Terramechanics 2: Traction

- Slip
- Grousers
- Drawbar Pull

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Shearing Strength of Soil

We want to know the maximum shear stress the soil can accommodate to find maximum tractive force of wheel

$$\tau \equiv \text{shearing resistance per unit area}$$

$$\tau = c_0 + \sigma \tan\phi = c_0 + \frac{W}{A}\tan\phi$$

$$\sigma \equiv \text{normal stress on the soil}$$

$$H_0 \equiv \text{ideal soil thrust}$$

$$H_0 = Ac_0 + W\tan\phi$$

Wheel Slip Ratio

- Wheel circumferential speed ωr will never exactly match vehicle speed V
- The difference is slip ratio: $s \equiv 1 - \dfrac{V}{\omega r}$
- If $\omega r = V$ then $s = 0$
- If $\omega r > V$ then $0 < s < 1$
- If $\omega r \gg V$ (or $V = 0$) then $s = 1$
- If $\omega r < V$ (deceleration) then $-1 < s < 0$
- New definition becomes $s_d = \dfrac{\omega r}{V} - 1$

Tractive Force per (Smooth) Wheel

$$H = \left(Ac + W \tan\phi\right)\left[1 - \frac{K}{s\ell}\left(1 - e^{\frac{-s\ell}{K}}\right)\right]$$

$$A = \text{area of contact} = b\ell$$

$$c = \text{soil cohesion}$$

$$\phi = \text{soil angle of internal friction}$$

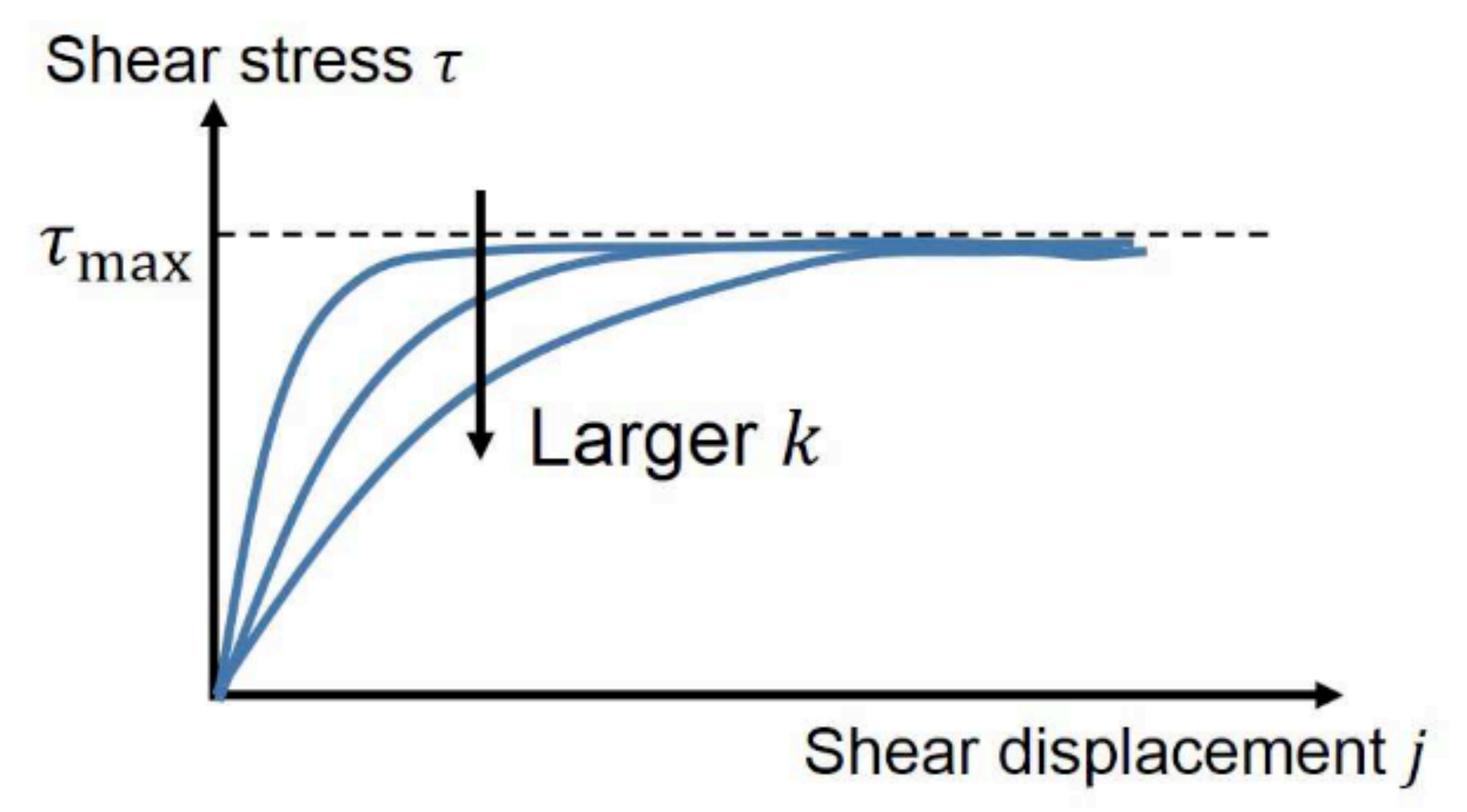
$$s = \text{wheel slip ratio}$$

$$K = \text{shear deformation modulus}$$

$$\ell = \text{length of contact patch} = \frac{D}{2}\cos^{-1}\left(1 - \frac{2z}{D}\right)$$

Shear Deformation Modulus

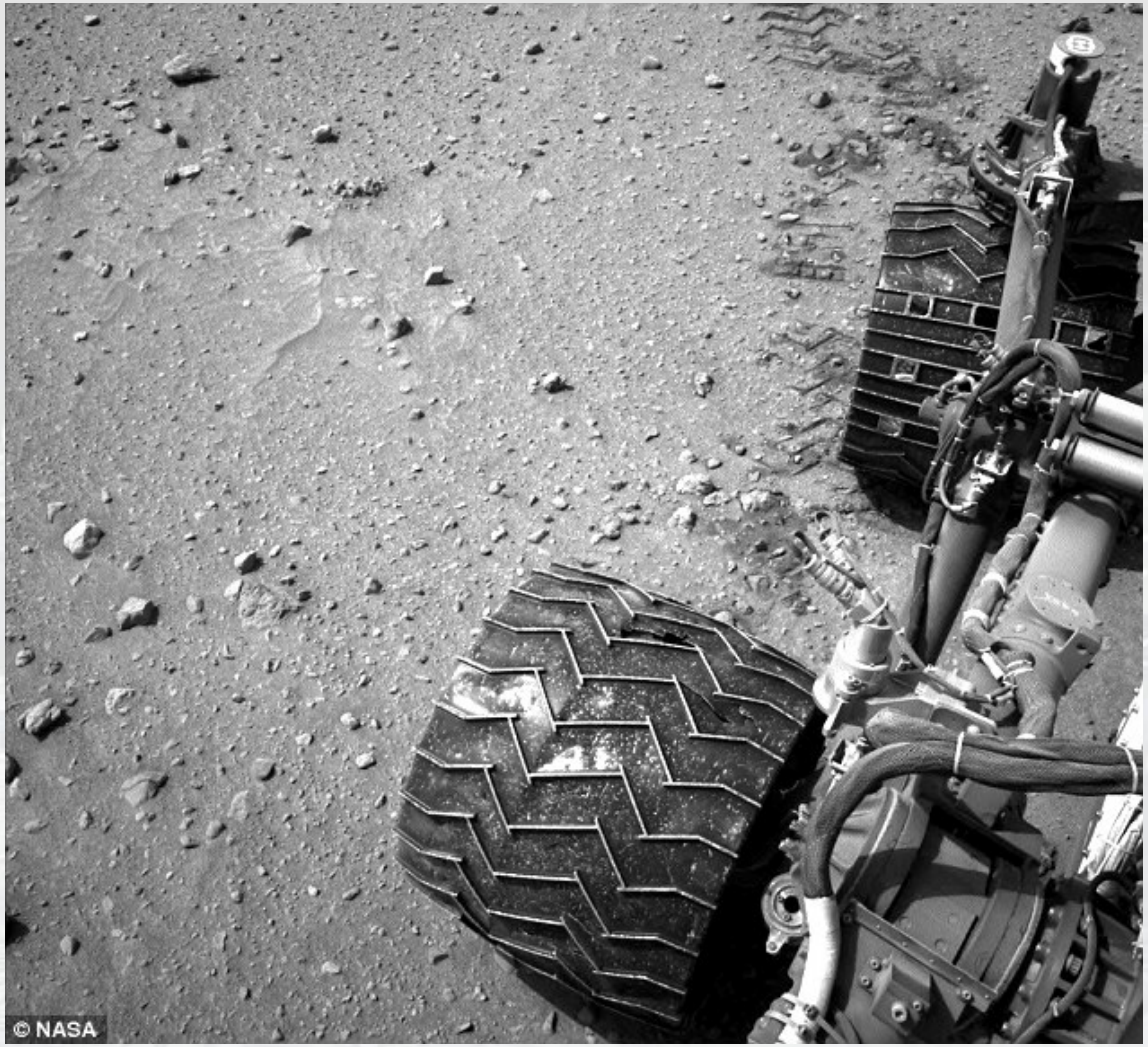
- Wheel drives in regolith…
- Regolith particles around the contact area are sheared by the rotational and sideslip motions of the wheel, and…
- The shear stress develops based on the displacement of the regolith
- Shear stress increases with increasing shear displacement
- Shear deformation modulus is a parameter of the surface and is determined experimentally
- Typically K=1.8 cm



