Effective Depth of Soil Compaction in Relation to Applied Compactive Energy

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WHRP Project 0092-08-11

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Project Objectives

- To relate degree of soil compaction at various depths as a function of energy applied to the surface, compactor weight, and footprint.
- Development of a monitoring system to evaluate received energy and degree of compaction at various depths
- Determination of the influence of soil parameters (e.g., soil texture, plasticity, and moisture content) on compaction achieved.
- Draft recommendations to optimize lift thickness as function of Wisconsin construction experience and typical compaction equipment and delivered energy.

Compaction of Soils

- Several factors influence the compaction (i.e., maximum density or unit weight and optimum water content) of soils:
  - compaction method (i.e., pounding, kneading, pressure, vibration)
  - molding moisture content (soil water content when compacted)
  - compactive effort (applied energy and compactor size)
  - soil type (determines optimum moisture content and max, unit weight)
  - relative layer stiffness (stiff layer over soft layer)

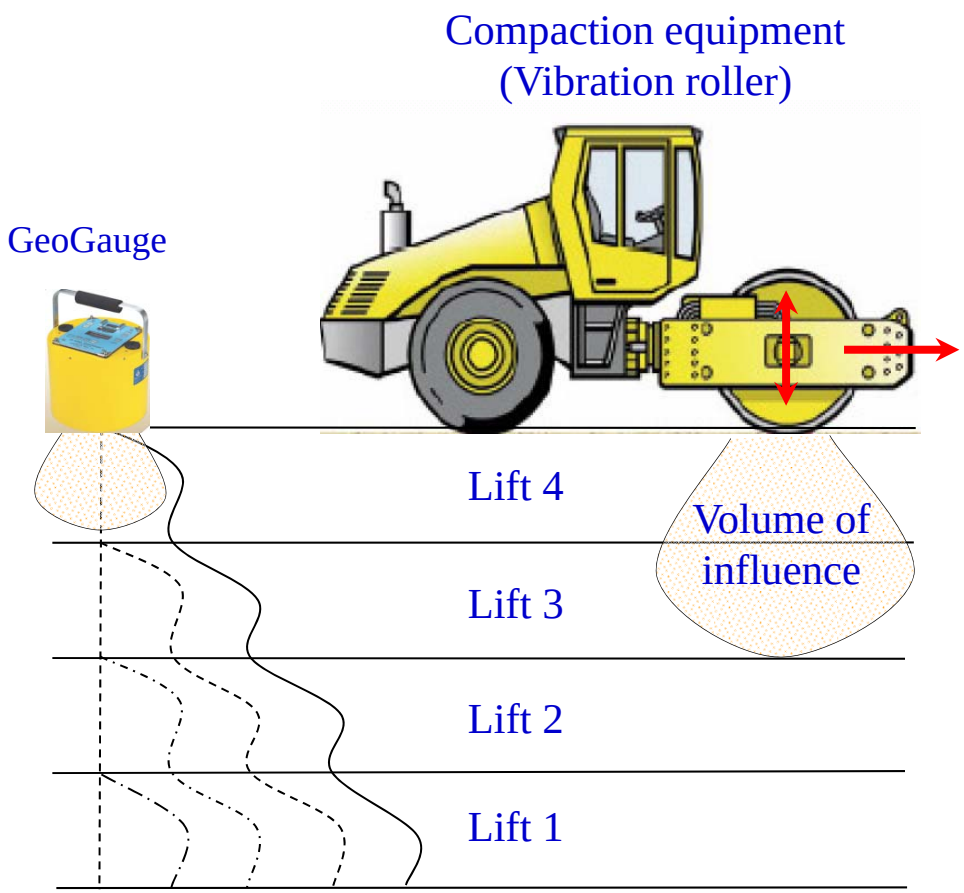
Lift-thickness Specifications

Specification	State DOTs
Max. 0.15 m (6 in) lift before compaction	Maryland, Massachusetts, Montana, North Dakota, Ohio, Oklahoma
Max. 0.15 m (6 in) lift after compaction	Connecticut, Kentucky
Max. 0.2 m (8 in) lift before compaction	Alabama, Arizona, California, Delaware, Florida, Idaho, Illinois, Indiana, Iowa, Kansas, Maine, Minnesota, Mississippi, Missouri, Oregon, South Carolina, South Dakota, Vermont, Virginia, Washington, Wisconsin
Max. 0.3 m (12 in) lift before compaction	Louisiana, New Hampshire, New Jersey, Texas, Wyoming

Note: New York DOT specifies lift thickness as function of soil and compaction equipment (State of New York 2008).

(after Hoppe 1999; Lenke 2006)

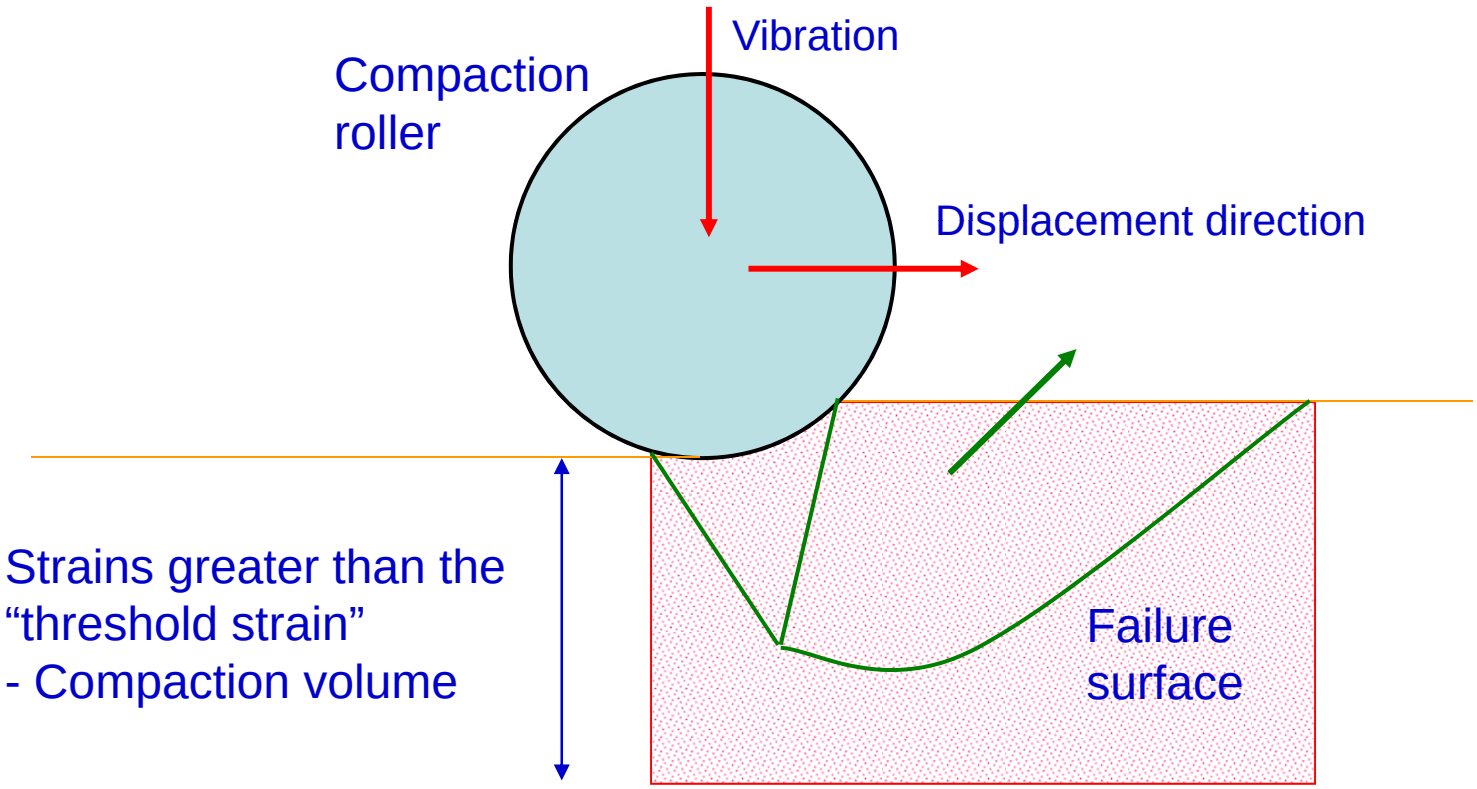
Research Question



Schematic stiffness and density profile versus depth after each lift compaction

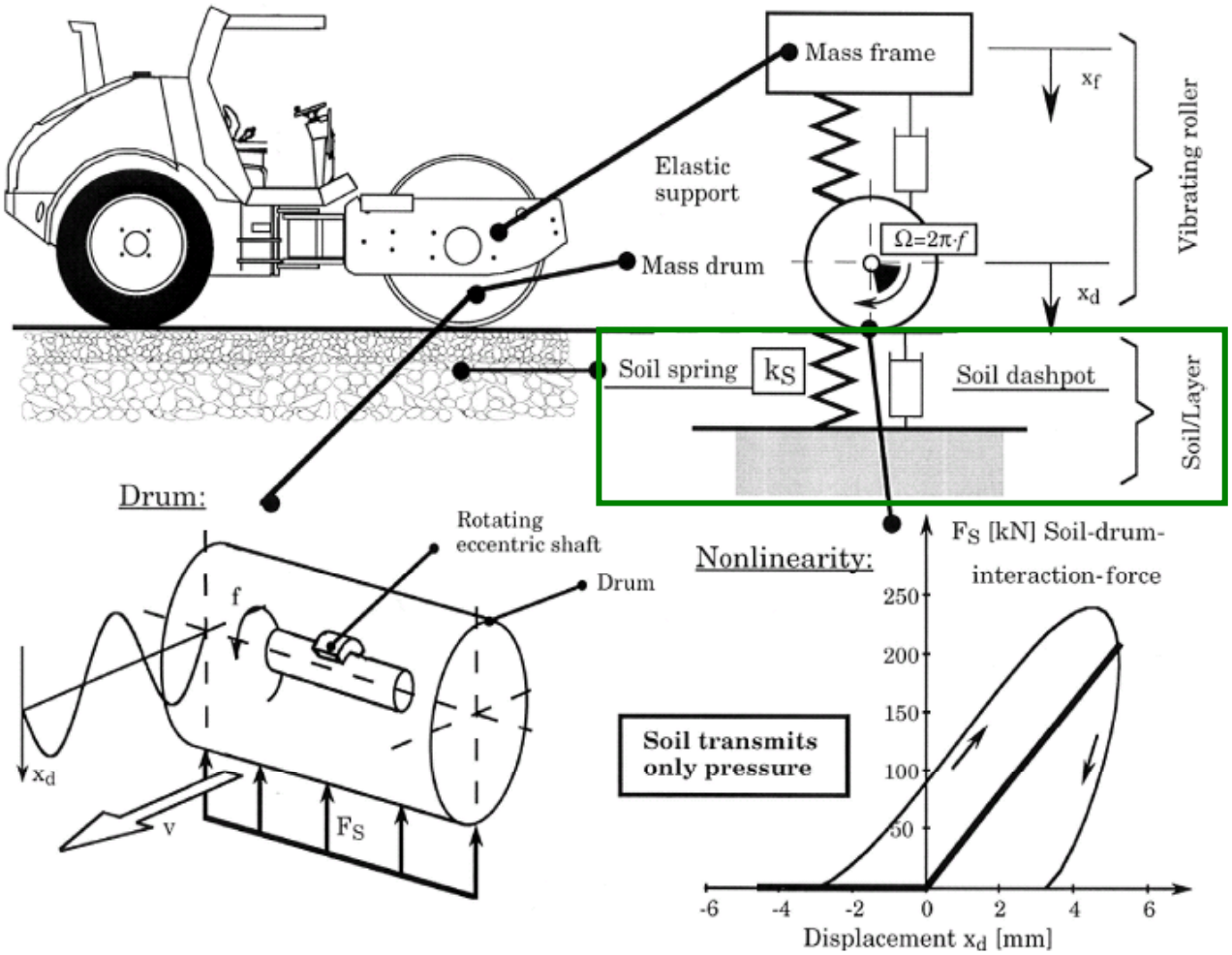
Given typical compaction equipment, what is the maximum lift thickness that can provide uniform compaction and proper engineering performance in road embankments?

Field Compaction



Field Compaction

- Energy propagation

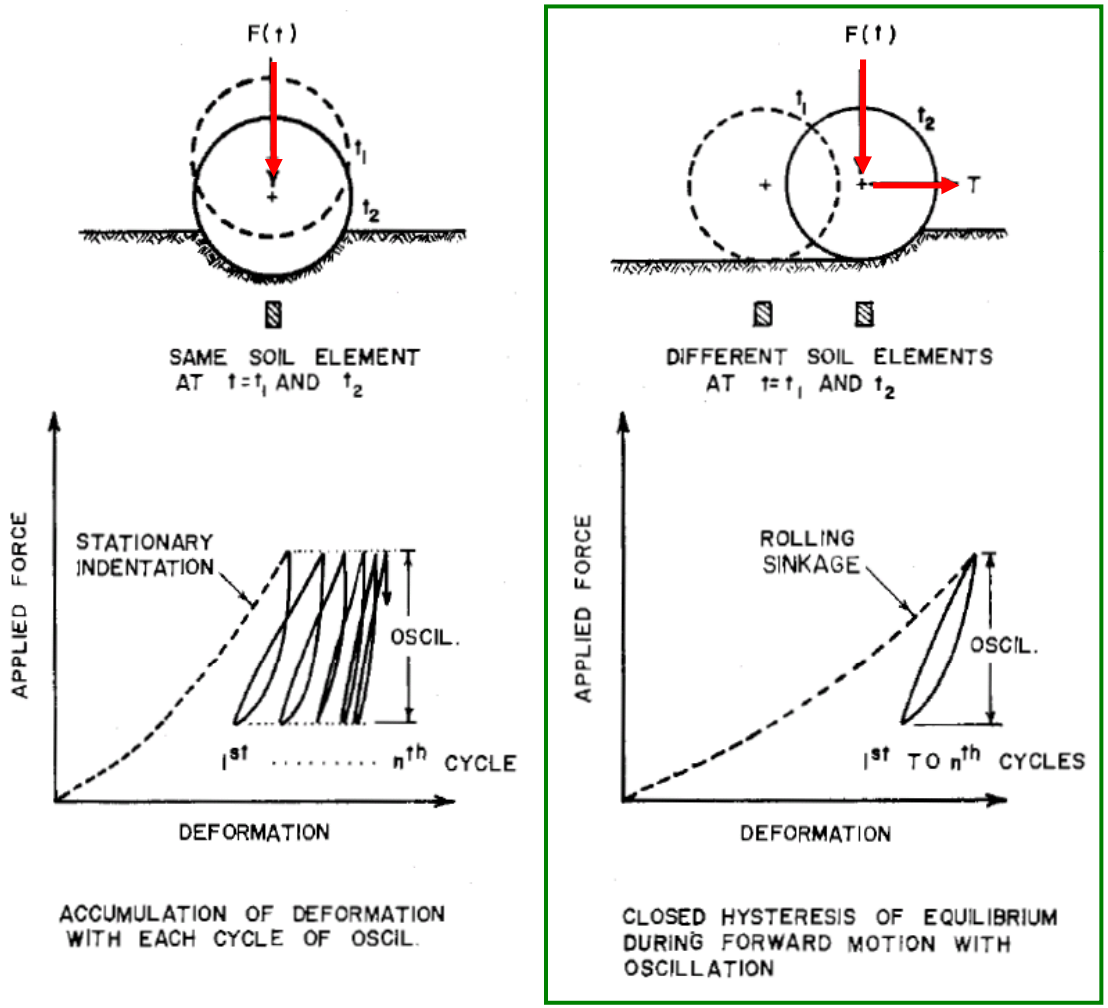


This is our problem

(Anderegg and Kaufmann 2004)

Field Compaction

- Energy propagation

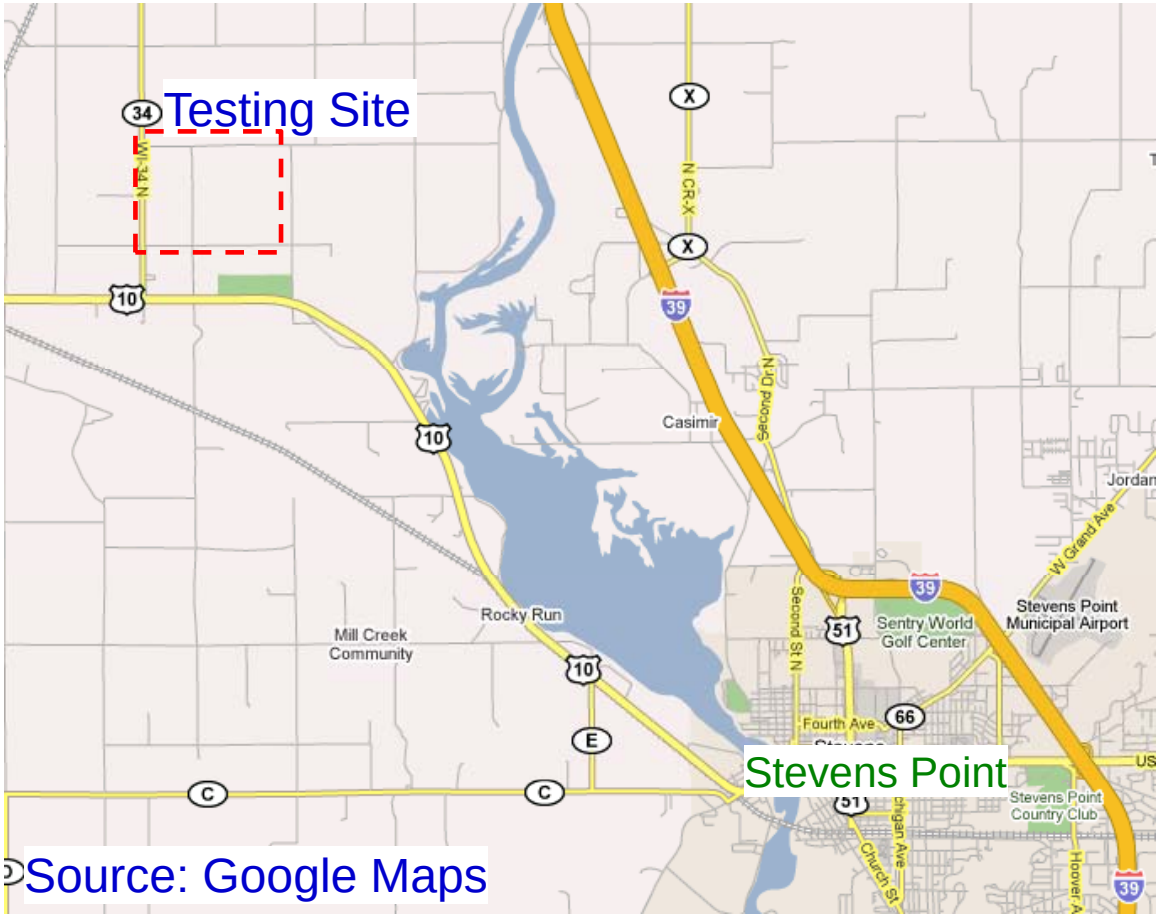


(Yoo and Selig 1979)

Field Site

Testing site: Junction City (15 mi NW of Stevens Points)
Contractor: Hoffman Construction (Black River Falls, WI)

