Surface Interaction Modeling

Engineering Methods

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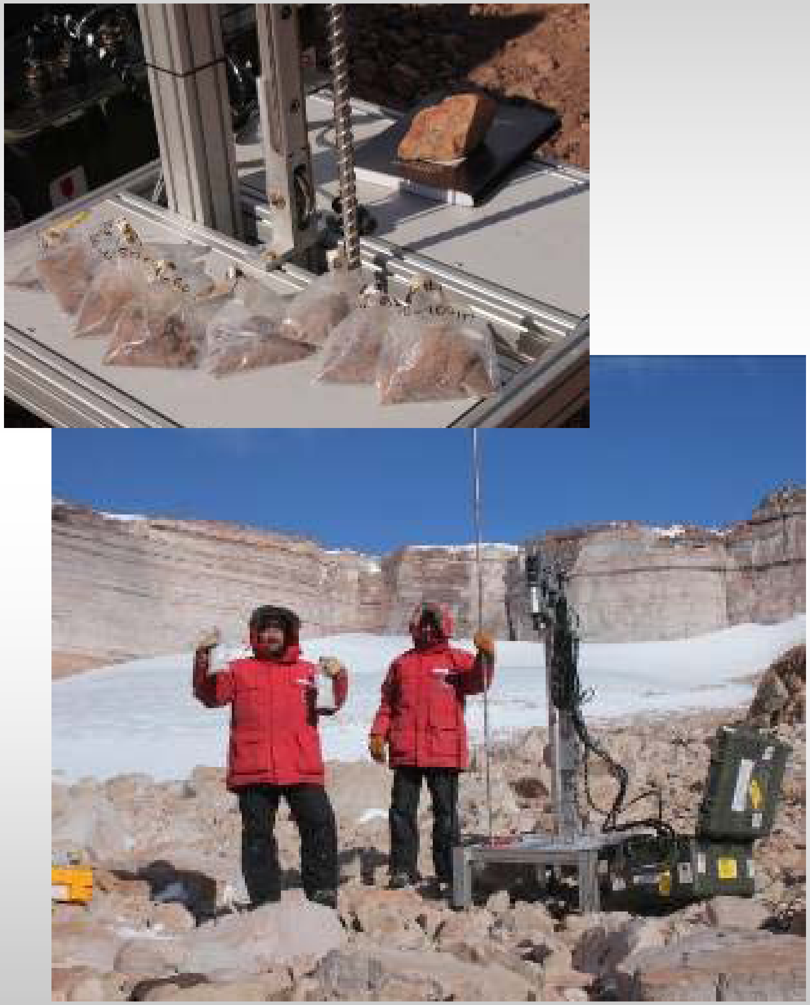
An Engineer’s Job

- Design vehicle for robust mobility on Mars surface
  - Wheels, tracks, legs?
    - Number, diameter and width?
    - Required nominal torque?
    - Required peak power?
  - Obstacle crossing performance?
    - Suspension configuration?
  - Steering mechanism?
- **How to address in a principled, systematic fashion?**

NASA’s Mars Science Laboratory (MSL) Design/Test Model (DTM) in the sandy Mars Yard at JPL

An Engineer's Job

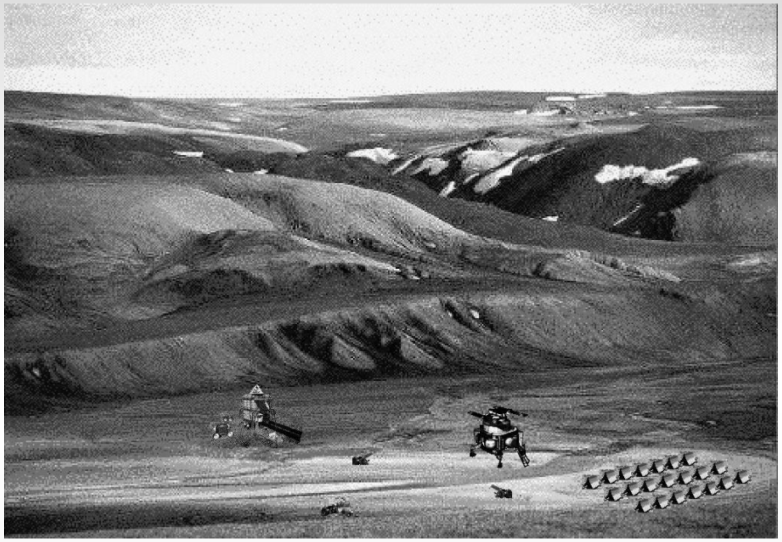
- Design drill system for subsurface access on Mars surface
  - Drilling mechanism?
    - Rotary, sonic, percussive?
  - Required power? Force?
  - Allowable drilling speed?
  - Resulting off-axis forces?
  - Effect of geomaterial properties on performance?
    - Effect of temperature, layering?



Honeybee Robotics IceBreaker rotary-percussive drill prototype being tested in Antarctica

An Engineer’s Job

- Design automated LHD vehicle for site preparation during human habitation precursor mission
  - Vehicle configuration?
    - Wheels, tracks, legs?
    - Regolith transportation mechanism?
    - Surface preparation mechanism?
  - Required force, power?

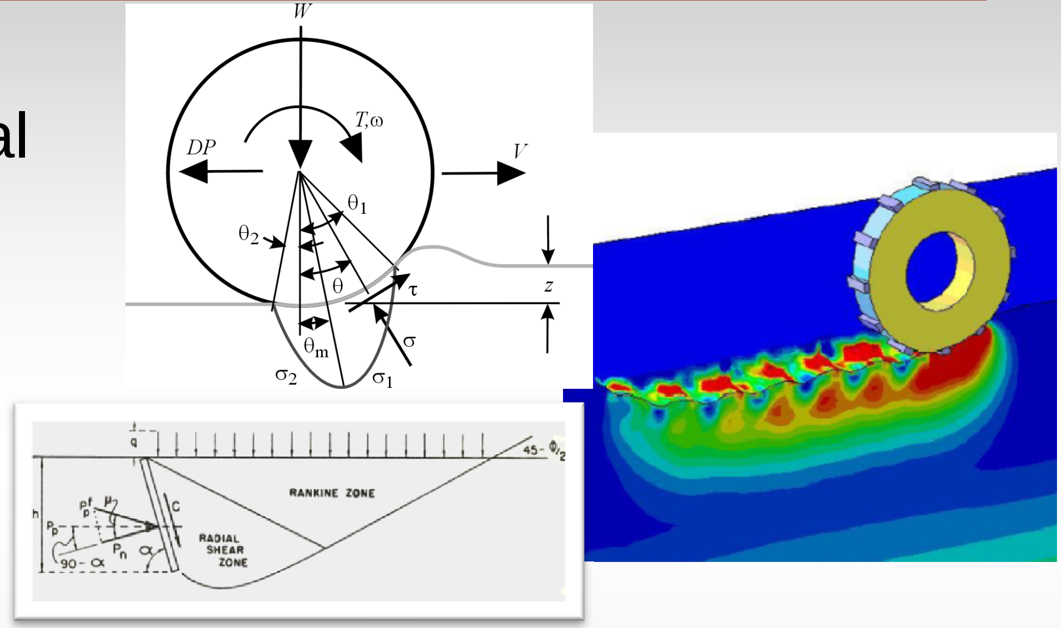


Notional Mars habitat and surface preparation being performed by autonomous dozers
(From Huntsberger, Rodriguez, and Schenker, *Robotica,* 2000)

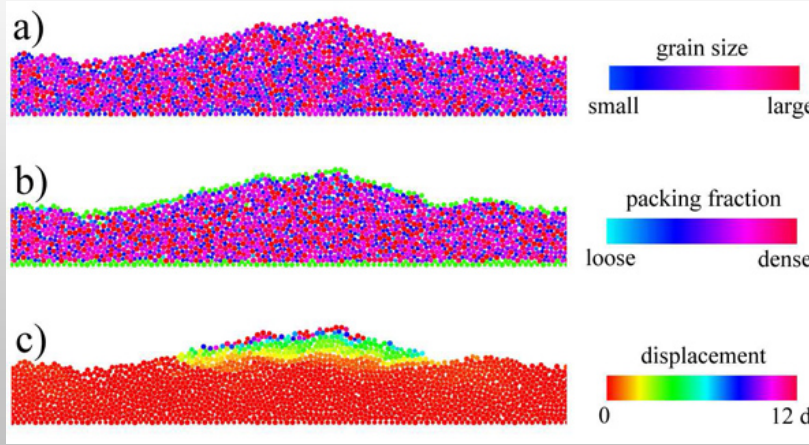
Surface Interaction Modeling

- Task: Modeling interaction of mechanical systems with planetary surfaces/subsurfaces

- Methods for surface interaction modeling
  - Empirical methods
  - Computational methods
    - FEA
    - DEM
  - Parametric methods
    - Terramechanics



FEA model of ExoMars rover wheel (Deltares Inc)



DEM model of vehicle passage over sandy road (Taberlet et al)

Surface Interaction Modeling

- Methods for surface interaction modeling
  - Empirical methods
    - Strengths
      - Model phenomena with arbitrary complexity
    - Weaknesses
      - Can require extensive experimental testing
      - Scales poorly with complexity
      - Extrapolation is questionable
    - Example: Cone index

Figure E-3. Using a cone penetrometer in the upright position

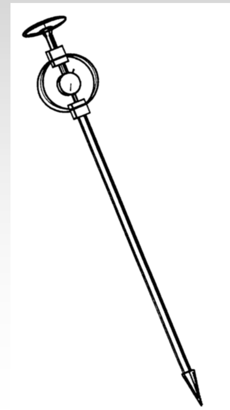
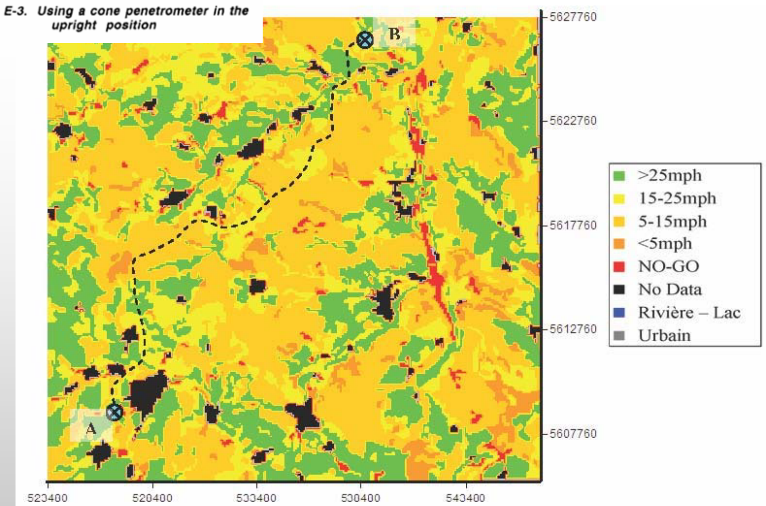


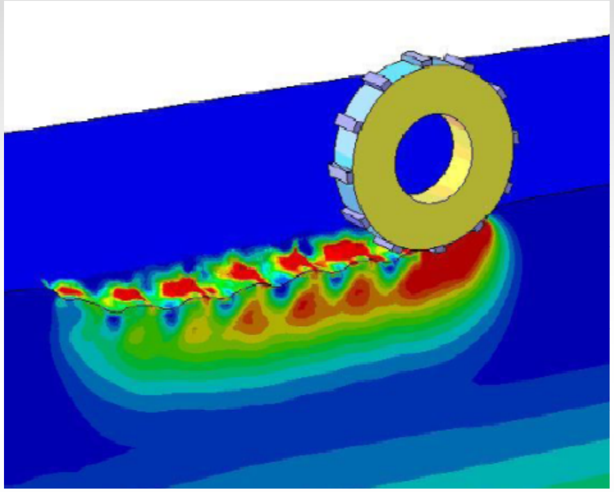
Figure E-2. Cone penetrometer



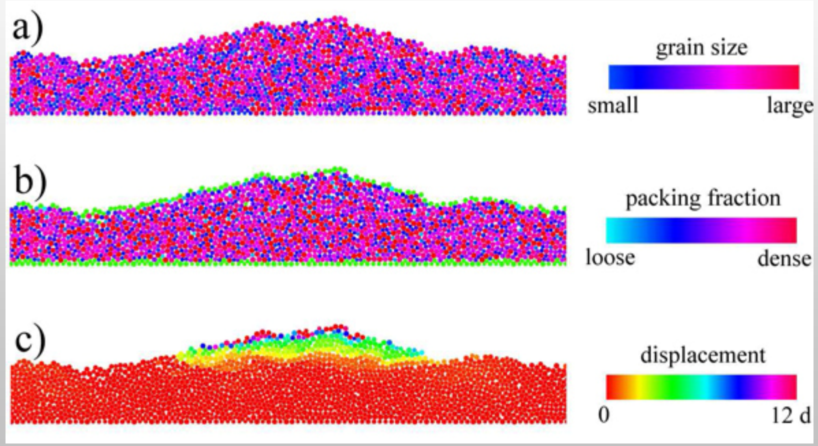
Map of HMMWV max speed based on cone index analysis

