COMPACTION INNOVATIONS AND CONTROL BASED ON SOIL MODULUS

By
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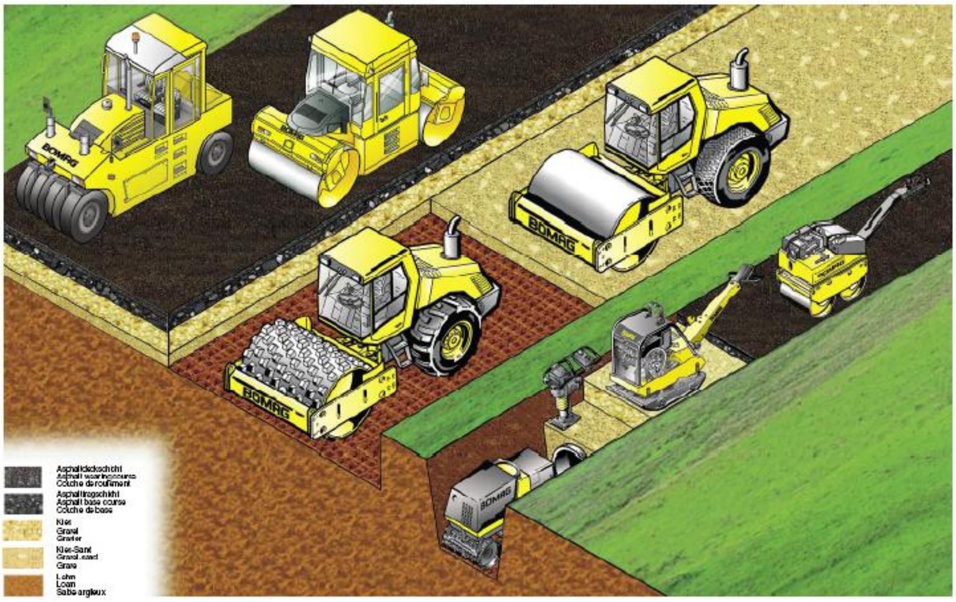

Current compaction practice

Future practice

Modulus and dry density

Intelligent compaction

Non cylindrical roller compaction

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CURRENT PRACTICE
Based on Density

- LAB: Proctor test to get dry density vs. water content curve
- SPEC: x% of $\gamma_{d\ max}$ within range of w_{opt}
- FIELD: Compact and check that γ_d and w meet the specs

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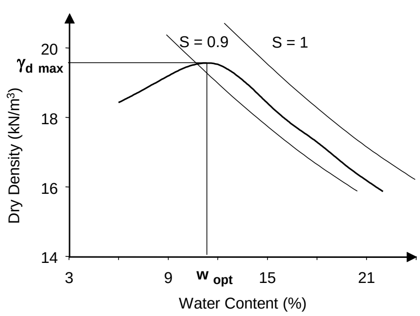
CURRENT PRACTICE
Based on Density

- LAB : Proctor Test



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CURRENT PRACTICE
Based on Density

- SPECIFICATIONS.

  X % of $\gamma_{d\ max}$ within range of w $_{opt}$

- FIELD

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Dry Density: Advantages and Disadvantages

1. Advantages

Accumulated knowledge
Well defined parameter
Indication of solids per unit volume

2. Disadvantages

Not related to design
Not very sensitive
Not easy to measure quickly in field

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FUTURE PRACTICE

Based on Modulus

- LAB: Modulus test to get modulus vs. water content curve
- SPEC: x% of E_{max} within range of w_{opt}
- FIELD: Intelligent compaction and check that E_{max} and w meet the specs

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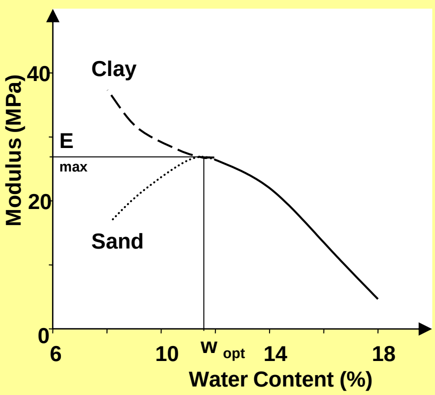
FUTURE PRACTICE

Based on Modulus

- LAB : Modulus Test



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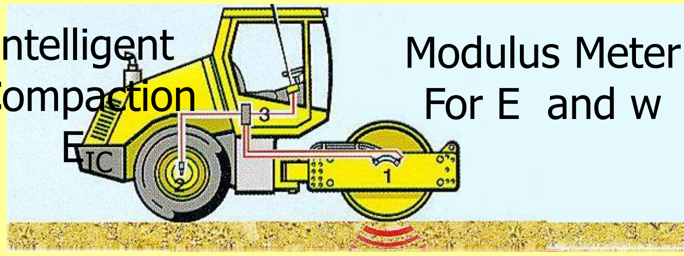
FUTURE PRACTICE
Based on Modulus

- SPECIFICATIONS

  X % of E_{max} within range of w_{opt}

- FIELD



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Modulus: Advantages and Disadvantages

1. Advantages
- **Directly related to design**
- **Very sensitive to water content**
- **Easy to measure quickly in field**

2. Disadvantages
- **Many influencing factors**
- **No lab test to get E vs. w**
- **No target values**
- **New concept**

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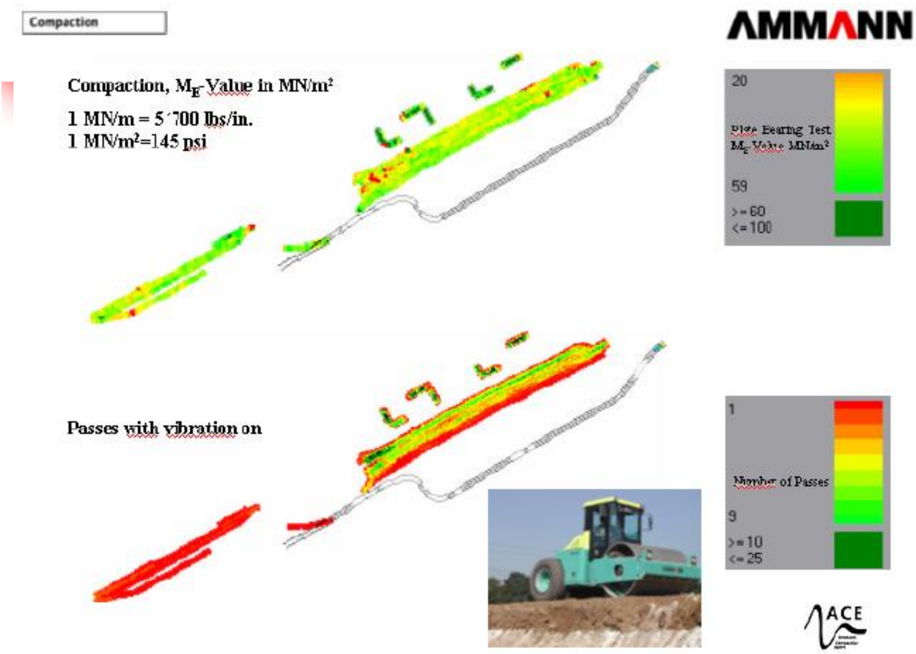

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Stiffness or Modulus?

$K = F/x$ in MN/m

$E \sim \sigma/\varepsilon$ in MN/m^2 or MPa

$E = \alpha F/Bx$

$K = F/x = EB/\alpha$

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Stiffness or Modulus?

Stiffness depends on the size of the roller.

Modulus does not; it is a property of the soil only.

<u>Use the modulus, not the stiffness</u>

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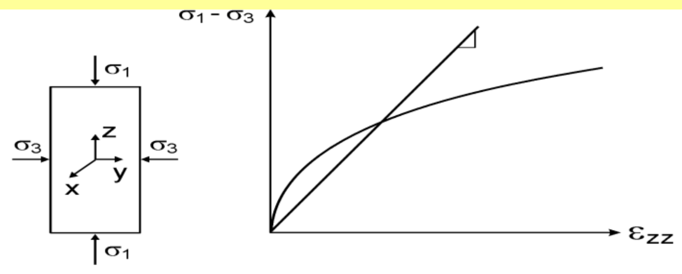
CALCULATION OF MODULUS



$$\varepsilon_{xx} = \frac{1}{E}(\sigma_{xx} - \nu(\sigma_{yy} + \sigma_{zz})) = \frac{1}{E}(\sigma_3 - \nu(\sigma_1 + \sigma_3)) \quad (1)$$

$$\varepsilon_{yy} = \frac{1}{E}(\sigma_{yy} - \nu(\sigma_{xx} + \sigma_{zz})) = \frac{1}{E}(\sigma_3 - \nu(\sigma_1 + \sigma_3)) \quad (2)$$

$$\varepsilon_{zz} = \frac{1}{E}(\sigma_{zz} - \nu(\sigma_{xx} + \sigma_{yy})) = \frac{1}{E}(\sigma_1 - \nu(\sigma_3 + \sigma_3)) \quad (3)$$

$$E = \frac{\sigma_1 - 2\nu\,\sigma_3}{\varepsilon_{zz}} \quad (4)$$

$$\frac{\varepsilon_{xx}}{\varepsilon_{zz}} = \frac{\sigma_3 - \nu\,(\sigma_1 + \sigma_3)}{\sigma_1 - 2\nu\,\sigma_3} \quad (5)$$

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Which Modulus?

DEFINITION

- Initial
- Secant
- Tangent
- Unload-Resilient
- Cyclic
- Reload

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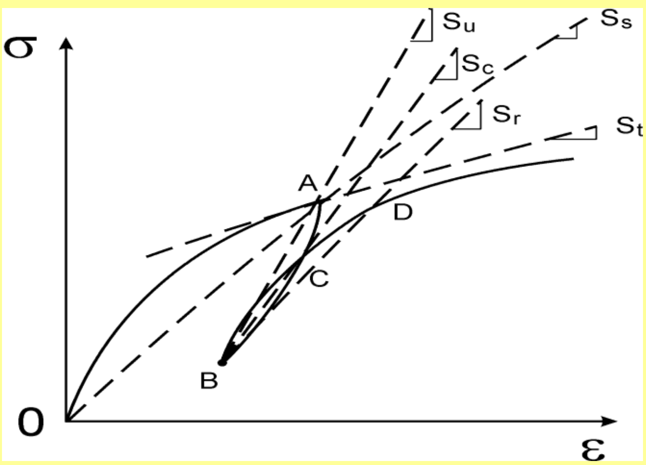
WHICH MODULUS?



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Which Modulus?

STATE FACTORS

- Density
- Structure
- Water content
- Stress history
- Cementation

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Which Modulus?

LOADING FACTORS

- Stress level
- Strain level
- Strain rate
- Number of cycles
- Drainage

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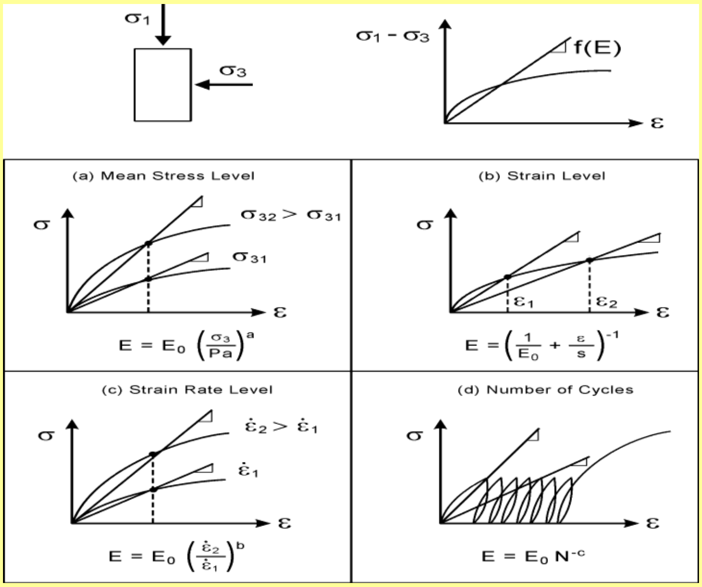
WHICH MODULUS?