To Junction City

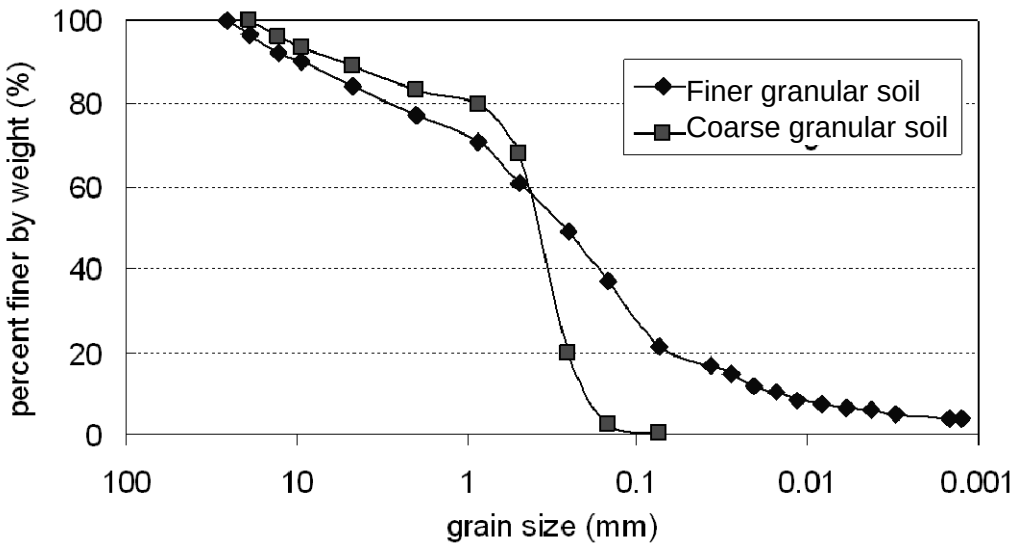


Source: Google Maps

Soil Properties

- Basic properties

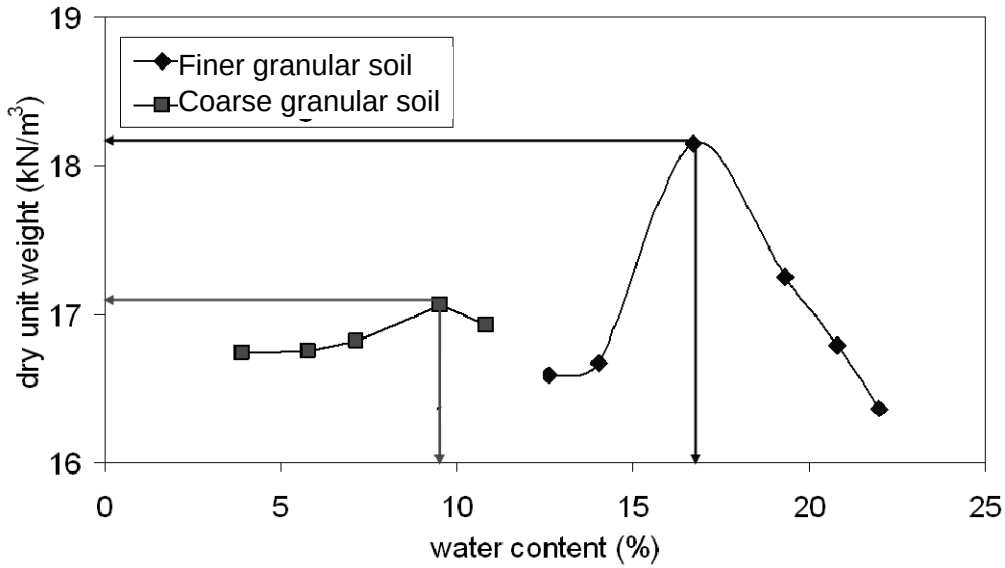
Soil type	Specific Gravity (Gs)	Coefficient of uniformity (Cu)	Coefficient of curvature (Cc)	USCS
Silty soil (finer granular soil)	2.83	2.37	1.00	SM
Brown sand (coarser granular soil)	2.66	31.95	1.72	SP



Soil Properties

- Compaction properties

Soil type	maximum dry unit weight (kN/m^3)	optimum water content (%)
Silty soil (finer granular soil)	18.2	16.7
Brown sand (coarser granular soil)	17.1	9.5



Field Measurements

- Soil property and response measurements:
  - Internal soil deformation: MEMS inclinometers
  - Internal pressure: pressure gauges
  - Density profile: nuclear density gauge and sand cone
  - Surface stiffness: GeoGauge
  - Internal stiffness: P-wave velocity – MEMS accelerometers
  - Volumetric water content: time domain reflectometry (TDR)

Field Measurements

Originally proposed field testing matrix

1 - 6 passes			
Fine-grained Soil		**Coarse-grained Soil**	
Sheepsfoot Roller	**Rubber-tired Roller**	**Smooth-drum Vibratory Roller**	**Rubber-tired Roller**
Dry: 8, 12, 16, and 20” lifts	Dry (4-5%<w_{op}): 8, 12, 16, and 20” lifts	Dry (4-5%<w_{op}): 8, 12, 16, and 20” lifts	Dry (4-5%<w_{op}): 8, 12, 16, and 20 lifts
Wet (4-5%>w_{op}): 8, 12, 16, and 20” lifts	Wet (4-5%>w_{op}): 8, 12, 16, and 20” lifts	Wet (4-5%>w_{op}): 8, 12, 16, and 20” lifts	Wet (4-5%>w_{op}): 8, 12, 16, and 20” lifts

Field Measurements

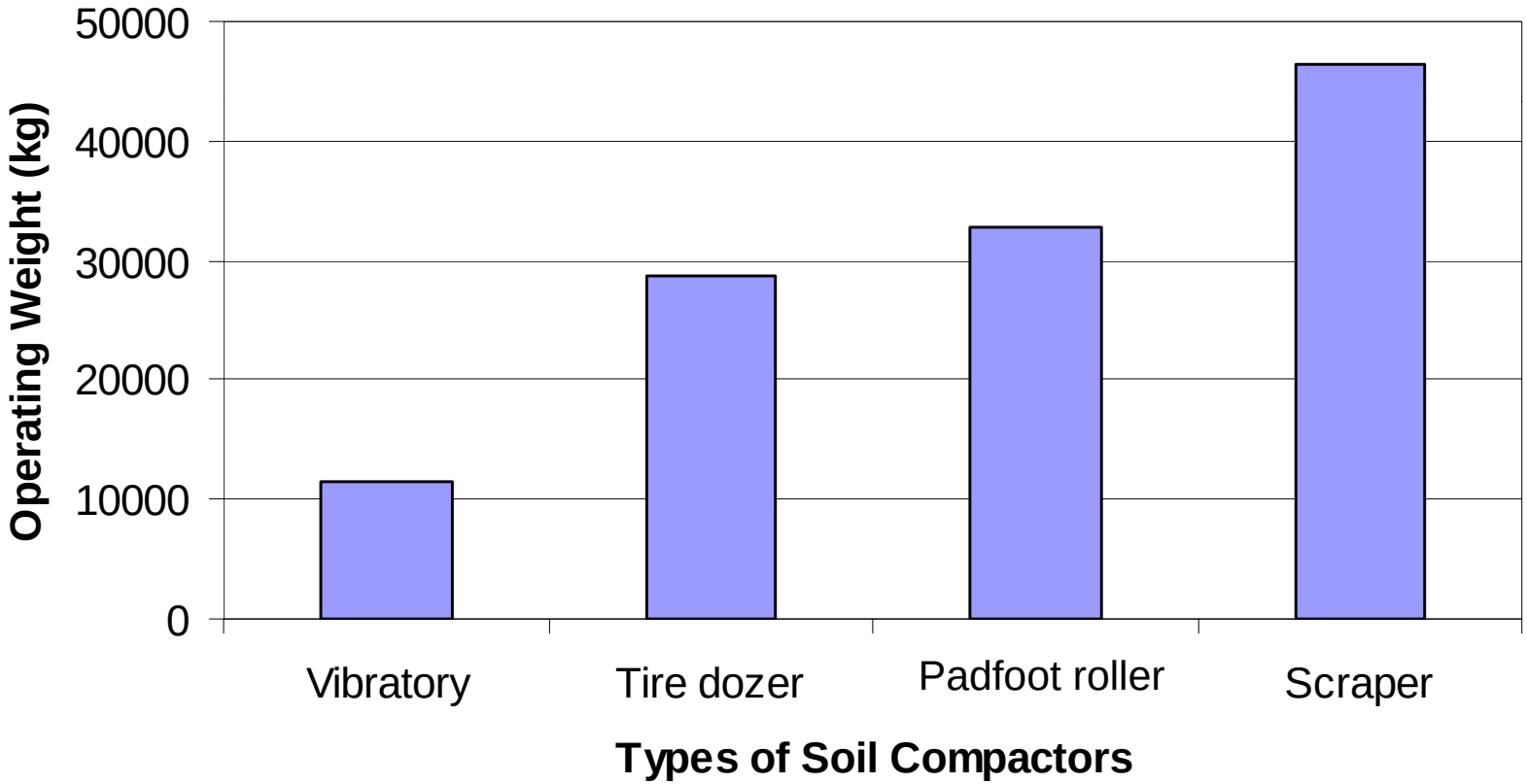
- Compaction equipment:
  - Caterpillar CS-563E Smooth-drum vibratory roller
  - Caterpillar 824C Rubber-tired roller (dozer)
  - Caterpillar 825C Padfoot roller
  - Caterpillar 631G Scraper
- Two soil types: finer and coarser granular soils

Field Compactors

Caterpillar compaction and earthmoving equipment

Specifications of Compactors

- Operating weight of compactor is related to the transferred compactive energy



Source: Caterpillar - http://www.cat.com

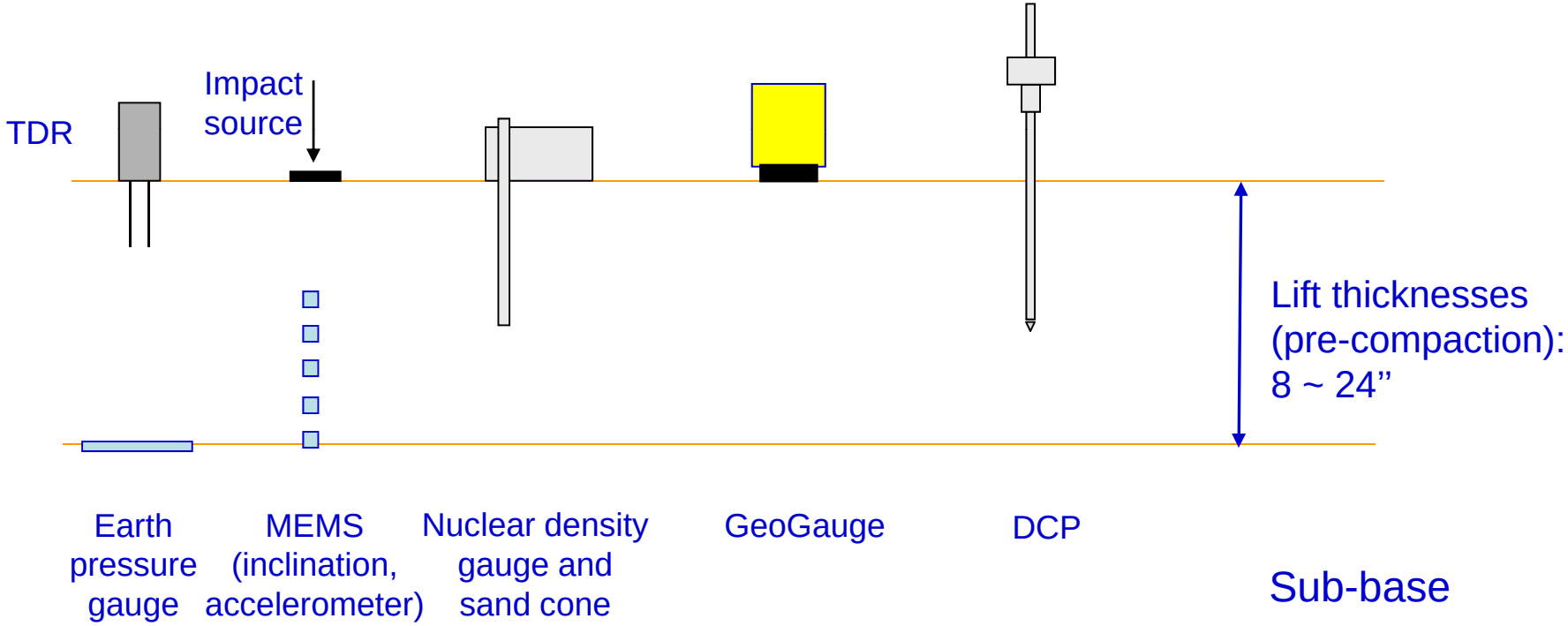
Field Measurements

Actual conducted field testing matrix

Soil type / compactor	Finer granular soil	Nat. moisture coarser granular soil	Wet coarser granular soil
Vibratory roller	12, 17, and 24” lifts	8, 13, and 24” lifts	8, 13, and 23” lifts
Rubber-tired roller	8~11, and 20” lifts	8, 13, and 20” lifts	13, and 23” lifts
Scraper	24” lift	13, and 23” lifts	-
Padfoot roller	10~16, and 20” lifts	-	-

Field Measurements

- Field deployment / test section

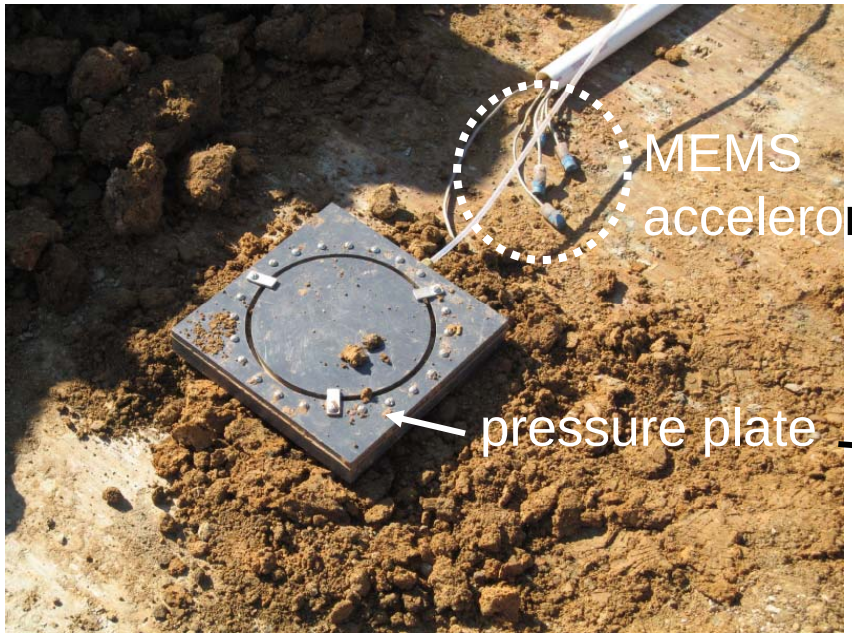


Field Testing: Soil Properties

Field Testing: Energy Compaction

Measurements of changes in internal stresses and accelerations (pressure cell plate and accelerometers)

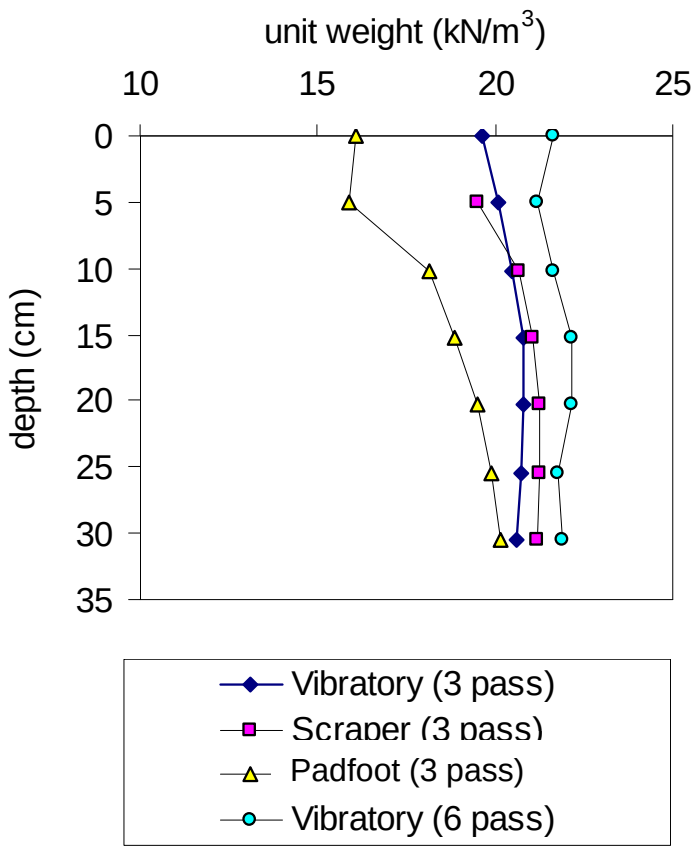
Installation of Sensors

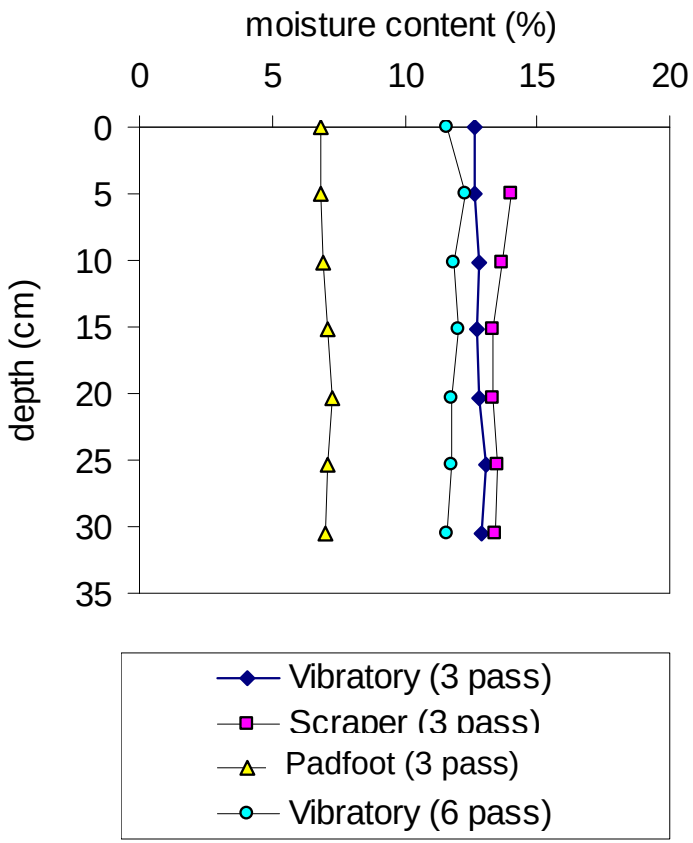


Extraction of Sensors

Effect of Compactor on Dry Unit Weight and Water Content

Nuclear Density Gauge – Finer granular soil





Dynamic Cone Penetrometer

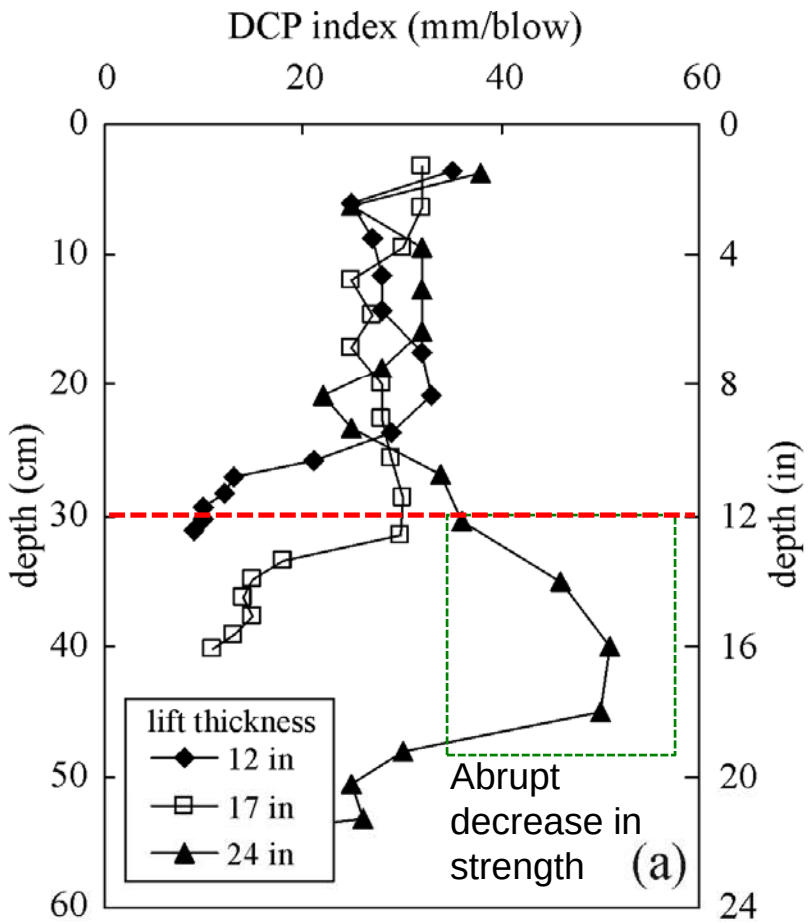
- Dynamic cone penetrometer (DCP): provides indication of the shear strength uniformity of soil layers.

- DCP index: is a measure of soil shear strength as function of dry density and effective stress. That is, the DCP index profiles give indication of the quality of compaction both in depth and across the compaction path.