From Hiroaki Inotsume, “Analysis of Angle of Attack for Efficient Slope Ascent by Rovers” CMU-RI-TR-15-22, Carnegie Mellon University, August 2015

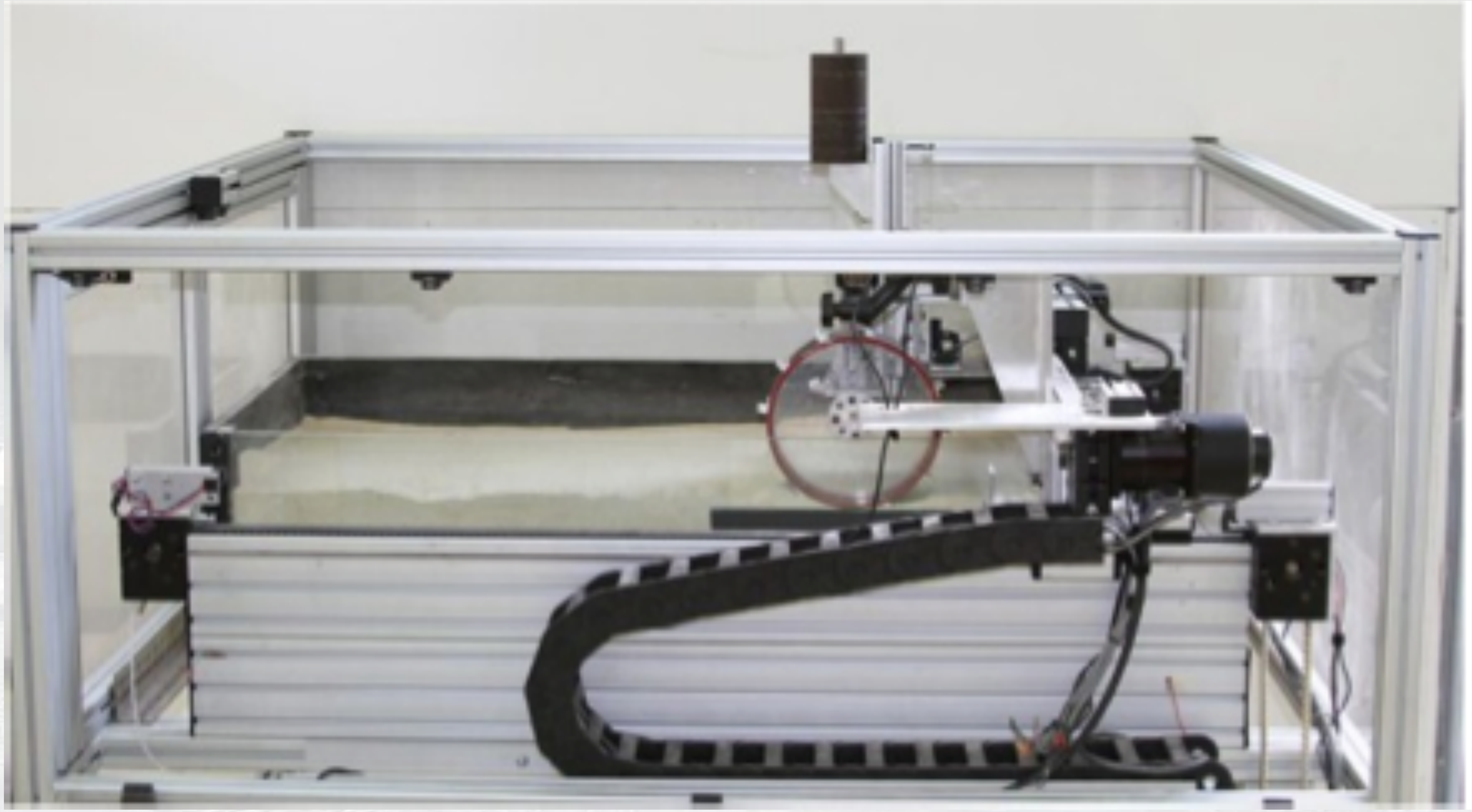
Grousers (on Tracked Vehicle)

Grousers (MSL Wheels)



Mars Rover Wheels

Terramechanics Test Rig (CMU)



K. Skonieczny, S. Moreland, and D. Wettergreen, “A Grouser Spacing Equation for Determining Appropriate Geometry of Planetary Rover Wheels” *2012 IEEE/RSJ International C* *Robots and Systems*

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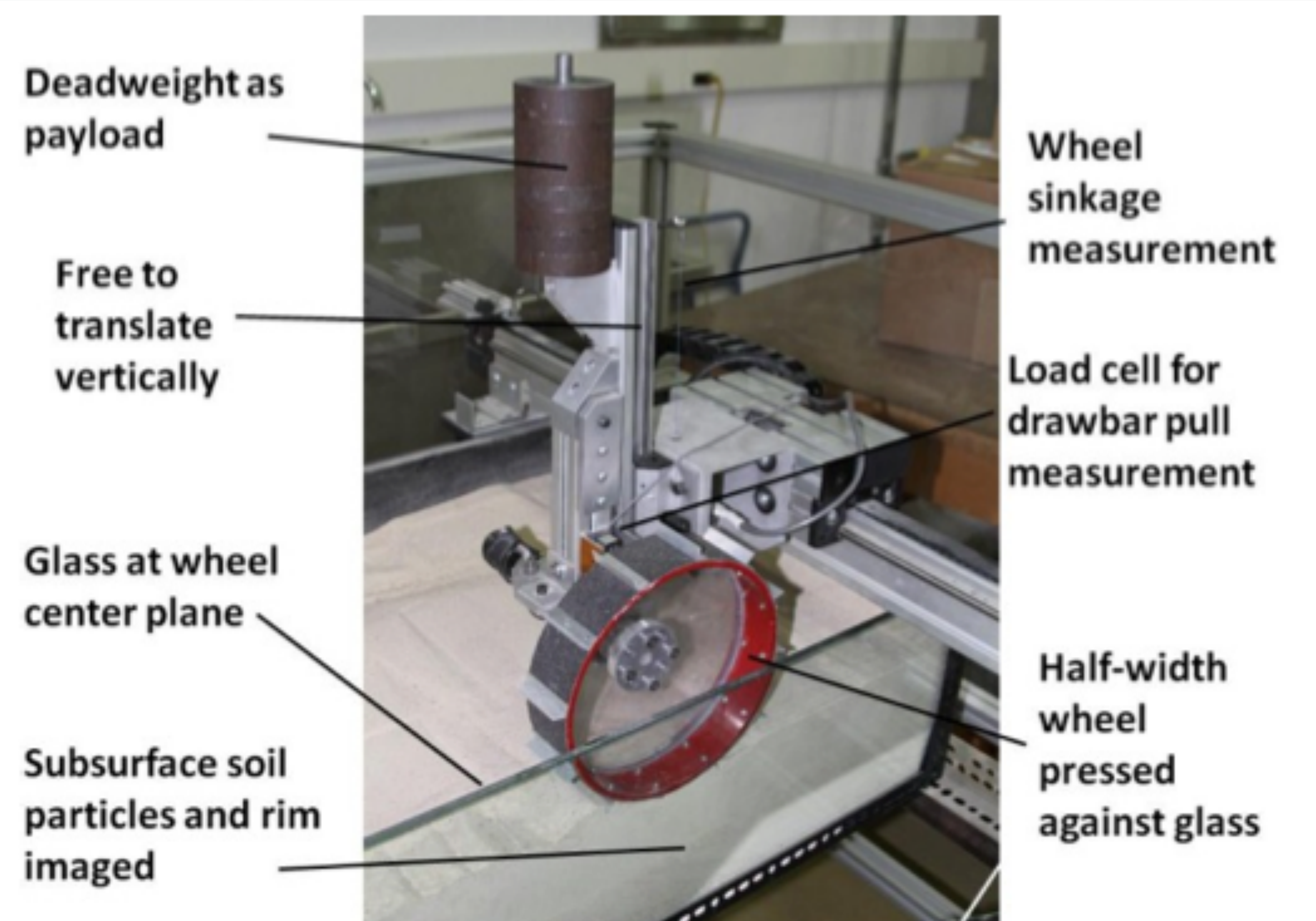

