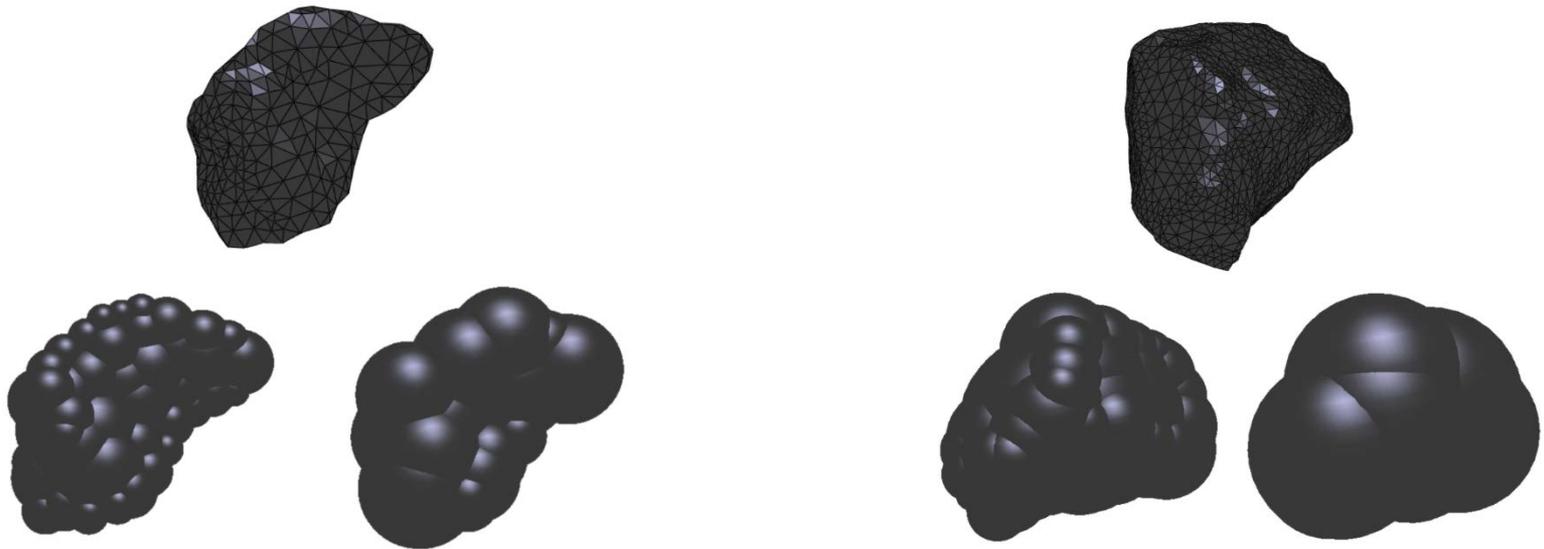


# Shape characterization of railway ballast stones for discrete element calculations

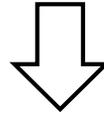


# Outline

1. Motivation
2. Ballast layer
3. Discrete Element Method (DEM)
4. Geometric representation of railway ballast
5. Railway ballast modelling within the DEM
6. Conclusions

# Motivation

Increasing interest all over the world in high-speed trains



Sometimes under unfavorable conditions



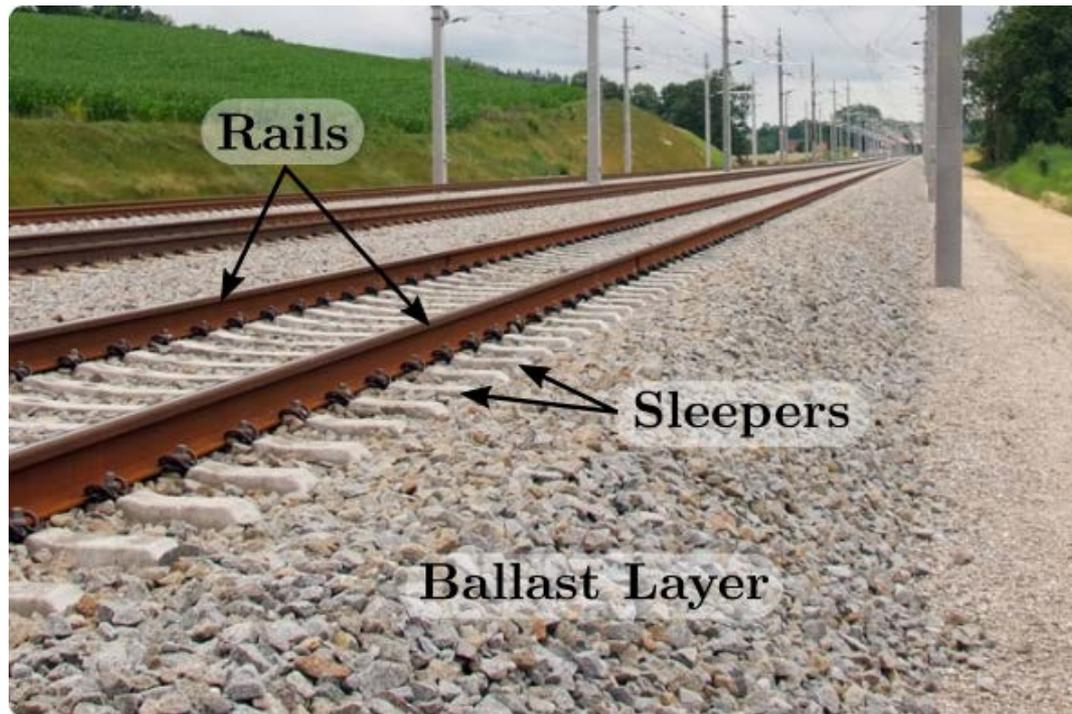
**BALAMED** (Jan. 2013 – Dec. 2015)

**MONICAB** (Jan. 2016 – Dec. 2018)

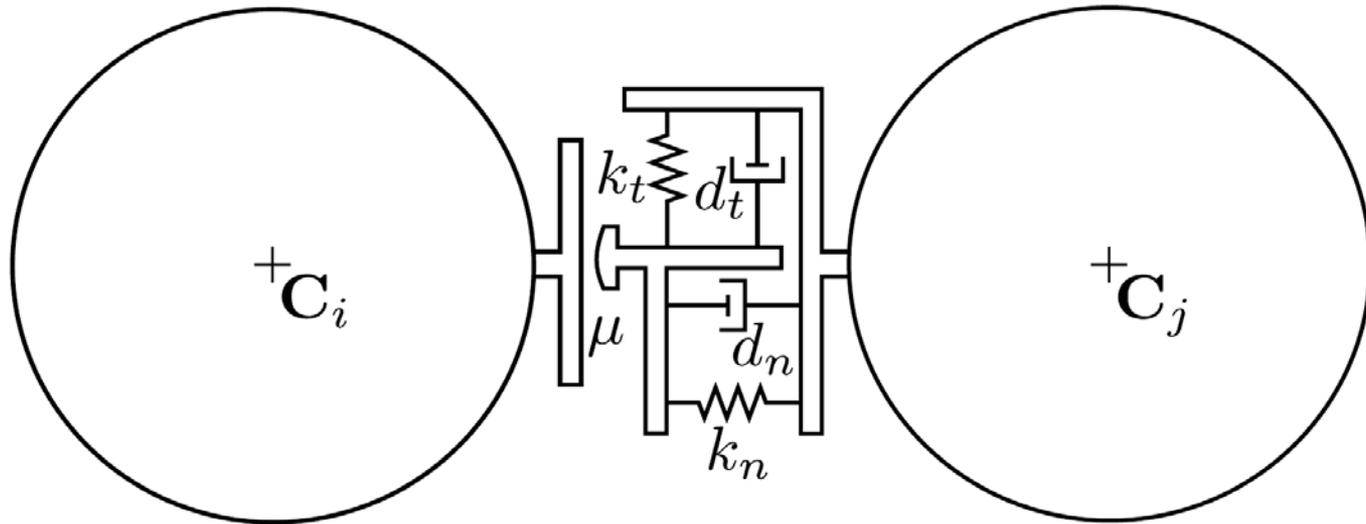


# Ballast layer

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



# Discrete Element Method (DEM)



Force balance

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

Torque balance

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

# Geometric representation

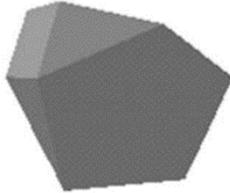
Spheres



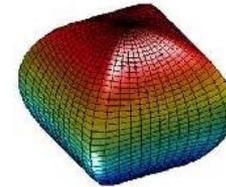
Clusters of spheres



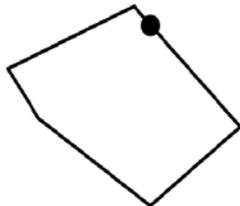
Polyhedra



Superquadrics



Spheropolyhedra



Potential particles



# Geometric representation requirements

- Low computational cost
- Efficient neighbour search and force evaluation
- Geometrical variety
- Allow concave particles