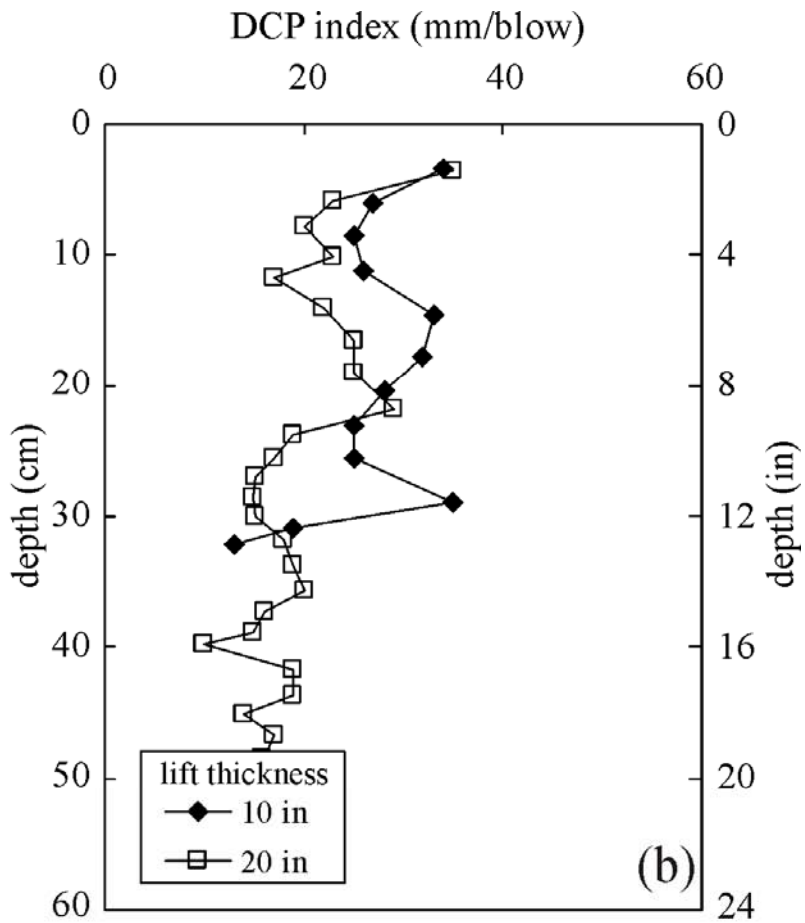
Dynamic Cone Penetrometer

Finer granular soil

Smooth-drum vibratory roller



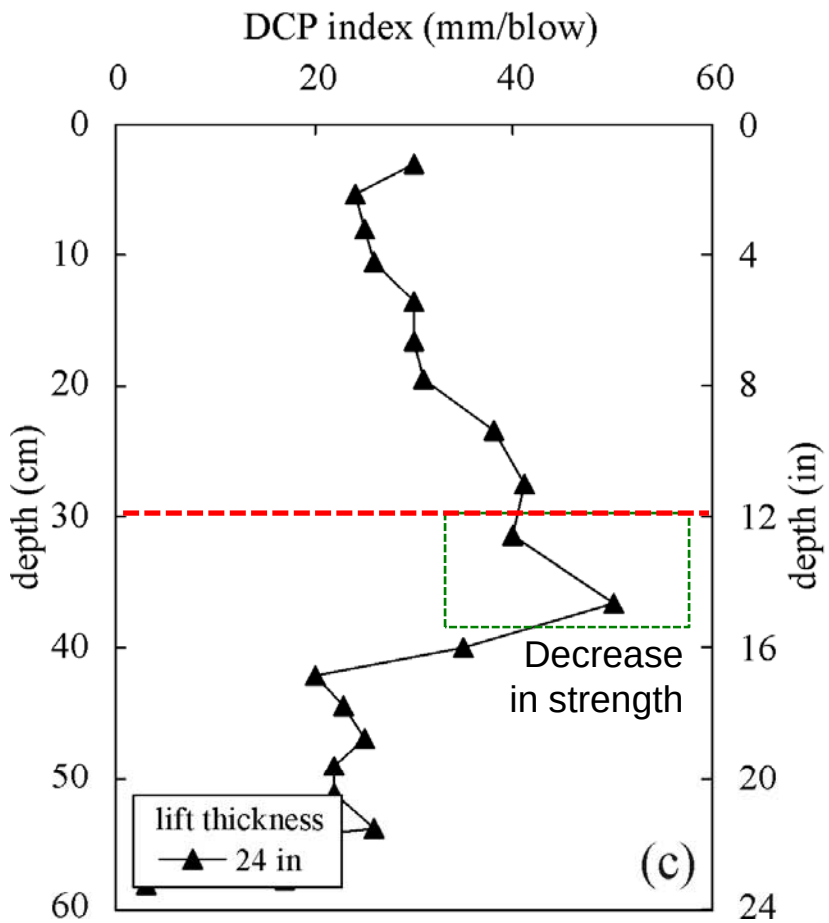
Rubber-tired roller



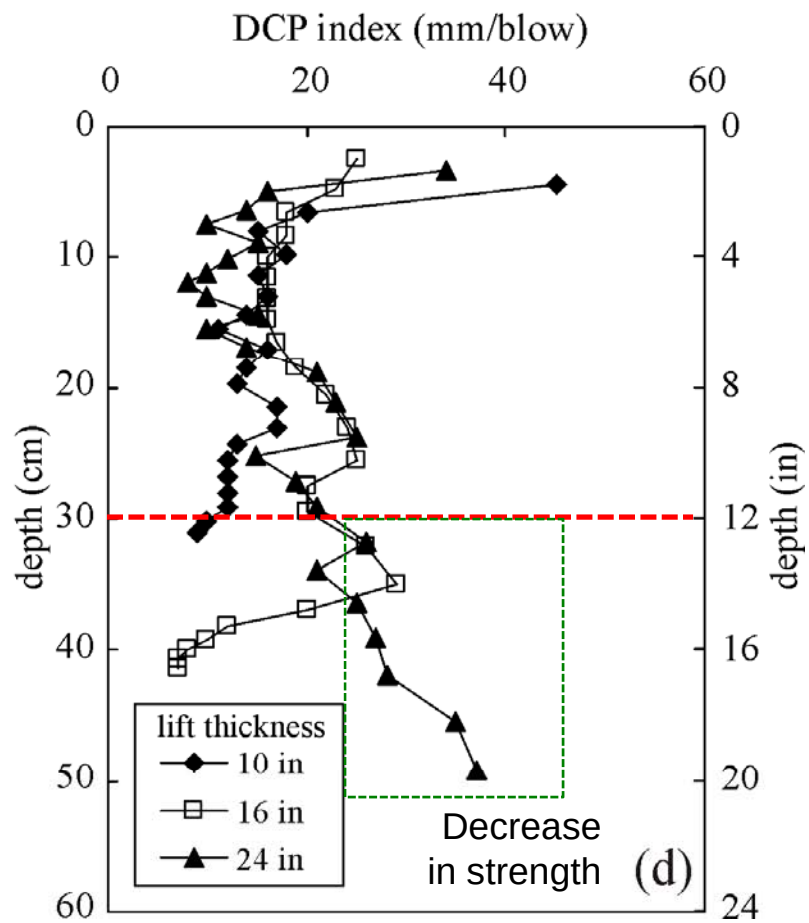
Dynamic Cone Penetrometer

Finer granular soil

Padfoot roller



Scraper



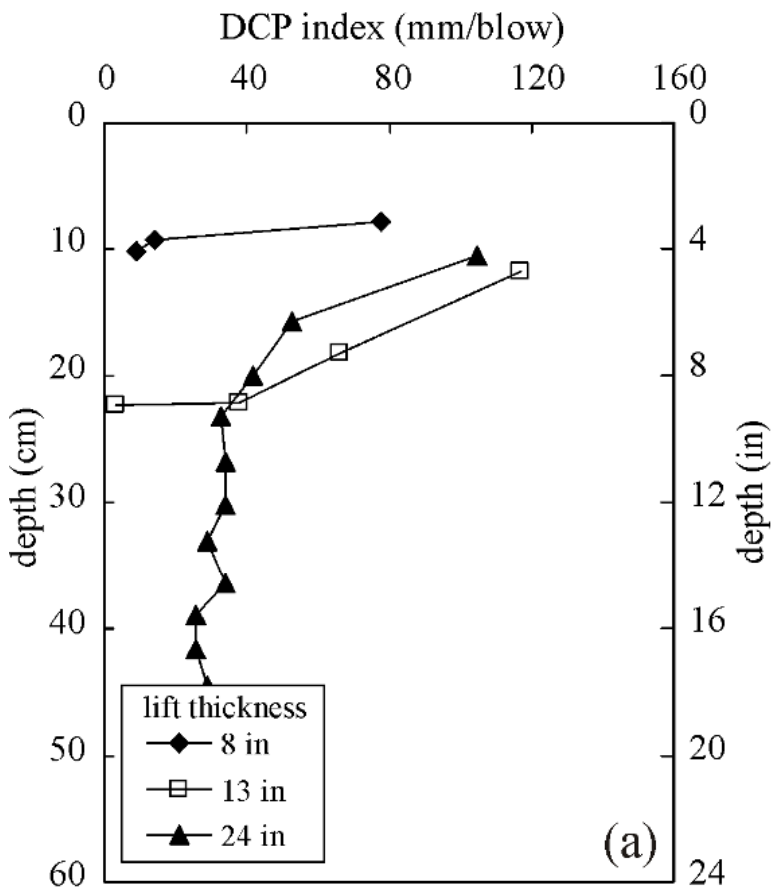
Padfoot roller

Scraper

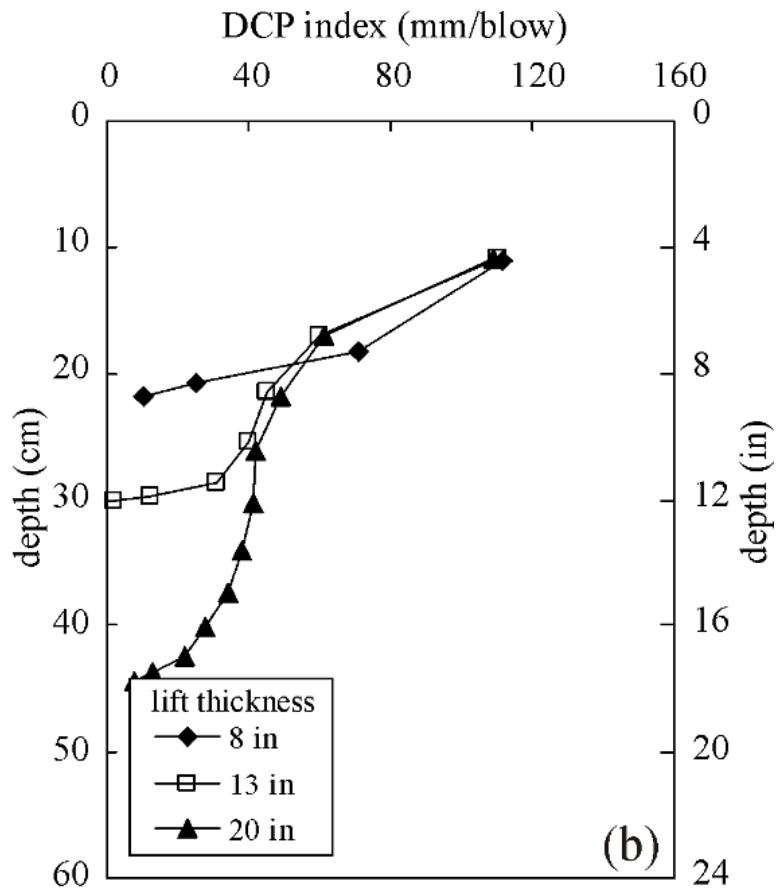
Dynamic Cone Penetrometer

Natural moist coarser granular soil

Smooth-drum vibratory roller



Roller tire roller



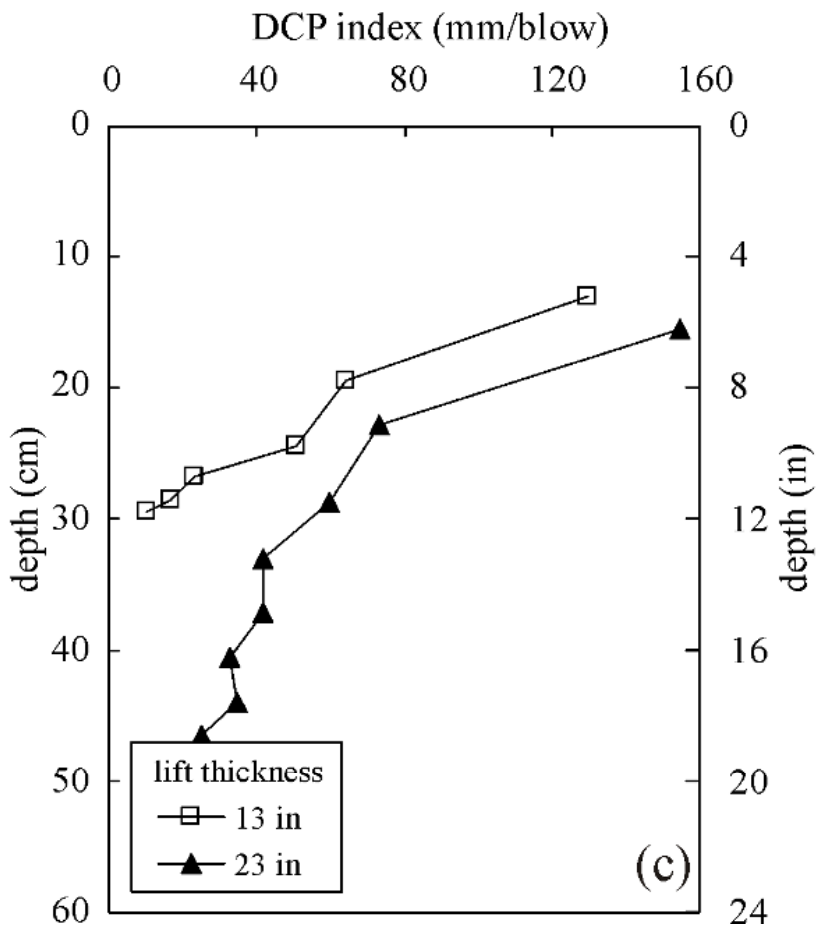
Smooth-drum vibratory roller

Roller tire roller

Dynamic Cone Penetrometer

Natural coarser granular soil

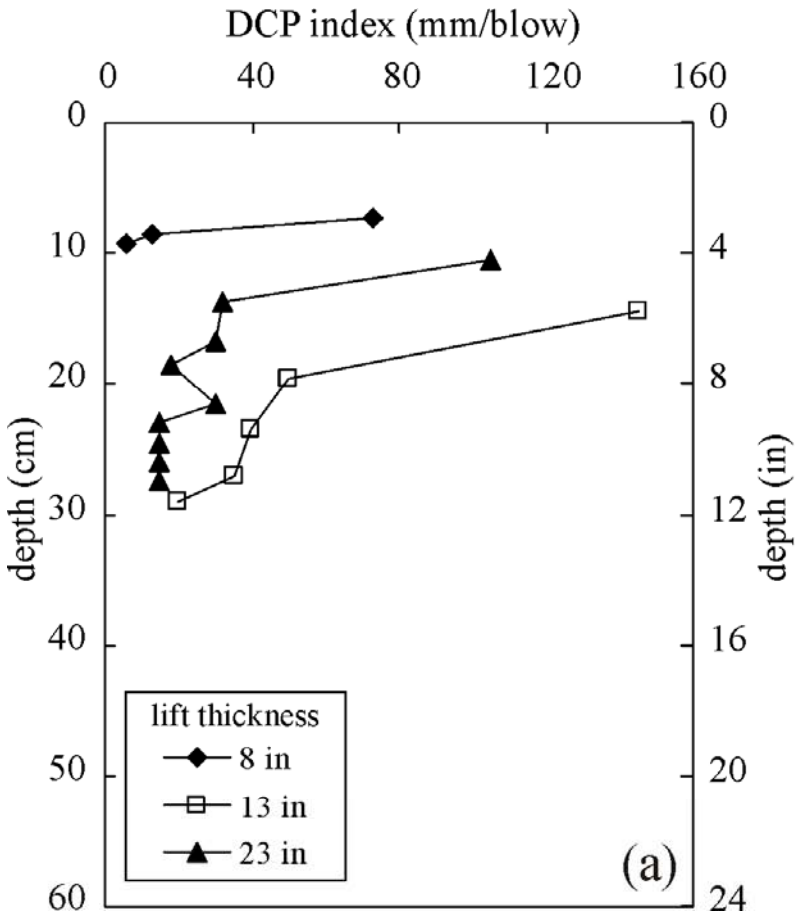
Scraper



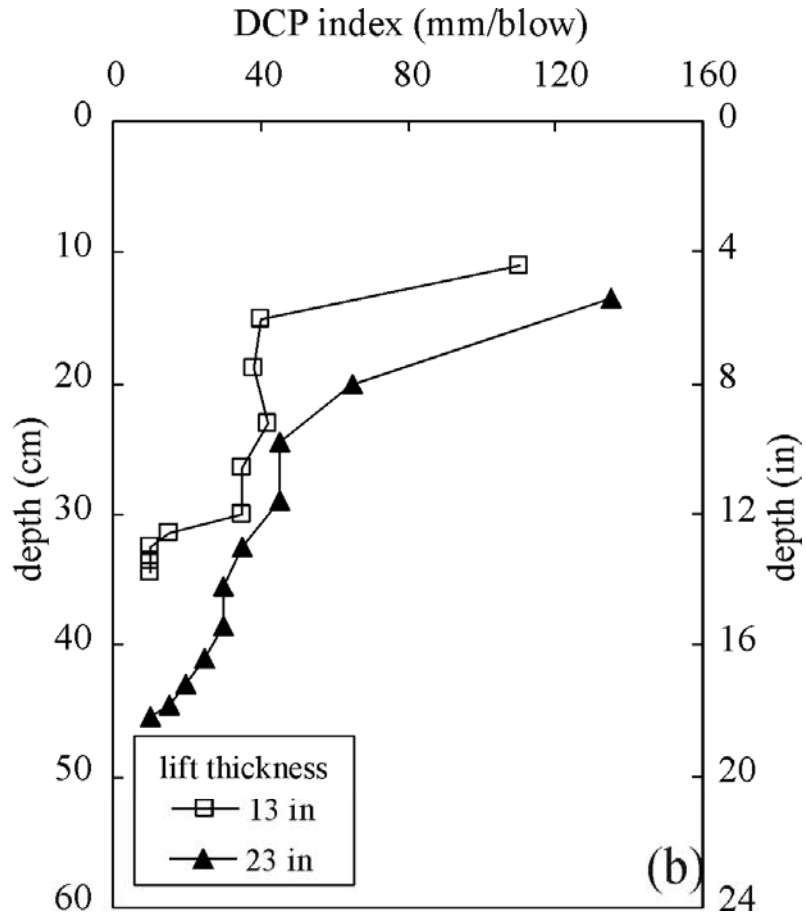
Dynamic Cone Penetrometer

Moist coarser granular soil

Smooth-drum vibratory roller

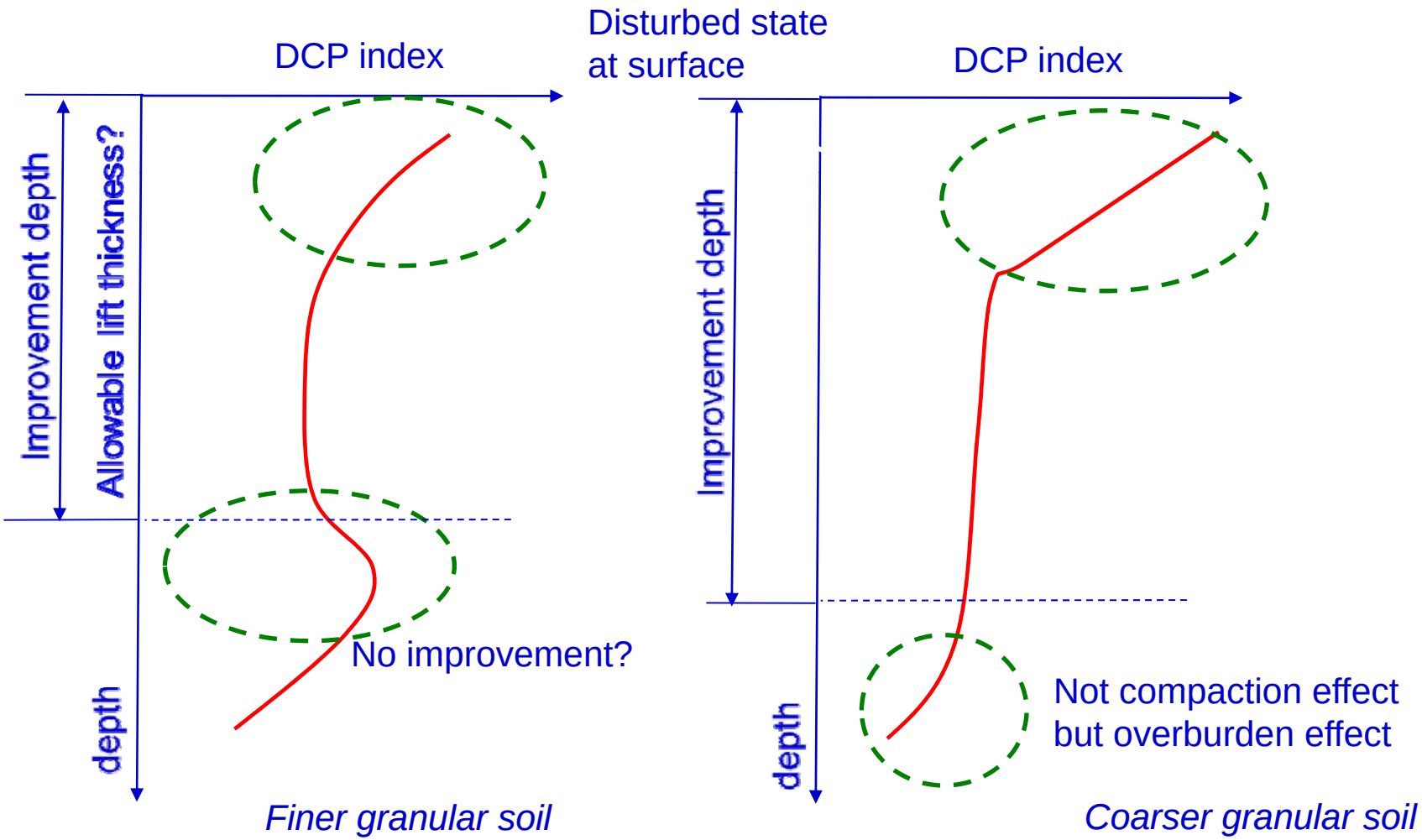


Roller tire roller



DCP Observations

DCP index and compaction effectiveness

