Annex F – THRUST 2 – SIMPLE TERRAMECHANICS MODEL AND DATA

Note: This Annex appears in its original format.

Simple Terramechanics in the Next Generation-NATO Reference Mobility Model (NG-NRMM)

CDT Meeting

KRC, Houghton MI

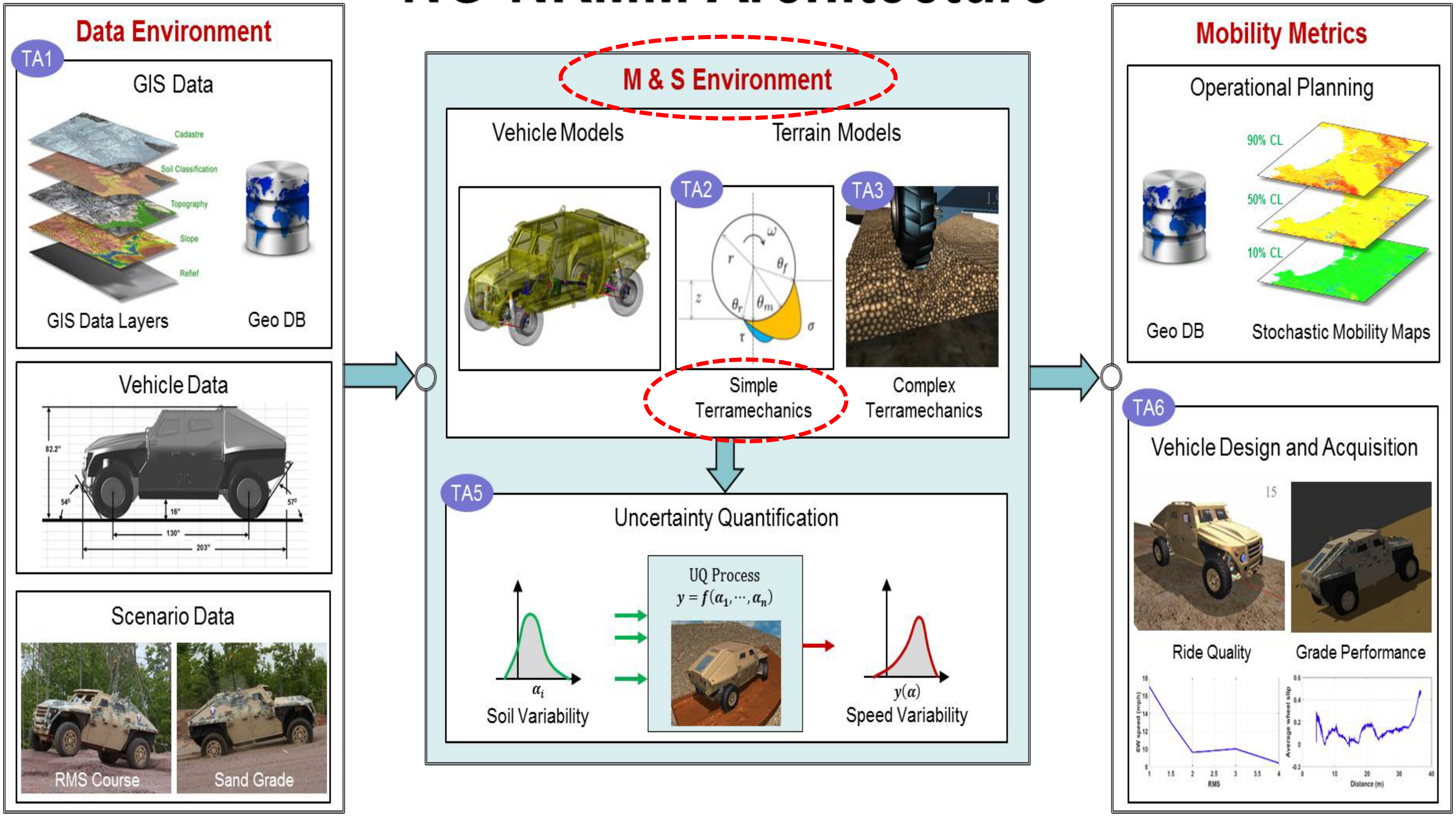
Dr. Michael McCullough
Technical Fellow
BAE Systems Inc.

September 25, 2018

Outline

- **Terramechanics For NG-NRMM**
- **Appeal, Limitations, and Continuing Value of Cone Index**
- **Bekker Value (Bevameter) meter data acquisition**
- **Derived efficient data acquisition approaches**
  - Vehicle as a sensor
  - Using Rut Depth and Motion Resistance to get Soil Strength
- **Terramechanics Database**
  - Lab data and complex terramechanics models
- **Assumptions and Limitations of Simple Terramechanics**
- **Conclusions**

NG-NRMM Architecture



Data Environment

TA1

GIS Data

GIS Data Layers

Geo DB

Vehicle Data

Scenario Data

RMS Course

Sand Grade

M & S Environment

Vehicle Models

Terrain Models

TA2

TA3

Simple Terramechanics

Complex Terramechanics

TA5

Uncertainty Quantification

UQ Process
$y = f(\alpha_1, \cdots, \alpha_n)$

α_i
Soil Variability

$y(\alpha)$
Speed Variability

Mobility Metrics

Operational Planning

Geo DB

Stochastic Mobility Maps

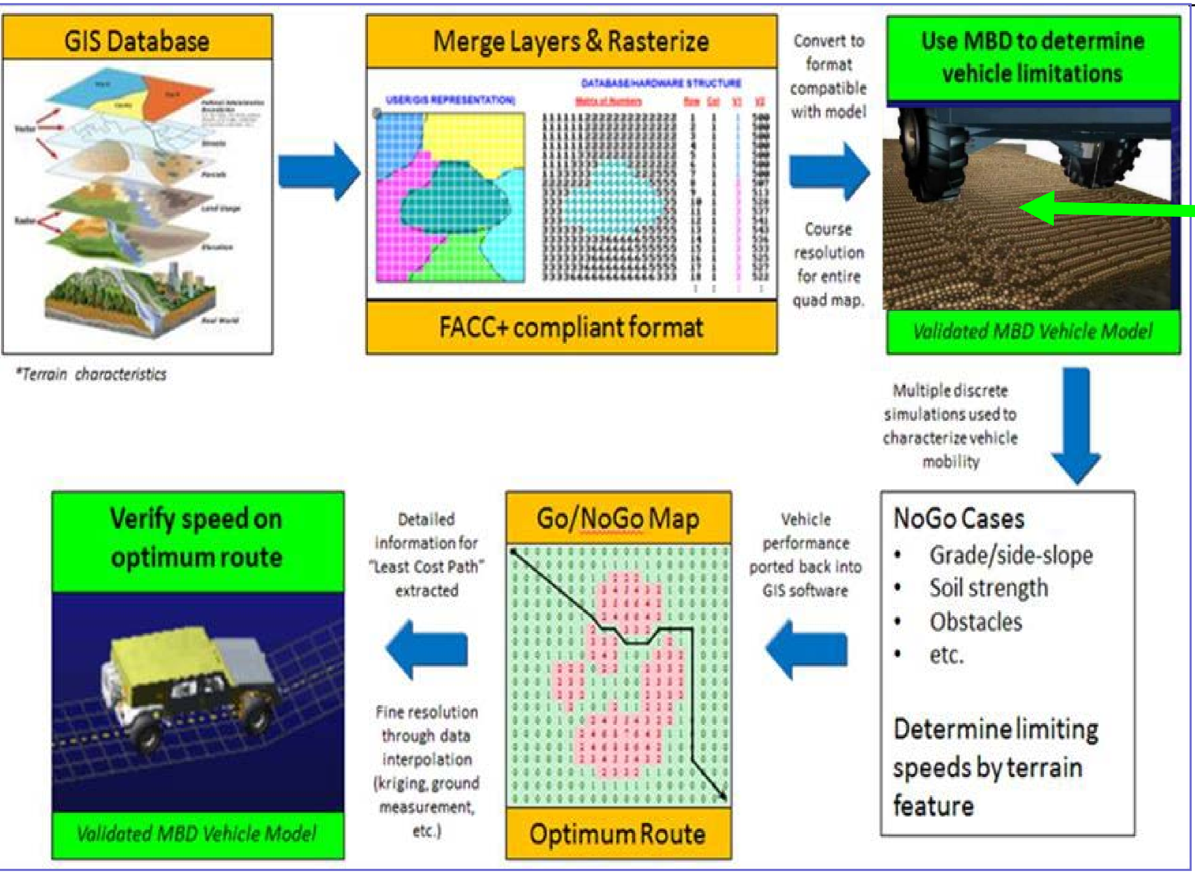
TA6

Vehicle Design and Acquisition

Ride Quality

Grade Performance

GIS Data to GIS Mobility: Terramechanics



GIS Database

*Terrain characteristics

Merge Layers & Rasterize

FACC+ compliant format

Convert to format compatible with model

Course resolution for entire quad map.

Use MBD to determine vehicle limitations

Validated MBD Vehicle Model

Multiple discrete simulations used to characterize vehicle mobility

NoGo Cases

- Grade/side-slope
- Soil strength
- Obstacles
- etc.

Determine limiting speeds by terrain feature

Vehicle performance ported back into GIS software

Go/NoGo Map

Optimum Route

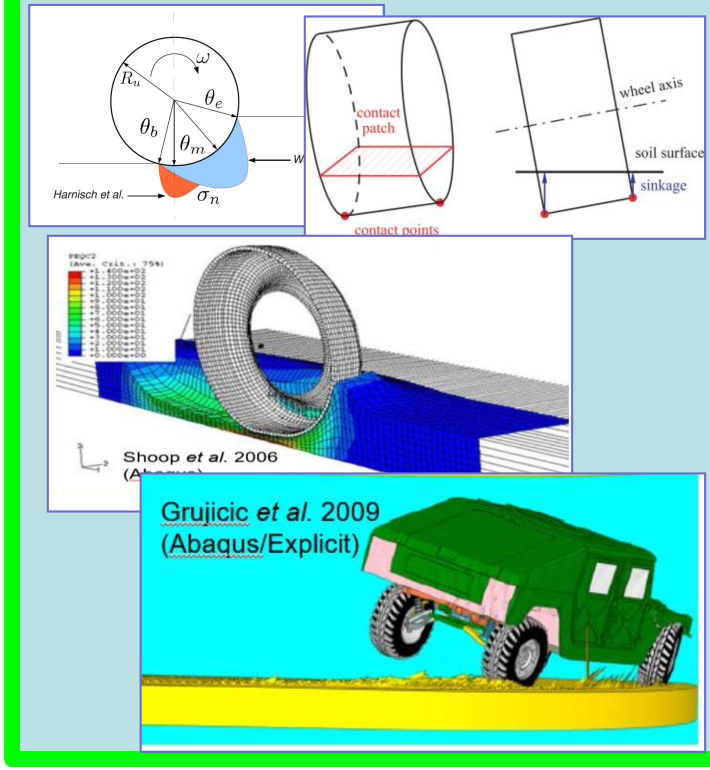
Detailed information for "Least Cost Path" extracted

Fine resolution through data interpolation (kriging, ground measurement, etc.)

Verify speed on optimum route

Validated MBD Vehicle Model

Terramechanics Models Account For Soil-Vehicle Interaction Physics



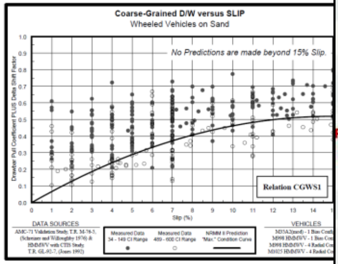
Harnisch et al.

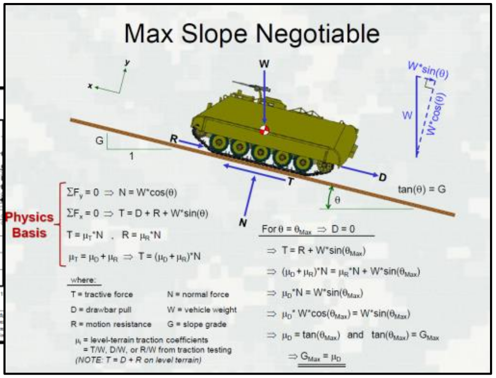
Shoop *et al.* 2006 (Abaqus)

Grujicic *et al.* 2009 (Abaqus/Explicit)

NG NRMM Terramechanics

- **CONE INDEX: VEHICLE LEVEL EMPIRICAL**





Max Slope Negotiable

$\tan(\theta) = G$

Physics Basis

$\Sigma F_y = 0 \Rightarrow N = W^*\cos(\theta)$

$\Sigma F_x = 0 \Rightarrow T = D + R + W^*\sin(\theta)$

$T = \mu_T{}^*N \quad , \quad R = \mu_R{}^*N$

$\mu_T = \mu_D + \mu_R \Rightarrow T = (\mu_D + \mu_R)^*N$

where:

T = tractive force
N = normal force
D = drawbar pull
W = vehicle weight
R = motion resistance
G = slope grade

μ_i = level-terrain traction coefficients
= T/W, D/W, or R/W from traction testing
(NOTE: T = D + R on level terrain)

For $\theta = \theta_{Max} \Rightarrow D = 0$

$\Rightarrow T = R + W^*\sin(\theta_{Max})$

$\Rightarrow (\mu_D + \mu_R)^*N = \mu_R{}^*N + W^*\sin(\theta_{Max})$

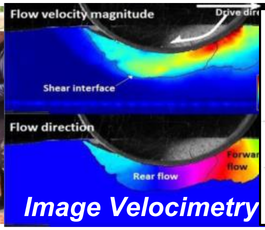
$\Rightarrow \mu_D{}^*N = W^*\sin(\theta_{Max})$

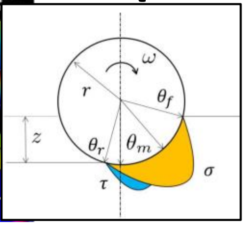
$\Rightarrow \mu_D{}^*\ W^*\cos(\theta_{Max}) = W^*\sin(\theta_{Max})$

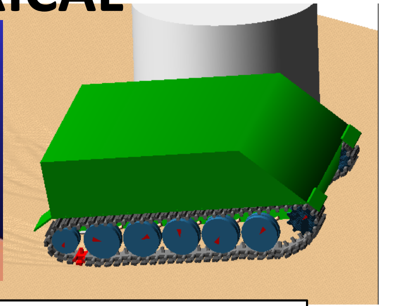
$\Rightarrow \mu_D = \tan(\theta_{Max})$ and $\tan(\theta_{Max}) = G_{Max}$

$\Rightarrow G_{Max} = \mu_D$

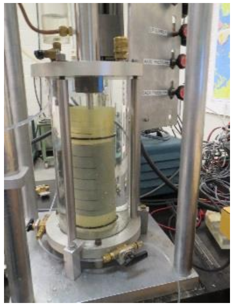
- **SIMPLE: RUNNING GEAR (WHEEL,TRACK PAD) EMPIRICAL**

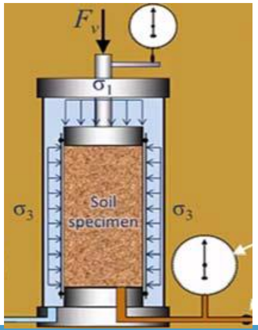


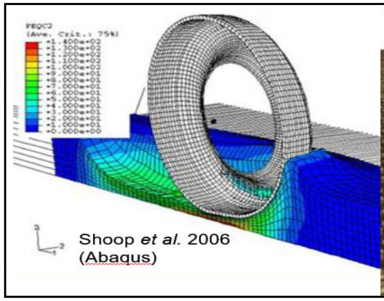




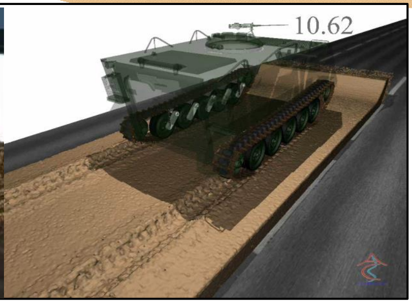
- **COMPLEX: SOIL MEDIA EMPIRICAL**







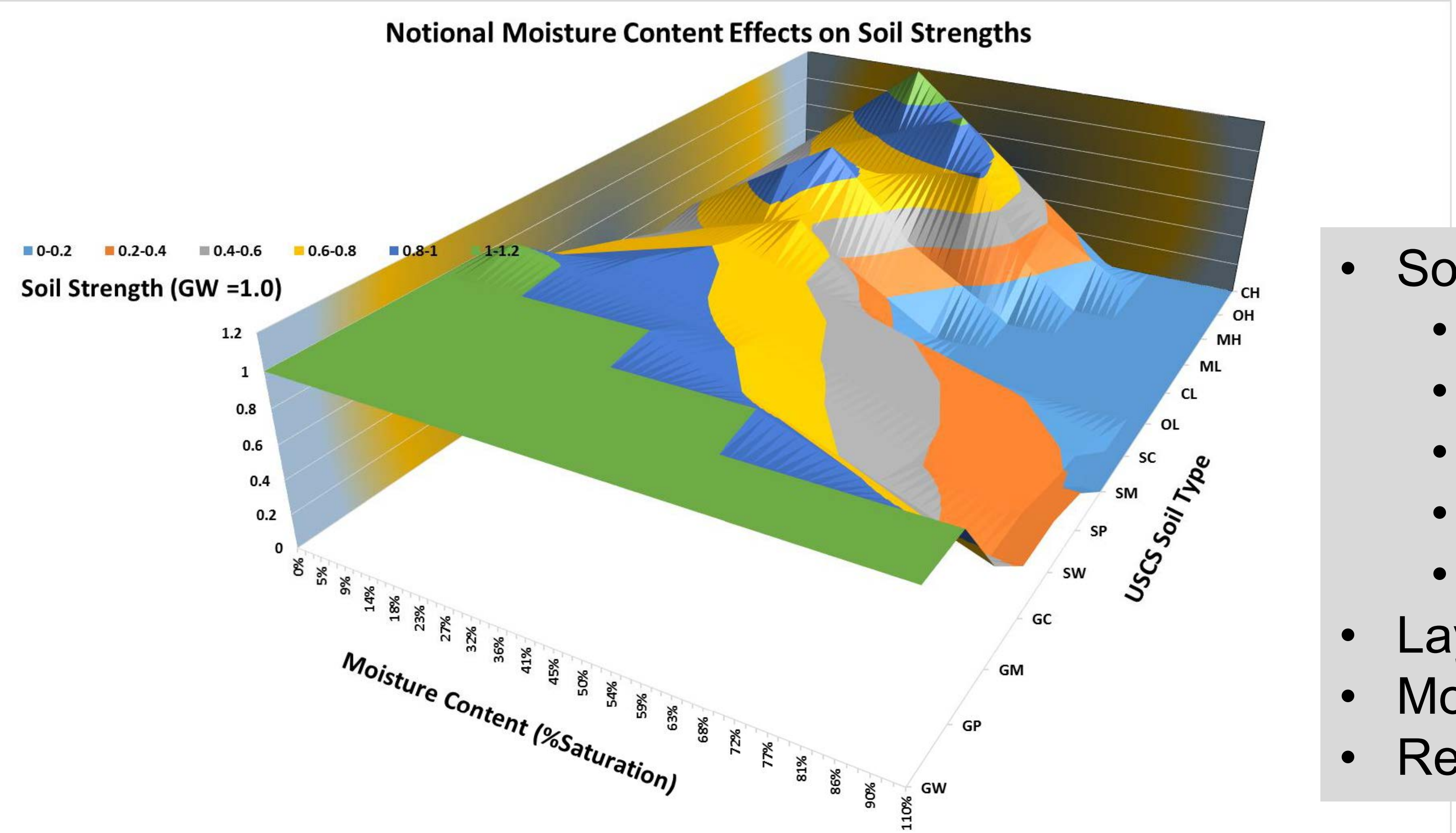
Shoop *et al.* 2006 (Abaqus)



NG NRMM Terramechanics Definitions

- **Focused on vehicle terrain interaction that accounts for soft soil (i.e. deformable soil) effects on vehicle mobility, i.e. bearing and tractive strength of soils at the scale of vehicle running gear.**
  - ***Simple Terramechanics***: models based on the use of pressure-sinkage and traction-slip data developed from instrumented bearing plates and shear rings (and/or wheel load cells) that more closely resemble vehicle running gear interaction with the soil
  - ***Complex Terramechanics:*** models using fully coupled 3D soil media failure and flow models

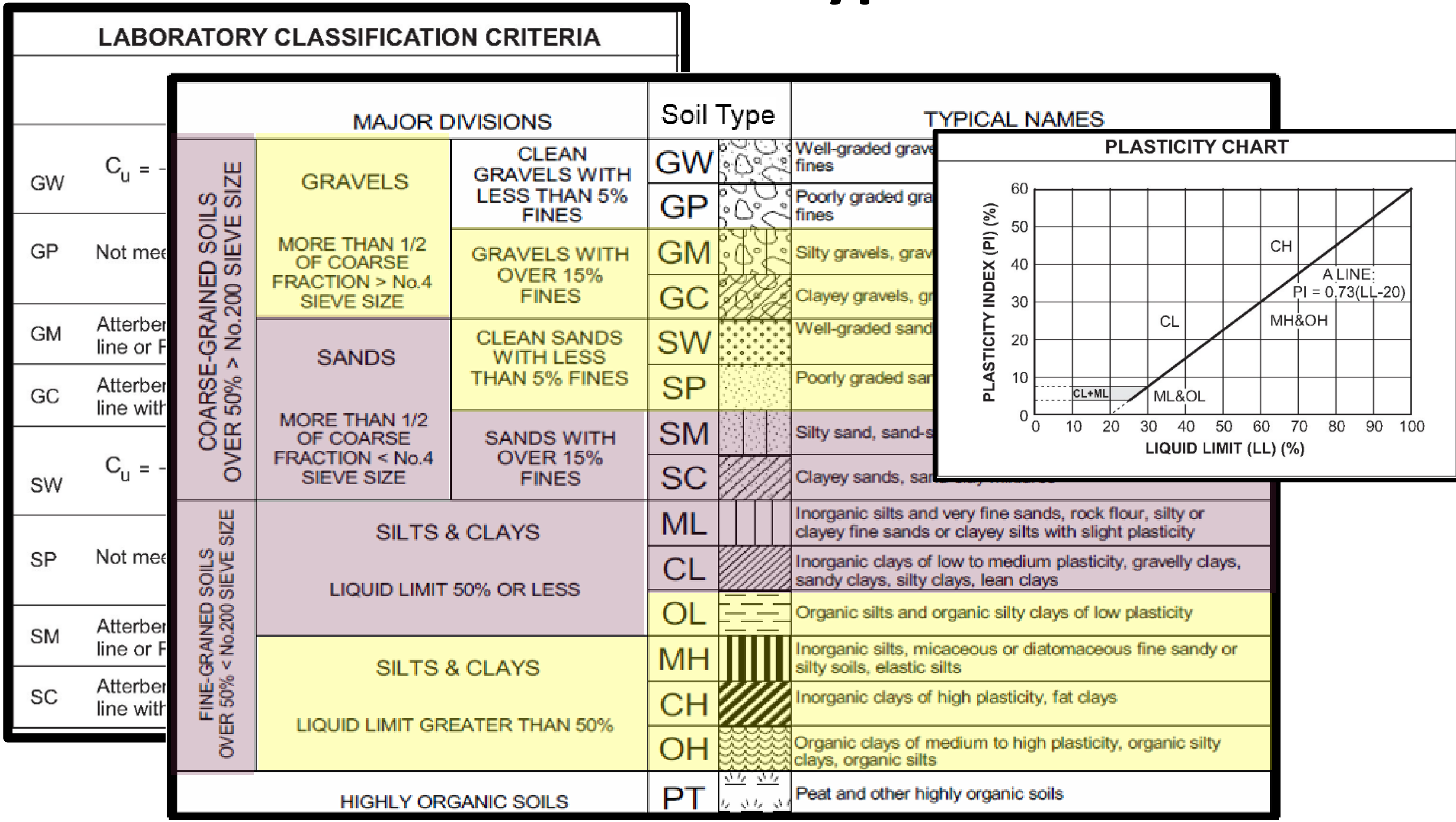
Soil Strength



- Soil Classification
  - Gravel
  - Sand
  - Silt
  - Clay
  - Organics
- Layers
- Moisture Content
- Relative Density

