



Incorporating surface roughness into DEM models of crushable soils

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OUTLINE

1. Introduction
2. Model description of rough crushable contact
3. Effect of contact roughness on single particle breakage
4. Effect of contact roughness on sand high stress behavior
5. Conclusions

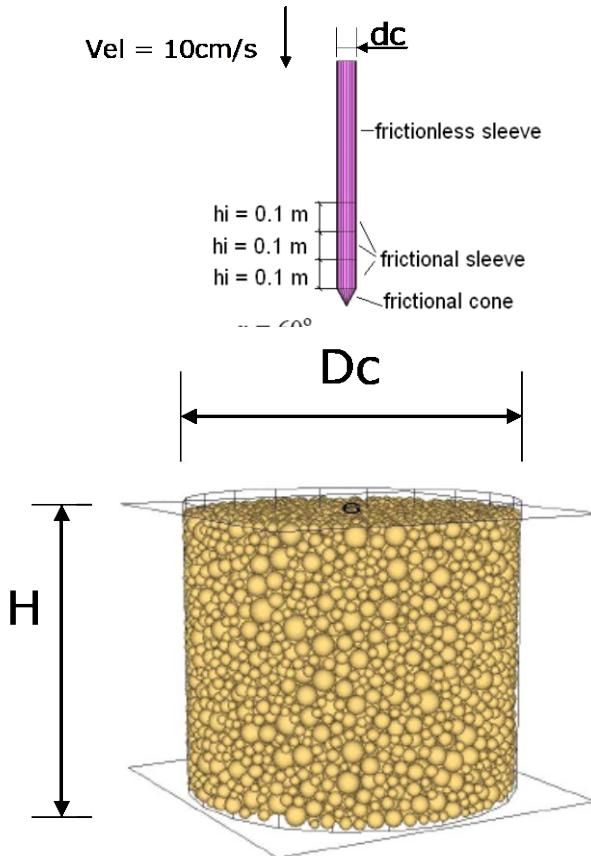


OUTLINE

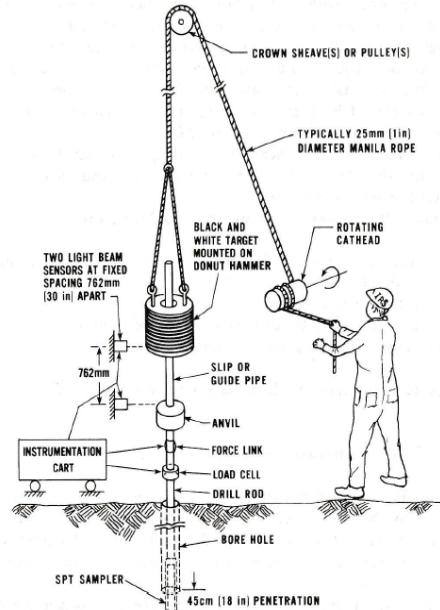
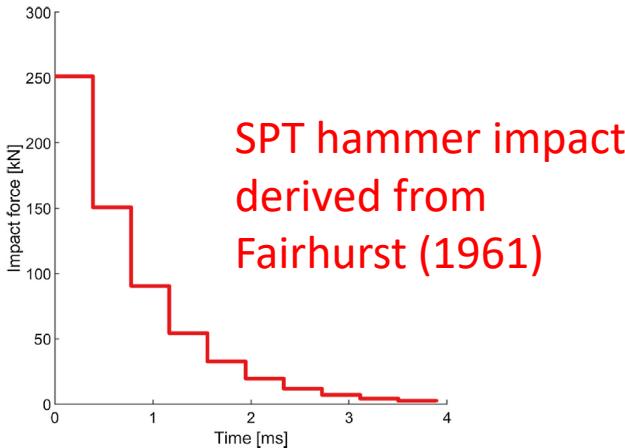
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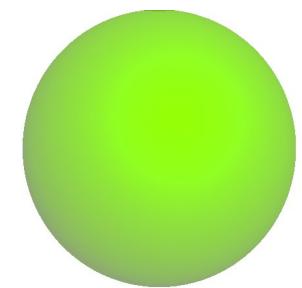
In Barcelona...