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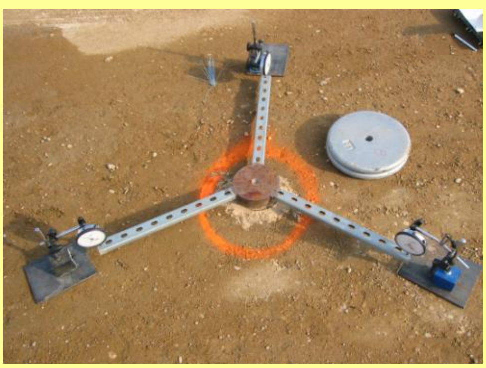
Which Modulus?

PLATE MODULUS in FIELD



BPT: Briaud Plate Test

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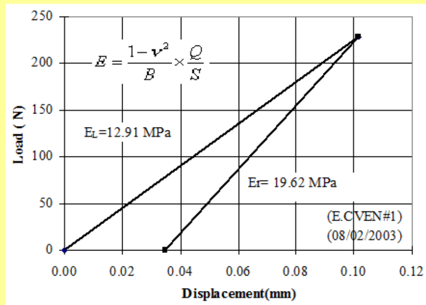
Which Modulus?

PLATE MODULUS in LAB



BPT: Briaud Plate Test

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Range of Modulus

Steel:	**200,000 MPa**
Concrete:	**20,000 MPa**
Wood, Plastic:	**13,000 MPa**
Rock:	**2,000 to 30,000 MPa**
Asphalt:	**150 to 25000 MPa**
Soil:	**5 MPa to 1000 MPa**
Mayonnaise:	**0.5 MPa**

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Asphalt Modulus

150 to 300 MPa at 140ºC

3000 to 4500 MPa at 20ºC

25000 MPa at -10ºC

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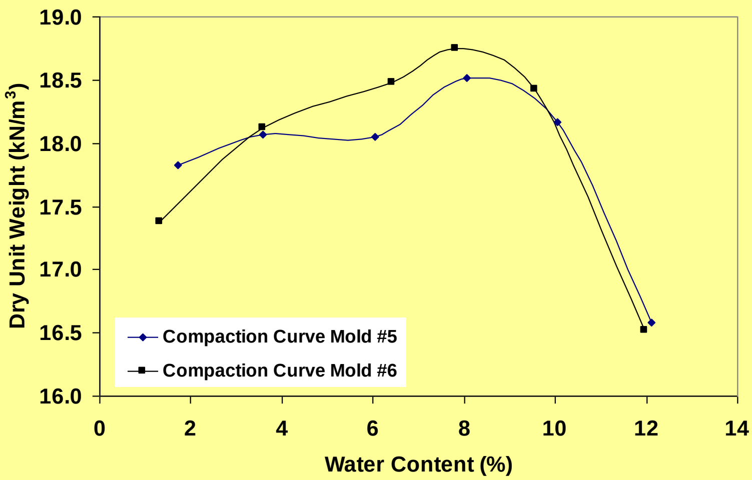
NGES Sand



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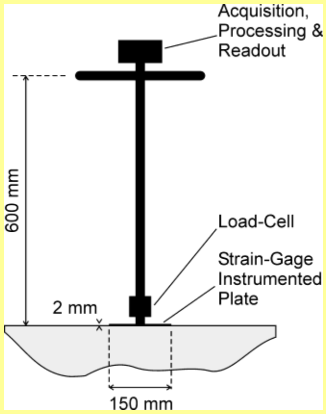
Example of same modulus test in lab and in field

BCD Test: Briaud Compaction Device

BCD on Proctor Mold



BCD in the Field

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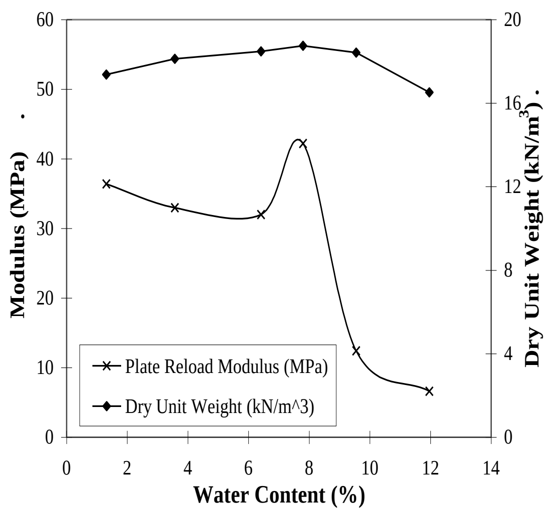

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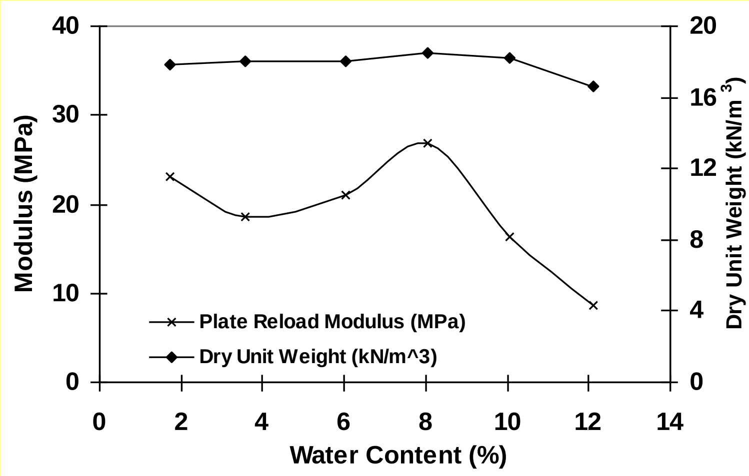
NGES Silty Sand (Mold #5)



Modulus measured with BPT: Briaud Plate Test

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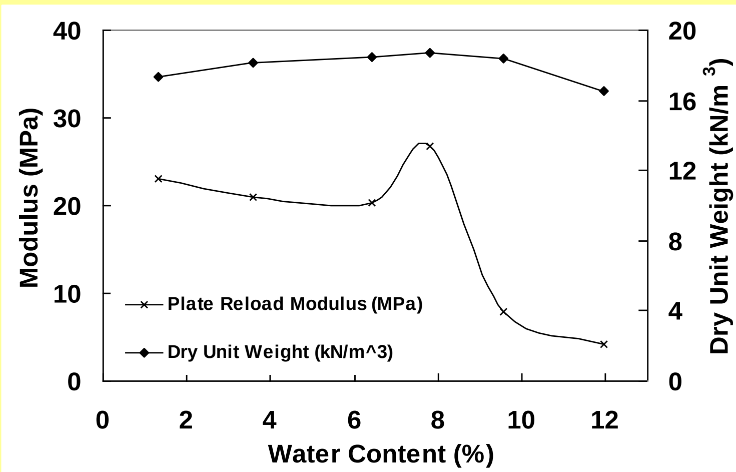
NGES Silty Sand (Mold #6)



Modulus measured with BPT: Briaud Plate Test

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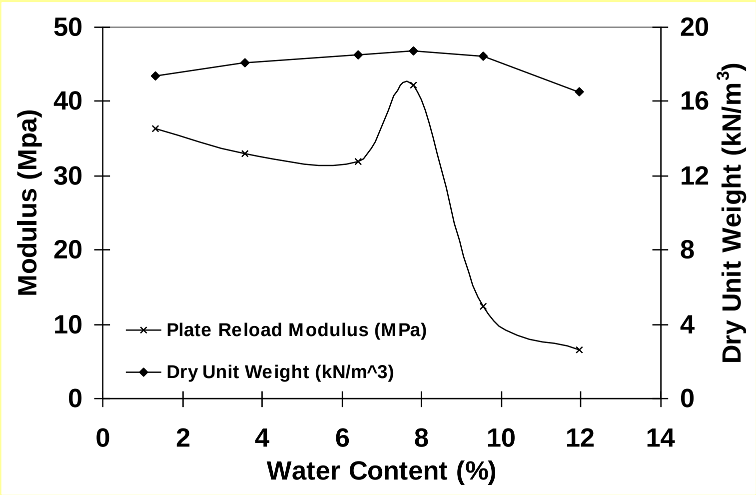
NGES Silty Sand



Modulus measured with BPT: Briaud Plate Test

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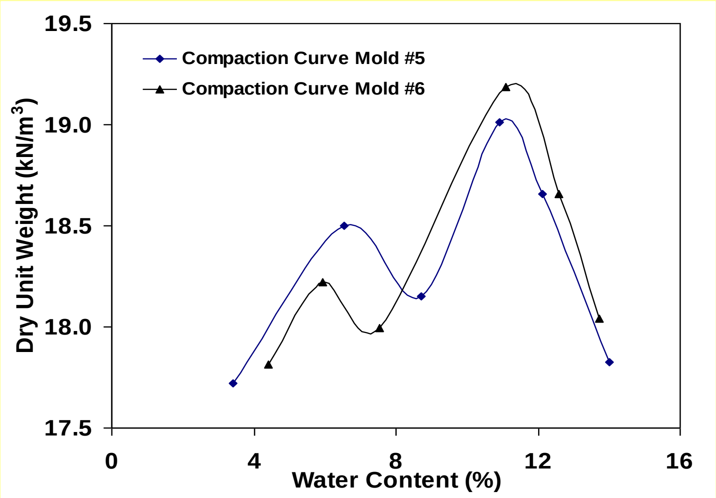
NGES Sand + Porcelain Clay



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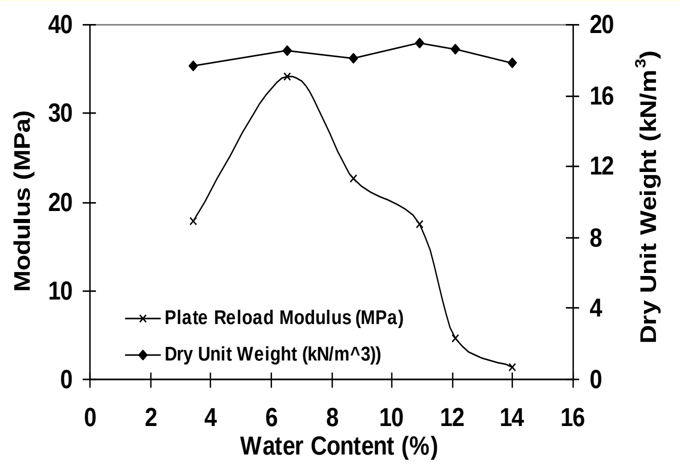
NGES Sand + Porcelain Clay (Mold #5)