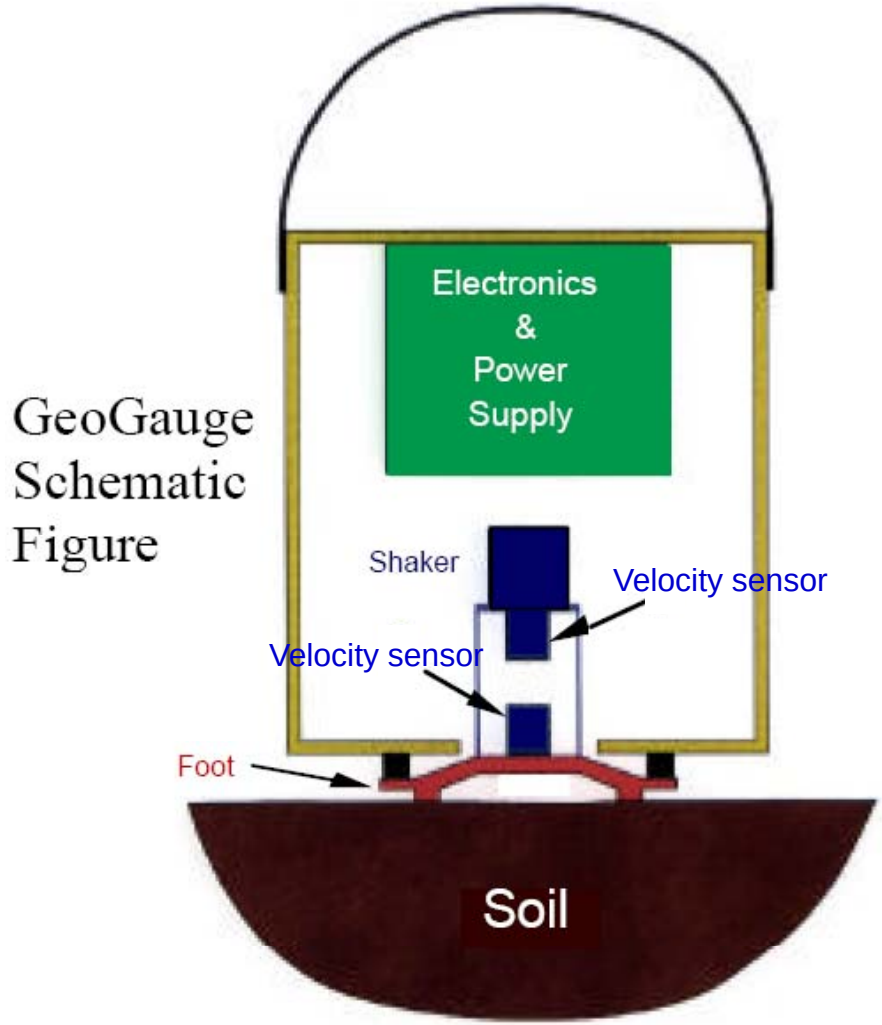


Soil Stiffness Gauge

- SSG
  - SSG measures the impedance at the surface of soil
  - Soil stiffness can be calculated by the impedance

$$K = \frac{P}{\delta} \approx \frac{1.77 \cdot R \cdot E}{1 - \nu^2}$$

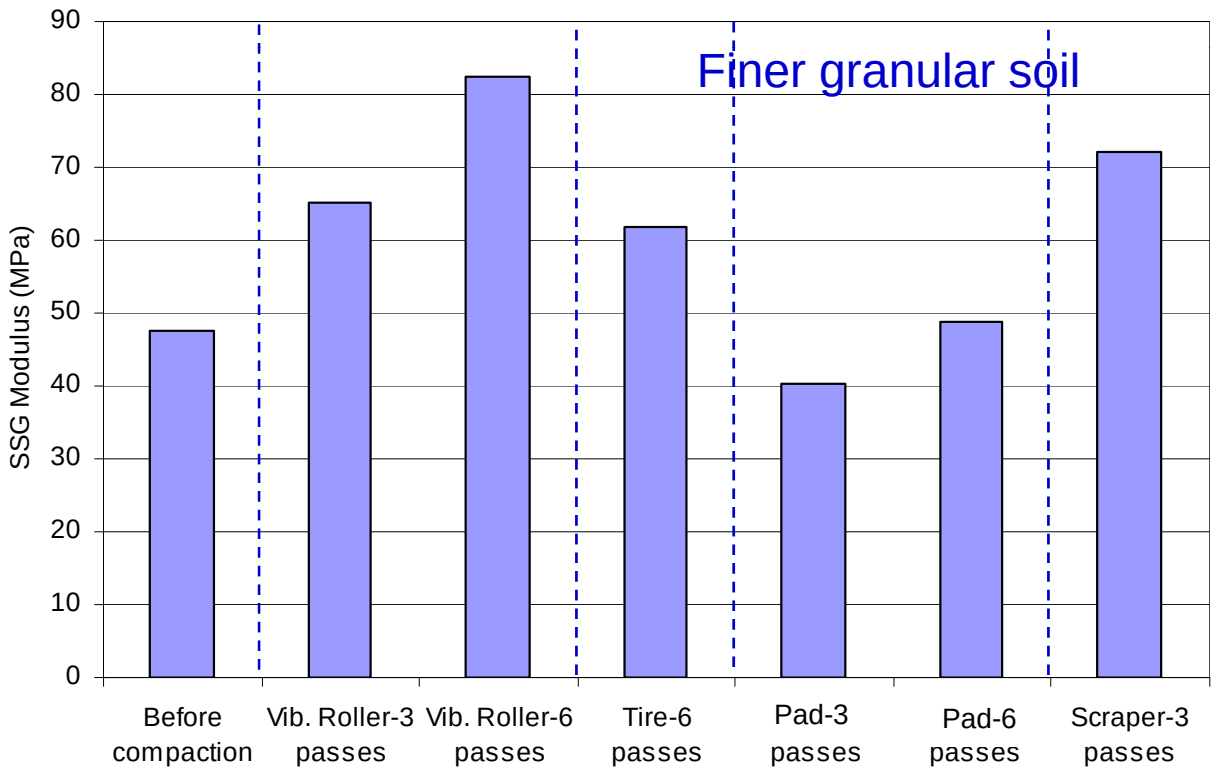
Where,
R: the outer radius of ring foot
E: Young's modulus



http://www.impact-test.com

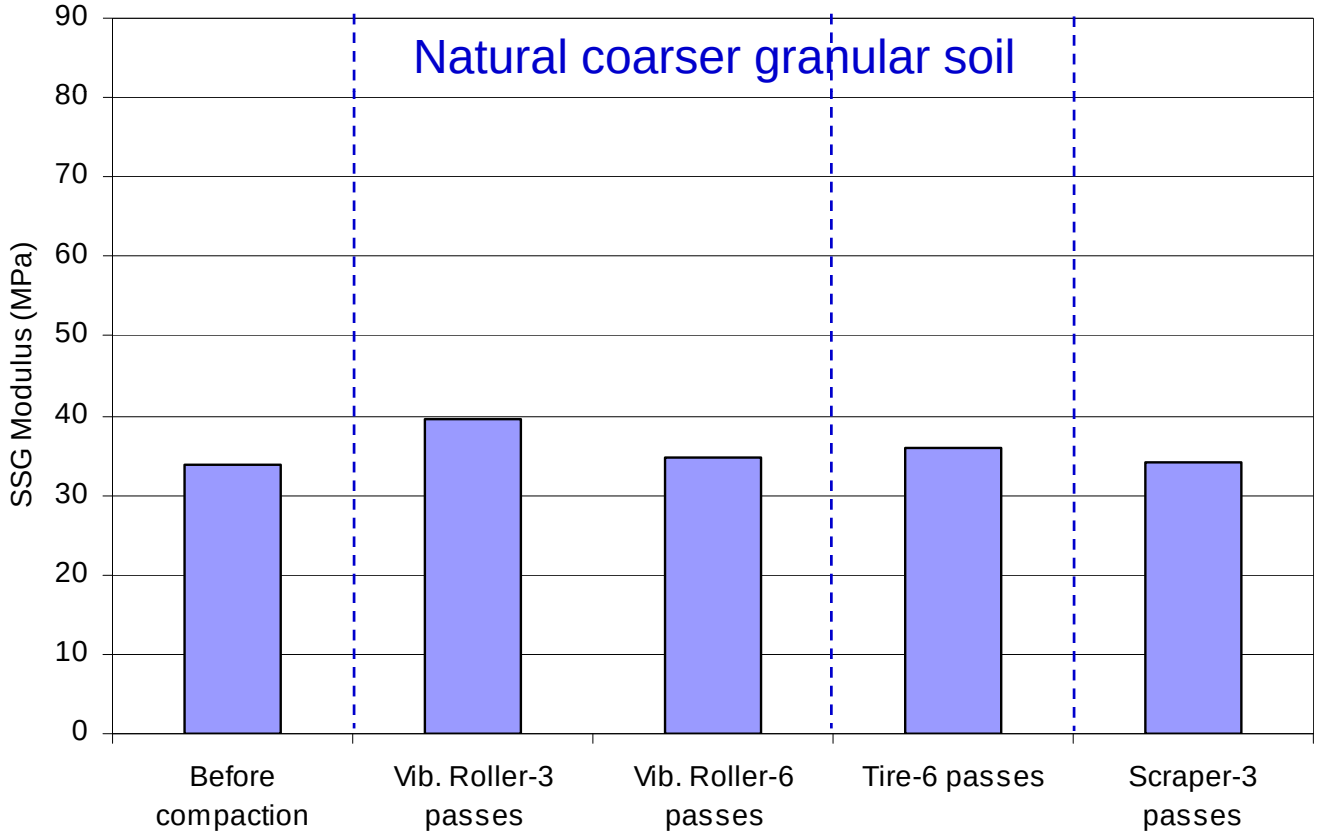
Soil Stiffness Gauge

- The use of different compactors is reflected on modulus.
- Passes also affects stiffness measurements
- Sheep foot compactor does not show improvements (depth limitation of SSG and surface disturbances)



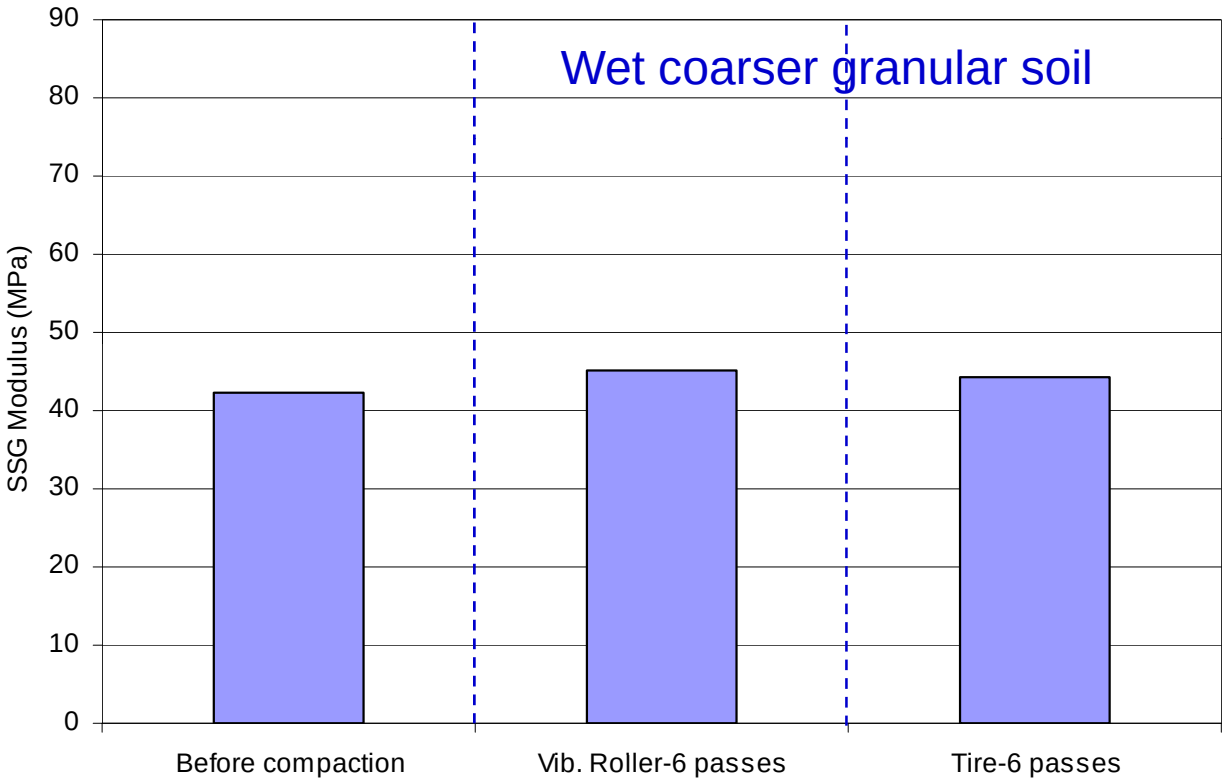
Soil Stiffness Gauge

- Tire roller and scraper on sand created lots of soil displacement.

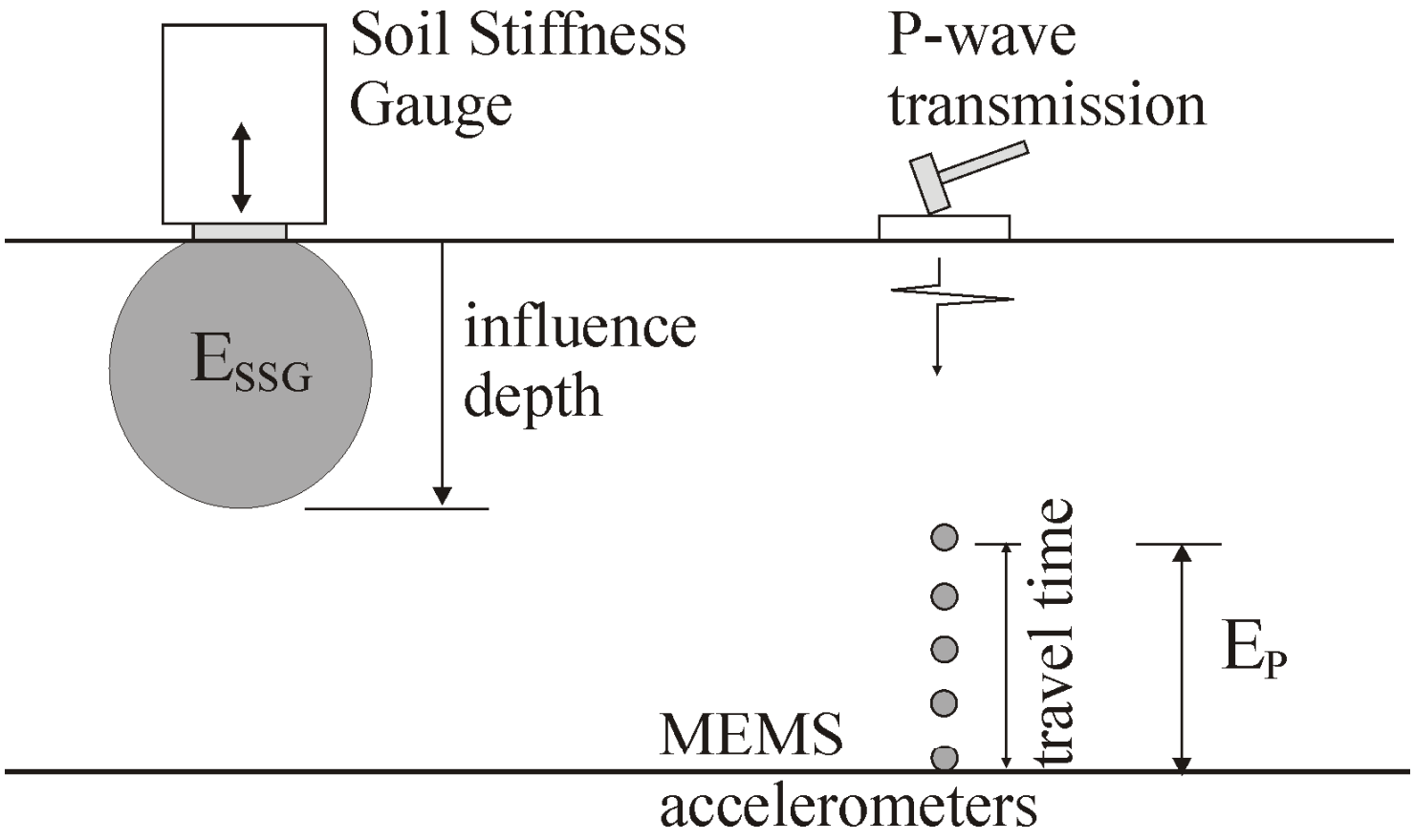


Soil Stiffness Gauge

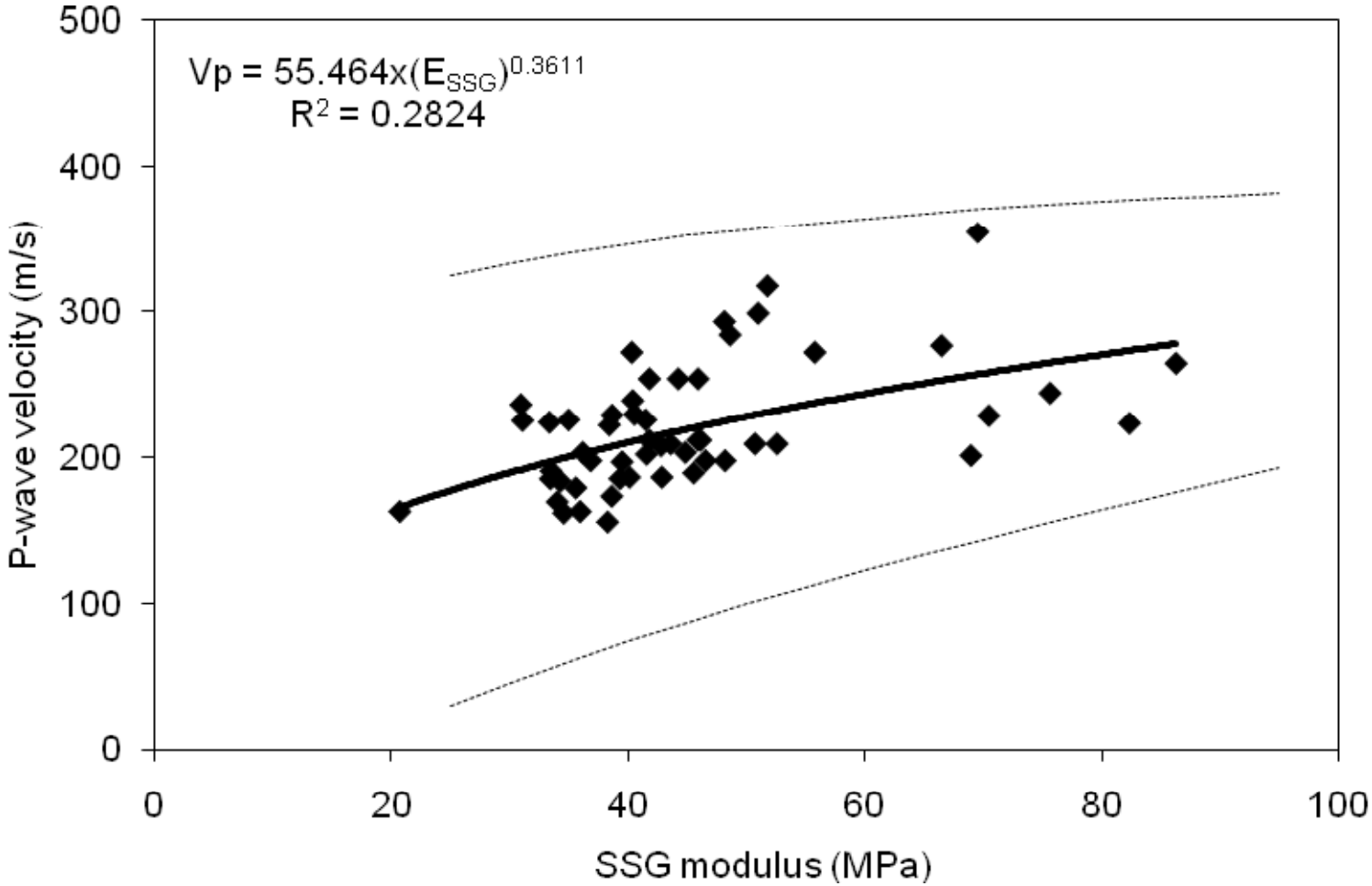
- Wet sand stiffness is higher than that of natural moisture sand



