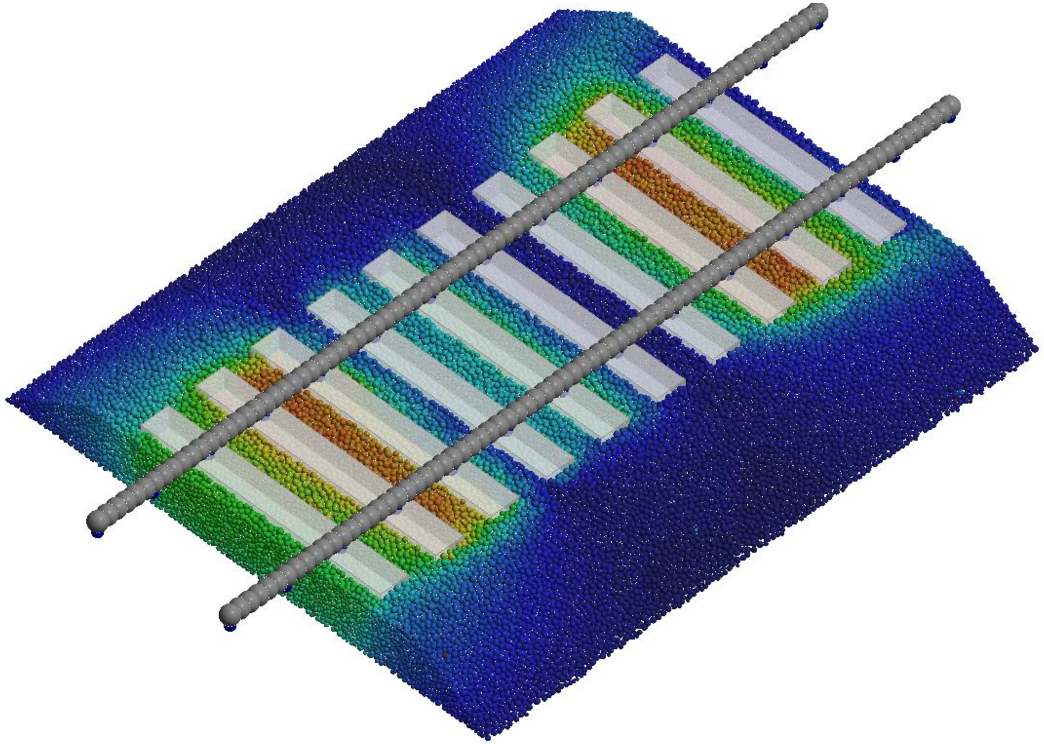
The Fourth International Conference on Railway Technology
RAILWAYS 2018
3–7 September 2018
Sitges, Barcelona, Spain

Advances in the modelling of railway ballast using the Discrete Element Method (DEM)



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Joaquín Irazábal, Fernando Salazar and Eugenio Oñate

I am happy for you to photograph or tweet the slides from my talk

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Outline

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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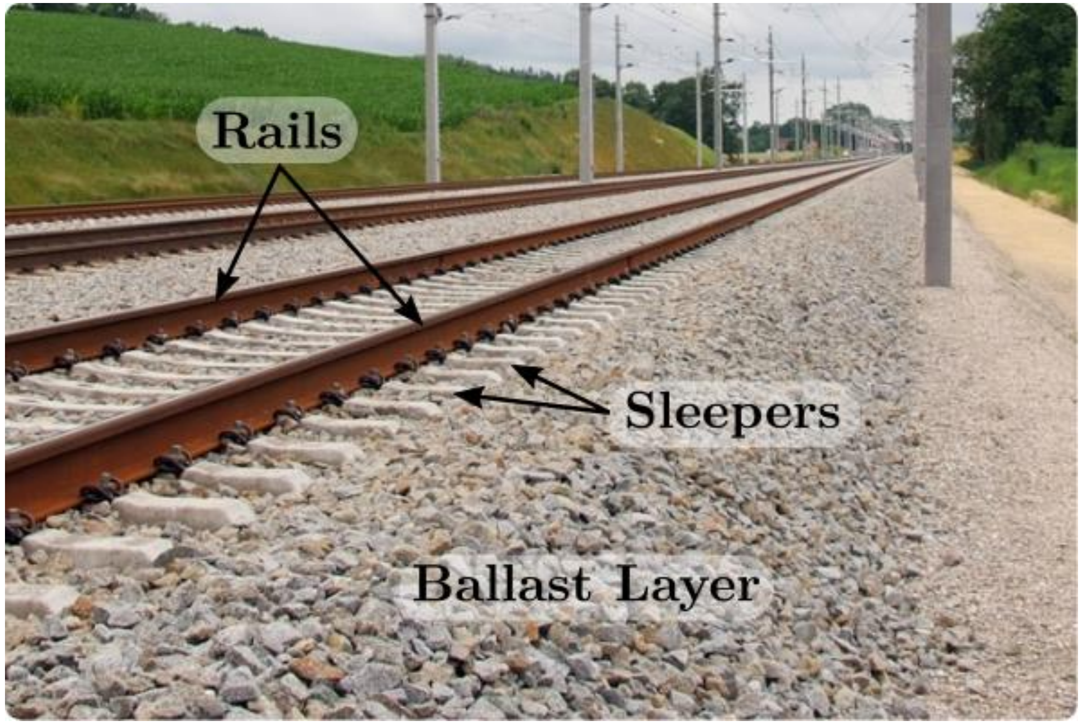
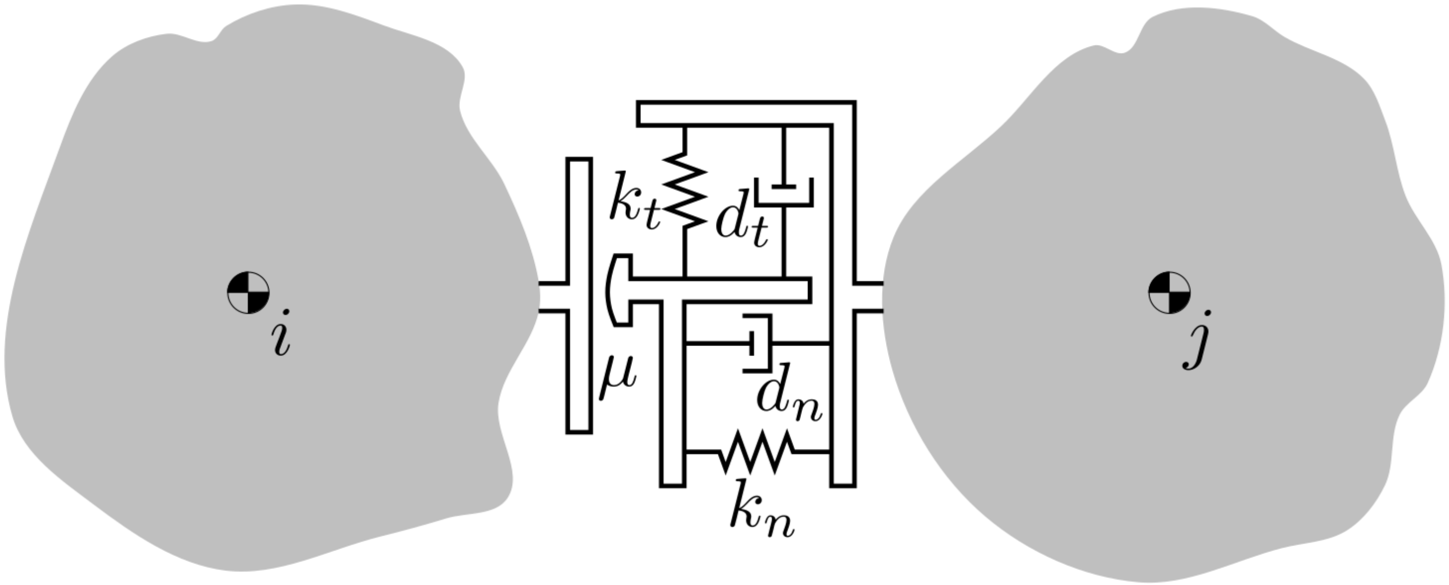
Introduction to the DEM – Railway ballast

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



Introduction to the DEM – Force Evaluation



Force balance

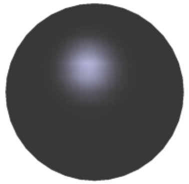
$$m_i \ddot{\mathbf{u}}_i = \mathbf{F}_i^{ext} + \sum_{j=1}^{n_i^c} \mathbf{F}^{ij}$$

Torque balance

$$\mathbf{I}_i \dot{\boldsymbol{\omega}}_i = \mathbf{T}_i^{ext} + \sum_{j=1}^{n_i^c} \mathbf{r}_c^{ij} \times \mathbf{F}^{ij}$$

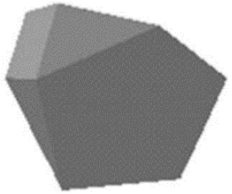
Introduction to the DEM – Geometrical Approaches

Spheres

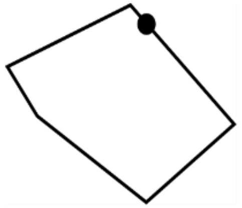


Clusters of spheres

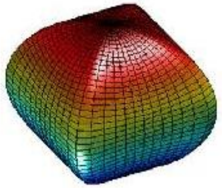
Polyhedra



Spheropolyhedra



Superquadrics



Potential particles

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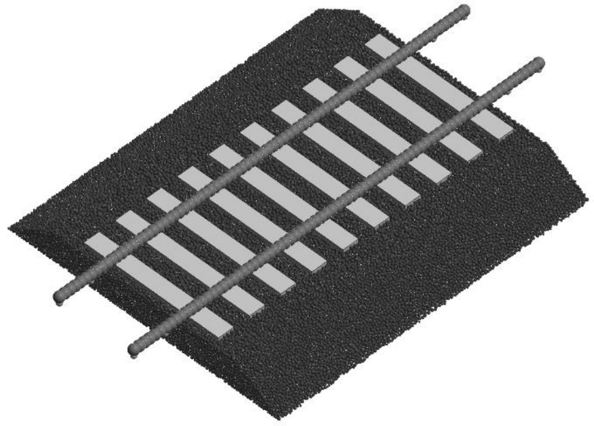
Introduction to the DEM – Geometrical Approaches