Soil Strength varies with type, layering, moisture and density. Many specific metrics of soil strength exist for differing purposes, but there is no single soil strength metric that directly correlates to mobility—thus the need for terramechanics models

USCS Soil Types



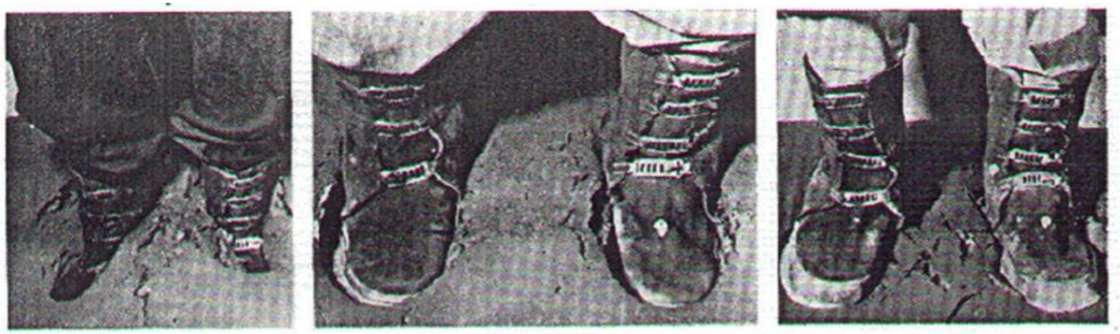
LABORATORY CLASSIFICATION CRITERIA

GW	C_u = -
GP	Not mee
GM	Atterber line or P
GC	Atterber line with
SW	C_u = -
SP	Not mee
SM	Atterber line or P
SC	Atterber line with

MAJOR DIVISIONS			Soil Type	TYPICAL NAMES
COARSE-GRAINED SOILS OVER 50% > No.200 SIEVE SIZE	GRAVELS MORE THAN 1/2 OF COARSE FRACTION > No.4 SIEVE SIZE	CLEAN GRAVELS WITH LESS THAN 5% FINES	GW	Well-graded grave fines
			GP	Poorly graded gra fines
		GRAVELS WITH OVER 15% FINES	GM	Silty gravels, grav
			GC	Clayey gravels, gr
	SANDS MORE THAN 1/2 OF COARSE FRACTION < No.4 SIEVE SIZE	CLEAN SANDS WITH LESS THAN 5% FINES	SW	Well-graded sand
			SP	Poorly graded sar
		SANDS WITH OVER 15% FINES	SM	Silty sand, sand-s
			SC	Clayey sands, sar
FINE-GRAINED SOILS OVER 50% < No.200 SIEVE SIZE	SILTS & CLAYS LIQUID LIMIT 50% OR LESS		ML	Inorganic silts and very fine sands, rock flour, silty or clayey fine sands or clayey silts with slight plasticity
			CL	Inorganic clays of low to medium plasticity, gravelly clays, sandy clays, silty clays, lean clays
			OL	Organic silts and organic silty clays of low plasticity
	SILTS & CLAYS LIQUID LIMIT GREATER THAN 50%		MH	Inorganic silts, micaceous or diatomaceous fine sandy or silty soils, elastic silts
			CH	Inorganic clays of high plasticity, fat clays
			OH	Organic clays of medium to high plasticity, organic silty clays, organic silts
HIGHLY ORGANIC SOILS			PT	Peat and other highly organic soils

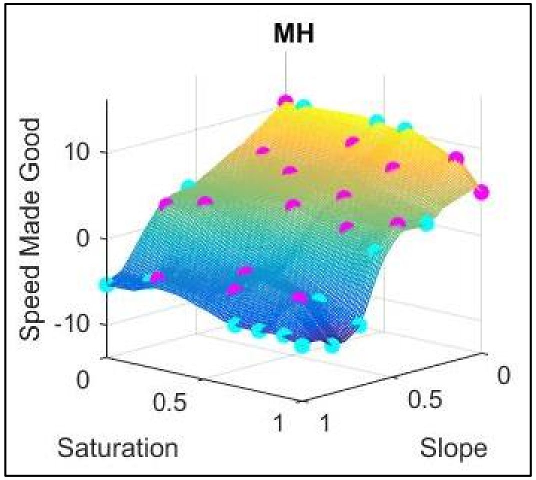
PLASTICITY CHART

Moisture Content Effects

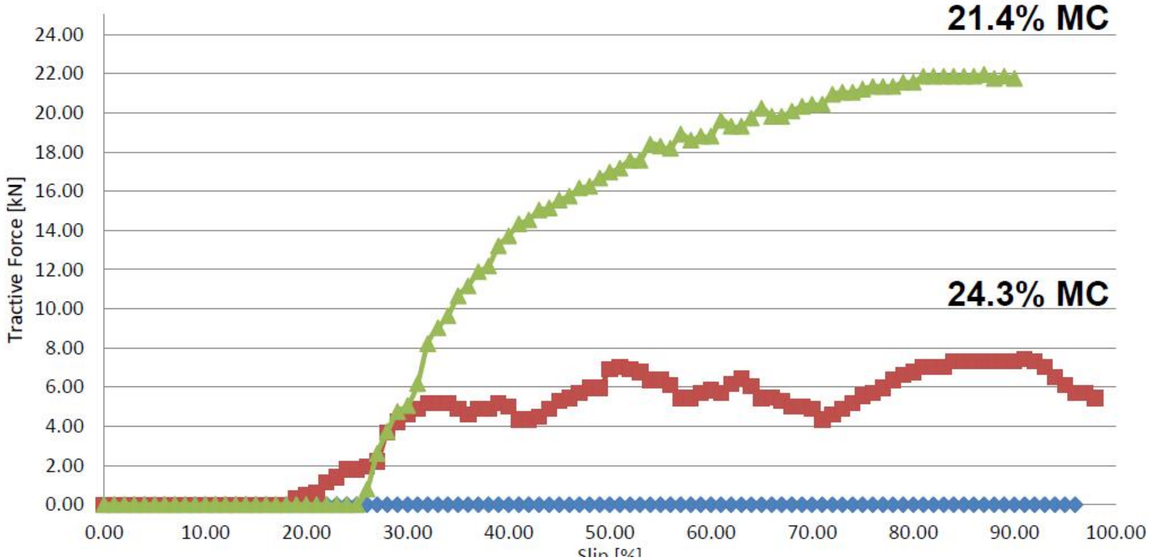


MC 22% MC 20% MC 19%

Bekker, M. G., “Off-the-Road Locomotion,” University of Michigan Press, 1960

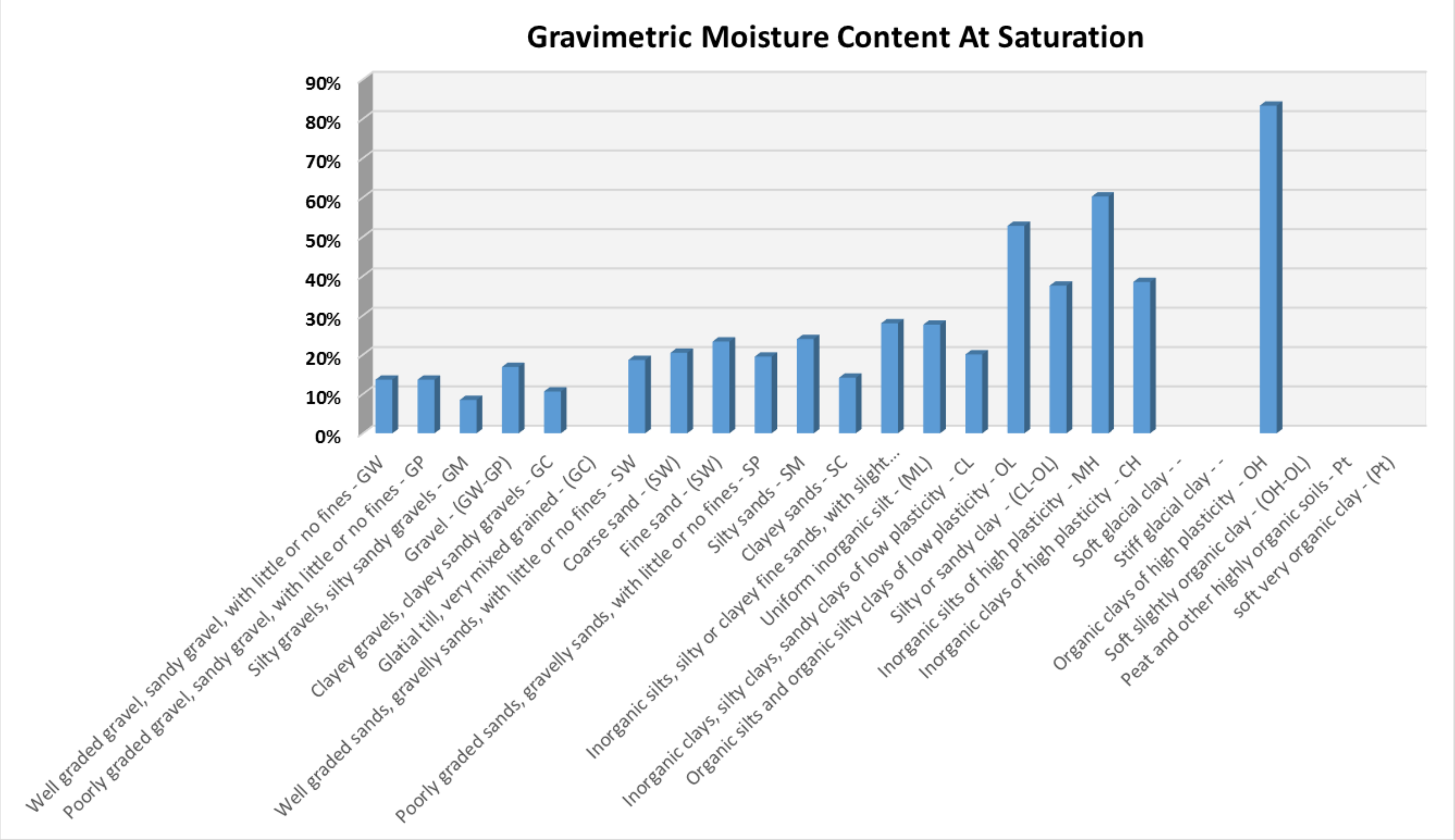


Drawbar Pull



Tom Von Sturm
Bundeswehr, Germany

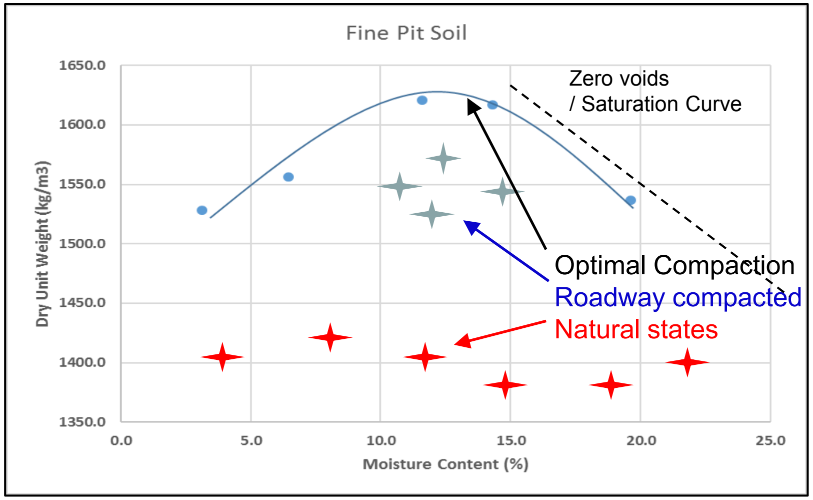
Saturation Soil Moisture Contents

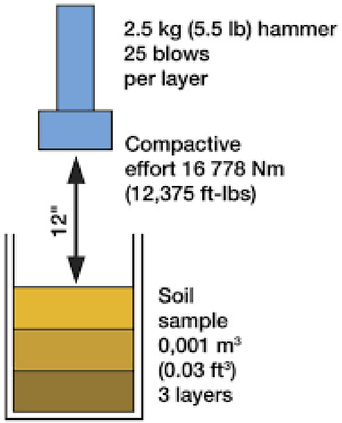


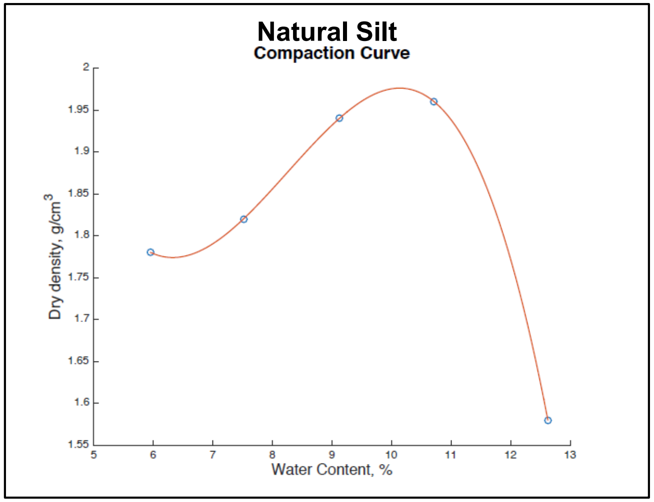
Soils vary significantly in their ability to hold water, but saturation is a common transition point in soil strength. Thus there is broad consensus that %Saturation is most relevant to Mobility

Soil Density (Compaction)

- **Relative Density (RD) has formal rigorous definition when it is used for cohesion-less soils (i.e. very little clay) and is based on void ratio**
  - ➢ RD = $(VR_{loose} - VR_{natural})/(VR_{loose} - VR_{dense})$
- **Proctor Curve (ASTM D698) plotting shows relative density of soils with significant cohesion**

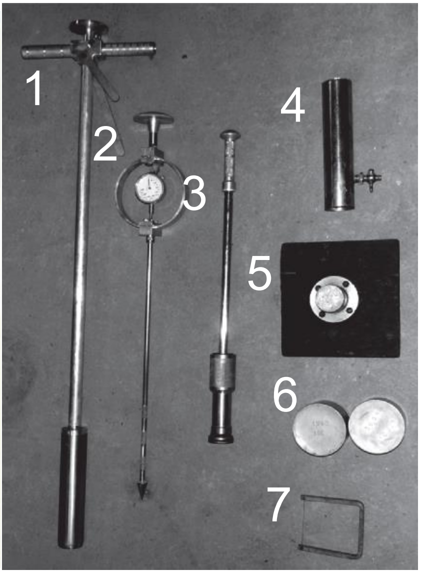






Cone Index (CI) Methods

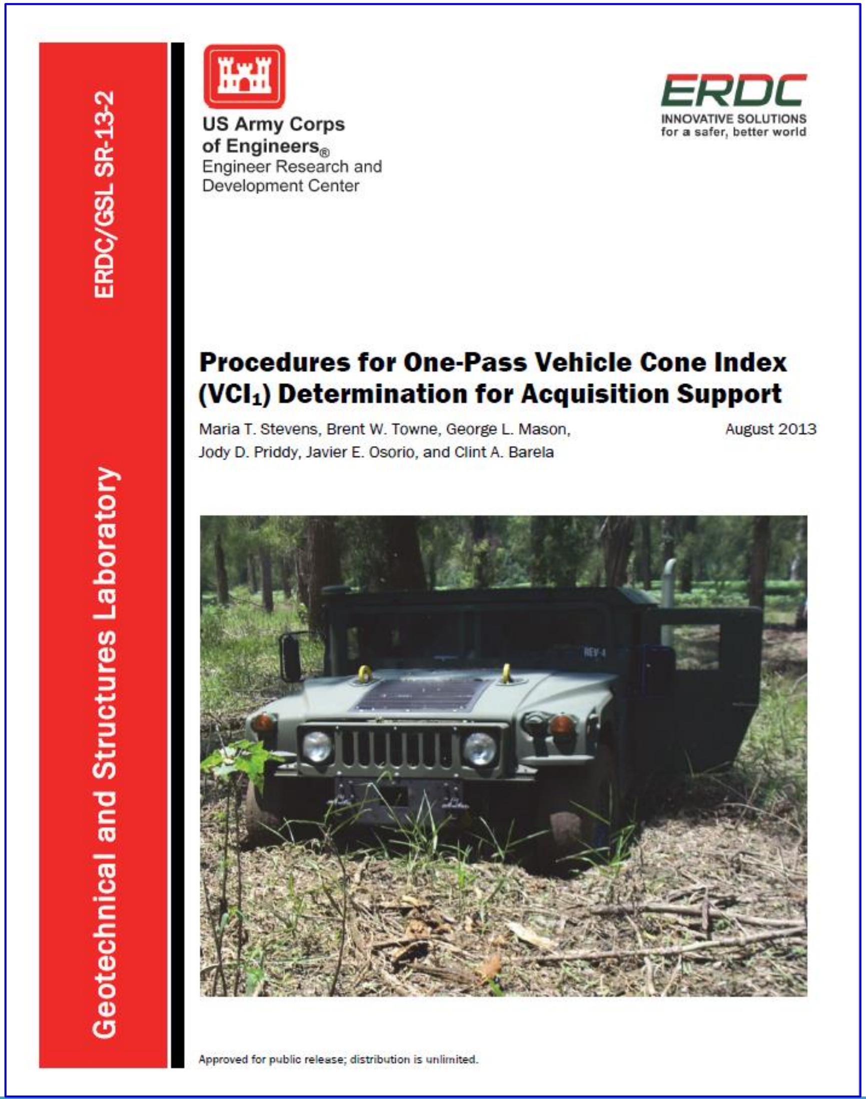
- **Originally developed for airfield and roadway construction field survey methods to establish strength and stratification**
- **Has evolved to become the most common point of reference for soil strength assessment for construction, agriculture and off road mobility**
- **Measuring CI and the remolding index (RI) and their product rating cone index (RCI) are quick and simple procedures, when measuring *soil* strength**



Remold equipment:
1. **Hvorslev sampler.**
2. **Cone penetrometer.**
3. **Drop hammer.**
4. **Remold cylinder.**
5. **Remold cylinder base.**
6. **Sample containers.**
7. **Wire saw.**

Vehicle Cone Index (VCI)

- **The correlation of RCI to vehicle mobility (Go/NoGo) is called the Vehicle Cone Index (VCI). This is the current soft soil mobility model in NRMM**
  - VCI_1 = single pass strength level
  - VCI_{50} = 50 pass strength level
- **Measuring *vehicle* <u>mobility limits</u> in terms of soil RCI requires significant time effort and special test site with large very flat area of CH soil with gradually varying moisture content (receding shallow lake bed or seasonal river flood zone).**
- **CH soil is a worst case assumption**



ERDC/GSL SR-13-2

Geotechnical and Structures Laboratory

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Procedures for One-Pass Vehicle Cone Index (VCI_1) Determination for Acquisition Support

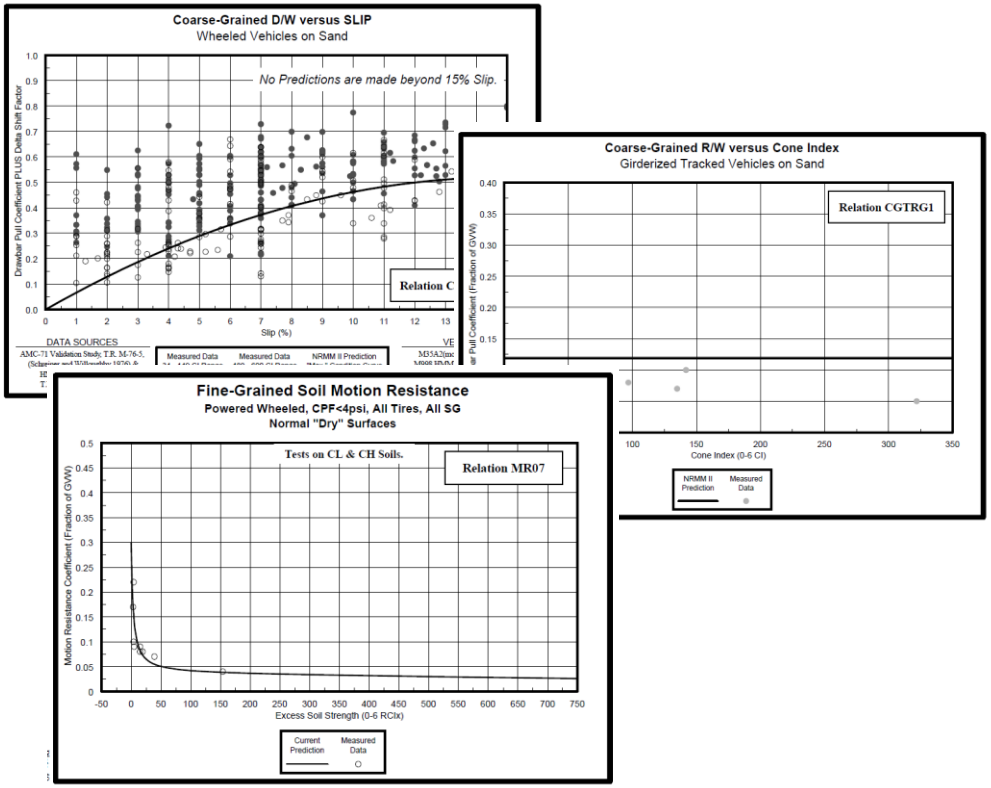
Maria T. Stevens, Brent W. Towne, George L. Mason, Jody D. Priddy, Javier E. Osorio, and Clint A. Barela

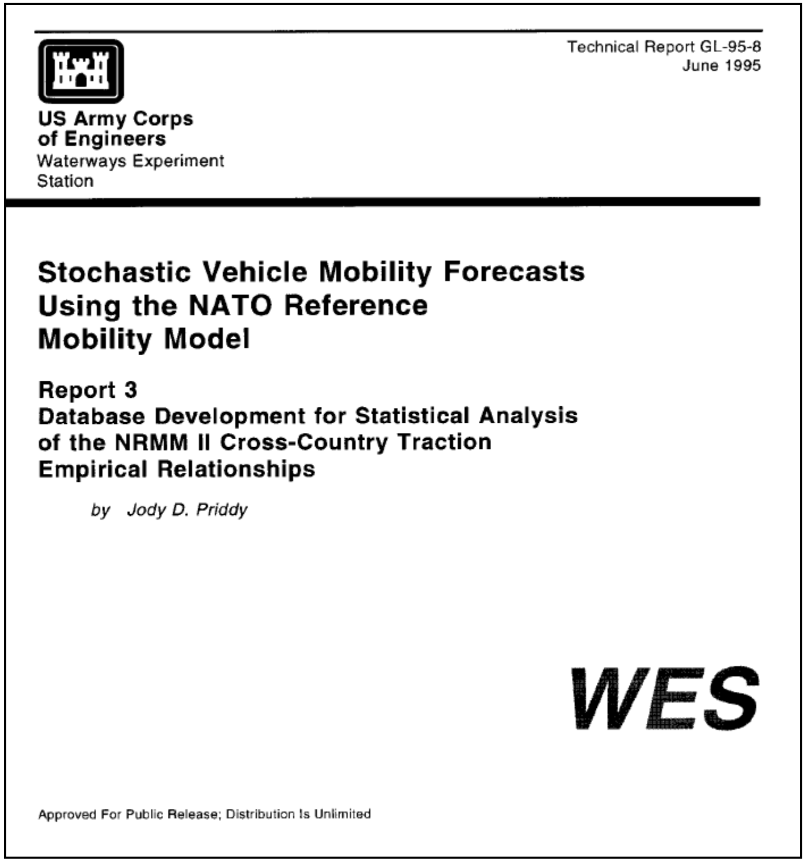
August 2013

Approved for public release; distribution is unlimited.