# Geometric representation comparison

	Spheres with RF	Sphere clusters	Squad.	Polyhed.	Sphero-Polyhed.	Potential Particles
Low comput. cost	✓	✗	✗	✗	✗	✗
Efficient	✓	✓	✗	✗	✓	✗
Geometrical variety	✗	✓	✓	✓	✓	✓
Concave particles	✗	✓	✗	✓*	✓*	✗

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. *Comput Geotech*, 85 220–229

# Geometric representation

Spheres



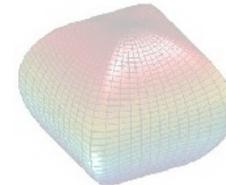
Clusters of spheres



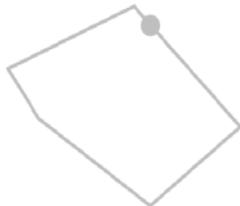
Polyhedra



Superquadrics



Spheropolyhedra



Potential particles



# Ballast properties

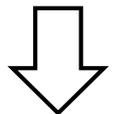
- Density
- Sample size distribution
- The inter-particle friction
- Particle-wall friction
- The initial void ratio
- Coefficient of restitution
- Particle shape
- Particle stiffness

Normally well-known

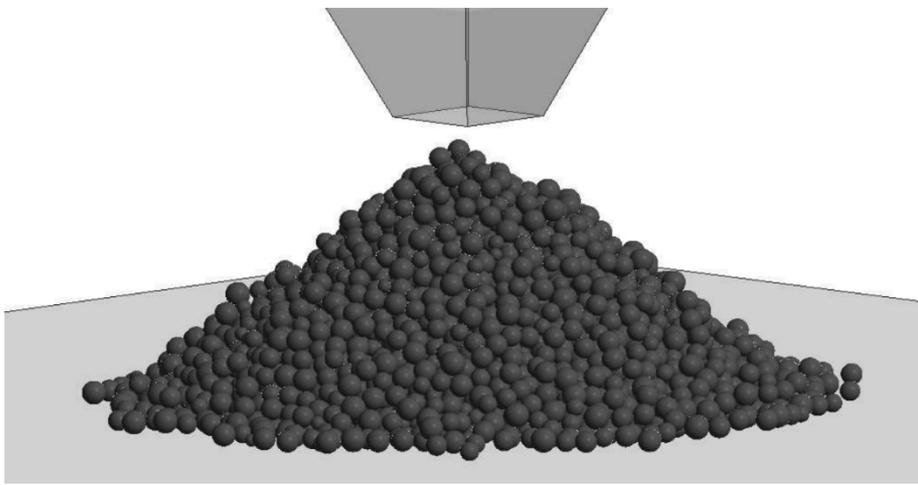
Some considerations  
to be taken into  
account

# Particle shape

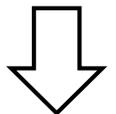
Spherical Particles



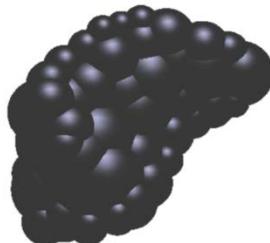
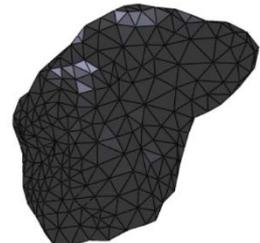
Rolling Friction



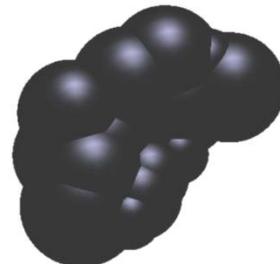
Clusters of spheres



Accuracy



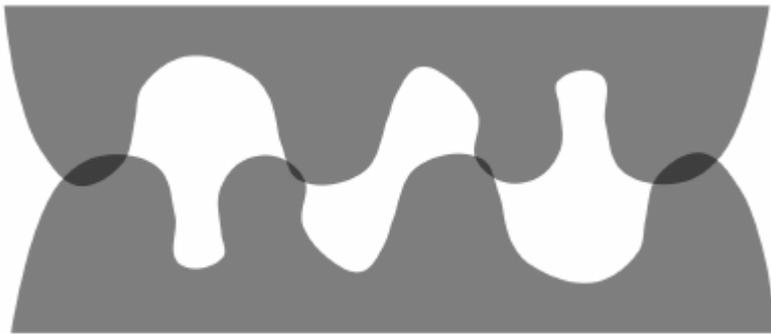
45 spheres



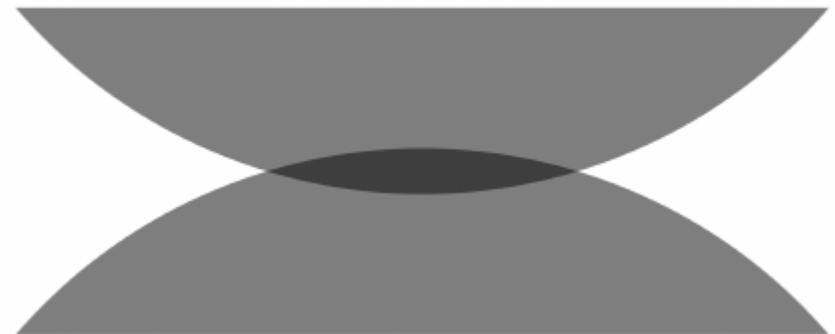
16 spheres

# Particle stiffness

Hertzian contact model: contact stiffness depends on the contact volume

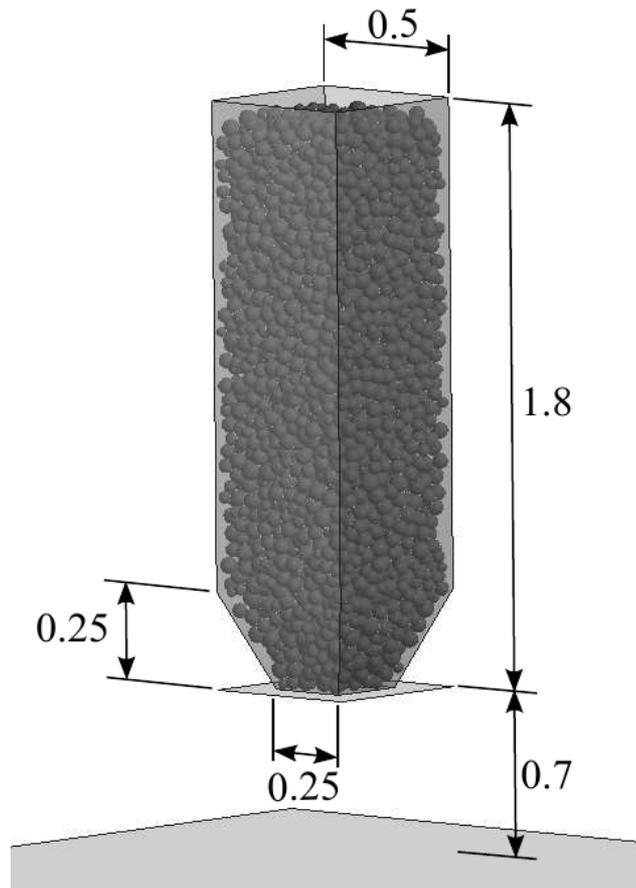


Real contact geometry



Numerical contact geometry

# Repose angle test with spheres



## Material properties

Density ( $\text{kg/m}^3$ )	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