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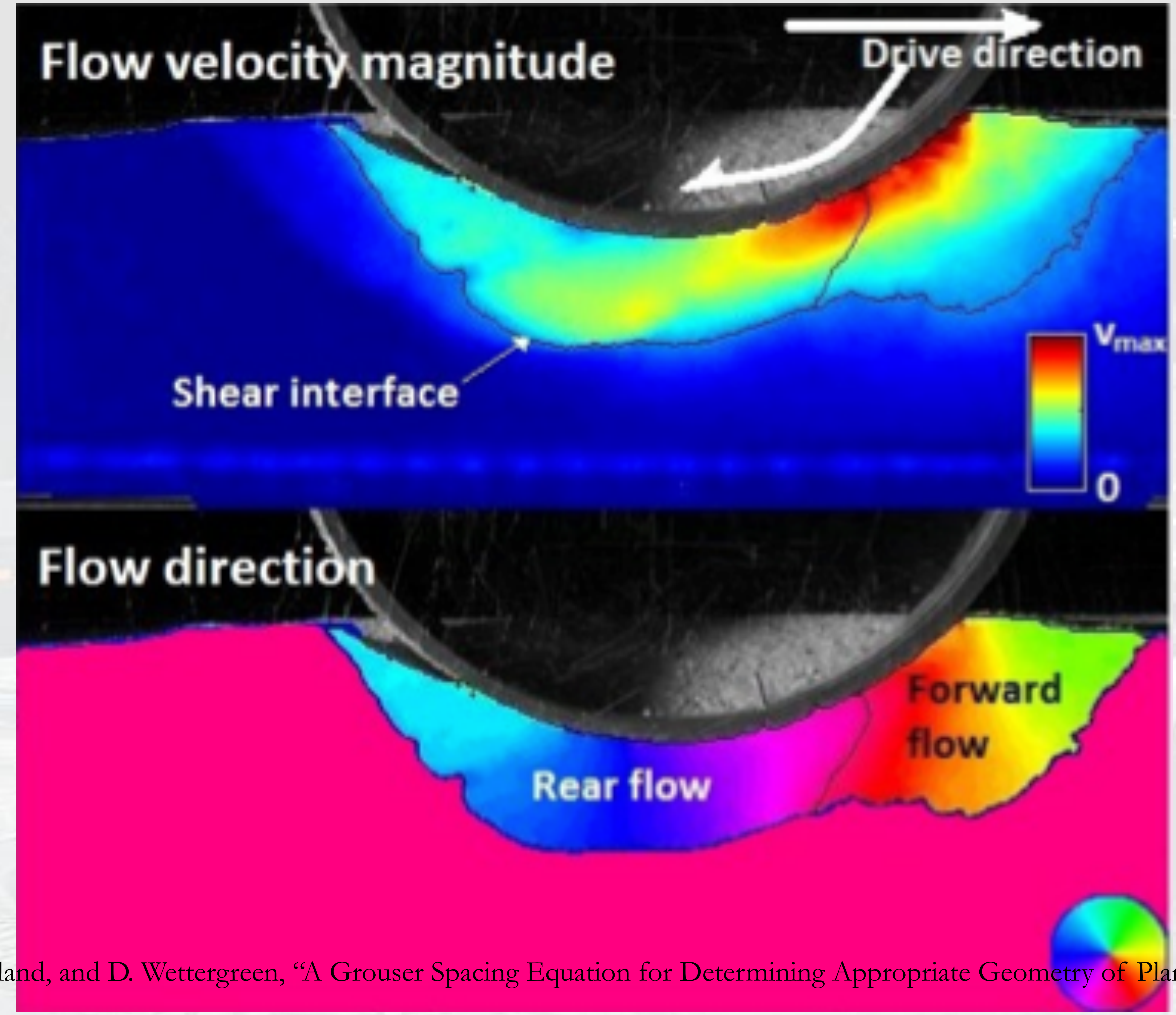
Soil Flow Visualization



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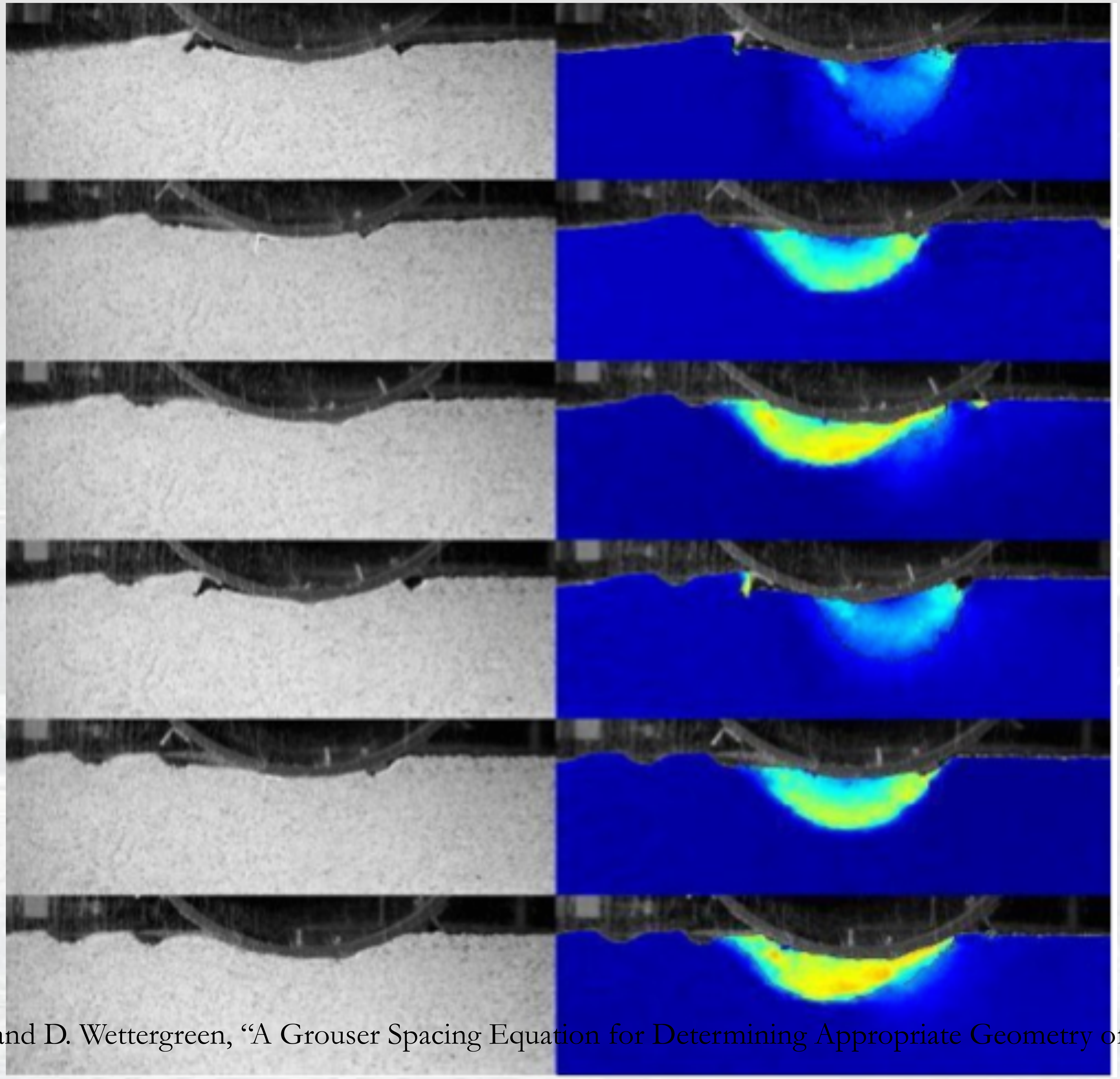
Periodic Soil Shearing by Grousers