Cone Index (CI) Models in NRMM

- **“The relationships were empirically derived from field tests conducted with all-drive vehicles from the nineteen sixties through the nineteen eighties.”**





Technical Report GL-95-8
June 1995

US Army Corps
of Engineers
Waterways Experiment
Station

Stochastic Vehicle Mobility Forecasts Using the NATO Reference Mobility Model

Report 3
Database Development for Statistical Analysis of the NRMM II Cross-Country Traction Empirical Relationships

by *Jody D. Priddy*

WES

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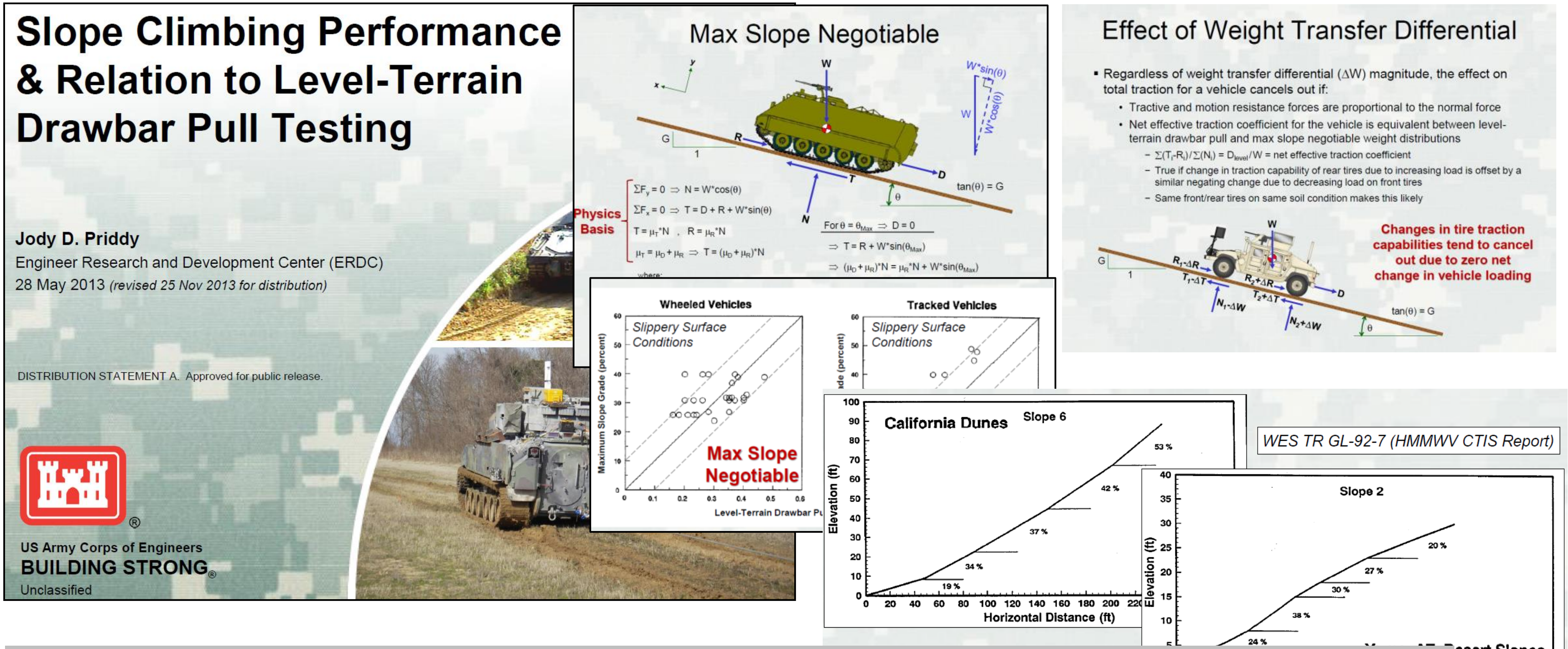
NRMM Supplementals



Slope Climbing Performance & Relation to Level-Terrain Drawbar Pull Testing

Jody D. Priddy
Engineer Research and Development Center (ERDC)
28 May 2013 *(revised 25 Nov 2013 for distribution)*

DISTRIBUTION STATEMENT A. Approved for public release.

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Max Slope Negotiable

Physics Basis

$\Sigma F_y = 0 \Rightarrow N = W^*\cos(\theta)$

$\Sigma F_x = 0 \Rightarrow T = D + R + W^*\sin(\theta)$

$T = \mu_T{}^*N \quad , \quad R = \mu_R{}^*N$

$\mu_T = \mu_D + \mu_R \Rightarrow T = (\mu_D + \mu_R)^*N$

where:

For $\theta = \theta_{Max} \Rightarrow D = 0$

$\Rightarrow T = R + W^*\sin(\theta_{Max})$

$\Rightarrow (\mu_D + \mu_R)^*N = \mu_R{}^*N + W^*\sin(\theta_{Max})$

Effect of Weight Transfer Differential

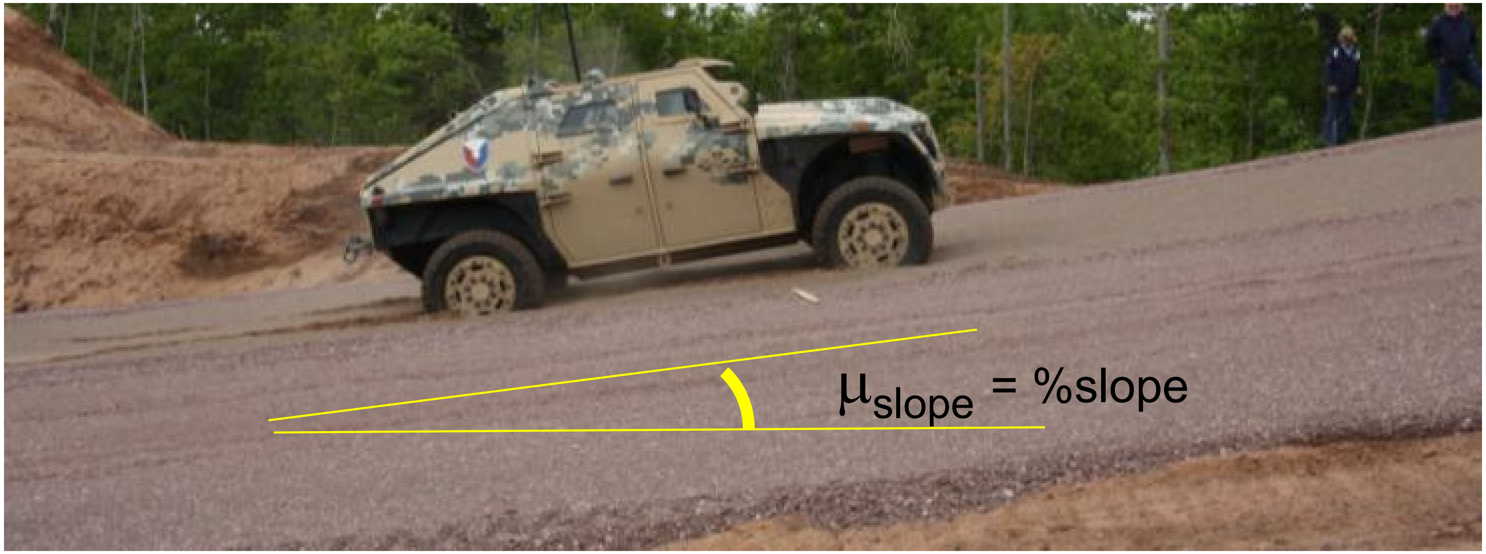
- Regardless of weight transfer differential (ΔW) magnitude, the effect on total traction for a vehicle cancels out if:
  - Tractive and motion resistance forces are proportional to the normal force
  - Net effective traction coefficient for the vehicle is equivalent between level-terrain drawbar pull and max slope negotiable weight distributions
    - $\Sigma(T_i\text{-}R_i)/\Sigma(N_i) = D_{level}/W$ = net effective traction coefficient
    - True if change in traction capability of rear tires due to increasing load is offset by a similar negating change due to decreasing load on front tires
    - Same front/rear tires on same soil condition makes this likely

Changes in tire traction capabilities tend to cancel out due to zero net change in vehicle loading

WES TR GL-92-7 (HMMWV CTIS Report)

US Army ERDC Study Shows Simple Terramechanics Physics is Reliable But Few Slopes Are Homogeneous, Sand Performance Requires a 2% Penalty for Slip-Sinkage, And All Predictions Degrade After 20% *(Note: CDT Slope is sand and progressively increasing)*

Go/NoGo and Speed Made Good: Motion Resistance Coefficients (MR)



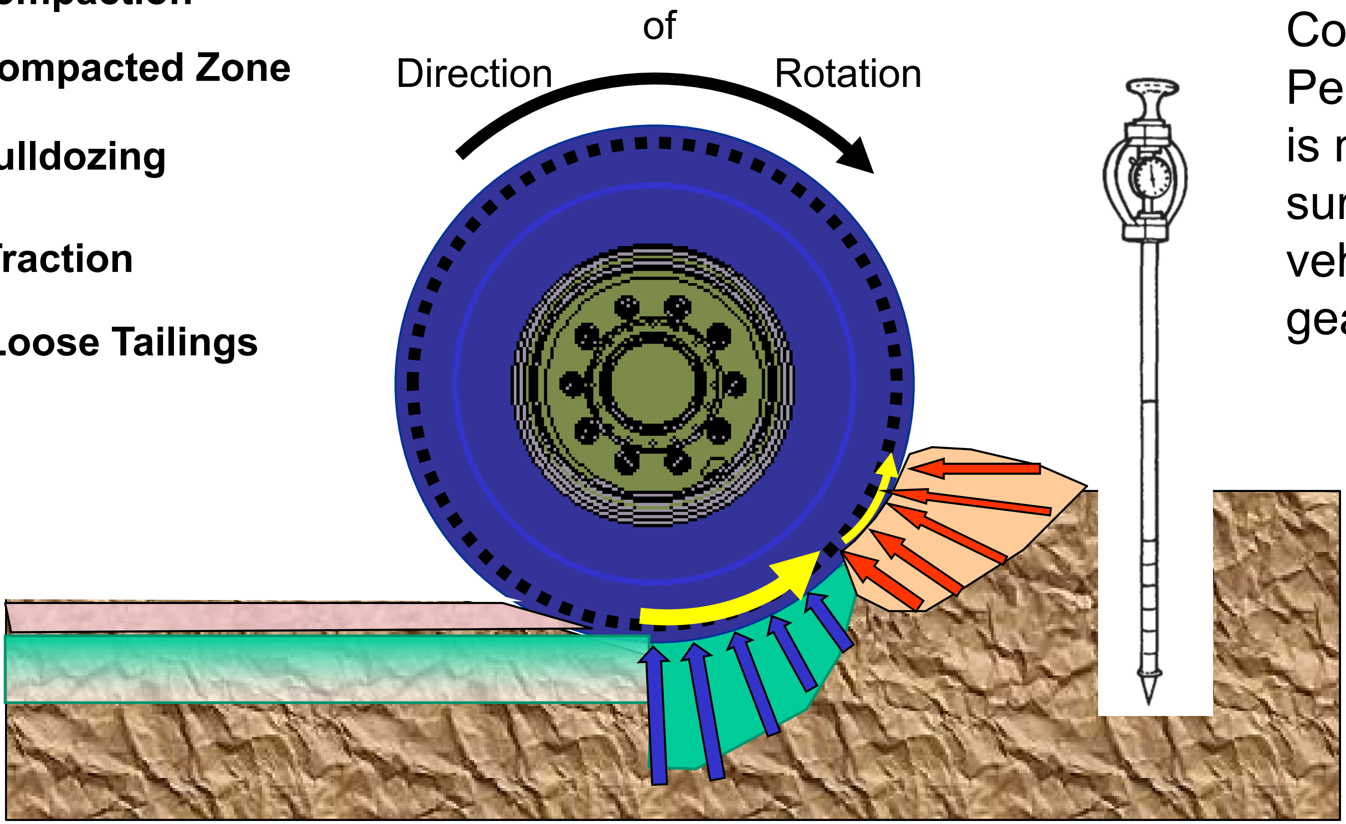
Power Limited Max Slope achievable (%) = $\sum \frac{\boldsymbol{Power}_{wheel}}{\boldsymbol{R}_{rolling}\ \boldsymbol{\omega}_{wheel}\ \boldsymbol{W}_{wheel}} - MR_{soil}$

Traction limited slope achievable $\mu_{slope} = \Sigma_{wheels} (\mu_{soil\_traction} - MR_{soil})$

Compaction, Traction, and Bulldozing Around a Driven Wheel in Soft Soil

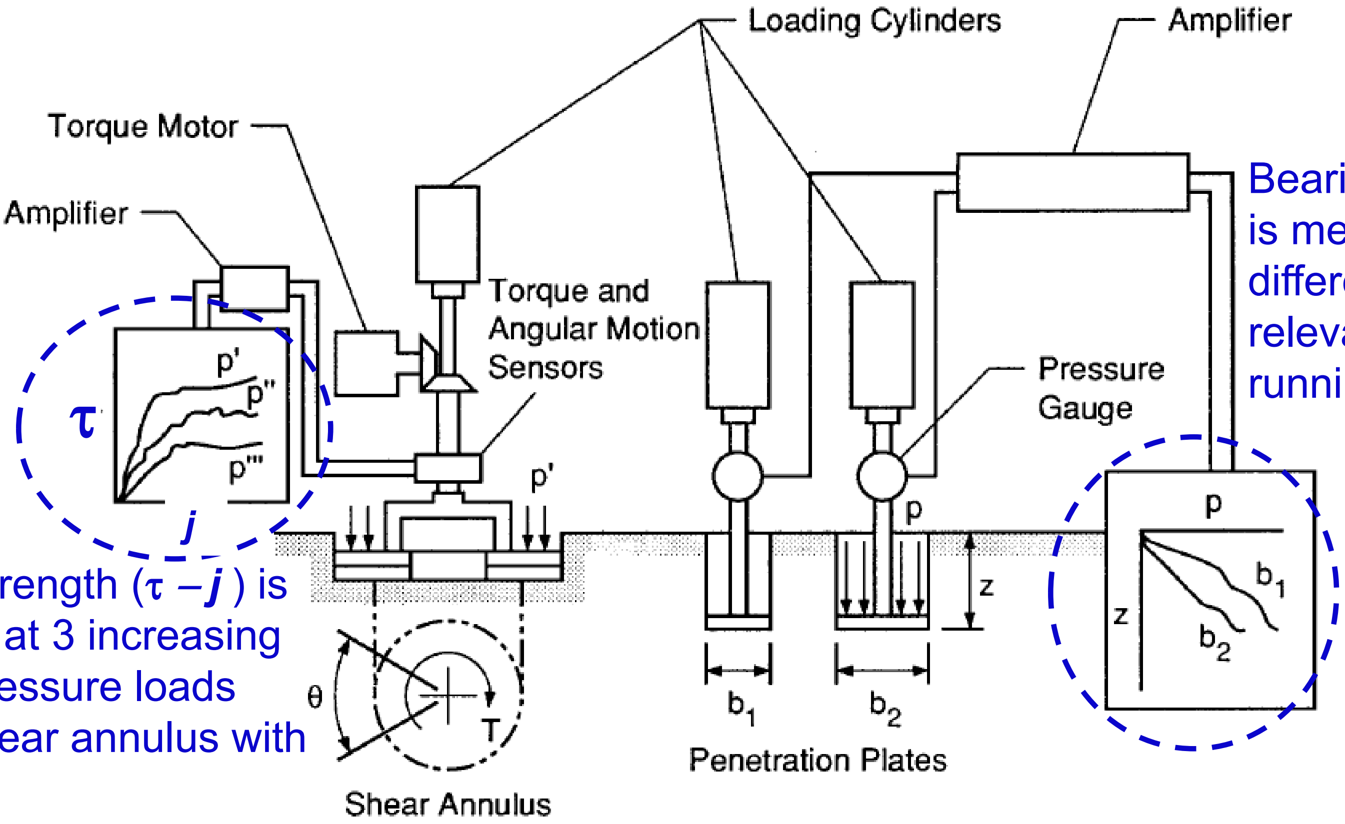
Key

- **Compaction**
- **Compacted Zone**
- **Bulldozing**
- **Traction**
- **Loose Tailings**



Cone Penetrometer is not a good surrogate for vehicle running gear physics

ST Bevameter



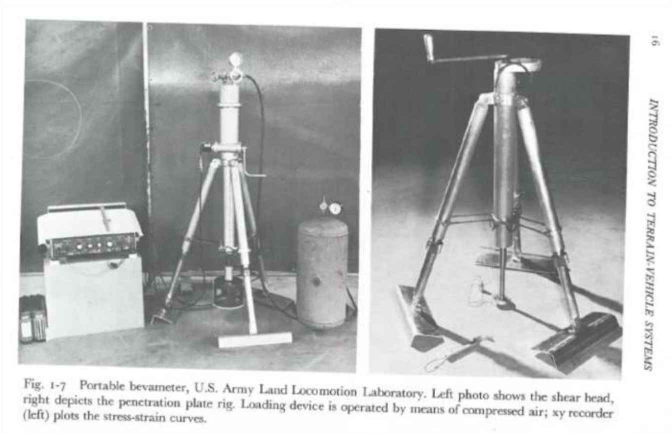
Bearing strength (***p-z***) is measured with two different plate sizes relevant to vehicle running gear

Tractive strength ($\tau - j$) is measured at 3 increasing bearing pressure loads using a shear annulus with grousers

- The Bevameter method provides a better analog of vehicle running gear than CI
- Bearing strength in the presence of tractive loads is not measured
- All measurements are acquired on relatively flat (small slope) terrain

Bevameters

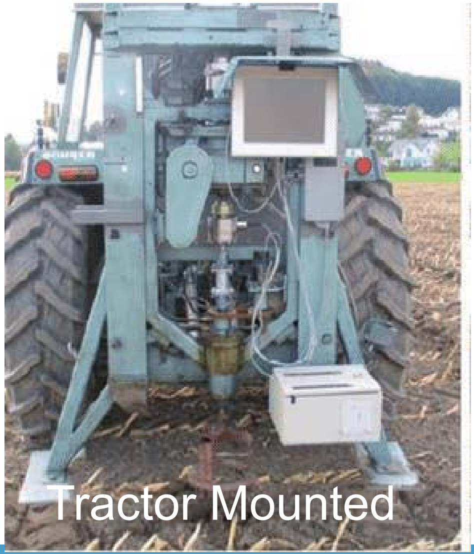
Vehicle Mounted (Wong)



16 INTRODUCTION TO TERRAIN-VEHICLE SYSTEMS

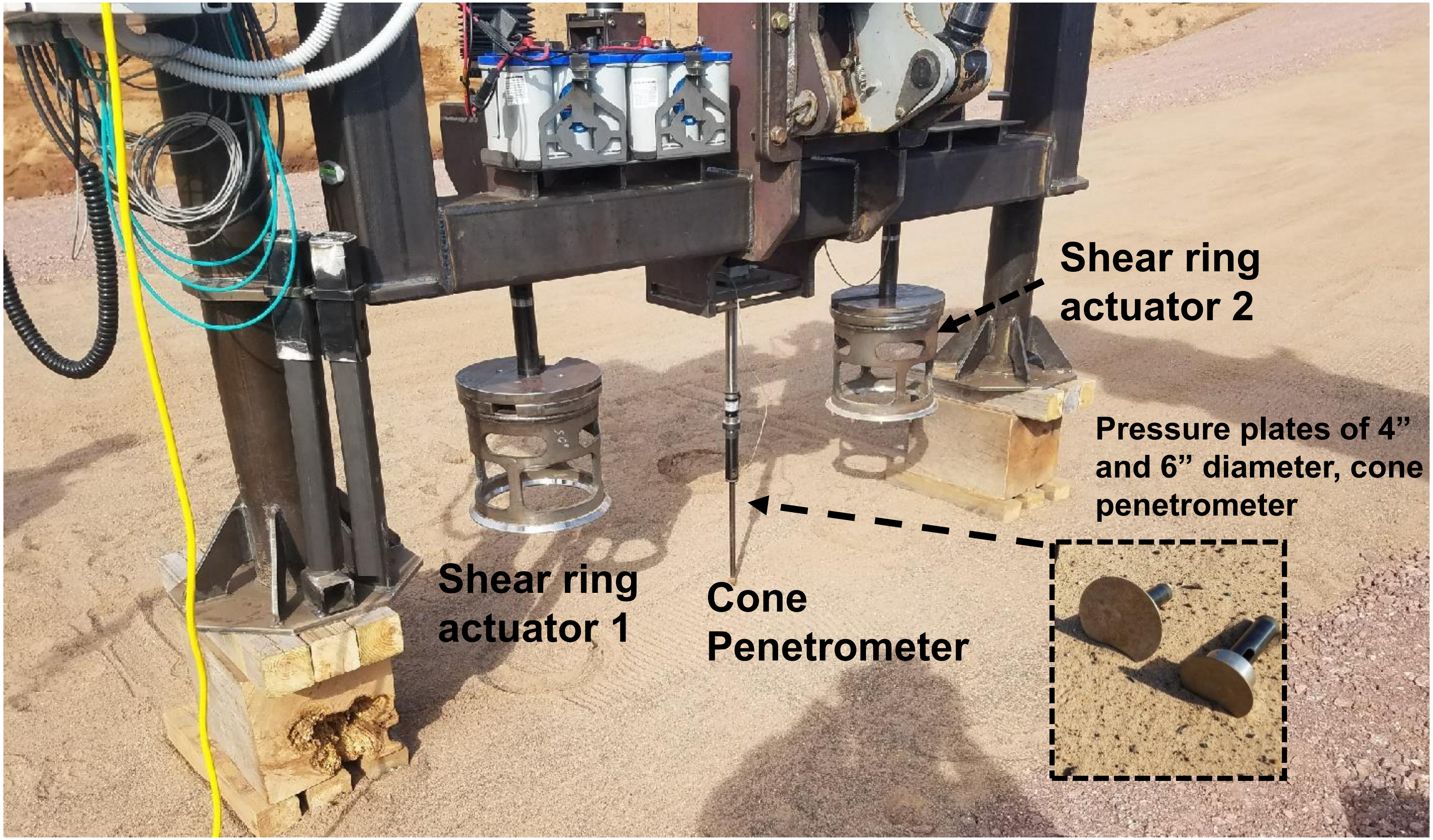
Fig. 1-7 Portable bevameter, U.S. Army Land Locomotion Laboratory. Left photo shows the shear head, right depicts the penetration plate rig. Loading device is operated by means of compressed air; xy recorder (left) plots the stress-strain curves.