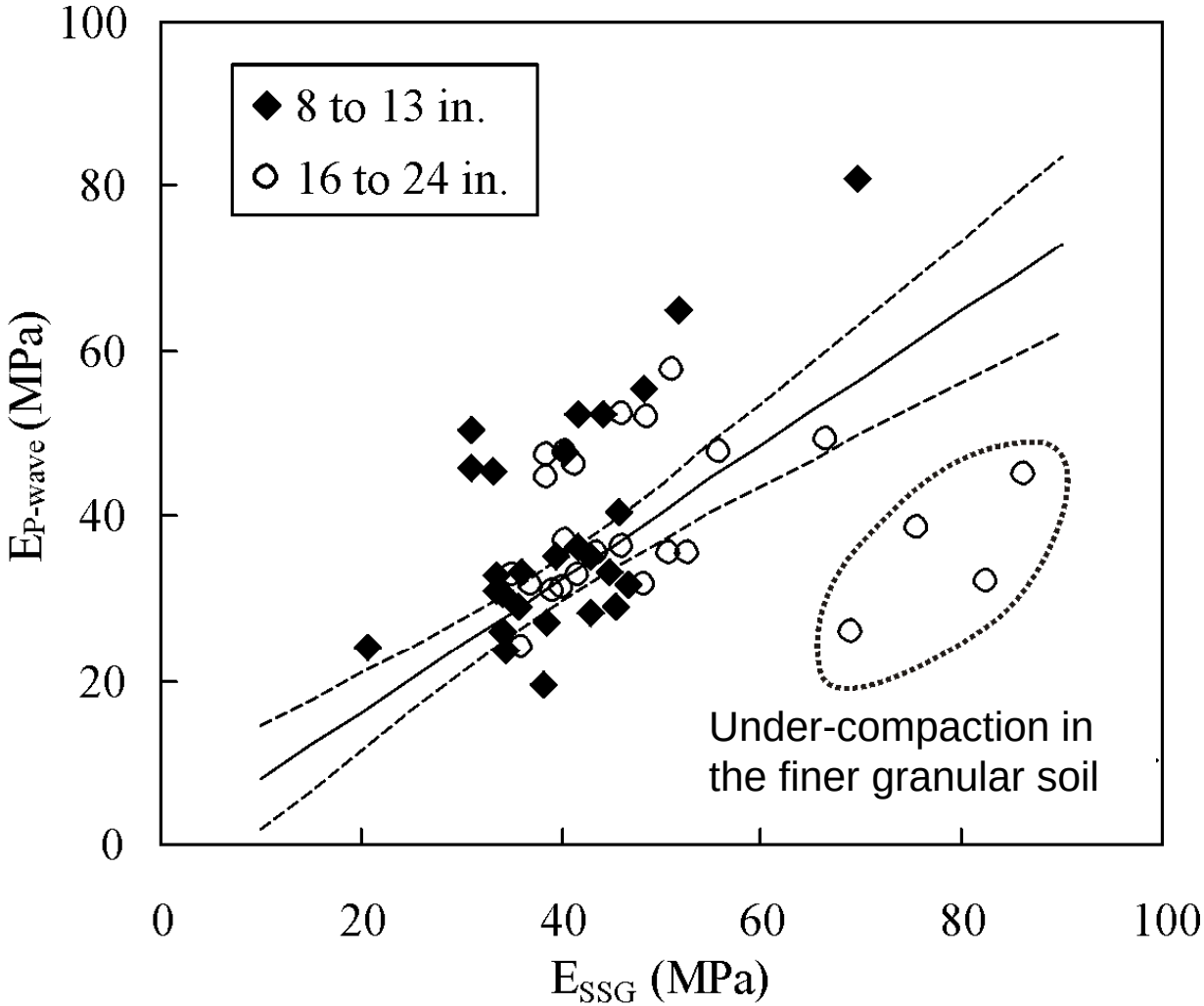
Soil Stiffness Gauge & P-wave velocity



Soil Stiffness Gauge & P-wave velocity



Soil Stiffness Gauge & P-wave velocity



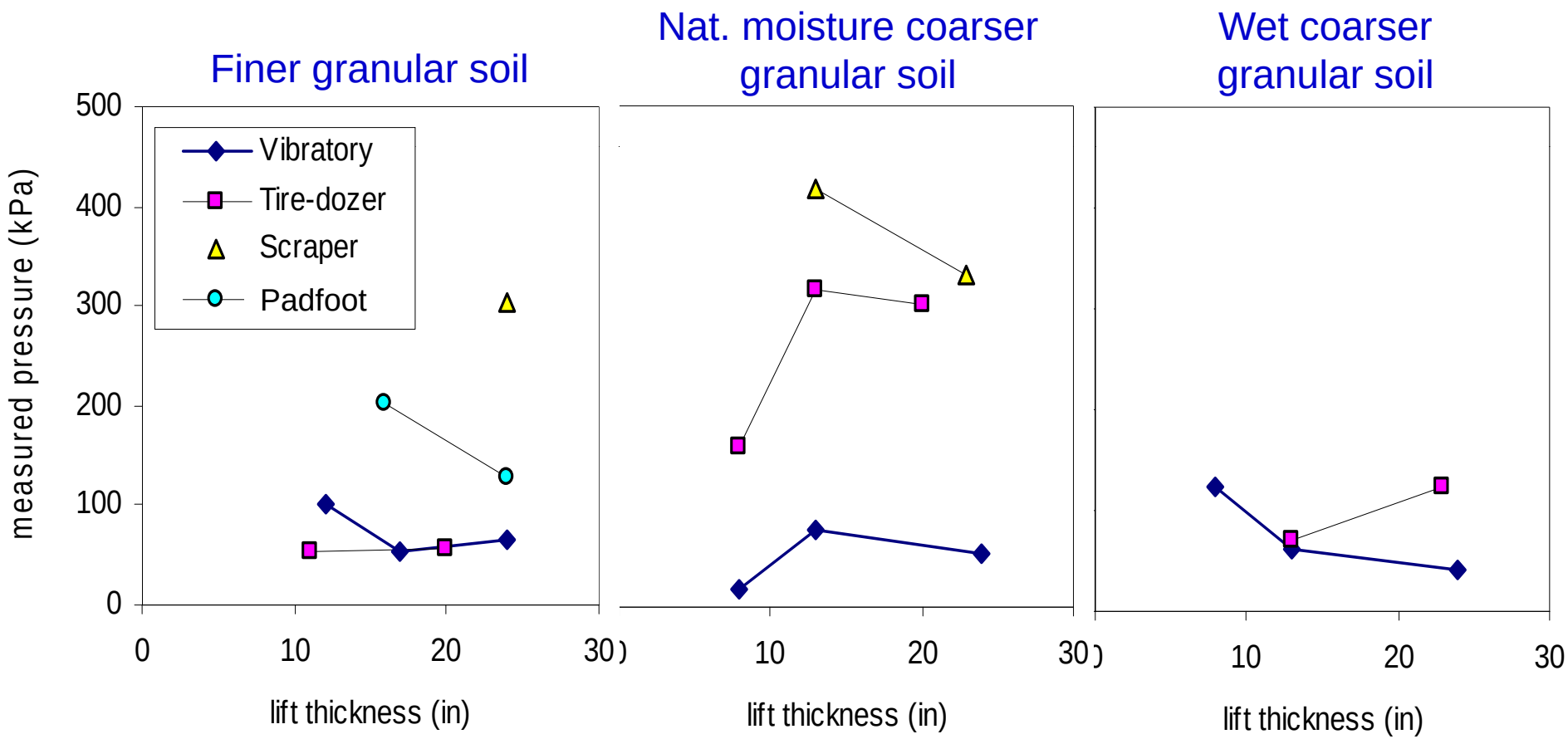
Pressure Cell Plate

- Maximum pressure response was captured for each compactor's passing

Soil Type	Compactor type	Maximum Pressure Response (kPa)		
Fine grained Soil	Vibratory	12" – **101.9**	17" – **53.0**	24" – **64.8**
	Tire-dozer	11" – **52.2**	-	20" – **56.9**
	Scraper	-	-	24" – **304.3**
	Padfoot	-	16" – **202.9**	24" – **126.7**
Natural moisture sand	Vibratory	8" – **17.2**	13" – **75.7**	24" – **52.0**
	Tire-dozer	8" – **161.1**	13" – **316.5**	20" – **302.4**
	Scraper	-	13" – **417.1**	23" – **330.9**
Wet sand	Vibratory	8" – **122.2**	13" – **61.9**	24" – **42.3**
	Tire-dozer	-	13" – **69.5**	23" – **124.1**

Pressure Cell Plate

- Weight of compaction equipment and lift thickness affect the transferred pressure.

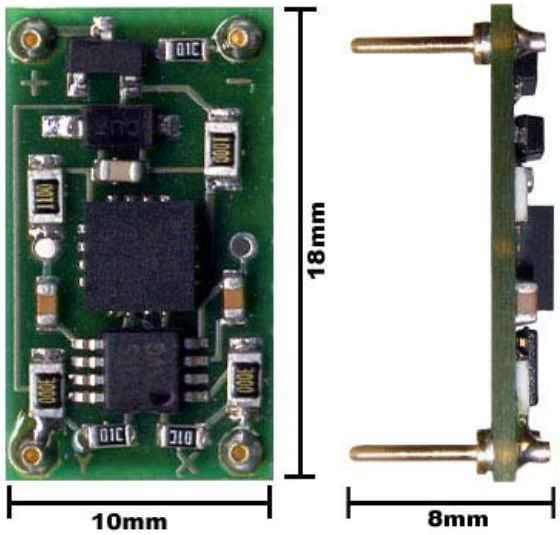


MEMS Measurements

- Direct measurements:
  - Internal soil deformation: MEMS inclinometers

Analog Devices ADLX203 iMEMS accelerometers

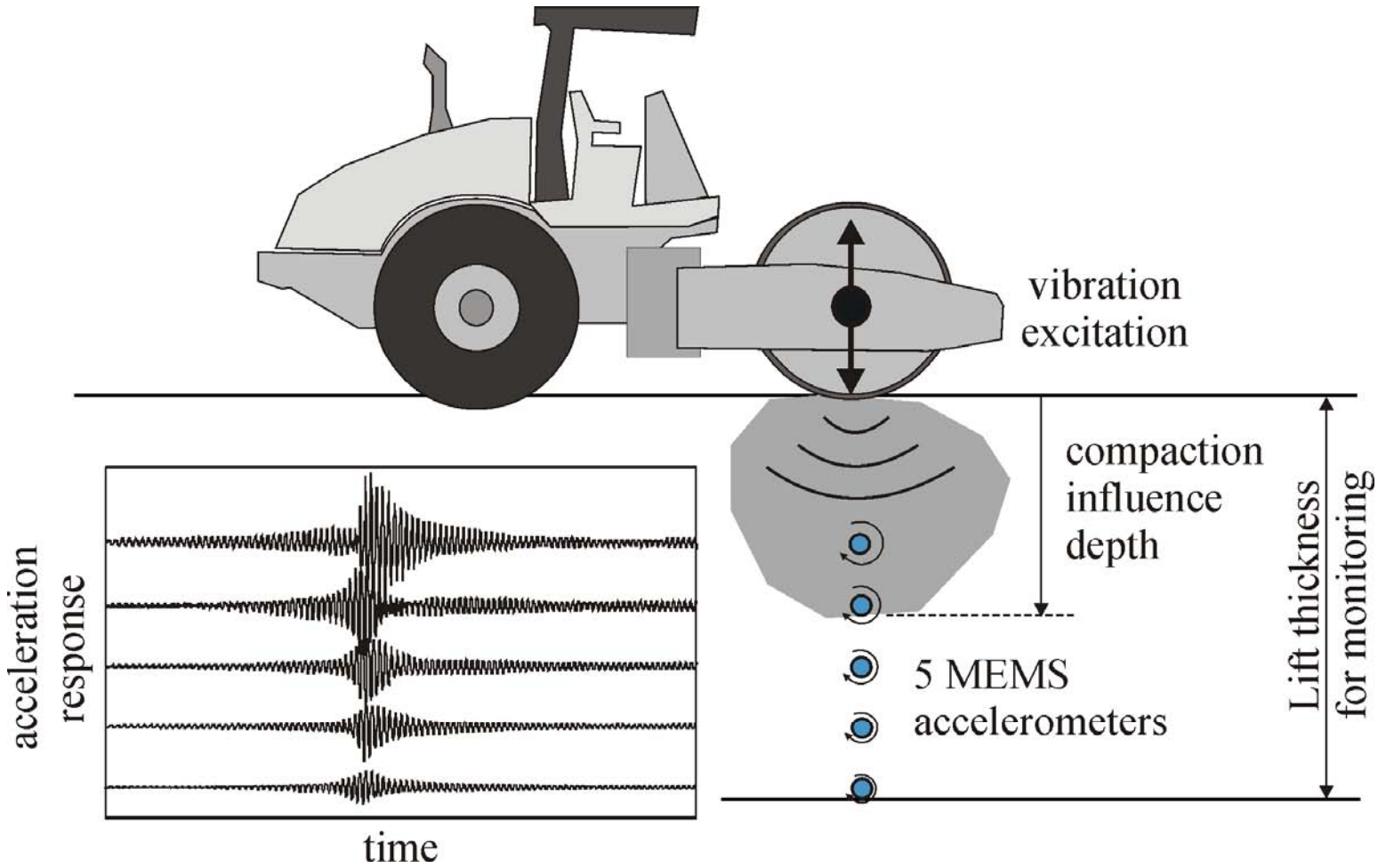
- Low-power consumption; Low-cost
- High sensitivity (750 mV/g)
- Dual axis “Static” Acceleration
  - Gravity: Rotation measurements



Source: http://www.dimensionengineering.com

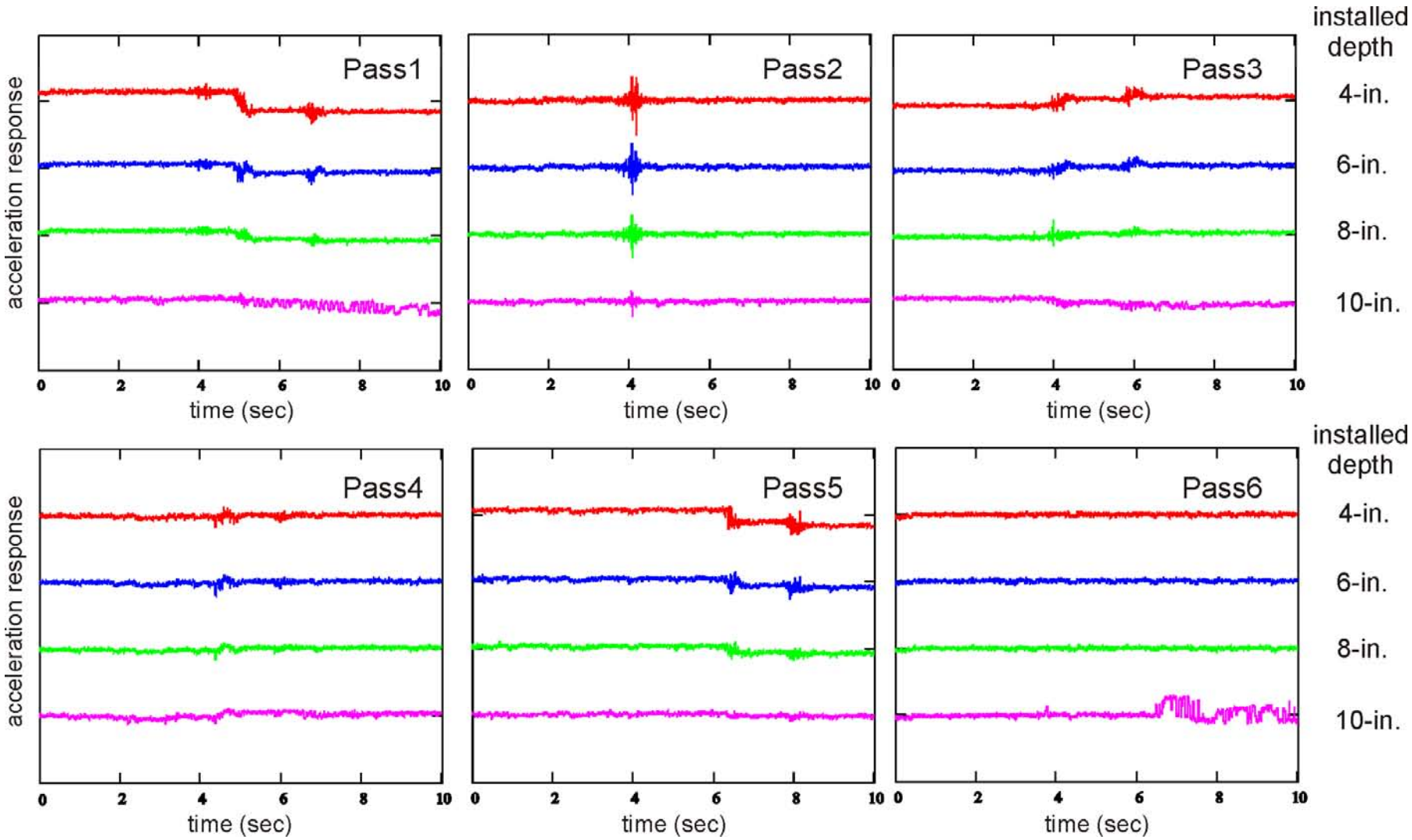
MEMS Measurements

Field setup



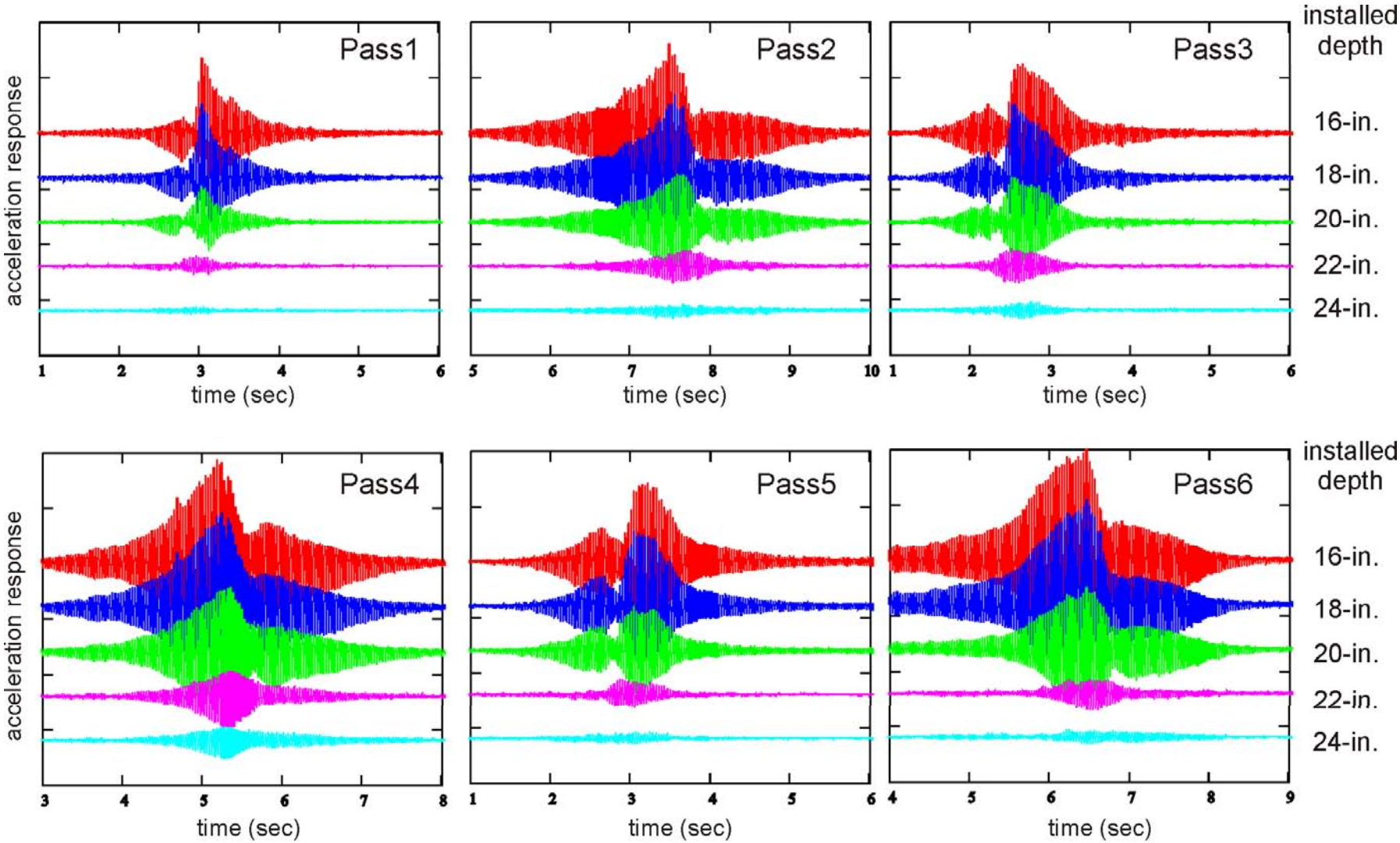
MEMS Measurements

- Finer granular soil, tire roller, 10-inch lift thickness, Y-axis acc.