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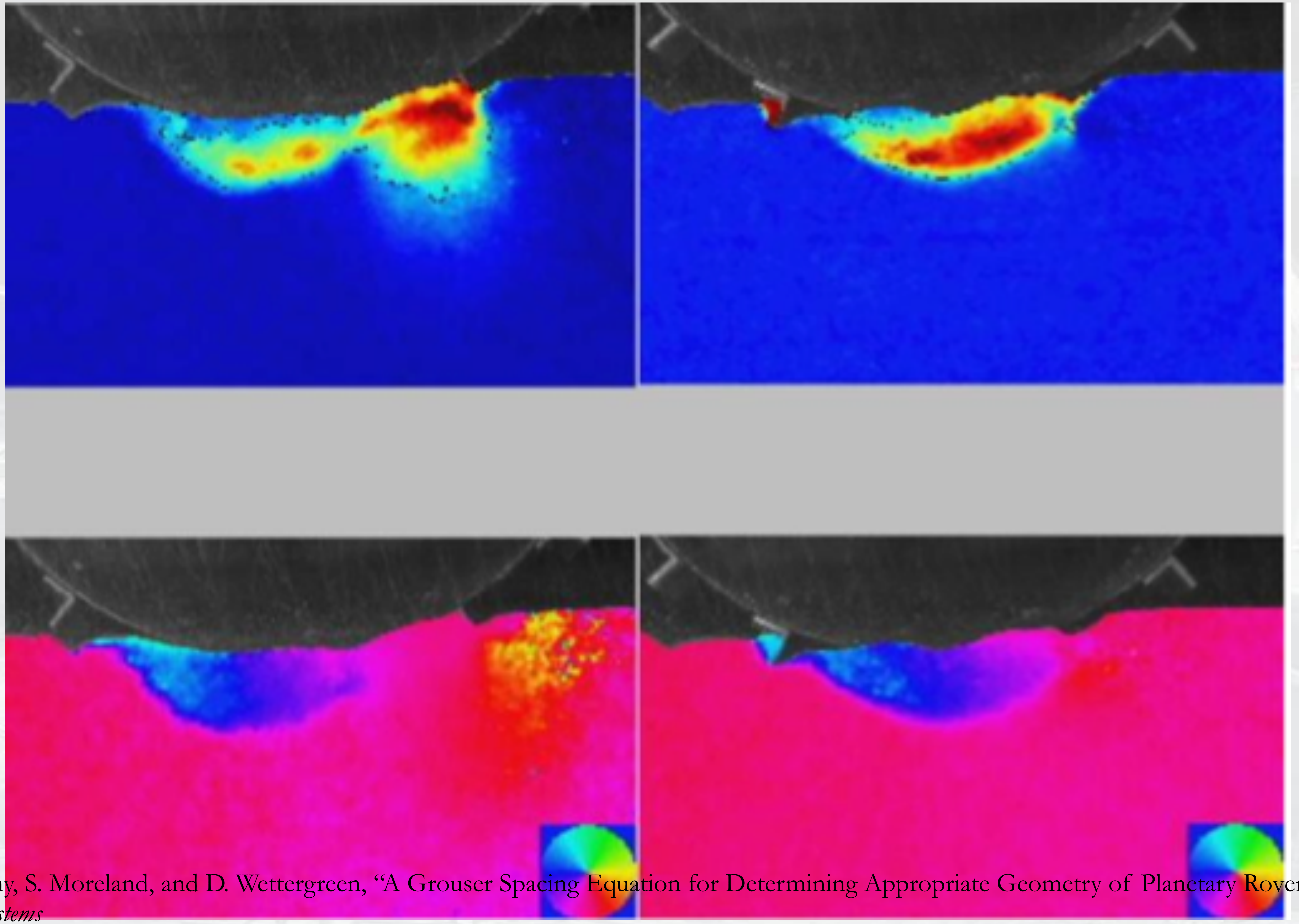
Soil Flow with 16 Grousers



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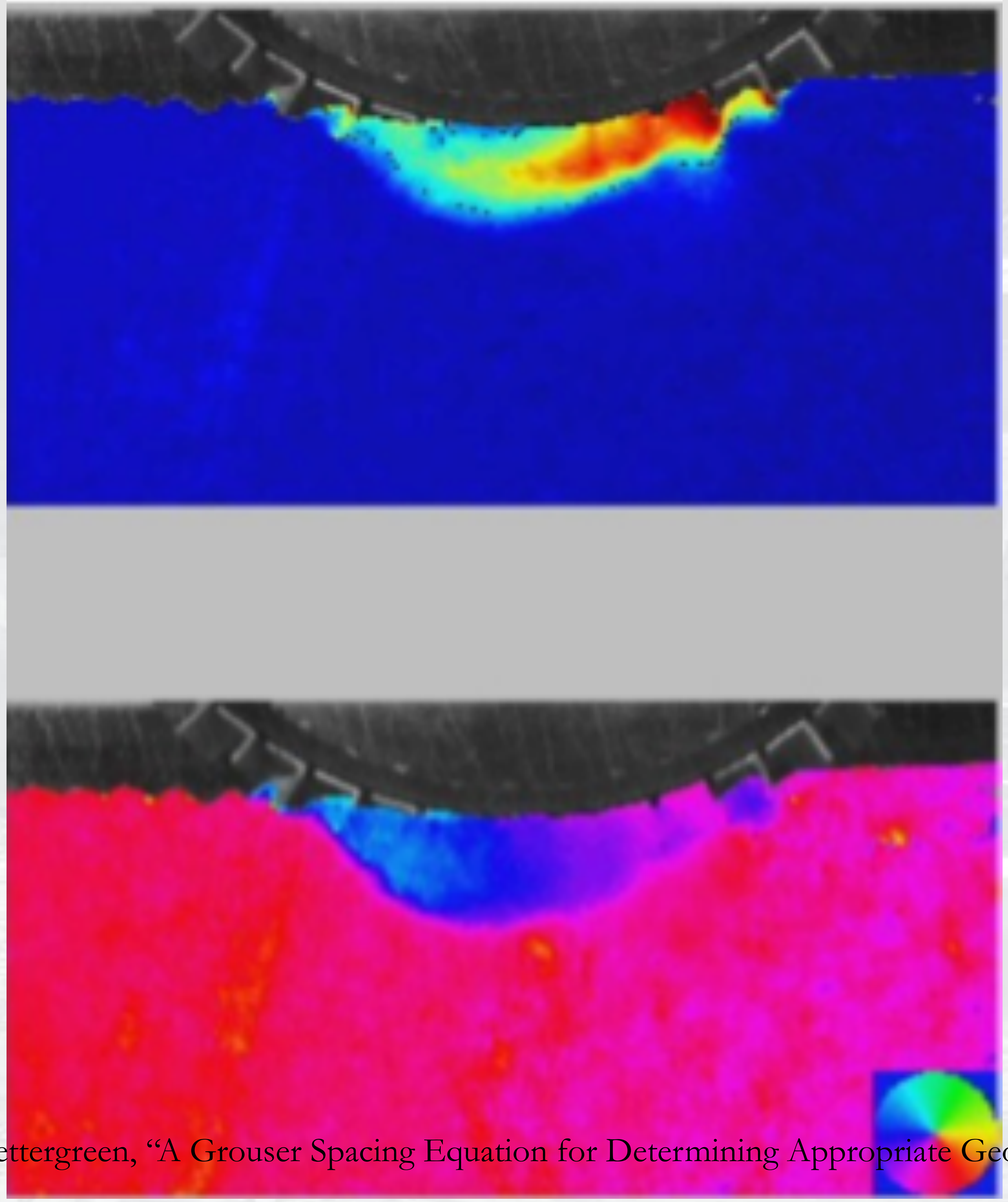
Soil Flow with 48 Grousers