Surface Interaction Modeling

- Methods for surface interaction modeling
  - Computational methods
    - Strengths
      - Model inhomogeneous, anisotropic, discontinuous media
      - Model granular material
    - Weaknesses
      - Constitutive laws, parameter values not clearly defined
      - Computation time scales poorly with model size
    - Examples: FEA, DEM



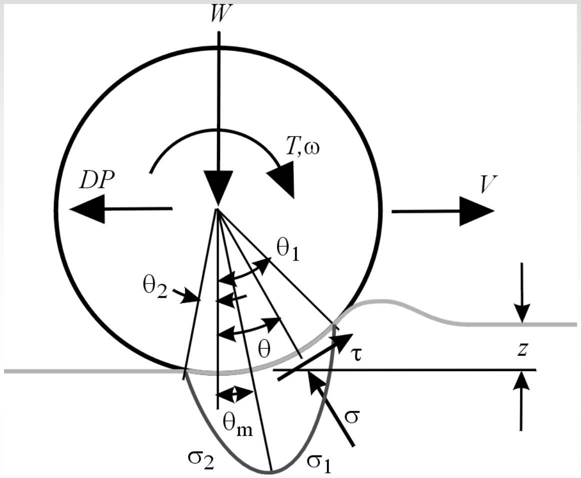
FEA model of ExoMars rover wheel (Deltares Inc)

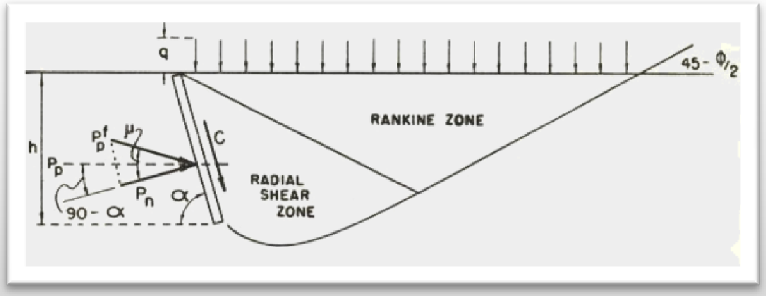


DEM model of vehicle passage over sandy road (Taberlet et al)

Surface Interaction Modeling

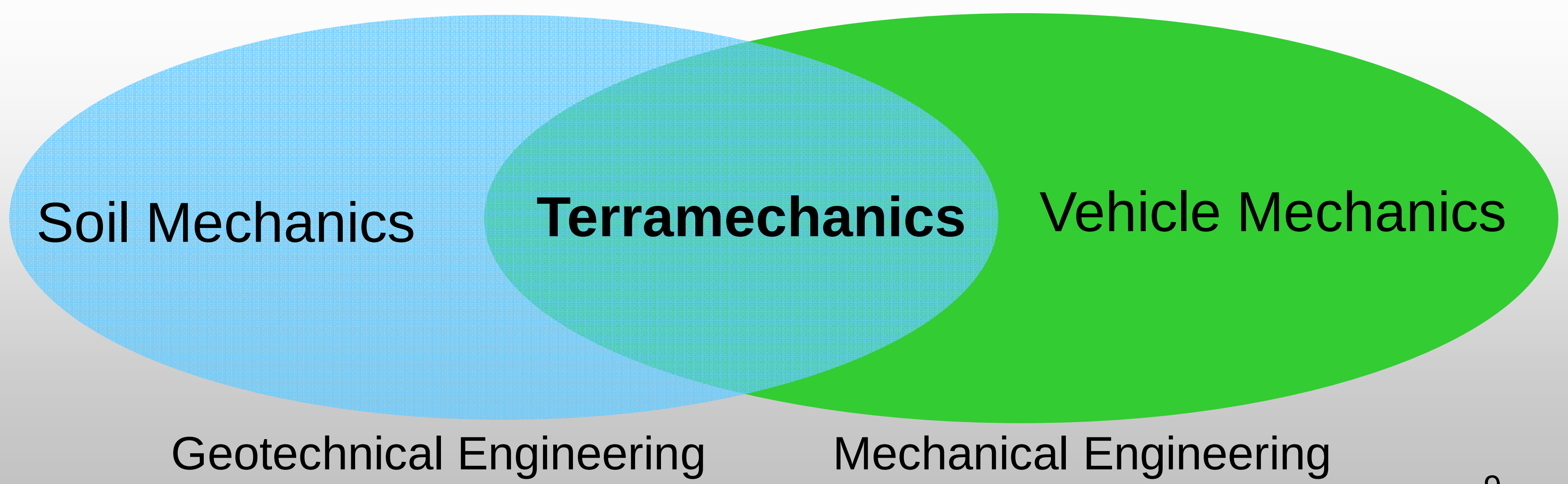
- Methods for surface interaction modeling
  - Parametric methods
    - Strengths
      - Physics-based models employ measurable physical parameters
      - Computationally efficient
      - Applicability to many soil types
    - Weaknesses
      - Ignore some important effects (rate, soil state, material transport)
      - Scaling of classical models is questionable
    - Examples: Terramechanics





Terramechanics

- Terramechanics
  - Engineering science that studies the interaction between vehicles and (deformable) terrain
- Soil mechanics and vehicle mechanics
- Analysis of wheeled, tracked, legged systems



Terramechanics Principles

- Terramechanics applies soil mechanics principles to solve engineering problems
  - Application of bearing capacity theory for structures, foundations
  - Example: Soil stress distribution beneath track modeled as strip-load

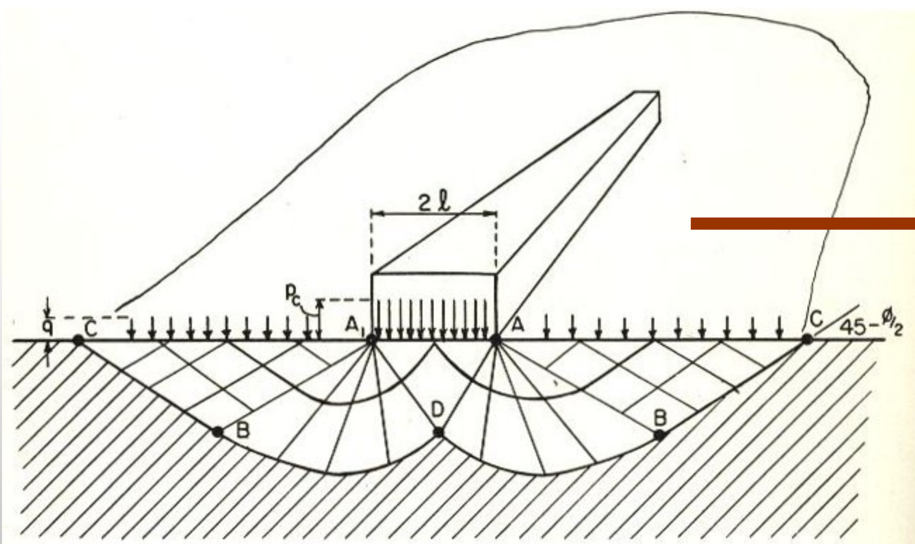
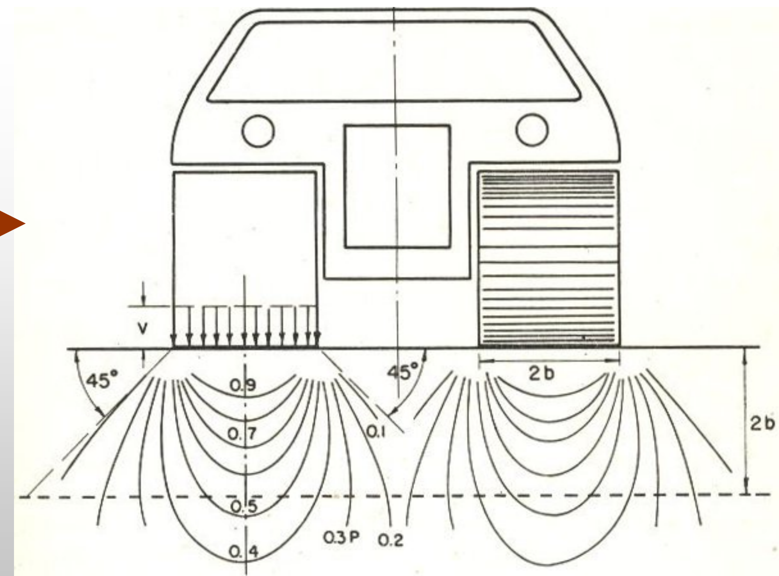
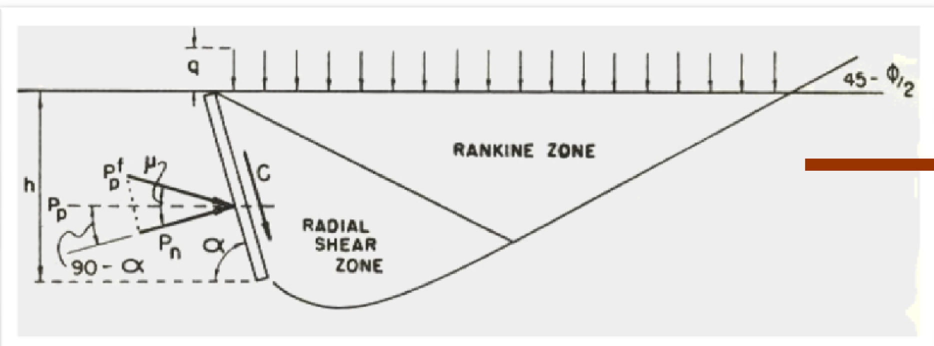


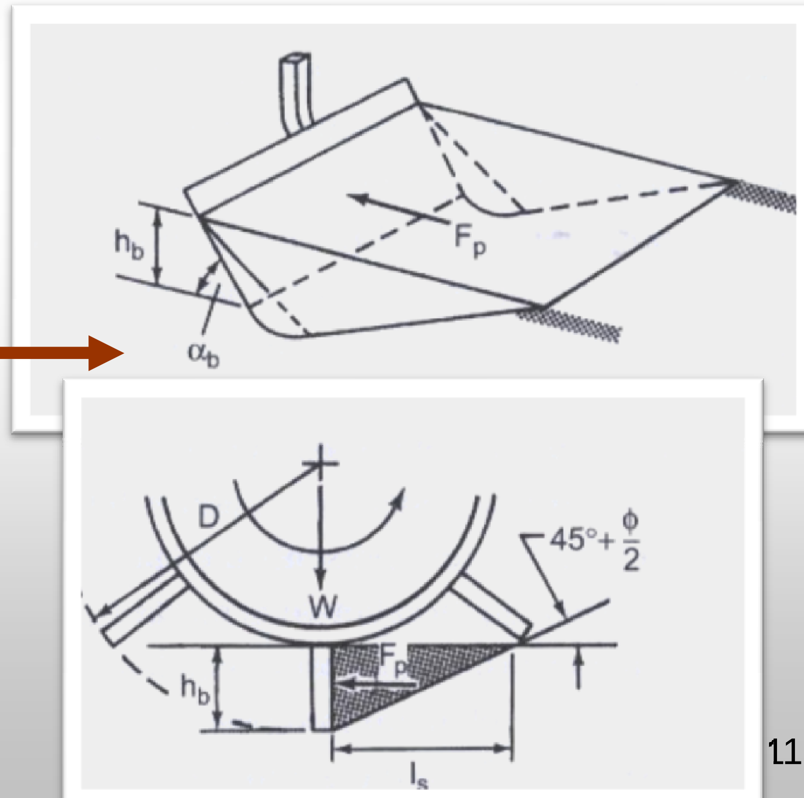
Fig. 72



Terramechanics Principles

- Terramechanics applies soil mechanics principles to solve engineering problems
  - Example: Shearing action of wheel lugs modeled as cutting blade





Terramechanics Principles

- Fundamental relations
  - Pressure-sinkage
  - Shear stress-shear displacement
    - Wheel slip
- Other effects
  - Grousers/lugs
  - Lateral forces
  - Repetitive loading
- Case study