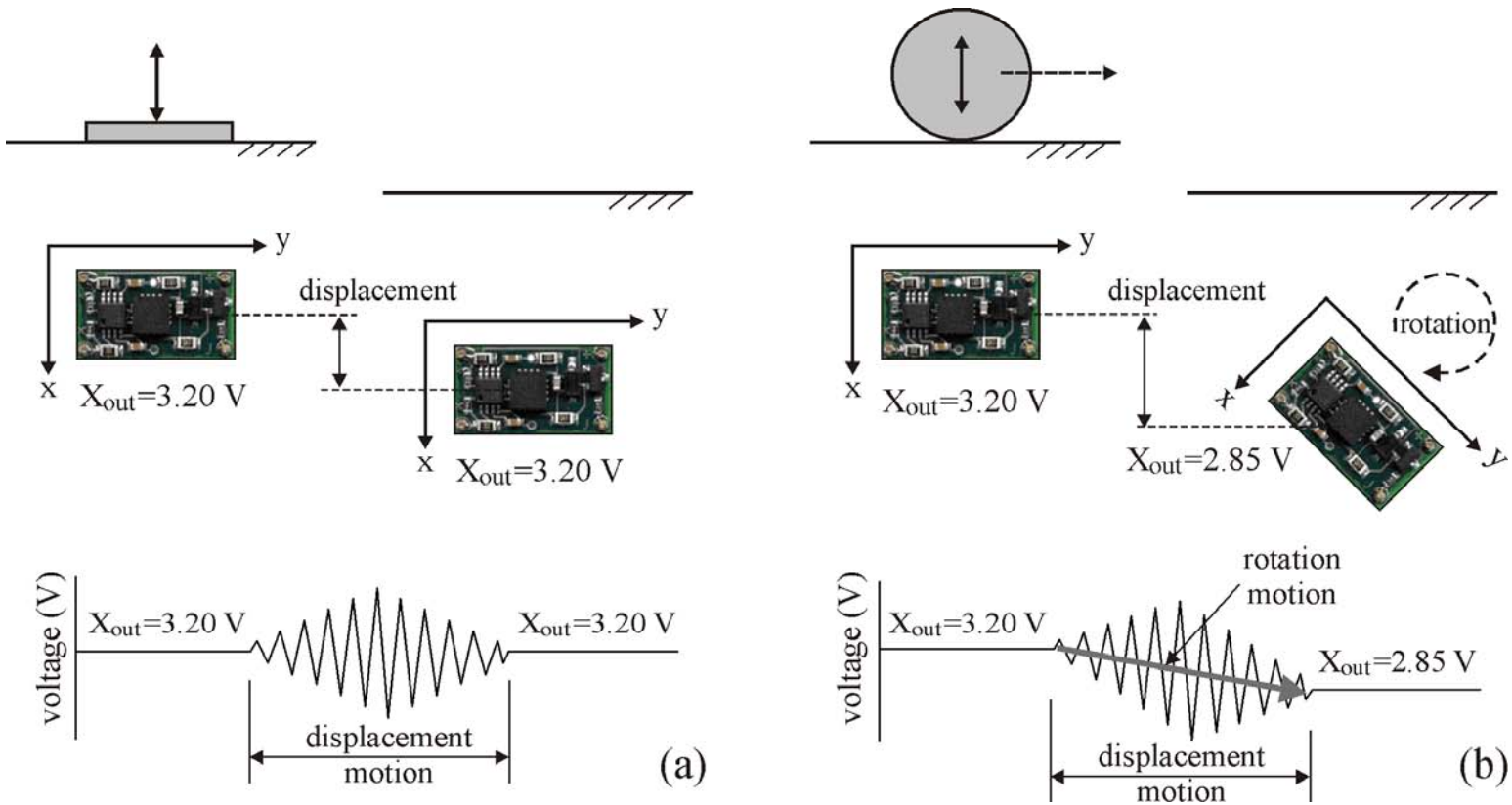
MEMS Measurements

- Finer granular soil, vibratory roller, 24-inch lift thickness, Y-axis acc.