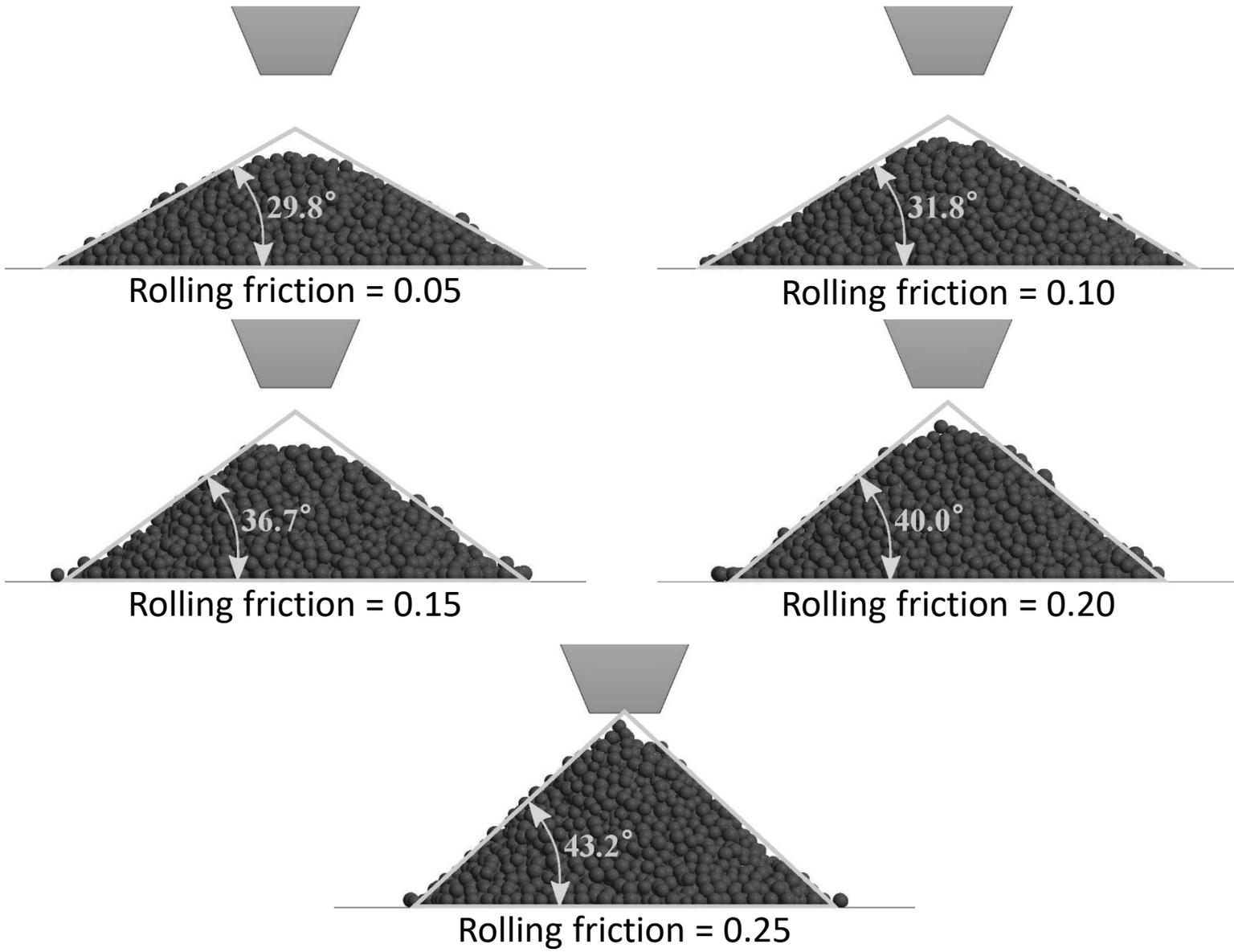
Irazábal, J., Salazar, F., & Oñate, E. (2017) Numerical modelling of granular materials with spherical discrete particles and the bounded rolling friction model. Application to railway ballast. *Comput Geotech*, 85 220–229

# Reuse angle test with spheres

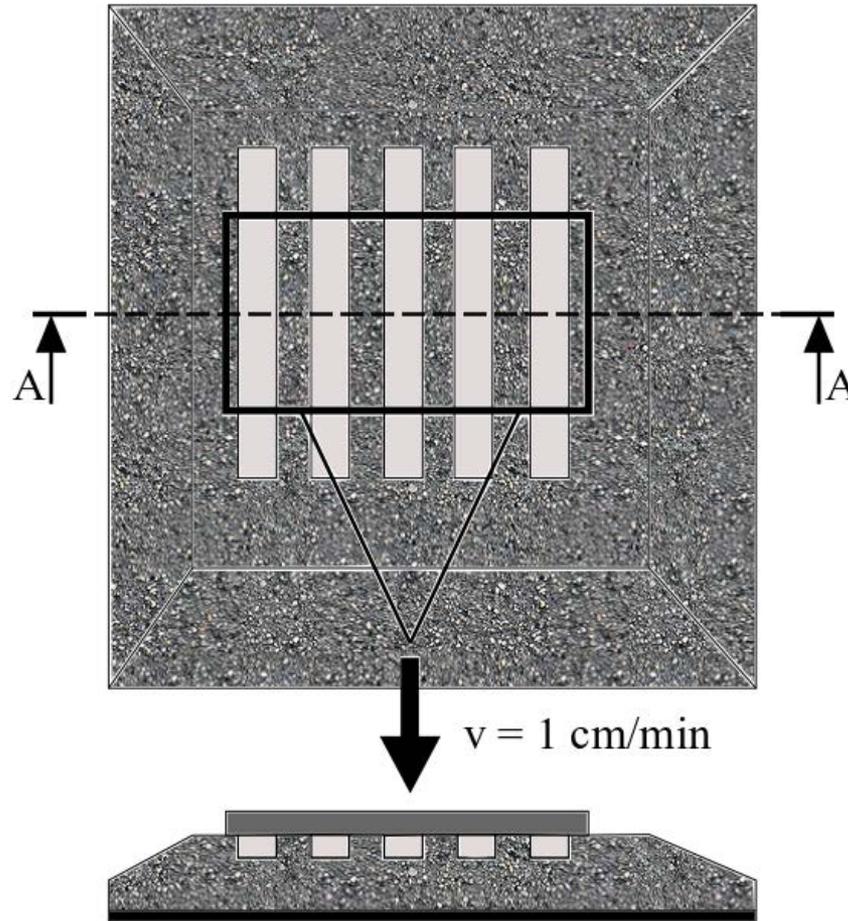


Irazábal, J., Salazar, F., & Oñate, E. (2017) Numerical modelling of granular materials with spherical discrete particles and the bounded rolling friction model. Application to railway ballast. *Comput Geotech*, 85 220–229

# Shape characterization of railway ballast stones for discrete element calculations

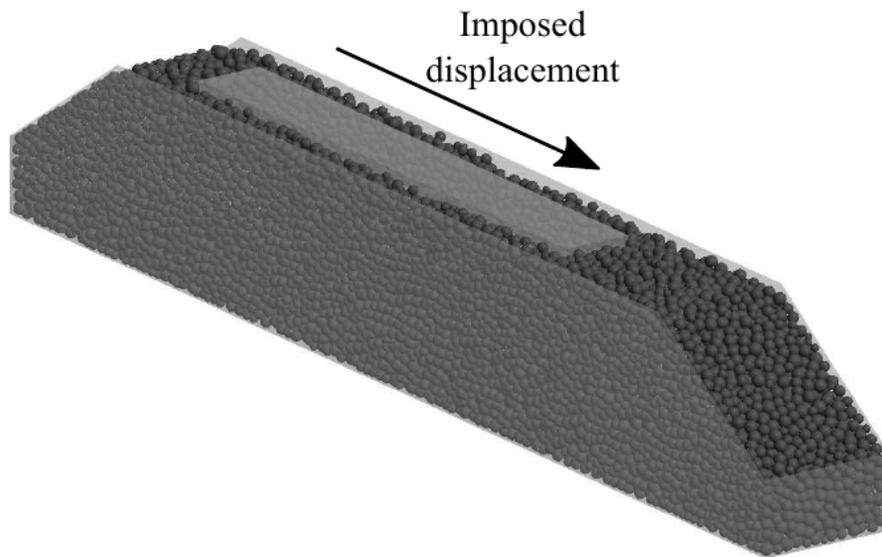


# Lateral resistance force test



Zand and Moraal (1997) Roads and Railways Research Laboratory Technical University of Delft

