM F1805-20 [25] standards in the United States and Canada
- Testing Methodology
  - Controlled acceleration of test tire from 0 to 300% slip
- Testing of commercial tires is benchmarked against specific tires
- SRTT should be less than 2 years old
- Testing is conducted on at least 3 separate days
- Some factors having an effect but not being quantified are
  - Effect of variation in sunlight
  - Effects of melt and refreeze cycle within a season
  - Drift effect due to wind on certain days
  - Change in the control tire being used every season as it is a predominantly new tire distributed and correlated against other tester's SRTTs in NA

Instrumented traction truck used for ASTM F1805 testing of winter tires. Courtesy: <u>Smithers: Snow and Ice Traction</u>

Outline: Snow Testing

- **Introduction**
- **Literature Review**
- **Identification of Snow Properties affecting Tire Traction**
- **Design of Device**
- **Results of Field Tests**
- **Summary**

1. Introduction – Background and Motivation

Two types of terrains for tires

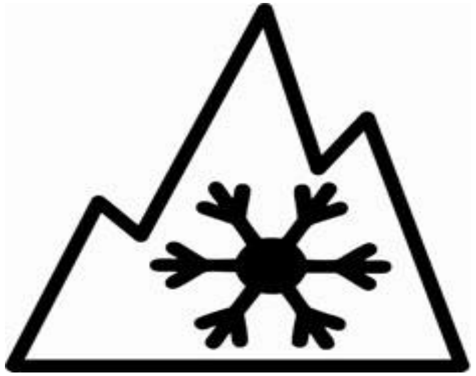
- Un-deformable (asphalt, ice, etc.)
- Deformable (snow, soil, etc.)

Increased reliance on driver skill

- Reduced friction at the tire-snow interface
- Water film formation at the contact patch

Difficulty in modeling snow

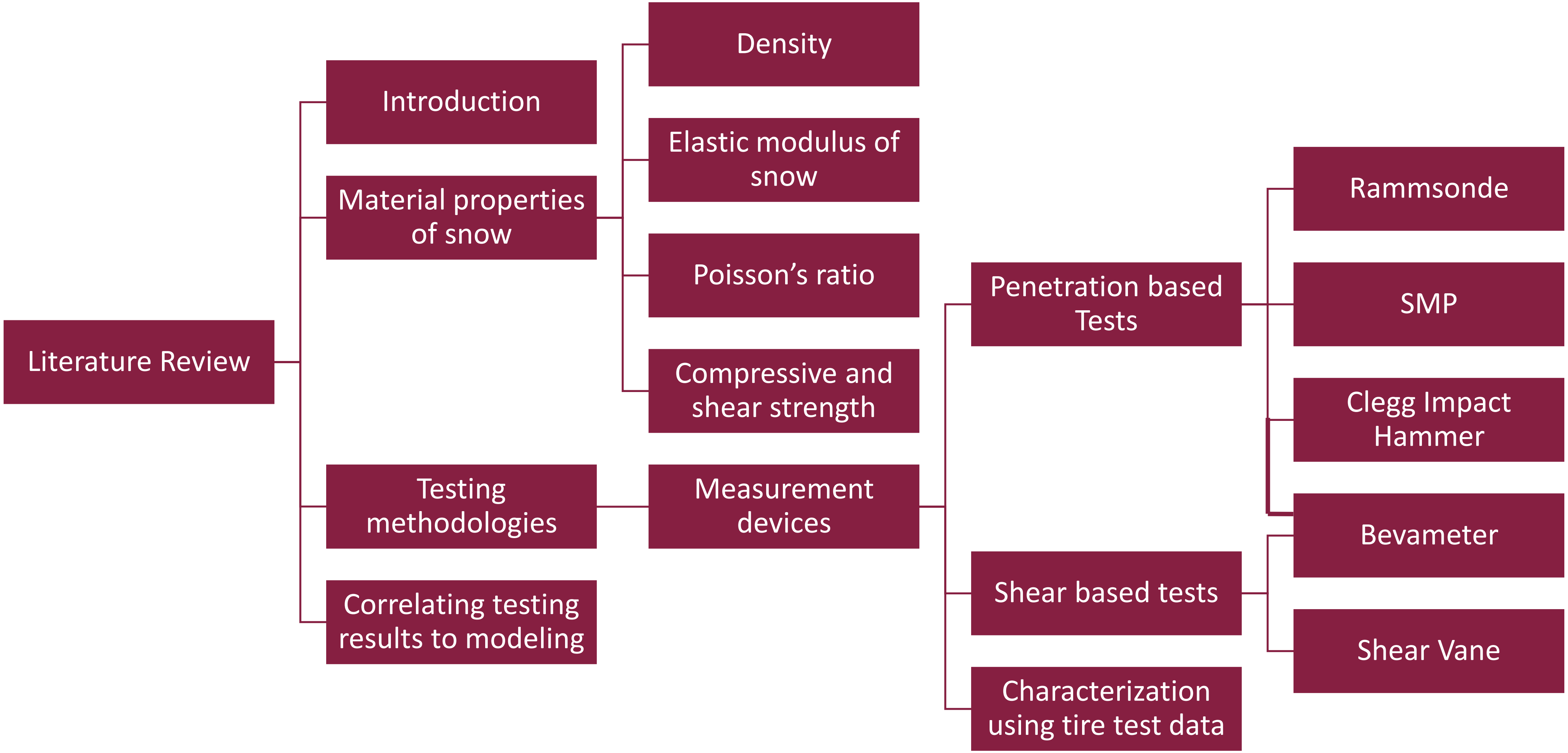
- Phase distribution changes in response to external factors
- Characteristics depend on temperature and strain rate
- Fewer indoor studies for characterization especially in the compacted snow domain



Mountain/Snowflake symbol (Image Courtesy: Tirebuyer.com)

Snow blower delivery vehicle by Sierra Buttes Trail Stewardship is licensed under CC BY-NC-SA 2.0.

2. Literature Review



Shenvi, M. N., Sandu, C., & Untaroiu, C. (2022). Review of compressed snow mechanics: Testing methods. Journal of Terramechanics, 100, 25-37. doi:10.1016/j.jterra.2021.11.006

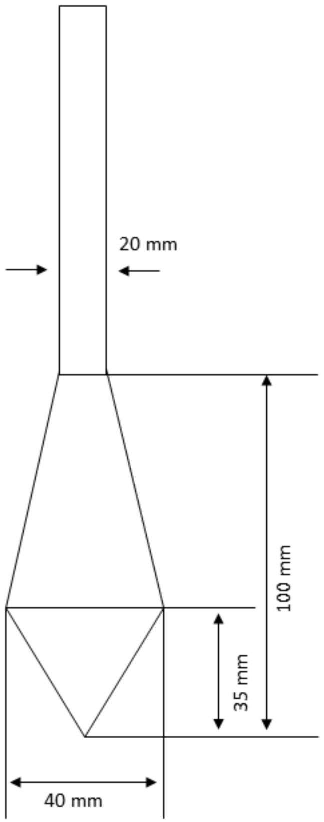
2. Review of Relevant Literature – Rammsonde and Clegg Impact Hammer