M.G. Bekker

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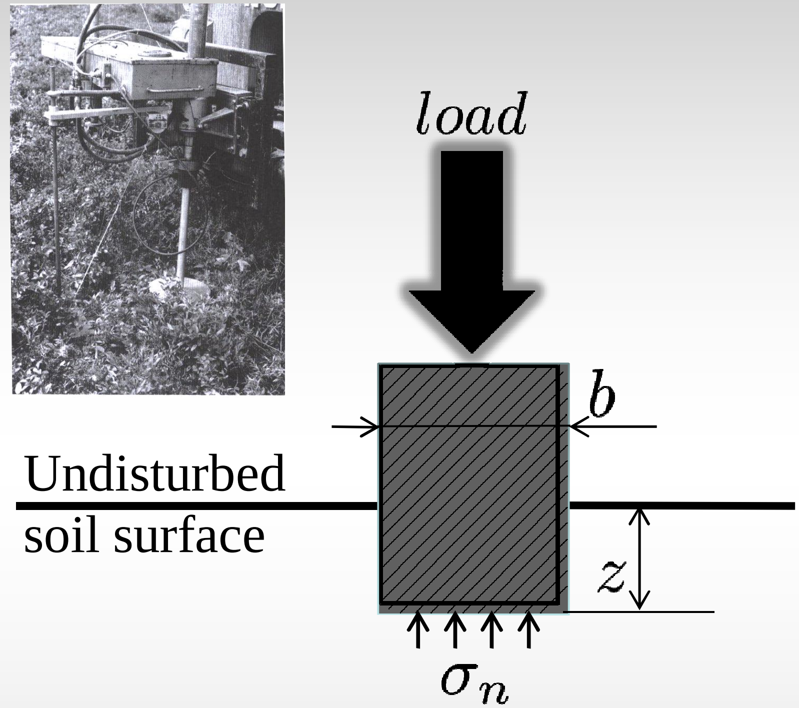
M.G. Bekker

Pressure-Sinkage

- Pressure-sinkage relationship for geomaterials

$$\sigma = kz^n$$

  - σ is normal pressure
  - *k* is empirical constant
  - *z* is sinkage from free surface
- Bekker proposed semi-empirical formulation



Cohesion-dependent soil coefficient

Friction-dependent soil coefficient

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

Sinkage exponent

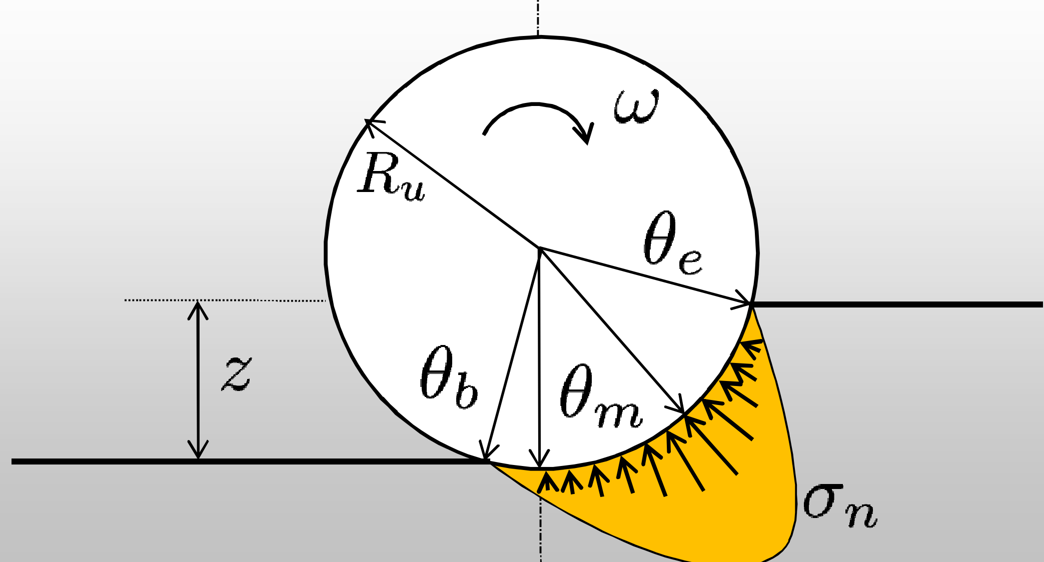
M. G. Bekker. *Theory of Land Locomotion*. Ann Arbor, University of Michigan Press, 1950.

Pressure-Sinkage for Wheels

- Can compute normal stress for wheels along terrain interface

$$\sigma_{nf} = \left(\frac{k_c}{b} + k_\phi\right)\left[R\left(\cos(\theta) - \cos(\theta_e)\right)\right]^n \qquad \theta_m < \theta \leq \theta_e$$

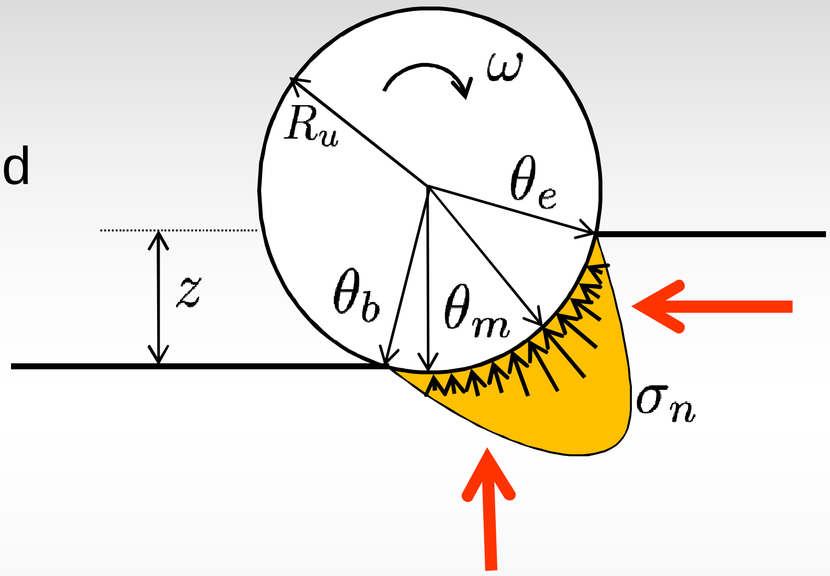
$$\sigma_{nr} = \left(\frac{k_c}{b} + k_\phi\right)\left[R\left(\cos\left(\theta_e - \left(\frac{\theta - \theta_r}{\theta_N - \theta_r}\right)(\theta_e - \theta_N)\right) - \cos(\theta_e)\right)\right]^n \qquad \theta_b \leq \theta \leq \theta_m$$

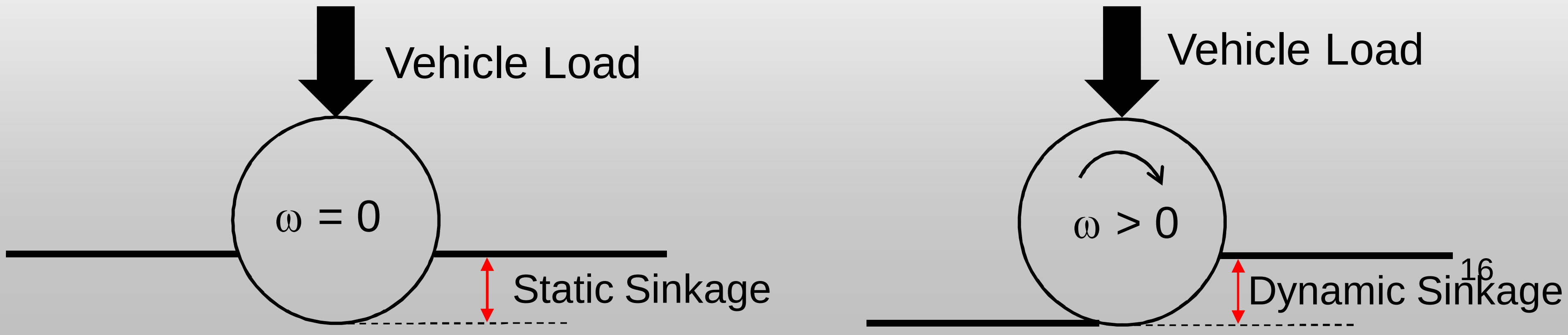


J. Y. Wong and A. R. Reece. Prediction of rigid wheel performance based on analysis of soil-wheel stresses. J. Terramechanics,1967

Pressure-Sinkage for Wheels

- Sinkage plays critical role in mobility
  - Increased sinkage causes increased motion resistance
  - Energy lost in terrain compaction
- Sinkage can be divided in two components
  - Static sinkage
  - Dynamic sinkage (or slip-sinkage)





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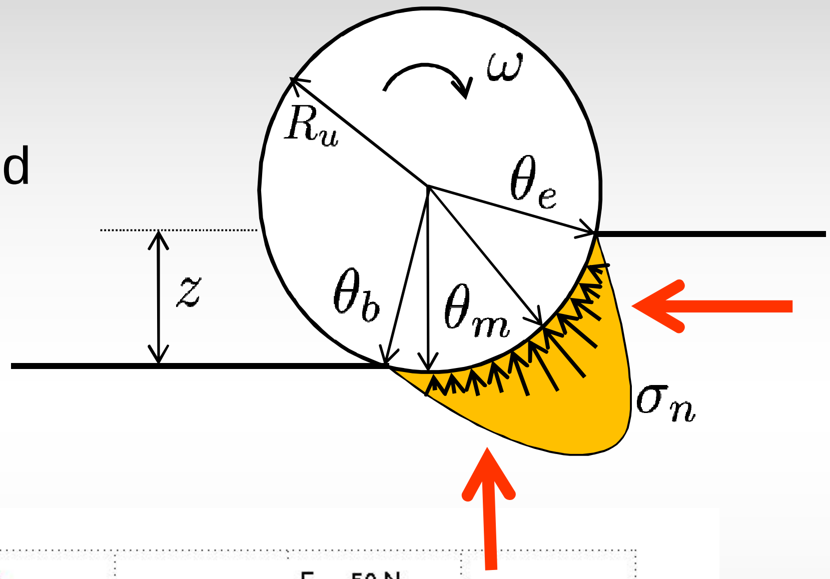

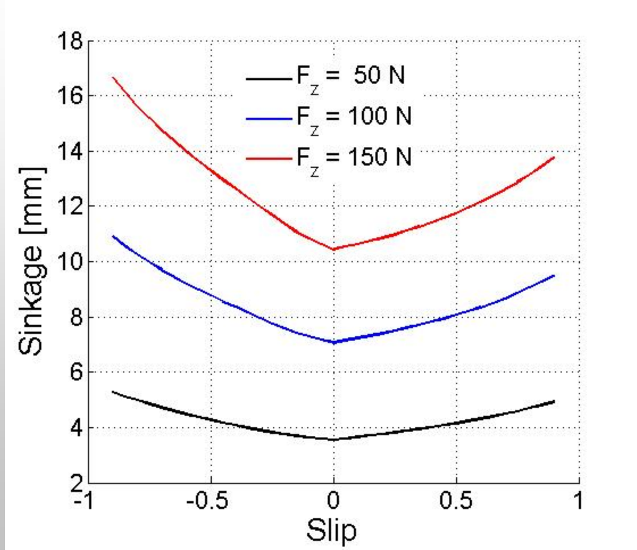

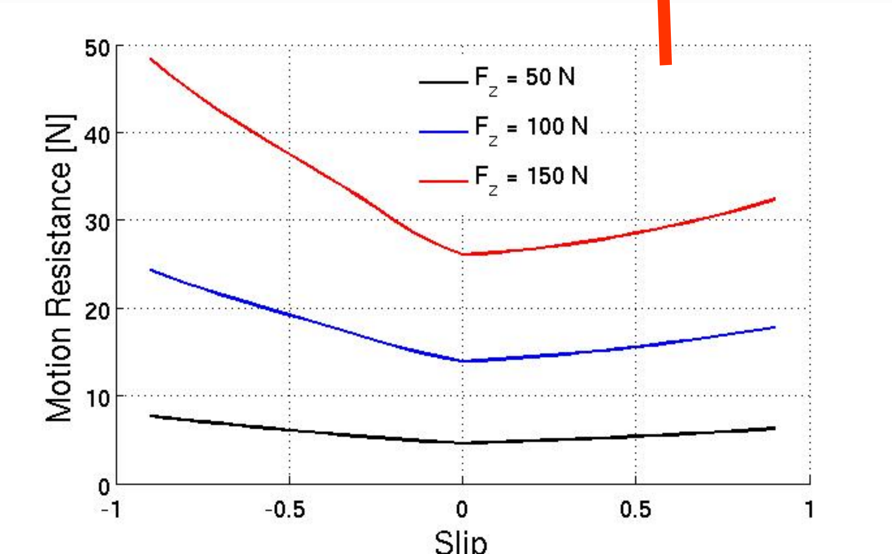

Terramechanics Principles

- Fundamental relations
  - Pressure-sinkage
  - Shear stress-shear displacement
    - Wheel slip
- Other effects
  - Grousers/lugs
  - Repetitive loading
  - Lateral forces
- Case study

