Advances in the modelling of railway ballast using the Discrete Element Method (DEM)
I am happy for you to photograph or tweet the slides from my talk.

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1. Introduction to the Discrete Element Method (DEM)
2. Railway ballast modelling within the DEM
3. Calibration and validation tests
4. Full scale railway track tests under dynamic loads
5. Conclusions and ongoing work
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Introduction to the DEM – Railway ballast

Layer of **granular material** placed under the sleepers whose roles are resisting to vertical and horizontal loads and facing climate action.

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Introduction to the DEM – Force Evaluation

Force balance

\[ m_i \ddot{y}_i = F^\text{ext}_i + \sum_{j=1}^{n_c^i} F^{ij} \]

Torque balance

\[ I_i \ddot{\omega}_i = T^\text{ext}_i + \sum_{j=1}^{n_c^i} r^{ij}_c \times F^{ij} \]

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Introduction to the DEM – Geometrical Approaches

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1. Introduction to the DEM

## Geometrical Approaches

<table>
<thead>
<tr>
<th>Analysed approaches</th>
<th>Spheres</th>
<th>Sphere clusters</th>
<th>Squad.</th>
<th>Polyhed.</th>
<th>Sphero-Polyhed.</th>
<th>Potential Particles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low computational cost</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>Efficient force evaluation</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
<td>✗</td>
</tr>
<tr>
<td>Geometrical variety</td>
<td>✗</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Concave particles</td>
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<td>✓</td>
<td>✗</td>
<td>✓*</td>
<td>✓*</td>
<td>✗</td>
</tr>
<tr>
<td>Distribution of contacts</td>
<td>✗</td>
<td>✓</td>
<td>✓*</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>
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http://www.cimne.com/dempack/
http://www.cimne.com/kratos/
http://gid.cimne.upc.es/

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Ballast properties

- Density
- Sample size distribution
- The inter-particle friction
- Particle-wall friction
- The initial void ratio
- Coefficient of restitution

- Particle shape
- Particle stiffness

Normally well-known

Some considerations to be taken into account
Ballast properties – Particle shape

To avoid excessive particle rotation → Rolling friction
Ballast properties – Particle shape

Ballast properties – Particle shape
Ballast properties – Particle stiffness

Hertzian contact model: contact stiffness depends on the contact volume

Real contact geometry

Numerical contact geometry
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Zand, J. van’t, & Moraal, J. (1997) Roads and Railways Research Laboratory Technical University of Delft

Lateral resistance force test

Ballast properties
- Density (kg/m³): 2700
- Poisson ratio: 0.2
- Young modulus (GPa): 2.4/9.6/16.8/24.0
- Friction coefficient: 0.6
- Restitution coefficient: 0.0
- Rolling friction coefficient: 0.2

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Lateral resistance force test

<table>
<thead>
<tr>
<th>Vertical load</th>
<th>0 N</th>
<th>5000 N</th>
<th>10000 N</th>
<th>15000 N</th>
<th>20000 N</th>
<th>25000 N</th>
<th>30000 N</th>
<th>35000 N</th>
</tr>
</thead>
</table>

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Full scale test

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$$Q_s (x, t) = Q \frac{k_{eq}}{K} e^{-\frac{|x- vt|}{L}} \left[ \cos \frac{|x- vt|}{L} + \sin \frac{|x- vt|}{L} \right]$$

- $Q_s \rightarrow$ load over the sleeper
- $Q = 168732$ N $\rightarrow$ axle load
- $K = 75$ kN/mm $\rightarrow$ track stiffness
- $k_{eq} = 33.58$ kN/mm $\rightarrow$ bearing stiffness
- $L = 0.881$ m $\rightarrow$ elastic length
- $v = 300$ km/h $\rightarrow$ velocity of the train

![Full scale test diagram]
Quality evaluation of a railway track subjected to vertical loads

1. Conventional track
2. Bumpy track
3. Track fouled with sand

Porosity: 39.41%
Porosity: 43.86%
Full scale test – Ballast velocity
Full scale test – Sleepers vertical displacement

![Graph showing sleepers vertical displacement](image)

- **Well compacted track**
- **Poorly compacted track**
- **Fouled track**

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Full scale test with rails

Numerical representation of rails and bearing plates

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Full scale test with rails

- $Q = 168732 \text{ N} \rightarrow \text{axle load}$
- $A = 77.45 \text{ cm}^2 \rightarrow \text{rail cross section}$
- $I_{xx} = 3217 \text{ cm}^4 \rightarrow \text{moment of inertia horizontal axis}$
- $I_{yy} = 524 \text{ cm}^4 \rightarrow \text{moment of inertia vertical axis}$
- $k_{bq} = 30.75 \text{ kN/mm} \rightarrow \text{bearing plate stiffness}$
- $v = 250 \text{ km/h} \rightarrow \text{velocity of the train}$
- $R = 4000 \text{ m} \rightarrow \text{radius of the curve}$

2 more wagons
Full scale test with rails – Ballast lateral velocity
Full scale test with rails – Sleepers lateral displacement

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Conclusions

- The DEM is a valid numerical model for the calculation of ballast behavior
- There is uncertainty in the assignment of properties (mainly shape and stiffness), so calibration is necessary
- Spherical particles are useful if the contacts force and distribution is not a key aspect of the analysis
- The numerical tool presented allows the user to test different situations:
  - Reduction of ballast material
  - Changes in ballast granulometry or properties
  - Improve of sleepers design
  - Changes in sleepers roughness
Ongoing work

- Validation of the conditions to introduce ballast fouling
- Calculations with other particle geometries (clusters of spheres) to evaluate wear and fouling
- Improvements in the user interface
Thank you for your attention!