Portable (Bekker)



Tractor Mounted

KRC CDT Bevameter



Shear ring actuator 2

Pressure plates of 4” and 6” diameter, cone penetrometer

Shear ring actuator 1

Cone Penetrometer

Pressure-Sinkage (p-z) Equations

- **Bernstein (1913):** $p = kz^n$
- **Bekker (~1950s):** $p = \left(\frac{k_c}{b} + k_\varphi\right) z^n$
- **Reece (1965):** $p = \left(k'_c + bk'_\varphi\right)\left(\frac{z}{b}\right)^n$
- **Wong (1984):** $\mathrm{k_{unload} = k_0 + A_{unload}\, z_{unload}}$

Accounts for known components of soil material model strength from footing bearing capacity theory to account differing running gear geometries

repetitive loading effects thru tracking of permanent deformation and modeling the elastic reaction on compacted soil

Key Characteristics of p-z Data

Data from [Jayakumar, 2014] shows typical p-z data

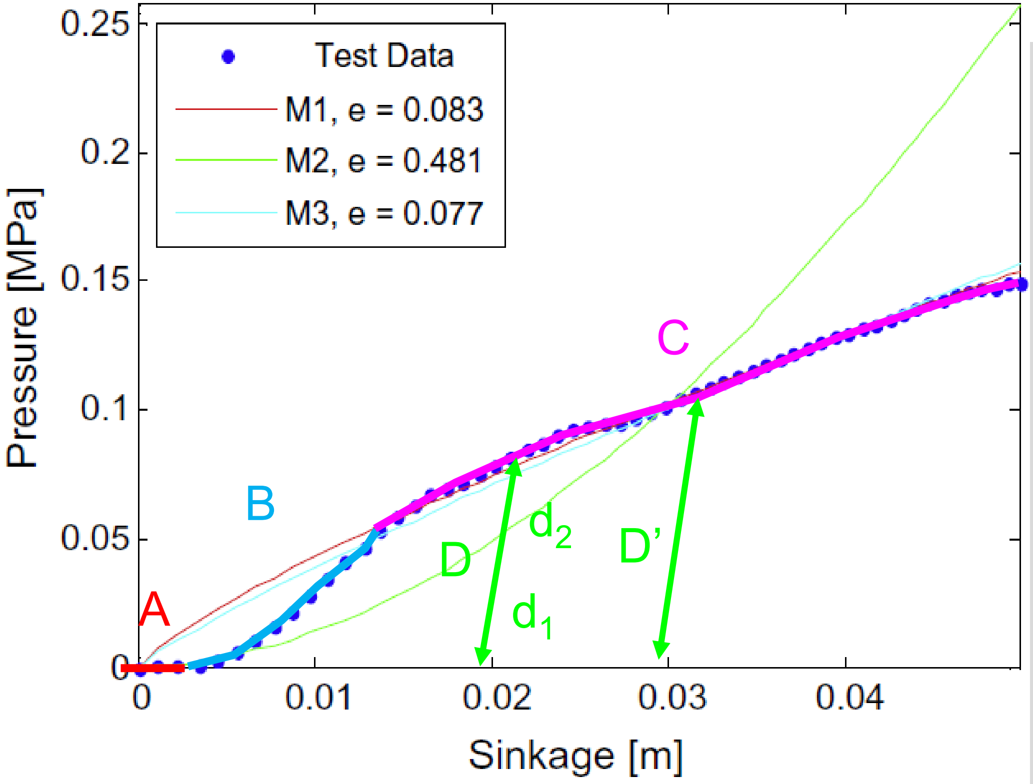


Fig. 7. Sample estimation for 5-cm plate.

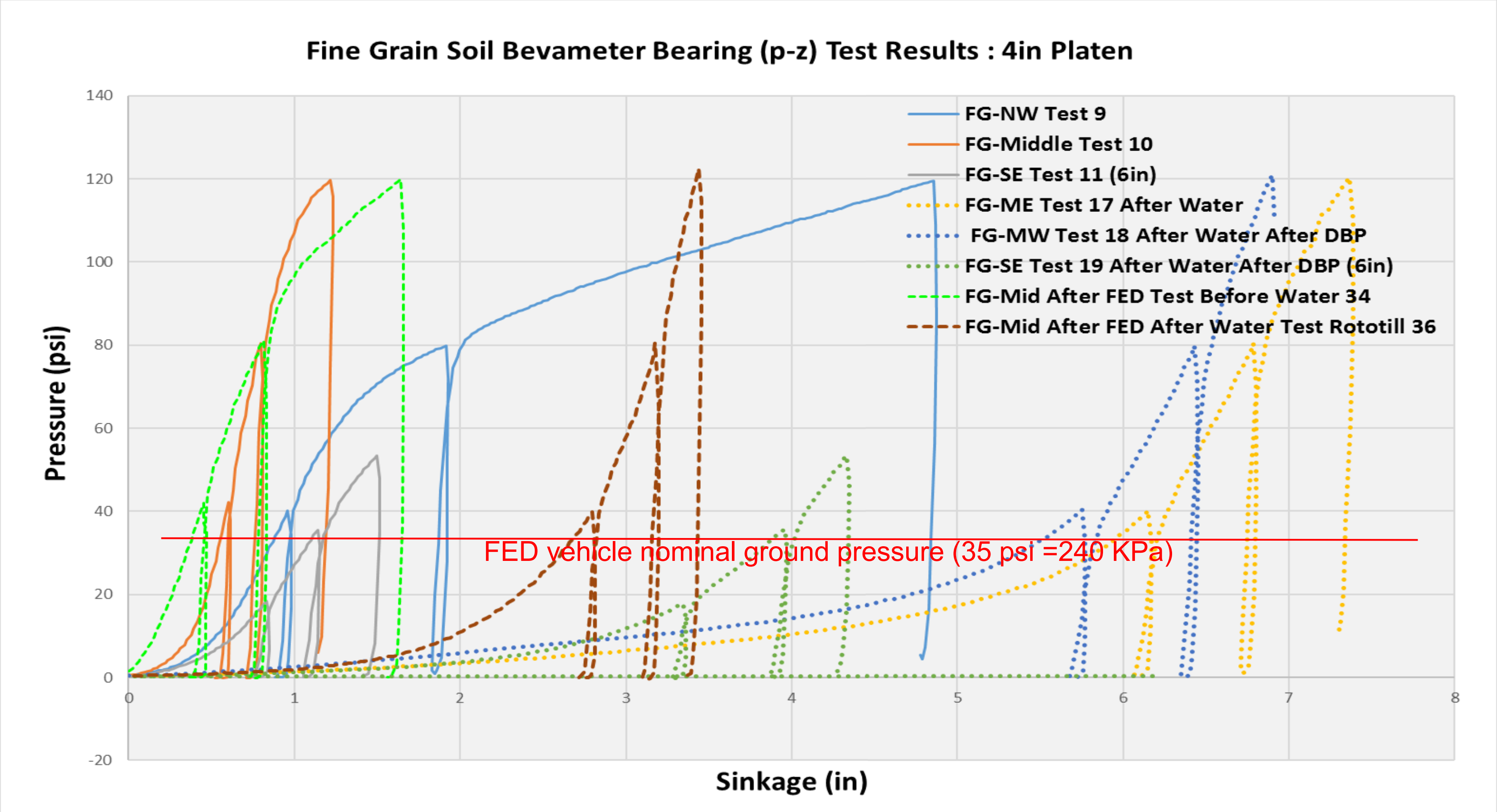
Regime A: *is sinkage measurement error offset to the onset of actual soil loading; ("fluff" layer)*

Regime B: *is the compacting of loose soil; the soil is strengthening and n>1;*

Regime C: *There is an inflection point with changing exponent, moving toward n≤1 in which soil bearing failure is controlled by Terzaghi theory. Model parameter identification is dependent upon peak pressure p_{max} regime in the specific vehicle application for which it will be used*

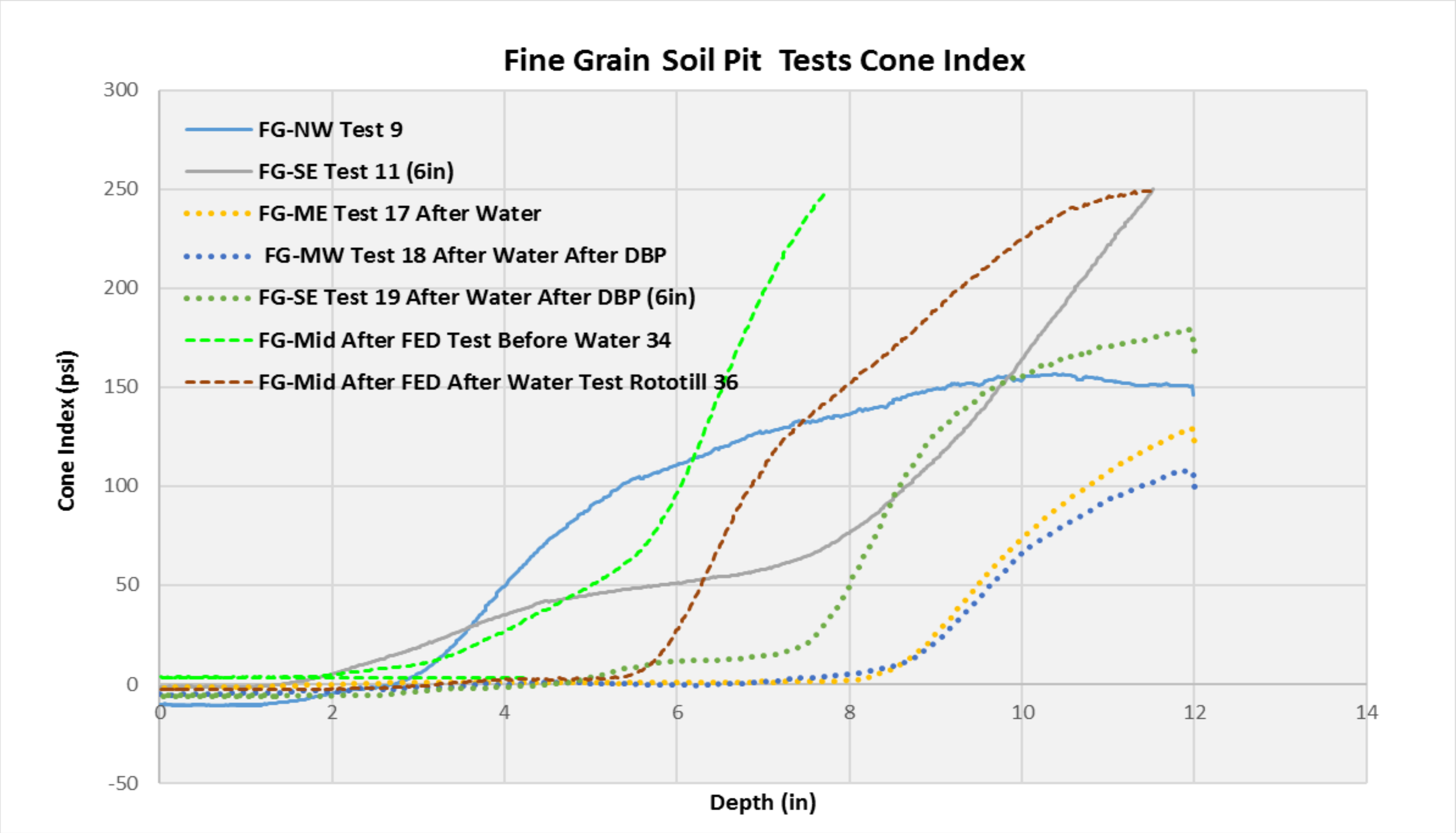
Regime D: *elastic unload/reload portions of the response*

CDT p-z Data Fine Grain



Fine Grain Soils are very sensitive to moisture and density (tillage and traffic)
Nominal pressure value reduces as sinkage increases due to larger tire footprint

CDT p-z Data Fine Grain: CI Correlation

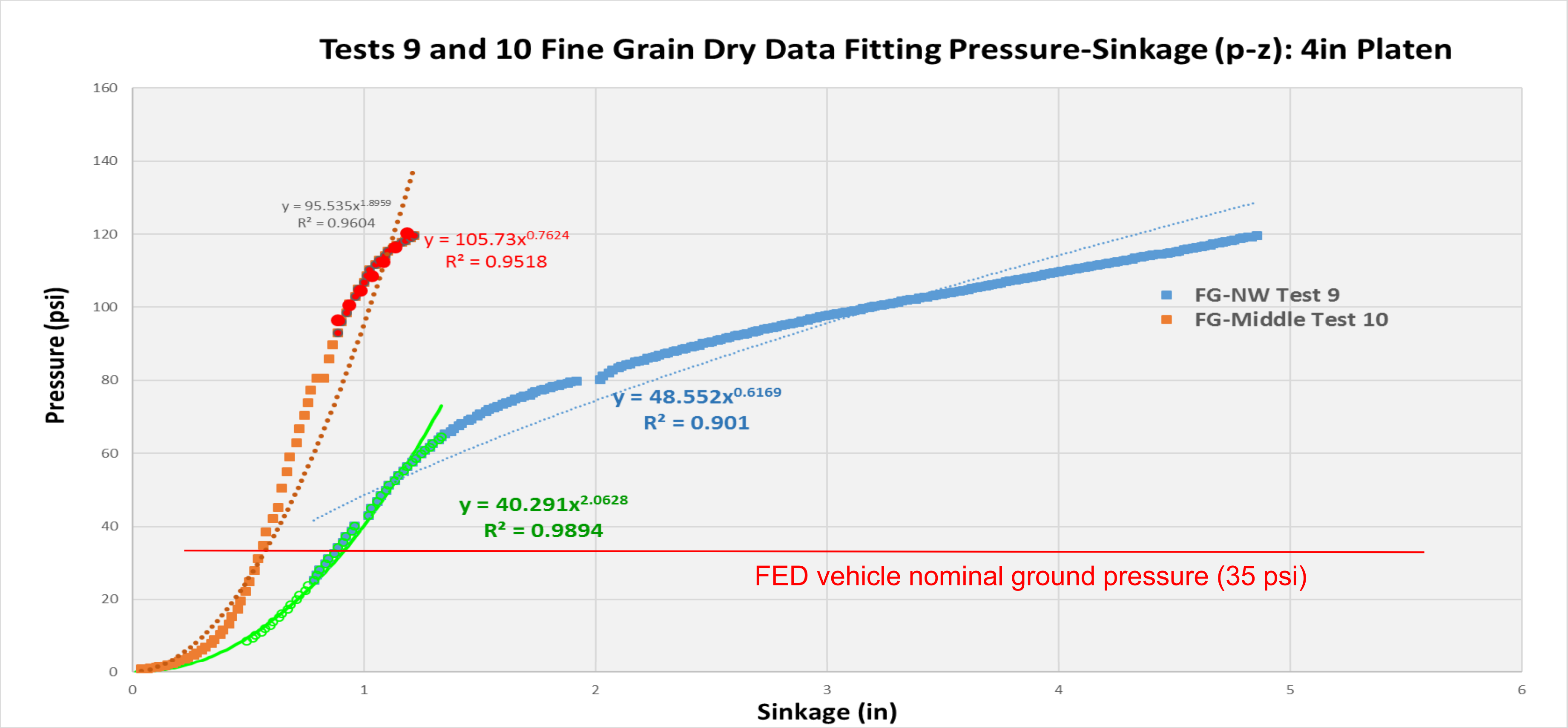


Cone Index Traces Give a Qualitative Clue, but are not a quantitative predictor of the relative trends with Fine Grain Soils Bevameter p-z results

CDT Bevameter Results

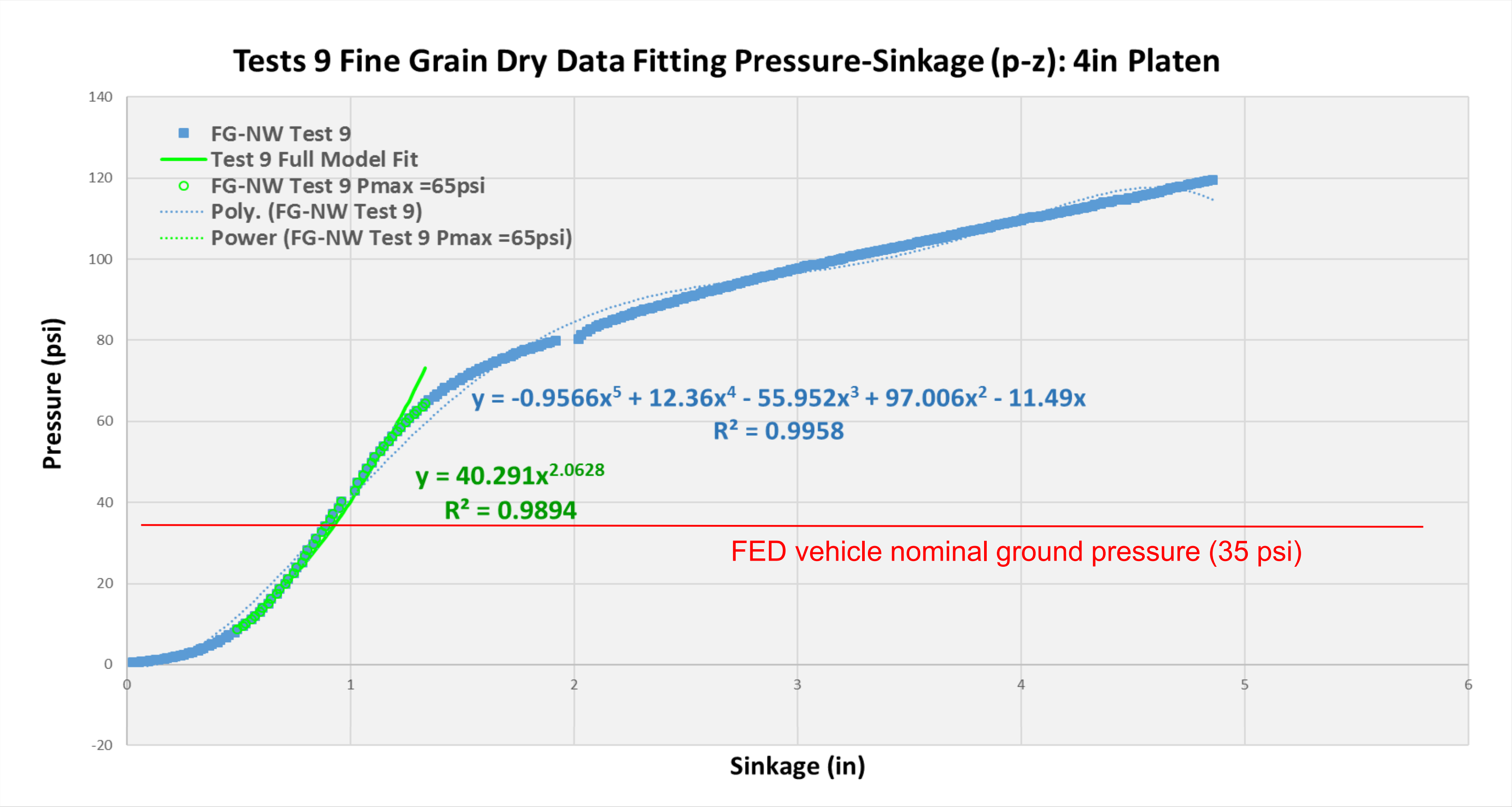
	Sinkage Plates				Grouser Shear Ring			Rubber Ring		
Location	n	Kc (lb/in n+1)	Kp (lb/in n+2)	ε	C (psi)	Phi (deg)	K avg (in)	C (psi)	Phi (deg)	K avg (in)
Variable Hill Climb, 2NS Sand, Dry	0.5	46.9	10.2	0.9	0.2	32.0	0.8	0.0	26.7	0.3
Fine Grain Pit, Dry	1.8	420.9	-106.8	0.9	0.2	36.7	0.7	0.0	28.8	0.3
Coarse Grain Pit, Dry	0.6	34.7	17.6	0.9	0.2	31.4	0.8	0.0	26.7	0.4
Fine Grain Pit, Wet	3.3	0.1	0.1	0.8	0.5	35.2	1.2	0.1	28.8	0.3

P-z Model Data Fitting



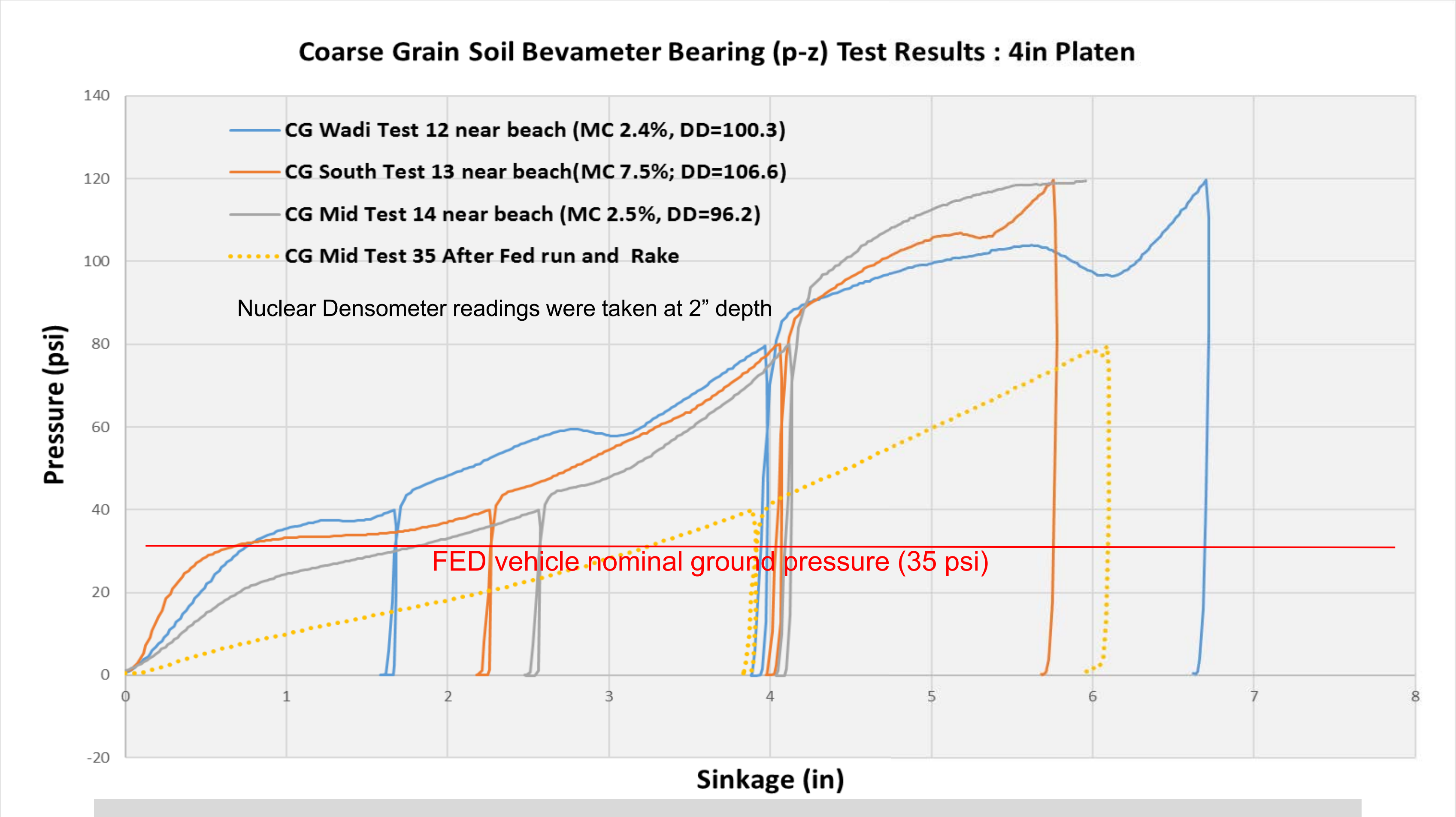
CDT data is applicable to a broad range of ground pressures.
P-Z power law model parameters must be selected to represent the operational range of ground pressures