Rammsonde Penetrometer

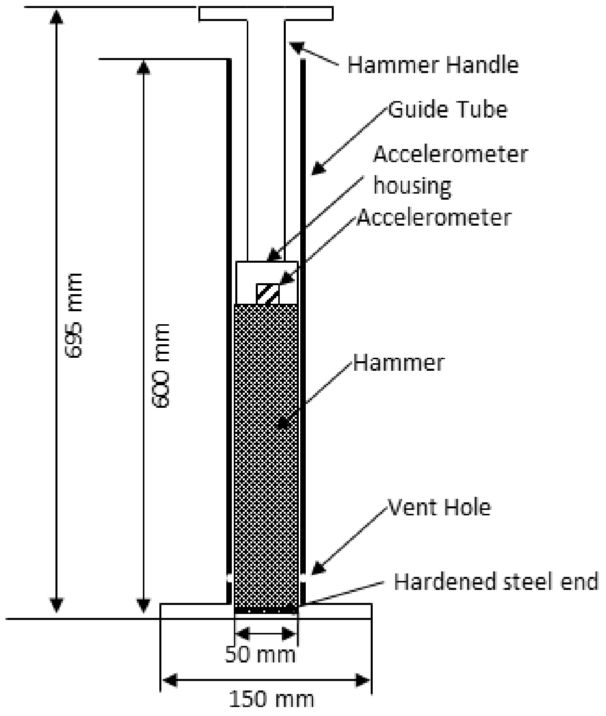
- Working methodology – Hammer drop from a fixed height (Impact Loading)
- Not suitable for higher hardness →**Russian Snow Penetrometer**
- Error introduction could be due to
  - Operator variability
  - Device not being exactly vertical
  - Variation in drop height
  - Wear of cone tip due to usage on hard surfaces
  - Bending of guide rod over time
- Profile of ram hardness generated is similar to a histogram and not a continuous plot over every unit length under consideration

Clegg Impact Hammer

- Construction and working principle
- Lower than standard hammer is ideal for snow property measurement
- Impact value varies over time at the same location
- Drawbacks – Only peak value is considered and filtering algorithm is unknown



Construction of Rammsonde penetrometer



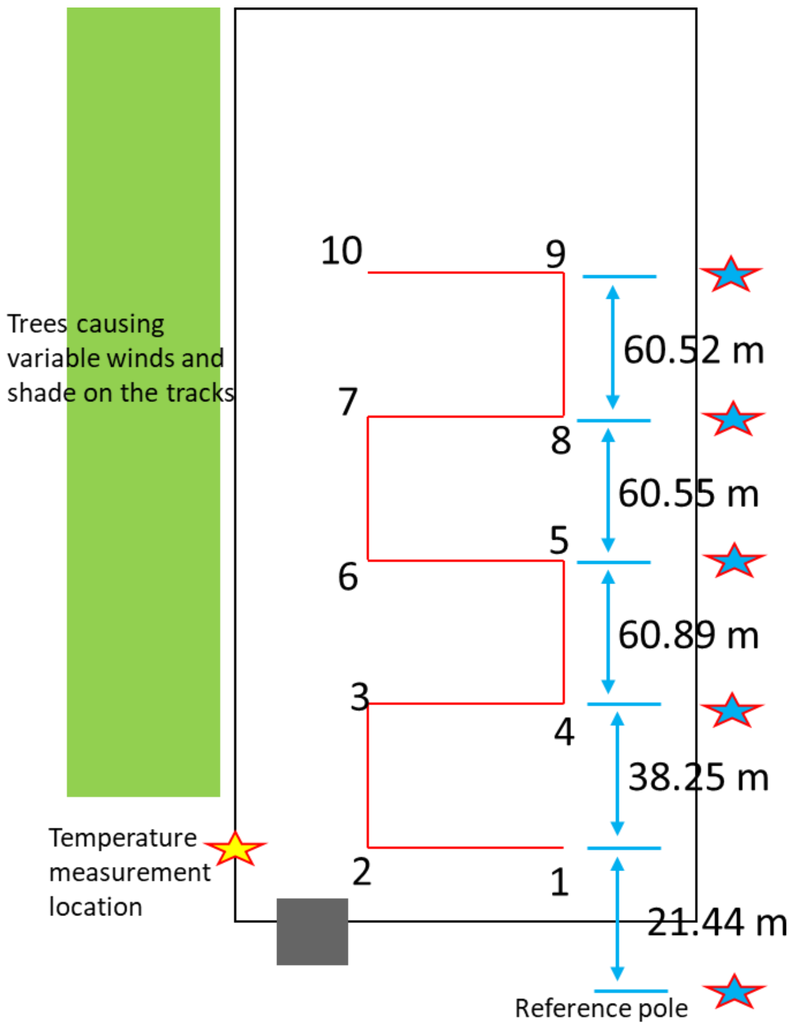
Construction of a Clegg Impact Hammer used for measuring Penetration resistance

3. Design Considerations for new device

- Accuracy and shorter time were the prime consideration
- Natural insertion of the shear vane in compacted snow is a constraint and requires hammering
- Use of a shear-cone type device is not attempted in snow property measurement previously
- **Major requirements of device design**
- Smaller cone angle would be utilized as it has advantage of easily digging into the snow (RSP)
- Replaceable cone would be helpful as it is the most affected part

Average shear strength of snow faced in 1st seasons testing – to be applied as pressure loading on the vanes: *Ranges from 37 to 88 kPa*

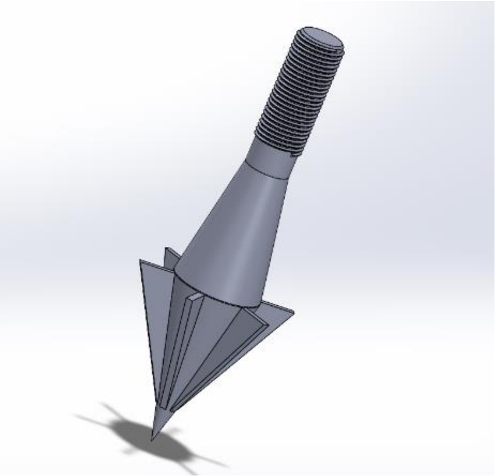
$$Avg.Impact\ force = \frac{m * g * h}{d} = \frac{1.5 * 9.81 * 0.4}{0.002} = 2943\ N$$



Depiction of test track and locations chosen in the year-0 of testing (Winter of 2021)

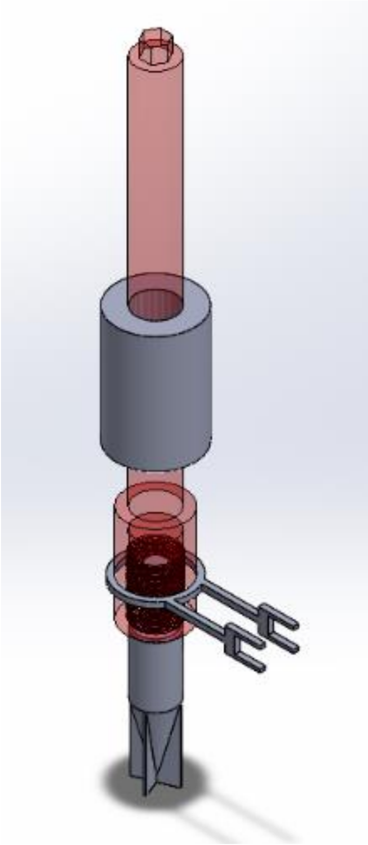
3. Development of new device

- Modifications made to the RSP
- Significance of vane design and its possible impact on pressure calculation
- Design changes made for manufacturing
- Measurement Methodology
- Preliminary CAE analysis was performed by evaluating possible peak shear and compressive loads



Initial Vane Cone design being considered

Cone designs used in winter of 2022 (unmounted) and winter of 2023 (mounted)