		Analysed approaches					
		Spheres	Sphere clusters	Squad.	Polyhed.	Sphero-Polyhed.	Potential Particles
Requirements	Low computational cost	✓	✗	✗	✗	✗	✗
	Efficient force evaluation	✓	✓	✗	✗	✓	✗
	Geometrical variety	✗	✓	✓	✓	✓	✓
	Concave particles	✗	✓	✗	✓*	✓*	✗
	Distribution of contacts	✗	✓	✓*	✓	✓	✓

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Introduction to the DEM – Software

DEMpack Discrete / finite elements simulation software

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

} Normally well-known

- Particle shape
- Particle stiffness

} Some considerations to be taken into account

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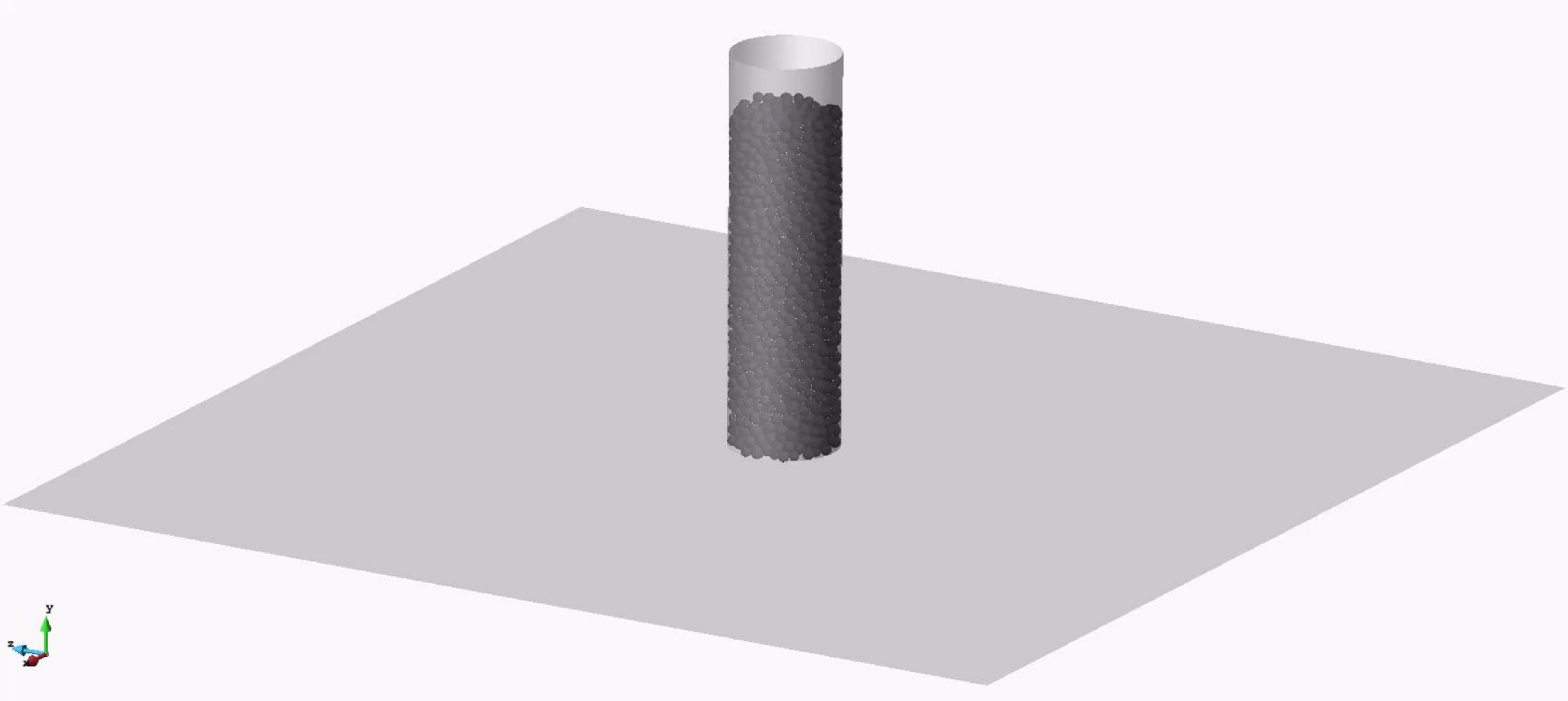
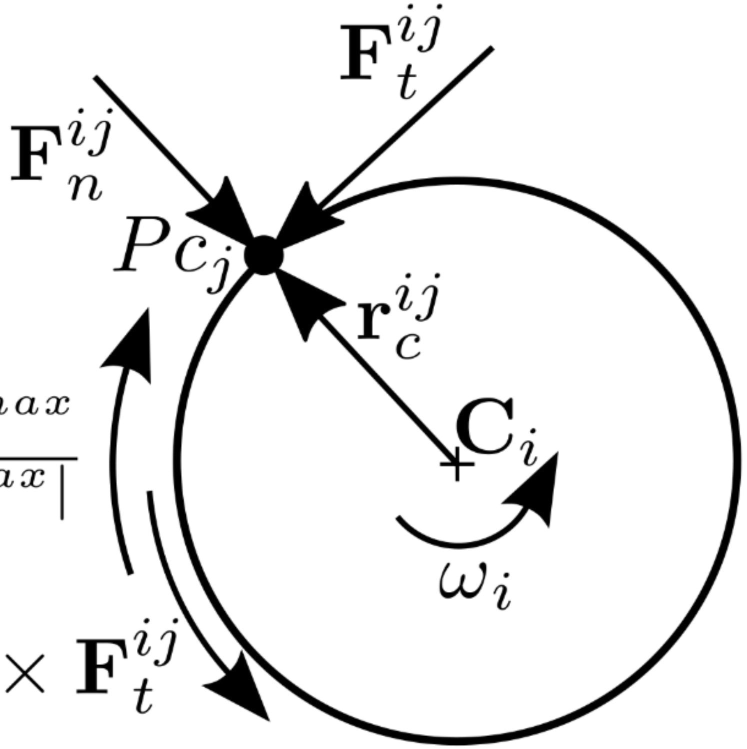
Ballast properties – Particle shape



To avoid excessive particle rotation → Rolling friction

Ballast properties – Particle shape

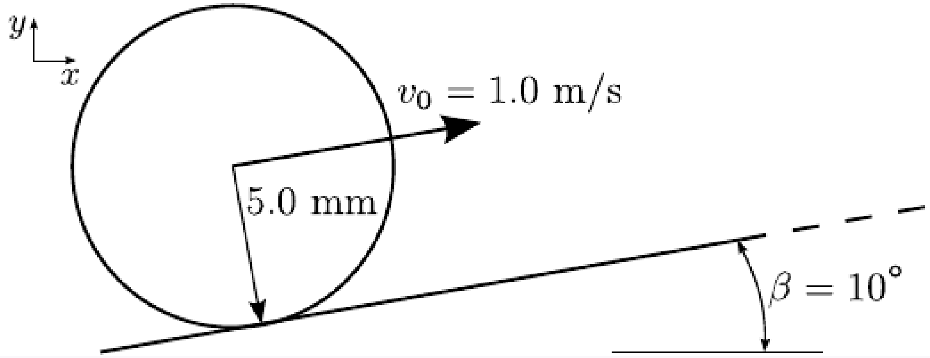


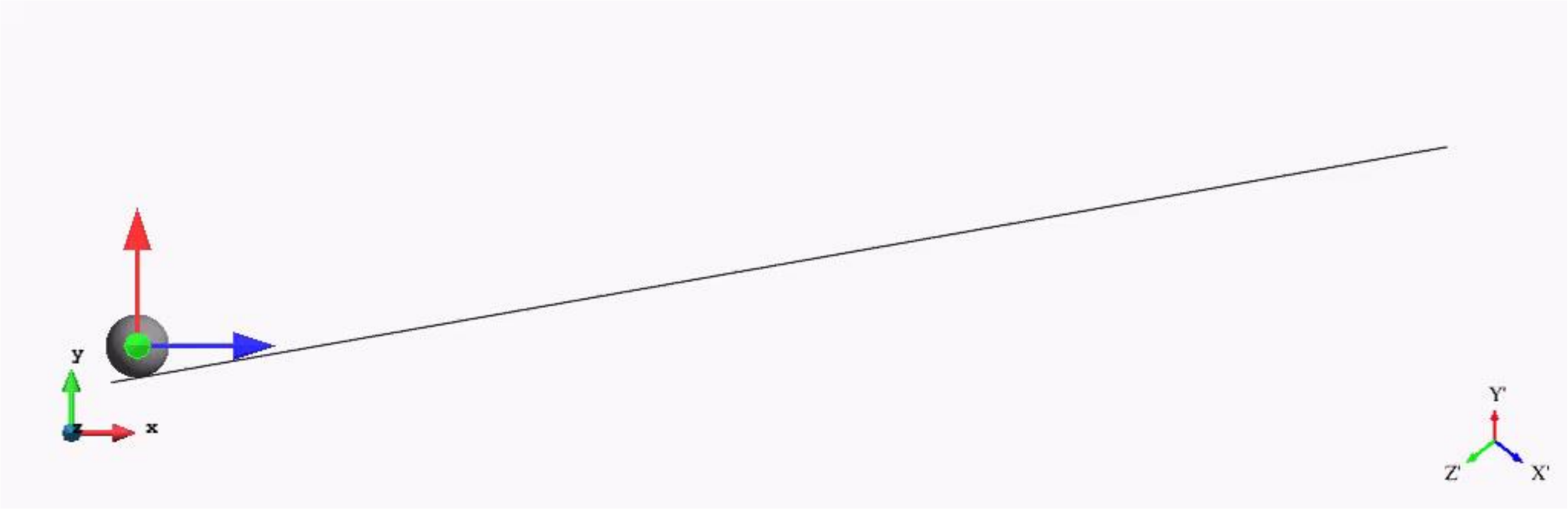
$$\mathbf{T}^{r,ij} = \eta|\mathbf{r}_c^{ij}||\mathbf{F}_n^{ij}|\frac{-\boldsymbol{T}_i^{max}}{|\boldsymbol{T}_i^{max}|}$$

$$\mathbf{T}^{ij} = r_c^{ij} \times \mathbf{F}_t^{ij}$$

Irazábal, J., Salazar, F., & Oñate, E. (2017). Numerical modelling of granular materials with spherical discrete particles and the bounded rolling friction model. Application to railway ballast. Computers and Geotechnics, 85, 220-229.