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Shearing Properties of Soil

- Relative motion between wheel or track and soil interface causes shearing
  - Resistance forces generated by soil mass
  - Depends on slip, loading conditions

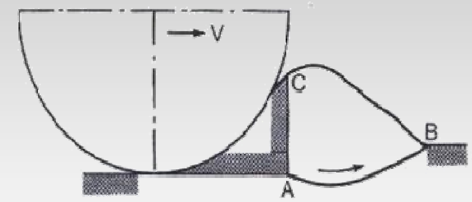


Figure 2.20: Flow patterns and soil wedge formed in front of a locked rigid wheel at 100% skid in sand

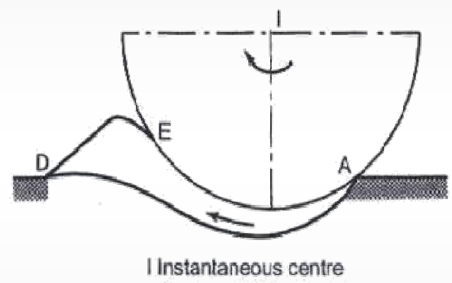


Figure 2.19: Flow patterns beneath a driven rigid wheel at 100% slip in sand

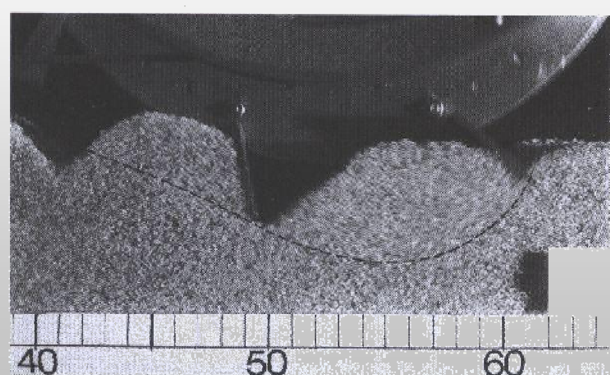
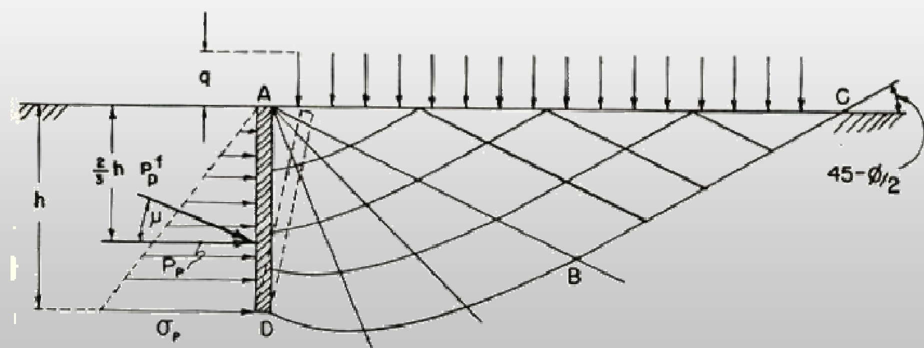


Figure 1.12: Soil flow under the action of grousers of a wheel in sand (Reprinted by permission of *ISTVS* from Wu et al., 1984)

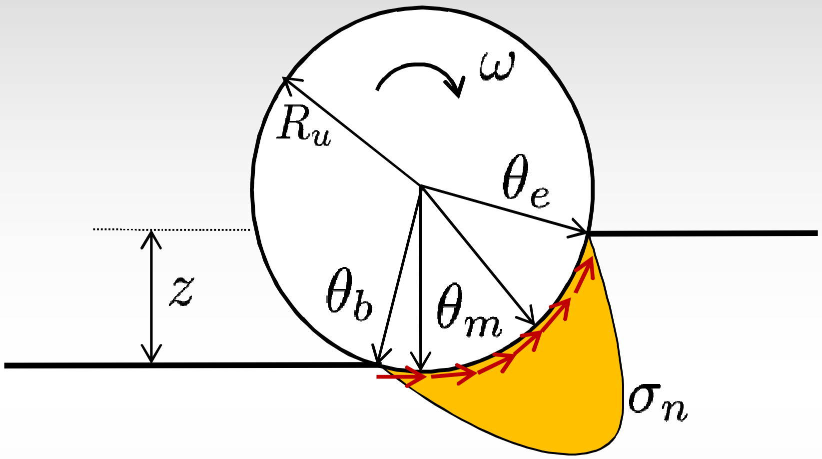


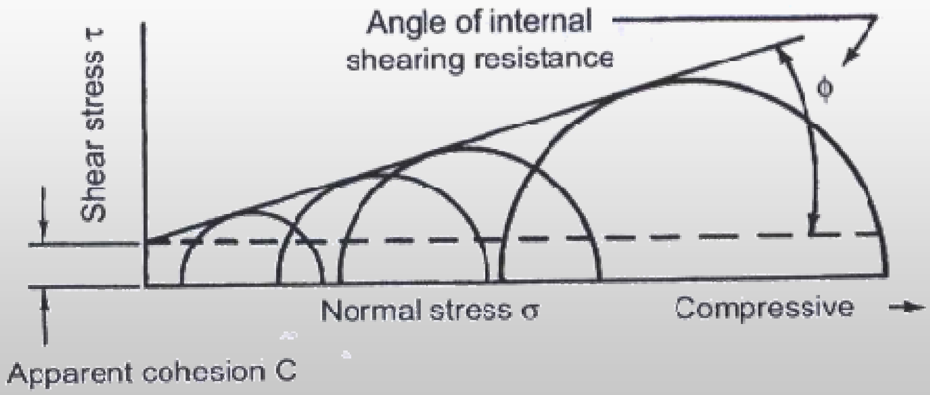
Shearing Properties of Soil

- Shear stress at wheel-soil interface produces traction
- Shear stress is a function of shear displacement
  - Relative motion required to generate traction
    - Non-zero slip ratio
- Soil failure estimated through Mohr-Coulomb failure criterion

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

  - τ is failure stress
  - c is soil cohesion
  - ϕ is soil internal friction angle





Shearing Properties of Soil

- Can compute shear stress at wheel-terrain interface
  - Janosi-Hanamoto formulation

Soil shear displacement

Limit tangential stress

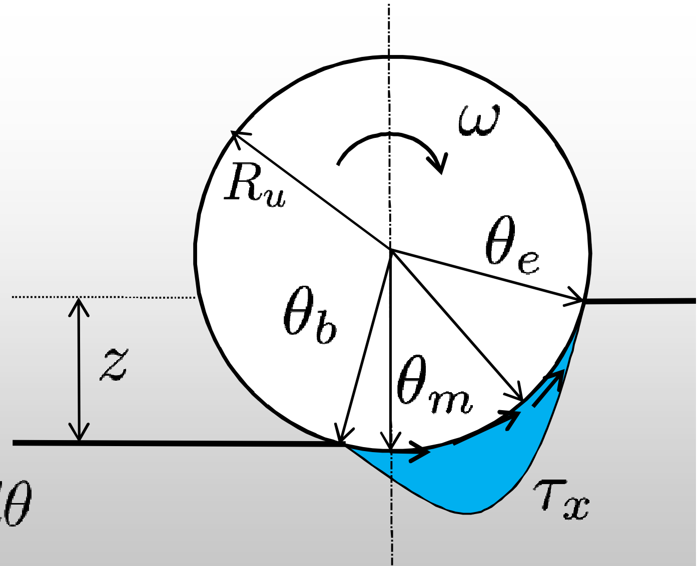
$$\tau_x(\theta) = \tau_{max}\left(1 - e^{\frac{-j_x}{k_x}}\right)$$

Soil shear deformation modulus

$$\tau_{max} = c + \sigma_n(\theta)\tan\phi$$

- Soil shear displacement

$$j_x(\theta) = \int_{\theta_b}^{\theta_e} R_u[1 - (1 - s_d)\cos(\theta)]\,d\theta$$



Z. Janosi and B. Hanamoto. Analytical determination of drawbar pull as a function of slip for tracked vehicles in deformable soils, Proc. ISTVS

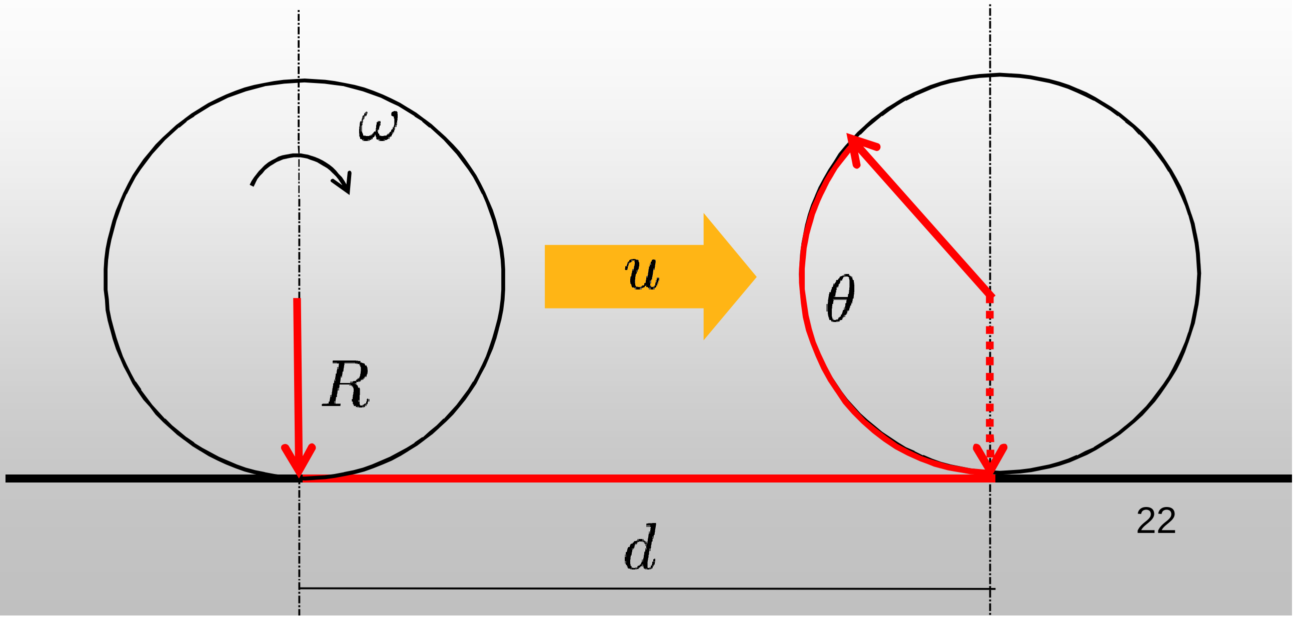
Slip Ratio

- Slip ratio is measure of relative motion between wheel and terrain surface
  - For driven wheel, distance traveled is less than that in free rolling
  - When slip ratio = 1, spinning in place
  - When slip ratio = 0, pure rolling
  - When slip ratio = -1, skidding

$$u \leq \omega R$$

$$d \leq \theta R$$

$$s_d = 1 - \frac{u}{\omega R}$$



Terrain Interaction Forces

- Forces between wheel and terrain can be computed from stress distribution along contact path
- Vertical load