Modulus measured with BPT: Briaud Plate Test

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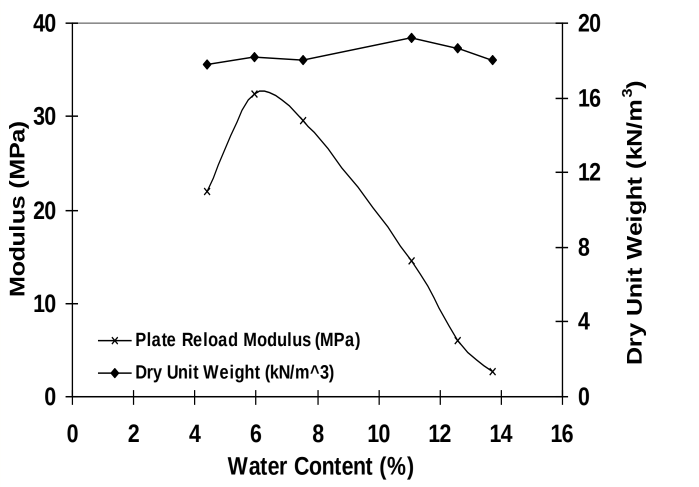
NGES Sand + Porcelain Clay (Mold #6)



Modulus measured with BPT: Briaud Plate Test

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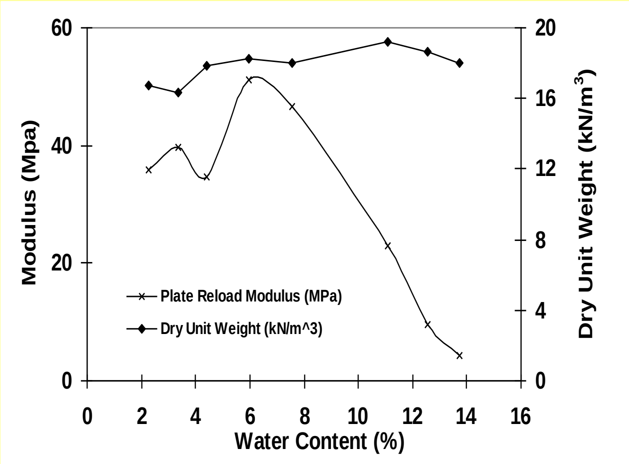
NGES Sand + Porcelain Clay



Modulus measured with BPT: Briaud Plate Test

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1. Density?
2. Modulus?
3. Water Content?

- Only one of those three is not enough
- Two of those three are sufficient
- All three would be nice

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Compaction Control Methods

- Conventional Compaction
- Intelligent Compaction
- Non cylindrical Compaction

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Conventional Compaction (static or vibratory smooth drum or sheep-foot)

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Intelligent Compaction

Non Cylindrical Compaction

Intelligent Vibratory Compaction

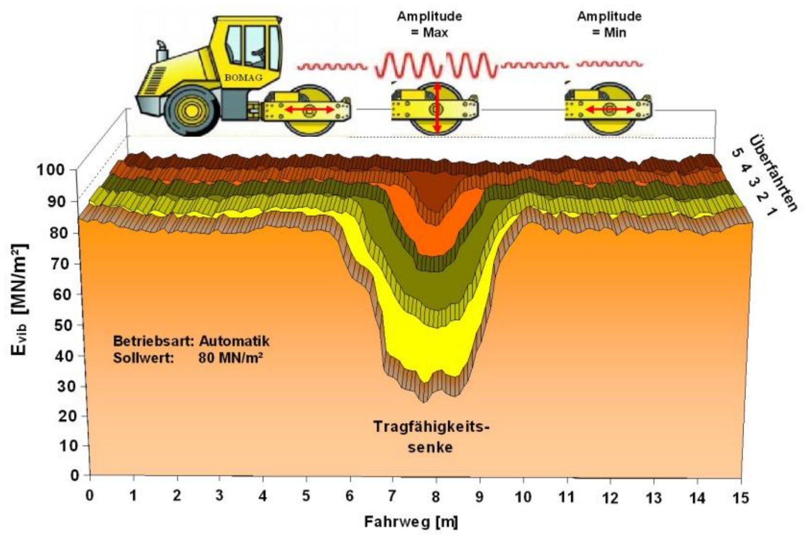
- Instrumented vibrating rollers
- Measure roller accel. as a function of time
- Calculate a soil modulus
- That modulus is/not independent of the roller
- Intelligent roller modifies automatically & instantaneously its own settings (force, ampl., freq.) to meet the target modulus

History

- First "Intelligent Compaction" Compactor: 1992
- BOMAG (Germany)
- AMMANN Compaction Expert (ACE, Switzerland)
- Geodynamik (Sweden)

BOMAG

Recompaction of soft formation area with VARIOCONTROL automatic mode, presetting (target value) E_{VIB} = 80 MN/m²



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Intelligent Compaction

AMMANN

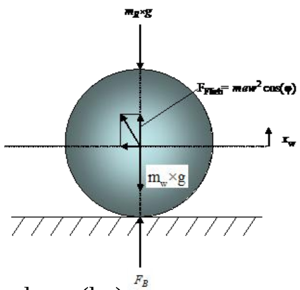
ACE

$\ddot{x}_d$

From Acceleration to Stiffness

$$F_B \cong -m_d \ddot{x}_d + m_u r_u \Omega^2 \cos(\Omega t) + (m_f + m_d) g$$

$$F_B \cong k_B x_d + d_B \dot{x}_d$$



F_B: soil-drum-interaction-force
x_d: vert. disp. of drum (m)
m_f: mass of the frame (kg)
r_u: radial distance for m_u
g: acc. due to gravity (m/sec^2)
$\dot{x}_d$: velocity of drum
d_B: damping coefficient (d_B ~ 0.2)

m_d: mass of the drum (kg)
$\ddot{x}_d$: acceleration of drum
m_u: unbalanced mass (kg)
$\Omega = 2\pi f$
f: frequency of rotating shaft (Hz)
k_B: stiffness of soil

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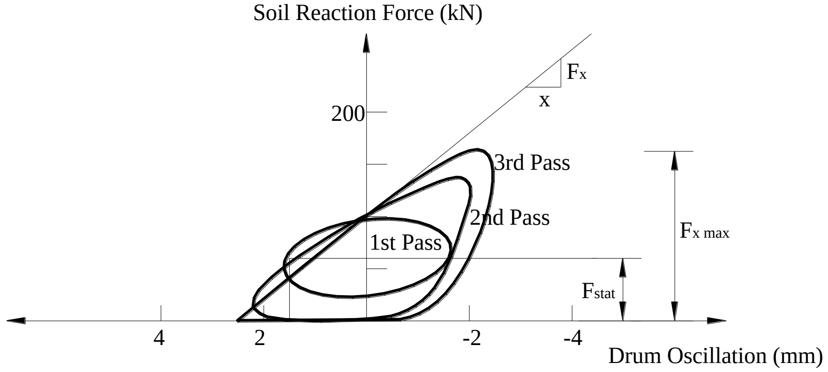
Force-Displacement Curves



From BOMAG

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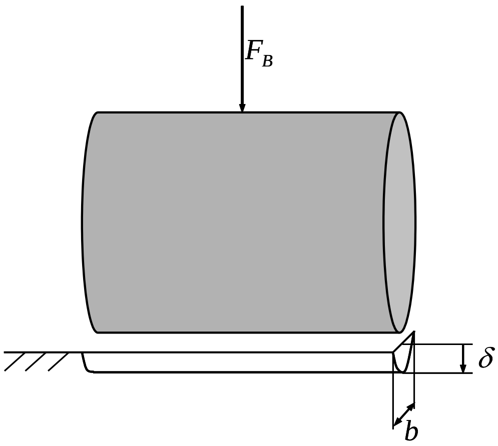
$\ddot{x}_d$

From Stiffness to Modulus



H. Hertz, 1895 :

$$b = \sqrt{\frac{16}{\pi} \cdot \frac{R(1-\nu^2)}{E} \frac{F_B}{l}}$$

G. Lundberg, 1939 :

$$\delta = \frac{1-\nu^2}{E} \cdot \frac{F_B}{l} \cdot \frac{2}{\pi} \cdot (1{,}8864 + \ln \frac{l}{b})$$

$$\delta = f(F_B, E)$$

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$\ddot{x}_d$

From Stiffness to Modulus (theoretical)

$$k_B = \frac{E \cdot L \cdot \pi}{2 \cdot \left(1-\nu^2\right) \cdot \left(2.14 + \frac{1}{2} \cdot \ln\left[\frac{\pi \cdot L^3 \cdot E}{\left(1-\nu^2\right) \cdot 16 \cdot \left(m_f + m_d\right) \cdot R \cdot g}\right]\right)} \quad [\mathrm{MN/m}]$$

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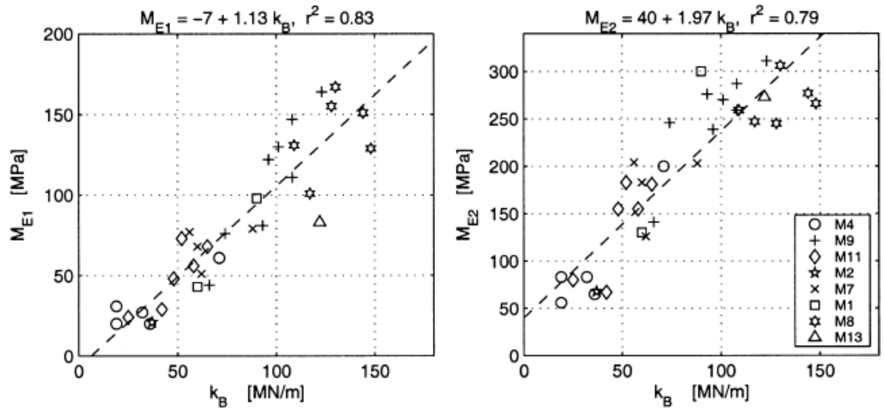
From Stiffness to Modulus (experimental)



From AMMANN

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Soil Modulus for Intelligent Compaction

Soil: 5 MPa unacceptable

200 MPa excellent

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Specifications based on Modulus

Laying and compaction specification for
road construction in Germany

Soil layers	Density (Standard Proctor)	Bearing capacity (load bearing test, EV2)	Eveness (4 m straight edge)
Subbase	100 - 103 % *	100 - 150 MN/m² *	20 mm
Capping layer	100 - 103 % *	100 - 120 MN/m² *	40 mm
Formation	97 - 100 % *	45 - 80 MN/m² *	60 mm

* depending on road classification and road design

From BOMAG

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Why Intelligent Compaction?

❑ TYPE OF CONTRACTS (EUROPE)

- Best-value awards rather than low bid
- Design-build rather than prescriptive specifications
- Performance contracting
- Continuous Compaction Control (CCC) in national standards: Austria (RVS 8S.02.6), Germany (ZTVE StB94), Sweden (VÄG 94), and Finland

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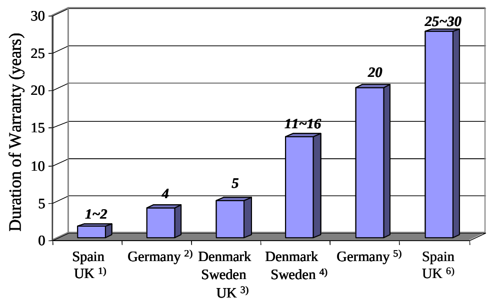
Why Intelligent Compaction?