# Lateral resistance force test



## Ballast properties

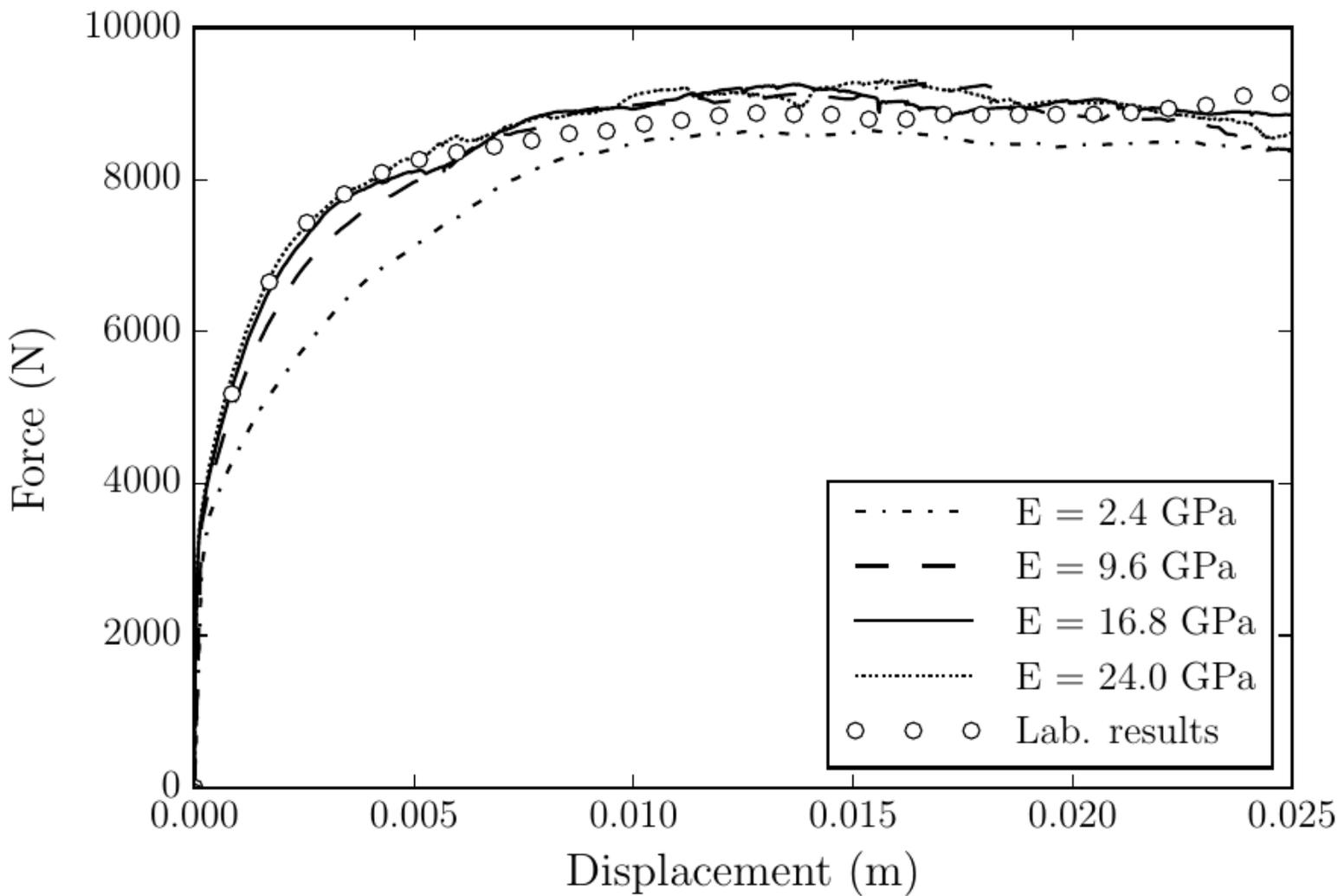
Density ( $kg/m^3$ )	2700
Poisson ratio	0.2
Young modulus (GPa)	2.4/9.6/16.8/24.0
Friction coefficient	0.6
Restitution coefficient	0.0
Rolling friction coefficient	0.2

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. *Comput Geotech*, 85 220–229

# Lateral resistance force test



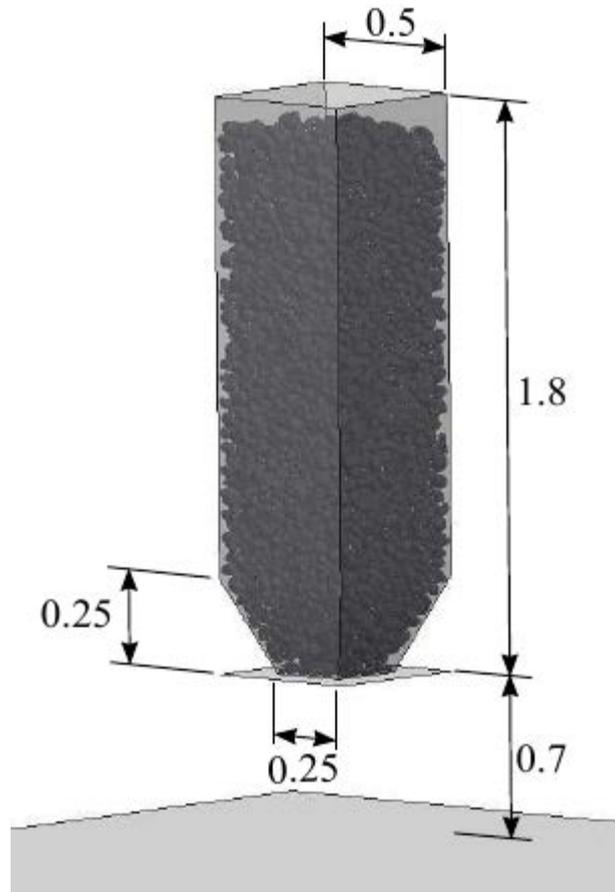
Irazábal, J., Salazar, F., & Oñate, E. (2017) Numerical modelling of granular materials with spherical discrete particles and the bounded rolling friction model. Application to railway ballast. *Comput Geotech*, 85 220–229



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. *Comput Geotech*, 85 220–229



