INVESTIGATION OF STRESS AND FAILURE IN GRANULAR SOILS FOR LIGHTWEIGHT ROBOTIC VEHICLE APPLICATIONS

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Gain deeper understanding of fundamental mechanics governing traction generation under small, lightweight vehicles.

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Motivation

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MODELING AND SIMULATION, TESTING AND VALIDATION

- Gain deeper understanding of fundamental mechanics governing traction generation under small, lightweight vehicles.
- Improve modeling accuracy and predictive power.
- This will allow small robots to be more effective performers and operate more reliably.

Methodology

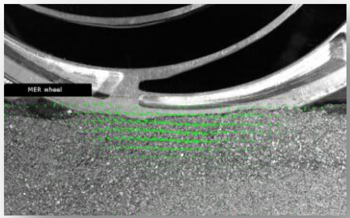
Soil Characterization → **Single Wheel Experiments** → **Terramechanics Modeling**

Direct Shear Tests

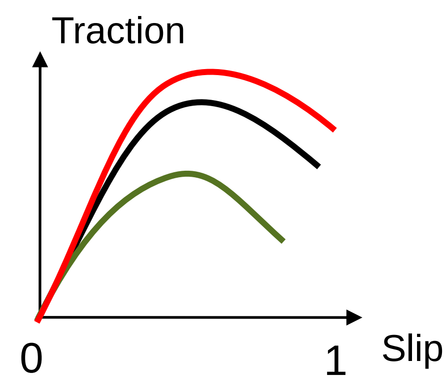
Penetration Tests

Radius = 13 cm
Width = 16 cm

Interfacial Stress Measurement



Soil Motion Measurement (PIV)



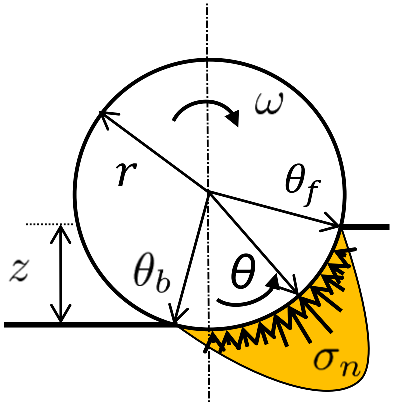
Presentation Outline

- State-of-the-art model for wheeled vehicles mobility.
- Soil characterization (i.e., how to obtain the parameters for the aforementioned model).
- Single wheel experimental methodologies
  - Particle Image Velocimetry
  - Force sensors
- Comparison between State-of-the-art modeling and measurements
- Conclusions and future work

Bekker-Wong Model

- Terramechanics models are based on:
  - **Bekker-Wong** equations for normal stress calculations

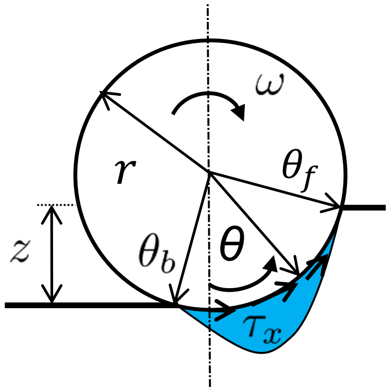
$$\sigma_n = \begin{cases} \sigma_1 = \left(\frac{k_c}{b} + k_\phi\right) r^n \left(\cos\theta - \cos\theta_f\right)^n & \theta_m < \theta < \theta_f \\ \sigma_2 = \left(\frac{k_c}{b} + k_\phi\right) r^n \left(\cos\left(\theta_f - \frac{\theta - \theta_b}{\theta_m - \theta_b}(\theta_f - \theta_m)\right) - \cos\theta_f\right)^n & \theta_b < \theta < \theta_m \end{cases}$$



θ_m *is the angle where normal stress reaches a peak*

  - **Janosi-Hanamoto** equation for tangential stress calculation

$$\begin{cases} \tau_x(\theta) = \tau_{max}\left(1 - e^{\frac{-j_x}{k_x}}\right) \\ \tau_{max} = c + \sigma_n(\theta)\tan\phi \quad \text{Mohr-Coulomb criterion} \end{cases}$$



Wong, J. Y., and Reece, A. R., "Prediction of rigid wheel performance based on the analysis of soil-wheel stresses part I," Journal of Terramechanics, Vol. 4, No. 1, pp. 81-98, 1967.

Soil Characterization
Direct Shear Test

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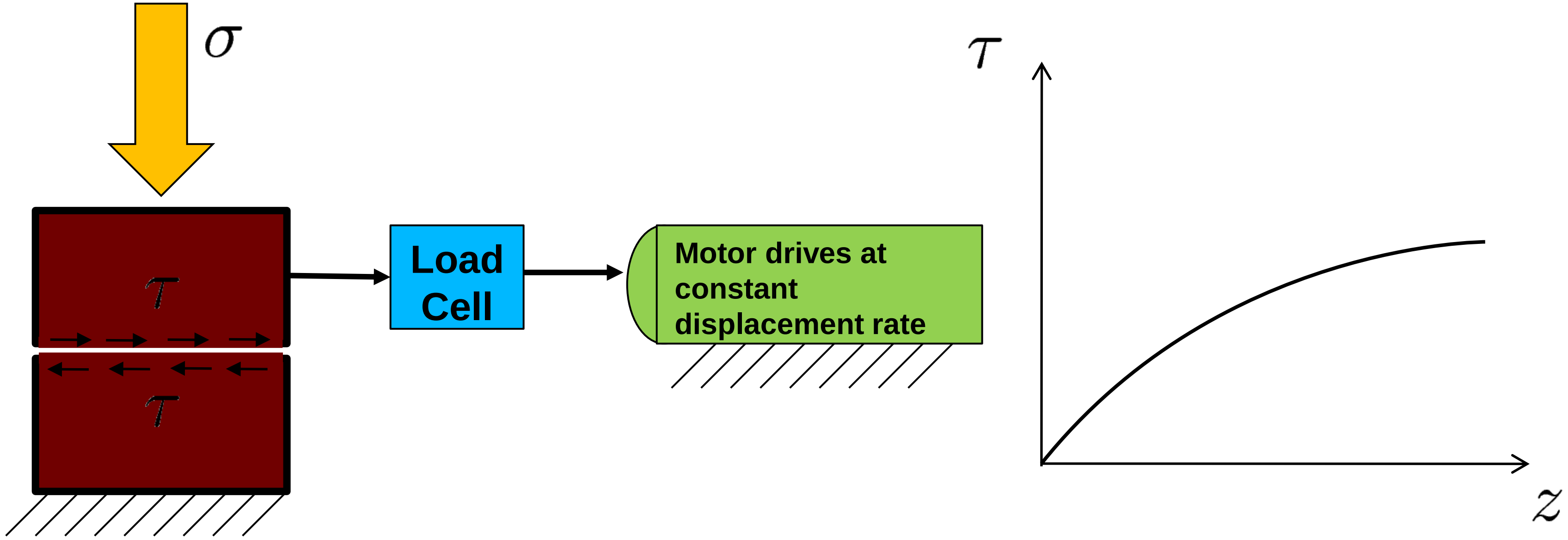
- Direct shear tests are used to characterize shearing properties of soils
- Direct shear tests are standard tests in the geotechnical practice