P-z Model Data Fitting



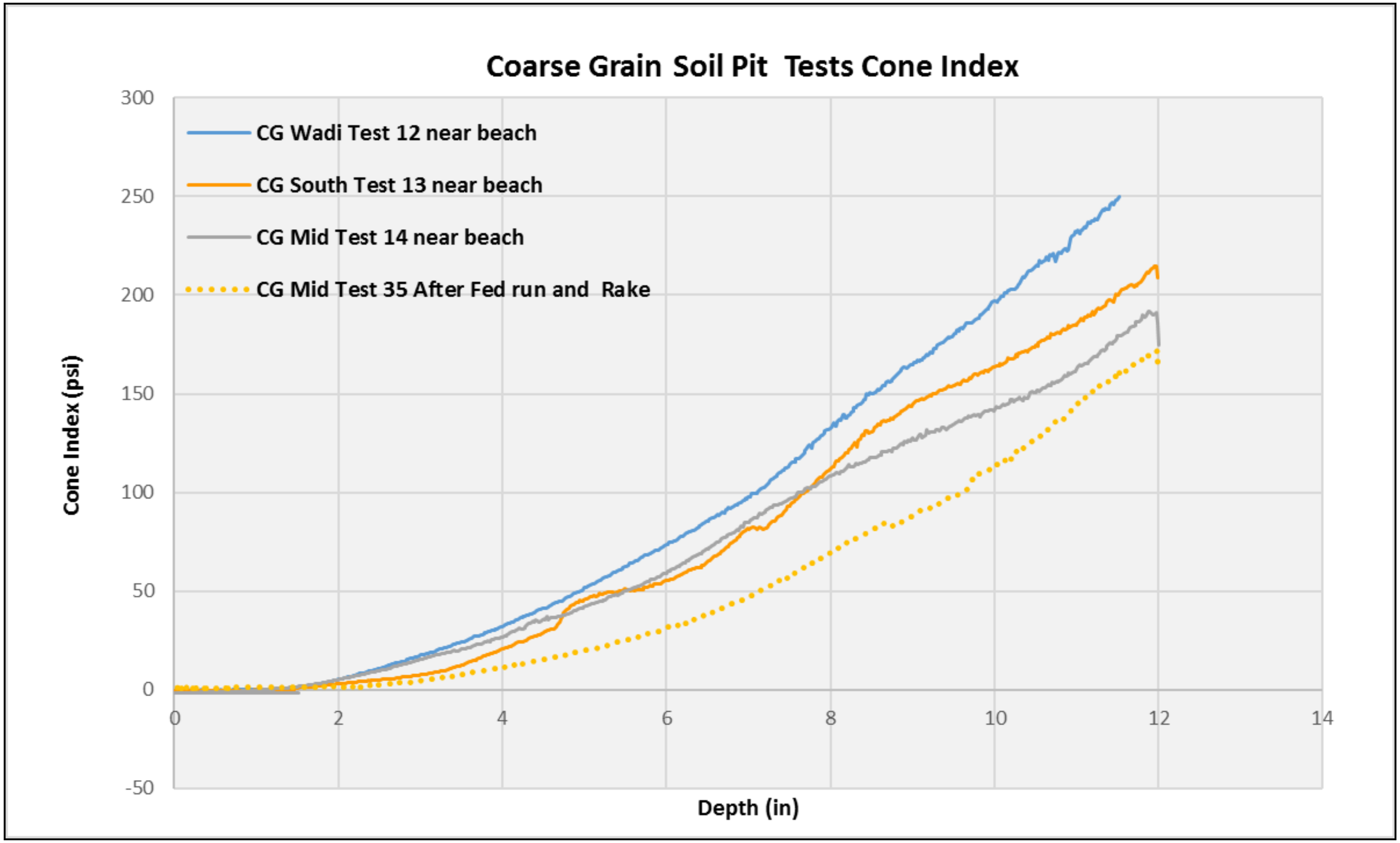
A polynomial is a more accurate data fit across the entire pressure range

CDT p-z Data Coarse Grain



Coarse Grain Soils showed ~1inch natural variation and were also sensitive to tillage and traffic

CDT p-z Data Coarse Grain: CI Correlation

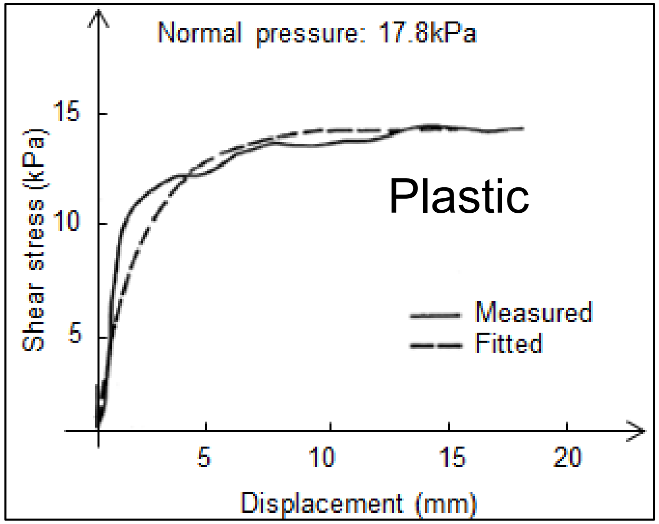


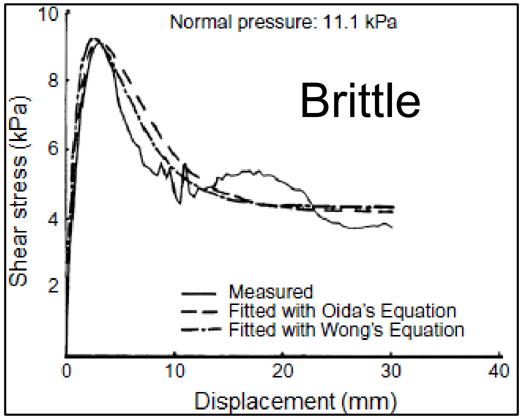
Cone Index Readings Are Qualitatively Predictive of Coarse Grain Soils
Bevameter p-z results for significant differences in density

Traction Equations ($\tau - j$)

Janosi-Hanamoto (~1950s):

$$\tau = [c + p \tan \phi](1 - e^{(-j/k)})$$





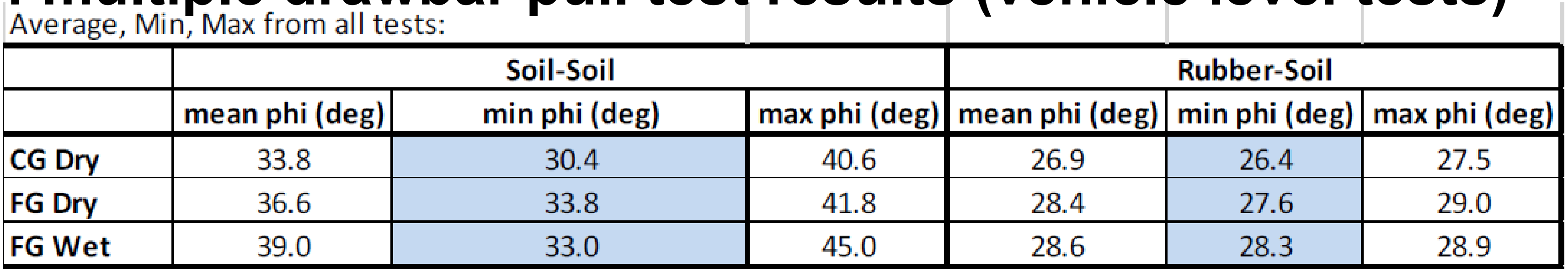
where:

τ : tractive stress
c : cohesion
p *: bearing pressure*
ϕ : friction angle
j : slip/shear displacement
k : slip/shear modulus

Model Parameters Used in ST Models for CDT Event Predictions

P-z: Pressure-sinkage equation most representative data set for each event/scenario was selected by the s/w vendor from a subset of all results recommended by KRC to be good representative model fits

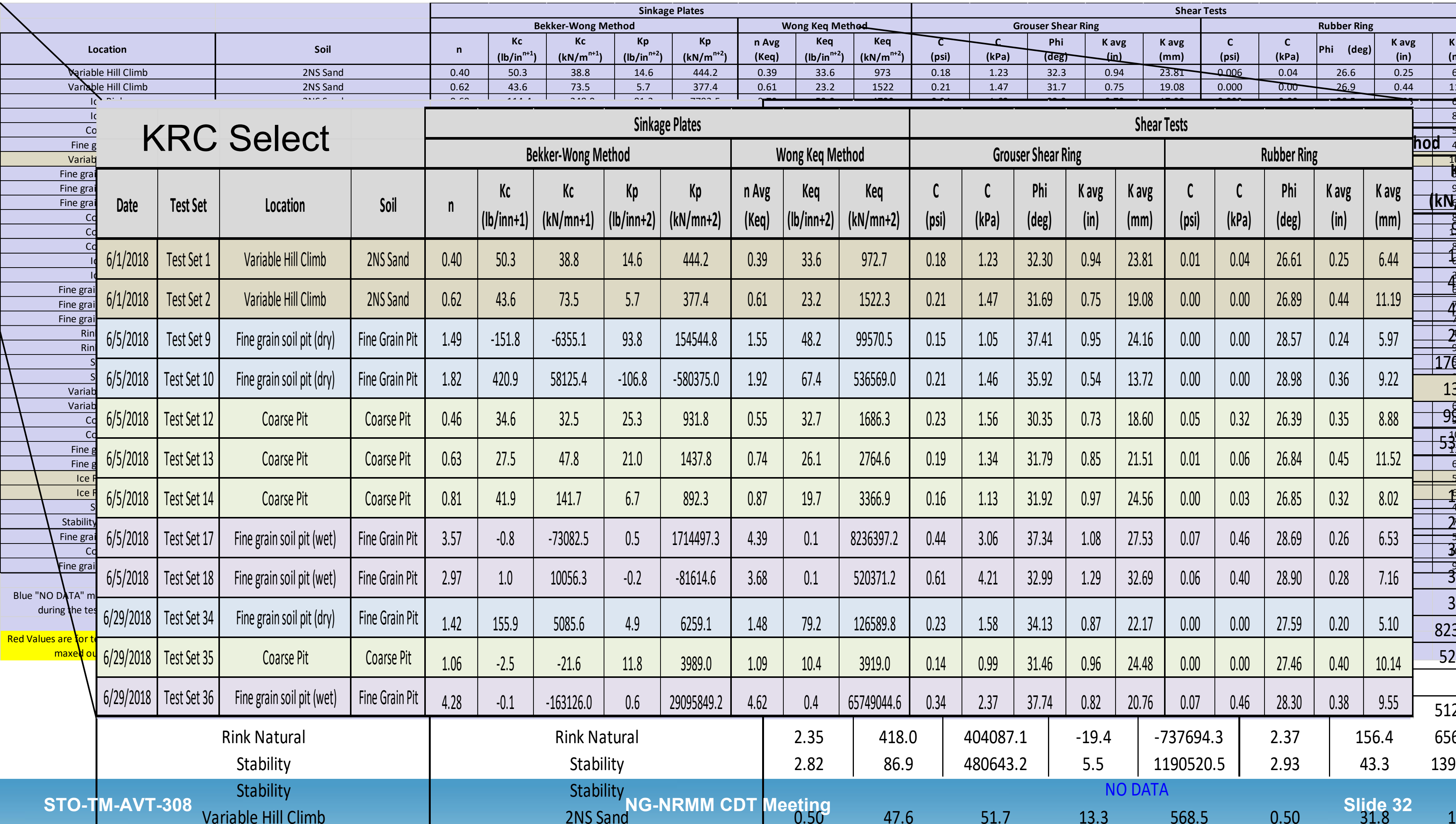
τ-j : Traction equation parameters were based on the average of multiple drawbar pull test results (vehicle level tests)



Average, Min, Max from all tests:

	Soil-Soil			Rubber-Soil		
	mean phi (deg)	min phi (deg)	max phi (deg)	mean phi (deg)	min phi (deg)	max phi (deg)
CG Dry	33.8	30.4	40.6	26.9	26.4	27.5
FG Dry	36.6	33.8	41.8	28.4	27.6	29.0
FG Wet	39.0	33.0	45.0	28.6	28.3	28.9

CDT Bevameter Data Sets



Location	Soil	n	Kc (lb/in^{n+1})	Kc (kN/m^{n+1})	Kp (lb/in^{n+2})	Kp (kN/m^{n+2})	n Avg (Keq)	Keq (lb/in^{n+2})	Keq (kN/m^{n+2})	C (psi)	C (kPa)	Phi (deg)	K avg (in)	K avg (mm)	C (psi)	C (kPa)	Phi (deg)	K avg (in)
		Sinkage Plates								Shear Tests								
		Bekker-Wong Method					Wong Keq Method			Grouser Shear Ring					Rubber Ring			
Variable Hill Climb	2NS Sand	0.40	50.3	38.8	14.6	444.2	0.39	33.6	973	0.18	1.23	32.3	0.94	23.81	0.006	0.04	26.6	0.25
Variable Hill Climb	2NS Sand	0.62	43.6	73.5	5.7	377.4	0.61	23.2	1522	0.21	1.47	31.7	0.75	19.08	0.000	0.00	26.9	0.44

KRC Select

Date	Test Set	Location	Soil	n	Kc (lb/inn+1)	Kc (kN/mn+1)	Kp (lb/inn+2)	Kp (kN/mn+2)	n Avg (Keq)	Keq (lb/inn+2)	Keq (kN/mn+2)	C (psi)	C (kPa)	Phi (deg)	K avg (in)	K avg (mm)	C (psi)	C (kPa)	Phi (deg)	K avg (in)	K avg (mm)
				Sinkage Plates								Shear Tests									
				Bekker-Wong Method					Wong Keq Method			Grouser Shear Ring					Rubber Ring				
6/1/2018	Test Set 1	Variable Hill Climb	2NS Sand	0.40	50.3	38.8	14.6	444.2	0.39	33.6	972.7	0.18	1.23	32.30	0.94	23.81	0.01	0.04	26.61	0.25	6.44
6/1/2018	Test Set 2	Variable Hill Climb	2NS Sand	0.62	43.6	73.5	5.7	377.4	0.61	23.2	1522.3	0.21	1.47	31.69	0.75	19.08	0.00	0.00	26.89	0.44	11.19
6/5/2018	Test Set 9	Fine grain soil pit (dry)	Fine Grain Pit	1.49	-151.8	-6355.1	93.8	154544.8	1.55	48.2	99570.5	0.15	1.05	37.41	0.95	24.16	0.00	0.00	28.57	0.24	5.97
6/5/2018	Test Set 10	Fine grain soil pit (dry)	Fine Grain Pit	1.82	420.9	58125.4	-106.8	-580375.0	1.92	67.4	536569.0	0.21	1.46	35.92	0.54	13.72	0.00	0.00	28.98	0.36	9.22
6/5/2018	Test Set 12	Coarse Pit	Coarse Pit	0.46	34.6	32.5	25.3	931.8	0.55	32.7	1686.3	0.23	1.56	30.35	0.73	18.60	0.05	0.32	26.39	0.35	8.88
6/5/2018	Test Set 13	Coarse Pit	Coarse Pit	0.63	27.5	47.8	21.0	1437.8	0.74	26.1	2764.6	0.19	1.34	31.79	0.85	21.51	0.01	0.06	26.84	0.45	11.52
6/5/2018	Test Set 14	Coarse Pit	Coarse Pit	0.81	41.9	141.7	6.7	892.3	0.87	19.7	3366.9	0.16	1.13	31.92	0.97	24.56	0.00	0.03	26.85	0.32	8.02
6/5/2018	Test Set 17	Fine grain soil pit (wet)	Fine Grain Pit	3.57	-0.8	-73082.5	0.5	1714497.3	4.39	0.1	8236397.2	0.44	3.06	37.34	1.08	27.53	0.07	0.46	28.69	0.26	6.53
6/5/2018	Test Set 18	Fine grain soil pit (wet)	Fine Grain Pit	2.97	1.0	10056.3	-0.2	-81614.6	3.68	0.1	520371.2	0.61	4.21	32.99	1.29	32.69	0.06	0.40	28.90	0.28	7.16
6/29/2018	Test Set 34	Fine grain soil pit (dry)	Fine Grain Pit	1.42	155.9	5085.6	4.9	6259.1	1.48	79.2	126589.8	0.23	1.58	34.13	0.87	22.17	0.00	0.00	27.59	0.20	5.10
6/29/2018	Test Set 35	Coarse Pit	Coarse Pit	1.06	-2.5	-21.6	11.8	3989.0	1.09	10.4	3919.0	0.14	0.99	31.46	0.96	24.48	0.00	0.00	27.46	0.40	10.14
6/29/2018	Test Set 36	Fine grain soil pit (wet)	Fine Grain Pit	4.28	-0.1	-163126.0	0.6	29095849.2	4.62	0.4	65749044.6	0.34	2.37	37.74	0.82	20.76	0.07	0.46	28.30	0.38	9.55

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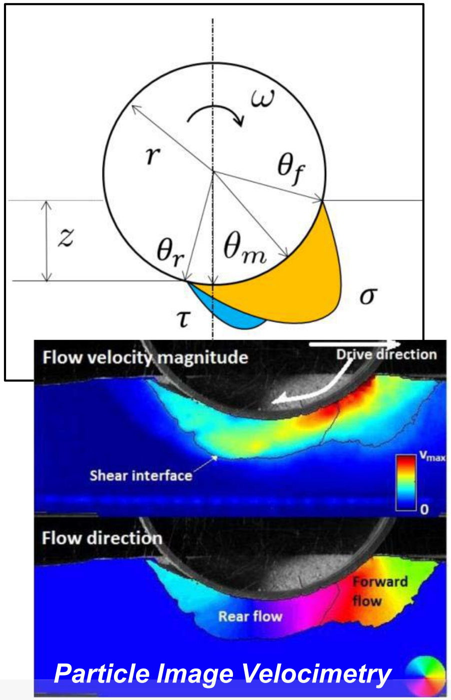
Red Values are for t
maxed ou

Rink Natural	Rink Natural	2.35	418.0	404087.1	-19.4	-737694.3	2.37	156.4
Stability	Stability	2.82	86.9	480643.2	5.5	1190520.5	2.93	43.3
Stability	Stability				NO DATA			
Variable Hill Climb	2NS Sand	0.50	47.6	51.7	13.3	568.5	0.50	31.8

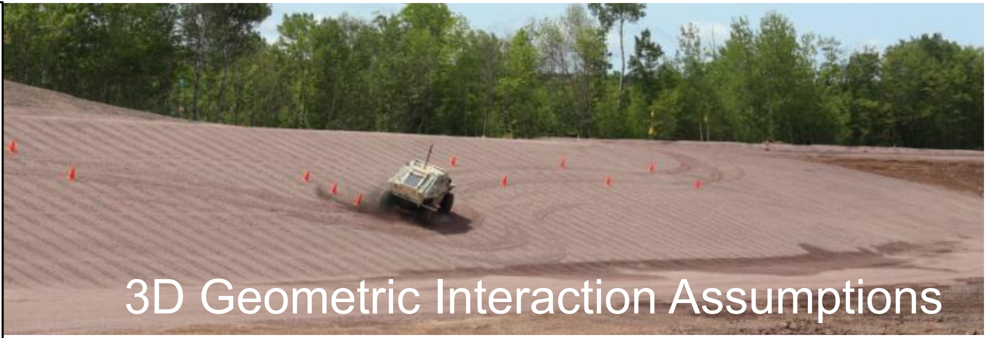
ST Numerical Models

- **Assume Bevameter data resolves downward to an arbitrary small dimension, allowing stress distributions to be integrated across any vehicle running gear and terrain interference**

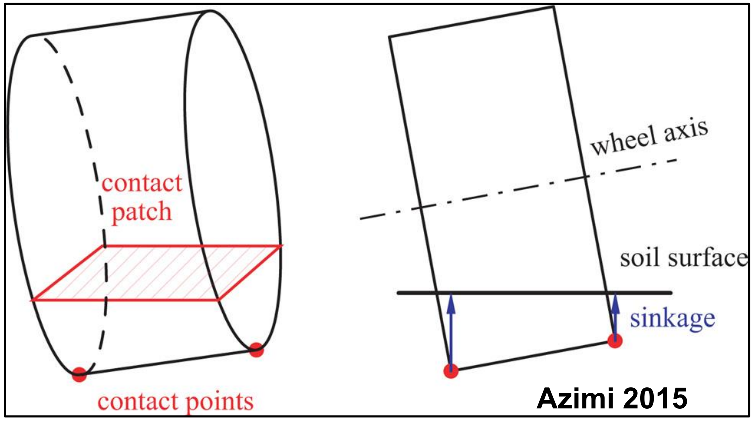


Validated wheel interaction equations

Lug Entrained Soil Shear Fraction



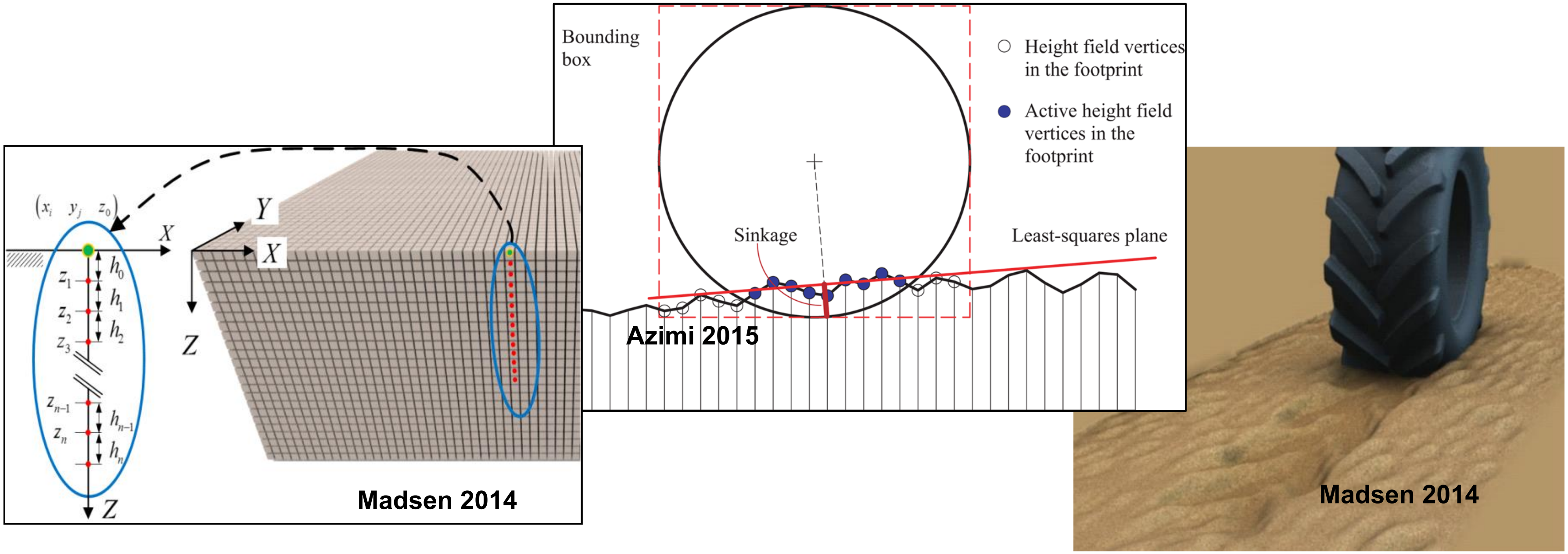
3D Geometric Interaction Assumptions



Azimi 2015

Permanent Deformation Tracking and Soil Transport Models Required For Soil Plasticity

- Soil compaction permanent deformation as well as shear states are tracked in height field cells
- Compute soil transport between cells based on slip grouser sinkage and shearing (slip-sinkage modeling)



Madsen 2014

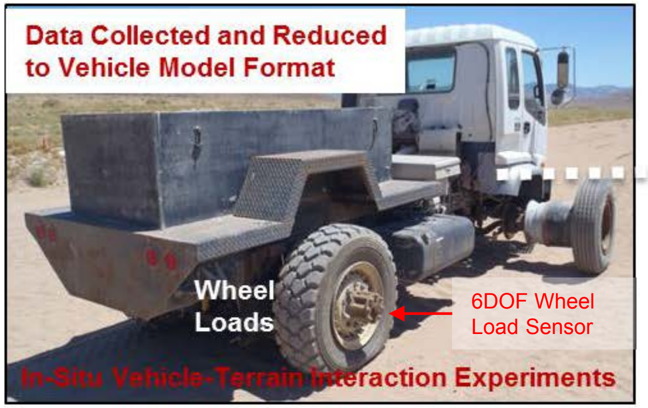
Azimi 2015

Madsen 2014

ST Model Features Used By CDT Participants

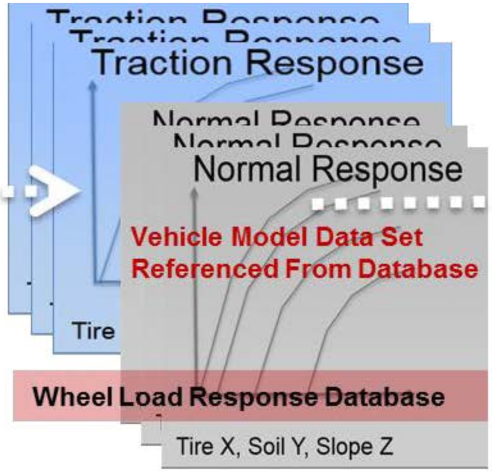
	3D Geometric Interaction	3D Force Model	Deformable Tire	Lug Effects	Permanent Deformation Tracking	Soil Transport (slip-sinkage)
AU	**YES**	**YES**	**YES**	**YES**		
CM Labs	**YES**	**YES**	**YES**	**YES**		
MSC	**YES**	**YES**	**YES**	**YES**		
NRMM			**YES**	**YES**		
VSDC			**YES**	**YES**	**YES**	

