Dynamic Rollers in Earthworks: Compaction and Continuous Compaction Control

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Roller Compaction

1. **Static** rollers

2. **Dynamic** rollers
   
   2.1 **Vibratory** rollers
   
   2.2 **Oscillatory** rollers
   
   2.3 Rollers with **control of vertical centrifugal force**
   
   2.4 **Feedback controlled** rollers (VARIOCONTROL, VARIOMATIC, ACE)
Oscillating rollers:
- two eccentric masses – eccentric but point symmetric to the drum axis
- same sense of rotation ⇒ sinusoidal torque around drum axis
- mainly dynamic shear forces
- low ambient vibrations

Vibrating rollers:
- eccentric mass in the drum axis
- circular translational vibration of the drum
- mainly vertical loading
- better compaction depth

Modes of operation:
Continuous Contact, Partial Uplift, Double Jump, Rocking Motion, Chaotic Motion

<table>
<thead>
<tr>
<th>drum motion</th>
<th>interaction drum-soil</th>
<th>mode of operation</th>
<th>soil contact force</th>
<th>application of CCC</th>
<th>soil stiffness</th>
<th>roller speed</th>
<th>drum amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>periodic</td>
<td>cont. contact</td>
<td>Continuous Contact</td>
<td></td>
<td>yes</td>
<td>low</td>
<td>fast</td>
<td>small</td>
</tr>
<tr>
<td></td>
<td>periodic</td>
<td>Partial Uplift</td>
<td></td>
<td>yes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>periodic</td>
<td>Double Jump</td>
<td></td>
<td>yes</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>chaotic</td>
<td>Chaotic Motion</td>
<td></td>
<td>no</td>
<td>high</td>
<td>slow</td>
<td>large</td>
</tr>
</tbody>
</table>
Workshop 4: Ground Improvement and Soil Stabilisation
**Compactometer**

**CMV**

is based on the evaluation of the acceleration in the frequency domain.

\[
	ext{CMV} = \text{Faktor}_1 \cdot \frac{a(2\omega)}{a(\omega)}
\]

where:

- \( a(\omega) \) is the acceleration at frequency \( \omega \)
- \( a(2\omega) \) is the acceleration at frequency \( 2\omega \)

\( \text{RMV} = \text{Faktor}_2 \cdot \frac{a(0.5\omega)}{a(\omega)} \)

where:

- \( a(\omega) \) is the acceleration at frequency \( \omega \)
- \( a(0.5\omega) \) is the acceleration at frequency \( 0.5\omega \)

\( \text{a}(0.5\omega) > 0 \) double jump

**Terrameter**

**OMEGA**

is based on the evaluation of the energy transmitted to the soil in the time domain.

\[
\text{OMEGA} = \text{Faktor}_3 \int_{-T}^{T} \cdot \frac{dF}{dz_1} \cdot dt
\]

**CCC Values**

**Terrameter**

**\( E_{\text{VIB}} \)**

⇒ inclination of the soil contact force displacement relationship during loading; time domain

\[
E_{\text{VIB}} = \frac{\text{double jump}}{\text{90\%}}
\]

\[
\Delta F = \frac{\Delta z_1}{\text{90\%}}
\]

**ACE**

**\( k_B \)**

⇒ derived from the soil contact force displacement relationship at maximum drum deflection; time domain

\[
k_B = \frac{2A(z_1)}{F_{\text{max}}}
\]
Modelling of the dynamic soil roller interaction system

Semi-analytical modelling

- Roller drum: rigid body with directed excitation unit
- Ground: approximation of linear elastic halfspace
  - cone model (SDOF) \((\text{Wolf, 1994})\)

Contact problem: relevant non-linearity in the interaction system

Finite element modelling

- Roller drum: rigid body with directed excitation unit
- Ground: approximation of linear elastic halfspace
  - linear elastic elements

variation of soil modulus

variation of the effective direction of the exciter
Workshop 4: Ground Improvement and Soil Stabilisation

Weak spot 40 cm BGL

Tri-axial accelerometer 55 cm BGL

Tri-axial accelerometer on the surface

Deformation measurement device

Dynamic soil pressure 55 cm BGL

Reference point of geodetic levelling

Fill height: 1. layer: 55 cm

Fill material: sandy gravel

Area for dynamic load plate tests

Lane 1

Lane 2

Lane 3

Lane 4

Container

Compaction device:
Hamm HD+ 90 VO tandem roller (ca. 9.8 t)

Vibration (ca. 1.9 t drum mass):
Small amplitude: 0.34 mm at 50 Hz
Large amplitude: 0.62 mm at 40 Hz

Oscillation (ca. 1.9 t drum mass):
Tangential amplitude: 1.44 mm at 39 Hz
Calculation of the CCC values based on acceleration measurements:

Lane 2, Vibration, $f = 50 \text{ Hz}$, $v = 2-6 \text{ km/h}$

Installation of the artificial weak spot

Dynamic load plate tests after each roller pass
Comparison of two test runs:

\( f = 40 \text{ Hz} \) (thin line) and \( f = 30 \text{ Hz} \) (bold line)

**Main influence on CCC values:**
- Modes of operation
- Roller speed
- Excitation frequency
- Excitation amplitude
Oscillating rollers:
- Two eccentric masses – eccentric, but point symmetric to the drum axis
- Same sense of rotation ⇒ sinusoidal torque around drum axis
- Mainly dynamic shear forces
- Low ambient vibrations
- Until recently: no CCC system!