Direct Shear Test Results

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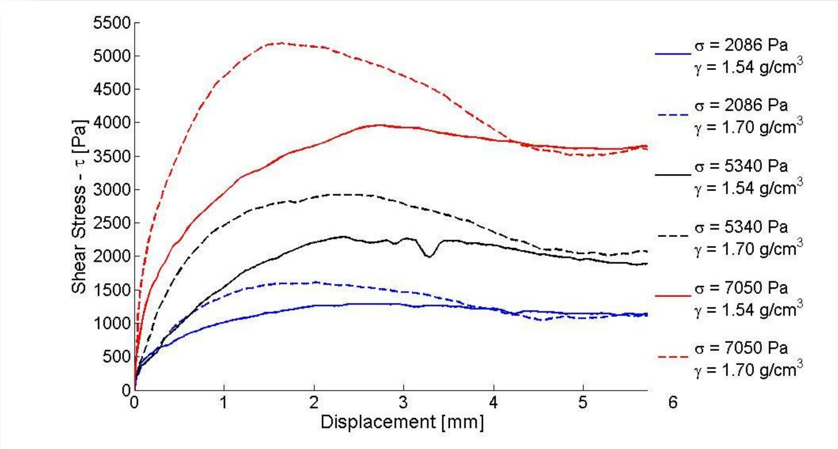
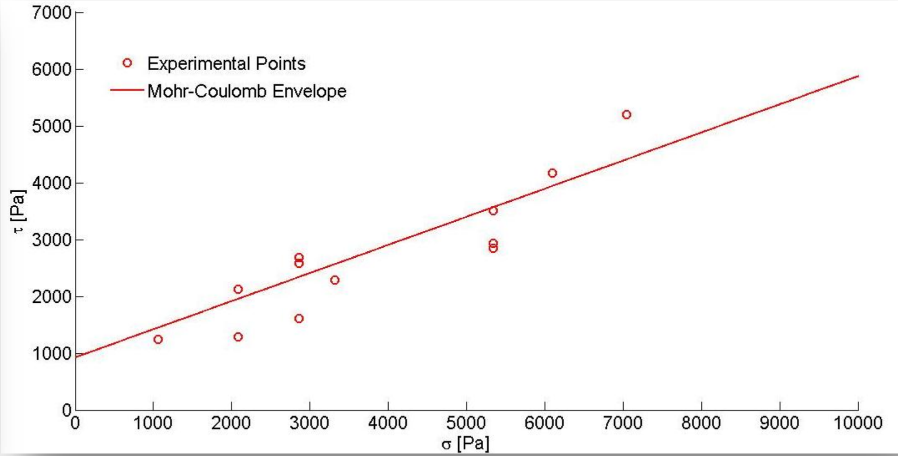
- Direct shear tests provide shearing properties of the soil:

$$\begin{cases} \tau_x(\theta) = \tau_{max}\left(1 - e^{\frac{-j_x}{k_x}}\right) \\ \tau_{max} = c + \sigma_n(\theta)\tan\phi \end{cases}$$

Shear Modulus
Cohesion
Angle of Internal Friction





$$\tau_x(\theta) = \tau_{max}\left(1 - e^{\frac{-j_x}{k_x}}\right)$$

$$\tau = c + \sigma\tan(\phi)$$

Soil Characterization Penetration Tests

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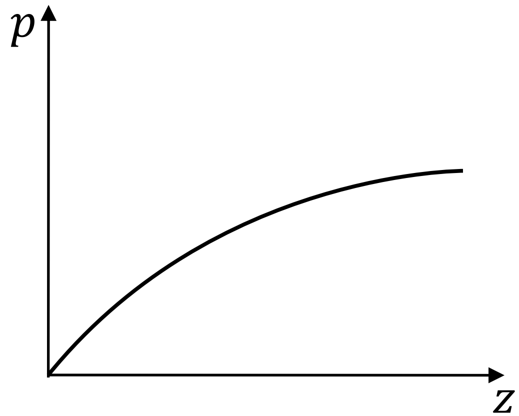
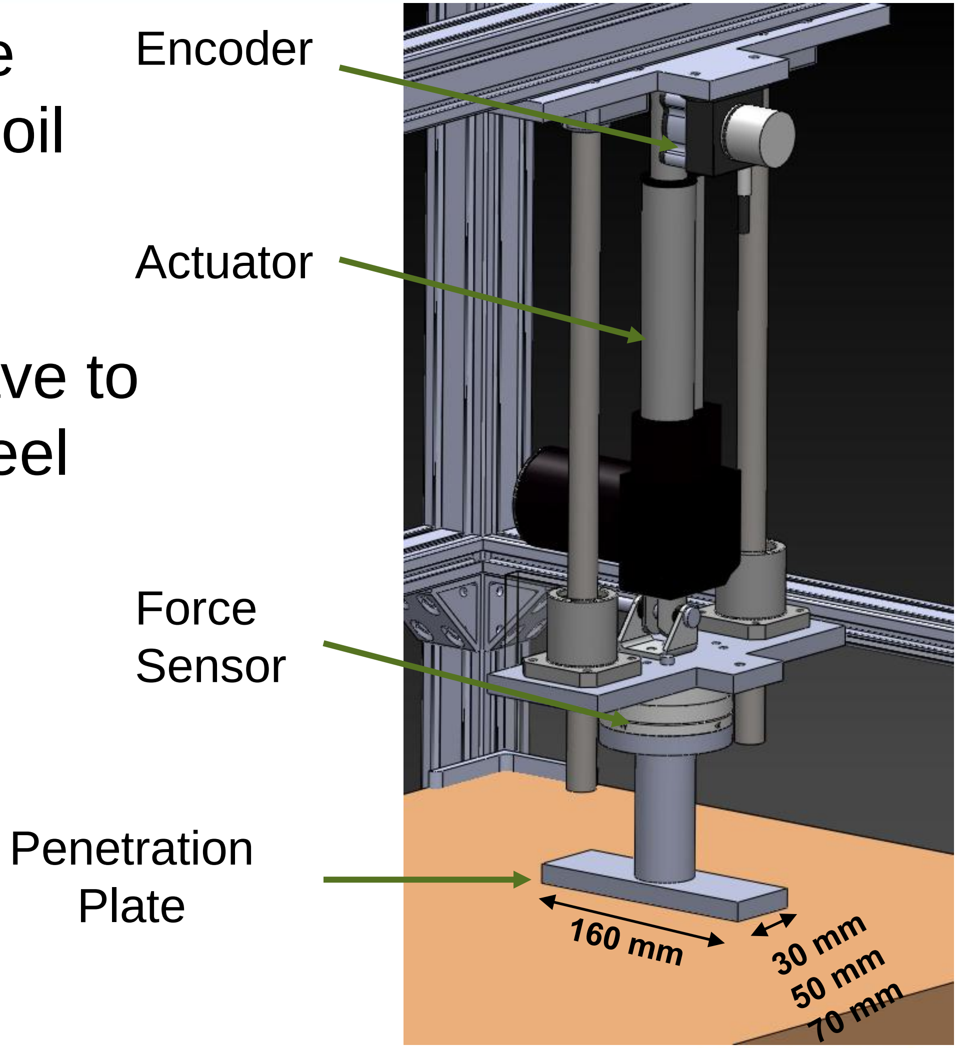
- Plate penetration tests were performed to characterize soil response to normal loading
- According to Bekker-Wong theory, plates dimension have to be comparable with the wheel contact patch under investigation.