K. Skonieczny, S. Moreland, and D. Wettergreen, "A Grouser Spacing Equation for Determining Appropriate Geometry of Planetary Rover Wheels" *2012 IEEE/RSJ International C*
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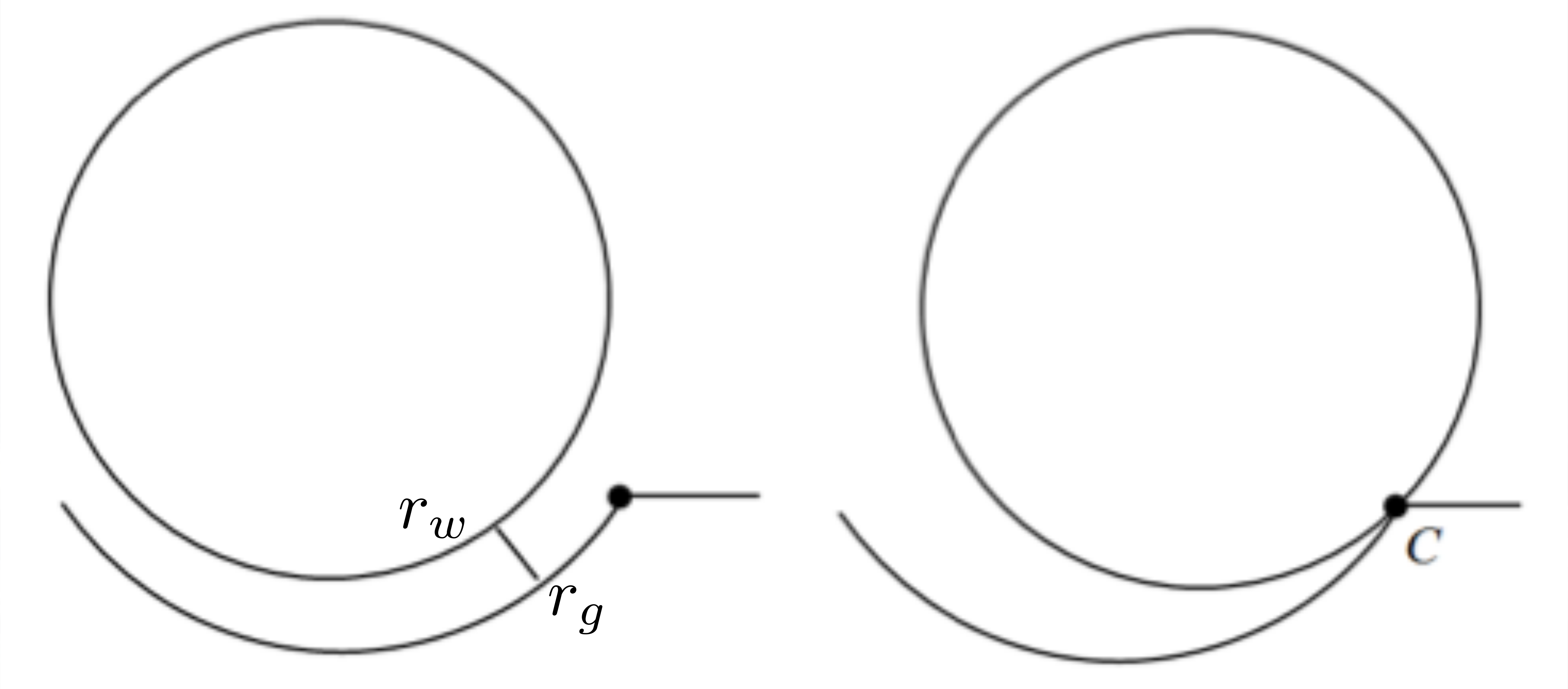
Soil Excavation by Grousers



$$r_g > r_w$$

K. Skonieczny, S. Moreland, and D. Wettergreen, "A Grouser Spacing Equation for Determining Appropriate Geometry of Planetary Rover Wheels" *2012 IEEE/RSJ International C*
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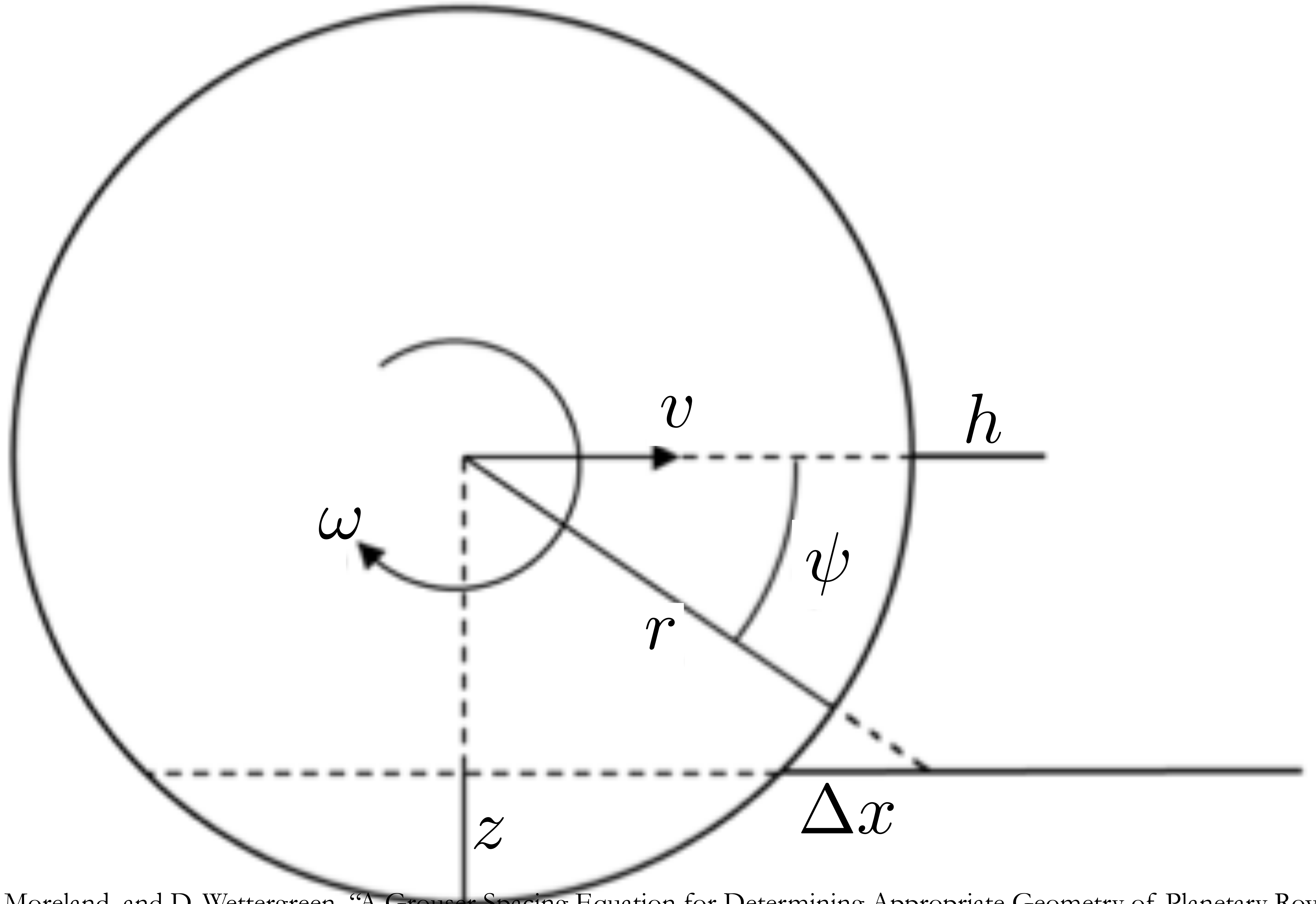
Wheel Parameters