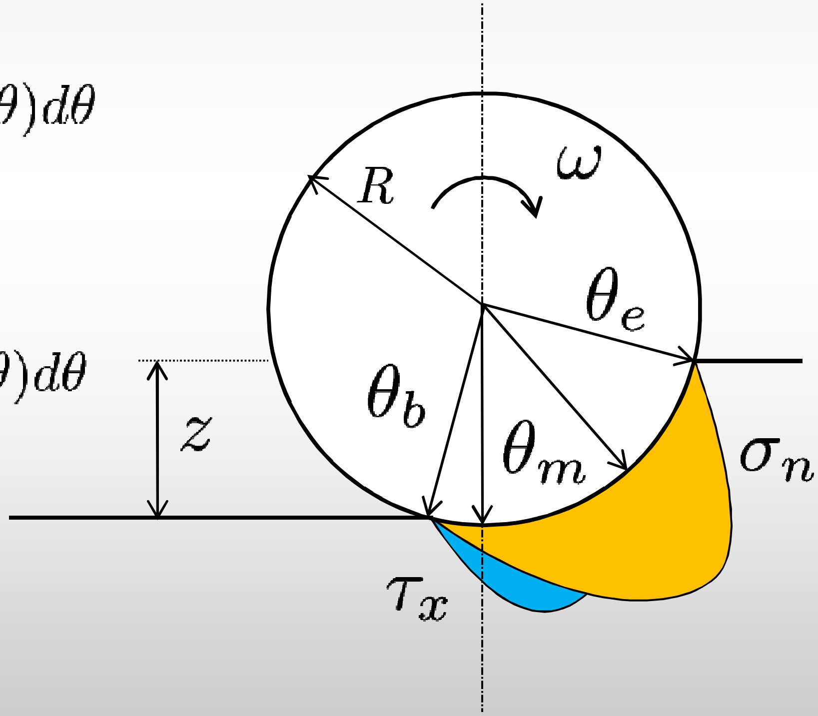
$$W = bR \int_{\theta_b}^{\theta_e} \tau_x(\theta) \sin(\theta) + \sigma_n(\theta) \cos(\theta) d\theta$$

- Longitudinal force

$$F_x = bR \int_{\theta_b}^{\theta_e} \tau_x(\theta) \cos(\theta) - \sigma_n(\theta) \sin(\theta) d\theta$$

- Torque on wheel axle

$$T = bR^2 \int_{\theta_b}^{\theta_e} \tau_x(\theta) d\theta$$



Terrain Interaction Forces

- Terrain interaction forces are coupled, nonlinear functions
  - Vehicle parameters (radius, width)
  - Loading conditions
  - Vehicle state (linear, angular velocity)
  - Terrain physical properties
- Two brief examples
  - Example #1: Identifying max allowable load on rover wheel
  - Example #2: Sizing a rover wheel

Terrain Interaction Forces

- Example #1: Identifying max allowable load on rover wheel
  - Increasing vertical load increases sinkage

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

  - Increasing sinkage increases motion resistance

$$F_x = bR \int_{\theta_b}^{\theta_c} \tau_x(\theta)\cos(\theta) - \sigma_n(\theta)\sin(\theta)d\theta$$

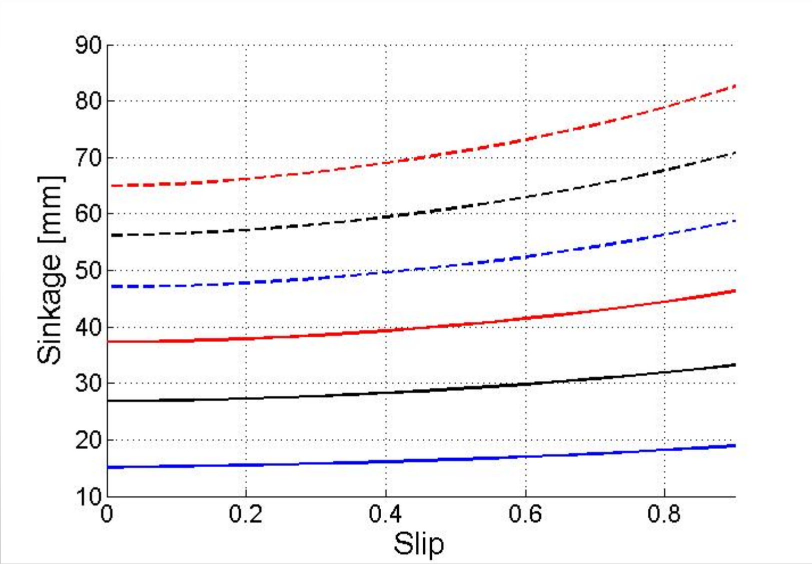
  - However, increasing vertical load leads to increased traction

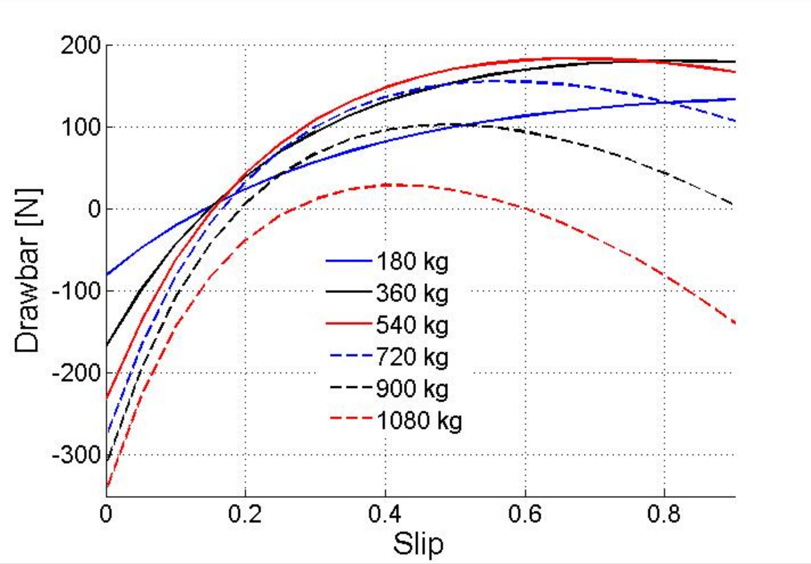
$$\tau_{max} = c + \sigma_n(\theta)\tan\phi$$

  - Thus, heavier vehicles sink more, and thus experience greater compaction resistance, but also develop more thrust

Terrain Interaction Forces

- Example #1: Identifying max allowable load on rover wheel
  - Thus, heavier vehicles sink more, and thus experience greater compaction resistance, but also develop more thrust





Terrain Interaction Forces

- Example #2: Sizing a rover wheel
- Increasing wheel size (diameter, width) decreases contact pressure, decreases sinkage

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

- However, width and radius influence required torque and compaction resistance in different ways

$$T = bR^2 \int_{\theta_b}^{\theta_e} \tau_x(\theta) d\theta \qquad F_x = bR \int_{\theta_b}^{\theta_e} \tau_x(\theta)\cos(\theta) - \sigma_n(\theta)\sin(\theta) d\theta$$

Summary

- Stresses at wheel-terrain interface
  - Decompose into normal and shear stresses
  - Modeled with semi-empirical formulations
  - Integration yields forces acting on vehicle
- Given
  - Running gear properties
  - Terrain properties
  - Loading conditions
- Can compute
  - Sinkage
  - Thrust
  - Required torque

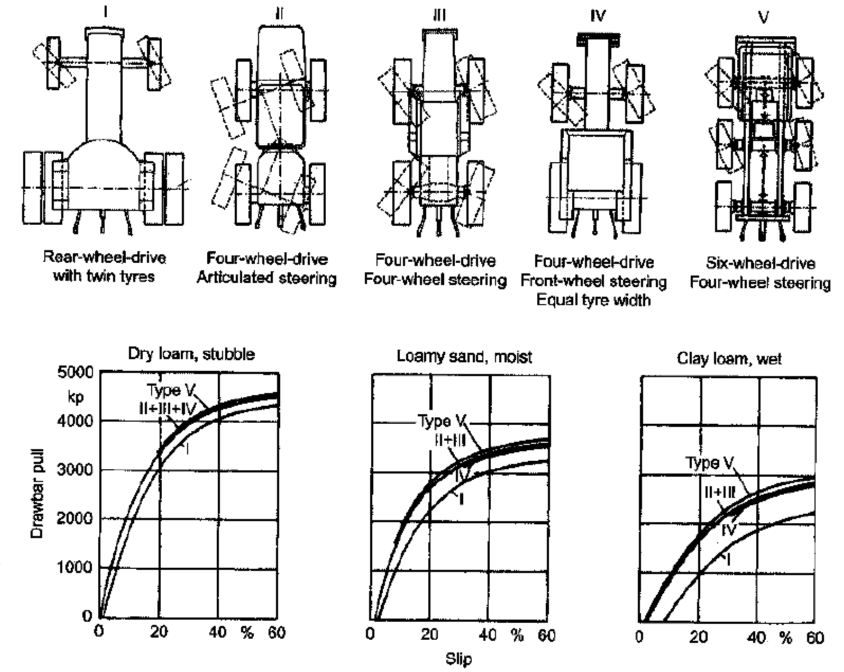


Figure 1.3: Comparison of various configurations for agricultural tractors (Reprinted by permission of *ISTVS* from Sohne, 1976)

Terramechanics Principles

- Fundamental relations
  - Pressure-sinkage
  - Shear stress-shear displacement
    - Wheel slip
- Other effects
  - Grousers/lugs
  - Lateral forces
  - Repetitive loading
- Case study

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Effect of Grousers

- Grousers are small features on wheel surface
  - Designed to improve traction and climbing performance
- Have been modeled through Terzaghi's bearing capacity theory

Pathfinder, MER, and MSL wheels

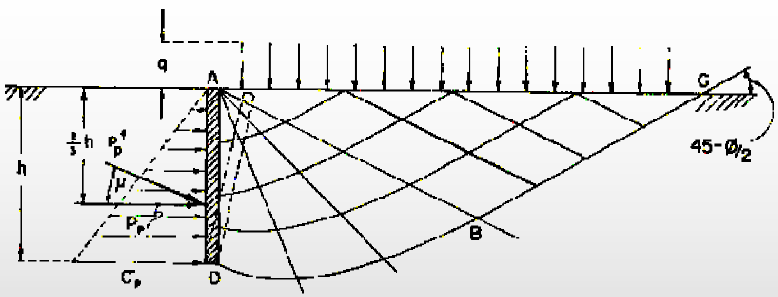


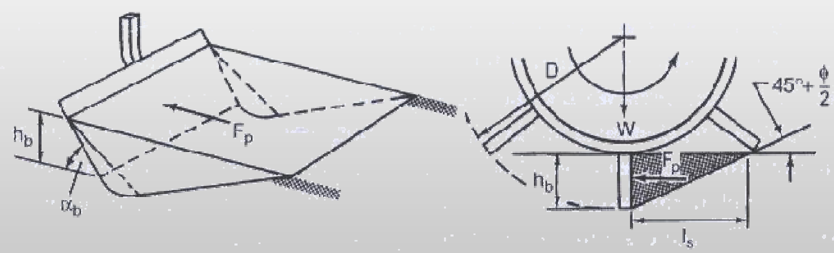
Fig. 69

The value of the force P_p assumed for $\mu = 0$ may be calculated by integrating the pressure σ_p determined by equation (134):

$$P_p = \int_0^h \sigma_p \, dz = \int_0^h (q N_\phi + 2c\sqrt{N_\phi} + \gamma z N_\phi)\, dz$$