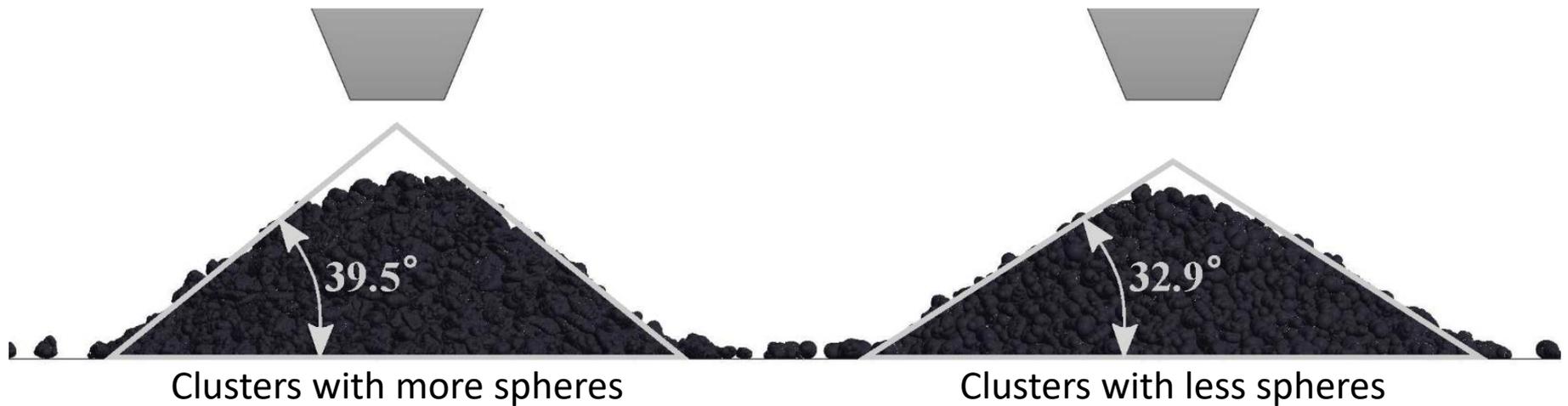
# Repose angle test with clusters



## Material properties

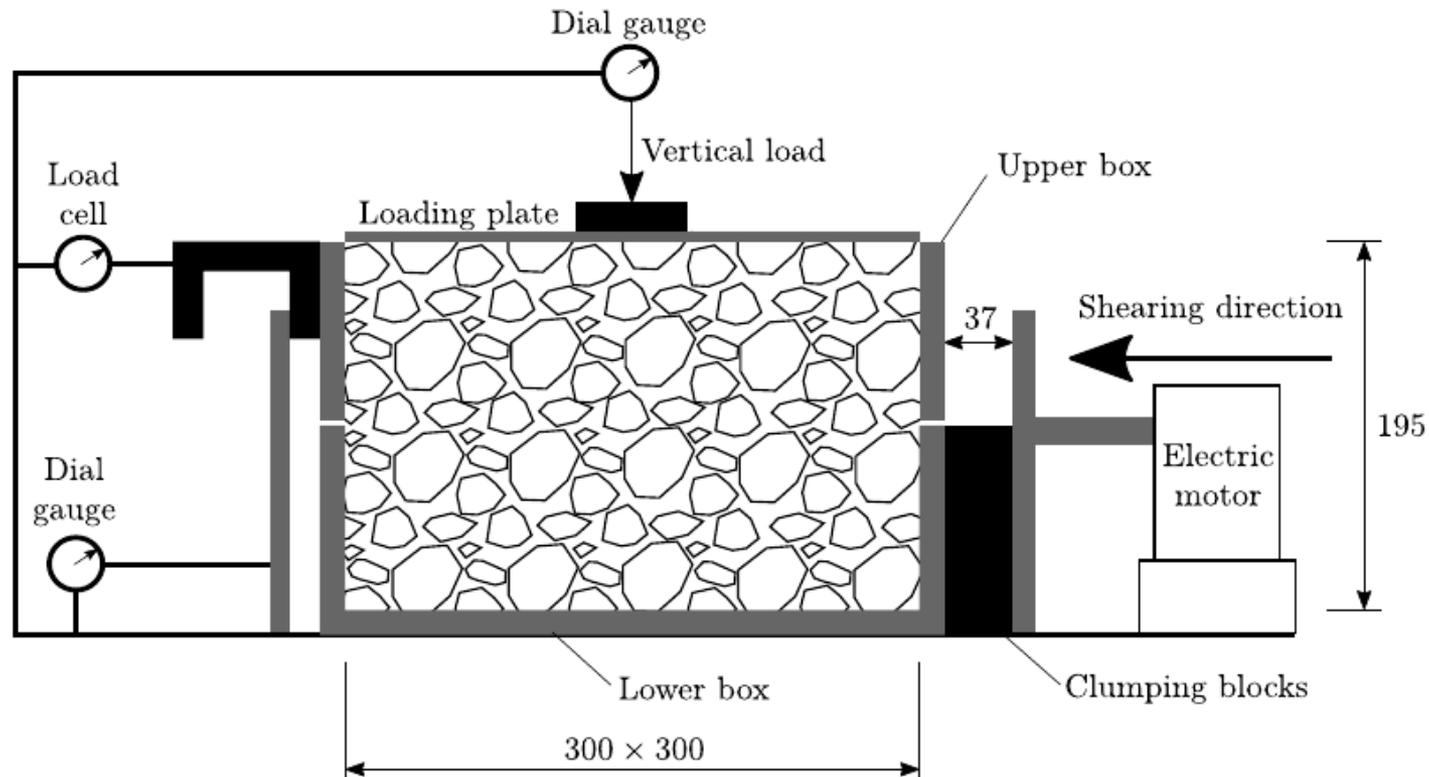
Density ( $\text{kg/m}^3$ )	2700
Poisson ratio	0.2
Young modulus (GPa)	2.4
Friction coefficient ballast	0.6
Friction coefficient ballast-floor	0.6
Restitution coefficient	0.0

Clusters with different number of spheres



# Large-scale direct shear test

High dependence in distribution of contacts  $\rightarrow$  Clusters



Indraratna, B., Ngo, N. T., & Rujikiatkamjorn, C. (2011) Behavior of geogrid-reinforced ballast under various levels of fouling, *Geotextiles and Geomembranes*, 29(3) 313–322.

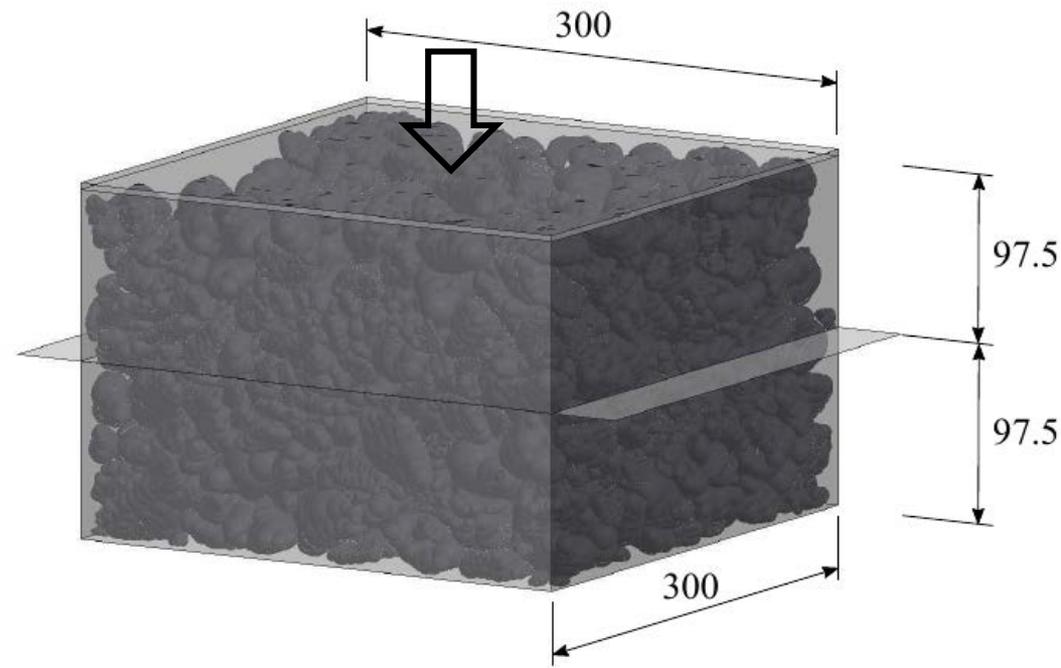
# Large-scale direct shear test

## Ballast properties

Density ( $kg/m^3$ )	2700
Poisson ratio	0.2
Young modulus (GPa)	0.24
Friction coefficient	0.6
Restitution coefficient	0.0