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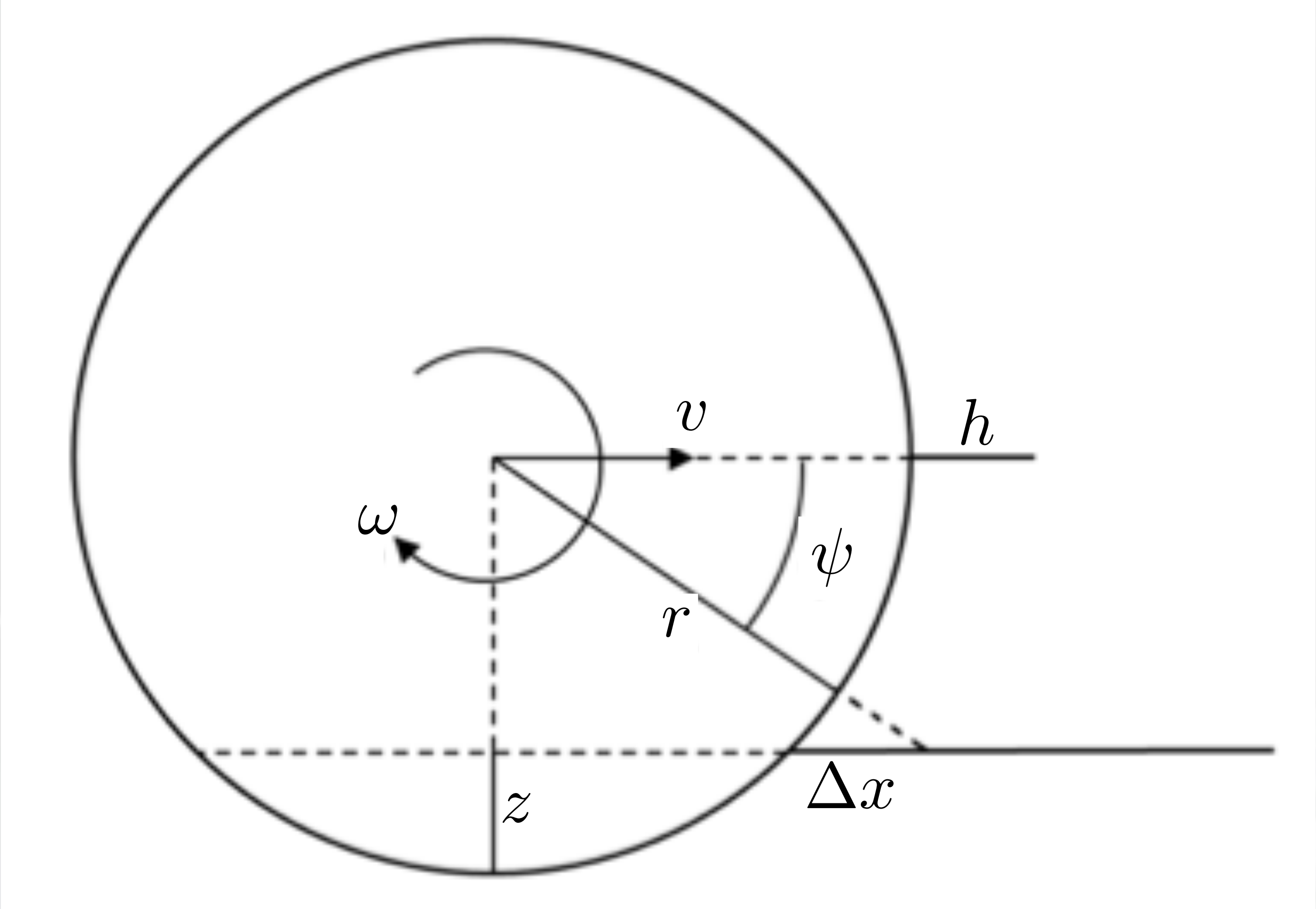
Minimum Grouser Condition



$$t_{rim\ contact} = \frac{\Delta x}{v}$$

$$t_{grouser\ contact} = \frac{\psi}{\omega}$$

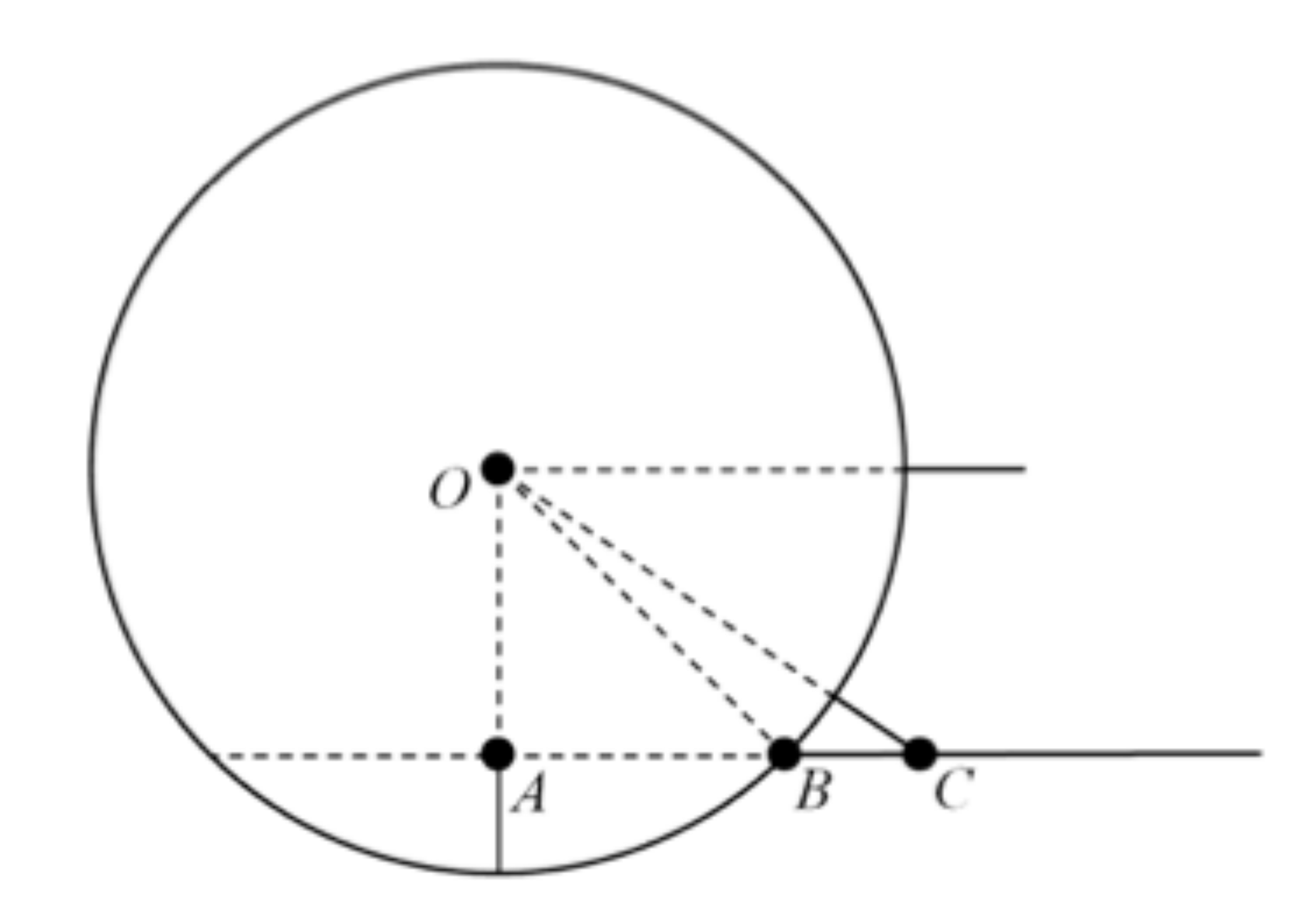
$$t_{grouser\ contact} \leq t_{rim\ contact}$$

$$\psi \leq \frac{\omega}{v}\Delta x$$

$$s = 1 - \frac{v}{\omega r} \implies v = \omega r(1-s)$$

$$\psi \leq \frac{1}{r(1-s)}\Delta x$$

Grouser-Soil Contact Geometry



Geometric Derivation of Grouser Spacing

$$\overline{AC} = \sqrt{(r+h)^2 - (r-z)^2} \qquad \overline{AB} = \sqrt{r^2 - (r-z)^2}$$