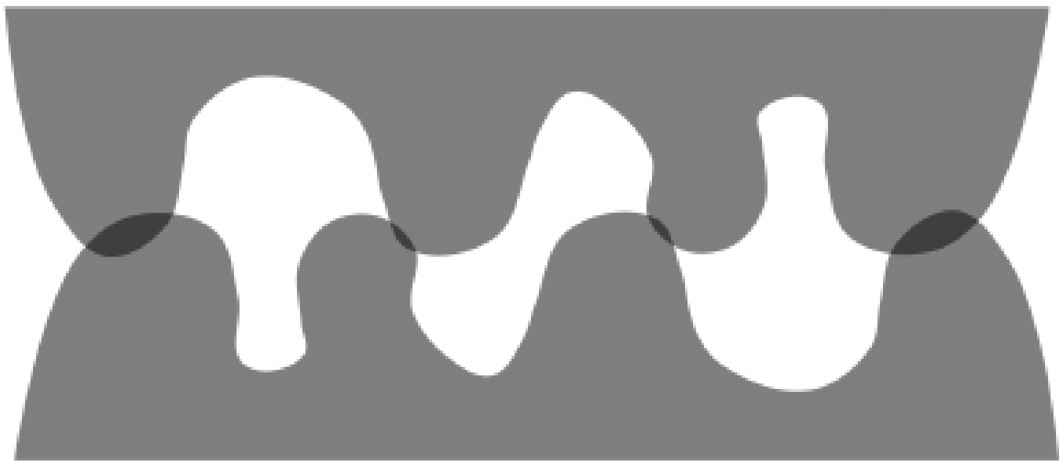
Ballast properties – Particle shape



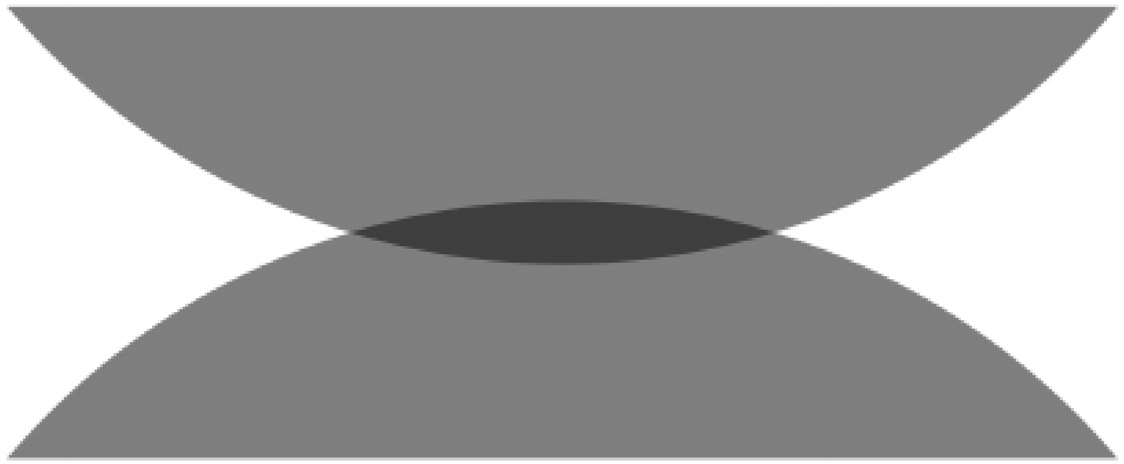


Ballast properties – Particle stiffness

Hertzian contact model: contact stiffness depends on the contact volume



Real contact geometry



Numerical contact geometry

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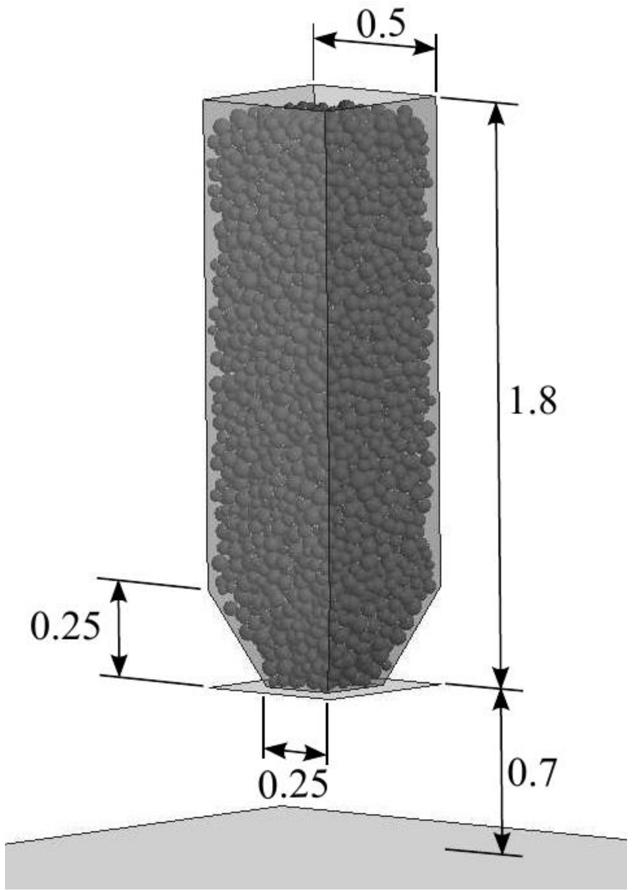
Repose angle test

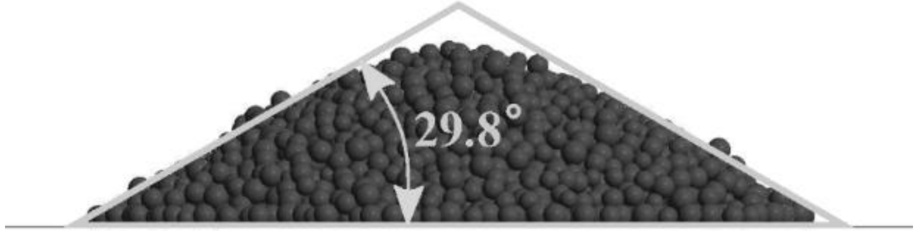


Material properties	
Density (kg/m^3)	2700
Poisson coefficient	0.2
Young modulus (GPa)	2.4
Friction coefficient ballast	0.6
Friction coefficient ballast-floor	0.6
Restitution coefficient	0.0
Rolling friction coefficient	0.05/0.1/0.15/0.2/0.25

Repose angle = 40º

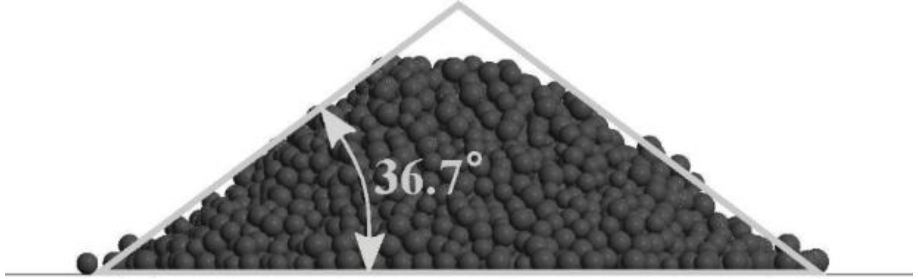
Chen, C., McDowell, G. R., & Thom, N. H. (2014). Investigating geogrid-reinforced ballast: Experimental pull-out tests and discrete element modelling. Soils and Foundations, 54(1), 1-11.