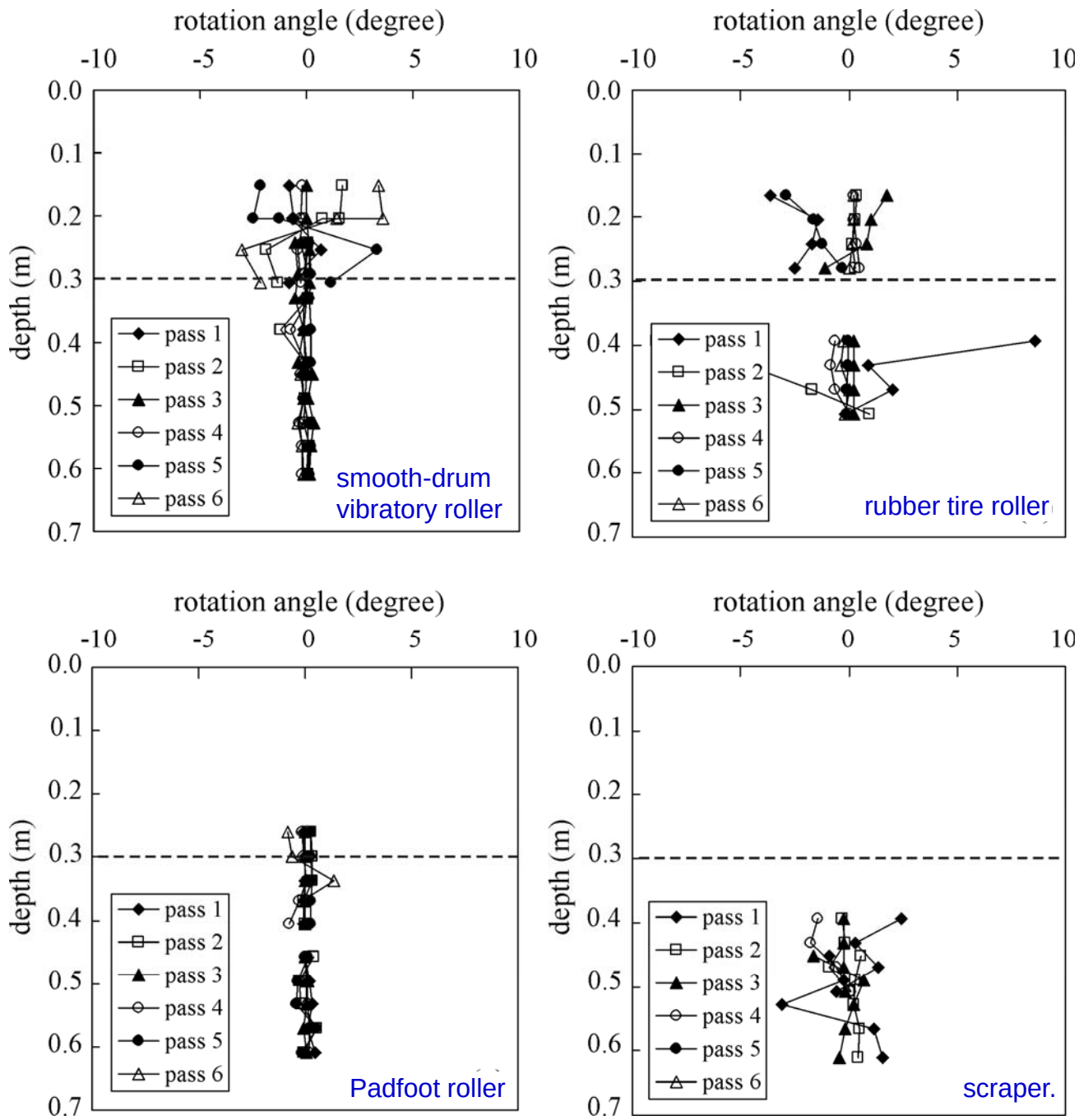
MEMS Measurements

Conceptual interpretation



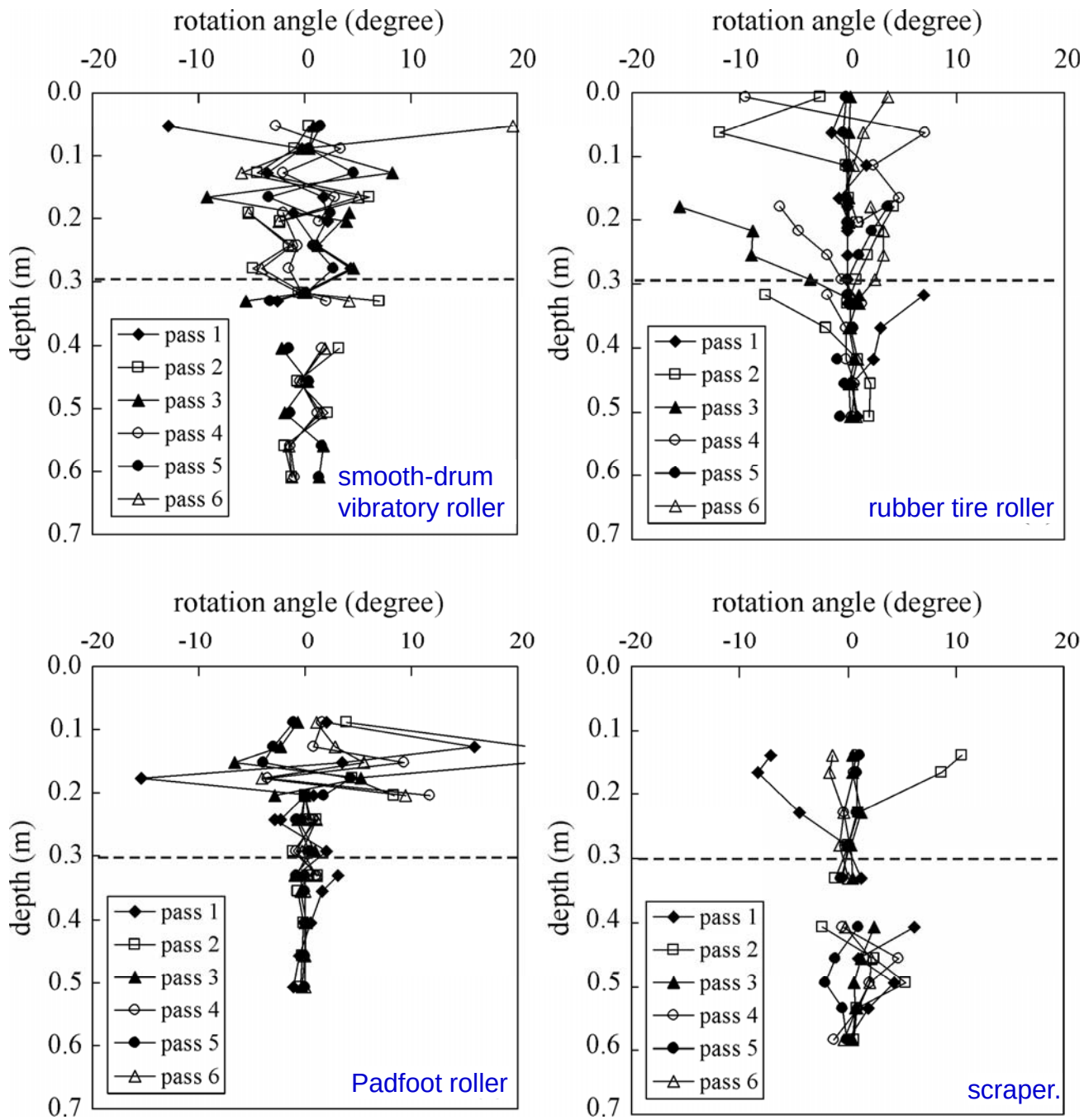
MEMS Measurements

Finer granular soils

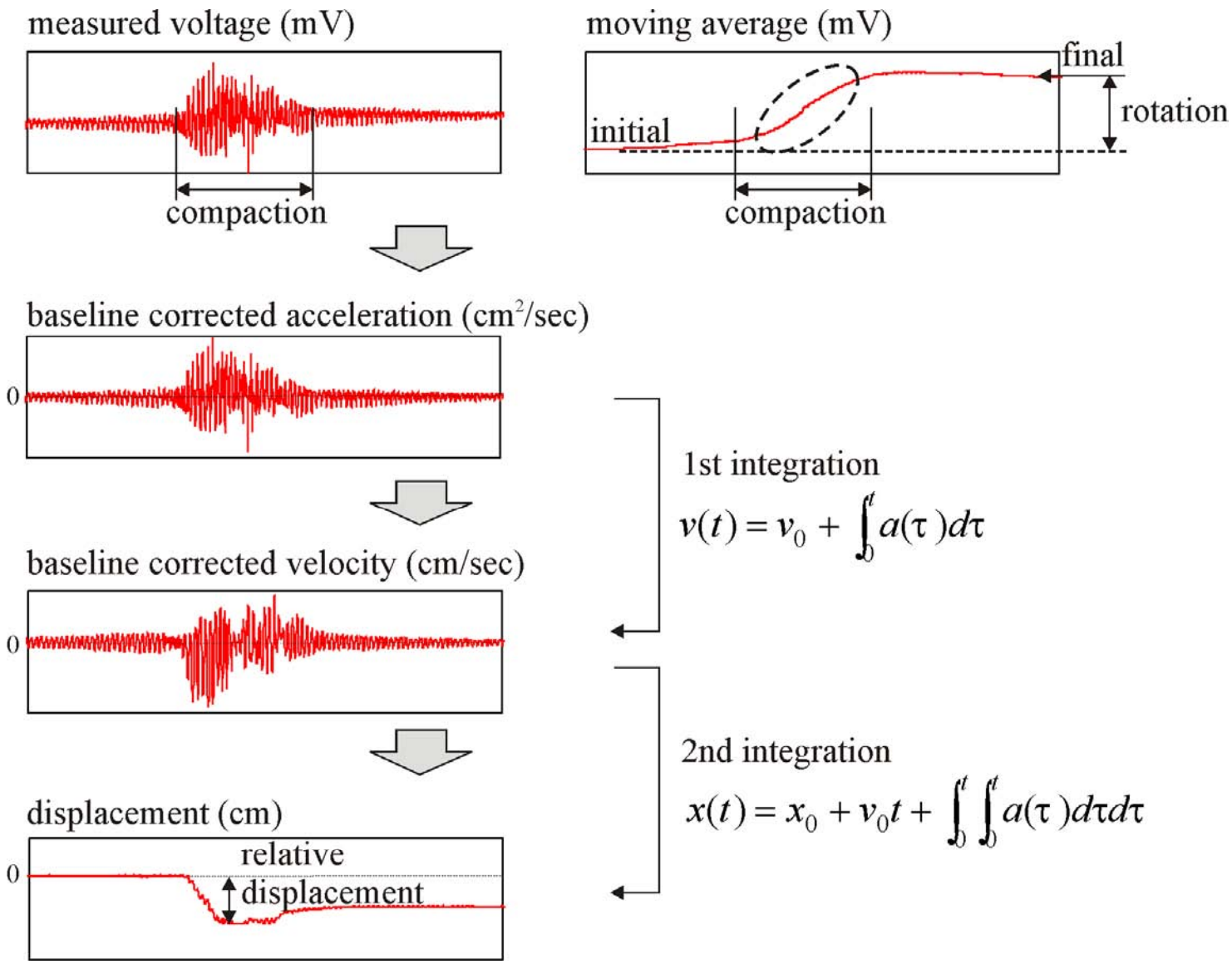


MEMS Measurements

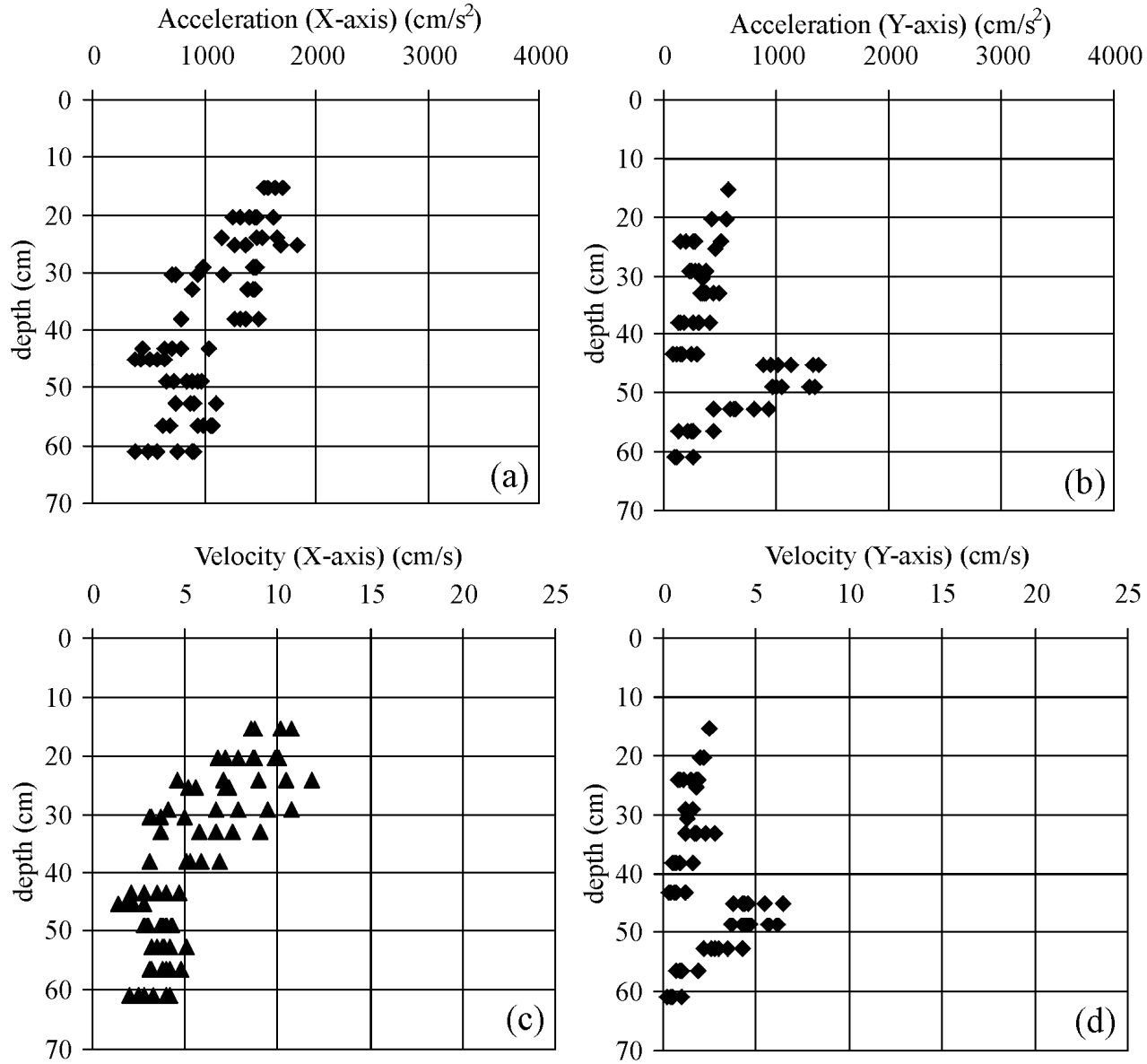
Coarser granular soils



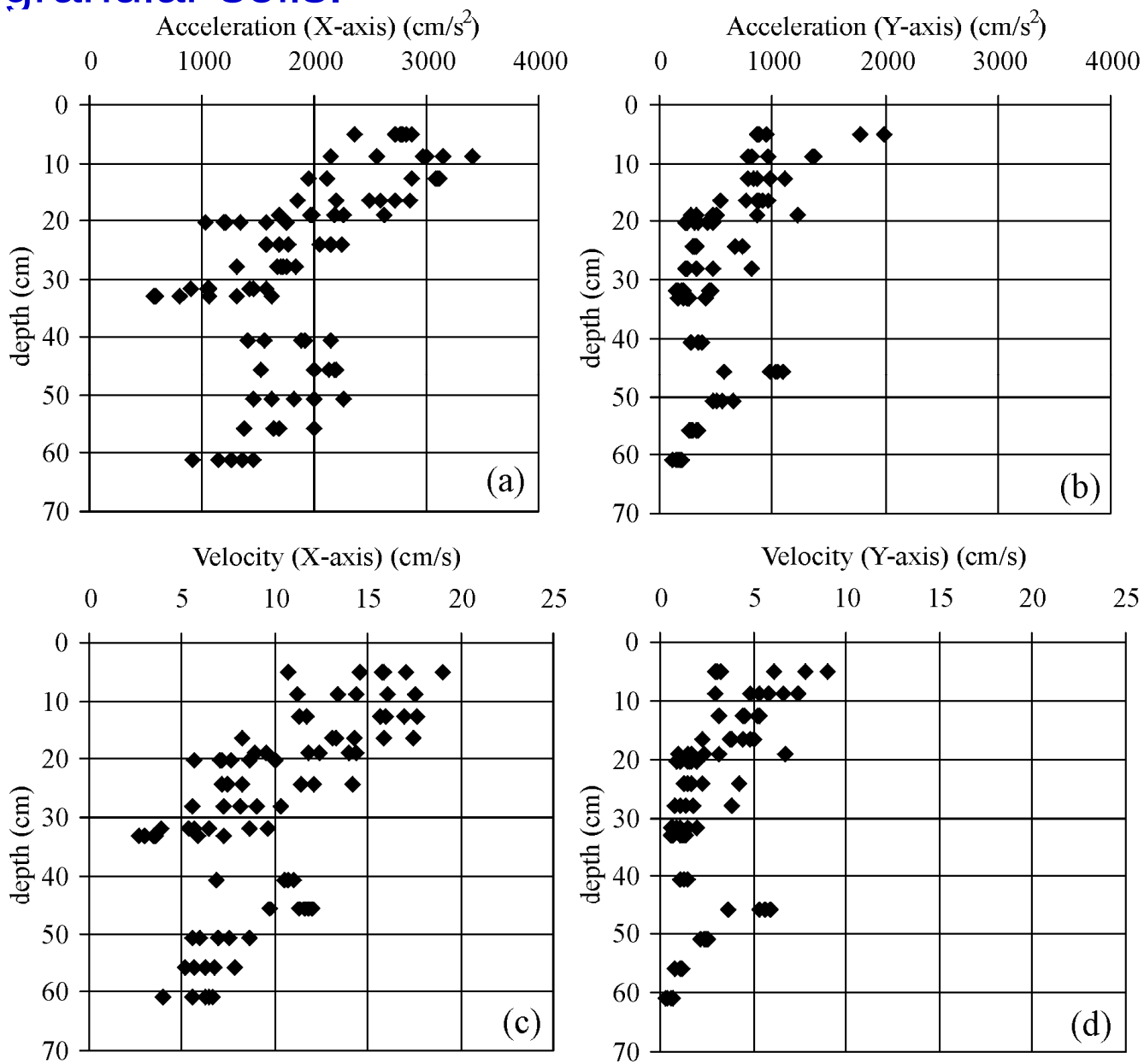
MEMS Measurements



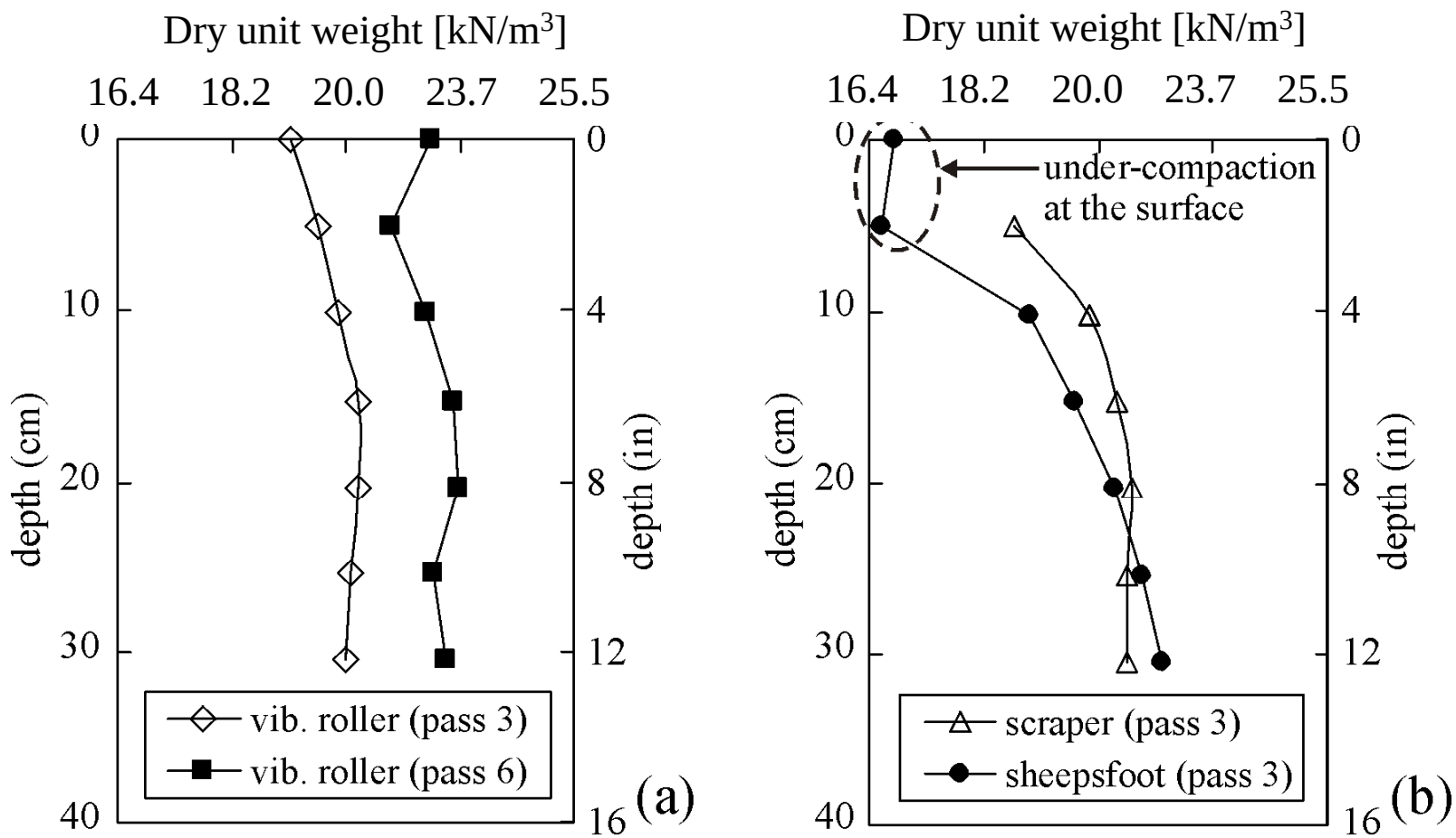
Peak particle acceleration and velocity by axis in finer granular soils.



Peak particle acceleration and velocity by axis in coarser granular soils.



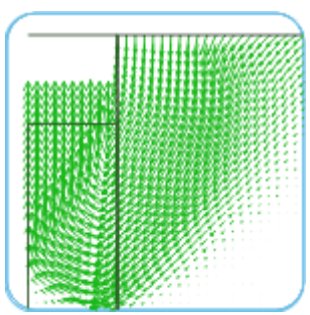
Relative compaction

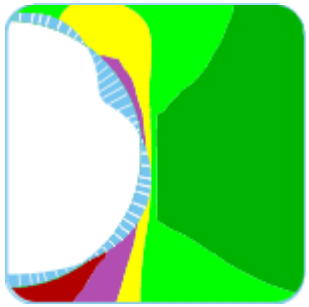


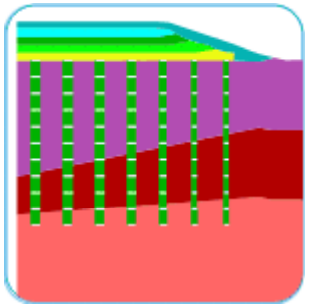
Relative compaction results for finer granular soils using nuclear density gauge: (a) smooth-drum vibratory roller; (b) scraper and padfoot rollers

Numerical Simulation

- *FLAC* (Fast Lagrangian Analysis of Continua) is a 2D continuum code for modeling geomaterials and structural behavior.
- The explicit finite difference formulation of the code makes *FLAC* suited for modeling geomechanical problems including static and dynamic

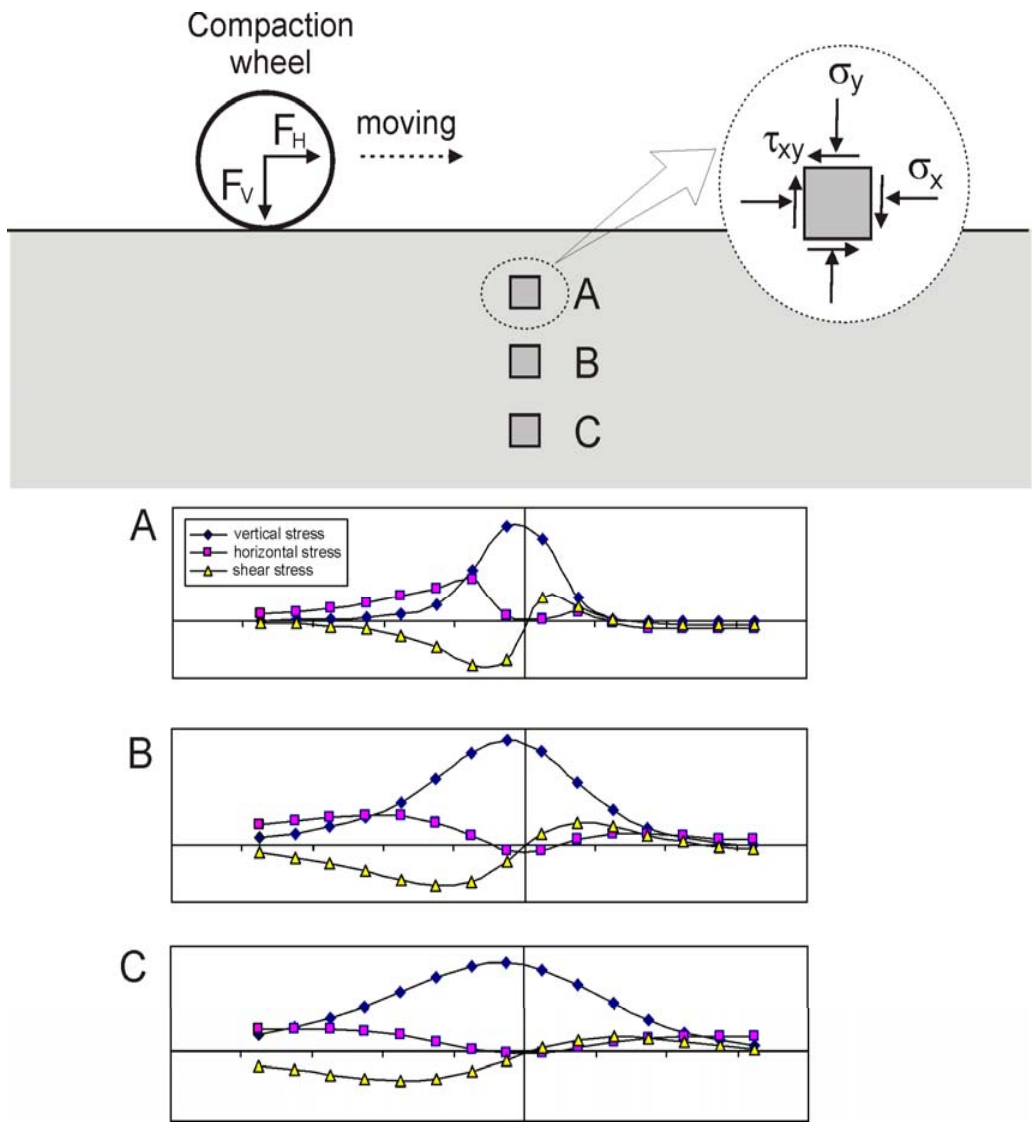




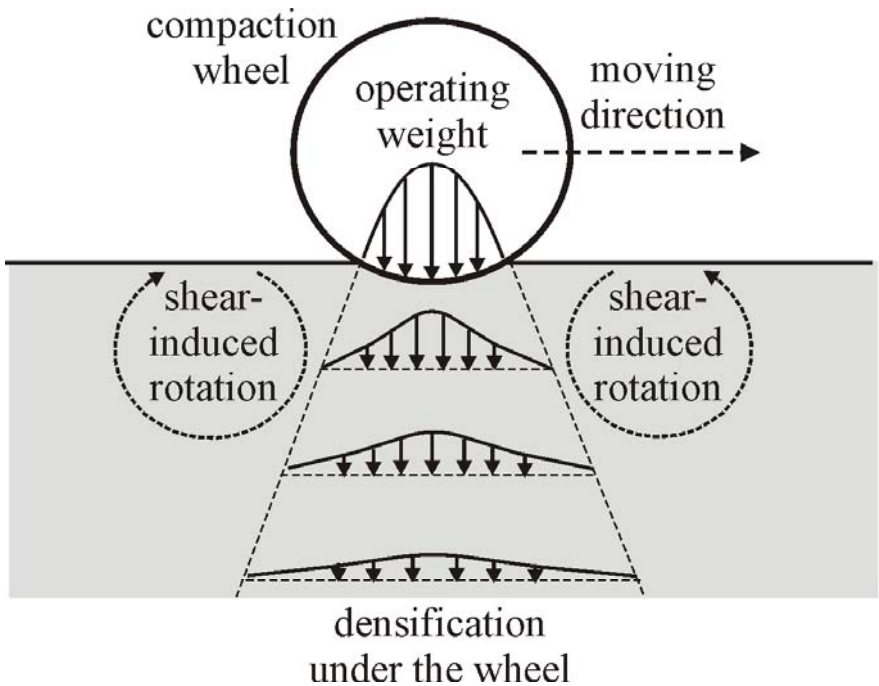


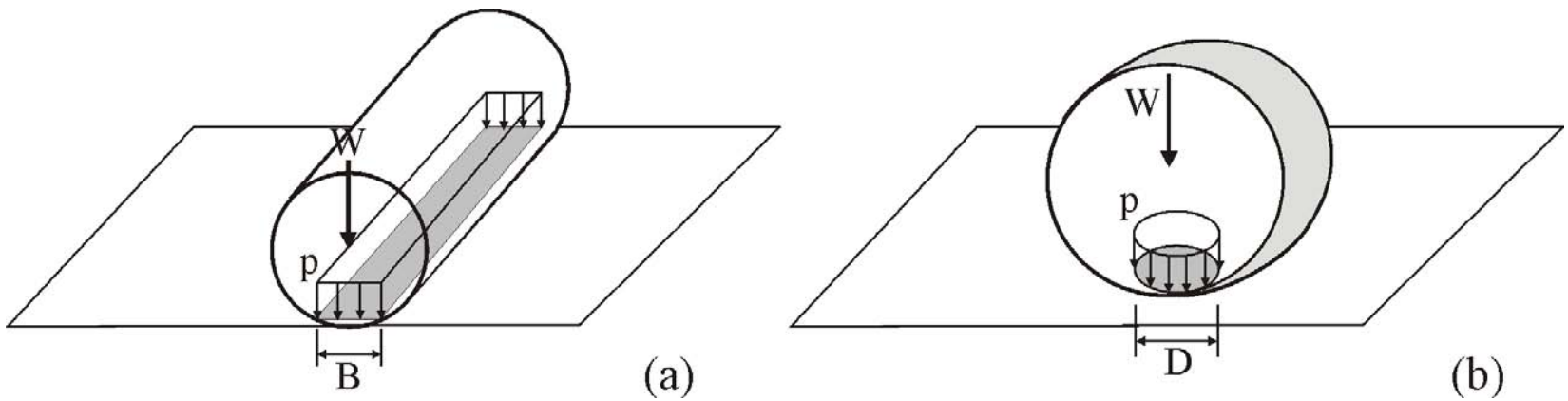
Stress Rotation

- Stress rotation is simulated by FLAC.
- The combination of vertical stress and horizontal stress may affect the induced shear stress -> related to shear distortion which directly affect the compaction.