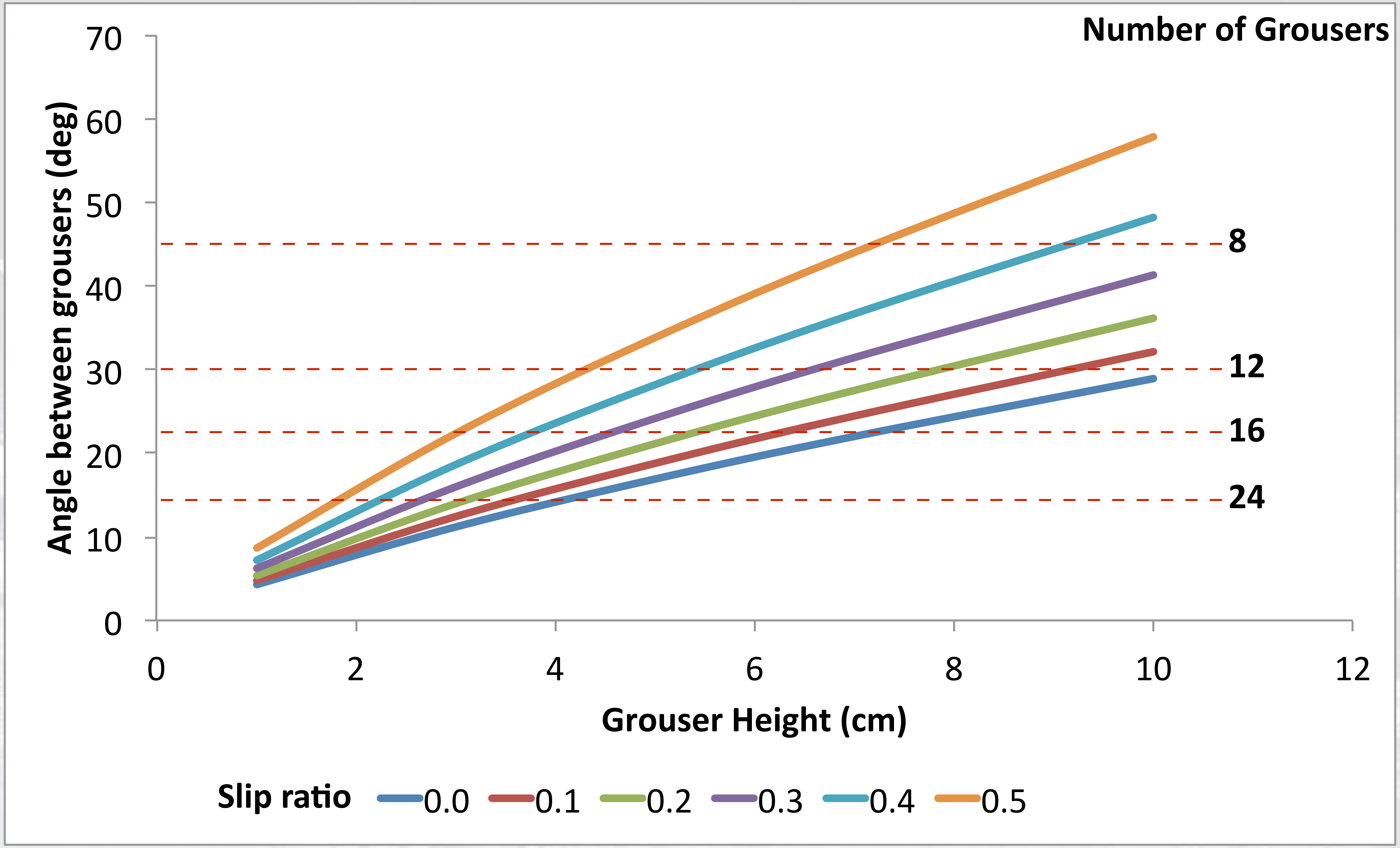
$$\overline{BC} = \overline{AC} - \overline{AB} = \Delta x$$

$$\psi \leq \frac{1}{r(1-s)} \left[\sqrt{(1+h)^2 - (1-z)^2} - \sqrt{1 - (1-z)^2} \right]$$

$$\psi \leq \frac{1}{(1-s)} \left[\sqrt{\left(1 + \frac{h}{r}\right)^2 - \left(1 - \frac{z}{r}\right)^2} - \sqrt{1 - \left(1 - \frac{z}{r}\right)^2} \right]$$

$$\psi \leq \frac{1}{(1-s)} \left[\sqrt{\hat{h}^2 + 2\hat{h} + 2\hat{z} - \hat{z}^2} - \sqrt{2\hat{z} - \hat{z}^2} \right]$$

Required Grouser Spacing



Number of Grousers in Ground Contact

$$z = 1.812\ cm \qquad r = 40.6\ cm$$

$$\text{Number of grousers} = N$$

$$\text{Angle between grousers} \equiv \psi = \frac{2\pi}{N}$$

$$\text{Distance between grousers} \equiv \ell_g = \psi r = \frac{2\pi r}{N}$$

$$\text{Number of grousers in ground contact} \equiv N_g = \frac{2\pi r}{N\ell}$$

$$\text{LRV example: choose } N = 16$$

$$N_g = 1.3 \approx 1$$

Tractive Force per Wheel (With Grousers)

$$H = \left[b\ell c \left(1 + \frac{2h}{b} \right) N_g + W \tan\phi \left(1 + 0.64 \frac{h}{b} \arctan \frac{b}{h} \right) \right] \left[1 - \frac{K}{s\ell} \left(1 - e^{-\frac{s\ell}{K}} \right) \right]$$

$A =$ area of contact $\cong b\ell$

$c =$ soil cohesion $= 0.017\ \mathrm{N/cm^2}$

$\phi =$ soil angle of internal friction $= 35^o$

$s =$ wheel slip ratio (typ. 0.02-0.05)

$K =$ shear deformation modulus $= 1.8\ cm$

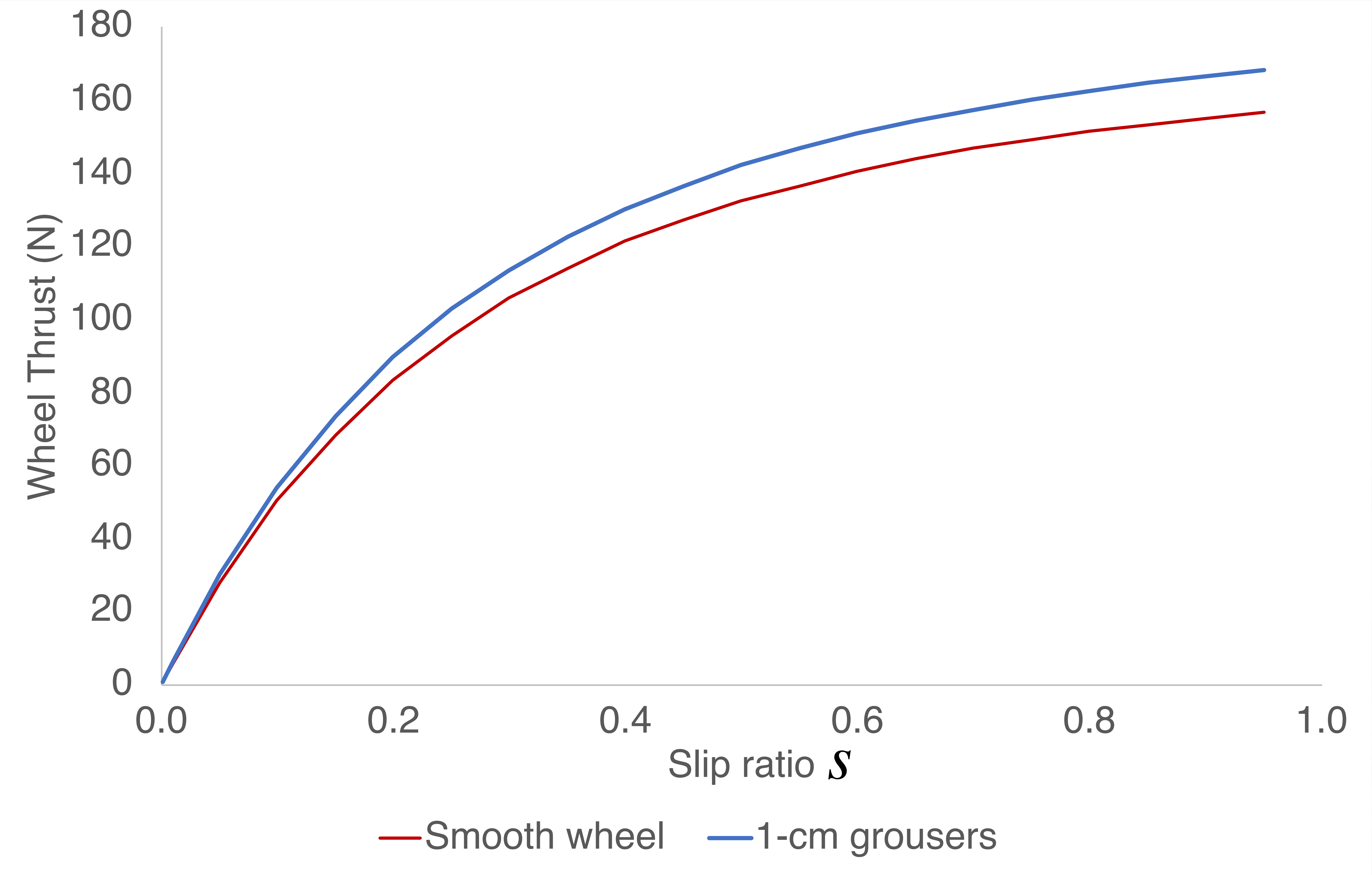
$\ell =$ length of contact patch $= \frac{D}{2} \cos^{-1} \left(1 - \frac{2z}{D} \right)$

$h =$ height of grouser

$N_g =$ number of grousers in contact with ground

All values typical for lunar soil

Effect of Slip Ratio on Wheel Thrust



Basic Equation of Vehicle Propulsion

DP: Drawbar pull (residual drive force)