❑ WARRANTY



1) Material and Workmanship
2) Material and Workmanship
3) Performance
4) Pavement Performance Contracts
5) Pavement Performance Contracts "Functional"
6) Design-Build Finance Operate

❑ ECONOMICS

- More than 30% reduction in labor time and fuel costs
- Reduce the number of conventional spot tests
- Increase the roller's useful life

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ISSUES

1. Reference modulus = plate test?
2. Develop simple lab modulus test
3. Study modulus vs water/asph. Content
4. Demonstrate that IC is better than CC
5. Calibrate rollers against plate modulus
6. Use same modulus test (lab and field)

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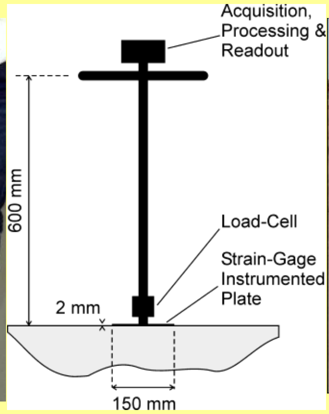
Example of same modulus test in lab and in field

BCD Test: Briaud Compaction Device

BCD on Proctor Mold



BCD in the Field

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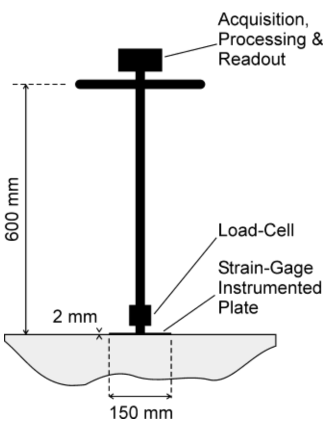
Example of same modulus test in lab and in field

BCD Test: Briaud Compaction Device

BCD on Proctor Mold



BCD in the Field

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ISSUES

7. Develop specs based on modulus for diff. pavement cond.
8. Can the asphalt modulus be isolated from the soil modulus
9. Use modulus control equipment
10. Demonstrate the IC equipment
11. First International Conference on Compaction?

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Non cylindrical compaction

- Triangular and polygonal rollers
- Impact generated
- Landpac
- Broons
- Bomag

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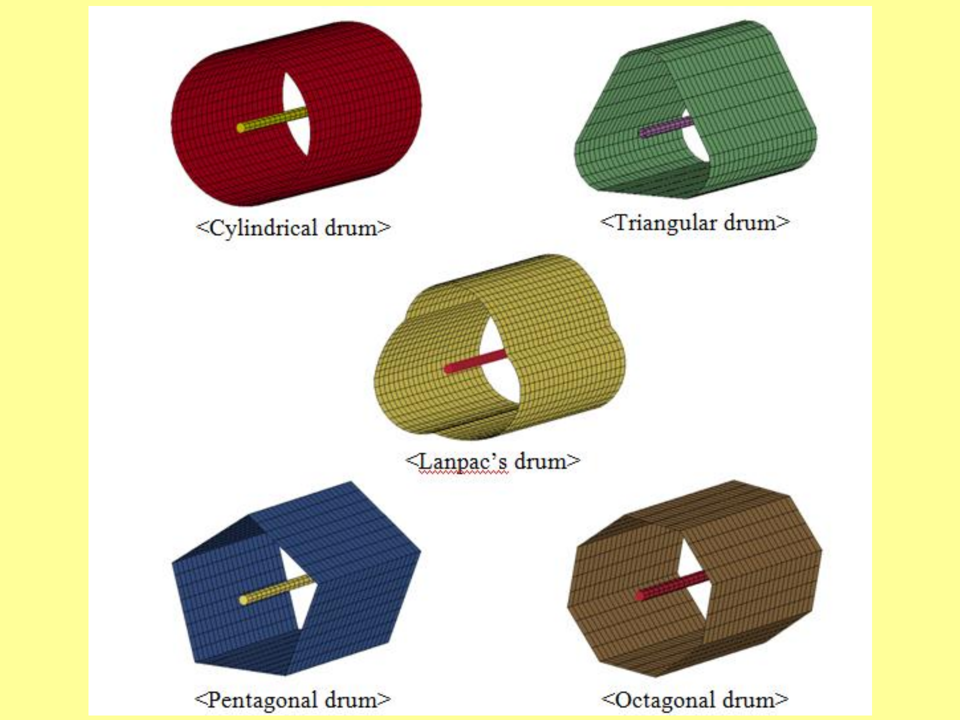
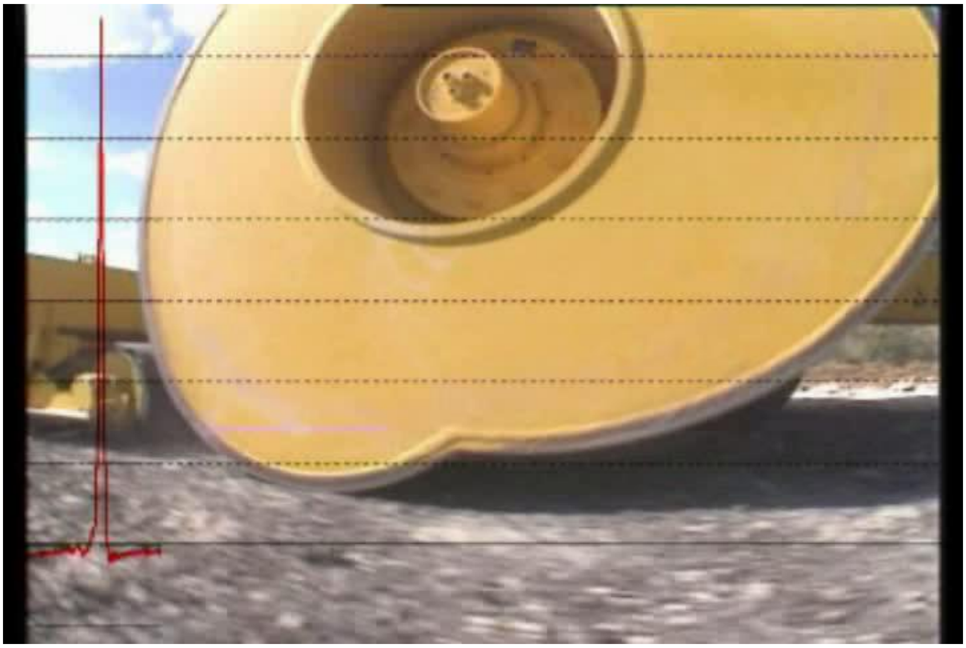
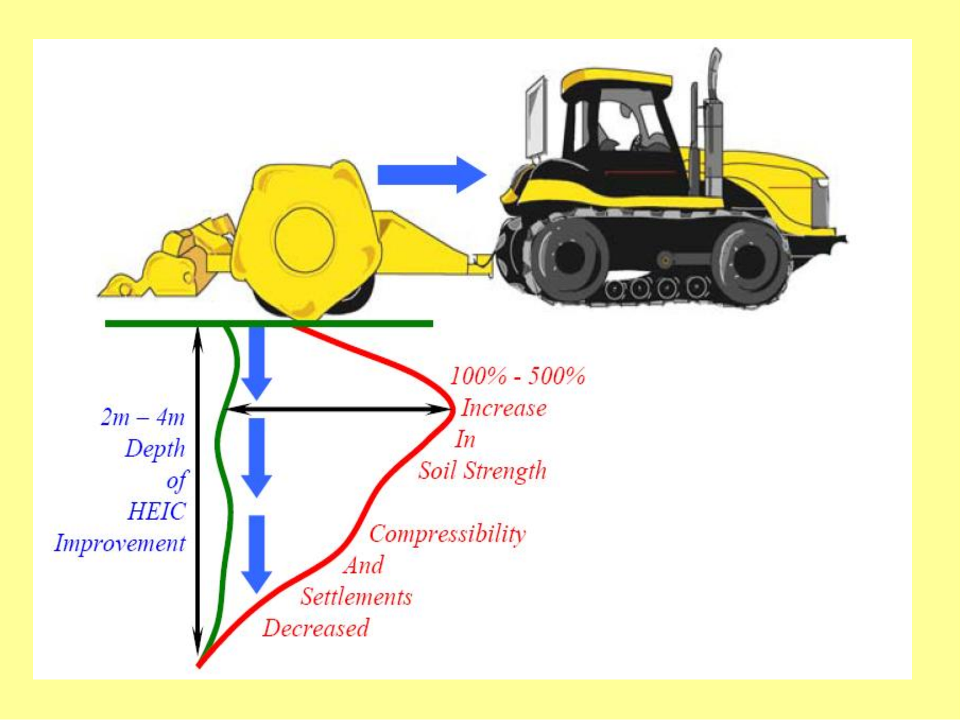

<Cylindrical drum>
<Triangular drum>
<Lanpac's drum>
<Pentagonal drum>
<Octagonal drum>