Running Gear Sensors of ST Model Parameters



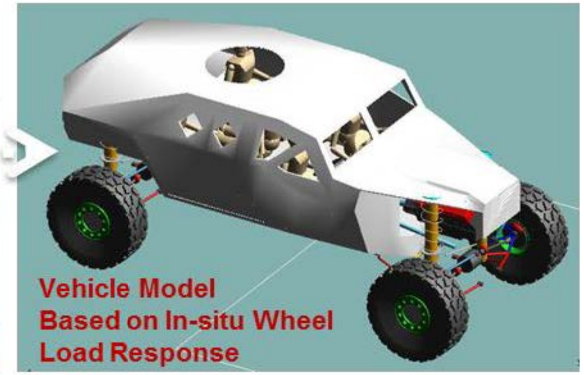
Data Collected and Reduced to Vehicle Model Format

NATC Instrumented Vehicle (NIV) (Hodges, 1992)



Vehicle Model Data Set Referenced From Database

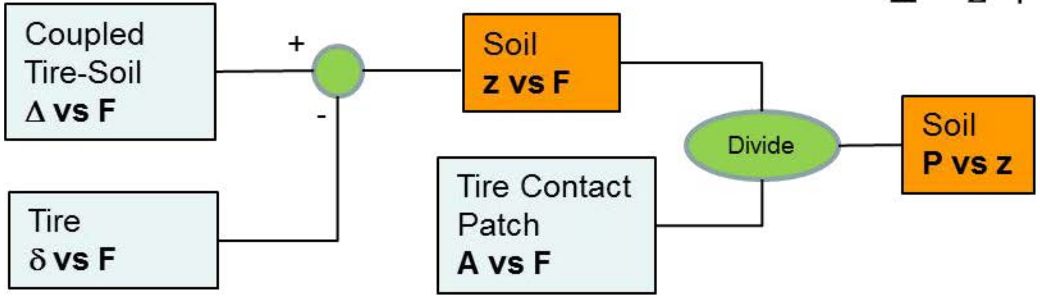
Wheel Load Response Database



Vehicle Model Based on In-situ Wheel Load Response

$$L = \sqrt{R^2 - (R - \Delta)^2} = \sqrt{2R\Delta - \Delta^2}$$

$$\Delta = z + \delta$$



Coupled Tire-Soil **Δ vs F**

Tire **δ vs F**

+

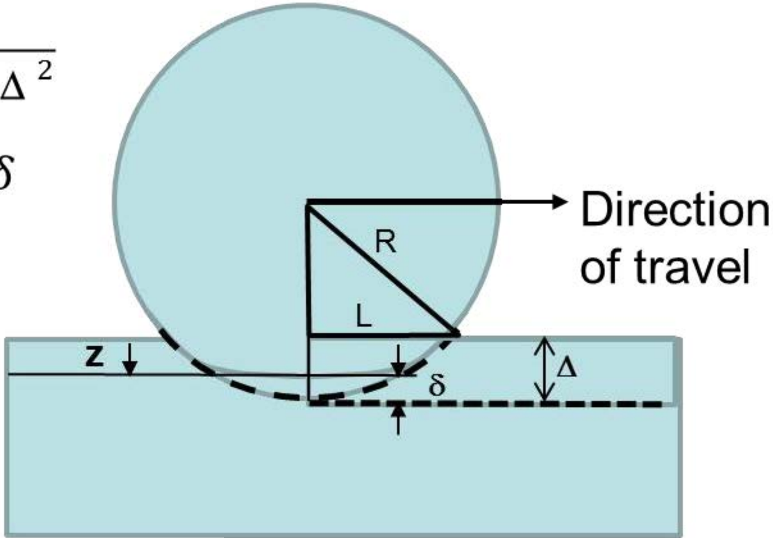
-

Soil **z vs F**

Divide

Tire Contact Patch **A vs F**

Soil **P vs z**



Running Gear Sensors of ST Model Parameters

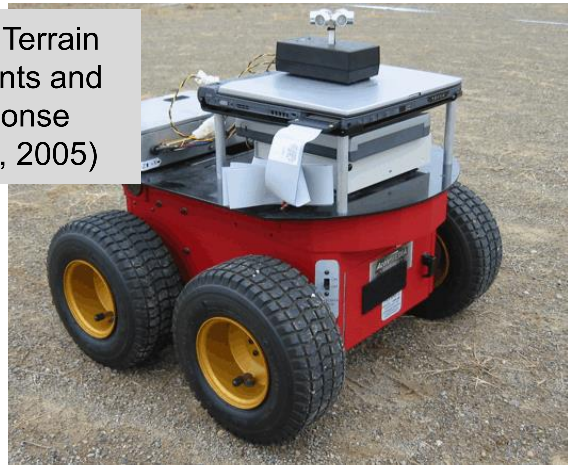
Tom Von Sturm
Bundeswehr, Germany

US Army CRREL Shoop et al, 1994

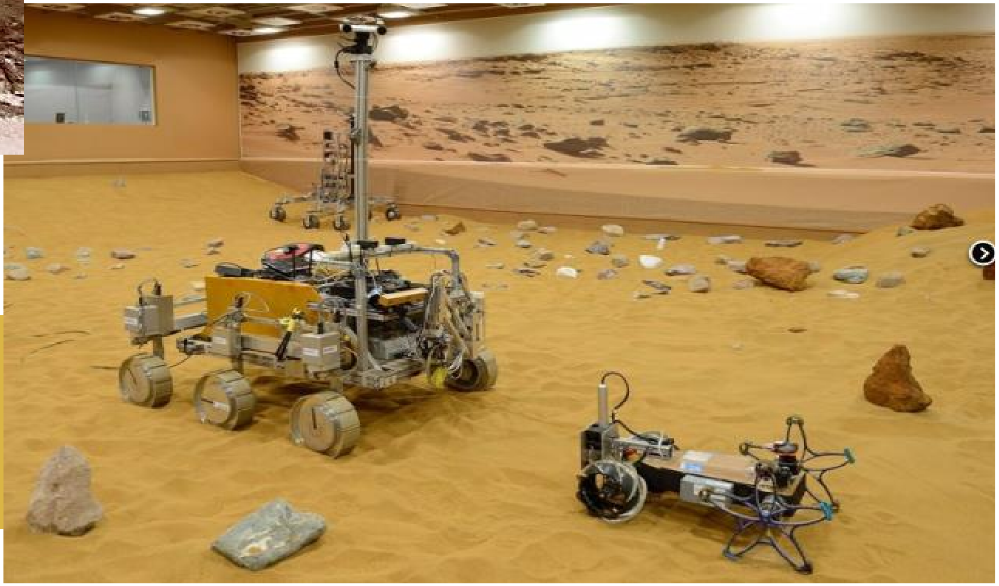
3DOF Wheel Load Sensor

Instrumented Vehicles / Vehicle as a Sensor

Nevada Automotive Test Center



Mobile Robot Identifies Terrain Type From Motor Currents and Vehicle Turning Response (Ojeda, et al, U of Mich, 2005)



FASTER (Forward Acquisition of Soil and Terrain Data for Exploration Rovers) employed a wheeled bevameter deployed ahead of vehicle as a bearing and traction strength sensor (European Planetary Science Congress 2014)

Vehicle as a Sensor: Path Average Values

- **Since the 1950s, it has been well understood (Bekker, Wong, others), for terrains where compaction is the primary motion resistance, the p-z equation parameters can be estimated from rut depth (z_s) and motion resistance (μ_{soil}) which can be continuously measured using the autonomy sensor suite (LIDAR, DIC using stereo vision, GPS, wheel torques). Traction vs slip can also be measured.**

$$\mu_{soil} = \frac{P_{wheels}}{W\, v_{GPS}}$$

$$n = \left[\frac{z_S}{NL\mu_{soil}}\right] - 1$$

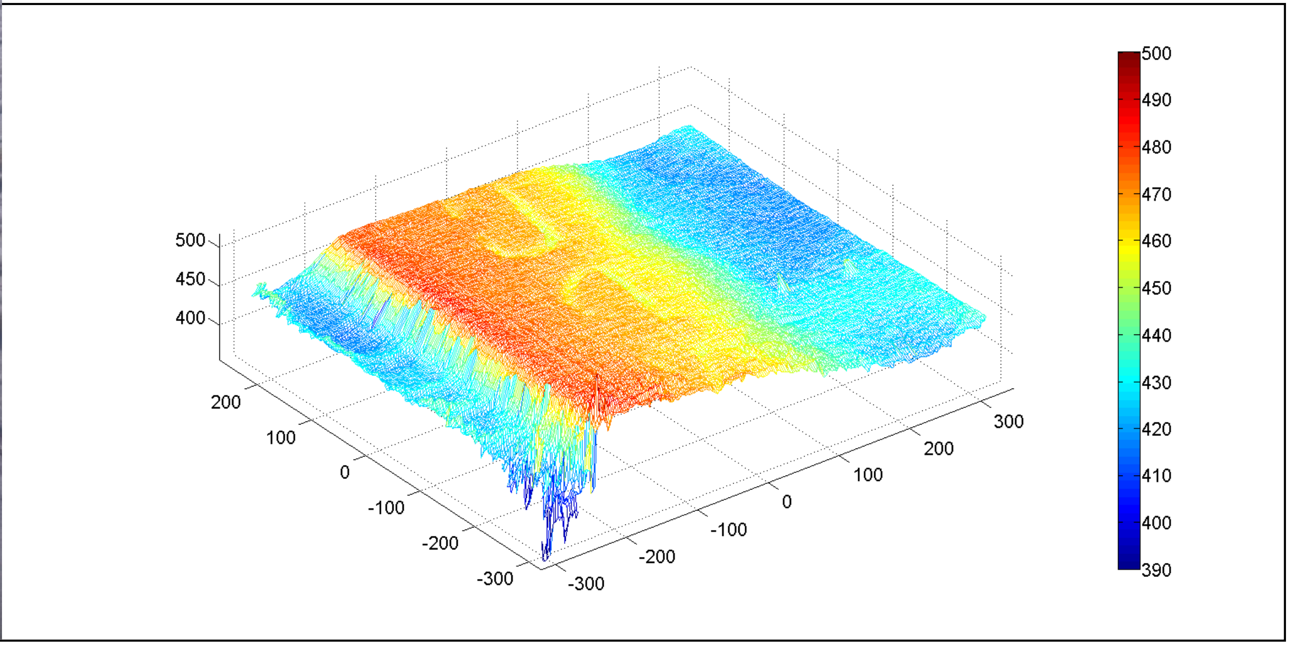
$$k = \frac{W}{2NbLz^n}$$

Wheel ruts are a continuous path witness of soil strength

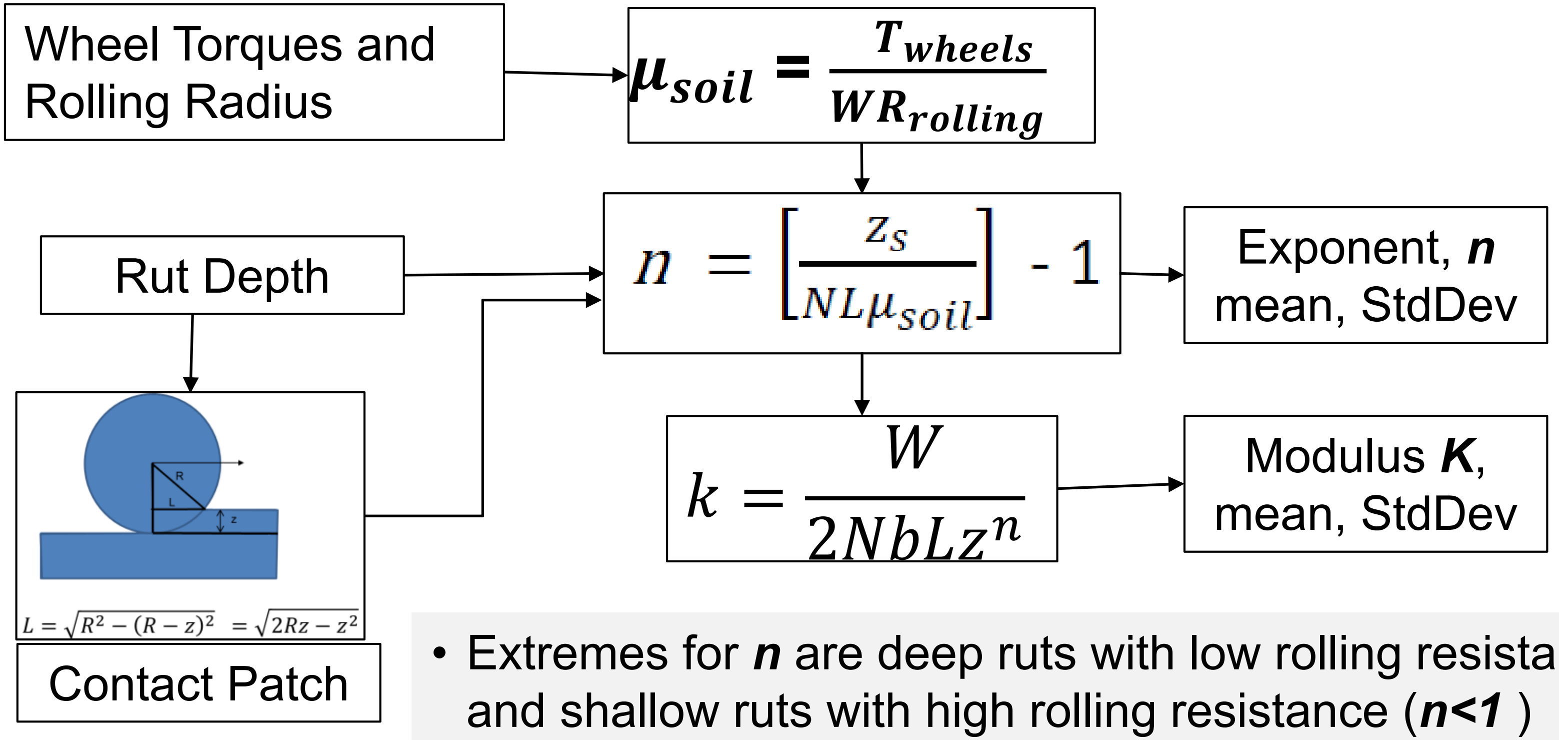
Automated in-line ST model data measurement overcomes geospatial sparsity of manual bevameter measurements and captures a rich data stream of mean, variance and geospatial correlation to causal parameters such as moisture content

Rut Depth (RD) Sensing

- Dr. Sally Shoop, et al, US Army Cold Regions Research and Engineering Lab (CRREL) demonstration at 2016 GVSETS
- Laser technologies for pavement monitoring is standard commercial off-the-shelf technology



Data Processing for Parameter ID from Wheel Torques and Rut Depth



Wheel Torques and Rolling Radius

$$\mu_{soil} = \frac{T_{wheels}}{WR_{rolling}}$$

Rut Depth

$$n = \left[\frac{z_S}{NL\mu_{soil}}\right] - 1$$

Exponent, ***n*** mean, StdDev

$$L = \sqrt{R^2 - (R-z)^2} = \sqrt{2Rz - z^2}$$

Contact Patch

$$k = \frac{W}{2NbLz^n}$$

Modulus ***K***, mean, StdDev

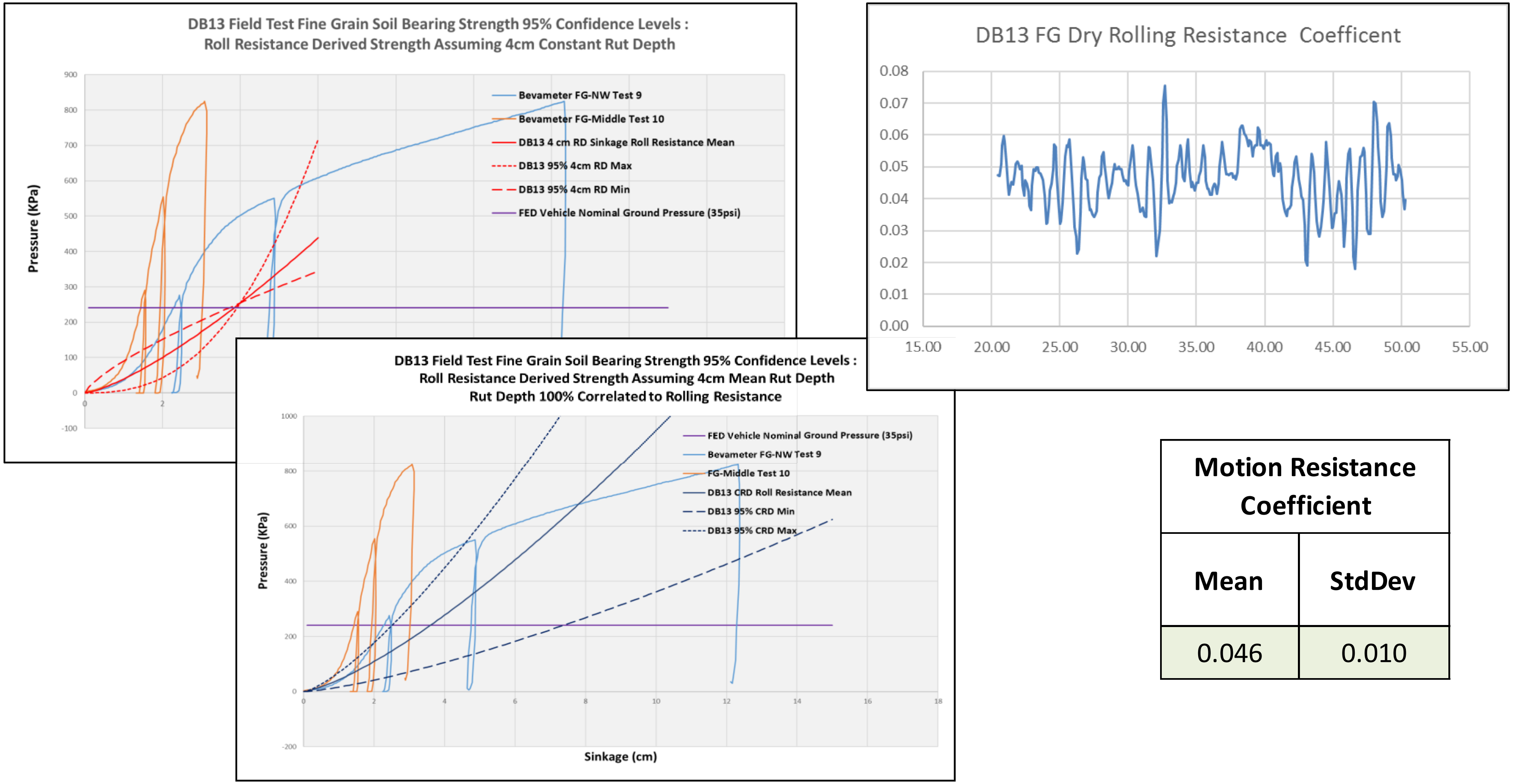
- Extremes for ***n*** are deep ruts with low rolling resistance (***n>1***) and shallow ruts with high rolling resistance (***n<1***)
- Constant rut depth assumption artificially increases variance
- Real rut depth data will be correlated with MR and will reduce variance

CDT Motion Resistance (MR) Runs Results

- Vehicle runs on the drawbar pull courses were made with no drawbar pull load
- Rut depth (RD) was also measured/observed manually
- Treated RD as constant increases variance in n
- Assuming 100% correlation of RD to MR reduces variance (probably most accurate)
- FG Dry unsynchronized brittle fracture slipping at each wheel drives noise in wheel torques that results in artificial variance in motion resistance

Motion Resistance and Rut Depth Based Pressure Sinkage Results							P = K z^n Pressure Sinkage Equation			
Date	Test Set	Location	Motion Resistance Coefficient		Pmax (Kpa)	Mean Rut Depth (m)	n		K (kN/m^{n+2})	
			Mean	StdDev			Mean	StdDev	Mean	StdDev
6/29/2018	DB19-RR constant RD	Coarse Pit Dry	0.133	0.016	167	0.100	0.35	0.16	407	n/a
6/29/2018	DB19-RR correlated RD	Coarse Pit Dry	0.133	0.016	167	0.100	0.33	n/a	361	14
6/29/2018	DB24-RR constant RD	Fine grain soil pit (wet)	0.109	0.019	141	0.150	1.11	0.36	1588	n/a
6/29/2018	DB24-RR correlated RD	Fine grain soil pit (wet)	0.109	0.019	141	0.150	1.54	n/a	3459	937
6/29/2018	DB13-RR constant RD	Fine grain soil pit (dry)	0.046	0.010	255	0.040	1.47	0.65	19187	n/a
6/29/2018	DB13-RR correlated RD	Fine grain soil pit (dry)	0.046	0.010	255	0.040	1.34	n/a	20885	7850

Path Averaged Motion Resistance Method for Model Parameter Identification



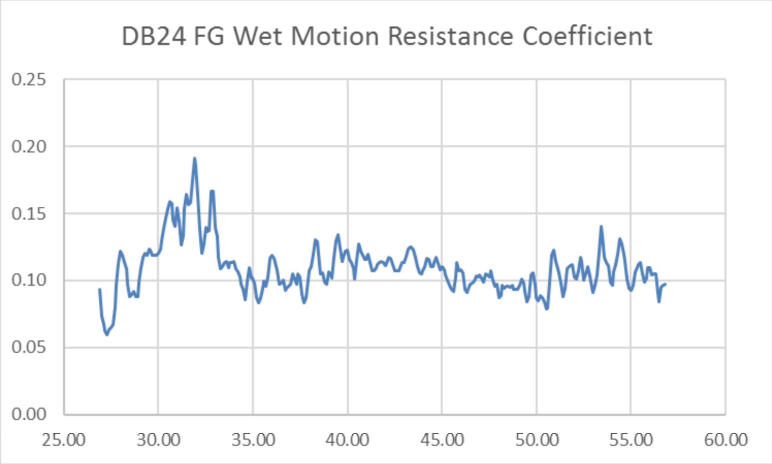
DB13 Field Test Fine Grain Soil Bearing Strength 95% Confidence Levels : Roll Resistance Derived Strength Assuming 4cm Constant Rut Depth

DB13 FG Dry Rolling Resistance Coefficent

DB13 Field Test Fine Grain Soil Bearing Strength 95% Confidence Levels : Roll Resistance Derived Strength Assuming 4cm Mean Rut Depth Rut Depth 100% Correlated to Rolling Resistance