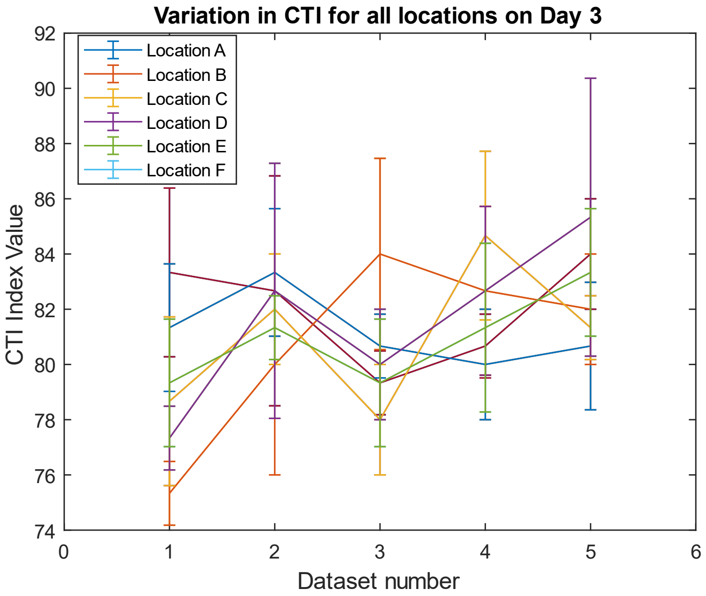
Cone design used in 2023 testing season

Video of measurement method

4. Results of field tests – CTI

Results and Discussion

- CTI index value was measured three times at each location, about 2 hours apart
- Mean value of the CTI of each location was nearing the upper limit of the medium-pack snow defined by the ASTM F1805.
- Values tend to increase as time elapsed from grooming
- Differences in locations D, E, and F and reasons
- Average COV is 0.0384



Plot of the mean and standard deviation of measured values of CTI Penetrometer on day 3

Location	Mean of CTI	Standard Deviation of CTI	Coefficient of Variation (COV)
A	82.0	2.82	0.034
B	81.2	2.11	0.026
C	80.8	3.99	0.049
D	80.9	3.20	0.040
E	81.6	4.10	0.050
F	80.9	2.50	0.031

Mean and Standard deviation of CTI data collected on day 3

4. Results of field tests – Clegg Impact Hammer

Results and Discussion

- Used to calculate the Clegg Hammer modulus, the sinkage per drop, and ram resistance force in Newtons
- Comparison of evaluated Clegg Hammer Modulus values and comparison with literature
- Sinkage values match literature however cumulative total has discrepancies to actual measurements
- Average coefficients of variation for CHM, sinkage, and resistance forces are 0.26, 0.13, and 0.41 respectively

Loca-tion	Mean of CHM (MPa)	Std. Dev. of CHM (MPa)	Coefficient of Variation (COV)
A	22.3	3.58	0.161
B	22.0	5.69	0.259
C	19.5	4.82	0.247
D	18.1	5.80	0.320
E	20.9	2.37	0.113
F	18.5	8.25	0.446

Mean and Standard deviation of Clegg Hammer Modulus (MPa) evaluated using Clegg data

Loca-tion	Mean of sinkage of 3-5 drops (mm)	Std. Dev. of sinkage of 3-5 drops (mm)	Coefficient of Variation (COV)
A	2.9	0.22	0.076
B	2.9	0.32	0.110
C	3.1	0.39	0.126
D	3.3	0.67	0.203
E	3.0	0.18	0.06
F	3.3	0.66	0.2

Mean and Standard deviation of sinkage (z) evaluated using Clegg data

Location	Mean of R (N)	Std. Dev. of R (N)	Coefficient of Variation (COV)
A	3250	880	0.271
B	3270	1490	0.456
C	2660	1050	0.395
D	2400	1100	0.458
E	2920	520	0.178
F	2600	1880	0.723

Mean and Standard deviation of resistance force (R) evaluated using Clegg data

4. Results of field tests – In-house developed device

Results and Discussion

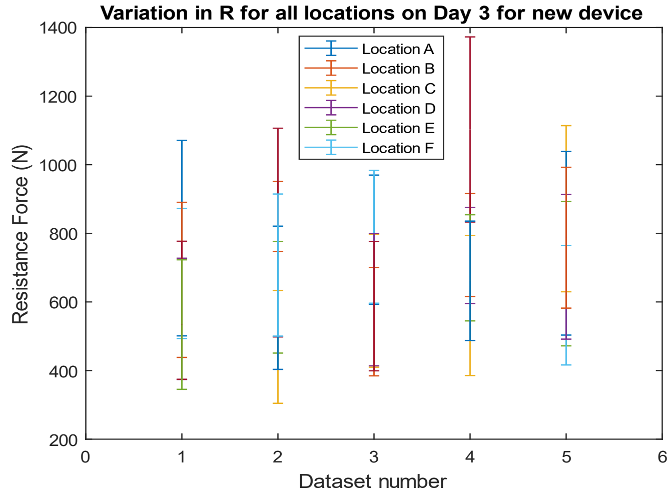
- Outputs from the in-house device consisted of height measurements by a laser distance sensor from a fixed point, yielding 5 sinkage values for each test approximately at 2-hour intervals
- Resistance force offered at locations D, E, and F to the penetration of the device were lower
- Higher consistency in the sinkage modulus values (albeit in two groups) in comparison to the sinkage exponent values
- Values do not match literature (Wong and Irwin, 1992) for two reasons – Density and Cone dimensions

Location	Mean of R (N)	Std. Dev. of R (N)	Coefficient of Variation (COV)
A	730	200	0.274
B	780	210	0.269
C	770	280	0.364
D	610	190	0.311
E	600	190	0.317
F	660	200	0.303

Mean and Standard deviation of resistance force (R) evaluated using sinkage measurements

Location	Mean		Std. Dev.	
	k	n	k	n
A	0.182	1.030	0.038	0.699
B	0.208	1.043	0.034	0.730
C	0.192	0.846	0.076	0.700
D	0.133	1.289	0.033	0.500
E	0.132	1.475	0.025	0.333
F	0.154	1.191	0.042	0.437

Mean and Standard deviation of pressure-sinkage parameters evaluated



Plot of the mean and standard deviation of penetration resistance to new device

4. Results of field tests – Findings and Conclusions

- CTI readings would not be useful for snow surface modeling perspective as it is difficult to accurately measure the sinkage in-situ after a specific drop of the device
- Low weight of CTI might be limitation as even 0.5 kg Clegg was found to unsuitable for compacted snow
- Evaluation of physical properties using the Clegg hammer matched the data found in the literature, however, some discrepancies were observed in comparison to the measurements made in-field
- The comparison of ram resistances using the in-house device and the Clegg leads to the finding that the Clegg hammer, by virtue of its greater weight and the plate-type surface, predicts a higher value of ram resistance
- Higher consistency in the sinkage modulus values than the sinkage exponent values with the new device

Outline: Snow Simulation

- **Introduction**
- **Snow modeling methods and material models**
- **Characterization of snow material model**
- **Comparison of different snow modelling methods**
- **Snow-Tire interaction study**
- **Summary**

1. Introduction

Snow Tire Performance

- The work aims to refine material models for compacted snow.
- Enhanced models will enable quicker and better design of high-performance snow tires.

Importance of Accurate Material Models

- Tire-snow interaction predictions heavily depend on model precision.
- Current models for snow interaction lack accuracy, affecting predictive reliability.

The Challenge with Snow Material Models

- Present snow material models are underperforming.
- Necessitates the development of more sophisticated material models.

Impact on the Tire Industry

- Tire Industry will benefit from improved design efficiency.
- Expectations for higher performance tires in snow conditions to be met with new models.