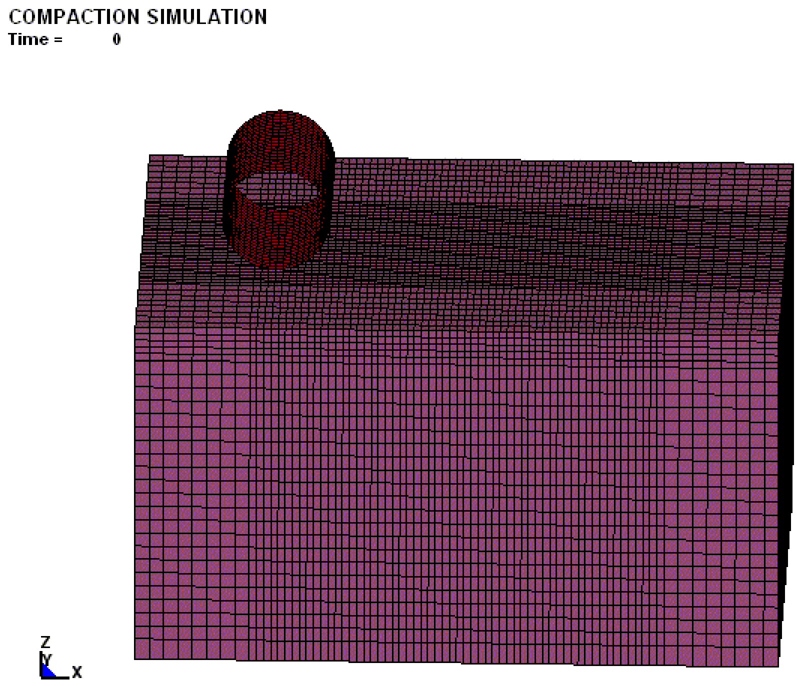

LANDPAC
CAT

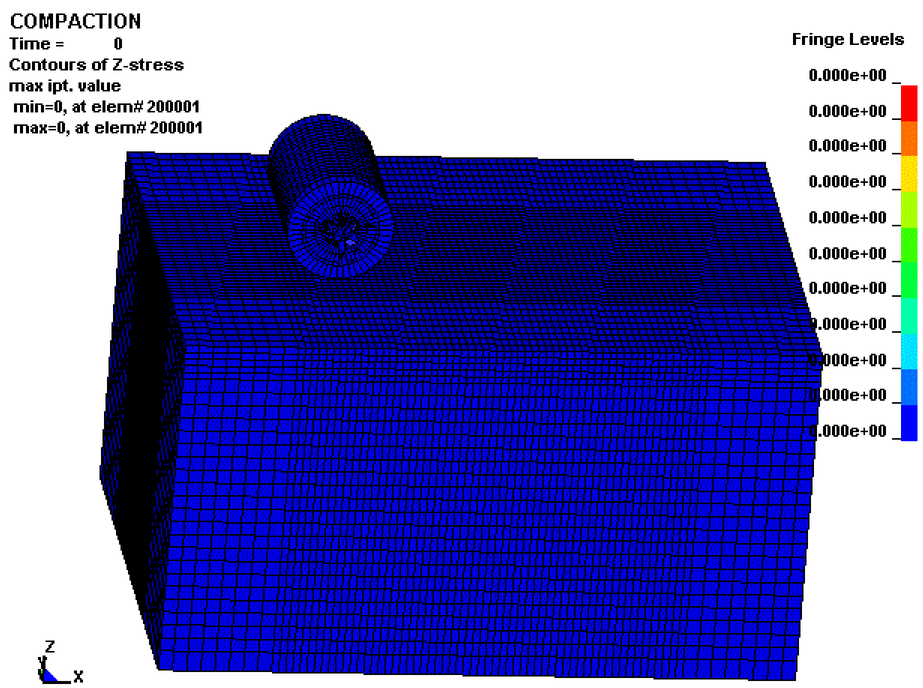
60

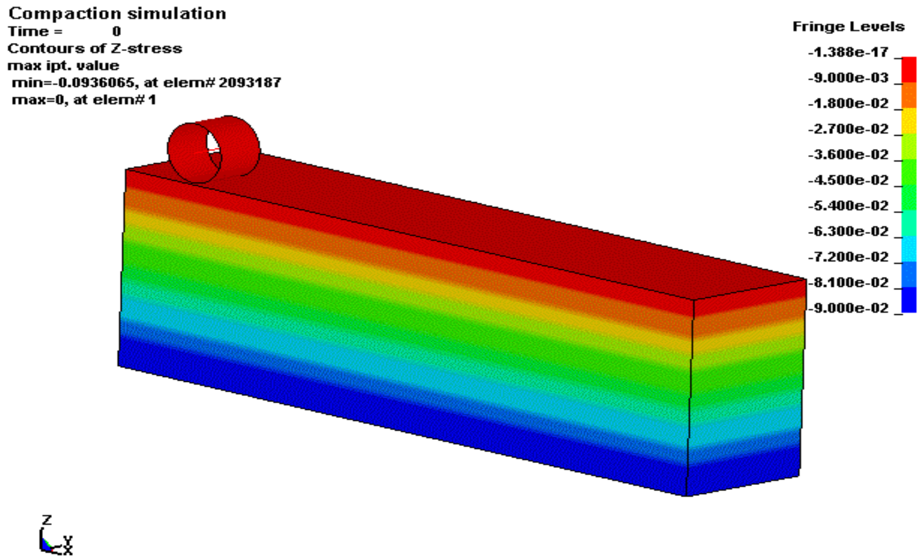
LANDPAC




100% - 500%
Increase
In
Soil Strength
2m – 4m
Depth
of
HEIC
Improvement
Compressibility
And
Settlements
Decreased


COMPACTION SIMULATION
Time = 0
Z
Y
X


COMPACTION
Time = 0
Contours of Z-stress
max ipt. value
min=0, at elem# 200001
max=0, at elem# 200001
Fringe Levels
0.000e+00
0.000e+00
0.000e+00
0.000e+00
0.000e+00
0.000e+00
0.000e+00
Z
X



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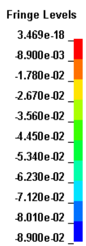
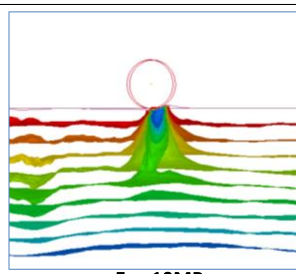
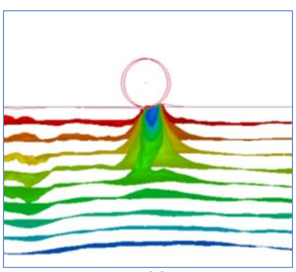
Visualized Compaction Mechanism

Cylindrical

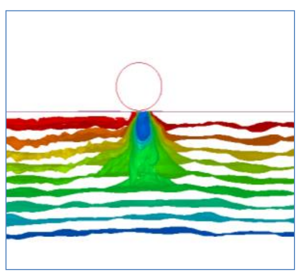




E_s = 10MPa



E_s = 30MPa



E_s = 50MPa

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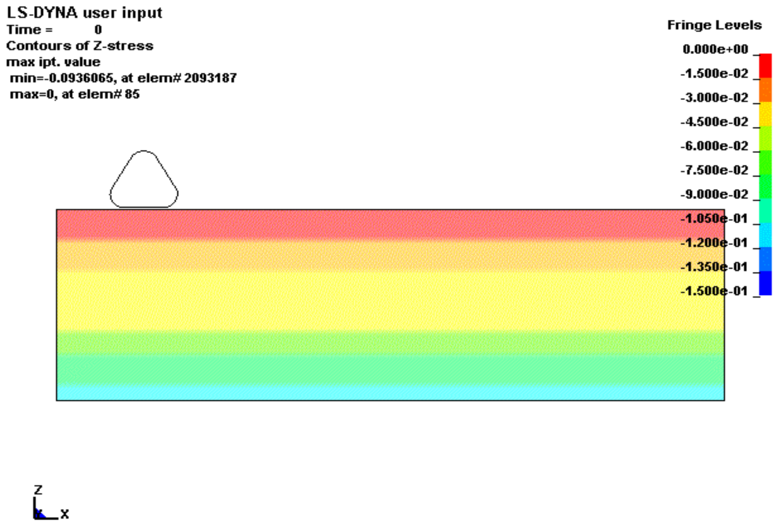
Triangular drum

•



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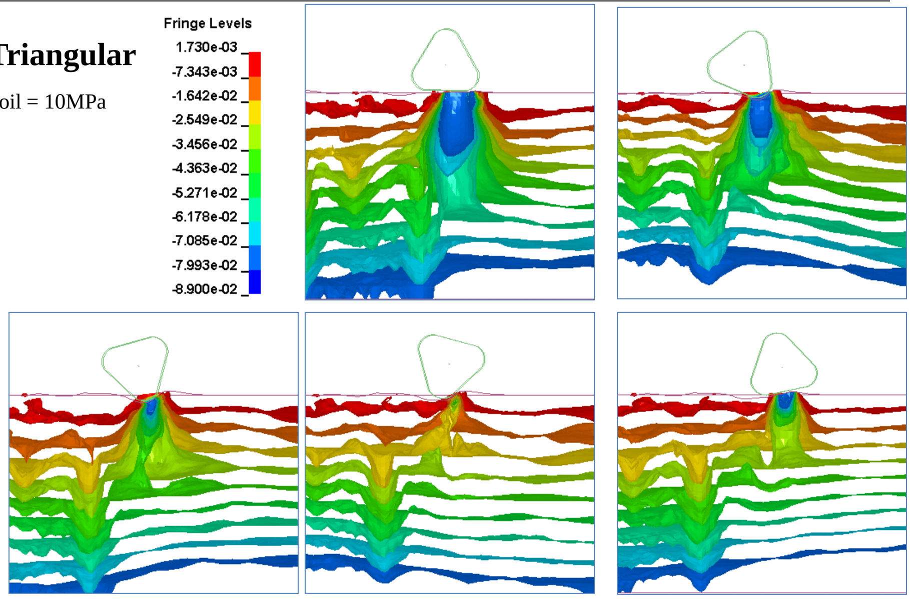
Visualized Compaction Mechanism(continued)

Triangular

Soil = 10MPa



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Modeling and methodology Simulation results

Landpac drum

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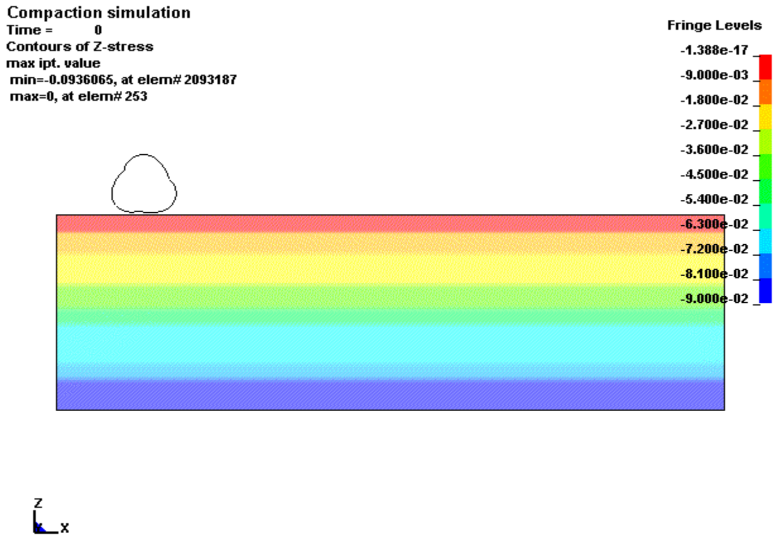

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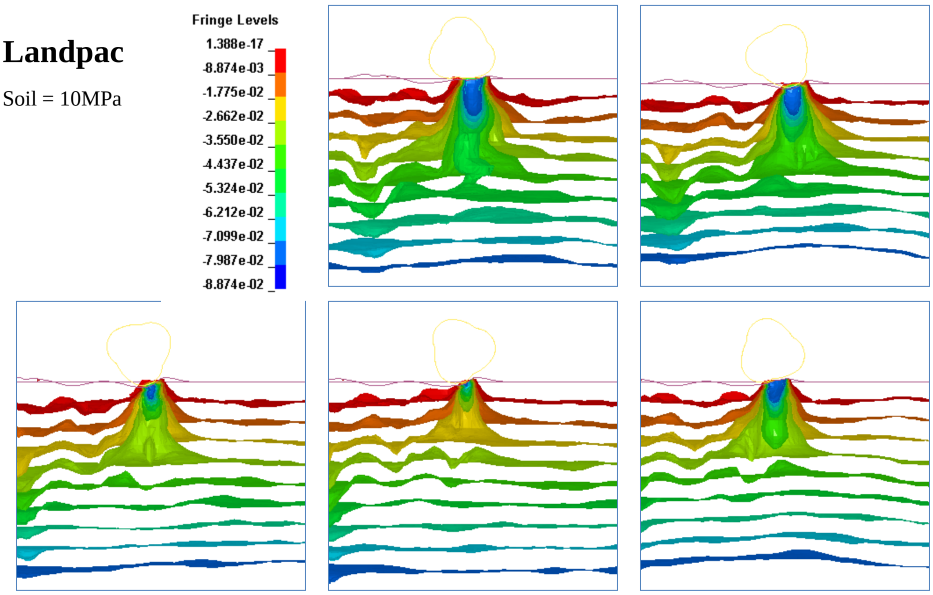
Modeling and methodology Simulation results

Visualized Compaction Mechanism(continued)

