Intelligent Compaction…

...GPS-based Compaction Control
Intelligent Compaction

Single Drum Roller SV 212 ACE<sub>plus</sub>

**ACE<sub>plus</sub>**
- Stiffness $k_B$ [MN/m]
- Number of Passes
- Process-Improvement

**ACE-Display**
- Material Preselection
- Compaction Values

**Drum**
- Amplitude changes stepless
- Variable Frequency

Intelligent Compaction

Tandem Roller AV 95-II ACE\textsubscript{plus}: additional Temp.-Measurement

ACE\textsubscript{plus}
- stiffness, Temperature
- number of passes
- process-improvement

ACE-Display
- material preselection
- compaction values
- Asphalt Temperature

Drum (splitted)
- amplitude changes stepless
- variable frequency

Asphalt Surface Temperature
- Infrared measurement principle

ACE\textsubscript{plus} : GPS-based Asphalt Compaction Control

Intelligent Compaction on Asphalt Job Sites

Switzerland, Einsiedeln 2007

IC Equipment - Basic Elements

1. Automatic Feedback Control System for Roller Parameters (Amplitude & Frequency)

2. In-situ Measurement of Material Stiffness

3. GPS-based Compaction Control, QA/QC
References (I)


References (II)

[10] Preisig, Noesberger
Dr. Caprez, Prof. Amann
R. Anderegg
Continuous Compaction Control based on Geotechnical Parameters
Forschungsauftrag VSS 2000/353; Federal Institute of Technology ETH, Zurich 2006

[11] Preisig, Dr. Caprez
& Prof. Amann
Validation of Continuous Compaction Control (CCC) Methods
Paper and Presentation: 9/23/2003; Workshop on Soil Compaction
Technical University of Hamburg-Harburg, Germany

[12] Kuno Kaufmann
Higher Compaction Performance using two Excitation Frequencies
Master Thesis (MSc.), in German with an English Abstract
Bern University of Applied Sciences, Engineering and Information Technology
Burgdorf (Switzerland) 2006

Formulae, Charts and Tables – Soil Mechanics and Foundation Engineerings
Stresses in Soils
A. A. Balkema, Rotterdam & Brookfield 1998
Intelligent Compaction

ACEplus: Control Loop & Sensors [5]

Display & Operation

Excitation

Control Unit

Automatic Closed-Loop Control

Sensors

Excentricity %

Acceleration sensor

Rotation sensor

Electronic Device

Differential Gear Box

Hydraulic Pump Valve

Exciter Position

Drum Acceleration

Phase Angle

1-Amplitude-Machine

Continuously changing of the amplitude

- Frequency $f$
- Amplitude $A$
- Speed $v$
- Contact force $F_B$

Automatically Controlled Roller Parameter
Intelligent Compaction

ACE<sub>plus</sub>: Control of Machine Parameters [5]

1. Phase Angle $\varphi$ $\Rightarrow$ Frequency $f$

2. Soil Force $F_S$ $\Rightarrow$ Eccentricity $m_0r_e$

$k_S = \frac{F_S(x'=0, x''>0)}{x}$

$k_S > k_S\text{ Target~?}$

Searching the Resonance Frequency [4]

Natural Frequency: the Frequency at which an Object vibrates by itself
This is the Point of maximum transmitted Force

Weak Material
- low Frequency
- high Amplitude

Hard Material
- high Frequency
- low Amplitude

Loam
Gravel

Intelligent Compaction

Drum

1-Amplitude

Continuously changement of the amplitude

Compaction/Soil Stiffness

Compaction Depth

Number of Passes/Time

CASE

Intelligent Compaction

Analytical Model [4], [5], [7]

\[ F_S = -m_d x_d'' + F_Z \cos(\Omega t) + (m_f + m_d)g \]
\[ F_Z = m_e r_\phi \Omega^2 \sin(\Omega \cdot t) + m_d g \]

Contact Conditions:
- \( F_S > 0: x_d = x_S = x \)
- \( F_S = 0: x_d > x_S \)

\[ F_S = k_S x_S + c_S x_S' \]