Penetration Tests

- Penetration tests provide information about soil normal loading response

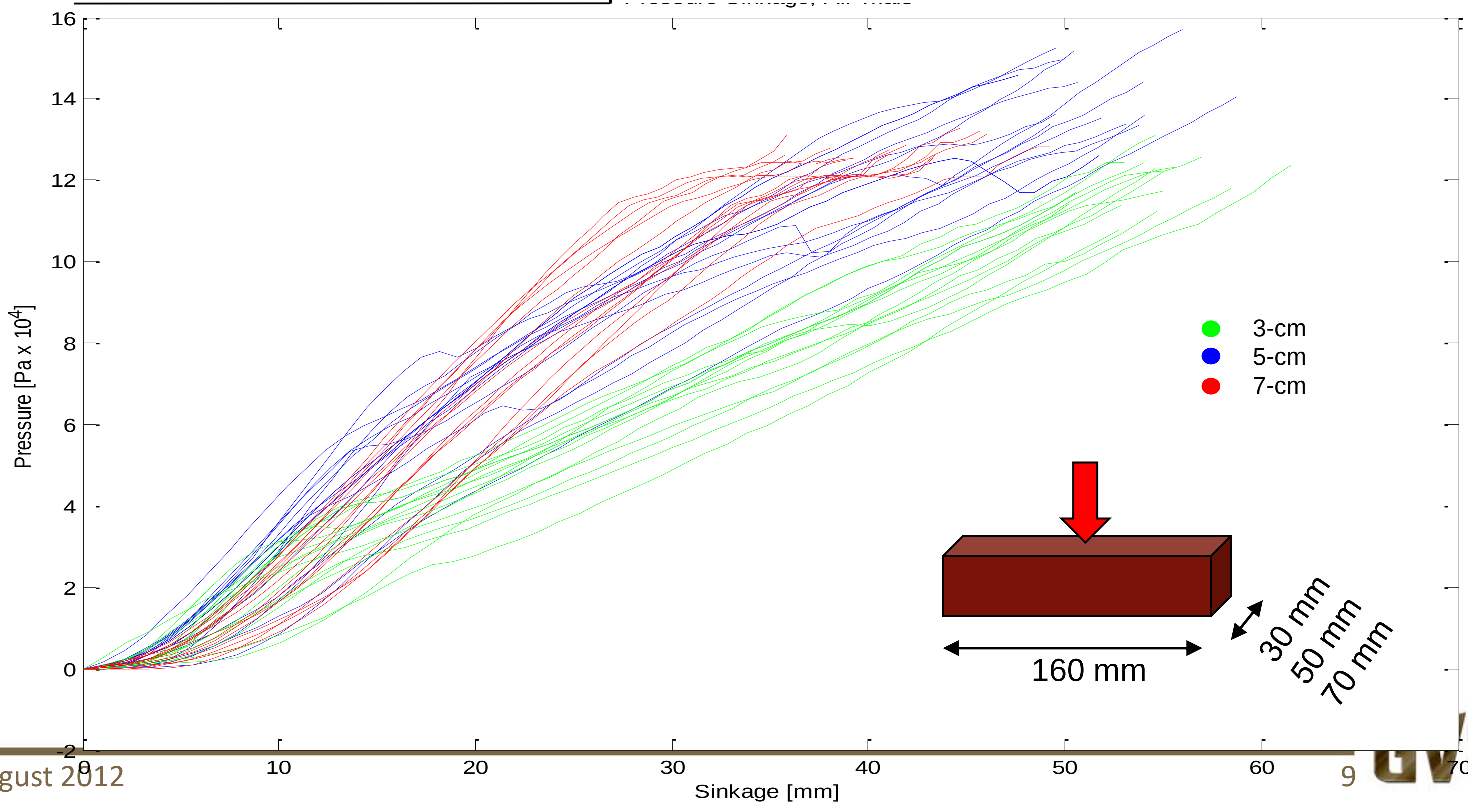
Cohesion dependent soil coefficient

Frictional dependent soil coefficient

$$\sigma_n = \left(\frac{k_c}{b} + k_\phi \right) z^n$$

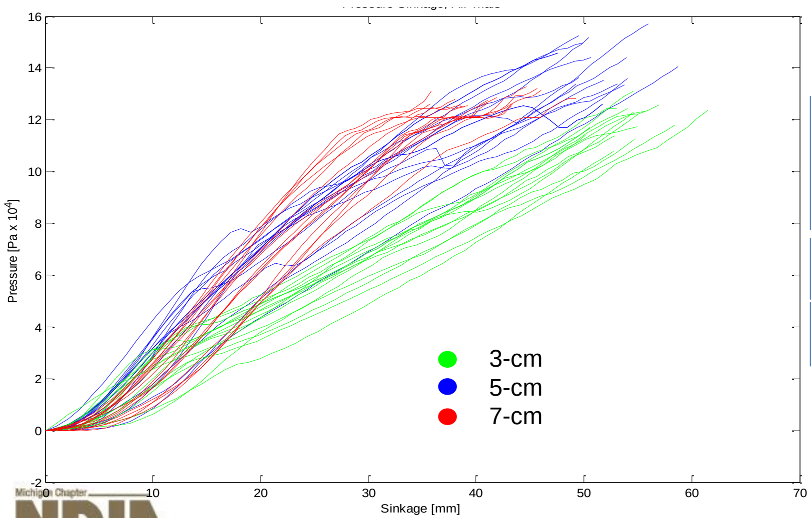
Plate width

Sinkage exponent



Penetration Tests Variability

- Penetration tests showed how variable, even under carefully controlled laboratory conditions, soil response can be.
- An initial attempt to statistically characterize soil response was made but further investigations are under way.
- Aspect ratio influence was not investigated because plate width is constrained by wheel geometry (wheel width is fixed while contact patch length depends on sinkage).
- Using the (deterministic) approach suggested by Wong*, two sets of parameters were calculated. 57 is obtained truncating the data at 50kPa.