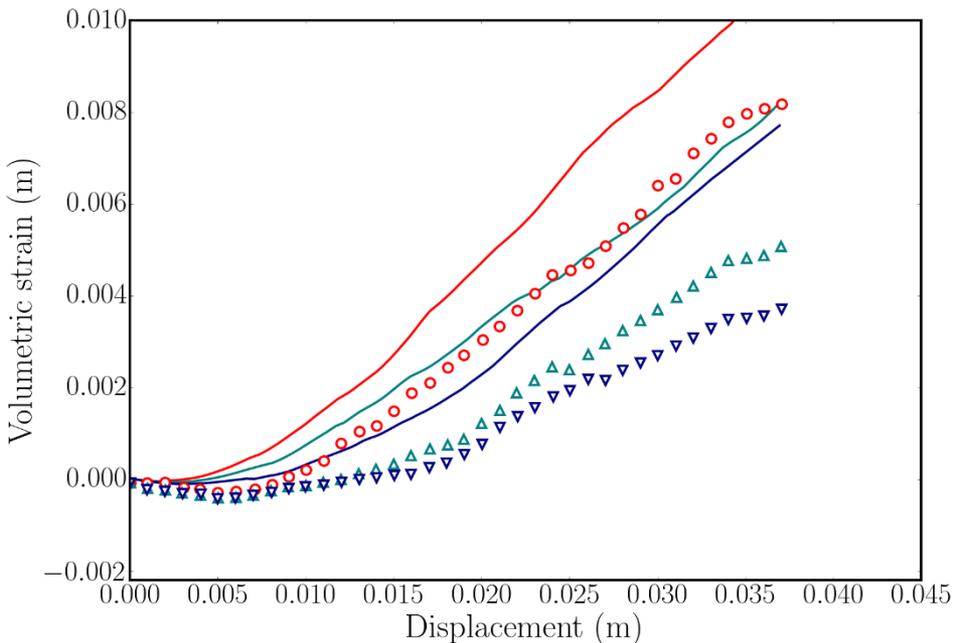
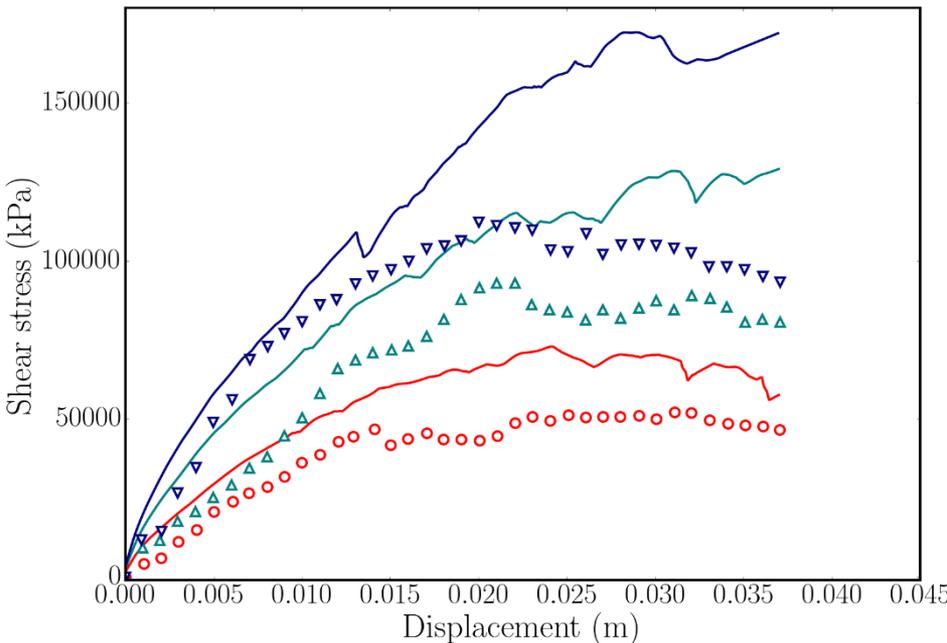
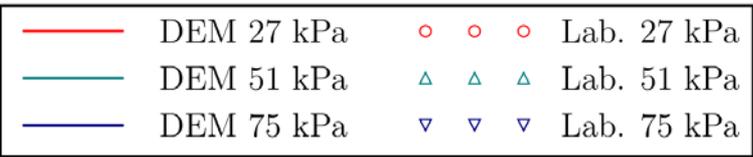
## Walls contact properties

Poisson ratio	0.2
Young modulus (GPa)	0.24
Friction coefficient	0.6
Restitution coefficient	0.0

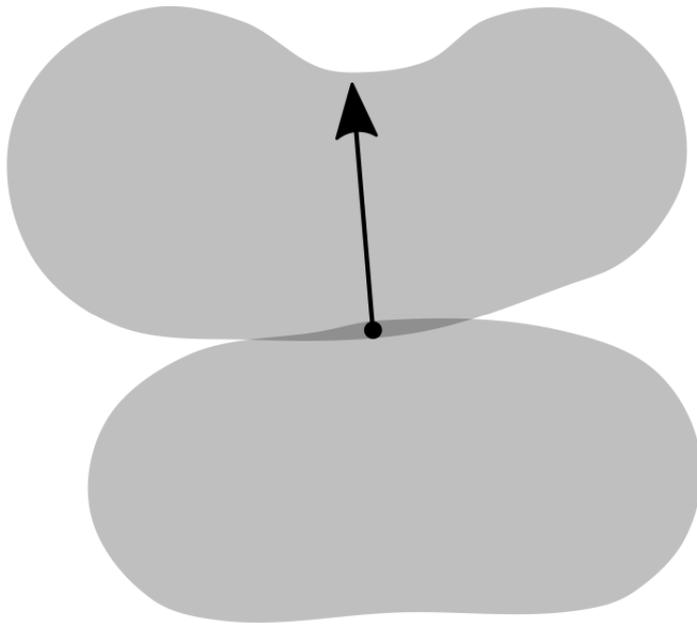




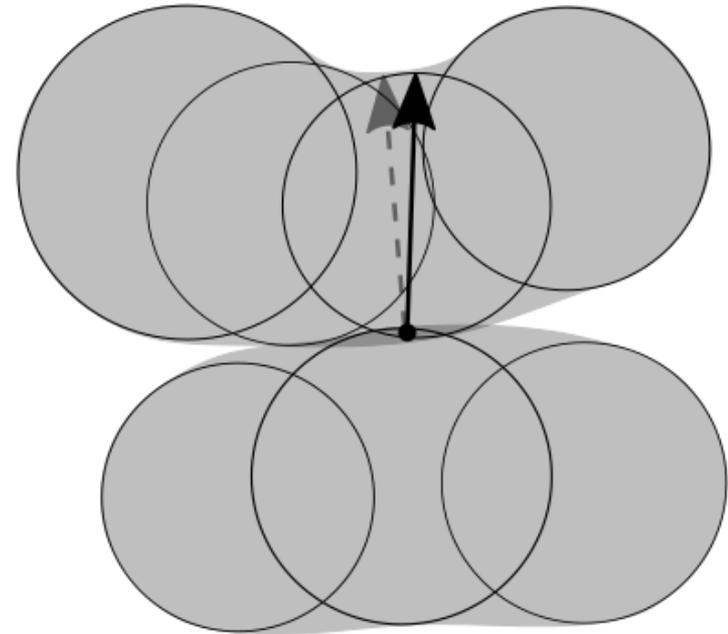
# Large-scale direct shear test



# Geometric friction



Real Particles



Clusters of spheres

# Geometric friction

Alternatives:

- Decrease the inter-particle friction coefficient globally
  - + Simple
  - One value for each compression stress

# Geometric friction

## Alternatives:

- Decrease the inter-particle friction coefficient globally
  - + Simple
  - One value for each compression stress
- Make the inter-particle friction coefficient dependent on the contact stress
  - + Non-dimensional
  - + Works for different compression stresses
  - Needs two new parameters to be defined

Harkness, J., Zervos, A., Pen, L. L., Aingaran, S., & Powrie, W. (2016) Discrete element simulation of railway ballast: modelling cell pressure effects in triaxial tests. *Granular Matter*, 18 (3) 65.

# Stress-dependent friction contact model

New parameters: critical maximum stress ( $\sigma_{cmax}$ ) and adimensional parameter  $\gamma$

# Stress-dependent friction contact model

New parameters: critical maximum stress ( $\sigma_{cmax}$ ) and adimensional parameter  $\gamma$

Stress in a Hertzian contact: 
$$\sigma_0 = \frac{3F_n}{2\pi R\delta}$$

# Stress-dependent friction contact model

New parameters: critical maximum stress ( $\sigma_{cmax}$ ) and adimensional parameter  $\gamma$

Stress in a Hertzian contact:  $\sigma_0 = \frac{3F_n}{2\pi R\delta}$

Critical contact force:  $F_{n,c} = \frac{2}{3}\pi R\delta\sigma_{cmax}$

# Stress-dependent friction contact model

New parameters: critical maximum stress ( $\sigma_{cmax}$ ) and adimensional parameter  $\gamma$

Stress in a Hertzian contact:  $\sigma_0 = \frac{3F_n}{2\pi R\delta}$

Critical contact force:  $F_{n,c} = \frac{2}{3}\pi R\delta\sigma_{cmax}$

Condition: 
$$\left\{ \begin{array}{l} \text{if } F_n > F_{n,c} \rightarrow \mu = \mu_0 \left( \frac{F_n}{F_{n,c}} \right)^\gamma \\ \text{if } F_n \leq F_{n,c} \rightarrow \mu = \mu_0 \end{array} \right.$$