Repose angle test

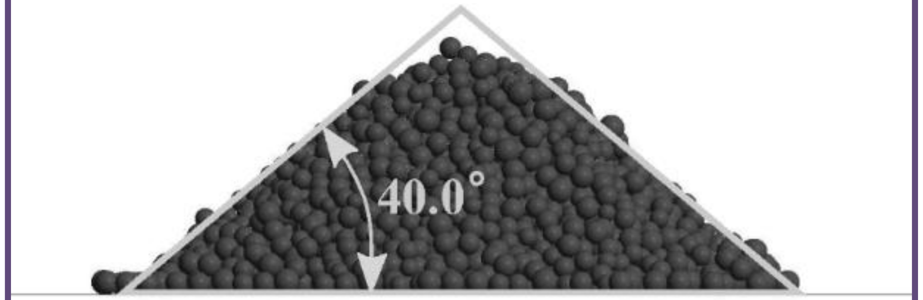


Rolling friction = 0.05

Rolling friction = 0.10



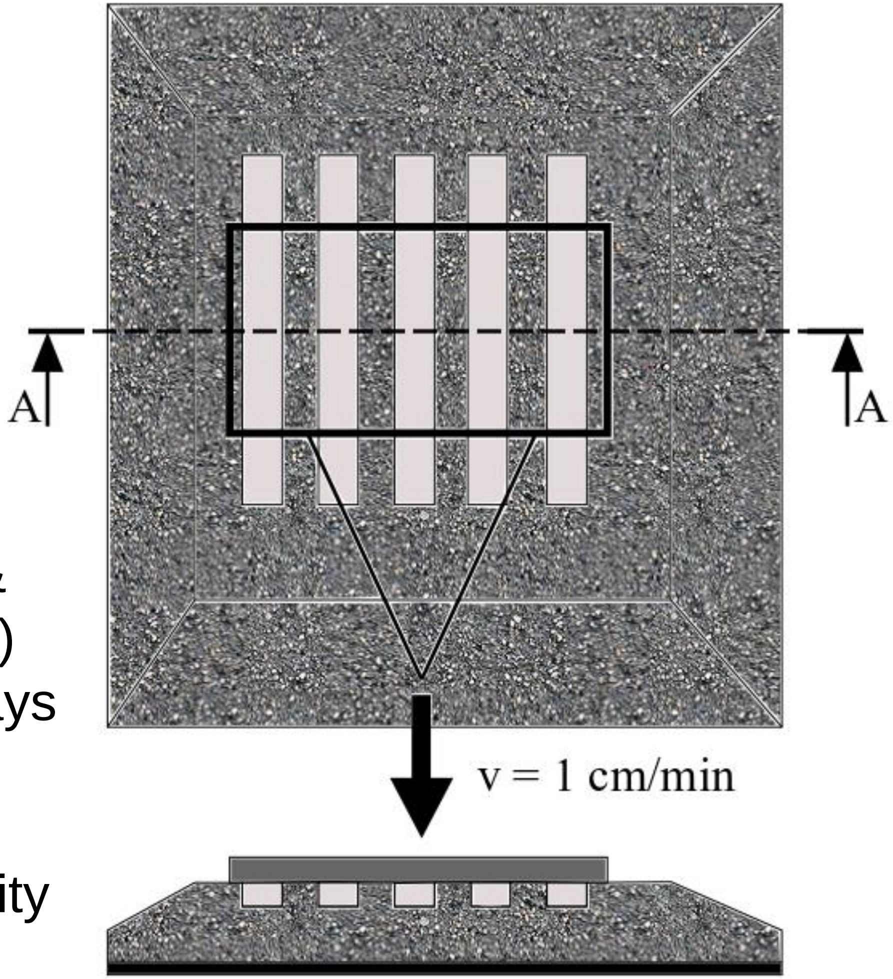
Rolling friction = 0.15



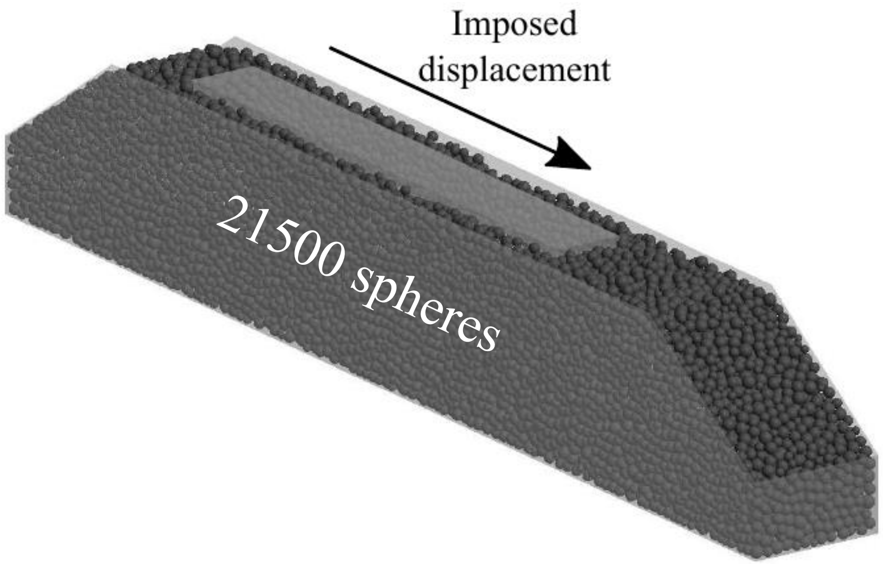
Rolling friction = 0.20

Irazábal, J., Salazar, F., & Oñate, E. (2017). Numerical modelling of granular materials with spherical discrete particles and the bounded rolling friction model. Application to railway ballast. Computers and Geotechnics, 85, 220-229.

Lateral resistance force test



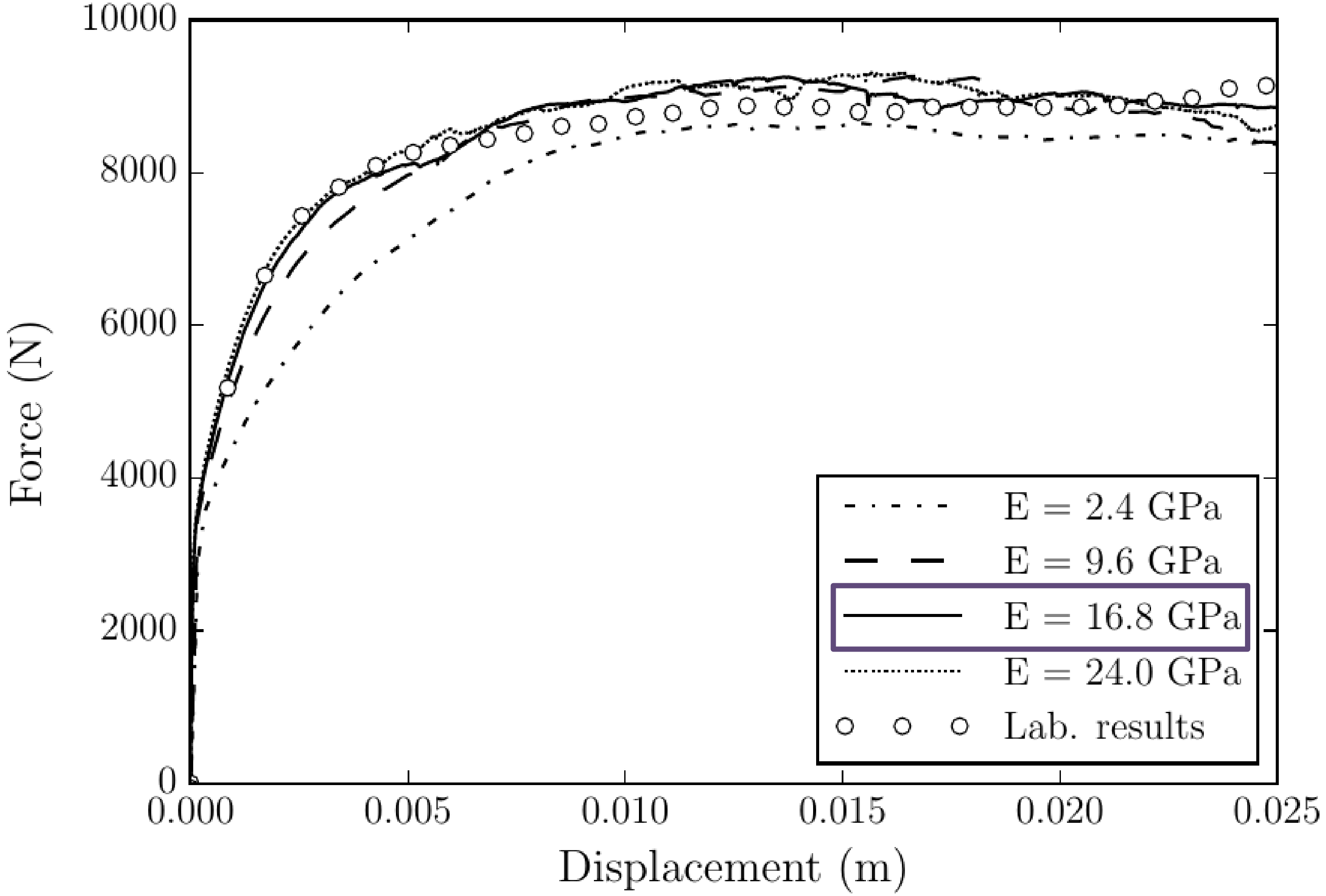
Zand, J. van't, & Moraal, J. (1997) Roads and Railways Research Laboratory Technical University of Delft



Ballast properties	
Density (kg/m^3)	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