Landpac

Soil = 10MPa



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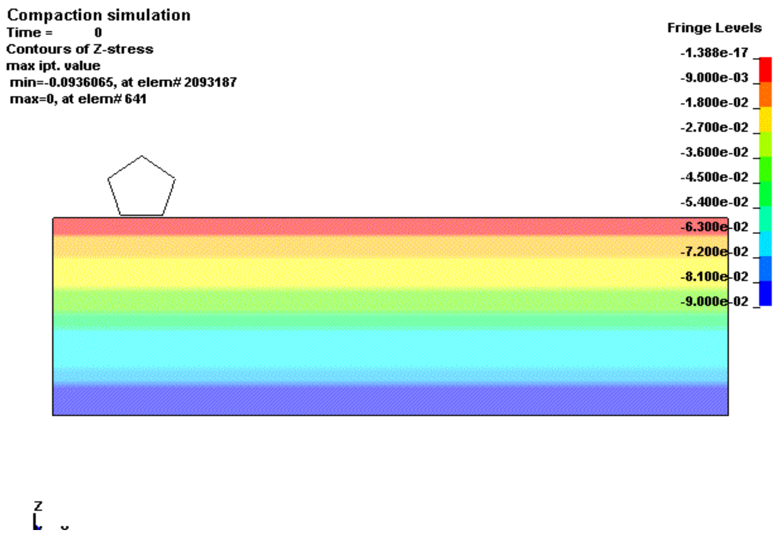
Pentagonal drum

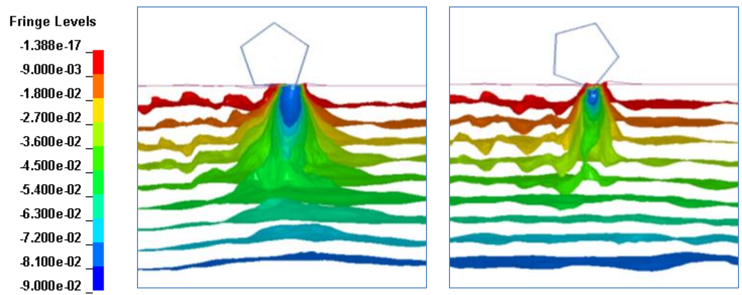
- Simulation results

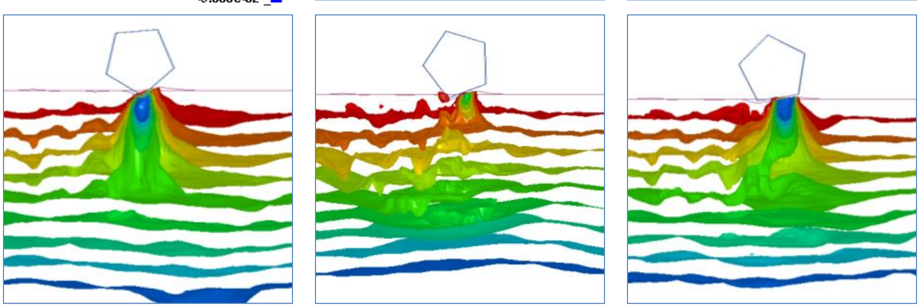


Visualized Compaction Mechanism(continued)

Pentagonal

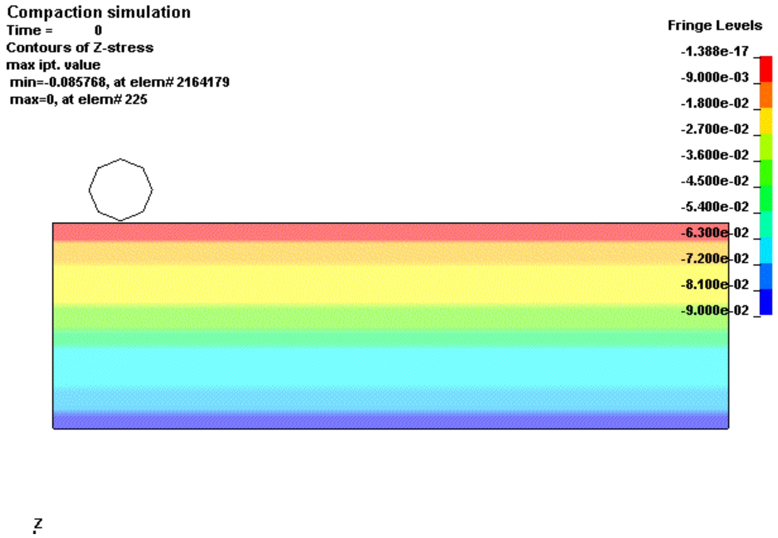
Soil = 10MPa





Octagonal drum

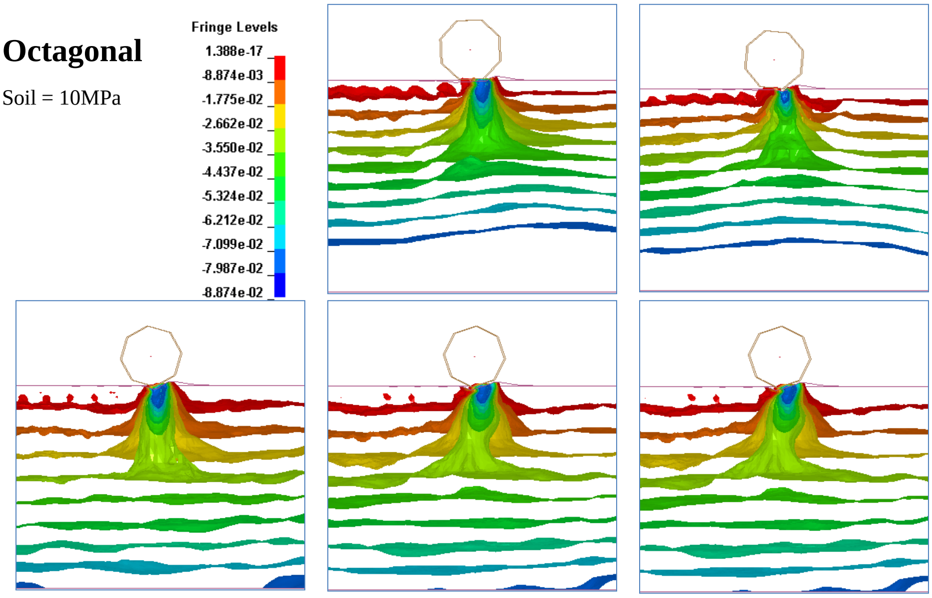
- Simulation results



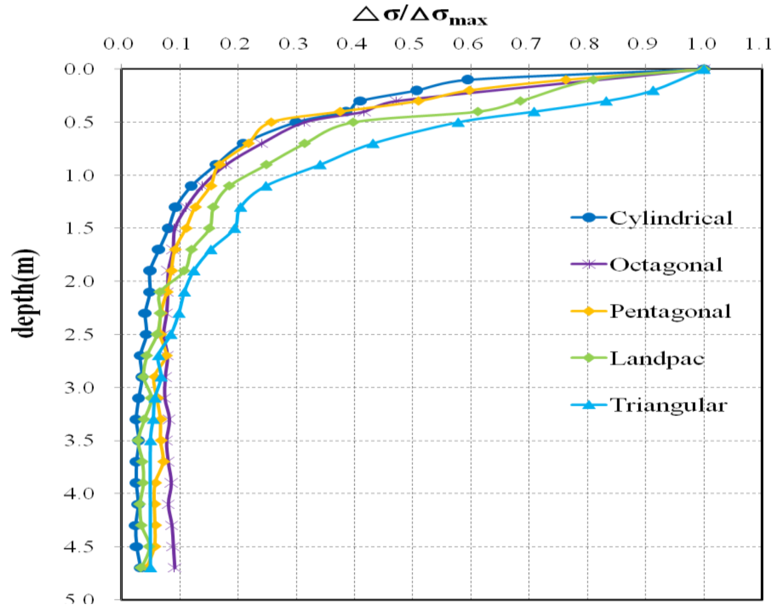
Visualized Compaction Mechanism(continued)

Octagonal

Soil = 10MPa



Soil Modulus = 10MPa



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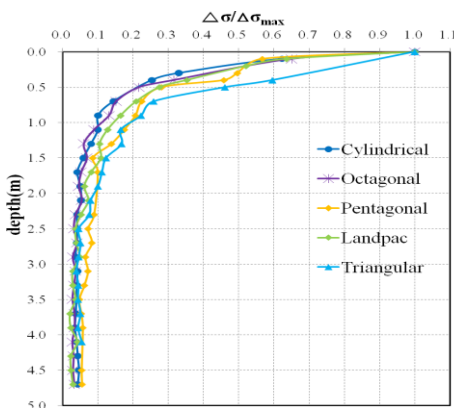
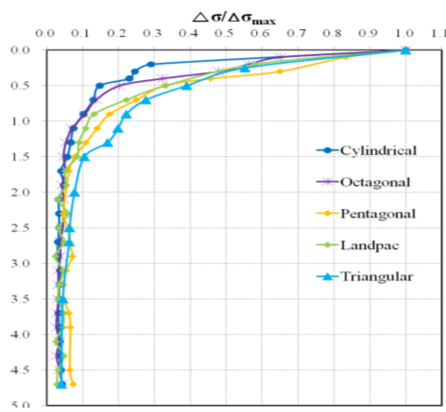
The depth of influence



Soil Modulus = 30MPa



Soil Modulus = 50MPa

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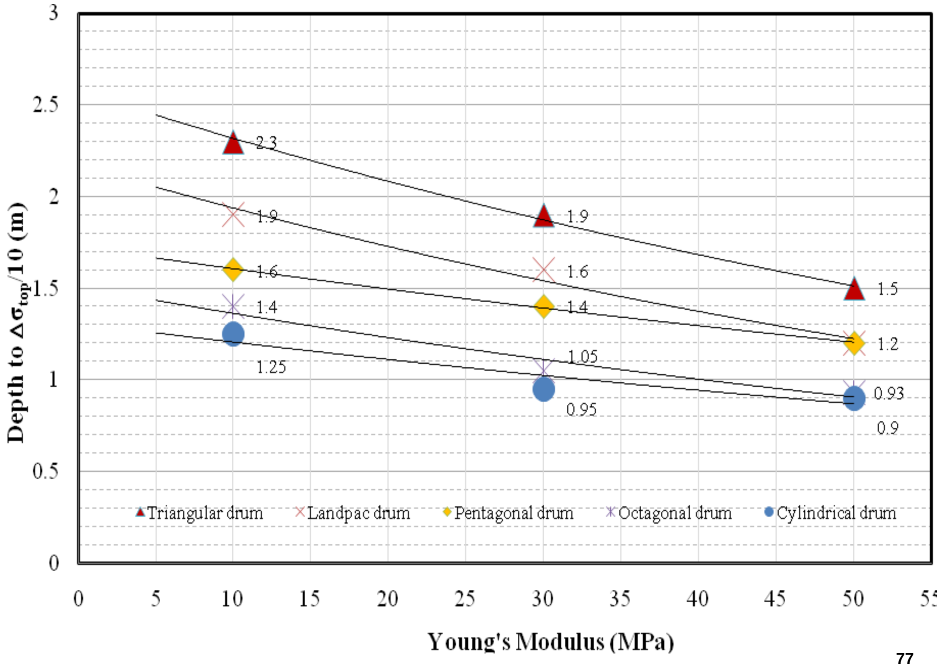