2. Snow modeling methods and material models

Snow Modelling Methods

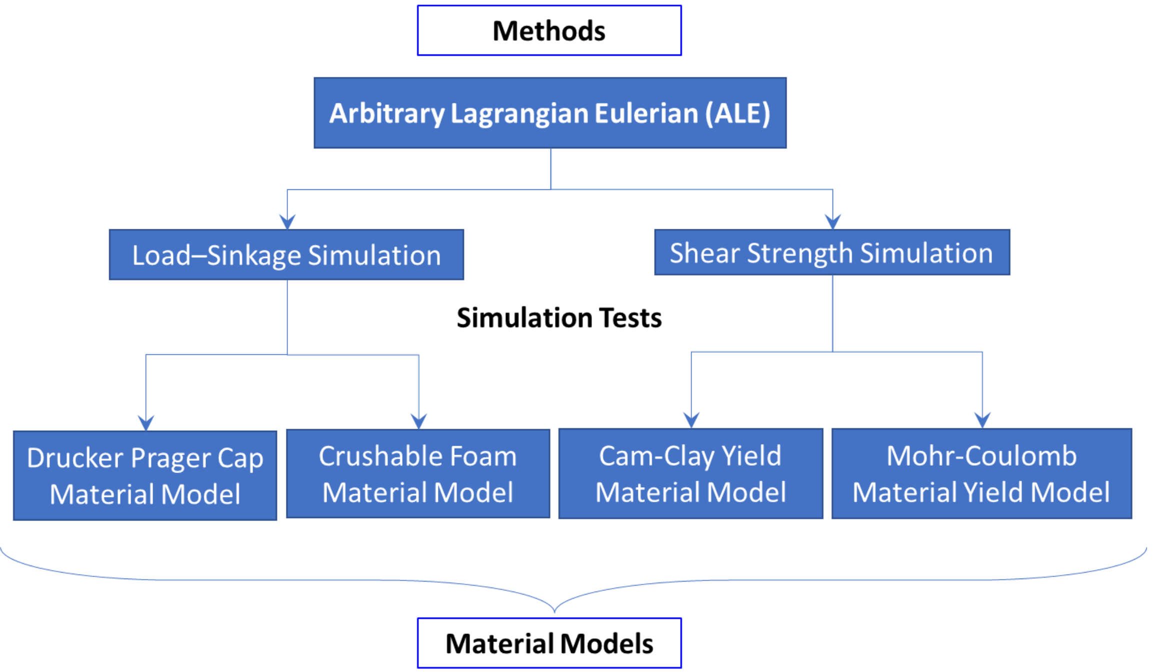
- Arbitrary Lagrangian–Eulerian (ALE) method
- Smoothed-Particle Hydrodynamics (SPH) method
- Discrete Element Method (DEM) method

Snow Material Models

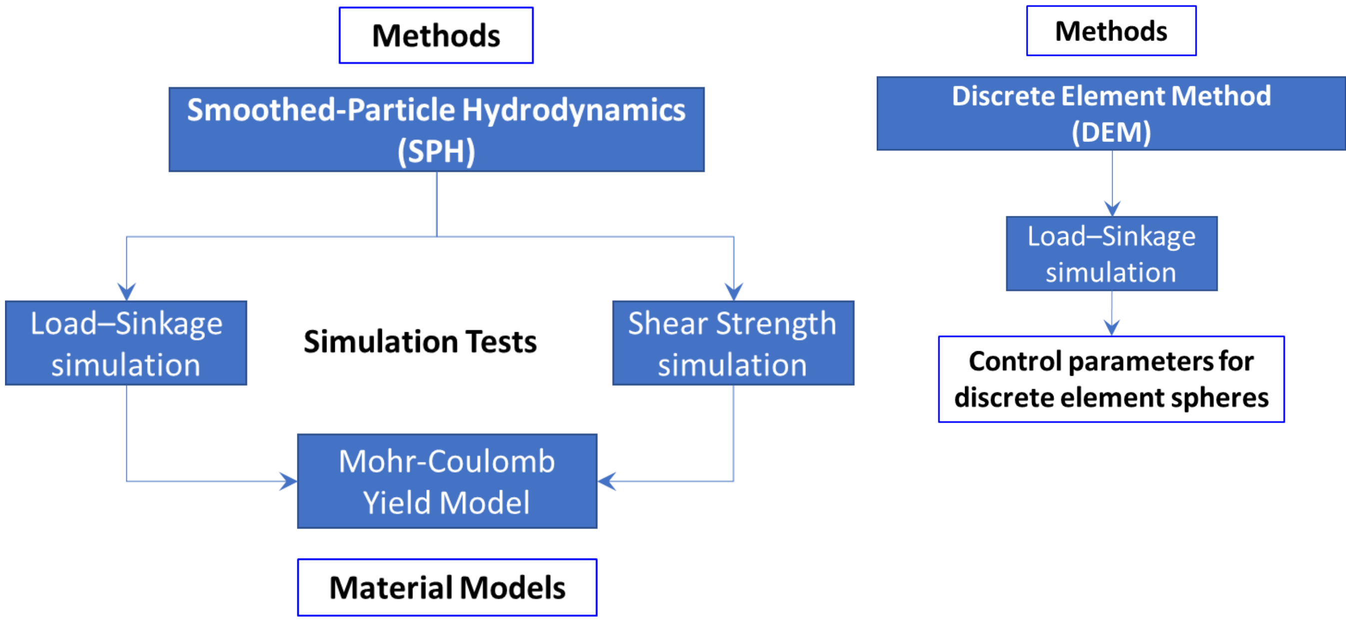
- Drucker Prager Cap Material Model **(Shoop 2001, Dongsub Kim, 2017)**
- Crushable Foam Material Model (**Shoop 2001, Dongsub Kim, 2017**)
- Cam-Clay Yield Model **(Seta 2003 & Meschke 1996)**
- Mohr-Coulomb Yield Model (**Seta 2003 & Meschke 1996**)

2. Snow modeling methods and material models

Arbitrary Lagrangian-Eulerian (ALE)



Particle Based Methods (SPH & DEM)



Surkutwar, Y., Sandu, C., & Untaroiu, C. (2023). Review of modeling methods of compressed snow-tire interaction. Journal of Terramechanics, 105, 27-40. doi:10.1016/j.jterra.2022.10.004

3. Characterization of snow material model

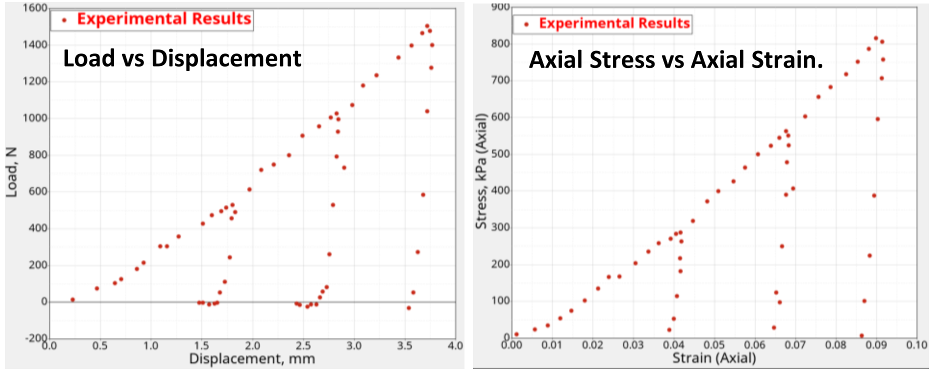
Material models for compacted snow

Reference: Compression and Shear experimental results for compacted snow (Density 500 kg/m^3)