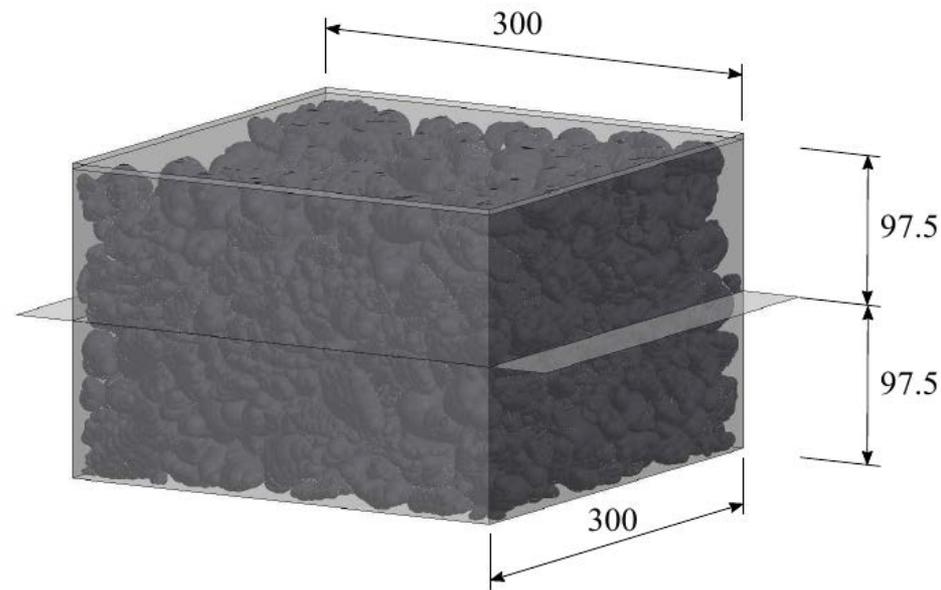
# Large-scale direct shear test

## Ballast properties

Density ( $kg/m^3$ )	2700
Poisson ratio	0.2
Young modulus (GPa)	0.24
Friction coefficient	0.6
Restitution coefficient	0.0
Critical contact stress (MPa)	5.17
$\gamma$ parameter	-0.05/ -0.10/ -0.15

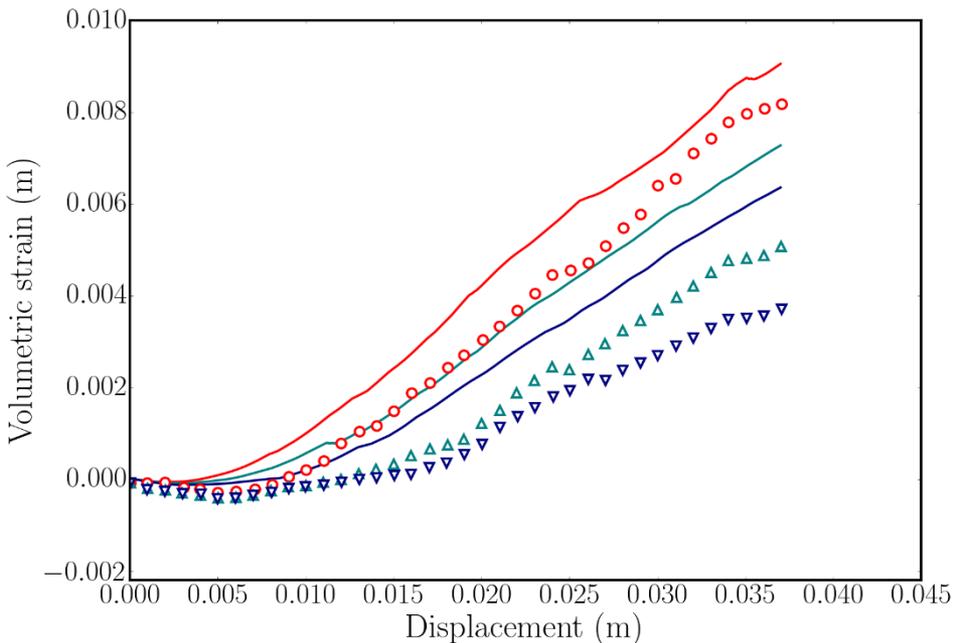
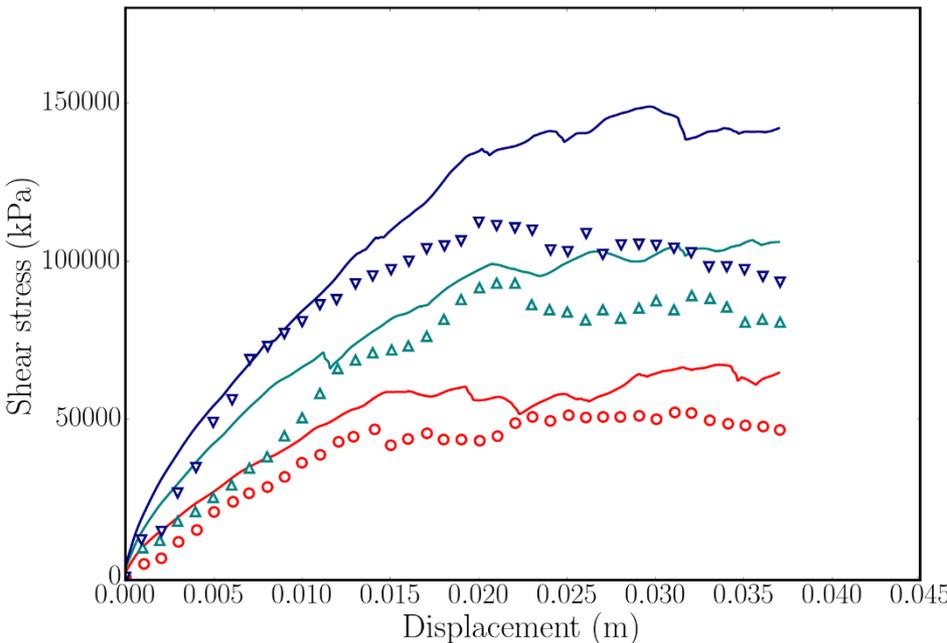
## Walls contact properties

Poisson ratio	0.2
Young modulus (GPa)	0.24
Friction coefficient	0.6
Restitution coefficient	0.0