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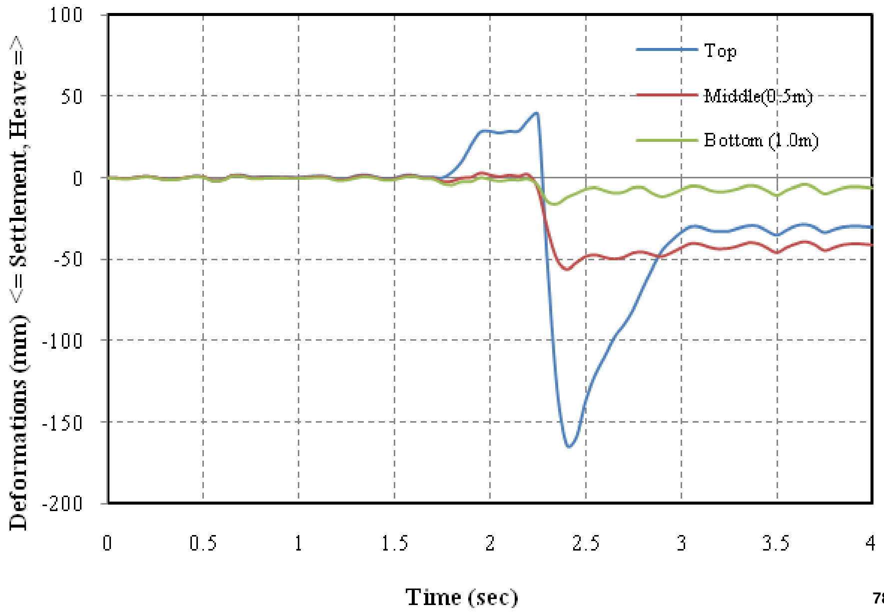
E_s = 10 MPa



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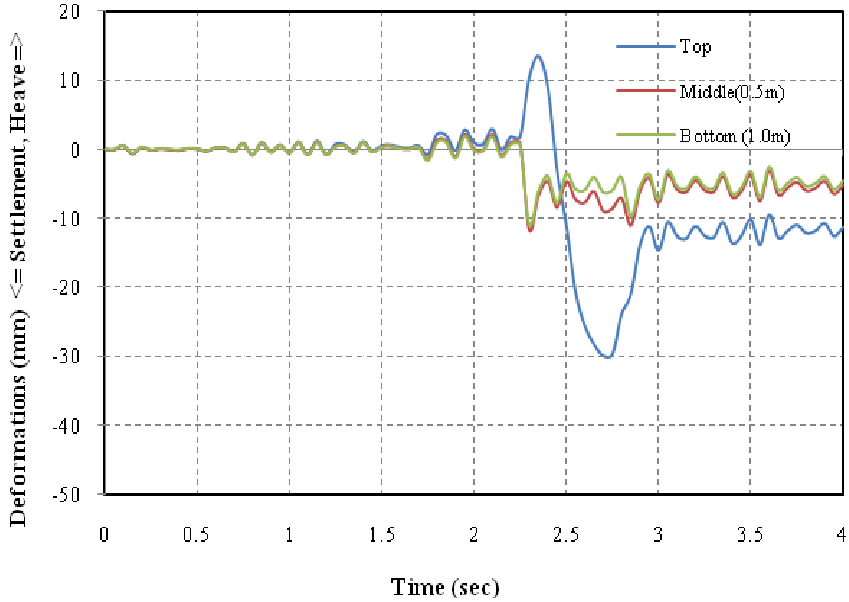
E_s = 50 MPa



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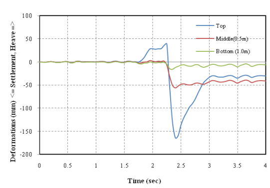
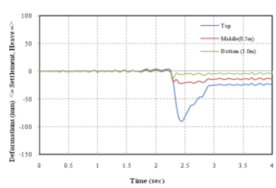
Modeling and methodology   **Simulation results**

Surface settlement (continued)

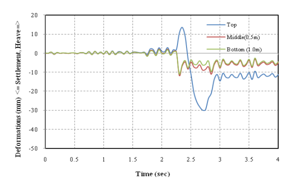
Triangular drum: 32.89mm, 22.82mm, and 10.92mm, respectively



E_s = 10MPa

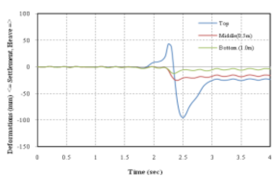


E_s = 30MPa

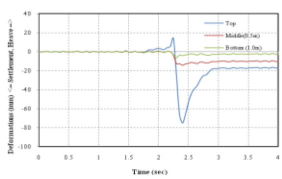


E_s = 50MPa

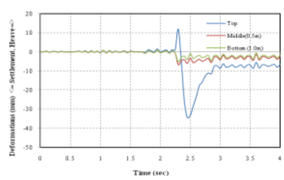
Landpac drum: 26.02mm, 17.28mm, and 8.42mm, respectively



E_s = 10MPa



E_s = 30MPa



E_s = 50MPa

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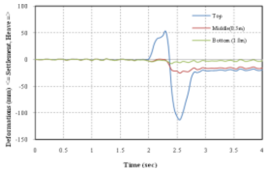
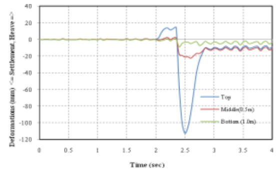
Surface settlement (continued)

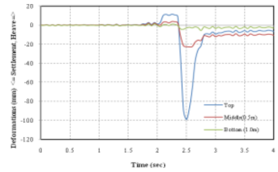
Pentagonal drum: 22.25mm, 14.42mm, and 5.49mm, respectively



E_s = 10MPa

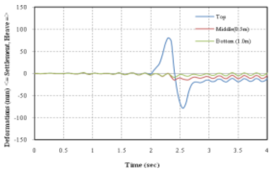


E_s = 30MPa

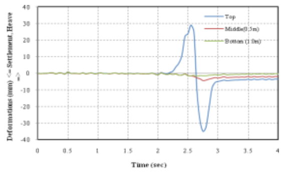


E_s = 50MPa

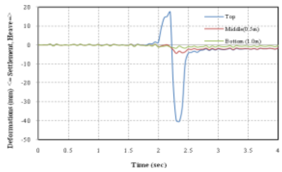
Octagonal drum: 20.13mm, 5.21mm, and 2.26mm, respectively