CPT, Arroyo et al. (2011)

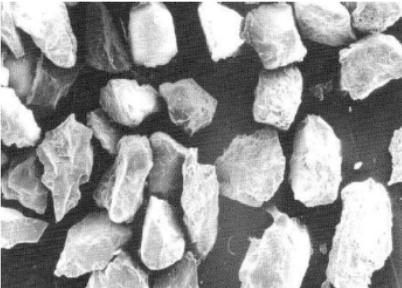
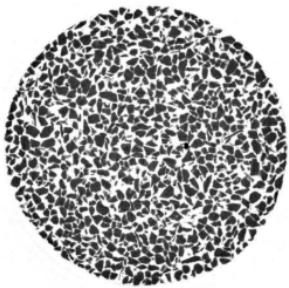


SPT, Zhang et al. (2019)

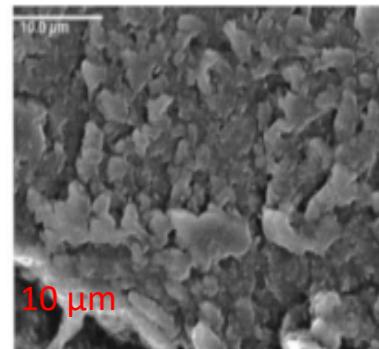
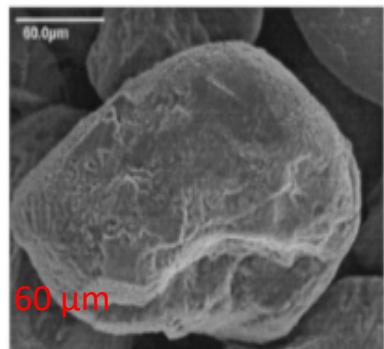


Round,
Smooth
Uncrushable

In Barcelona...

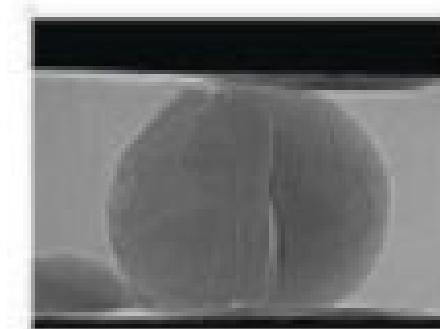


Shape, Rorato (2019)