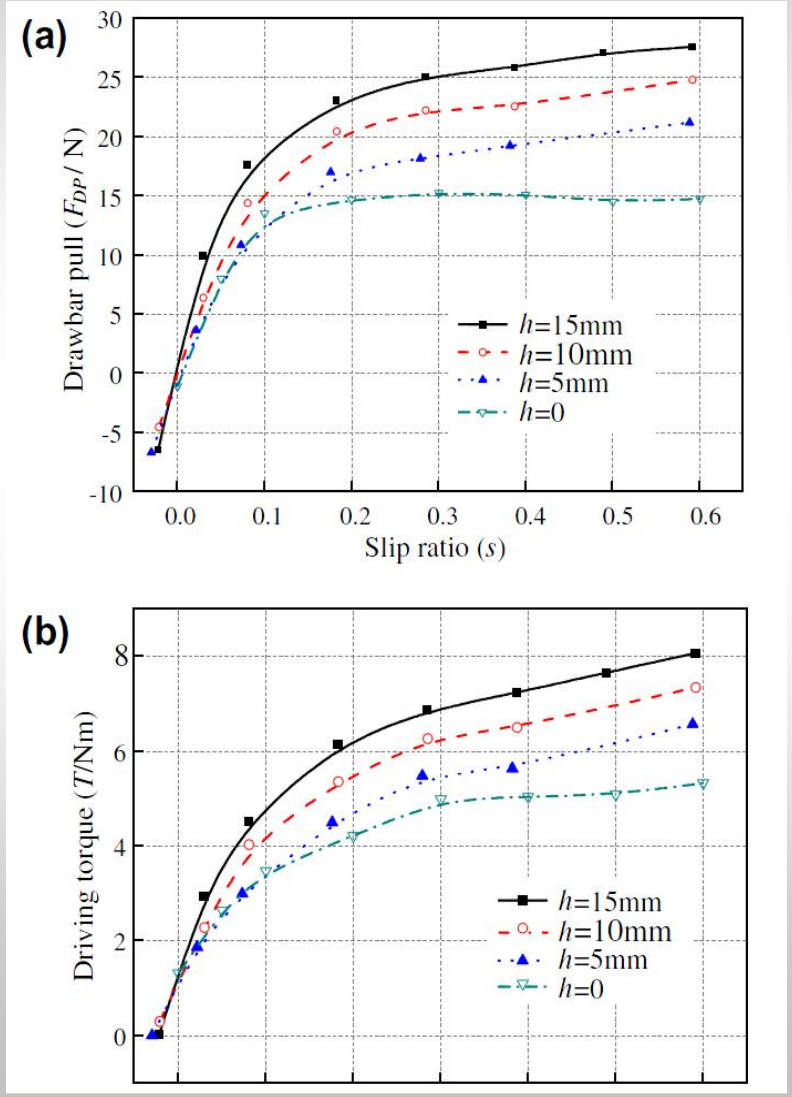
and

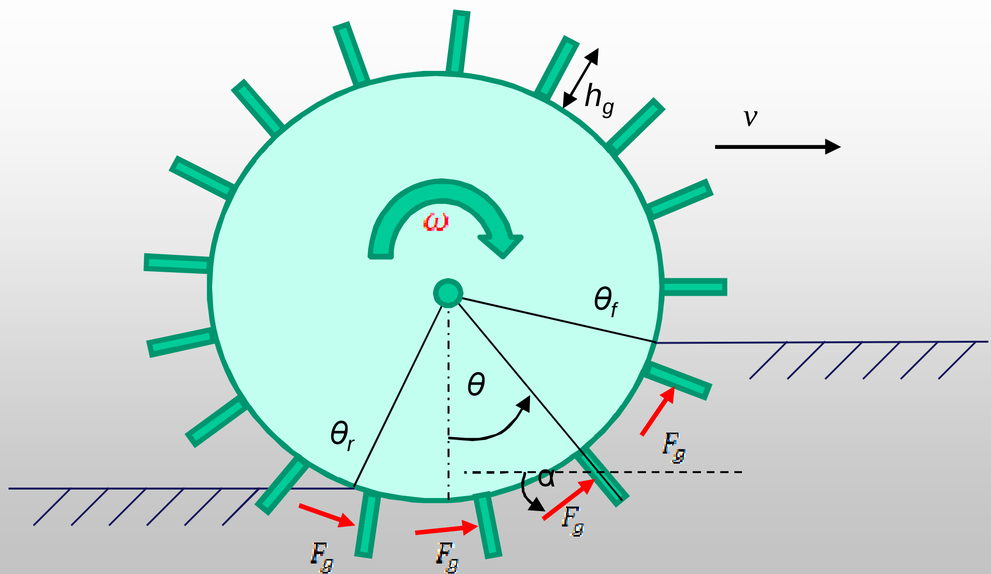
$$P_p = q h N_\phi + 2ch\sqrt{N_\phi} + \tfrac{1}{2}\gamma h^2 N_\phi .$$



Effect of Grousers

- Grouser effect has also been empirically studied
  - Grouser height, spacing, geometry affect torque, traction, turning performance





Ding L. et al. Journal of Terramechanics 48, 2011, 27-45

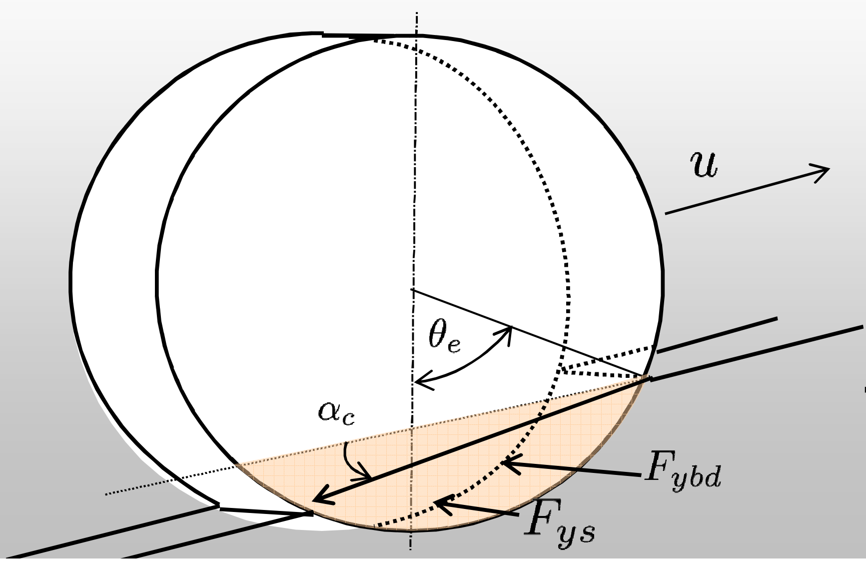
Lateral Forces

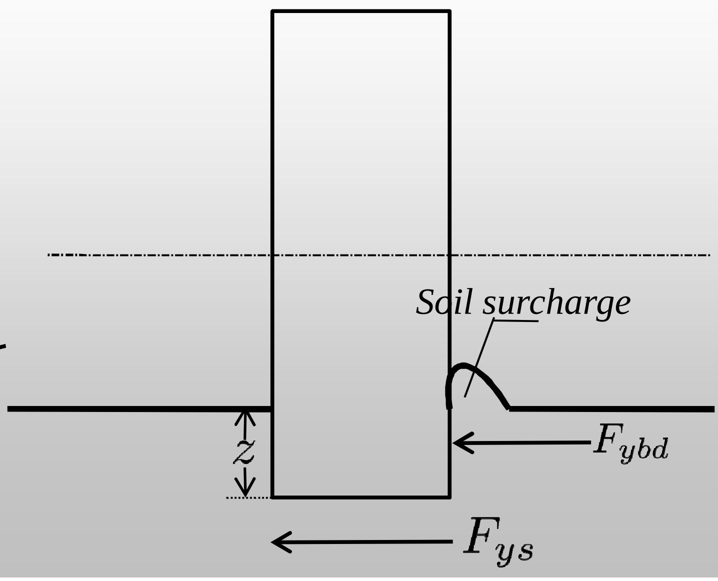
- Lateral forces act on wheel sidewall during turning
  - Forces arise from soil shearing and bulldozing

$$F_y = F_{ys} + F_{ybd}$$

$$F_{ybd} = w \int_{\theta_b}^{\theta_e} (\gamma_s z N_\gamma + c N_c + q N_q) \cos(\delta_f) d\theta$$

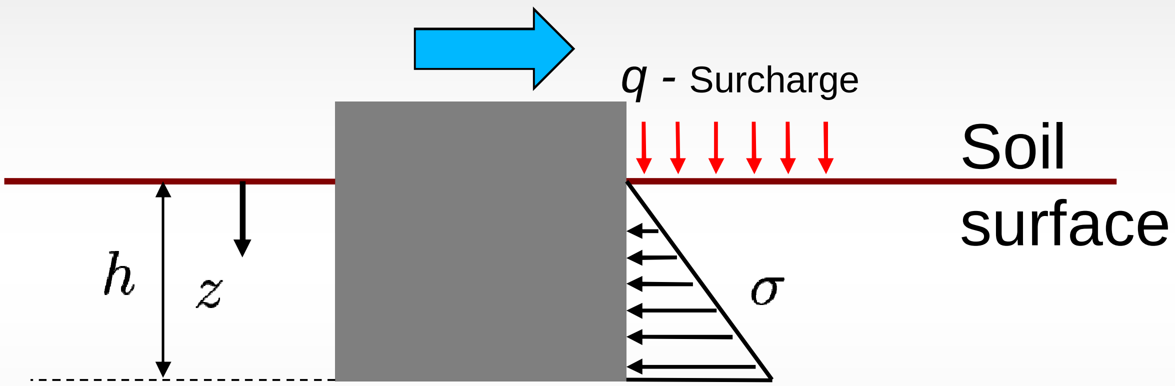
$$F_{ys} = b \int_{\theta_b}^{\theta_e} (c + \sigma_n(\theta) \tan(\phi)) \left(1 - e^{\frac{-j_y}{k_y}}\right) d\theta$$





Lateral Force - Bulldozing

- Like grouser effect, bulldozing is typically modeled through soil bearing capacity analysis



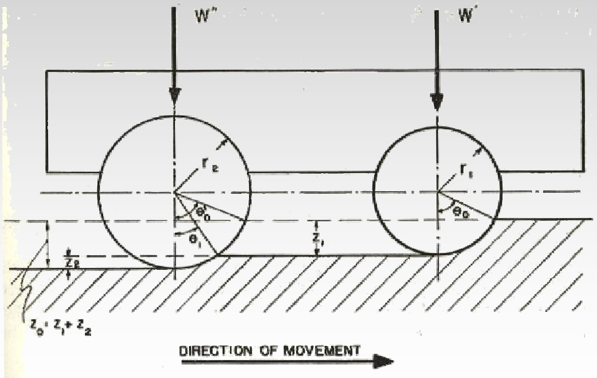
$$\sigma = \gamma z N_\gamma + c N_c + q N_q \quad \text{[Pa]}$$

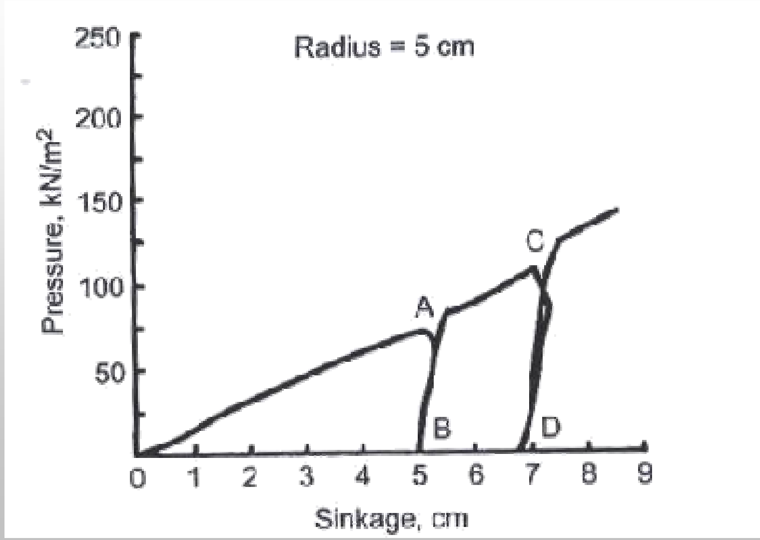
- *N*-factors are function of soil angle of internal friction

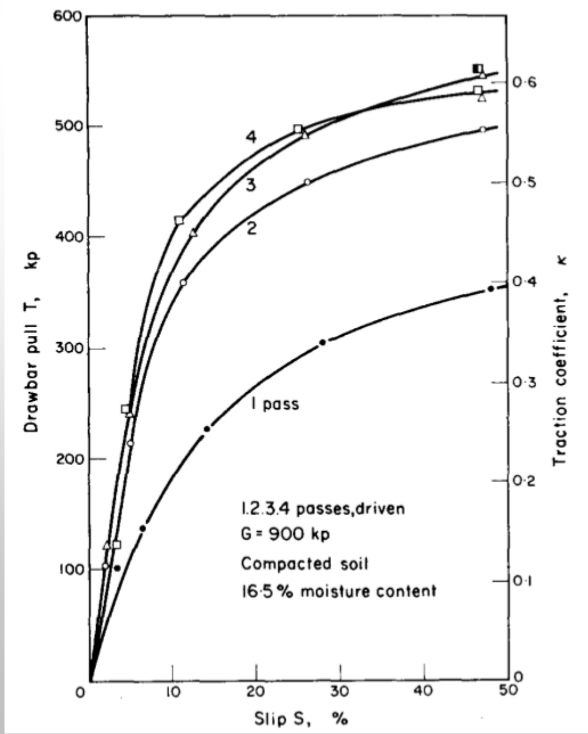
$$N_\gamma = \frac{2(N_q + 1)\tan\phi}{1 + 0.4\sin 4\phi} \qquad N_c = \frac{N_q - 1}{\tan\phi} \qquad N_q = \frac{e^{(1.5\pi - \phi)\tan\phi}}{2\,cos^2(\pi/4 + \phi/2)}$$