Set	n	k_c [kN/m^{n+1}]	k_ϕ [kN/m^{n+2}]
357	0.99	-55	4584
57	1.4	846	6708

* Wong, J.Y., *"Data processing methodology in the characterization of the mechanical properties of terrain," Journal of Terramechanics, 17(1):13 – 41, 1980.*

Single Wheel Testbed

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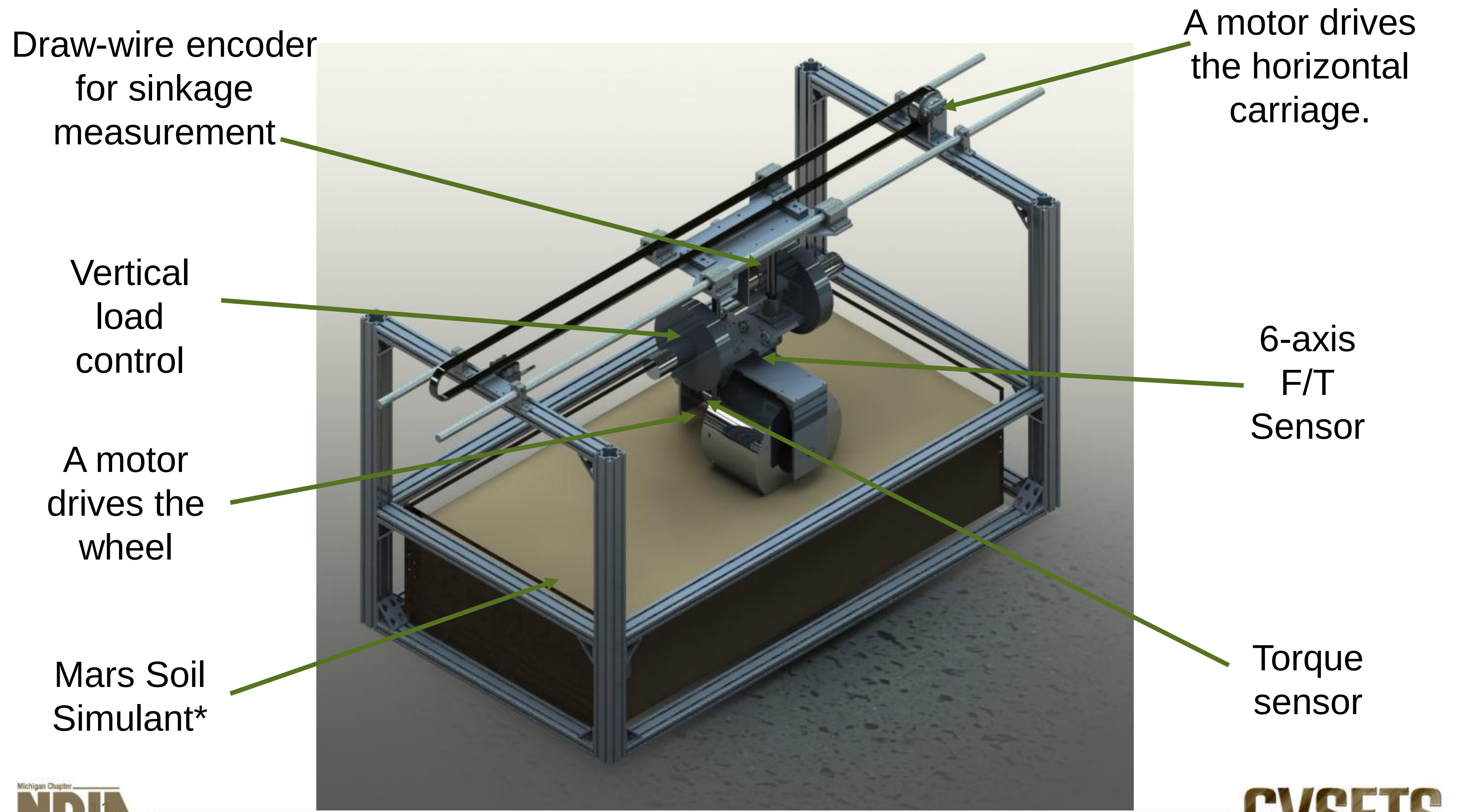

* L. W. Beegle et al., "*MOJAVE MARTIAN SIMULANT: A NEW MARTIAN SOIL SIMULANT,*" *Lunar and Planetary Science, XXXVIII, 2007*