E_s = 10MPa

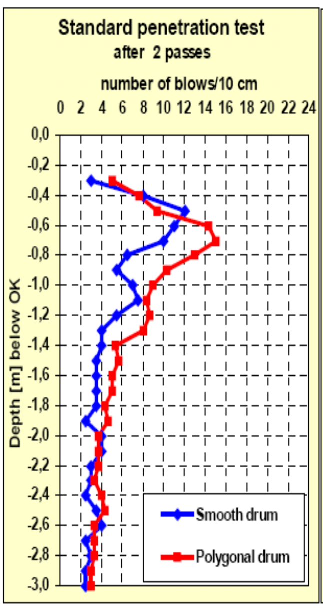


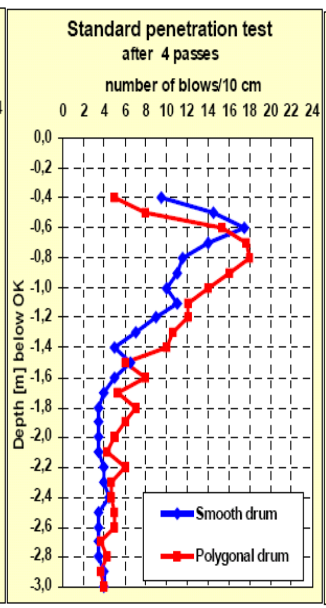
E_s = 30MPa

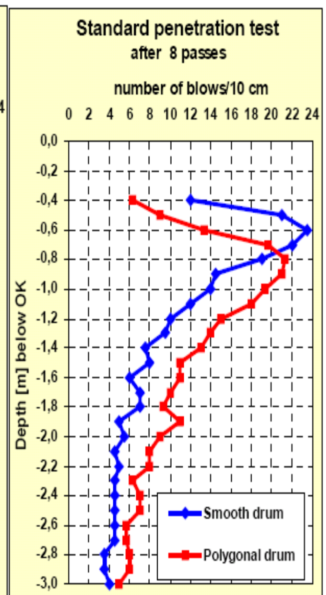


E_s = 50MPa

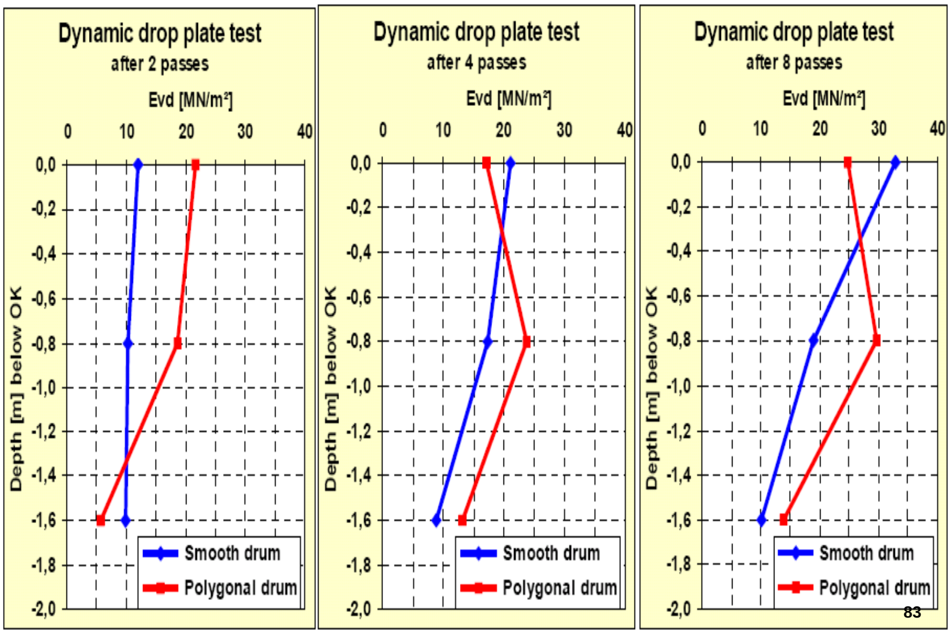
Bomag field test results







Bomag field test results



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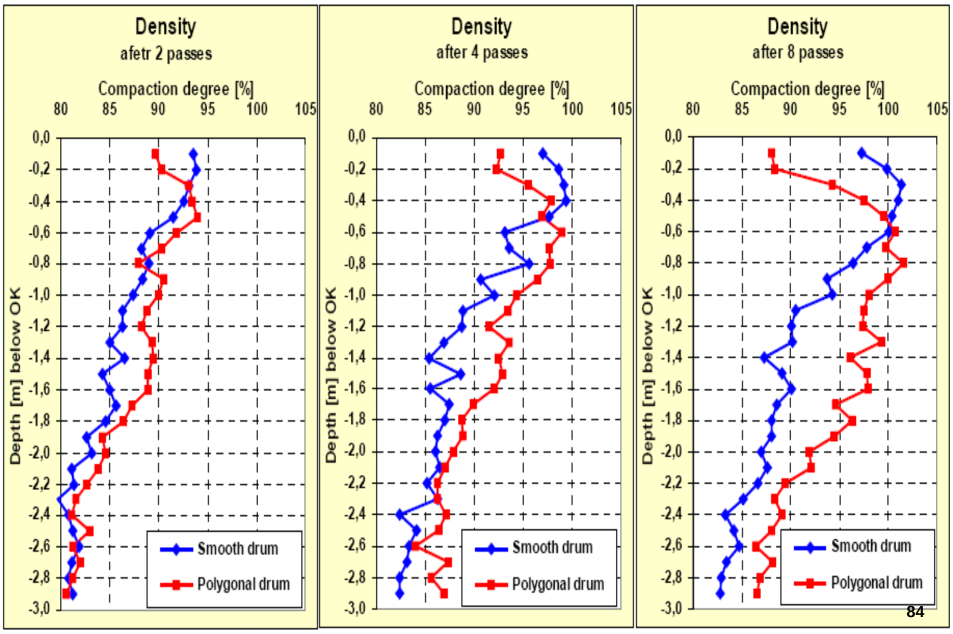
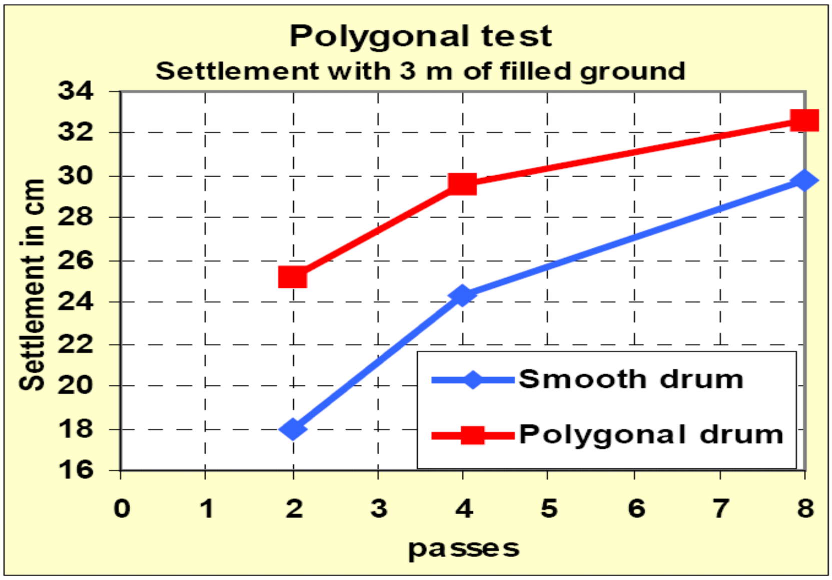


Bomag field test results



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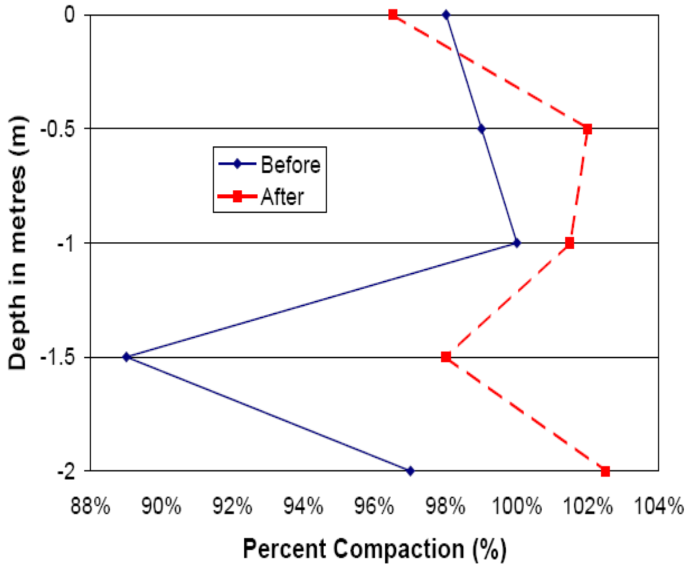
Broons field test results



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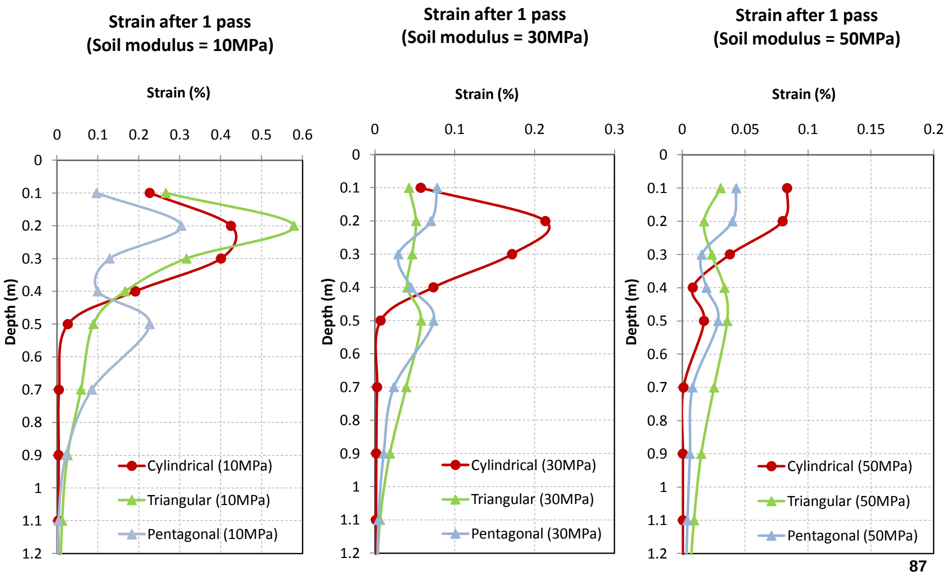
Texas A&M University simulations



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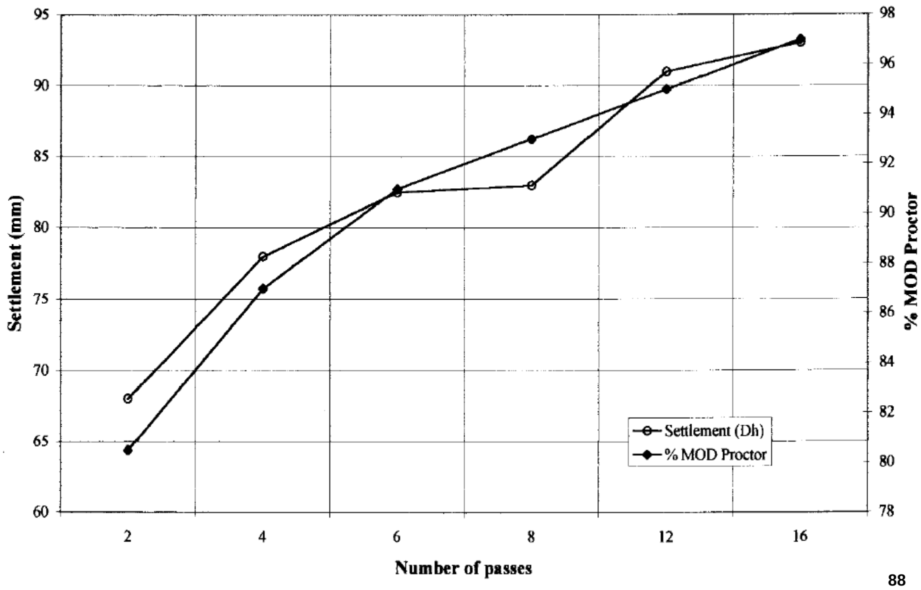
FORSSBLAD (1980)



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BROONS FIELD DATA

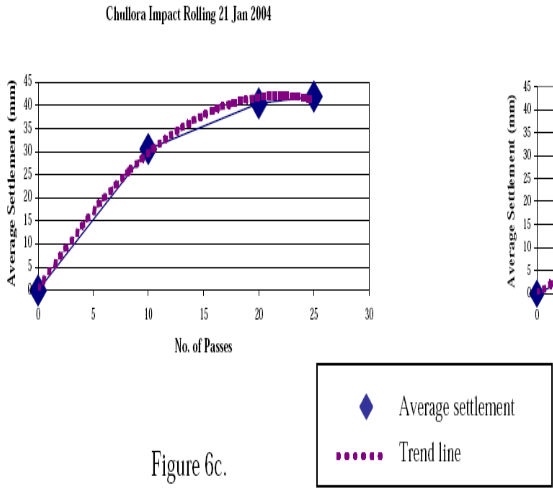

Figure 6c.

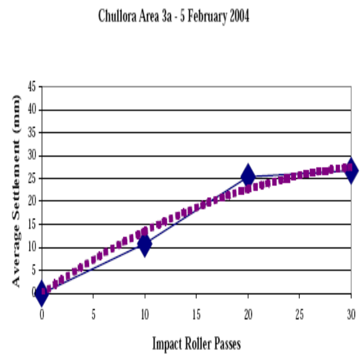

Figure 6d.

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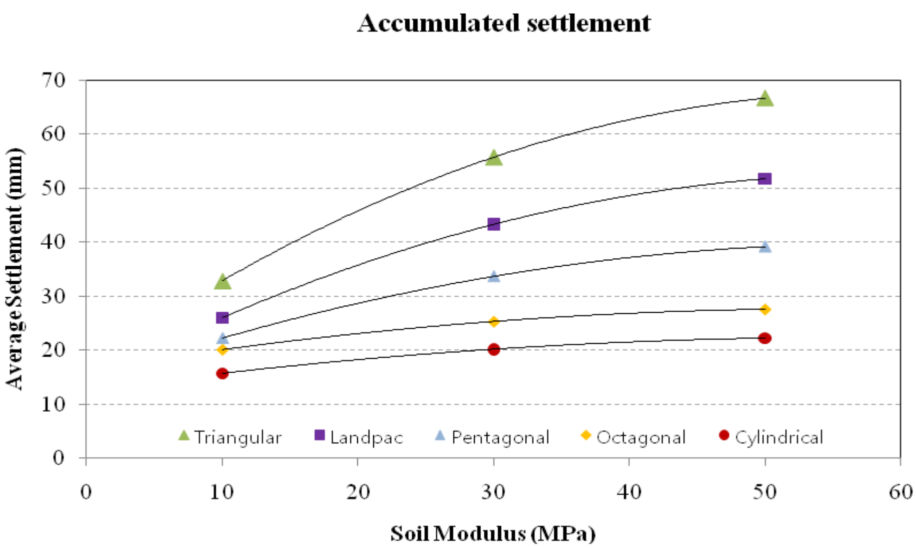
Predicted surface settlement



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CONCLUSIONS

- The width of the contact area between the drum and the soil controls the depth of compaction. The softer the soil is, the deeper the roller sinks in the soil, the wider the contact area is, and the deeper the compaction is. Therefore the depth of compaction depends on the stiffness of the soil. As such the depth of compaction decreases with the number of passes.
- The surface pressure controls the degree of compaction. This pressure is higher for the impact rollers than for the cylindrical rollers due to the dynamic effect. Yet the distribution of the pressure is much more uneven for impact rollers than for cylindrical rollers.

CONCLUSIONS

- The depth of compaction is larger for impact rollers because they impart higher stresses which increase the penetration of the roller drum into the soil thereby increasing the width and therefore depth of influence.
- It is also possible that the increase depth of influence is due to wave propagation during the impact. These waves can propagate much deeper than the typical depth of influence for static loading.
- The loosening effect of the surface is more prominent for the impact rollers than for the cylindrical rollers.

RECOMENDATIONS

- Compact first with an impact roller and use several passes to minimize the extent of the areas between impacts.
- Finish by using a cylindrical roller to optimize the compaction of the shallow layers.
- This process combines the benefits of both types of rollers: compaction of the deep layers (0.5 to 1.5 m) with the impact roller but loosening of the shallow layers (0 to 0.5 m) followed by compaction of the shallow layers (0 to 0.5 m) with the cylindrical roller without disturbing the deep layers.

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THANK YOU

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