Repetitive Loading

- Rover trailing wheels may pass through soil deformed by leading wheels
  - Repetitive loading alters soil behavior
  - Increases compaction (relative density)

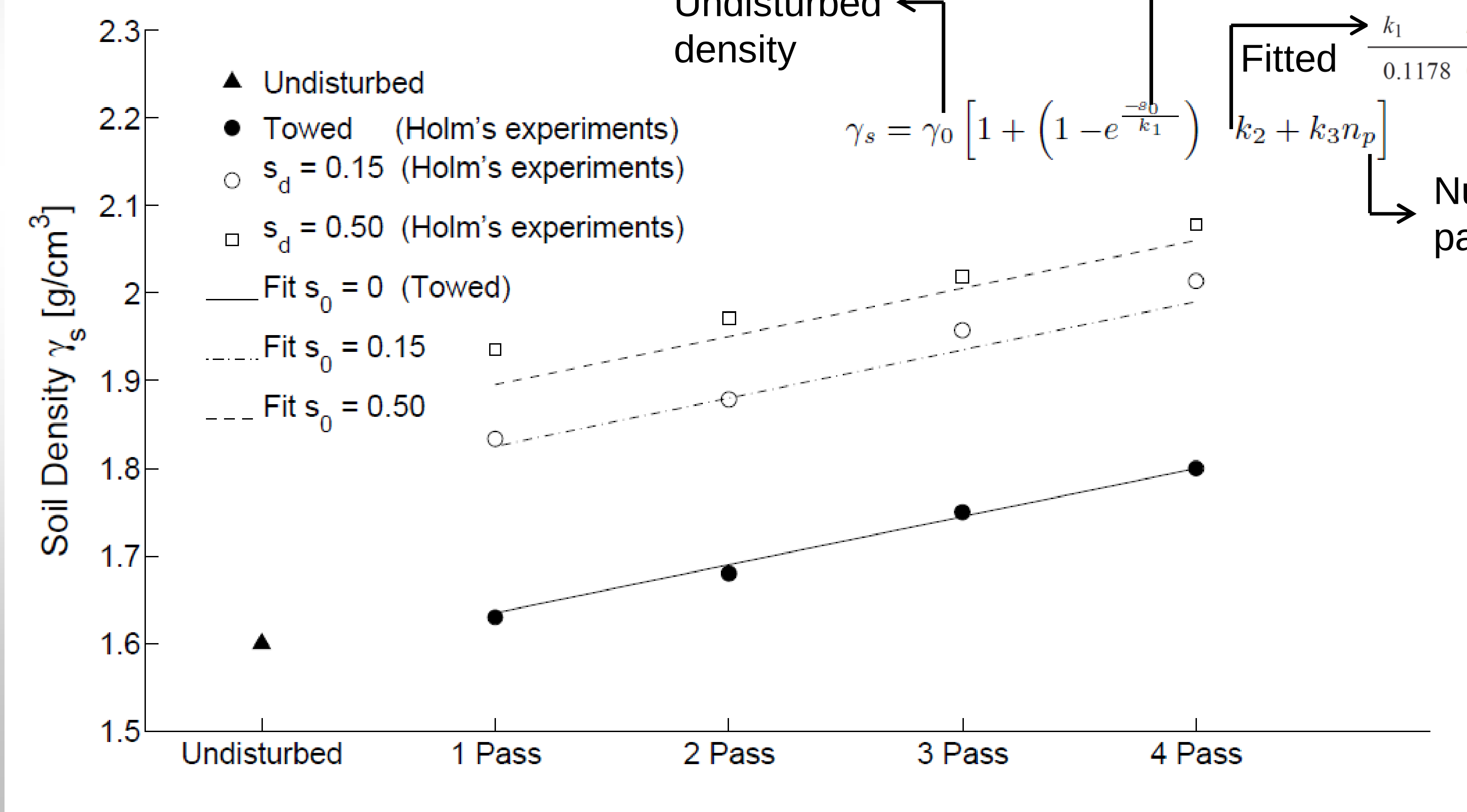






Repetitive Loading

- Multi pass can be modeled by modifying soil parameters according to number and type of passes



$$\gamma_s = \gamma_0 \left[1 + \left(1 - e^{\frac{-s_0}{k_1}}\right) k_2 + k_3 n_p\right]$$

- Undisturbed density → γ_0
- Wheel slip of previous pass → s_0
- Fitted → k_1, k_2, k_3
- Number of passes → n_p

k_1	k_2	k_3
0.1178	0.1672	0.0348

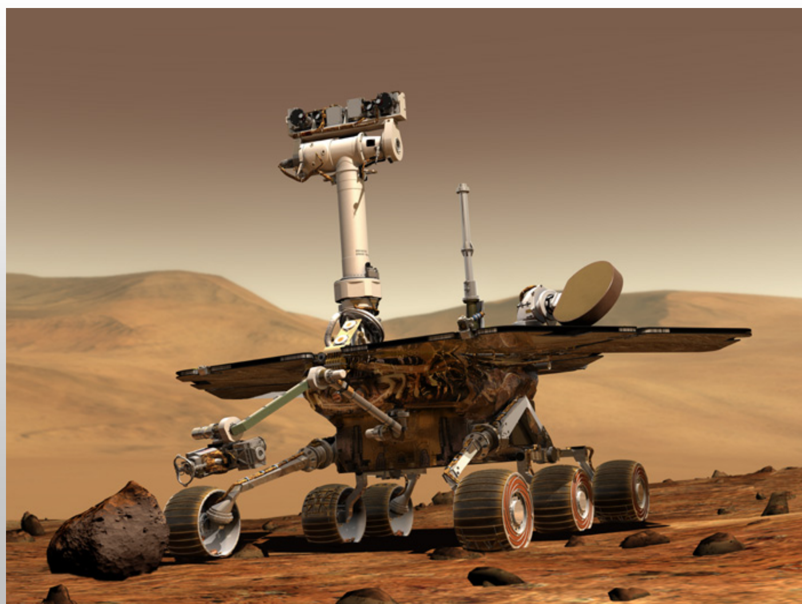
Terramechanics Principles

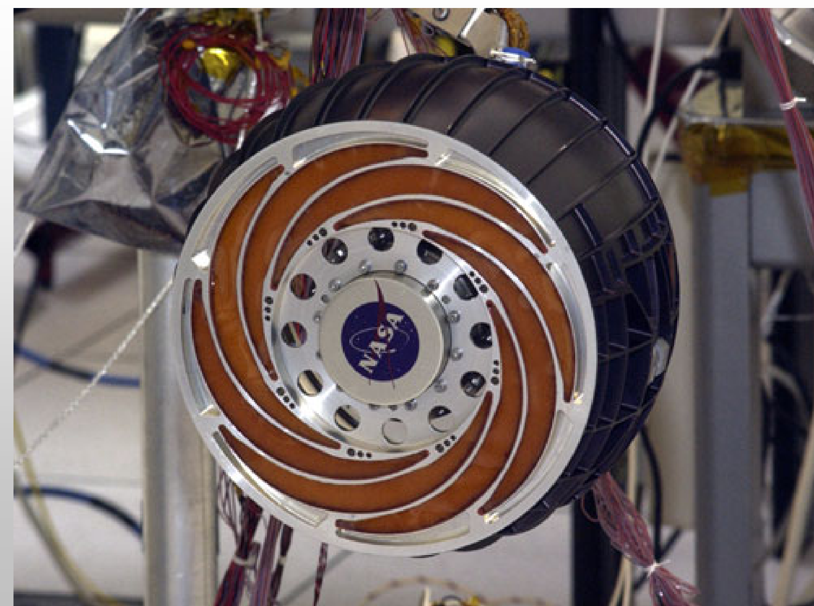
- Fundamental relations
  - Pressure-sinkage
  - Shear stress-shear displacement
    - Wheel slip
- Other effects
  - Grousers/lugs
  - Lateral forces
  - Repetitive loading
- Case Study

M.G. Bekker

Case Study:
Rover Design & Performance Prediction

- MER Rover
  - Lightweight, 6 wheels, rocker-bogie suspension system
- Wheel diameter 26 cm
- Static vertical load on each wheel ~ 100N
- Landing site area composed of bedrock outcrops, loose, sandy material





Case Study: Rover Design & Performance Prediction

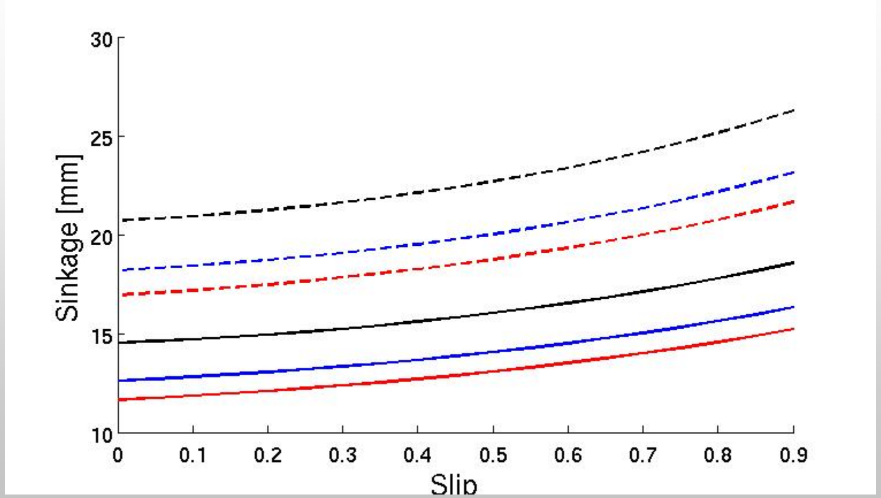
- Rover design problem
  - Given mass budget, choose wheel number and geometry
  - Examine tractive efficiency
  - Compute required torque
  - Estimate slope climbing capability

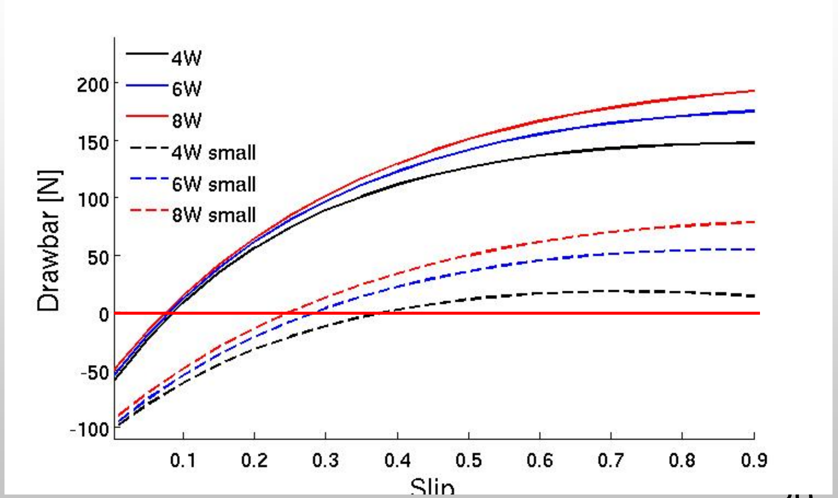
Terrain Parameters		Dry Sand
n	(sinkage exponent)	0.705
k_c	(cohesion parameter)	6.94 [kN/m^{n+1}]
k_ϕ	(angle of internal friction parameter)	505.8 [kN/m^{n+2}]
c	(cohesion)	960 [N/m^2]
ϕ	(angle of internal friction)	27.3 [deg]
k_x	(shear modulus)	0.0114 [m]

J. Y. Wong, *Terramechanics and off-road vehicle engineering*, Elsevier, 2010

Case Study: Rover Design & Performance Prediction

- Total mass: 180 kg (~ 650 N on Mars surface)
  - Three candidate configurations (4, 6, 8 wheels)
  - Two candidate diameters (*D* and *D*/2)
    - Increasing number, size of wheels decreases sinkage
    - Increasing number of wheels increases net thrust
    - "No go" regime for certain parameter combinations