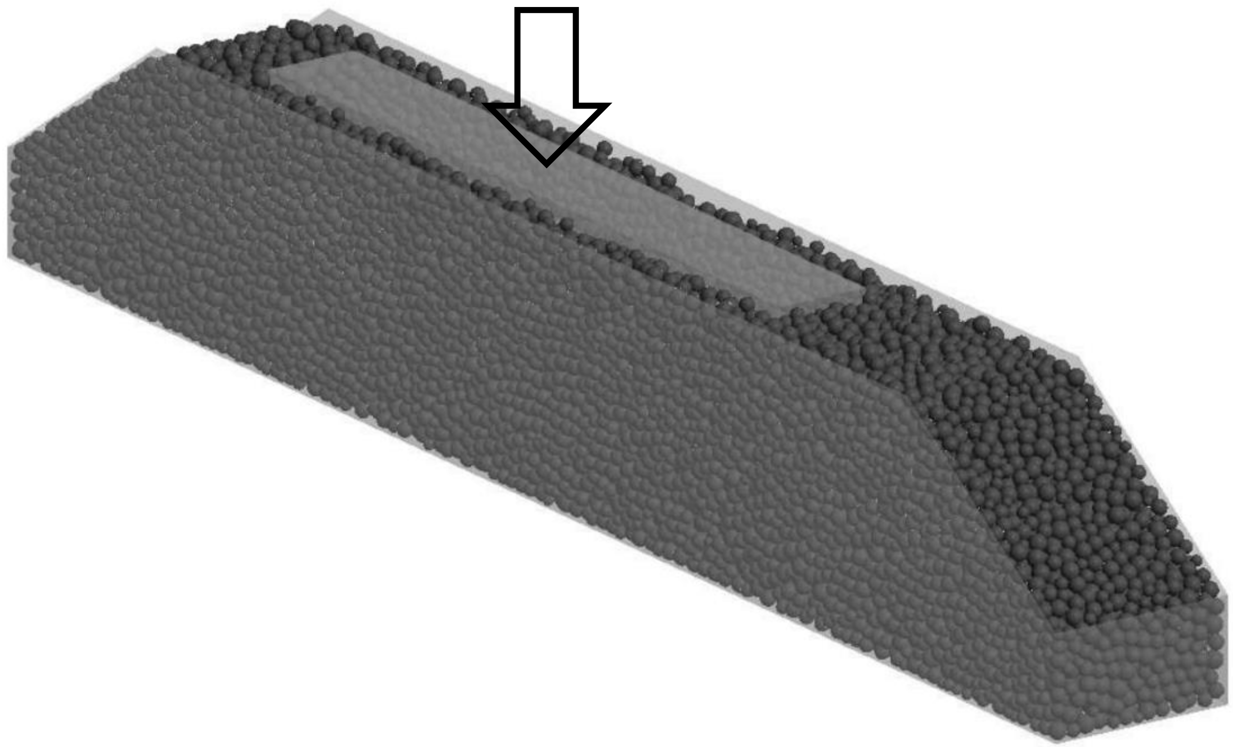
Lateral resistance force test

Irazábal, J., Salazar, F., & Oñate, E. (2017). Numerical modelling of granular materials with spherical discrete particles and the bounded rolling friction model. Application to railway ballast. Computers and Geotechnics, 85, 220-229.



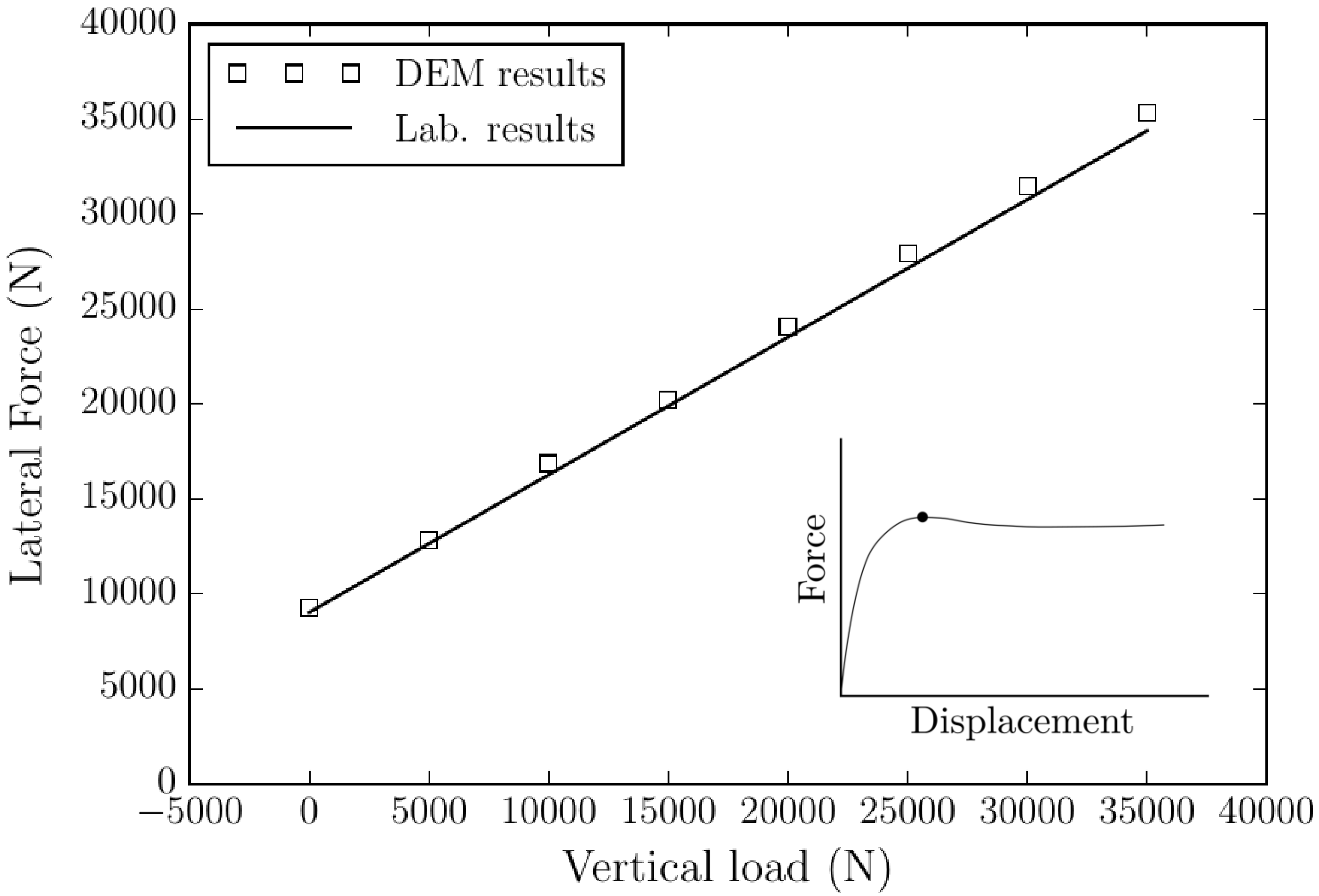
Lateral resistance force test

Vertical load
0 N
5000 N
10000 N
15000 N
20000 N
25000 N
30000 N
35000 N

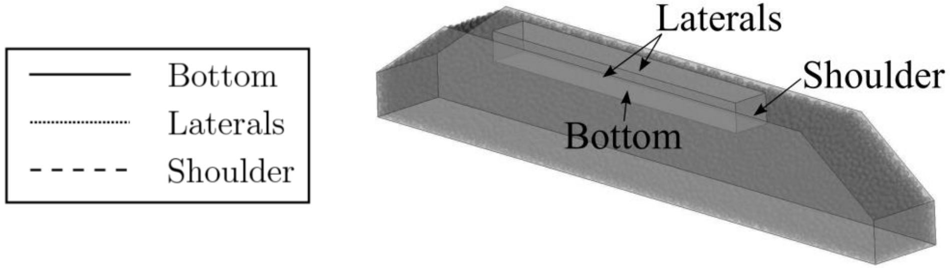


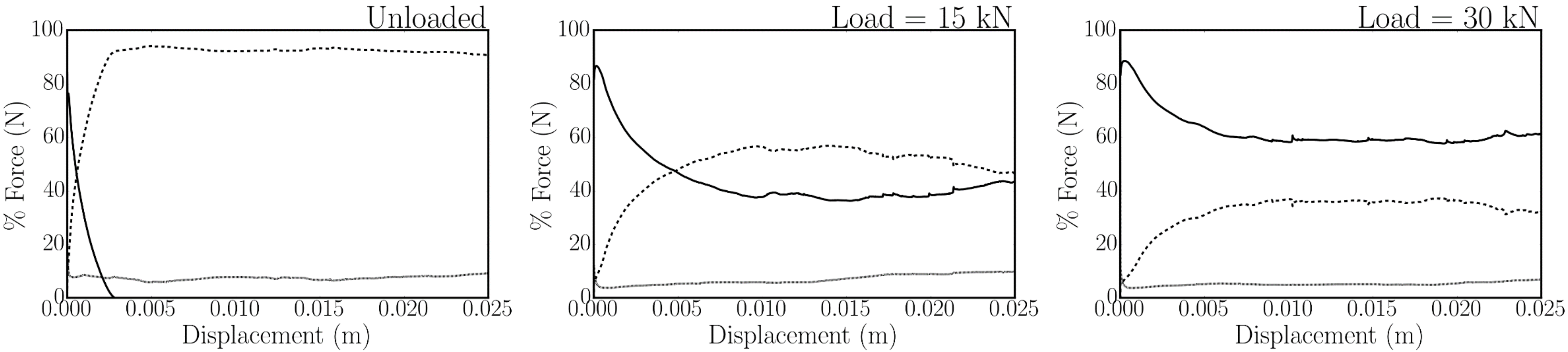
Lateral resistance force test

Irazábal J. Numerical analysis of railway ballast behaviour using the Discrete Element Method. PhD Thesis 2017.