PIV Setup

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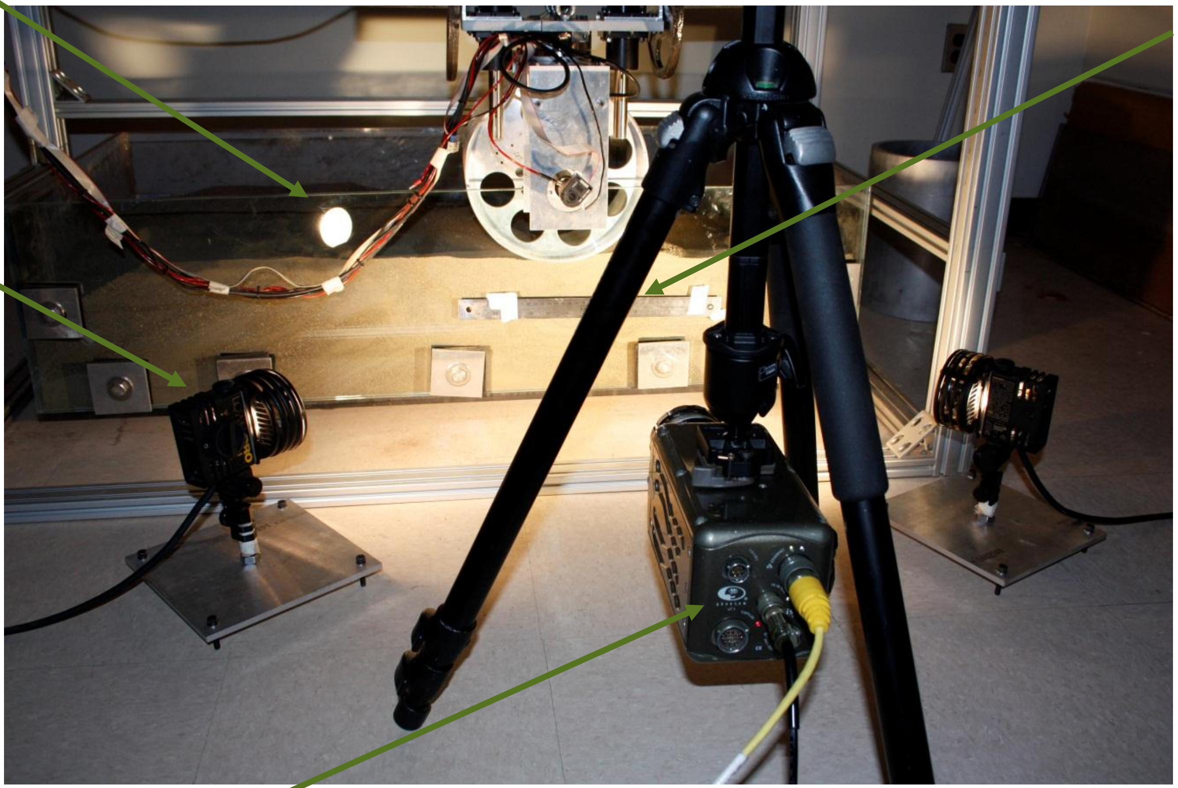
Tempered 1" Thick Glass

500W Spot Lights

Ruler, needed to calibrate pixel/mm ratio



Phantom 7.1 High Speed Camera

PIV Description

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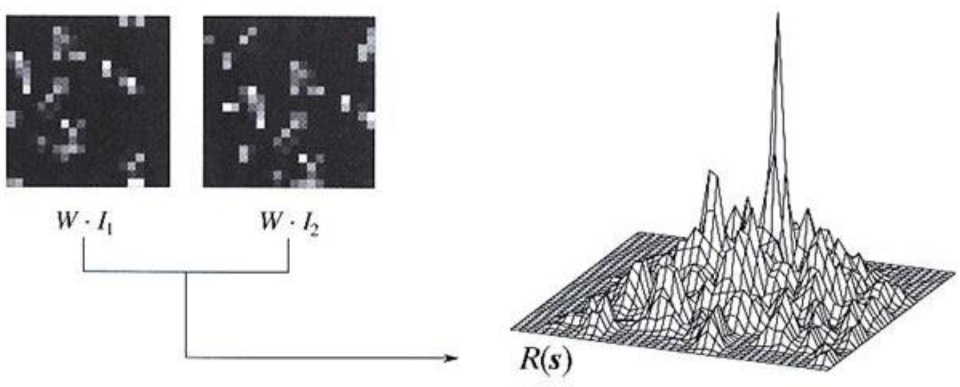
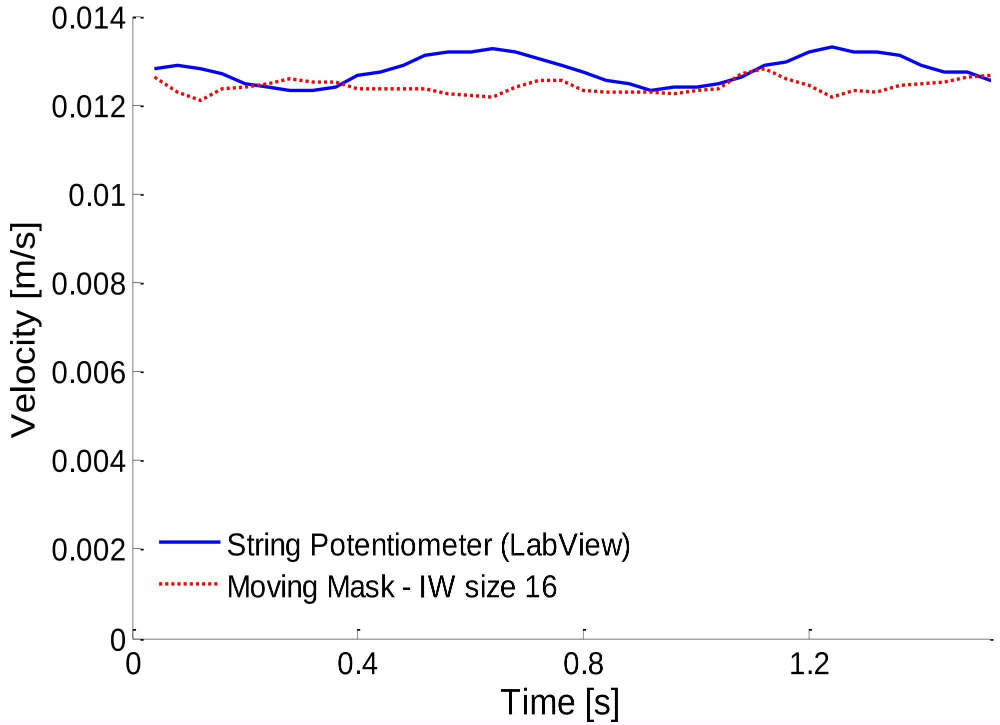
- PIV is a methodology for extracting instantaneous velocity fields from a series of images
- Probable displacement is determined by using the cross correlation function

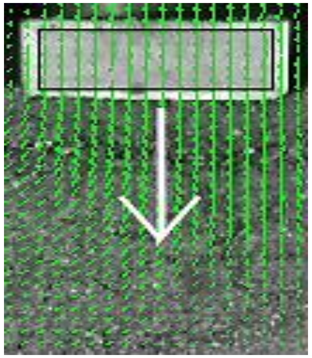
$$R_u(x,y) = \sum_{i=-K}^{K} \sum_{j=-L}^{L} I_1(i,j)\, I_2(i+x, j+y)$$



PIV Validation

- Since a ground truth for soil motion was not available, the velocity of a plate (precisely measured through a draw-wire encoder) was compared with PIV measurements.