Motion Resistance Coefficient	
Mean	**StdDev**
0.046	0.010

Path Average Model Identification from CDT Data Sets: Fine Grain Wet

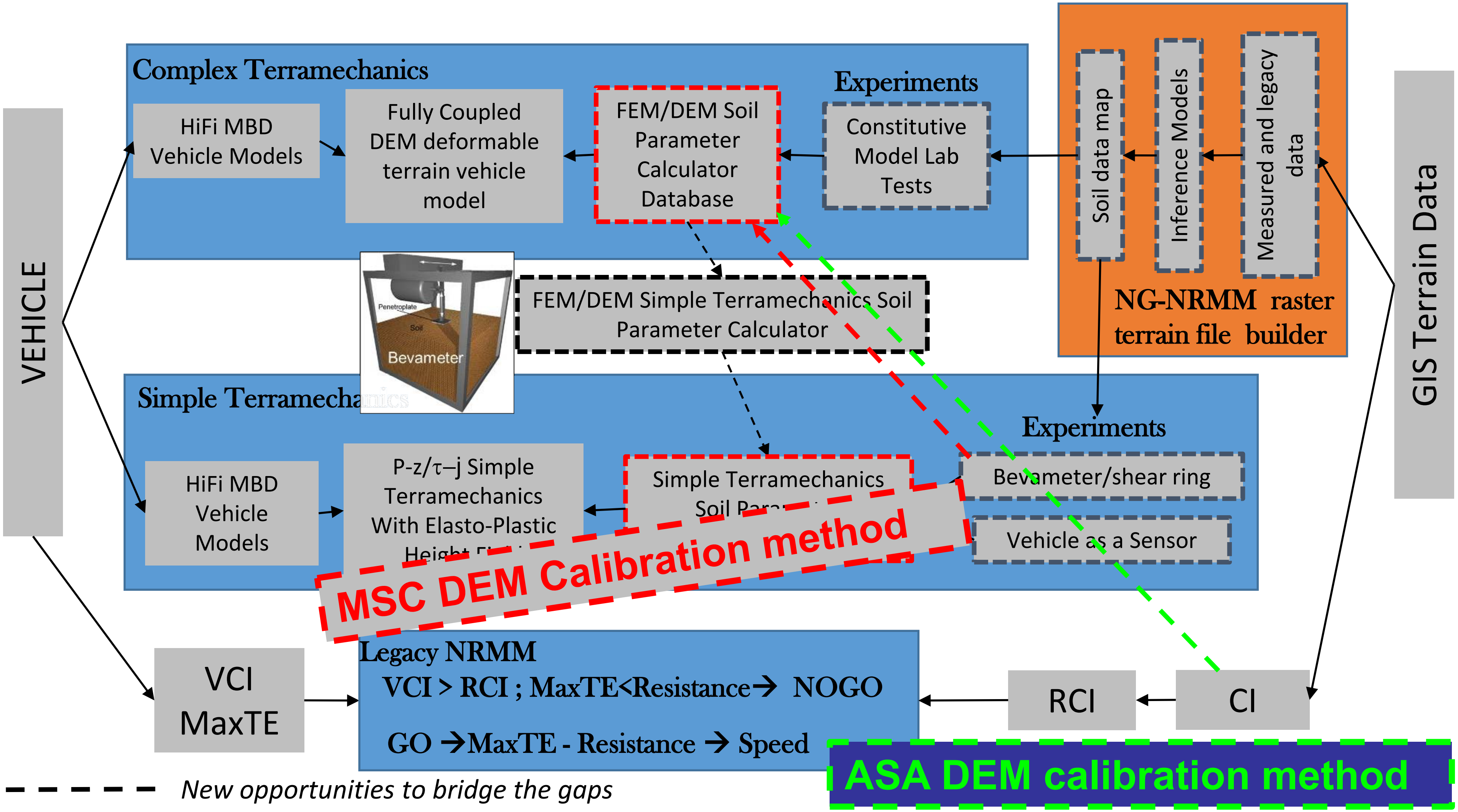


Variance in MR results drives the variance in model parameters

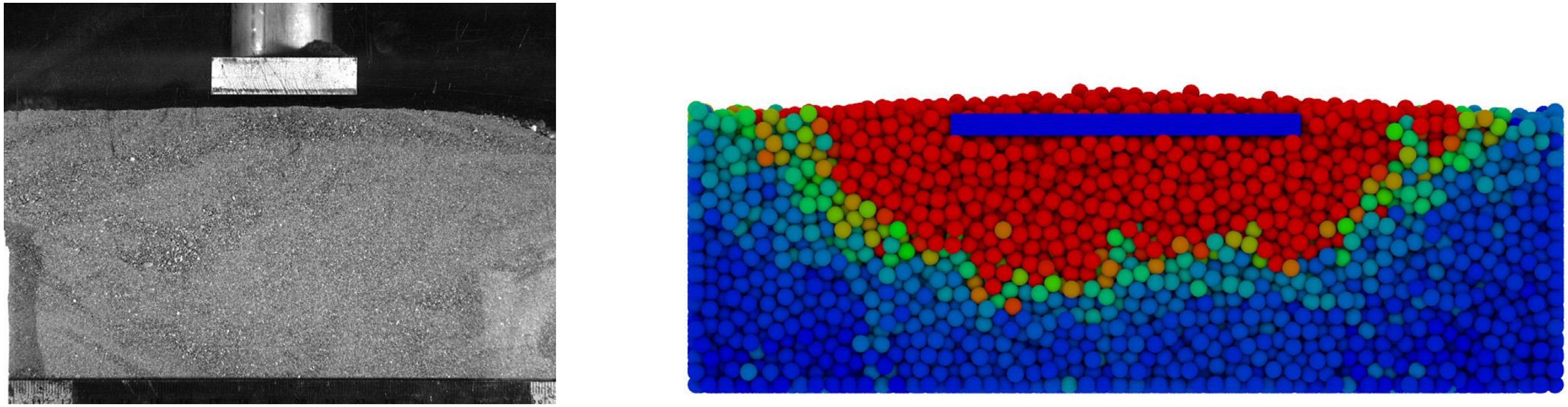
High rut depth with lower MR results in higher value of “n”, which is consistent with lighter layer of soil being encountered compared to CG Dry.

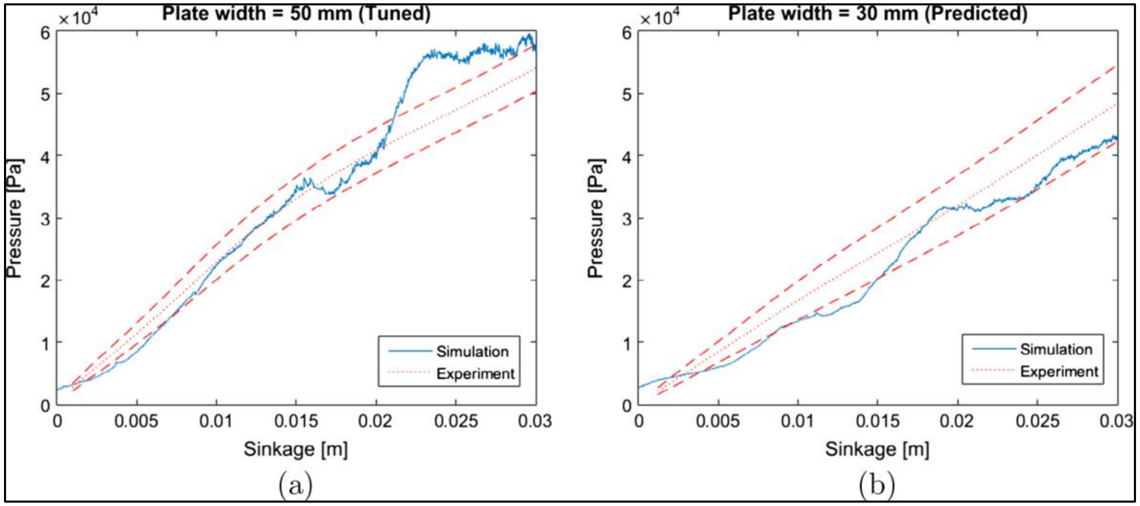
Bekker-Wong Method							**Wong Keq Method**			
Date	**Test Set**	**Location**	**Motion Resistance Coefficient**		**Pmax (Kpa)**	**Mean Rut Depth (m)**	**n (Keq)**		**Keq (kN/m $^{n+2}$)**	
			Mean	**StdDev**			**Mean**	**StdDev**	**Mean**	**StdDev**
6/5/2018	Test Set 17	Fine grain soil pit (wet)					4.39		8,236,397	
6/5/2018	Test Set 18	Fine grain soil pit (wet)					3.68		520,371	
6/29/2018	Test Set 36	Fine grain soil pit (wet)					4.62		65,749,045	
6/29/2018	DB24-RR constant RD	Fine grain soil pit (wet)	0.109	0.019	141	0.150	1.11	0.36	1588	n/a
6/29/2018	DB24-RR correlated RD	Fine grain soil pit (wet)	0.109	0.019	141	0.150	1.54	n/a	3459	937

Database Development for Terramechanics



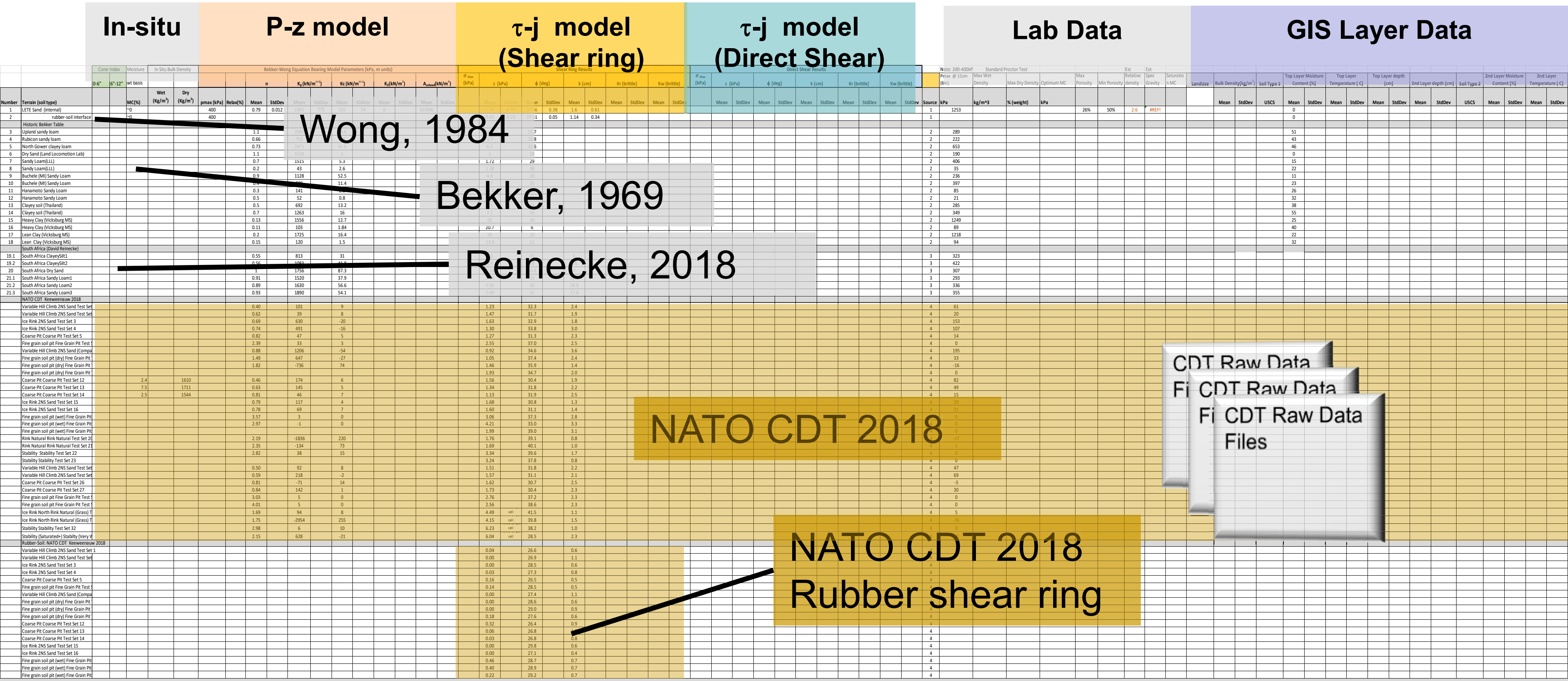
Validation of DEM Predictions of ST Parameters





D. Melanz et al. / Journal of Terramechanics 65 (2016) 1–13

Terramechanics Database



In-situ

P-z model

τ-j model (Shear ring)

τ-j model (Direct Shear)

Lab Data

GIS Layer Data

Wong, 1984

Bekker, 1969

Reinecke, 2018

NATO CDT 2018

CDT Raw Data Files

NATO CDT 2018 Rubber shear ring

The CDT contribution to the NG-NRMM Terramechanics database will include raw data files and expand to accommodate better data fitting models, such as P-z polynomials, and will fully associate data from correlated complementary GIS, CI and CT methods

Correlated Data Sets From CDT for ST Database

- **Soil Material Characterization (Lab)**
  - Triaxial and Compressibility
  - Direct shear
  - Bevameter
  - Proctor
  - Atterberg Limits
- **In-situ at vehicle performance test sites:**
  - Cone Index down to 12”
  - Bevameter p-z and τ-j , p_{max}, σ_{max}
  - Direct shear test
- **All tests collect moisture content and density (nuclear densometer)**

Detailed List of ST Database Parameters

- p_{max} applicable max pressure range
- R_{elax} 2-second normal stress relaxation of bevameter platen at p_{max} (%)
- MC applicable moisture content (dry weight basis)
- K_{USCS} soil type
- g_s specific gravity of solids
- G_s maximum dry (or wet) density (must specify) [also known as max bulk density]
- D_r relative density of natural in-situ sample [or natural bulk density]
- c surface layer cohesion
- f surface layer internal friction angle
- k surface layer shear strength modulus
- n bearing strength exponent
- k_f bearing strength frictional constant
- k_c bearing strength cohesive constant
- K_0 bearing elastic reload stiffness

- A_u bearing elastic progressive stiffening
- k_{f2} 2nd layer frictional bearing strength
- k_{c2} 2nd layer cohesive bearing strength
- n_2 2nd layer bearing strength exponent
- K_{02} bearing elastic reload stiffness
- A_{u2} bearing elastic progressive stiffening
- p_{max2} applicable max pressure range
- CI (0-15cm)
- CI (15-30cm)

Assumptions and Limitations of ST Models

- **Bevameter plates and shear rings are good surrogates for the vehicle tires and tracks**
- **Terrain discretization, such as Height Field Models (HFM) is necessary to account for plastic deformation and soil transport/flow**
- **Because of gravity effects on soil strength and increased coupling of shear and bearing capacity, accuracy progressively degrades with increasing slope and slip velocities**
  - ➢ However, Shear and Bearing strength coupling can be explicitly accounted for using permanent deformation tracking such as HFM, along with slip-sinkage models and soil transport models

Limitations of Terramechanics Data

- **Currently available data is very sparse and weakly validated.**
- **The CDT has created the richest data set ever, in terms of both quality and quantity**
- **In-situ point-by-point testing will always be geospatially sparse**
- **Vehicle as a sensor approaches have the potential to overcome geospatial sparsity**
    - ➢ Averages out soil substrate heterogeneities such as moisture, layers, rocks
    - ➢ Large data sample sets provide valid uncertainty quantification
- **Leveraging lab data, Complex Terramechanics models, and vehicle-born sensors, the Terramechanics database can become a validated cornerstone NATO mobility modeling asset**

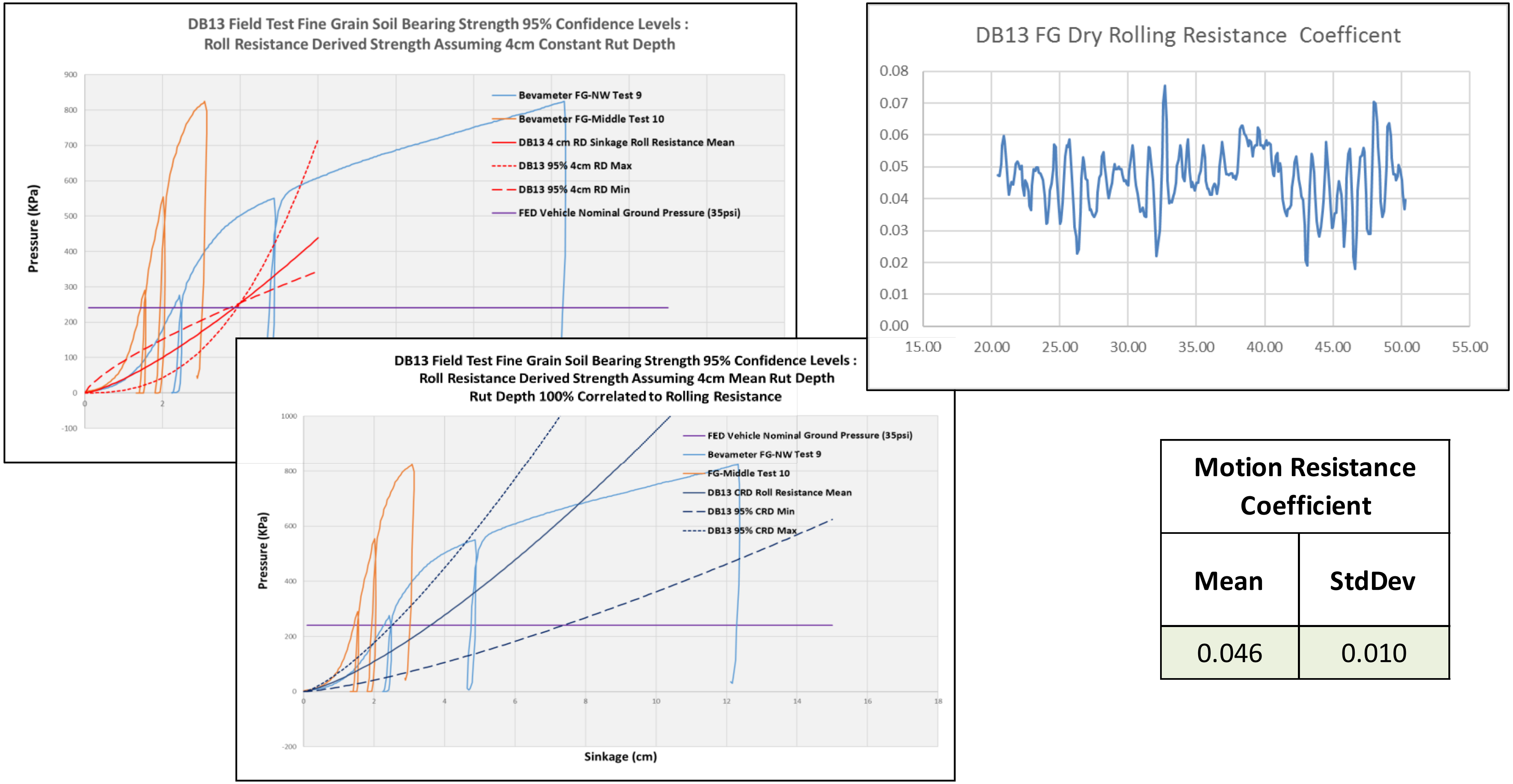
Simple Terramechanics Conclusions

- **ST models have achieved significant success when the bevameter data is sufficient to cover the specific model applications**
- **ST models can make every instrumented operational vehicle (e.g., autonomous vehicles) a reconnaissance sensor for terrain strength**
- **ST Database will establish a key foundation to Allied nations collaboration and uniform mobility model assumptions**
- **ST STANREC details supply the methods necessary for the Allied nations to acquire data for their country; CDT has validated those**
- **The NG-NRMM CDT has provided a key benchmark data set necessary to qualify and harmonize Allied nations disparate mobility models and their associated Terramechanics data acquisition**
    - ➢ Still need tracked vehicle data

THANK YOU

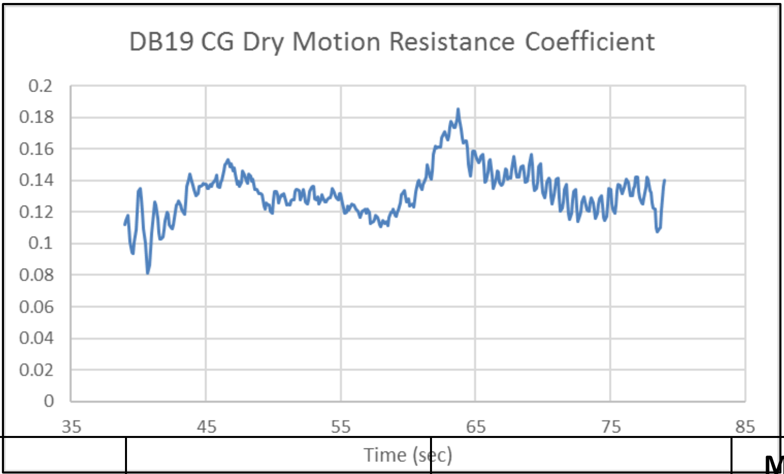
Backup

Path Averaged Motion Resistance Method for Model Parameter Identification



Motion Resistance Coefficient	
Mean	**StdDev**
0.046	0.010

Path Average Model Identification from CDT Data Sets: Coarse Grain Dry



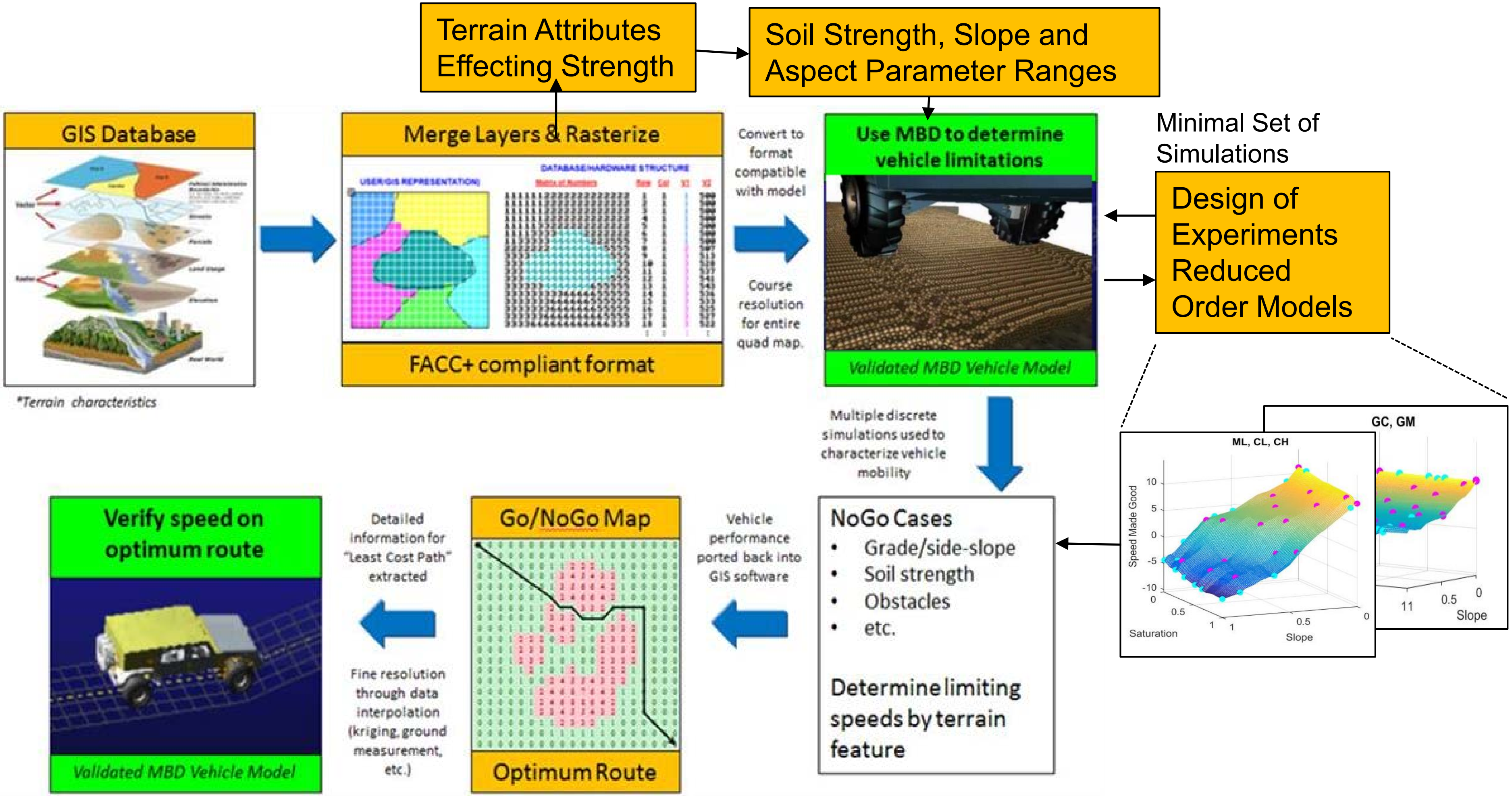
- Constant depth assumption is not realistic and it drives an unrealistically large variance in the exponent
- Rut depth correlated to the motion resistance is a more likely scenario and making this assumption results in much lower variance
- Actual synched rut depth data would reduce variance further

Date	Test Set	Location	Motion Resistance Coefficient		Pmax (Kpa)	Mean Rut Depth (m)	n (Keq)		Keq (kN/m $^{n+2}$)	
			Mean	StdDev			Mean	StdDev	Mean	StdDev
6/5/2018	Test Set 12	Coarse Pit					0.55		1686	
6/5/2018	Test Set 13	Coarse Pit					0.74		2765	
6/5/2018	Test Set 14	Coarse Pit					0.87		3367	
6/29/2018	Test Set 35	Coarse Pit					1.09		3919	
6/29/2018	DB19-RR constant RD	Coarse Pit Dry	0.133	0.016	167	0.100	0.35	0.16	407	n/a
6/29/2018	DB19-RR correlated RD	Coarse Pit Dry	0.133	0.016	167	0.100	0.33	n/a	361	14

Advantages of MR-RD Based Parameter ID

- **Results from MR-RD based ST model parameter ID can be extrapolated for similar nominal ground pressures**
  - Added payload
  - Different vehicles
- **True variances reflect actual Terramechanical model uncertainty**
- **Data acquisition can be automated and mapped with orders of magnitude increase in data geospatial sampling significance**
  - Solves the geospatial data sparsity problem
  - Geospatially mapped terrain strength for validation of remote sensing models
- **The TARDEC FED-Alpha vehicle only needs rut depth sensors and it will be ready to begin acquiring terrain strength data**

Role of Parametric Reduced Order Models



Terrain Attributes Effecting Strength

Soil Strength, Slope and Aspect Parameter Ranges

GIS Database

*Terrain characteristics

Merge Layers & Rasterize

FACC+ compliant format

Convert to format compatible with model

Course resolution for entire quad map.