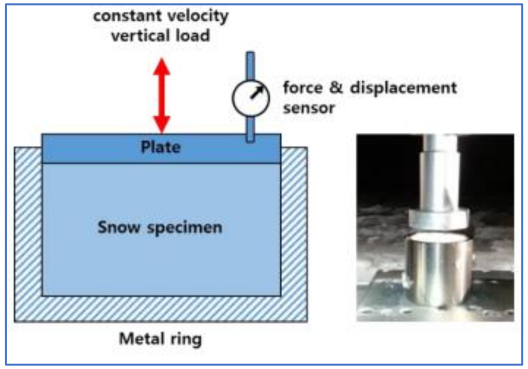
Drucker-Prager cap material properties (Dongsub Kim, 2017)					
Drucker–Prager material cohesion	DP material angle of friction	The cap eccentricity parameter	Initial cap yield surface position	The flow stress ratio	Density
C in MPa	β in Degrees	R	ε	K	ρ (kg/m^3)
0.0147	67.7	0.01	0.0001	1.0	500

Crushable foam material properties (Dongsub Kim, 2017)					
Compressive yield stress ratio	Hydrostatic yield stress ratio	Initial cap yield surface position	Youngs' Modulus	Poisson's ratio	Density
$k = \sigma_c / p_c$	$k_t = \sigma_c / p_c$	ε	E	Nu	ρ (kg/m^3)
2.37	0.1	0.0001	103	0.25	500

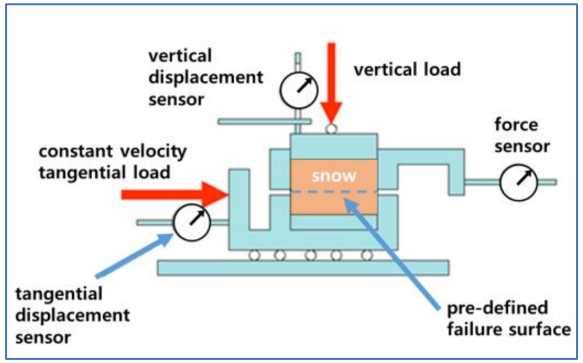
Hardening table	
p (MPa)	ε vol
0.000368	0
0.01434	0.0087
0.0371	0.0175
0.06232	0.0262
0.09	0.035
0.1201	0.0437
0.1527	0.0525
0.1878	0.0612
0.2253	0.07
0.2652	0.0787
0.3076	0.0875



Dongsub Kim, 2017



Compression Test



Shear Test

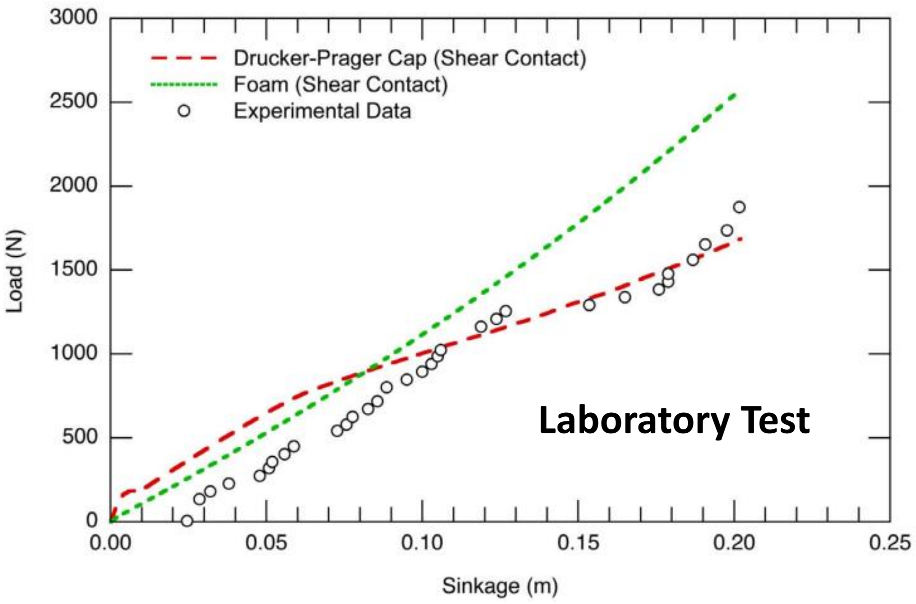
3. Characterization of snow material model

Pressure–sinkage simulation with Lagrangian method (Density 200 kg/m³)

Reference model details

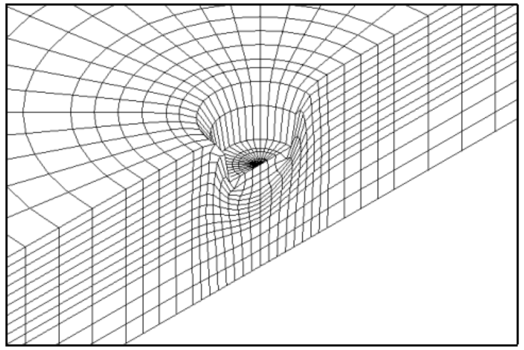
Drucker-Prager cap material properties (Shoop, 2001)					
Drucker–Prager material cohesion	DP material angle of friction	The cap eccentricity parameter	Initial cap yield surface position	The flow stress ratio	Density
C in MPa	β in Degrees	R	ε	K	ρ (kg/m³)
0.005 to 0.03	22.53	2.2E-2 to 1.1E-4	0.001	1.0	200

Result correlation study

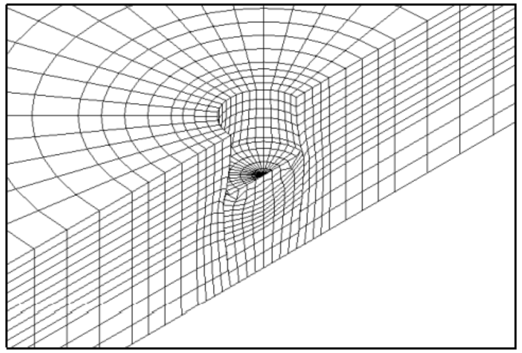


Shoop 2001

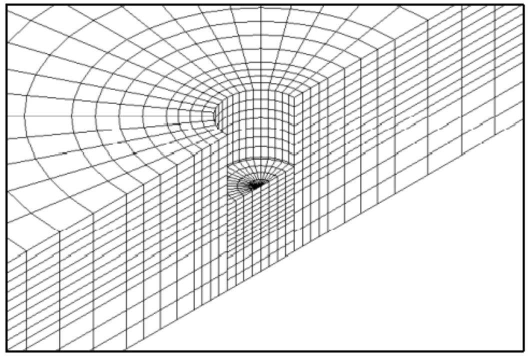
Constitutive models for snow



Drucker-Prager cap material



Drucker-Prager cap with vertical shear contact surface



Crushable foam with shear contact surface

3. Characterization of snow material model

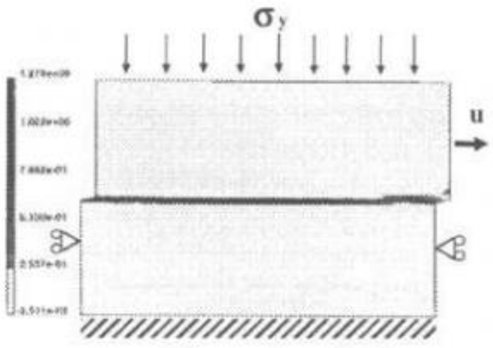
Shear Strength simulation with Lagrangian method (Density 500 kg/m³)