Lateral resistance force test





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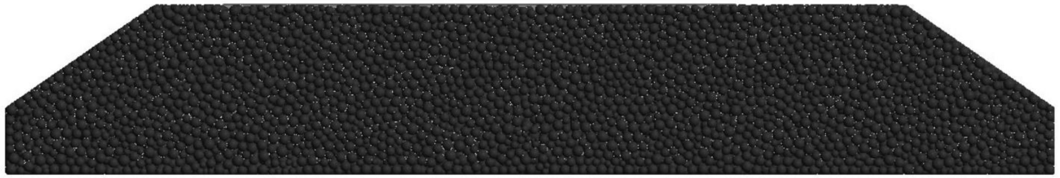
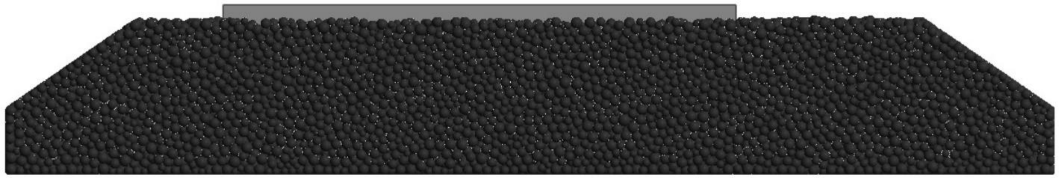
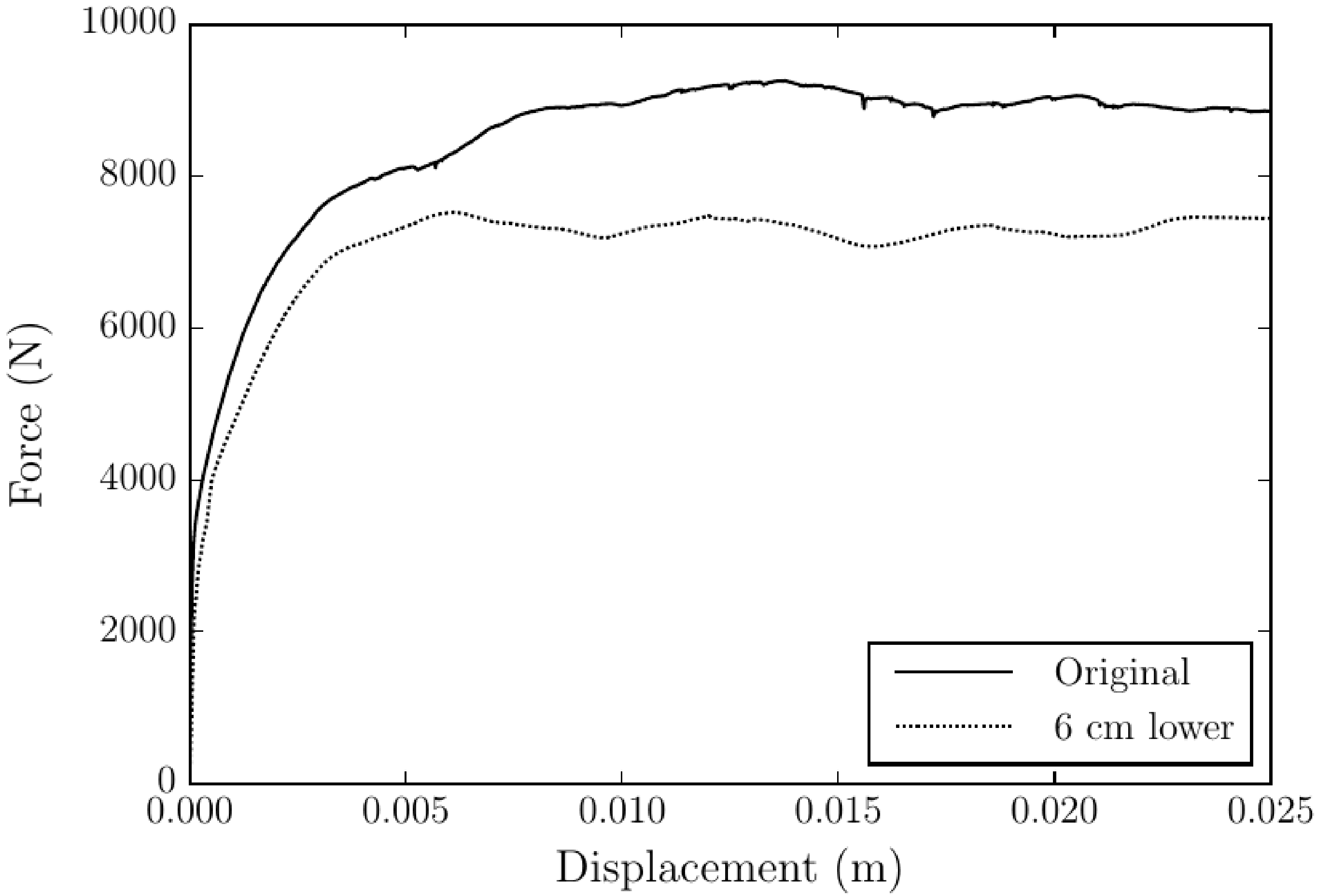
Lateral resistance force test



Original geometry



6 cm lower



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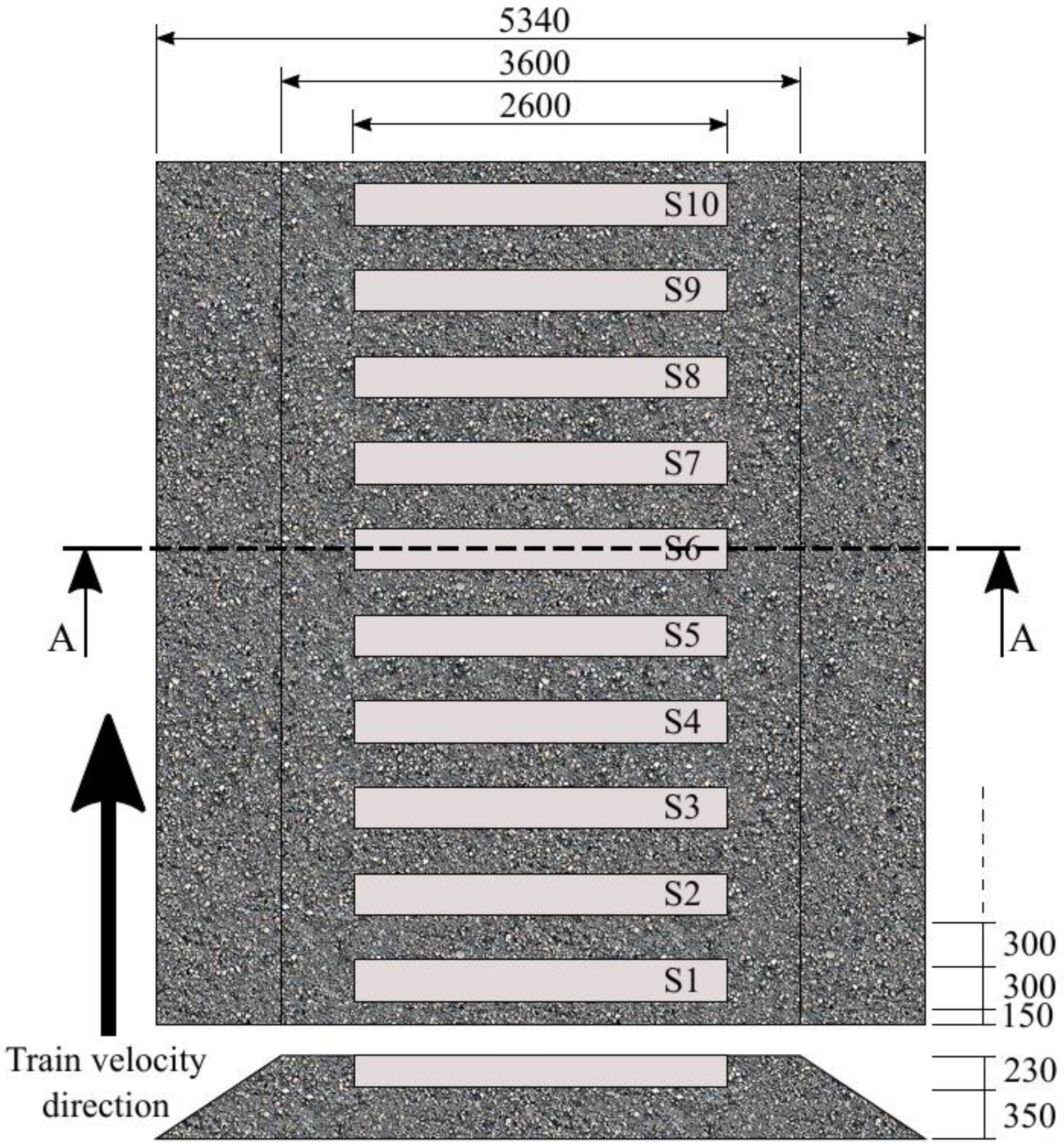
Full scale test