Use MBD to determine vehicle limitations

Validated MBD Vehicle Model

Minimal Set of Simulations

Design of Experiments Reduced Order Models

Multiple discrete simulations used to characterize vehicle mobility

NoGo Cases

- Grade/side-slope
- Soil strength
- Obstacles
- etc.

Determine limiting speeds by terrain feature

Vehicle performance ported back into GIS software

Go/NoGo Map

Optimum Route

Detailed information for "Least Cost Path" extracted

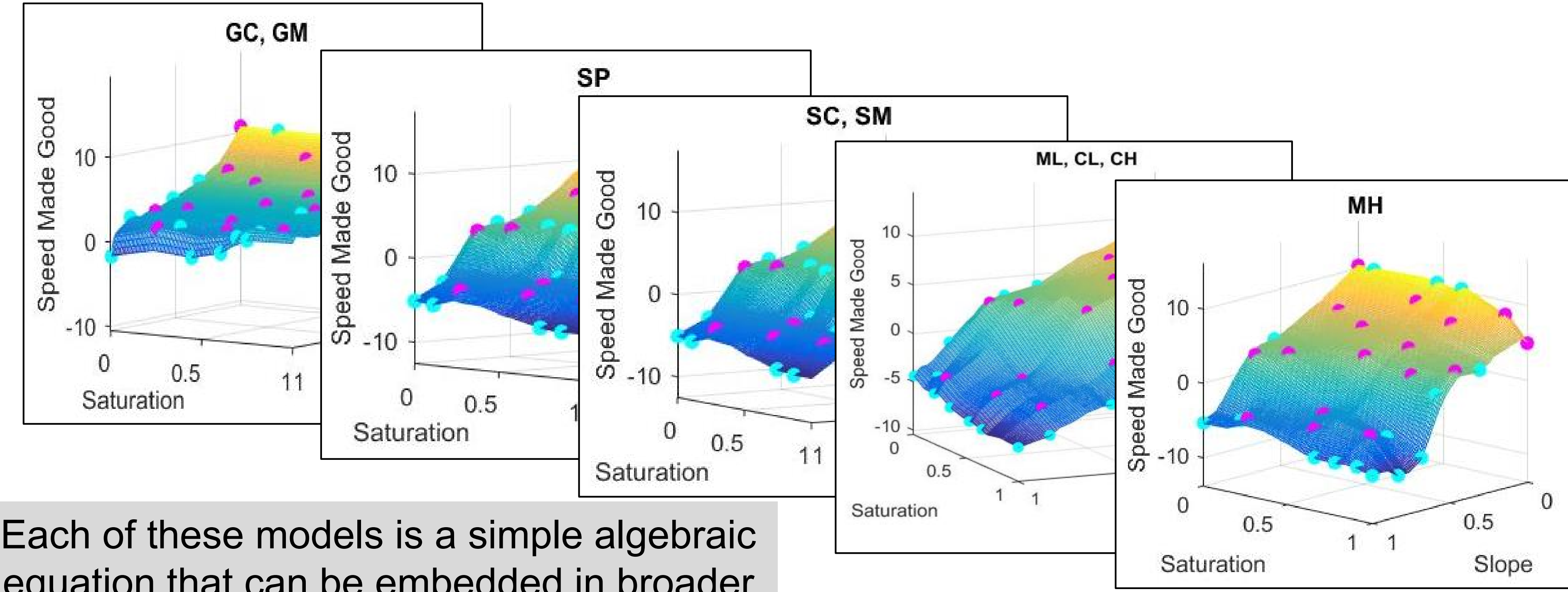
Fine resolution through data interpolation (kriging, ground measurement, etc.)

Verify speed on optimum route

Validated MBD Vehicle Model

Specialized Goal of Terramechanics Modeling

- **Valid Reduced Order Models for Specific Mobility Solutions (Go/NoGO, Speed Made Good) Across the Range of Limiting Slopes, Soil Types and Moisture Contents**



Each of these models is a simple algebraic equation that can be embedded in broader Operational Analysis Applications

Slope Climbing Performance & Relation to Level-Terrain Drawbar Pull Testing

Jody D. Priddy
Engineer Research and Development Center (ERDC)
28 May 2013 *(revised 25 Nov 2013 for distribution)*

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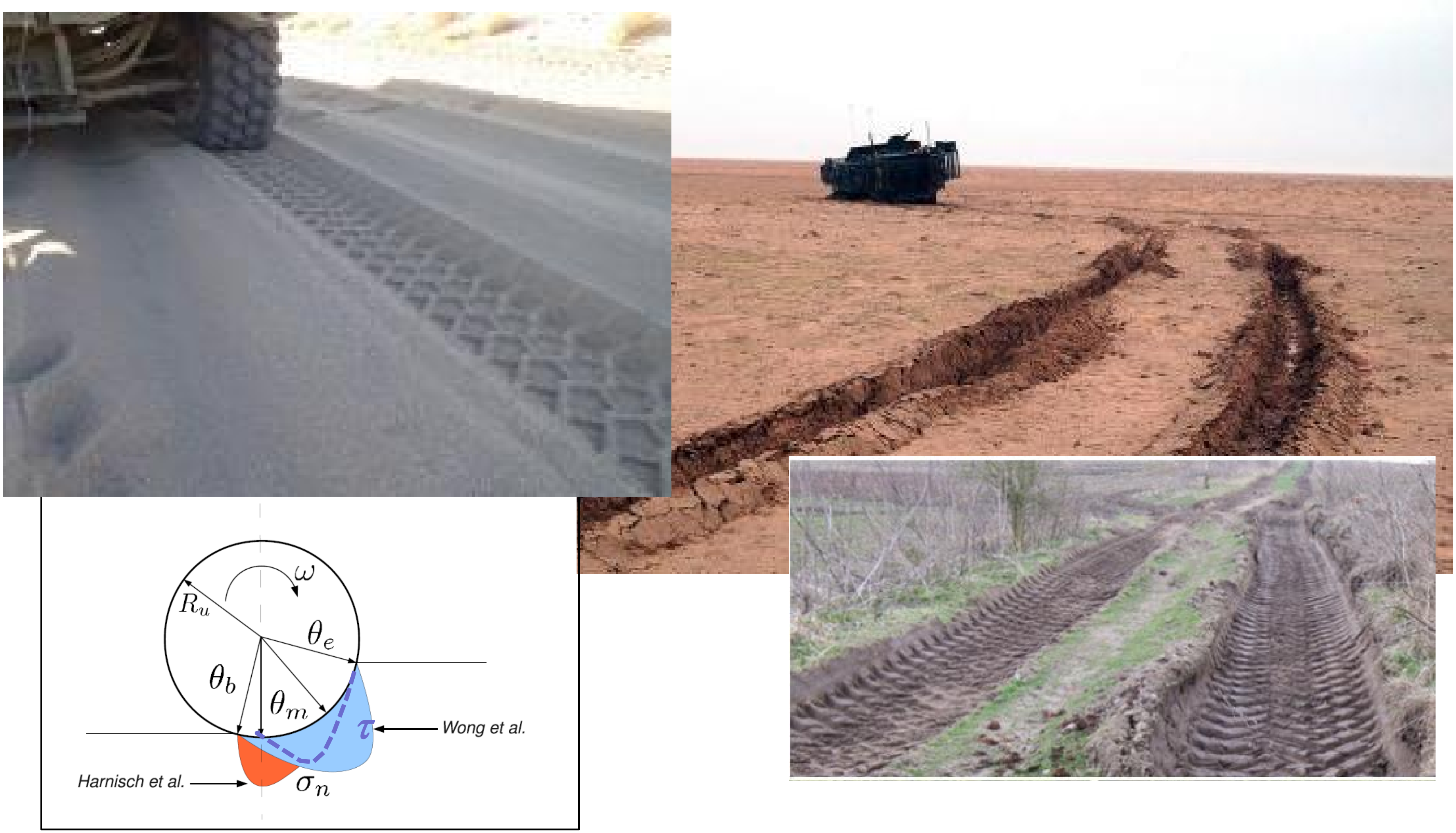
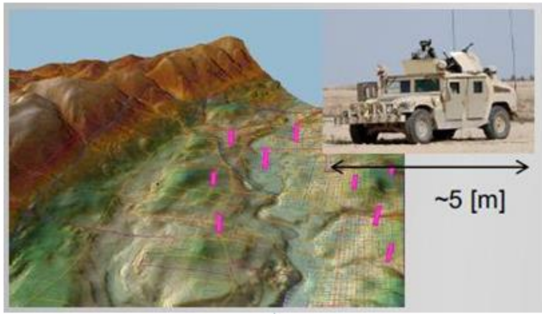
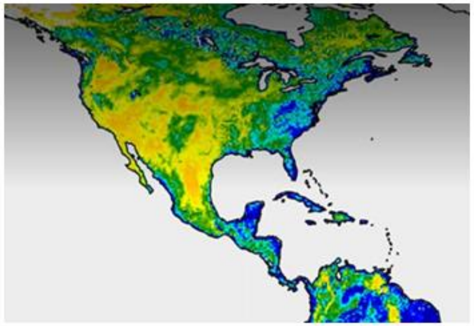

ω
R_u
θ_e
θ_b
θ_m
τ
Wong et al.
Harnisch et al.
σ_n

Past Slides that help

Terrain Elevation Map

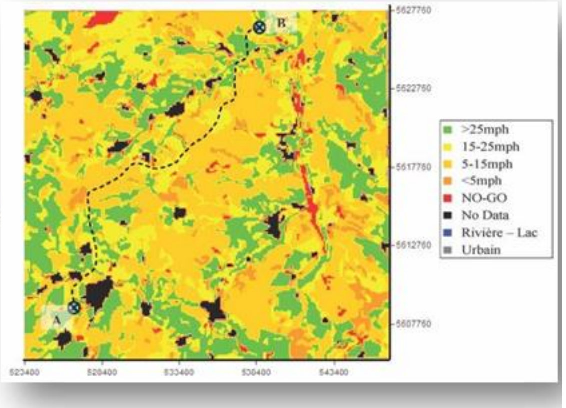


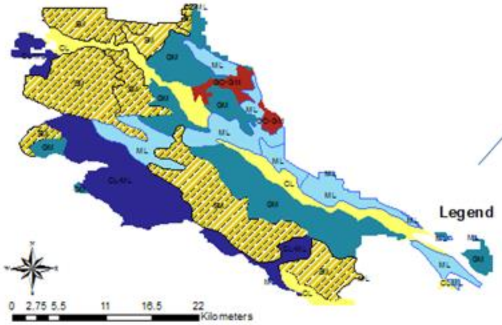
Soil Moisture Map



Physics-Based M&S

Mobility Go/NoGo Map





Soil Type

Qualitative

NRMM

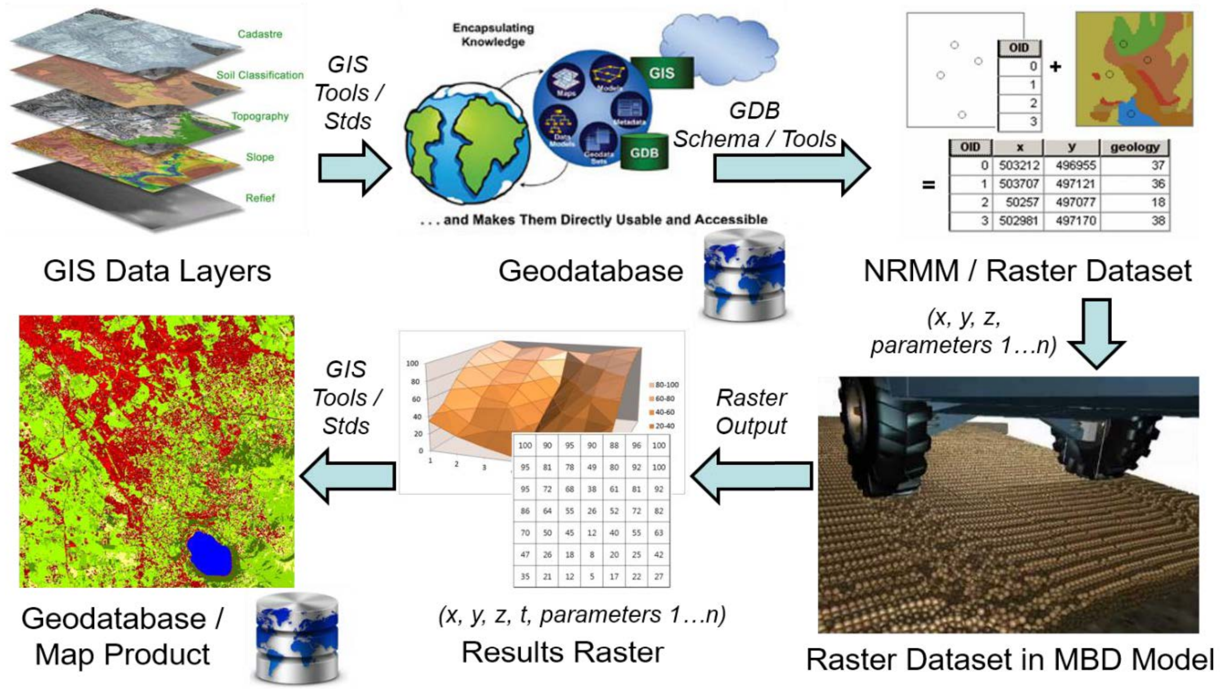
NG-NRMM

1970

2020

Flowchart from TA1 as reference

A Potential Interoperability Approach / Workflow



GIS Data Layers

Geodatabase

NRMM / Raster Dataset

OID	x	y	geology
0	503212	496955	37
1	503707	497121	36
2	50257	497077	18
3	502981	497170	38

(x, y, z, parameters 1…n)

Raster Dataset in MBD Model

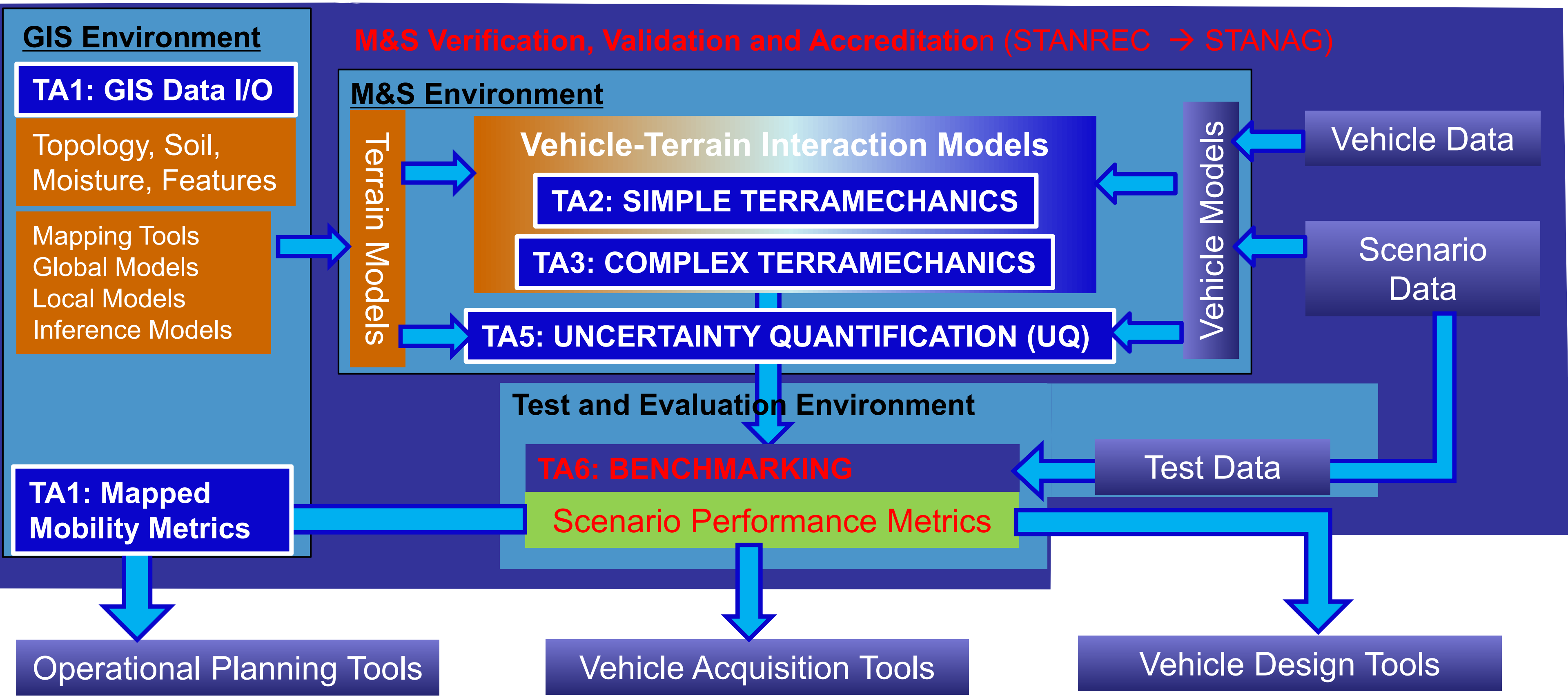
100	90	95	90	88	96	100
95	81	78	49	80	92	100
95	72	68	38	61	81	92
86	64	55	26	52	72	82
70	50	45	12	40	55	63
47	26	18	8	20	25	42
35	21	12	5	17	22	27

(x, y, z, t, parameters 1…n)

Results Raster

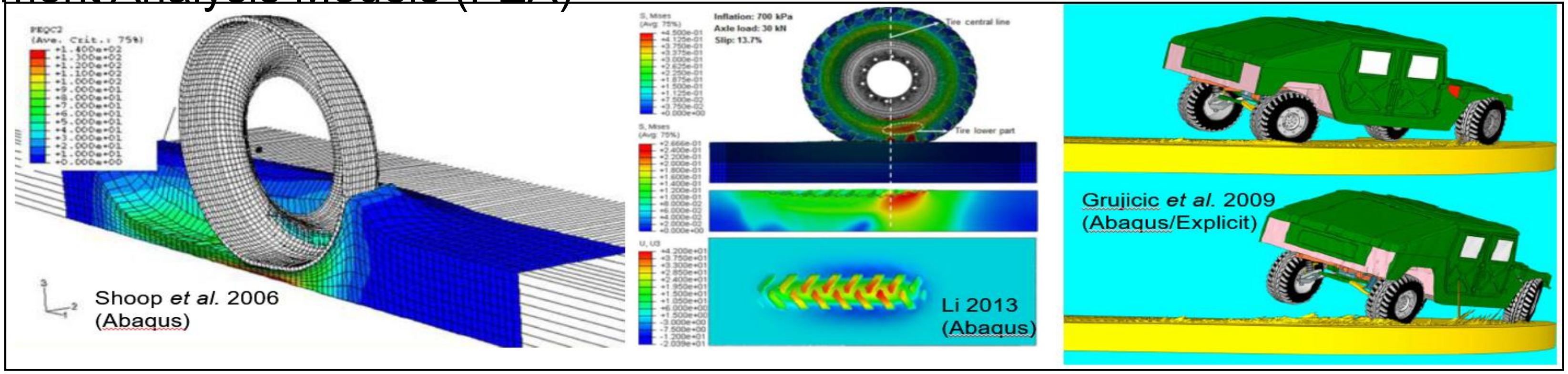
Geodatabase / Map Product

NG-NRMM Architecture

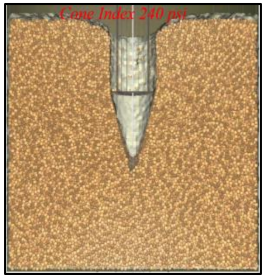


Complex Terramechanics

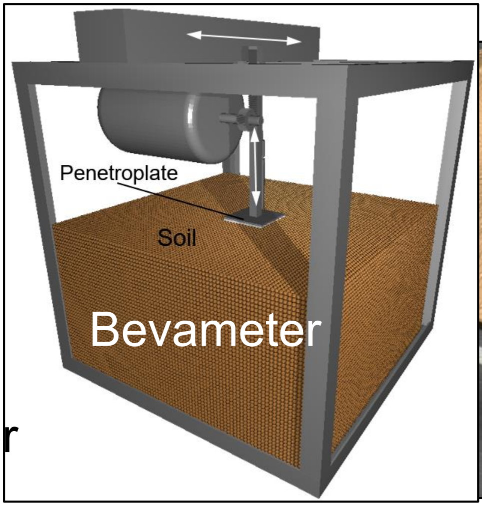
Finite Element Analysis Models (FEA)

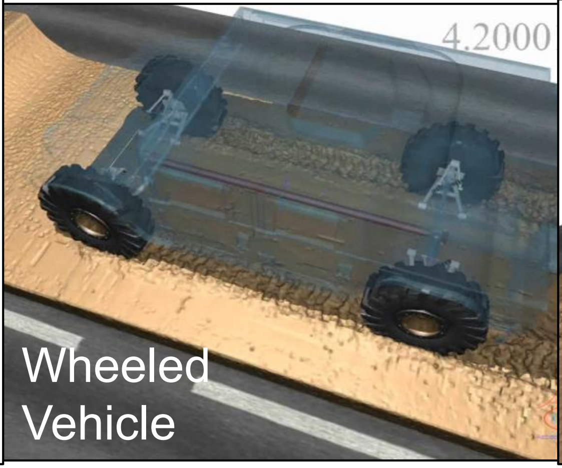


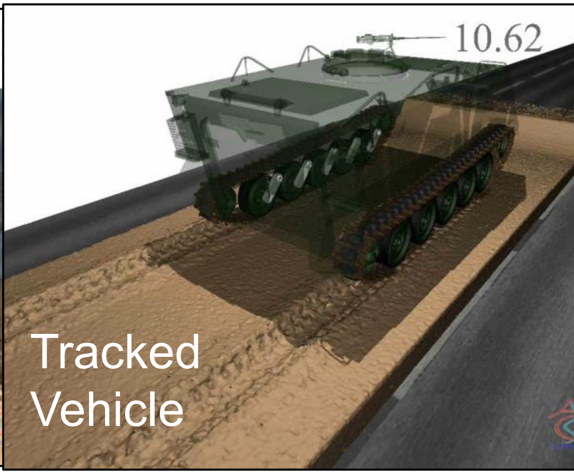
Discrete Element Models (DEM)



Cone Penetrometer







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