PIV Results

- Wong Experiments
  - Average Ground Pressure = 30-90 kPa
- MIT Experiments
  - Average Ground Pressure = 7-13 kPa

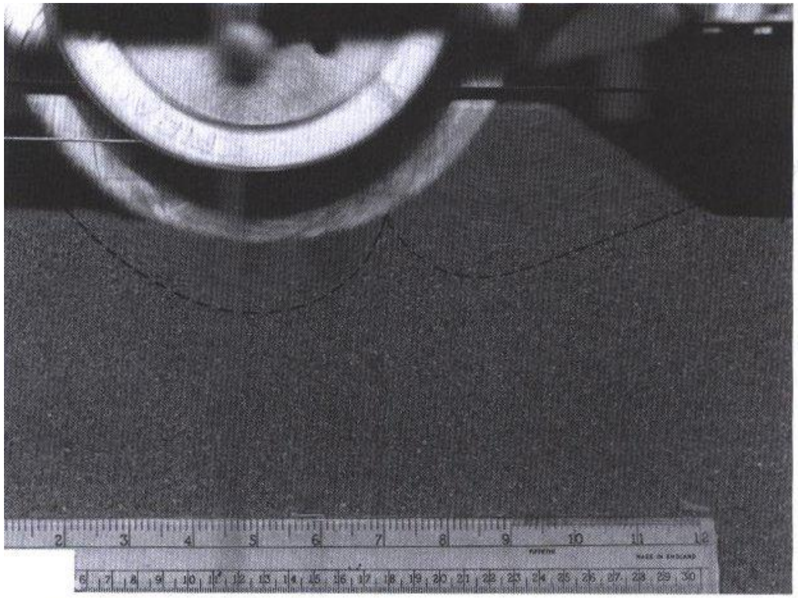
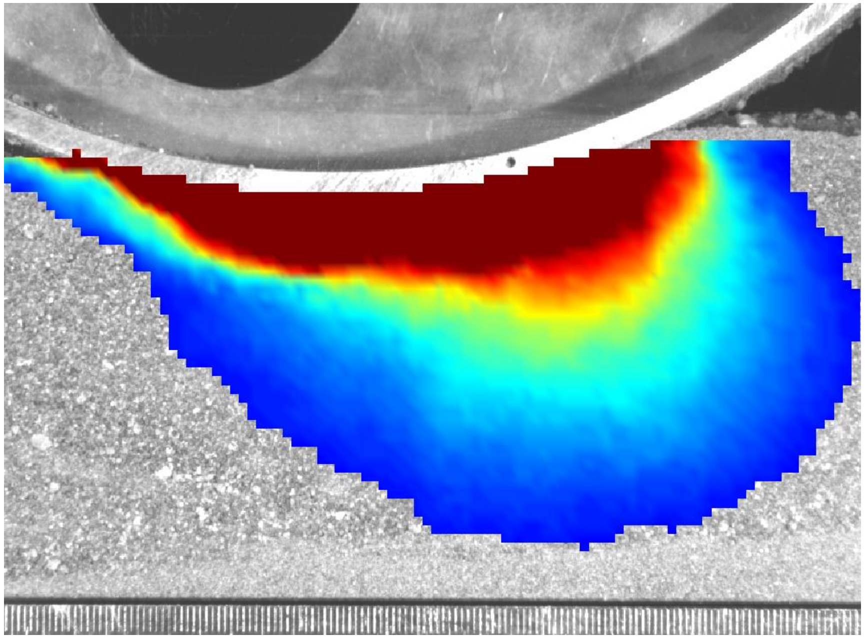
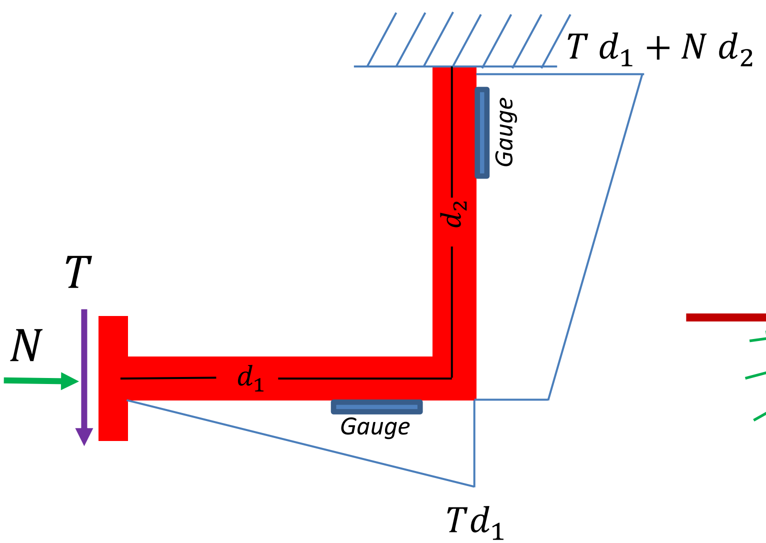


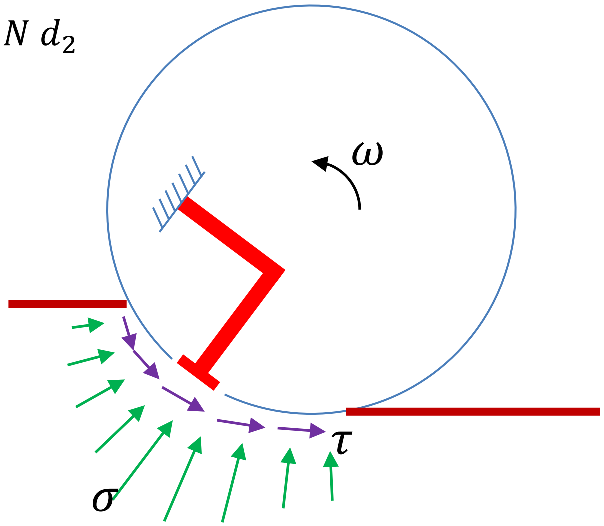
Figure 1.11: Soil flow patterns under a driven rigid wheel in sand