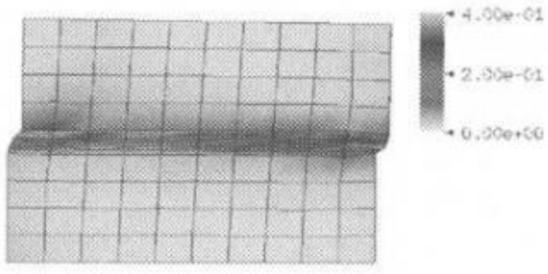
Reference model details

Cam-Clay yield model: material properties (Meschke 1996)						
Consolidation index	swelling/recompression index	specific volume at unit hydrostatic pressure	Slope of critical state line	Hardening Parameter	Min Hardening Parameter	Hydrostatic tensile str.
λ	**k**	**N**	**M**	**q_0**	**q_{res}**	**t**
0.38	0.015	3.05	2.88	0.07 MPa	0.02 MPa	0.01 MPa

Bulk Modulus (K) = 10 MPa, Shear Modulus (G) = 7.5 MPa

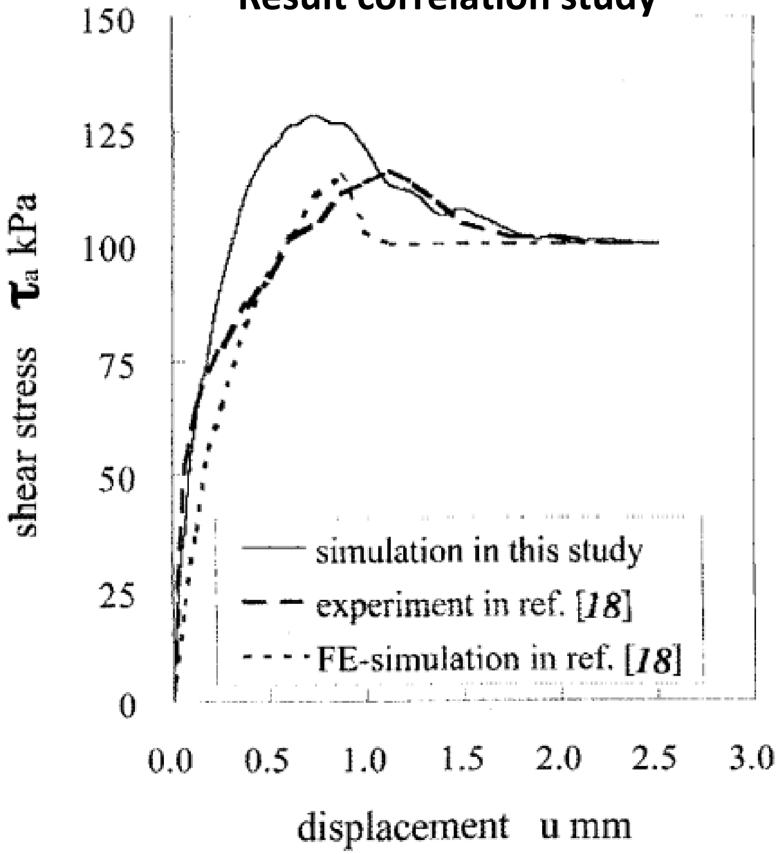
Constitutive models for snow





Cam-Clay yield model **Mohr-Coulomb yield model**

Result correlation study



Seta 2003 & Meschke 1996

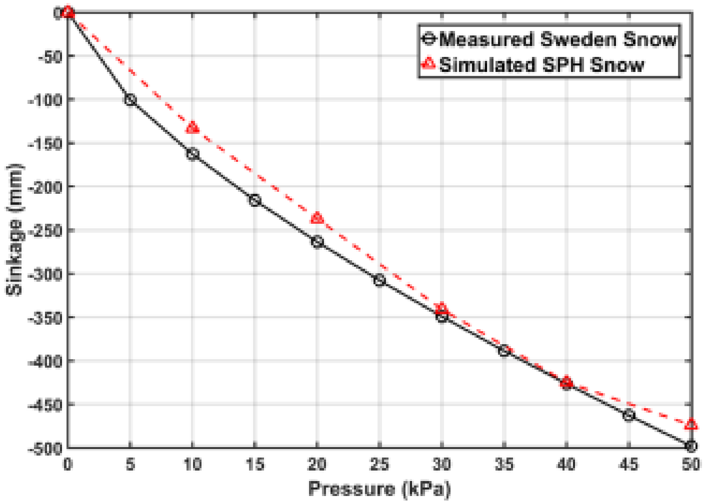
3. Characterization of snow material model

Pressure–sinkage simulation with Smoothed-Particle Hydrodynamics (SPH) method

Reference model details

Properties of modelled snow*				
	Cohesion constant (K_c) [kN/m$^{(n+1)}$]	Friction angle constant (k_ϕ) [kN/m$^{(n+1)}$]	Cohesion modulus (C) [MPa]	Internal friction angle (ϕ)
Sweden Snow	10.55	66.08	0.006	20.7^0

* Wong JY. Theory of ground vehicles. New York: John Wiley & Sons, 2008



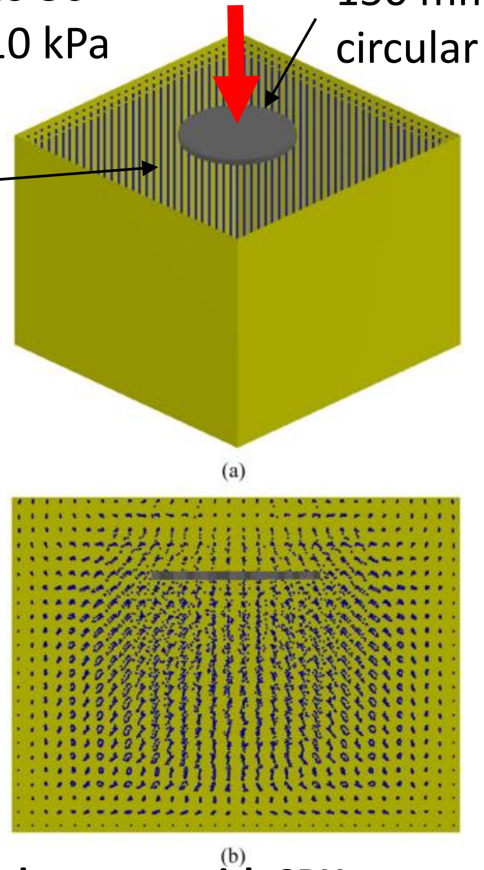
Calibration results for simulated and measured snow: (a) pressure–sinkage results**

**El-Sayegh, Z. and M. El-Gindy (2018)

Range of pressure from 0 to 50 kPa with an increment of 10 kPa

150 mm radius circular plate

Material is specified with using SPH method



Pressure–sinkage test with SPH snow particles**
(a) Initial stage and (b) Final stage.