Roughness

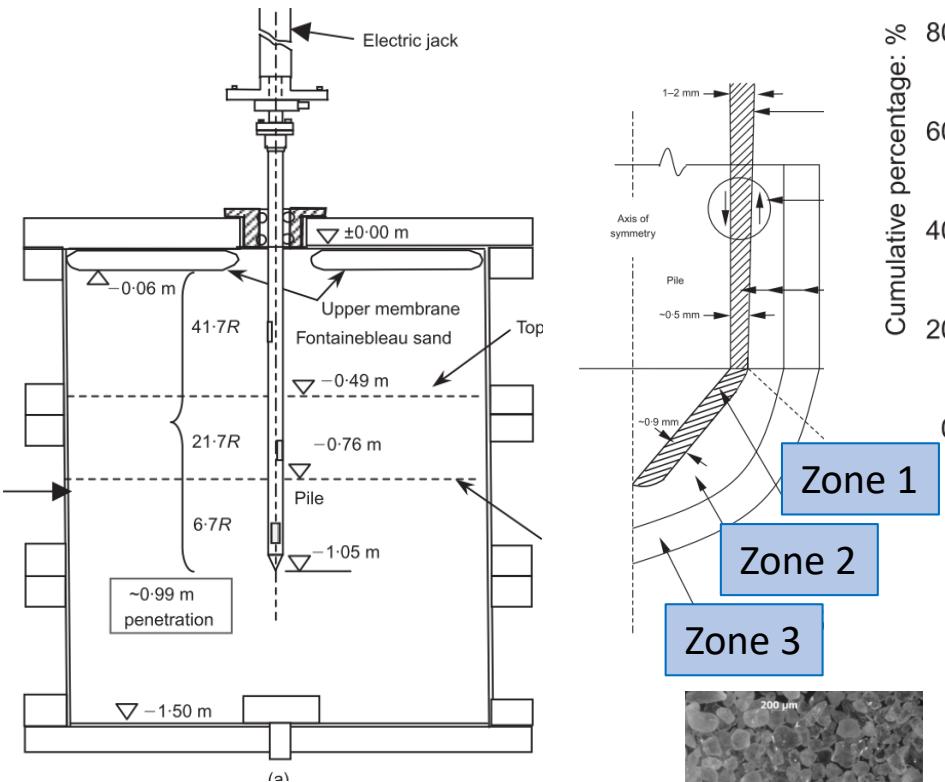
+



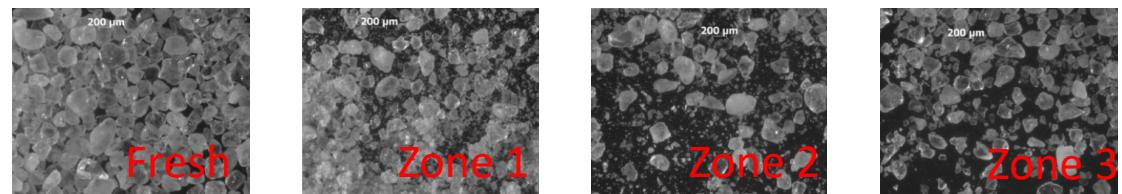
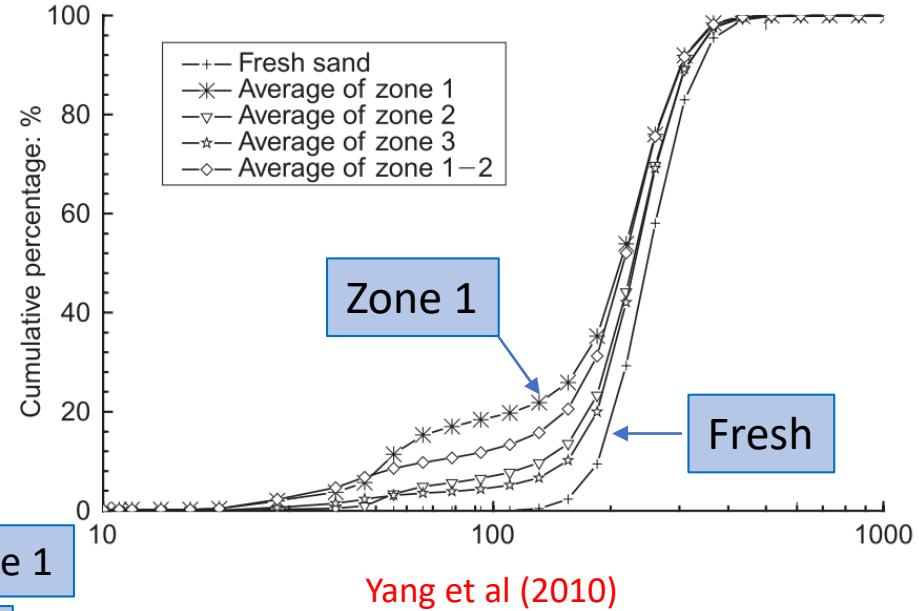
Breakage