Simulation-Model:
- \( F_S = c_d x_d + k_d x \) if \( F_S > 0 \)
- \( F_S = 0 \) else

Force-Driven Nonlinearity

\( m_f x_d'' + c_f (x_d - x_f) + k_f (x_d - x_f) = m_f r_\phi \Omega^2 \cos(\Omega \cdot t) + m_d g \)

\( m_f x_f'' + c_f (x_f - x_d) + k_f (x_f - x_d) = m_f g \)

Frame
Drum
Soil

Nonlinear Dynamic Behavior: Using a Simulation Tool [12]

Amplitude $A_1$ [mm]
- $A_{1/2}$ [mm]
- $A_{1/3}$ [mm]
- $A_{2/3}$ [mm]

Excitation Frequency [Hz]

Deflection $x_d$

FFT

Frame & elastic suspension

Soil-Drum Interaction

MathLab/Simulink-Model

Chaos

Poor Compaction, $k_B$ compacted

$0$-Pulse

Deflection $F_Z$

Period $T$

$10$ kg m

$7.2$ kg m

$13$ kg m

CASE

**Intelligent Compaction**

**ACE<sub>plus</sub>: Measuring the Soil Compaction [10], [11]**

**Loading the Plate**

Force $F_s$

**Measuring the Deflection**

Mechanistic Soil model:

Stiffness of Soil:

$$k_B = \frac{F_s}{x_s}$$

$$F_s = k_B x_s + c_s x_s$$

ACE\textsubscript{plus}: Soil Stiffness – practical Validation [4], [13]

$\Rightarrow$ the Soil/Drum-System vibrates near his lowest Resonance Frequency
$\Rightarrow$ the System reacts quasi-static like a Spring, complemented by a Dashpot
Correlation with Plate Bearing Test [10], [11]

\[ M_{E1} = -7 + 1.13 k_B, \quad r^2 = 0.83 \]

Adequate Testing

Plate Bearing Test → [1]

Layered Soil Measurement [4]

Layered Soils
- Odemark (1946)

Practical Measurement
Texas, 2007 (August)

FS = k_s(A)x_s + c_s(A)x_s`

Soil Stiffness k_s(A) [MN/m]

Amplitude A_0 [mm]
**ACEplus**: Layered Soils [4]

*Measurement Depth of the ACEplus*-System

- Loam, compacted; acting as a Spring
- Gravelly Soil, well compacted; acting as an anvil

Intelligent Compaction

ACE\textsuperscript{plus}: Using the System in Practice
Combining the Pass Number and the Stiffness Improvement

Gauge: Display

89.5% \\

Pass 1 Pass 2 Pass 3 Pass 4

Roller: Stiffness $k_B$

Increase $\Rightarrow$ one pass more

No increase $\Rightarrow$ Finished!

Spec’s for Aggregates and Moisture Content [2]

Correlation between Dry Unit Weight and Stiffness/Bearing Capacity

- Coarse Grain: Gravel
- Fine Material: Loam

Optimal Water Content

- Water Content %
- Dry Unit Weight kN/m³
- Modulus (Stiffness) kN/m

Zachry Department of Civil Engineering
Texas A&M Engineering

Prof. Dr. Jean-Louis Briaud

Intelligent Compaction

Compaction, Density, Dry Unit Weight & Stiffness

Constant Weight, shrinking Volume => Increasing Unit Weight, increasing Compaction

MN DOT: Testing ACE Measurement [8], [9]

Mankato MN, 2005

AMMANN $k_B$ Comparison to Test Rolling

Correlation ACE $k_B$ and U.S. Test Data [8]

LWD (Light Weight Deflectometer)

$K_B = 14.94 \ln E_{LWD} - 34.93$

$R^2 = 0.883$

DCP (Dynamic Cone Penetrometer)

$K_B = 91.16 \text{DCP}^{-0.503}$

$R^2 = 0.614$

CIV (Clegg Impact Hammer)