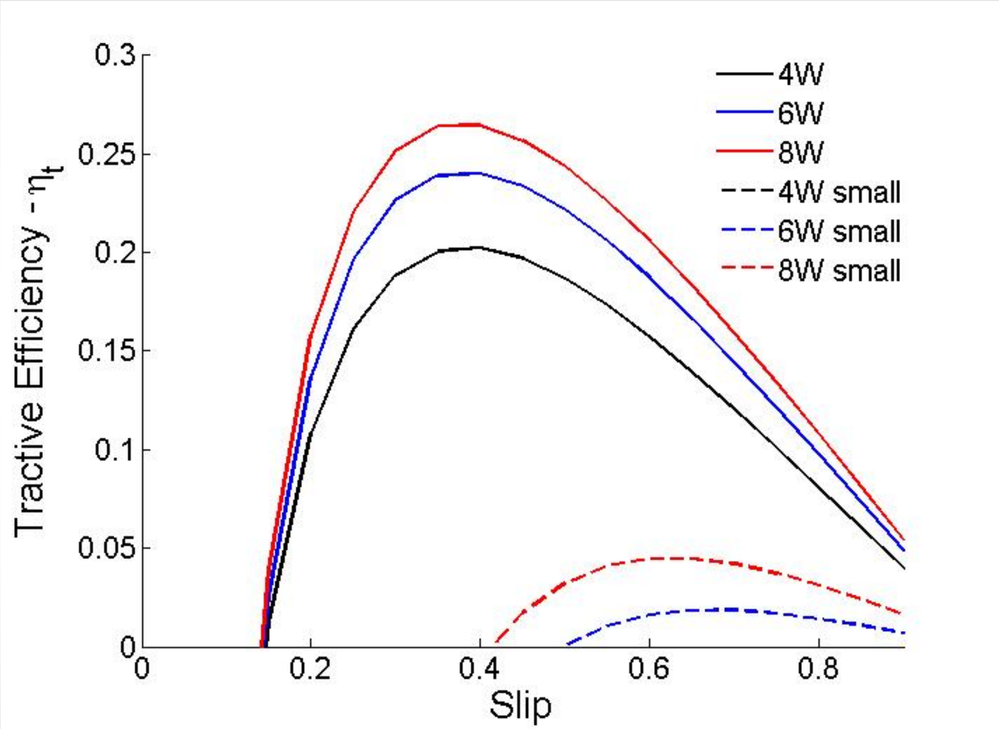


Case Study: Rover Design & Performance Prediction

- Efficiency is important aspect for rover operation
- Tractive efficiency is defined as follows:

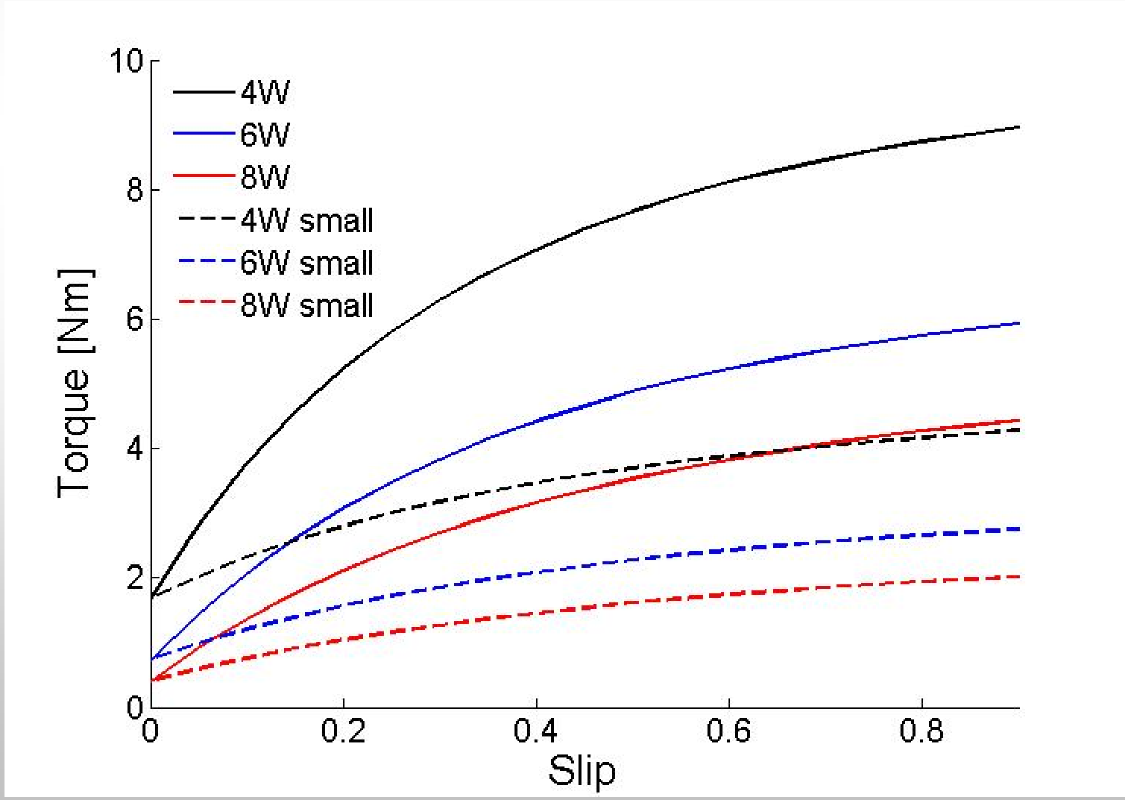
$$\eta_t = \frac{F_x v_x}{T\omega} = \frac{F_x(1-s_d)R_l}{T}$$

- Maximum at ~ 30% slip.
- Increasing wheel number, size increases efficiency



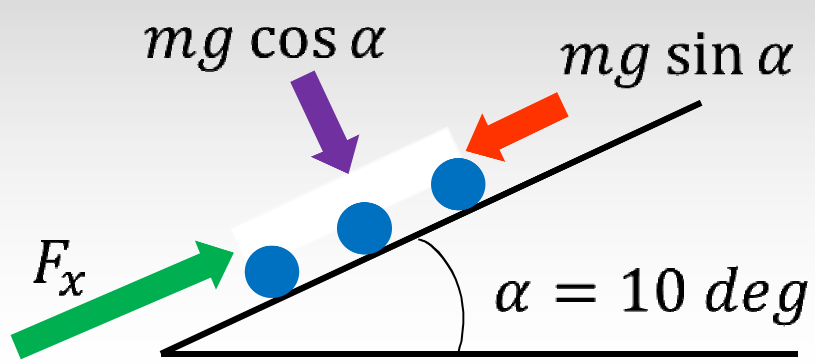
Case Study: Rover Design & Performance Prediction

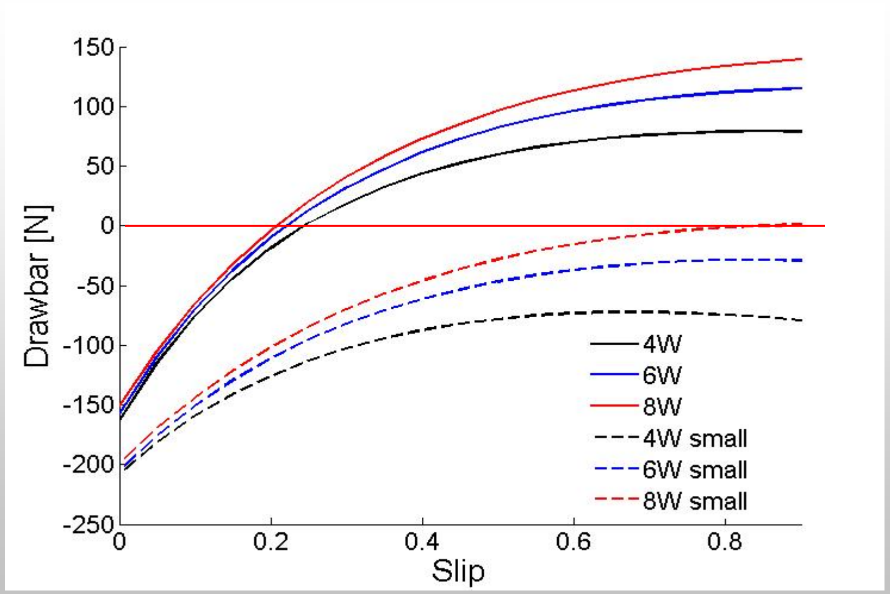
- Torque calculation provides estimate for actuator sizing
- Fewer, smaller wheels require less torque



Case Study: Rover Design & Performance Prediction

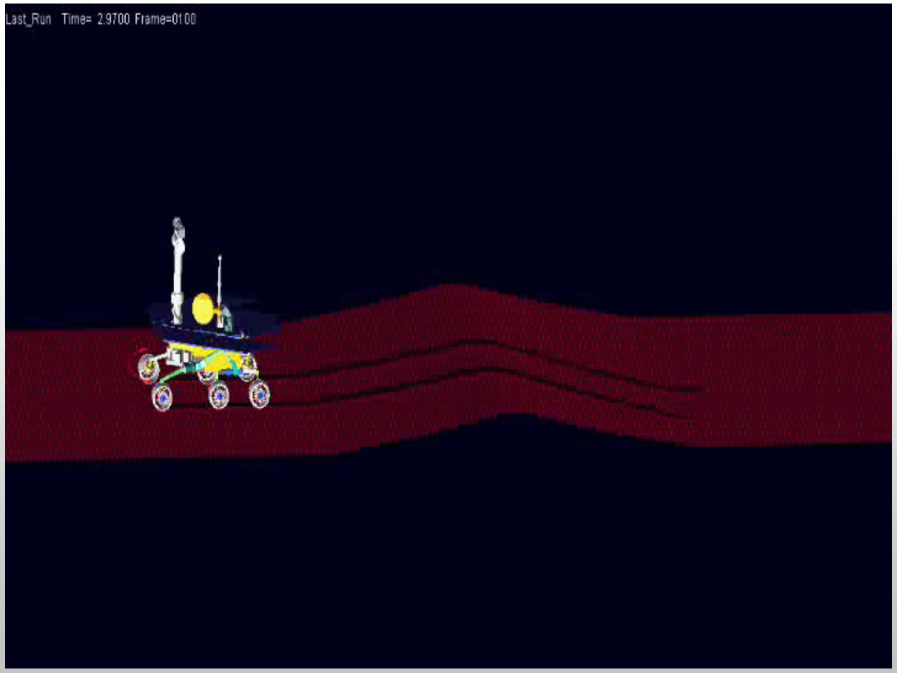
- Driving on slopes is an important requirement for rovers
  - Traction is reduced on slope due to gravitational load, reduced normal load
- Smaller wheels cannot climb 10 degree slope
- Larger wheels can climb slope at sufficiently large slip ratio

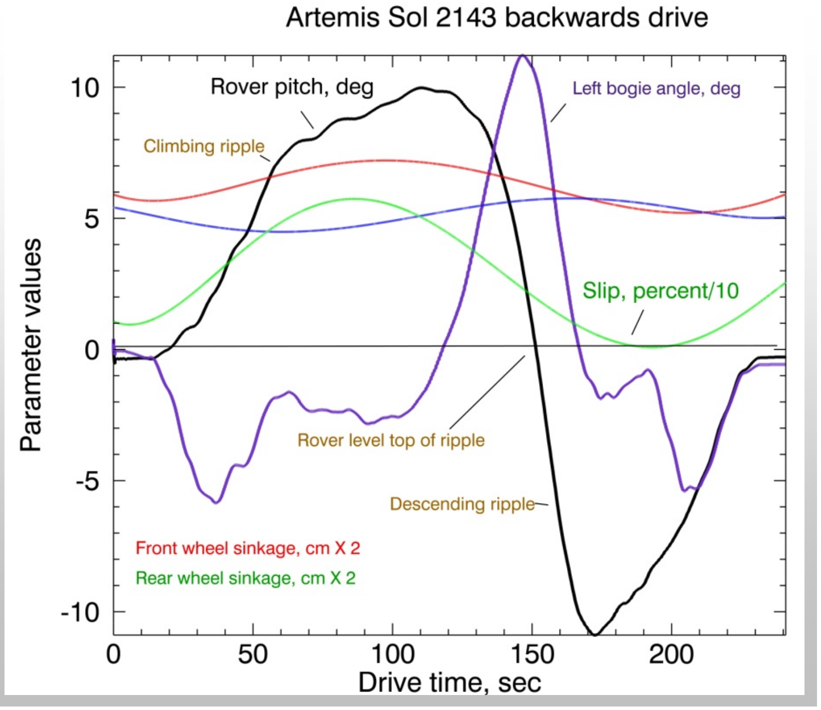




Case Study: Rover Design & Performance Prediction

- Analysis can be integrated in dynamic simulation
  - Validate against experimental data
  - Use for motion prediction





Conclusions

- Various tools available for surface interaction modeling
  - Empirical methods, computational methods, parametric methods
- Terramechanics is engineering science that studies the interaction between vehicles and terrain
- Key relationships
  - Pressure-sinkage
  - Shear stress-shear displacement

– Allows designer to analyze parameter trade spaces

– Allows rover planners to predict performance