**El-Sayegh, Z. and M. El-Gindy (2018)

Shear Strength simulation with Smoothed-Particle Hydrodynamics (SPH) method

Reference model details

Properties of modelled snow*				
	Cohesion constant (K_c) [kN/m$^{(n+1)}$]	Friction angle constant (k_ϕ) [kN/m$^{(n+1)}$]	Cohesion modulus (C) [MPa]	Internal friction angle (ϕ)
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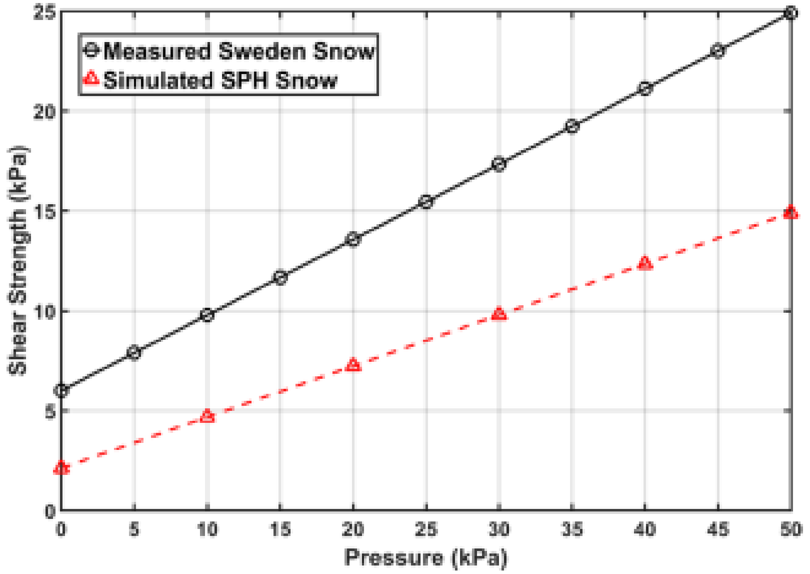
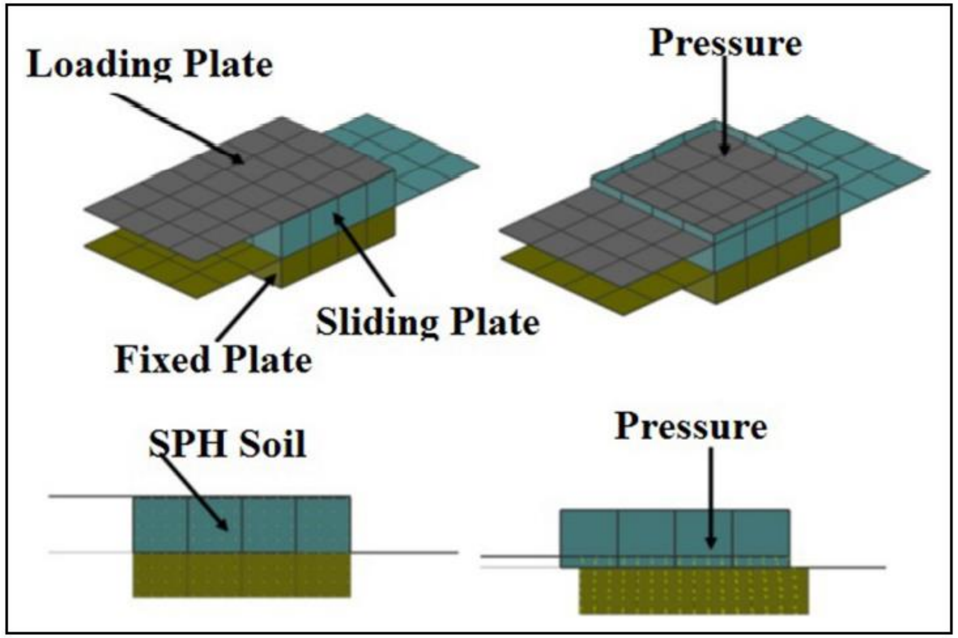


Calibration results for simulated and measured snow: shear–strength results**

**El-Sayegh, Z. and M. El-Gindy (2018)

Range of pressure from 0 to 50 kPa with an increment of 10 kPa



Shear–strength test with SPH snow

**El-Sayegh, Z. and M. El-Gindy (2018)

4. Comparison of different snow modelling methods

Limitations of Lagrangian Method

1. **Mesh Distortion**: In the Lagrangian framework, the computational mesh deforms along with the material. When deformations are large, this can lead to significant mesh distortion, potentially resulting in numerical inaccuracies or instabilities, especially in finite element analyses. This can limit the method's effectiveness in accurately capturing the material's response.
2. **Material Nonlinearities**: Large deformations often involve nonlinear material behavior that is not addressed by simpler, linear material models. The Lagrangian method needs to incorporate complex, nonlinear material models to accurately describe the stress-strain relationship under large deformation, which can significantly increase the complexity of the analysis.
3. **Geometric Nonlinearities**: With large deformations, geometric nonlinearities become prominent, affecting both the deformation gradient and strain measures. The standard assumptions of small deformations no longer hold, necessitating the use of more complex geometric descriptions and strain measures, which can complicate the analysis process.
4. **Computational Complexity**: Addressing the above issues within the Lagrangian framework often leads to increased computational complexity and cost. The need for advanced material models, refined meshing techniques, and more sophisticated numerical methods to handle large deformations can make simulations more time-consuming and resource-intensive.

These limitations highlight the need for careful consideration and potentially the adoption of enhanced or alternative methods when using the Lagrangian approach for modeling large deformations.

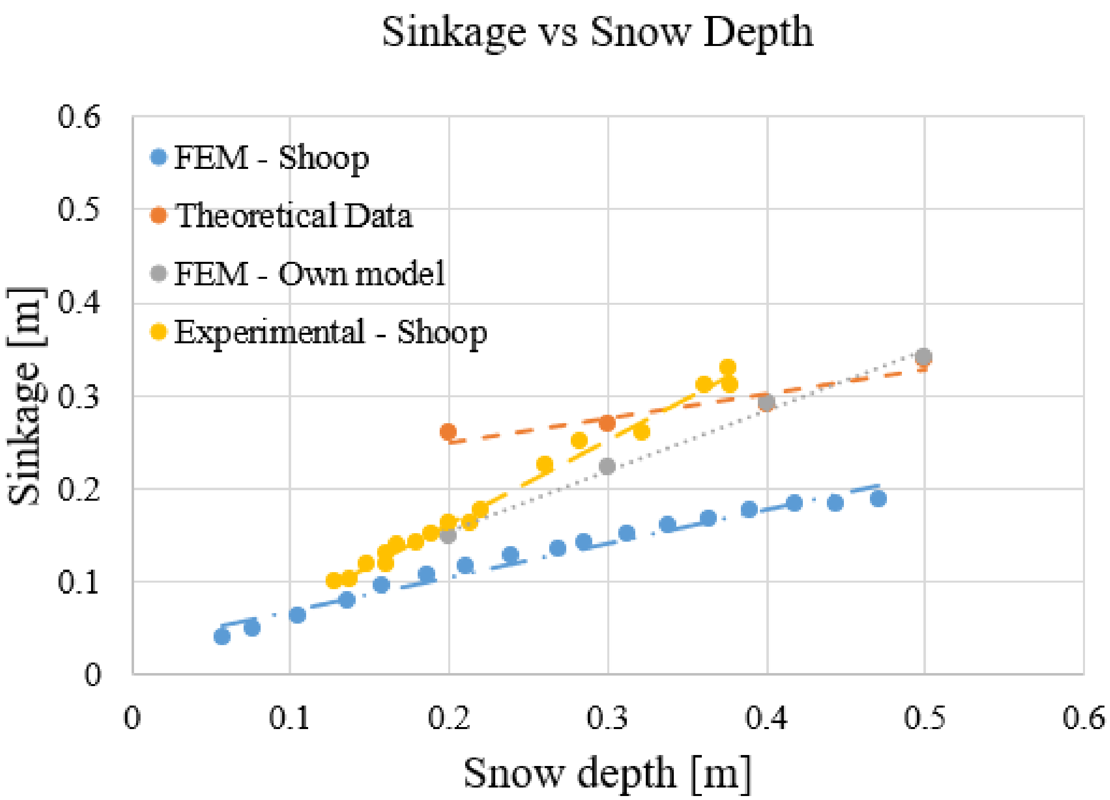
4. Comparison of different snow modelling methods