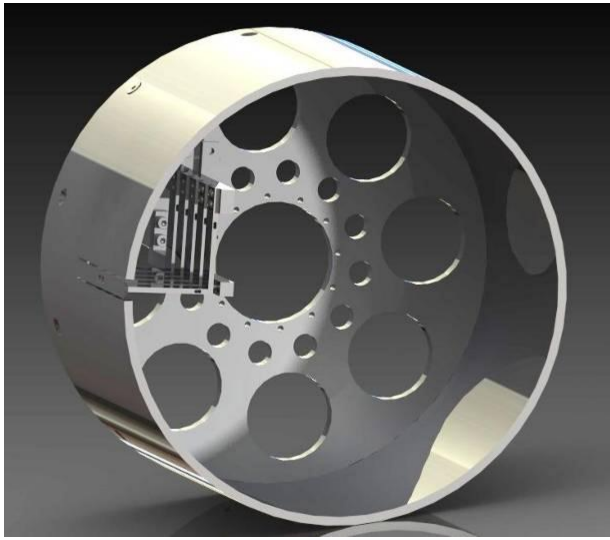


Force Sensors

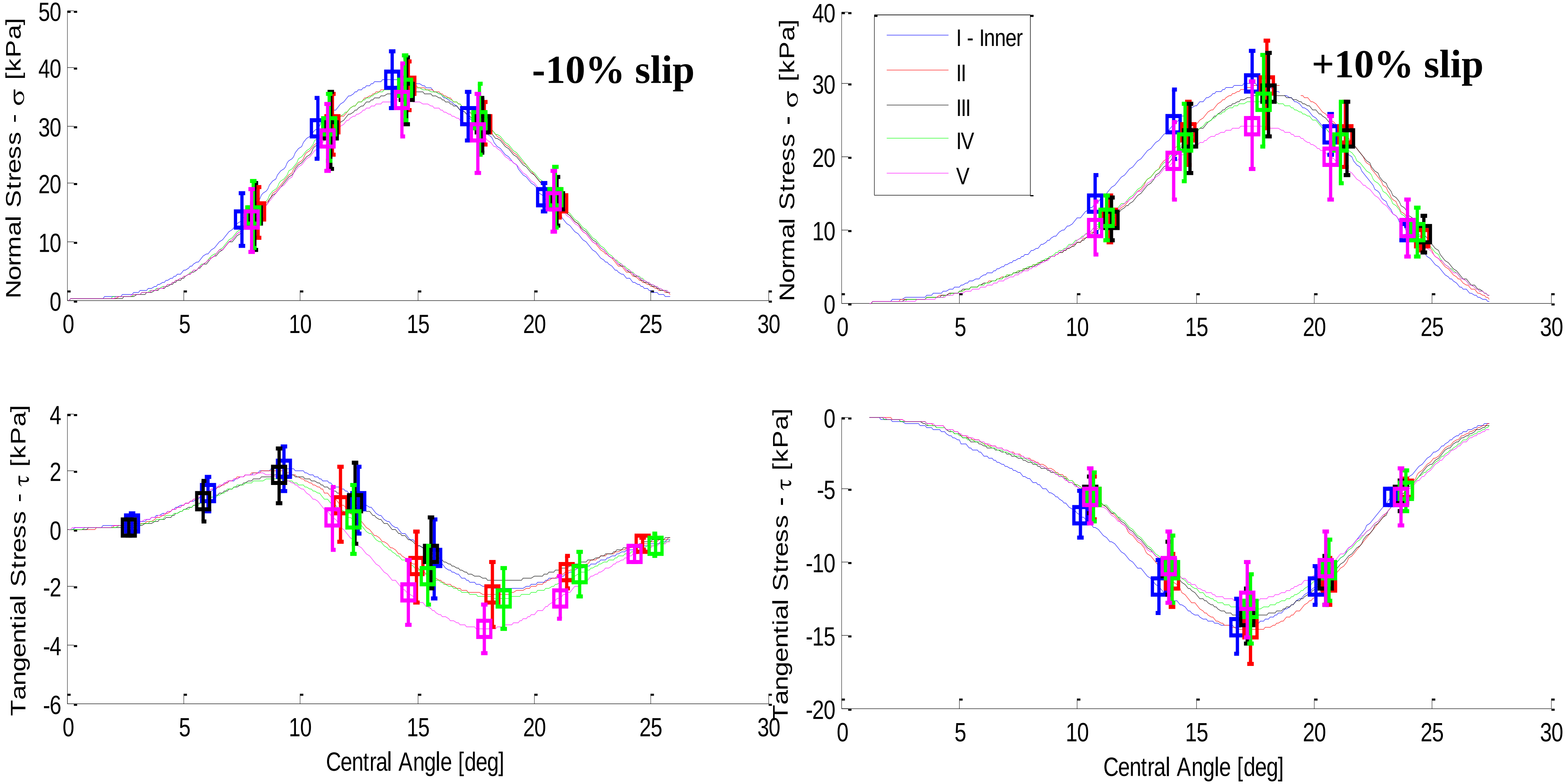
- Flexing beam instrumented with strain gauges
- Tangential and Normal forces applied to the tip can be reconstructed from gauges reading