Vibrating rollers:
- Eccentric mass in the drum axis
- Circular translational vibration of the drum
- Mainly vertical loading
- Better compaction depth

Table:

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<th>Interaction drum-soil</th>
<th>Mode of operation</th>
<th>Horizontal acceleration in the bearing</th>
<th>App. of CCC</th>
<th>Roller speed</th>
<th>Soil stiffness</th>
<th>Excitation amplitude</th>
<th>Excitation frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Continuous contact</td>
<td>Stick</td>
<td>[Graph]</td>
<td>yes</td>
<td>slow (Stick)</td>
<td>low (Stick)</td>
<td>small (Stick)</td>
<td>low (Stick)</td>
</tr>
<tr>
<td>Periodic loss of contact</td>
<td>One-sided Slip</td>
<td>[Graph]</td>
<td>yes</td>
<td>slow (Slip)</td>
<td>high (Slip)</td>
<td>large (Slip)</td>
<td>high (Slip)</td>
</tr>
<tr>
<td></td>
<td>Asymmetric Slip</td>
<td>[Graph]</td>
<td>yes</td>
<td>fast (Slip)</td>
<td>high (Slip)</td>
<td>small (Slip)</td>
<td>low (Stick)</td>
</tr>
<tr>
<td></td>
<td>Symmetric Slip</td>
<td>[Graph]</td>
<td>yes</td>
<td>fast (Slip)</td>
<td>high (Slip)</td>
<td>small (Slip)</td>
<td>low (Stick)</td>
</tr>
</tbody>
</table>

Modes of operation:
- Continuous Contact
- Partial Uplift
- Double Jump
- Rocking Motion
- Chaos

Modes of operation:
- Stick, One-sided Slip, Asymmetric Slip, Symmetric Slip

Diagram:
- Oscillation
- Vibration

Workshop 4: Ground Improvement and Soil Stabilisation
Fill heights:
1st Layer: 40 cm
2nd Layer: 30 cm

Fill material:
Sandy gravel

- Tri-axial accelerometer 70 cm BGL
- Tri-axial accelerometer on the surface
- Deformation measurement device
- Dynamic earth pressure cell 70 cm BGL
- Reference point of geodetic levelling

Compaction device:
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Oscillation (ca. 1.9 t drum mass):
Tangential amplitude: 1.44 mm at 39 Hz
Accelerations in the bearing of the drum (point M):
Motion behaviour of point $M$:

**Rotary motion:**

**Translatory motion:**

Mode of operation **Stick** Mode of operation **Slip**

Mode independence!

Formulation of the equations of motion:

\[
\begin{align*}
\dot{m}x_A + \frac{mr(R-r)}{R} \dot{\theta} - \frac{mr^2(R-r)}{R^2} \ddot{\theta} + k_H x_A + c_H \dot{x}_A &= 0 \\
(m + \Delta m)\ddot{x}_A - \frac{mr(r-R)}{R} \ddot{\theta} - \frac{mr^2(R-r)}{R^2} \dot{\theta}^2 + k_v \dot{x}_A - m g + c_v \dot{z}_A &= F_z \\
\left[I + \frac{mr^2(r-R)^2}{R^2}\right] \dot{\theta} + \frac{mr(r-R)}{R} \dot{x}_A - \frac{mr^2(R-r)}{R^2} \dot{z}_A \dot{\theta} + mg(r-R) \frac{r^2}{R^2} = M_0 \sin(\xi t)
\end{align*}
\]

Mechanical model
• Results of the experimental measurements:

- Expansion of the eight shape
  - with increasing number of passes
  - with increasing soil stiffness
- Distortion of the shape caused by travelling motion
- Characterisation of the shape = possible CCC

• Definition: area of the shape = CCC value for oscillating rollers

• Results of the model analysis:

- Expansion of the eight shape
- Distortion of the shape caused by travelling motion
- Characterisation of the shape = possible CCC

- Definition: area of the shape = CCC value for oscillating rollers
Application of the CCC algorithm on acceleration measurements:

2\textsuperscript{nd} layer, lane 2, Oscillation, $f = 39$ Hz, $v = 4$ km/h

Comparison to dynamic load plate tests:
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