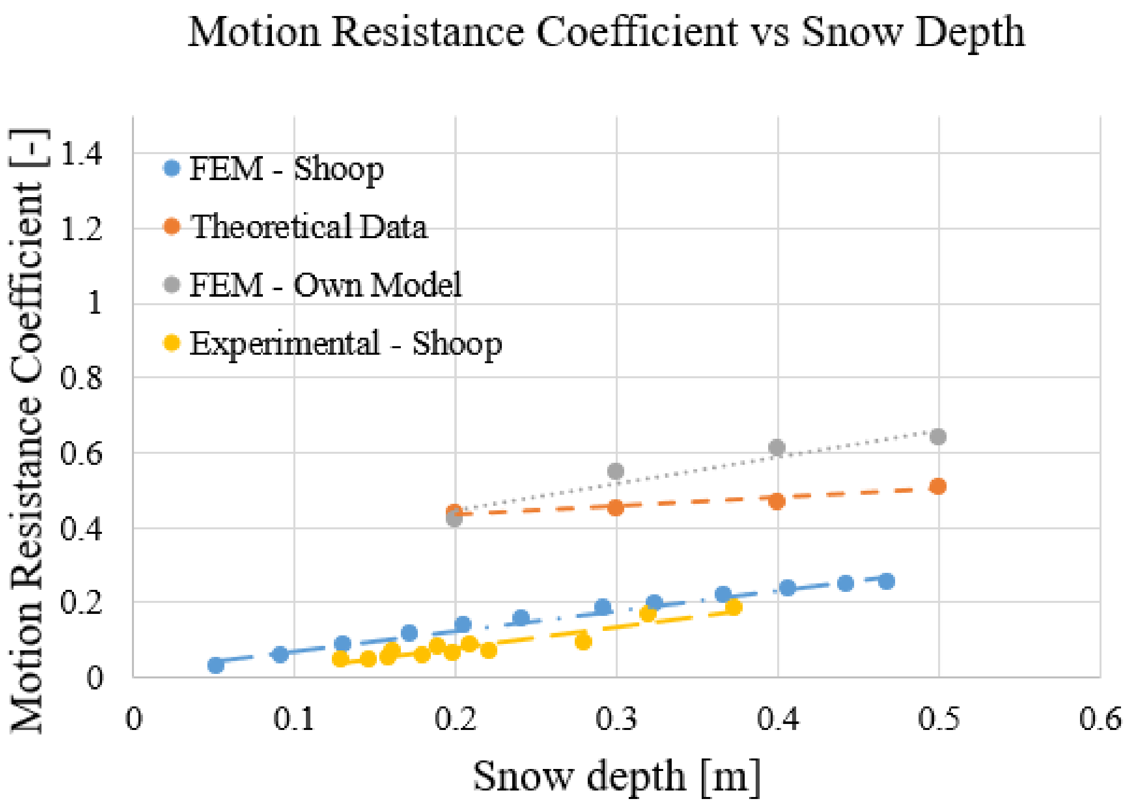
Advantages & Disadvantages of different snow modelling methods

Method	Advantages	Disadvantages	Challenges
ALE	• Accurate simulation of interaction in snow • Ability to handle large deformations in snow • Suitable for capturing snow compaction and consolidation	• Higher computational cost compared to SPH and DEM	• Not suitable for large and complex simulation. • Computational cost is high as compared to SPH and DEM
SPH	• Suitable for simulating snow deformations (Large Deformation) • Natural handling of free surfaces in snow	• Challenging boundary treatment for snow-surface interactions • Numerical noise and particle disorder can affect accuracy	• Computational Expensive as compared to DEM
DEM	• Granular nature allows for realistic representation of snow particles and their interactions	• Limited ability to capture continuum-level behavior of snow • Computational cost increases with the number of particles and their interactions	• Calibration of Material Model

5. Snow-Tire Interaction Study

Results: Comparison study- FEM Model, Analytical Model and Experimental data





6. Summary

1. Characterization of snow material parameters is crucial for enhancing the accuracy of snow simulation results.

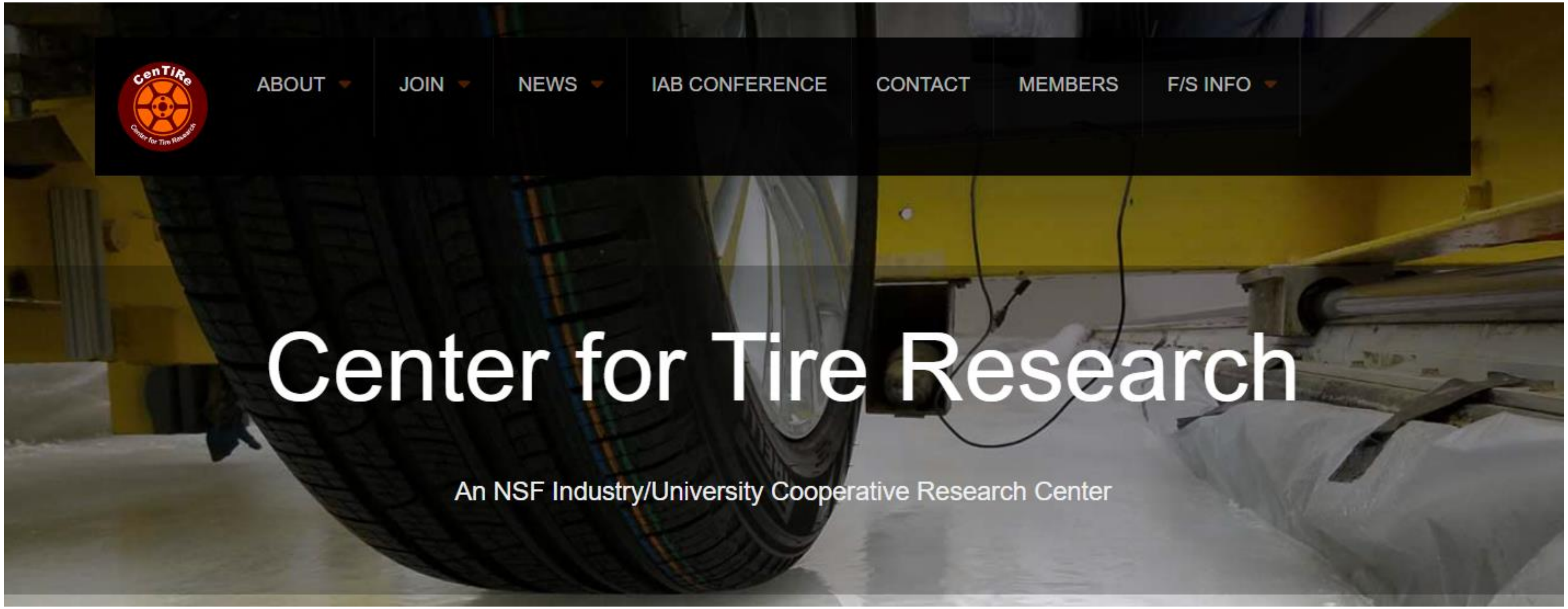
2. The Drucker Prager material model is identified as the most suitable for modeling snow.

3. Advanced modeling methods such as Arbitrary Lagrangian Eulerian (ALE) and Smoothed Particle Hydrodynamics (SPH) are highly recommended for accurately capturing snow behavior.

4. While the incorporation of these factors has shown improvement in the analysis accuracy of snow-tire interactions, there remains potential for further enhancement of the results.

Acknowledgments

The members of the Center for Tire Research (CenTiRe)



https://www.centire.org/