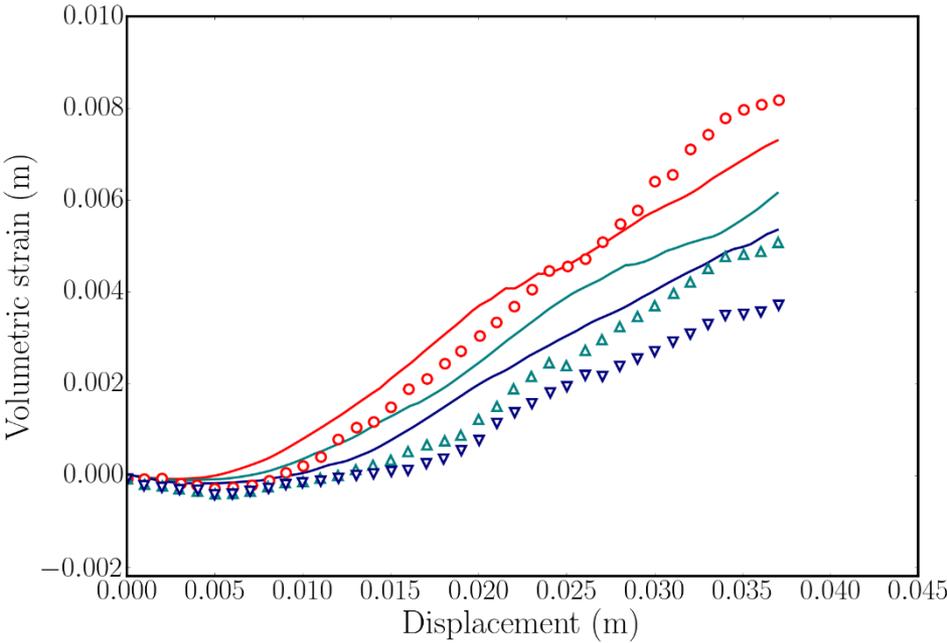
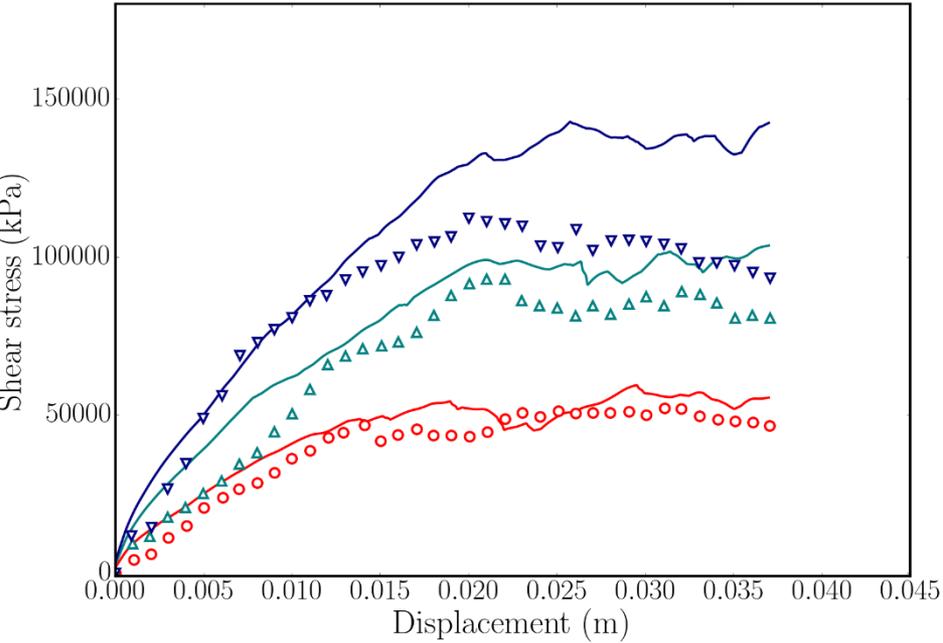
# Large-scale direct shear test: $\gamma = -0.05$

—	DEM 27 kPa	○ ○ ○	Lab. 27 kPa
—	DEM 51 kPa	△ △ △	Lab. 51 kPa
—	DEM 75 kPa	▽ ▽ ▽	Lab. 75 kPa

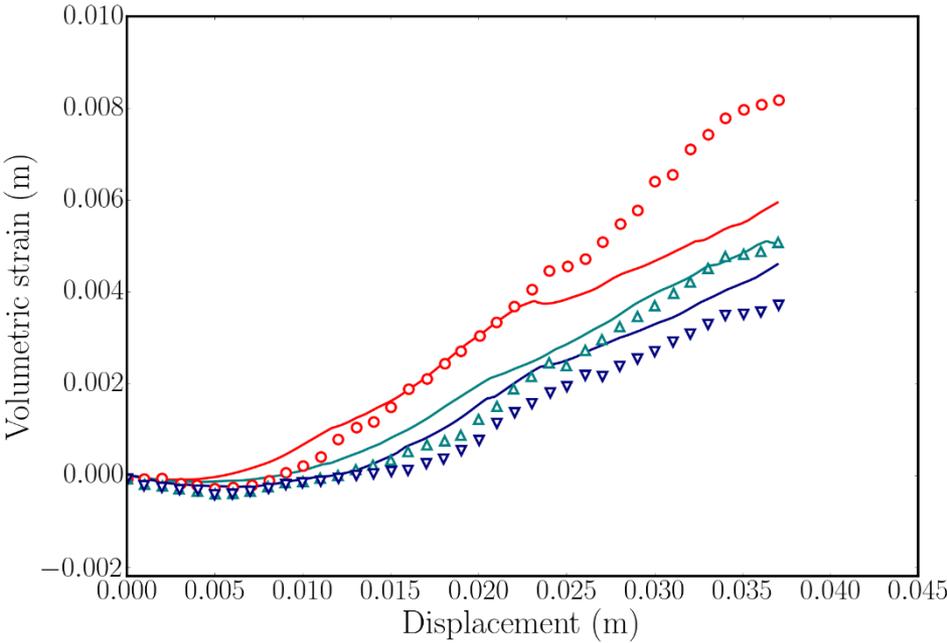
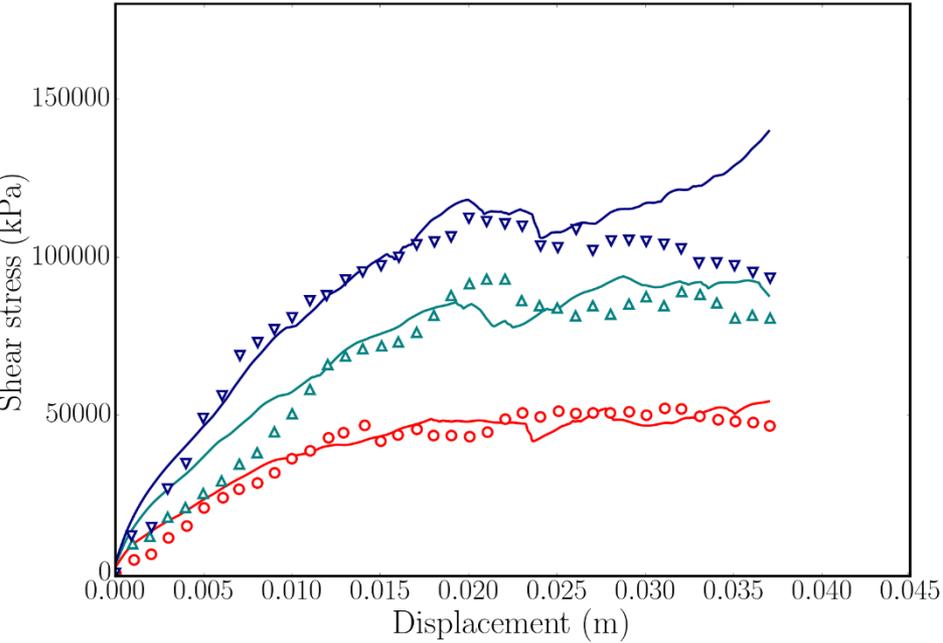
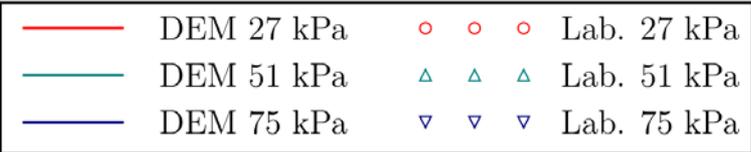


# Large-scale direct shear test: $\gamma = -0.10$

—	DEM 27 kPa	○ ○ ○	Lab. 27 kPa
—	DEM 51 kPa	△ △ △	Lab. 51 kPa
—	DEM 75 kPa	▽ ▽ ▽	Lab. 75 kPa



# Large-scale direct shear test: $\gamma = -0.15$



# Conclusions

- The angle of repose test allows us to characterize the shape of the particles
- To characterize the contact mechanism, stresses and deformations should be measured
- For tests with a big amount of material the calculations using spheres with rolling friction provides good results at a low computational cost
- Clusters of spheres should be used in calculations where the contacts distribution is important
- There is uncertainty in the assignment of properties even if the geometry of the DE is accurate

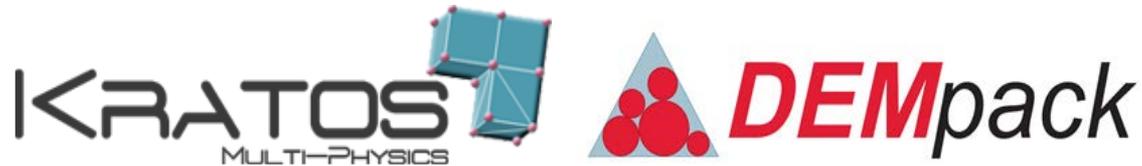


# ***PARTICLES 2017***

*26 - 28 September 2017 Hannover, Germany*

*V International Conference on Particle-Based Methods*

# **Thank you for your attention**



<http://www.cimne.com/dem/>  
[jirazabal@cimne.upc.edu](mailto:jirazabal@cimne.upc.edu)