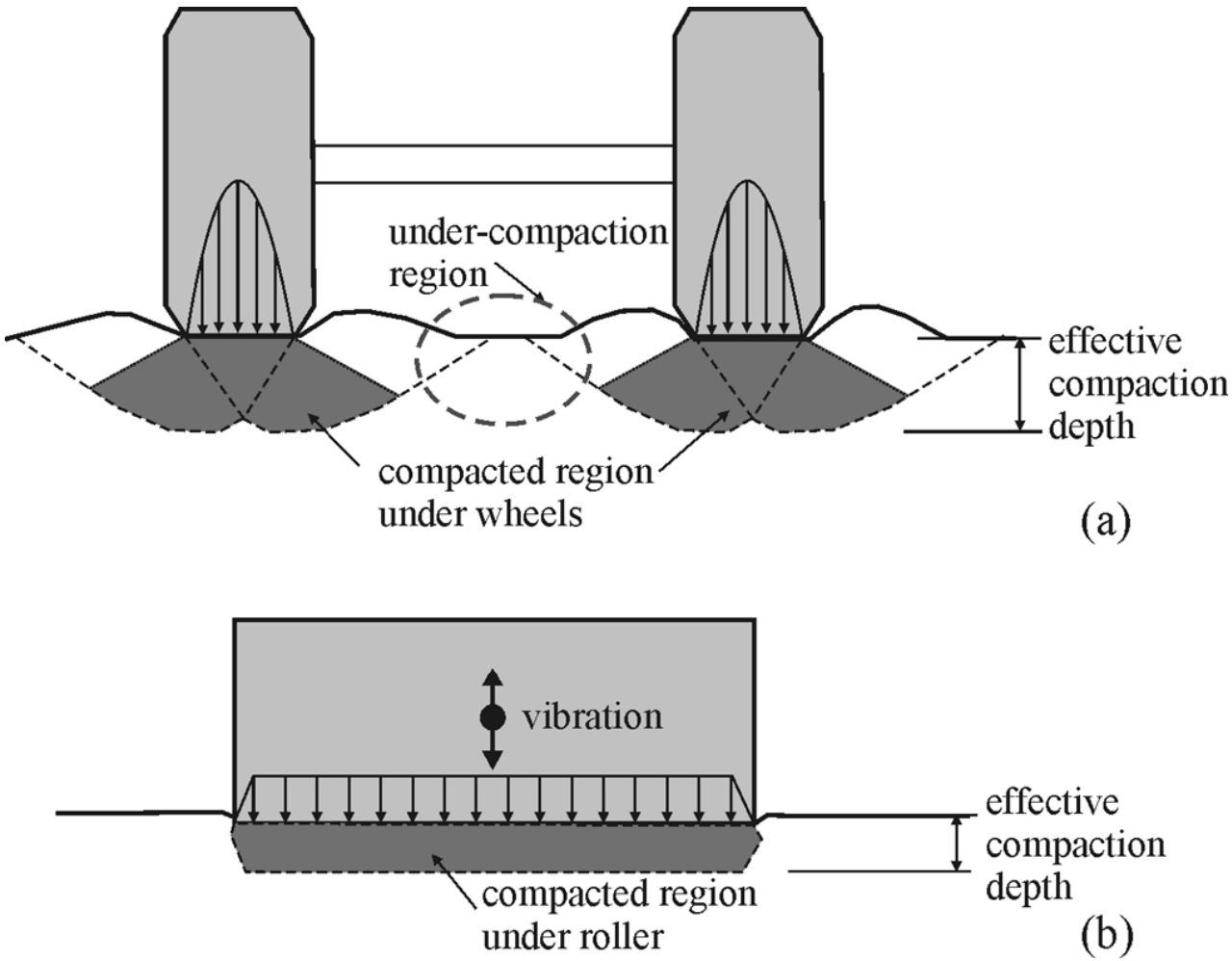
Contact Areas



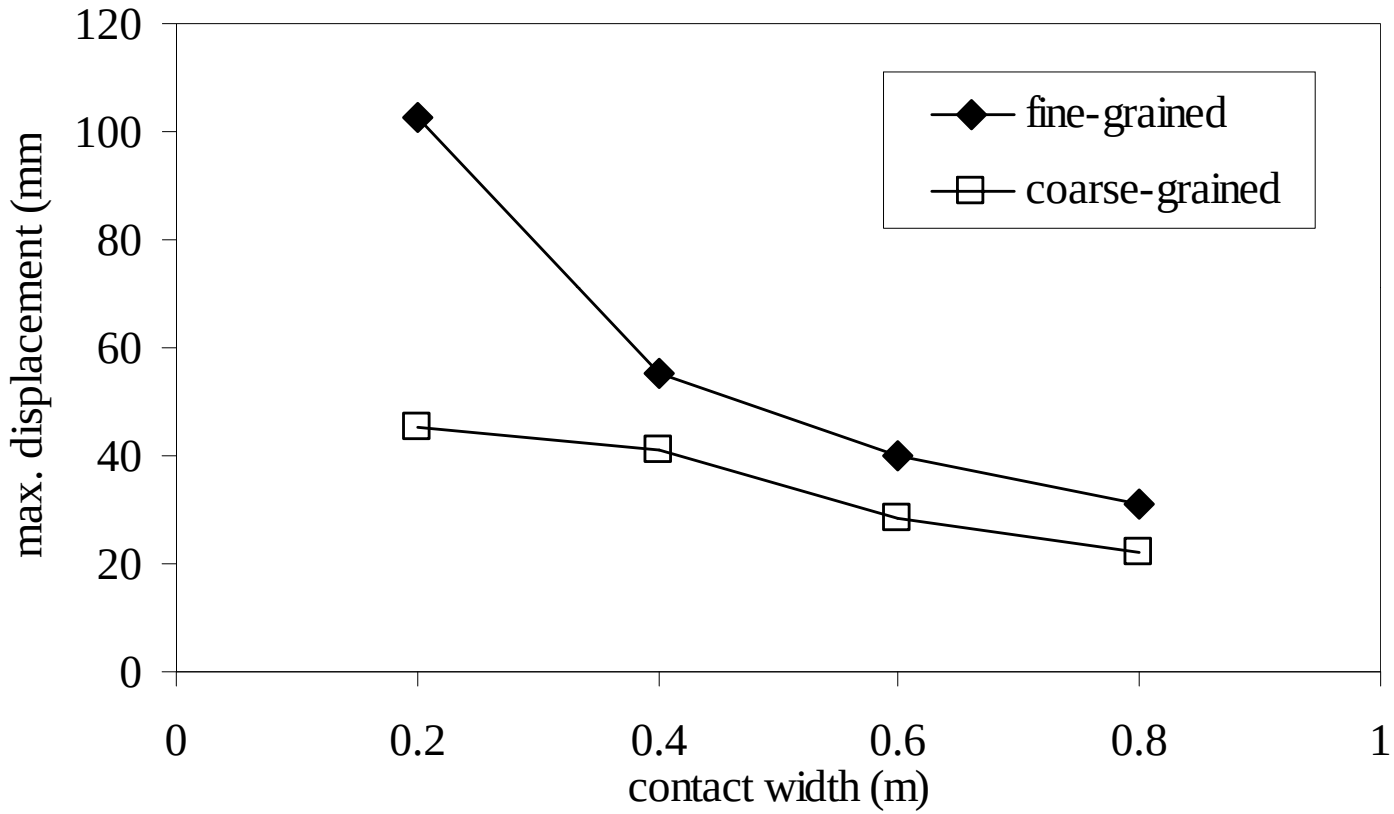


Contact areas and contact pressure distributions: (a) strip footing – drum-type roller and (b) circular footing - tire-based compactor

Contact Areas

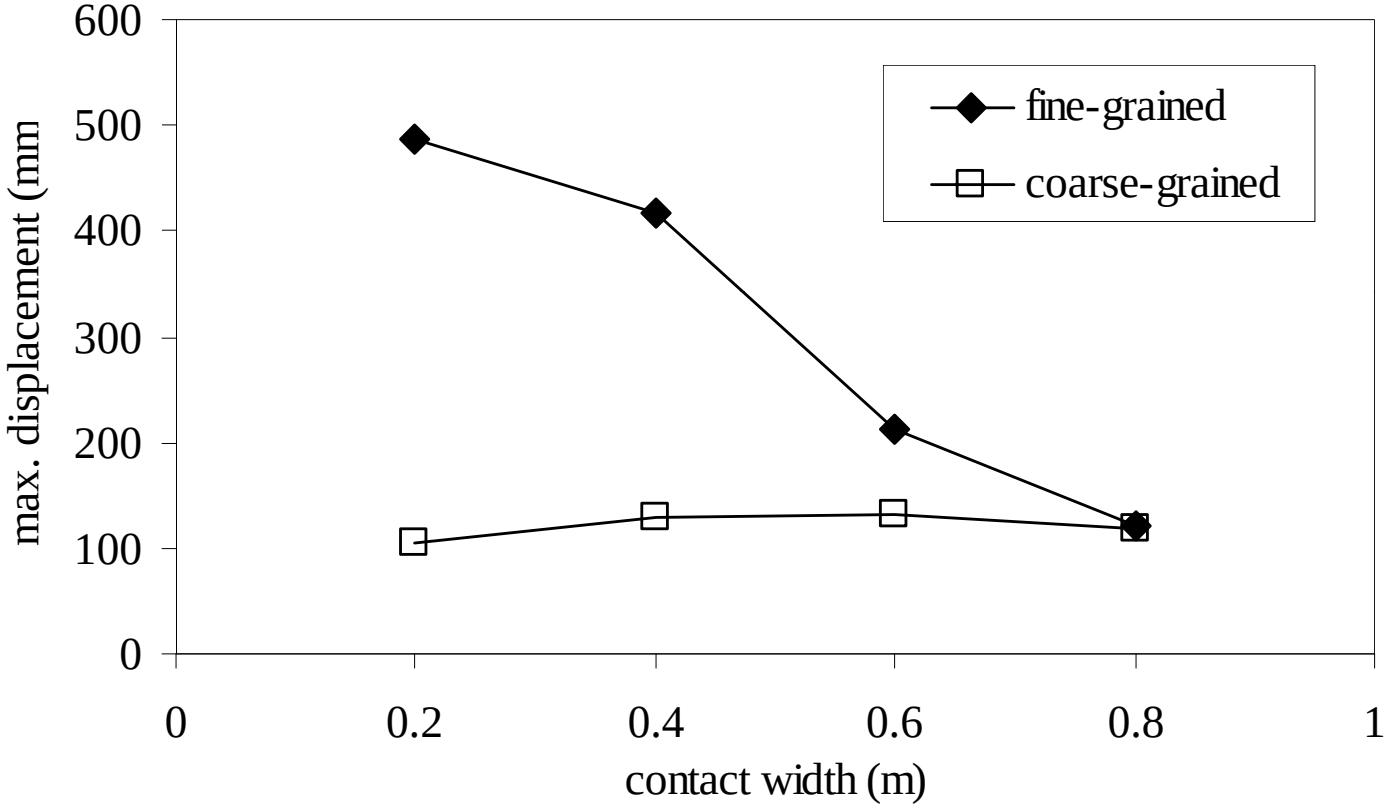


Contact Areas



Maximum displacement of drum-based compactor.

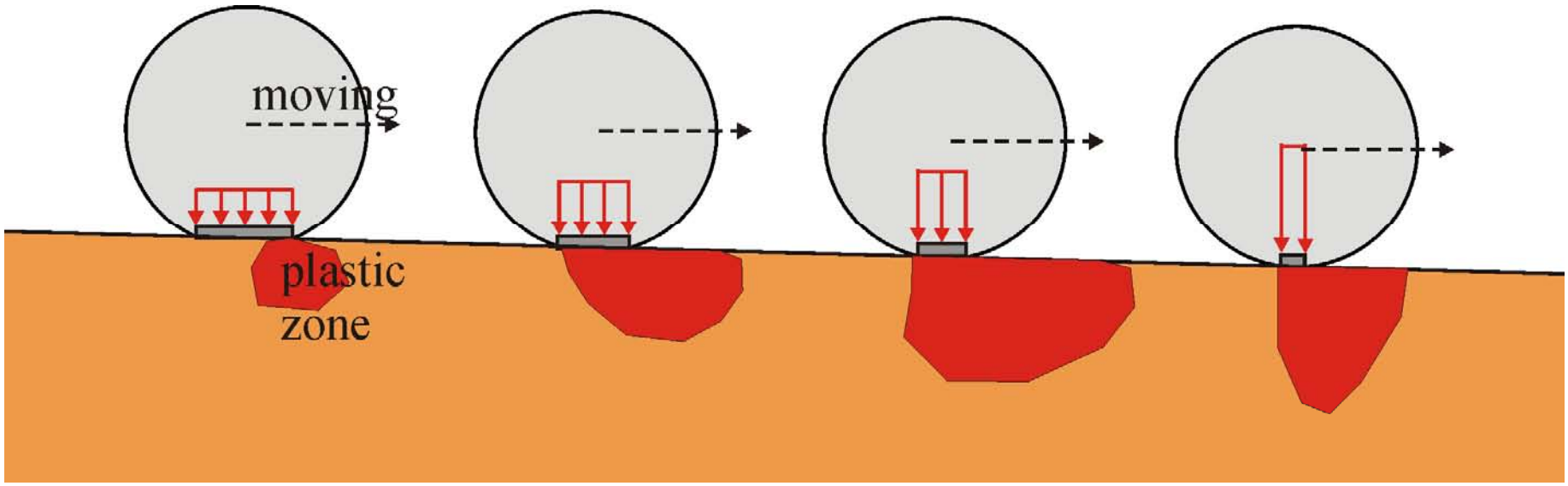
Contact Areas



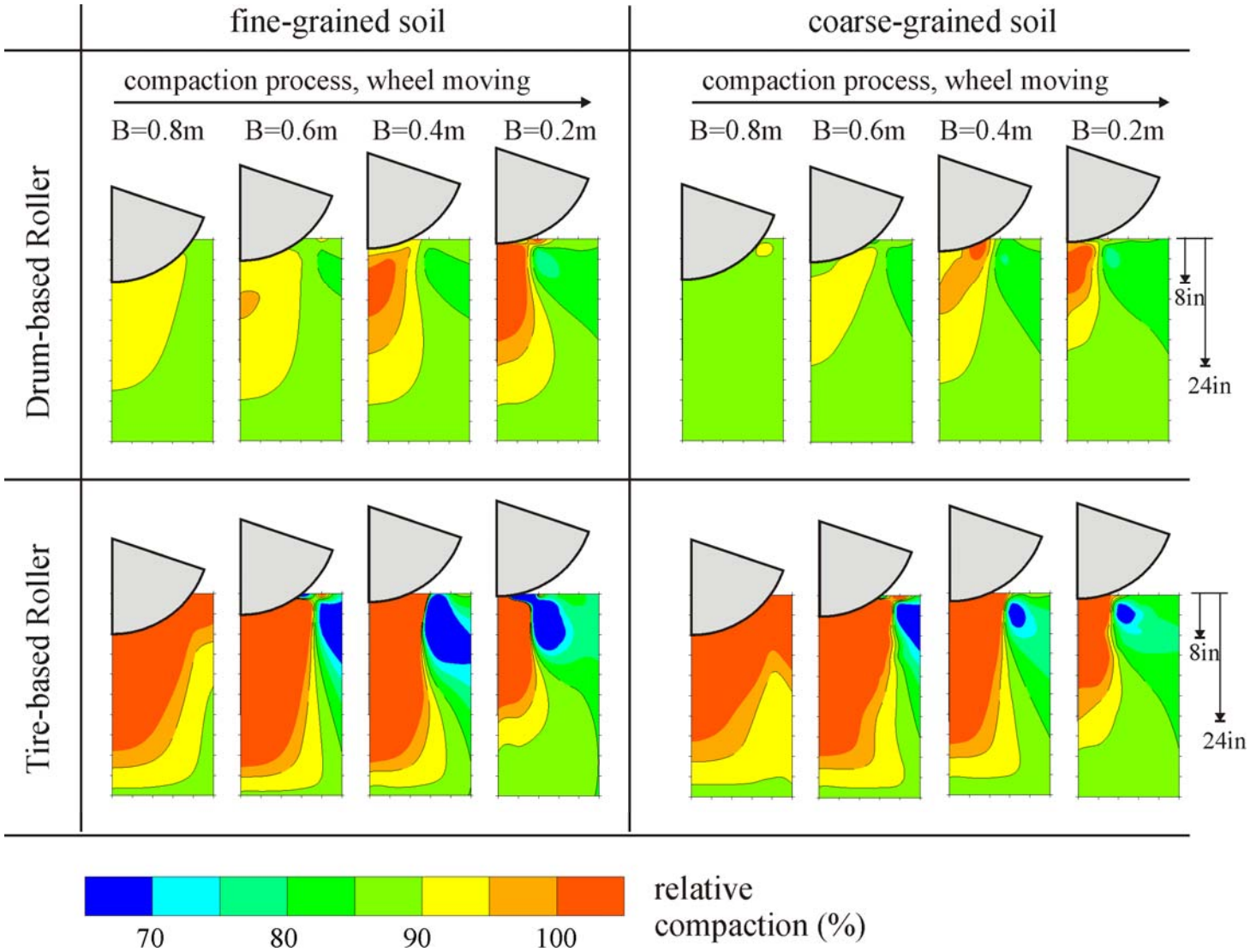
Maximum displacement of tire-based compactor.

Effect of Soil Stiffness

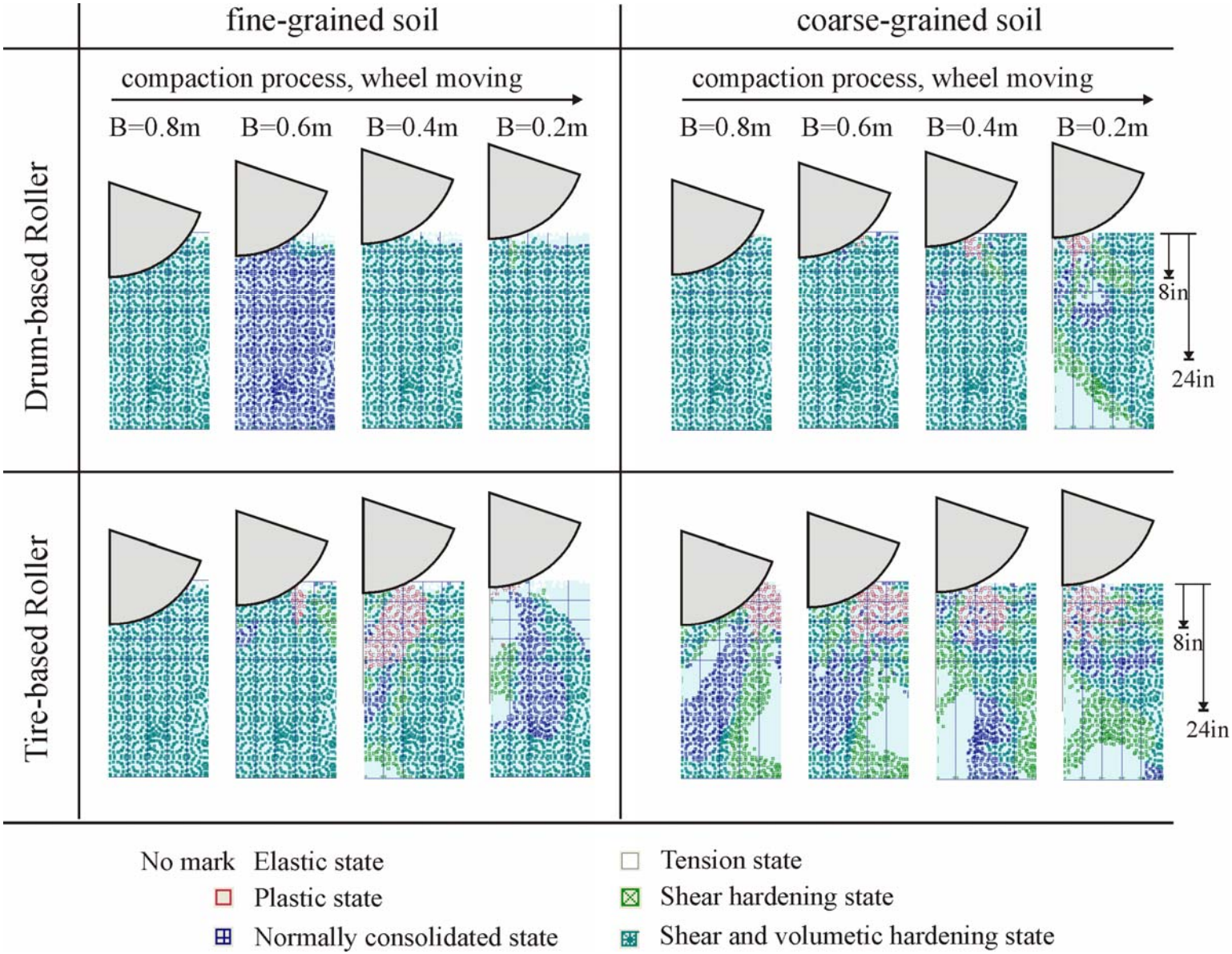
Zone of influence with reduced contact area



Volumetric Strain



Failure Zone Distribution



Conclusions and Recommendations

- Tire-based roller and earthmoving equipment (e.g., scraper) provided higher contact pressures. These high pressures propagate deep into the soil mass and allow the compaction of thick layers. However, this type of roller may produce uneven compaction regions (i.e., zones that were under-compacted).
- The interpretation of the SSG modulus at the near surface and P-wave-based modulus at the bottom of thick lift layers provided evidence of under-compaction regions at the bottom of lifts. This data justify setting maximum limits on lift thickness.

Conclusions and Recommendations

- Dynamic cone penetration index (DPI) profiles in fine-grained soils detected the areas of low shear strength at the bottom of thick lifts (i.e., greater than 0.30 m - 12 in).
- Shear-induced rotation measurements provide a good indication of soil particle movements. Rotation movements in coarse-grained soils are much larger than those of fined-grained soils. These observations imply that the current conservative lift thickness specification in coarse-grained soils may be increased by well controlled water contents of soils.

Conclusions and Recommendations

- The compaction process is a function of compactor's weight, soil type, and contact width of the wheel loading. Using various contact widths, the research team simulated the effect of the wheel load moving during compaction processes.
- A hardening soil model was implemented to simulate the compaction process using volumetric hardening (cap hardening) and deviatoric hardening (shear hardening). Volumetric strain and failure zones in numerical simulations can be indicators of depths of the compaction effectiveness.

Conclusions and Recommendations

- The evaluation of the relative compaction using volumetric strain analyses indicate that the compaction effectiveness (RC>95%) is observed at least 0.30-m (12-in) lift thickness of the tested soils and soil compactor types used in these studies. However, the tire-based roller may leave areas that are under-compacted regions due to highly localized and high pressure footprints.
- Numerical models seem to support field observations.