H: Maximum tractive force of wheels

R_c: Compaction resistance

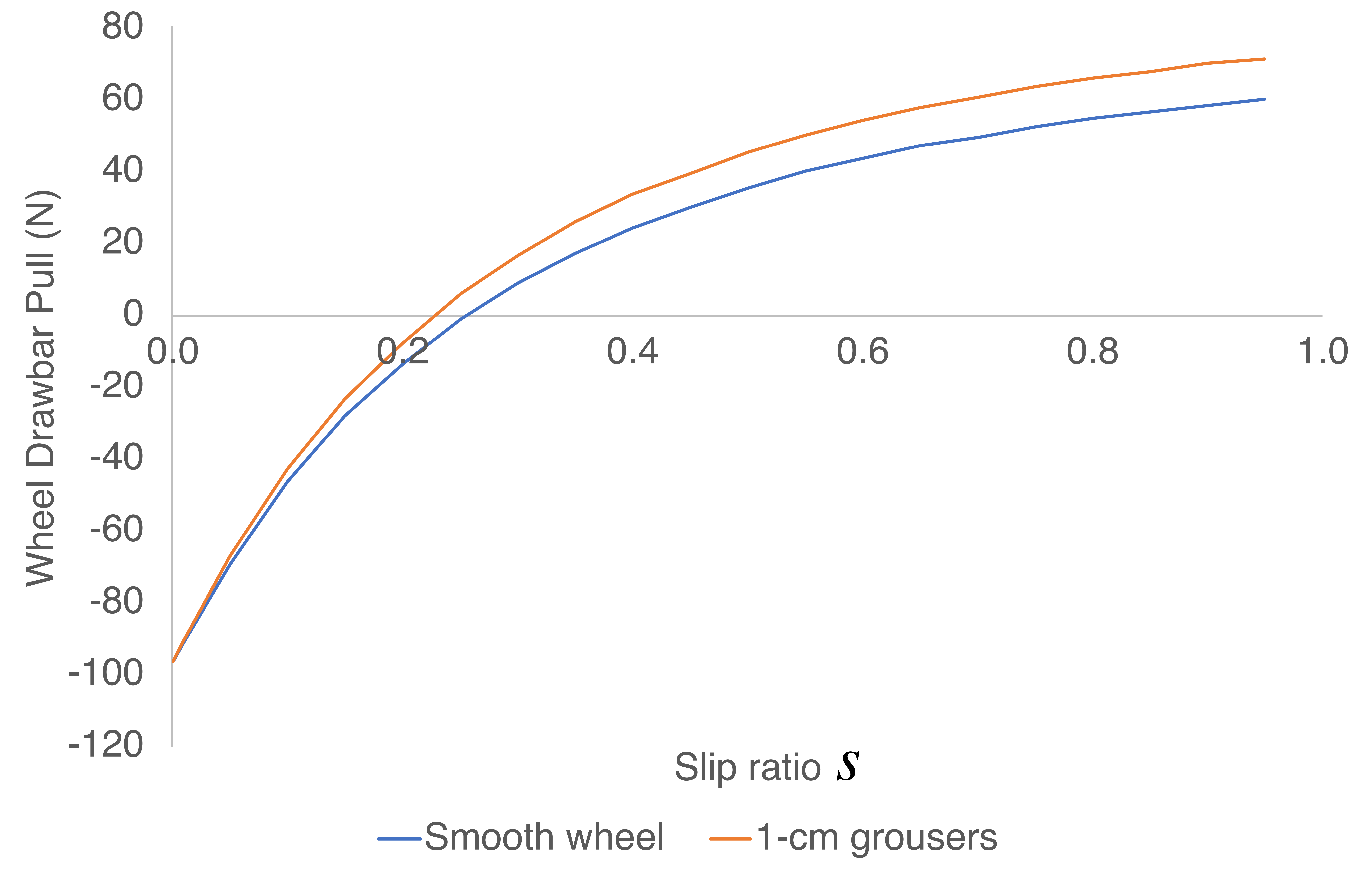
R_b: Bulldozing resistance

R_g: Gravitational resistance

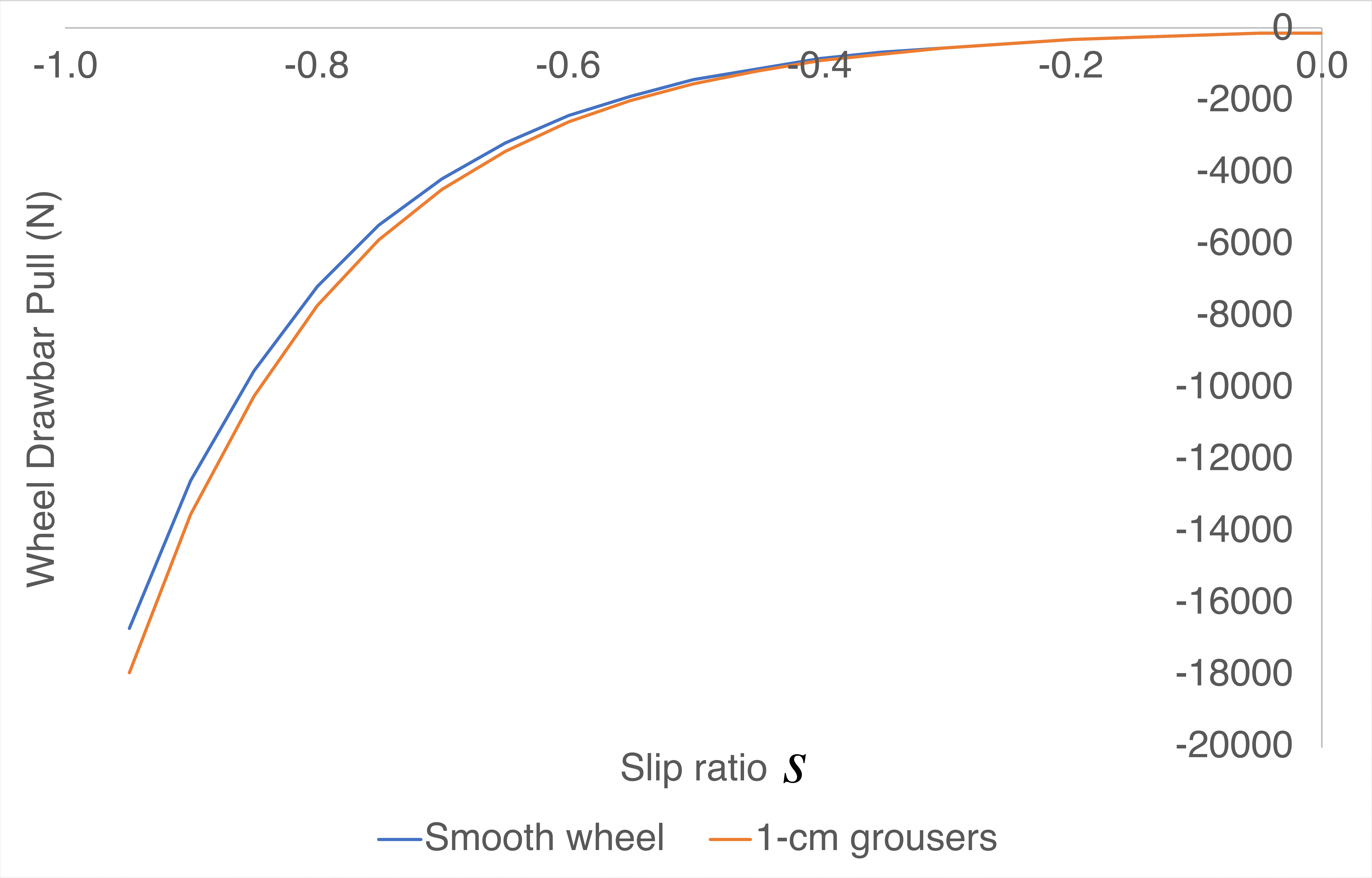
R_r: Rolling resistance (internal)

$$DP = H - (R_c + R_b + R_g + R_r)$$

Drawbar Pull vs. Slip (per wheel)



Deceleration (negative slip) ??



Some Notes on Terramechanics

- This is the simplest approach to calculating wheel-soil interactions
- Real-world issues not modeled include
  - Non-homogeneities
  - Soil layering
  - Soil transport under wheel
- This technique is conservative in estimating drawbar pull
- Braking is more complicated than sticking $s < 0$ into the equation for H – more to come