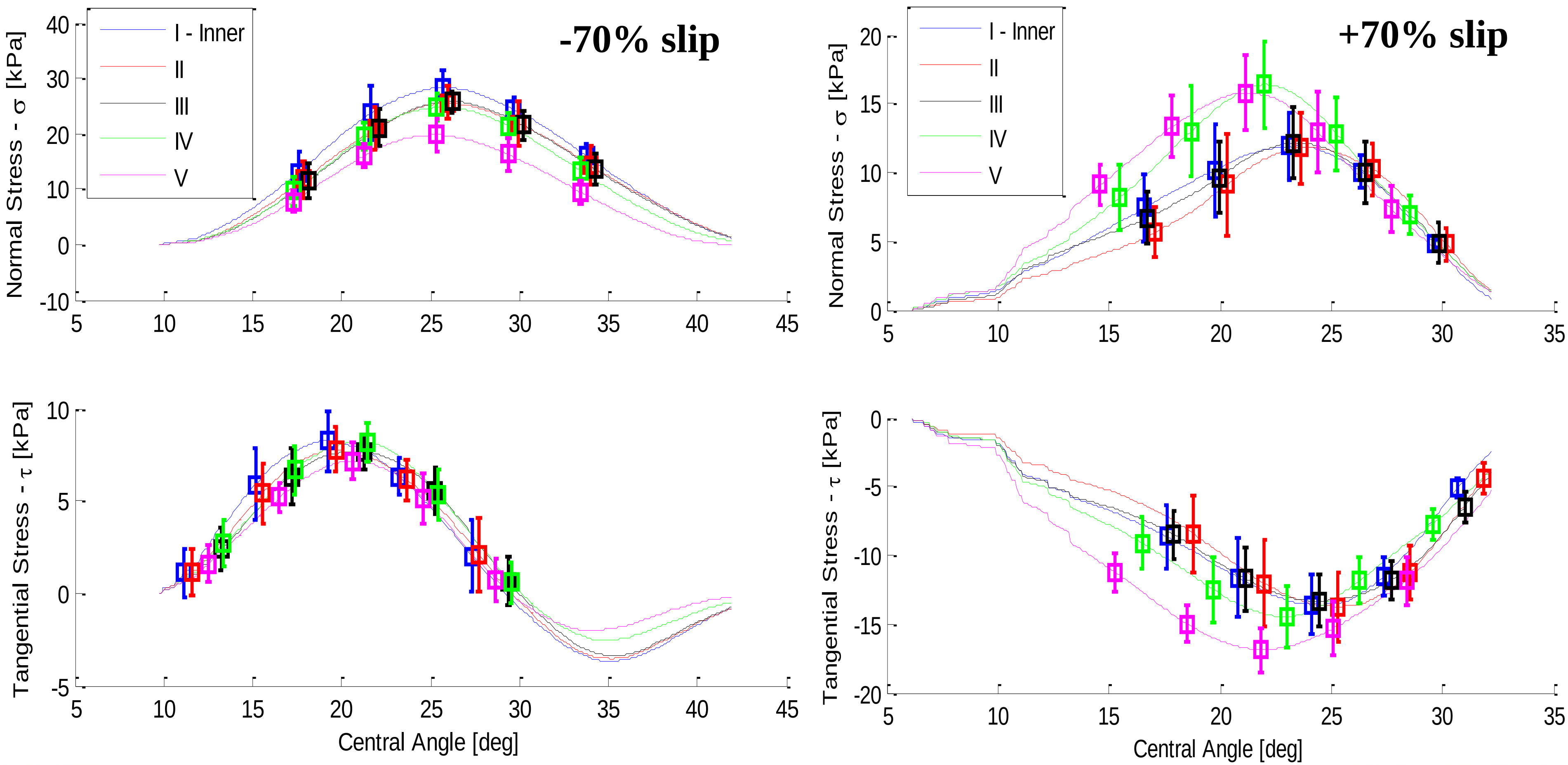




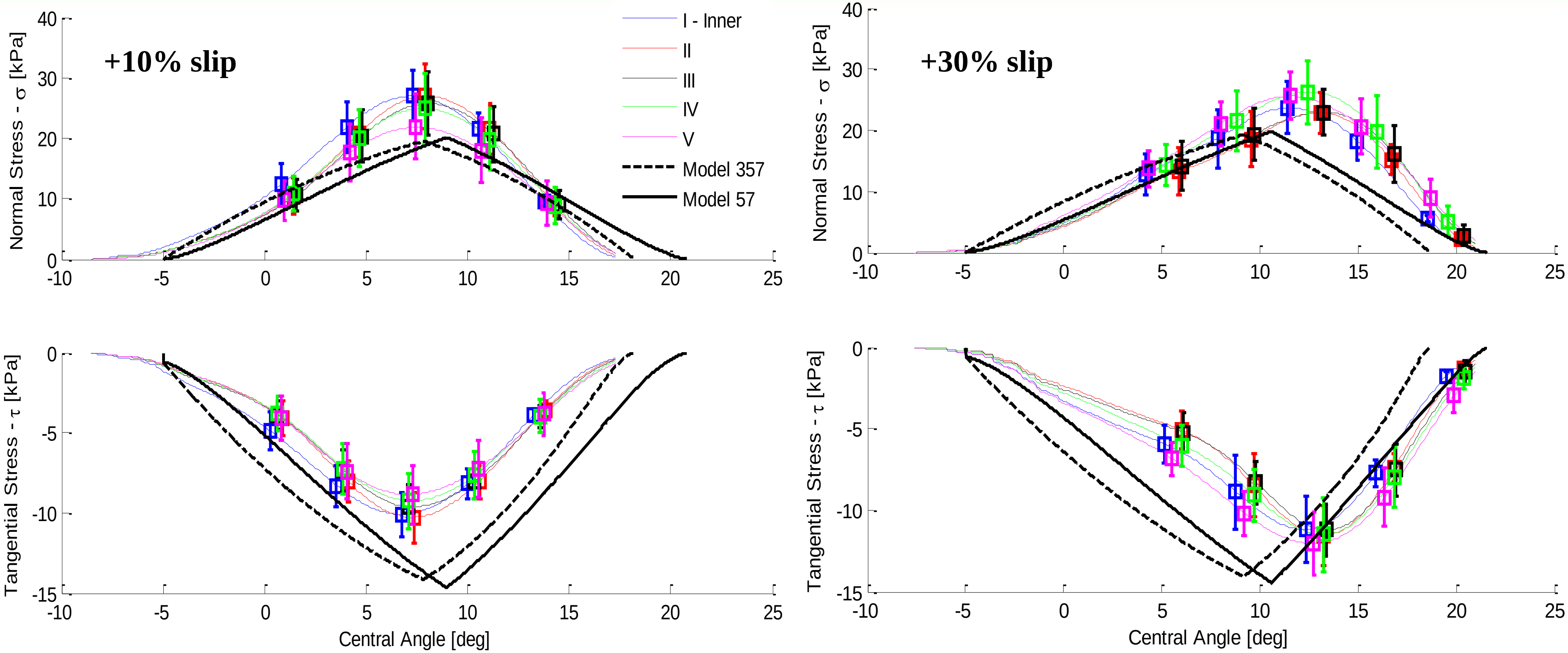
Stress Profile at Wheel-Soil Interface for Low Slip



Stress Profile at Wheel-Soil Interface for High Slip



Comparison Between Bekker-Wong Model and Measured Stress



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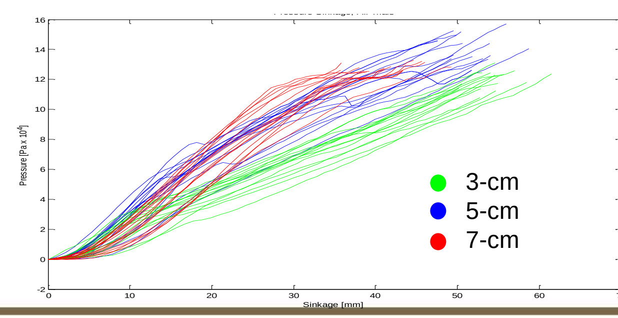

Conclusions and Future Work

- PIV shows phenomena that do not completely agree with assumptions behind classical models
  - Only one failure envelope develops (not two)
  - Soil failure is periodic
  - Soil is always attached to the wheel surface
- However, stress measurements show that Bekker-Wong model is still able to capture main trends (for low slip).
- Further efforts will be dedicated to characterize variability in soil response and how models are affected by it.
- The underlying complex mapping between soil displacement and stress (i.e., constitutive law) will be investigated in order to improve modeling capabilities.