Full scale test

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

Q_s → load over the sleeper

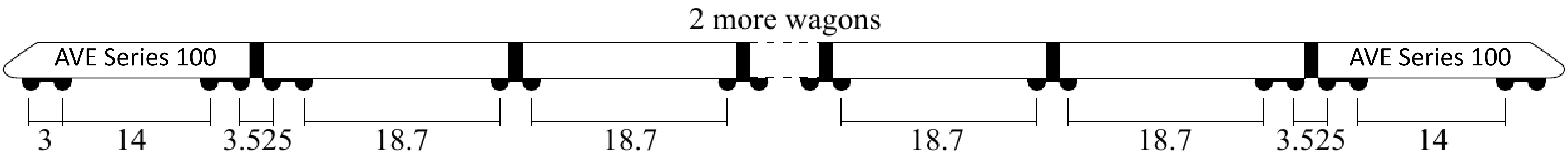
Q = 168732 N → axle load

K = 75 kN/mm → track stiffness

k_{eq} = 33.58 kN/mm → bearing stiffness

L = 0.881 m → elastic length

v = 300 km/h → velocity of the train



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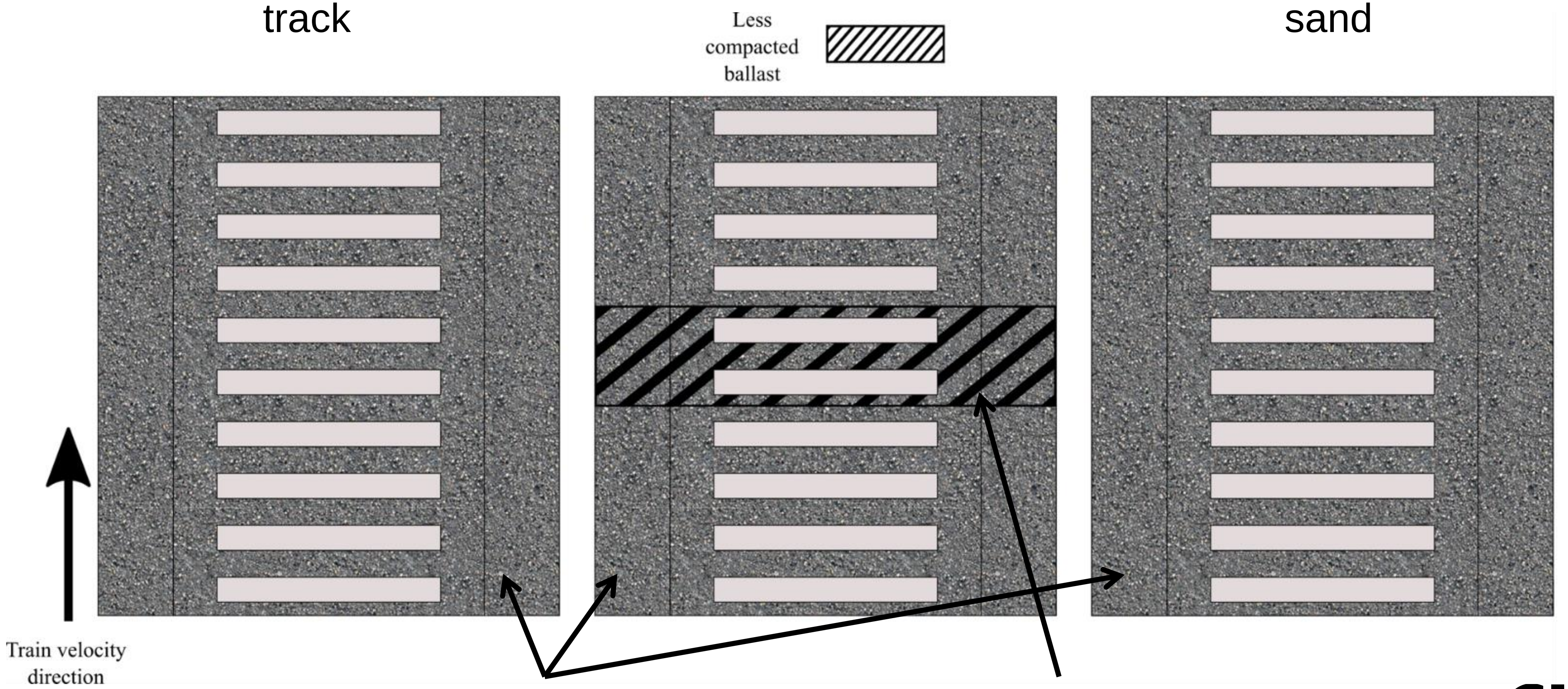
Full scale test

1) Conventional track

2) Bumpy track

3) Track fouled with sand

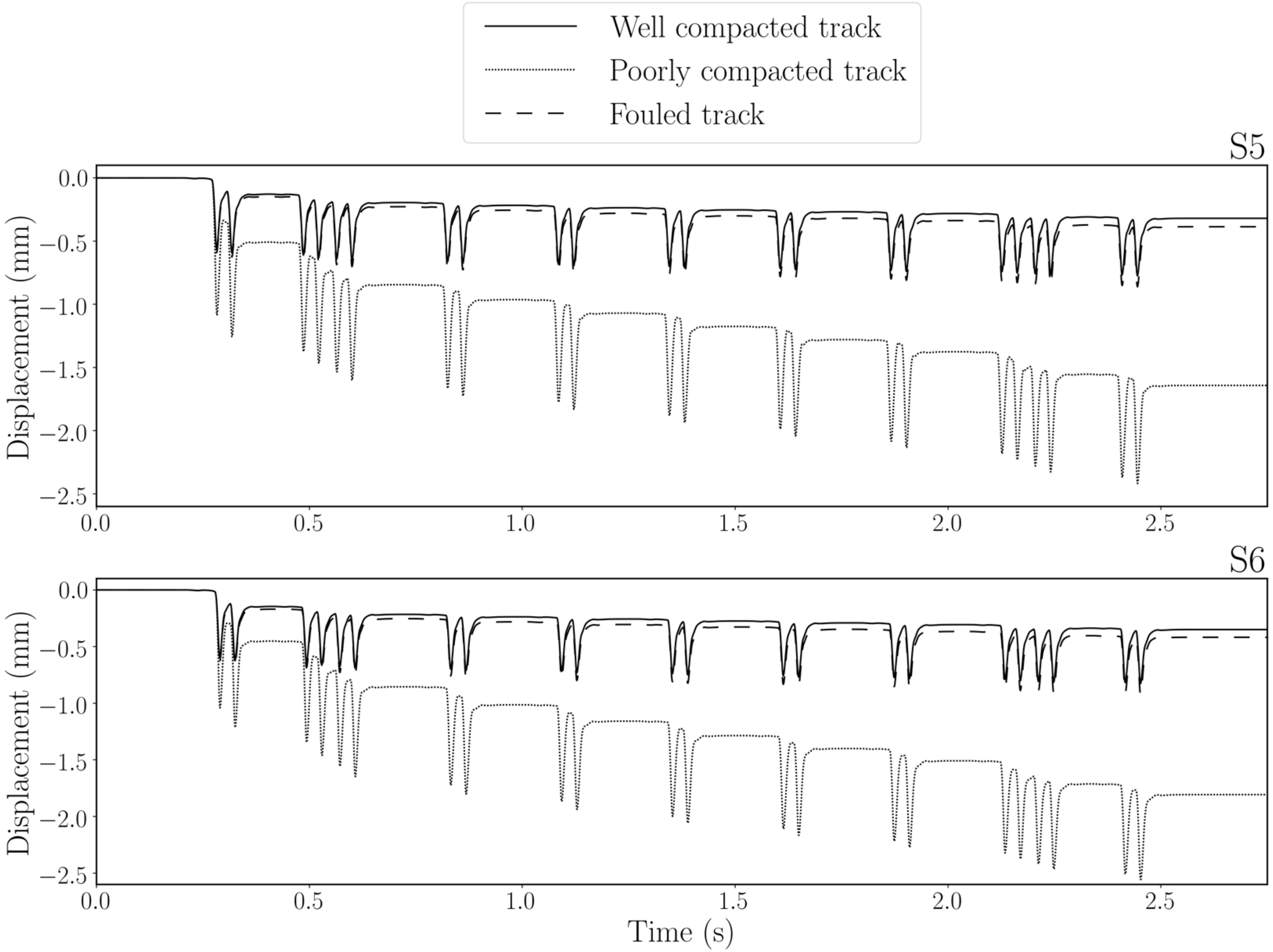


Porosity: 39.41%

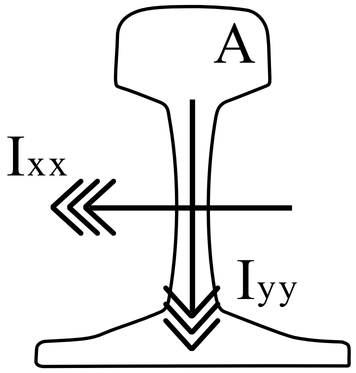
Porosity: 43,86%

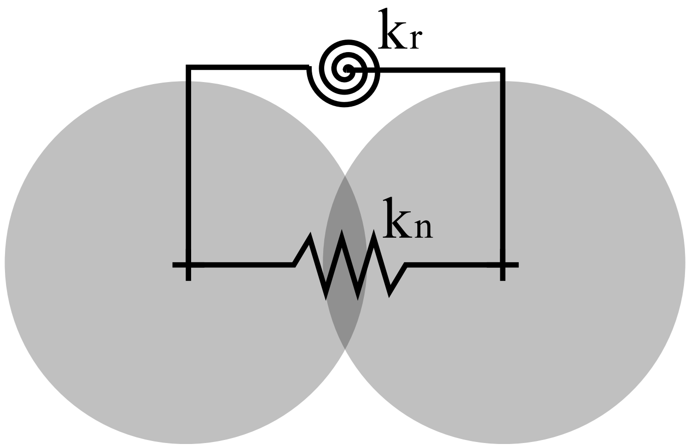
Full scale test – Ballast velocity

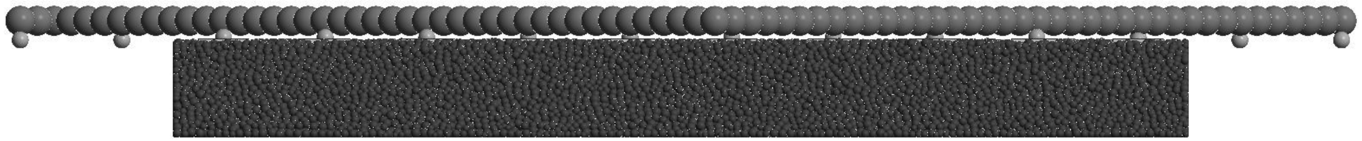
Full scale test – Sleepers vertical displacement