$k_B = 1.379 \text{CIV} + 1.110$

$R^2 = 0.861$
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ACE\textsubscript{plus}: GPS meets Roller

- simple, self-explaining Application
- integrated User Piloting
- excellent Job Site Overview
ACE\textsubscript{ plus}: Two Control Loops are interacting

Continuous Compaction Control

GPS-Data
- Position
- Time

Stiffness-Data

1 Hertz

Automatic Compaction Control System

Actuators

1'500 Hertz

Electronics

Soil-Drum-Interaction

Sensors

ACE\textsuperscript{plus}: Geometrical Parameters

„Map Grid Size“: 1/10 of the Drum width

„Relation Distance“: 0.5 m

Machine Width = Drum Width (SV 212: 2.2 m)
ACE<sub>plus</sub>: GPS-based Compaction Measurement

GPS – Satellite

Stiffness $k_B$

Roller Stiffness $k_B$:

- None
- 10 MN/m
- 70 MN/m
- 140 MN/m

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ACE<sub>plus</sub>: Counting the Passes

North American Clay-Engineering Conference
Intelligent Compaction

ACE<sub>plus</sub>: Process Control - increasing Compaction Values

CASE

ACE\textsuperscript{plus}: Checking the Compaction Development

Stiffness $k_B$

Variation of Compaction between passes

4. Pass $k_B$

• MINUS

3. Pass $k_B$

• EQUAL

Difference of Stiffness $\Delta k_B$

Variation $\Delta k_B$

Pass 3

Pass 4

ACE\textsuperscript{plus}: Checking the Compaction Development

Intelligent Compaction

ACE<sub>plus</sub> shows: Good Compactibility of Soil Material

Stiffness $k_B$:
- none
- 10 MN/m
- 70 MN/m
- 140 MN/m

$\Delta$Stiffness $\Delta k_B$:
- $\Delta k_B = 0$
- $\uparrow$
- $\uparrow\uparrow$
- $\uparrow\uparrow\uparrow$
- $\downarrow$
- $\downarrow\downarrow$

2. Pass $k_B$

2. Pass $\Delta k_B$

last Pass $k_B$

last Pass $\Delta k_B$

more Passes

ACE+ shows: *Bad* Compactibility of Soil Material

**Stiffness $k_B$:**
- none
- 10 MN/m
- 70 MN/m
- 140 MN/m

**$\Delta$Stiffness $\Delta k_B$:**
- $\uparrow\uparrow\uparrow\uparrow$
- $\uparrow\uparrow$
- $\Delta k_B=0$
- $\downarrow\downarrow$
- $\downarrow\downarrow\downarrow$

**2. Pass $k_B$**
- forward

**2. Pass $\Delta k_B$**
- forward

**Attention**
- last Pass $k_B$
- last Pass $\Delta k_B$

**more Passes**

ACE_{plus}: Compacted Soil Different Subgrade

Well compacted Soil

Subgarde: Pipeline Cover Material stays soft
Intelligent Compaction

ACE\textsuperscript{plus} in Soil Compaction...

Position (Satellite)

Reference Point

Radio Signal RTK
Accuracy 2-5 cm

Roller

...on a Airport Job Site [10]

Correlation [10]

- Single Drum Roller with GPS Position
- Plate Bearing Test [1] with GPS Position

Korrelation $M_{E1}$-$k_B$, Planum "Echo-Nord"

$k_B = 0.8027 \cdot M_{E1} + 11270$

$R^2 = 0.751$

$k_B \left[ \frac{MN}{m} \right] = 0.8 \cdot M_{E1} \left[ \frac{MN}{m^2} \right] + 11.3$

- Soft Subsoil
- one Layer of well graded Material

Intelligent Compaction (Benefits for the Customers)

1. Optimized/Maximized Productivity
   - Feedback Control System: Automatic Adjustment of Compaction Energy (Amplitude, Frequency, Impact Spacing)
   - Process-Integrated Measurement of Soil Stiffness
=> Easy to operate

2. Sustainable Compaction
   - Homogeneous, optimal Compaction Results
   - Continuous Compaction Control (GPS)