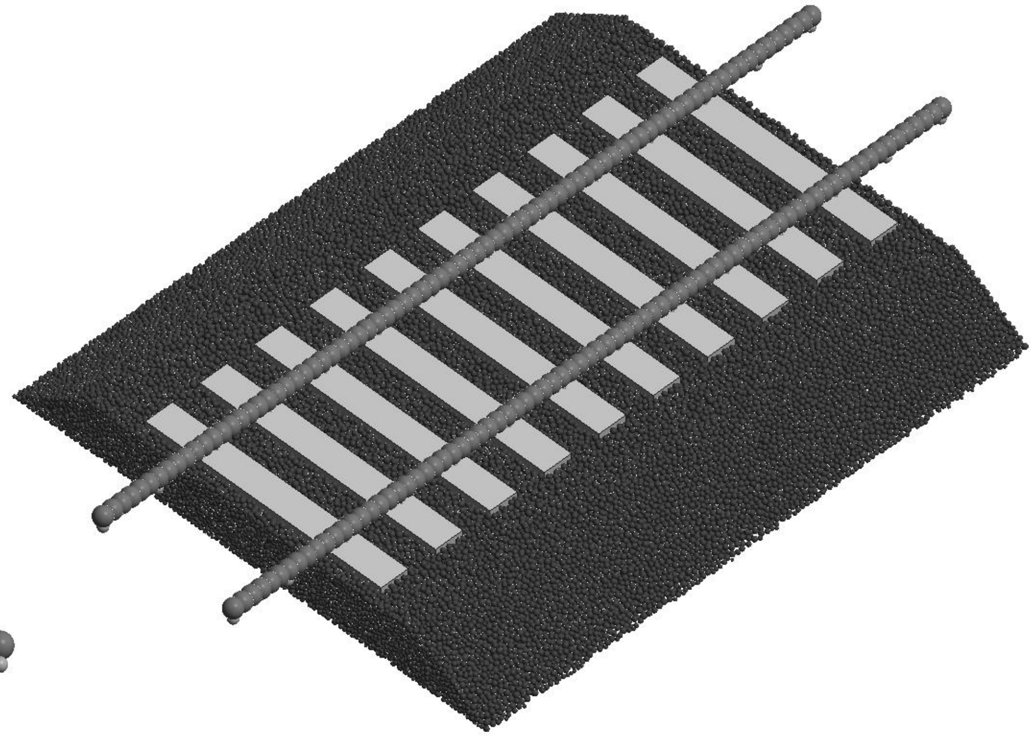


Full scale test with rails









Numerical representation of rails and bearing plates

Full scale test with rails

$Q = 168732$ N → axle load

$A = 77.45$ cm^2 → rail cross section

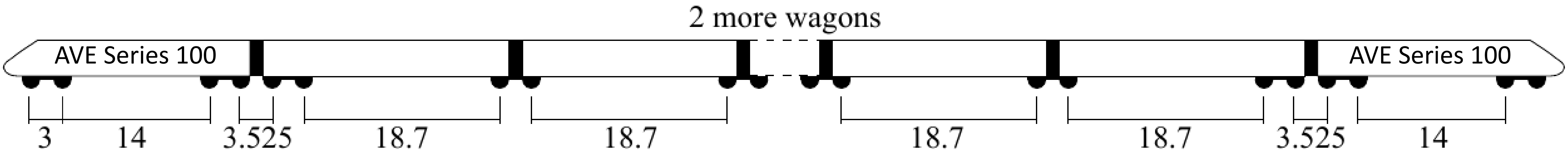
$I_{xx} = 3217$ cm^4 → moment of inertia horizontal axis

$I_{yy} = 524$ cm^4 → moment of inertia vertical axis

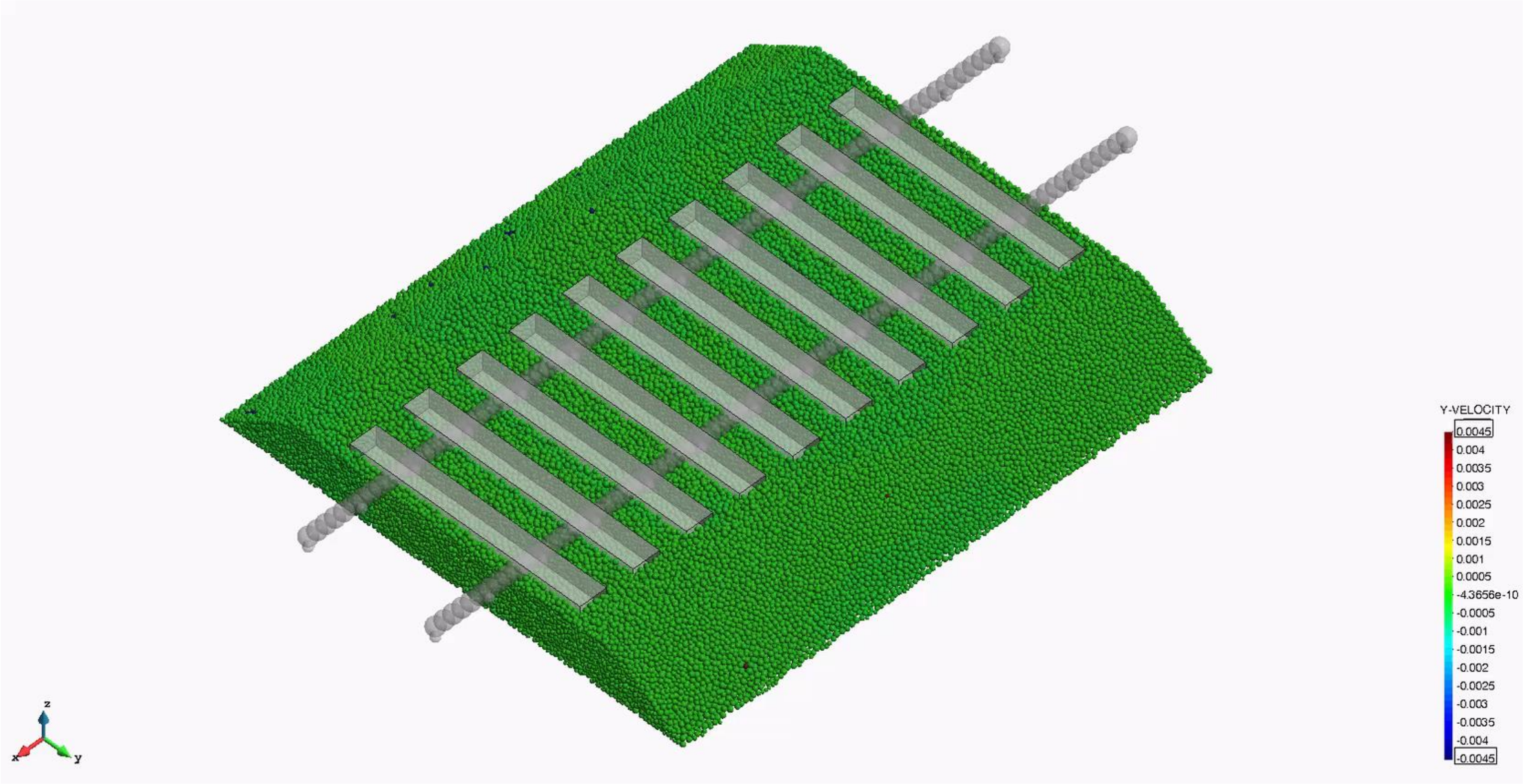
$k_{bq} = 30.75$ kN/mm → bearing plate stiffness

$v = 250$ km/h → velocity of the train

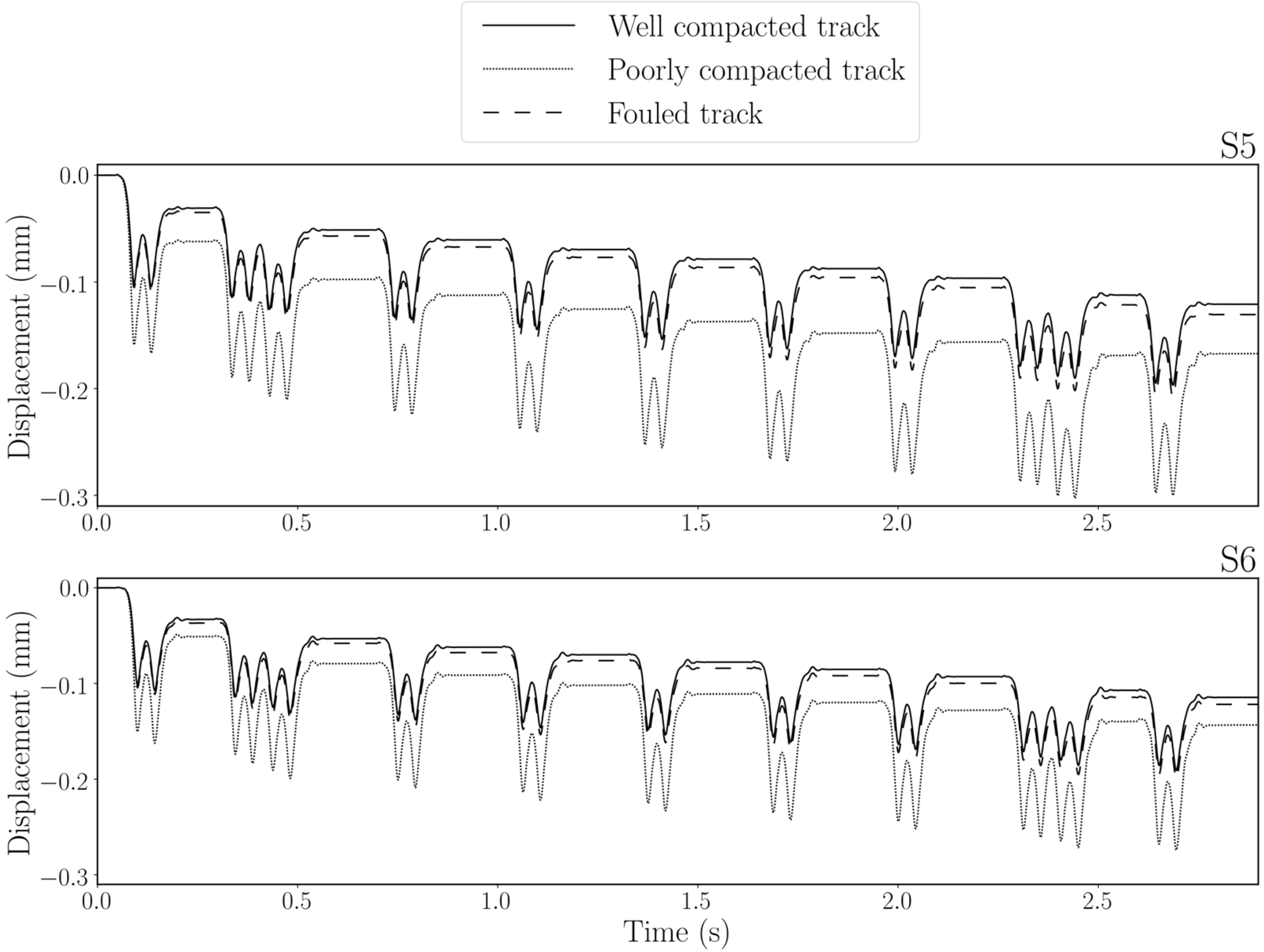
$R = 4000$ m → radius of the curve



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!