➤ Grain breakage

- Testing driven piles in the calibration chamber

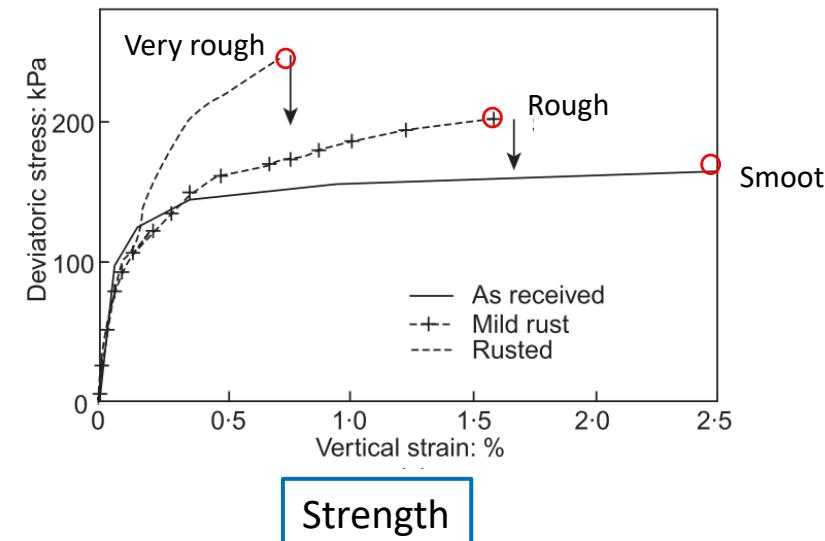
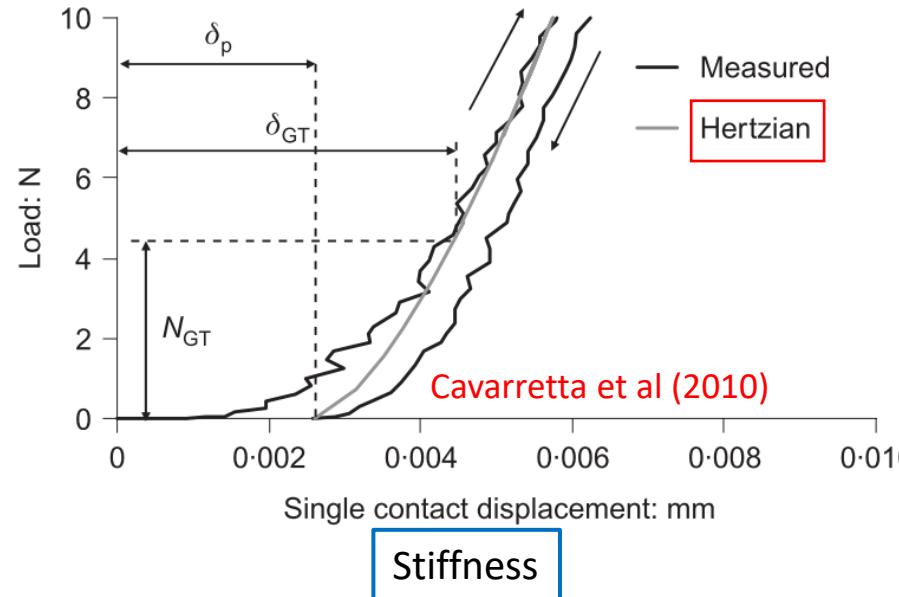
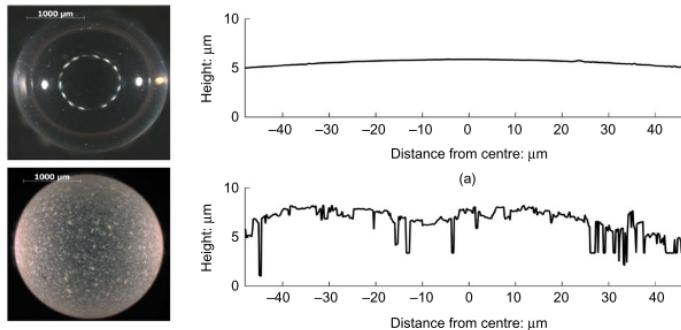


Fontainebleau (siliceous) sand



➤ Surface roughness

- Quantifiable
- Stiffness reduction at small stress level
- Strength increase



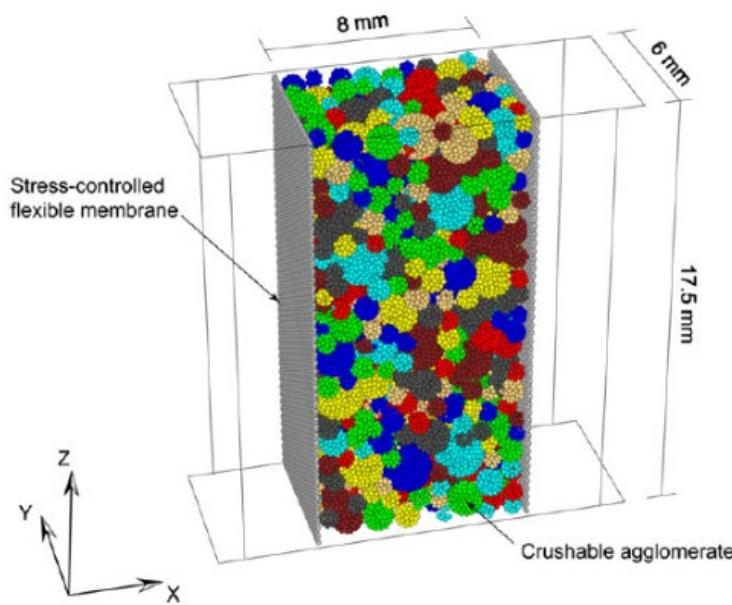
- For modelling rough breakable particles, the idea is to incorporate roughness effect into a particle crushing model.

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Crushing in DEM

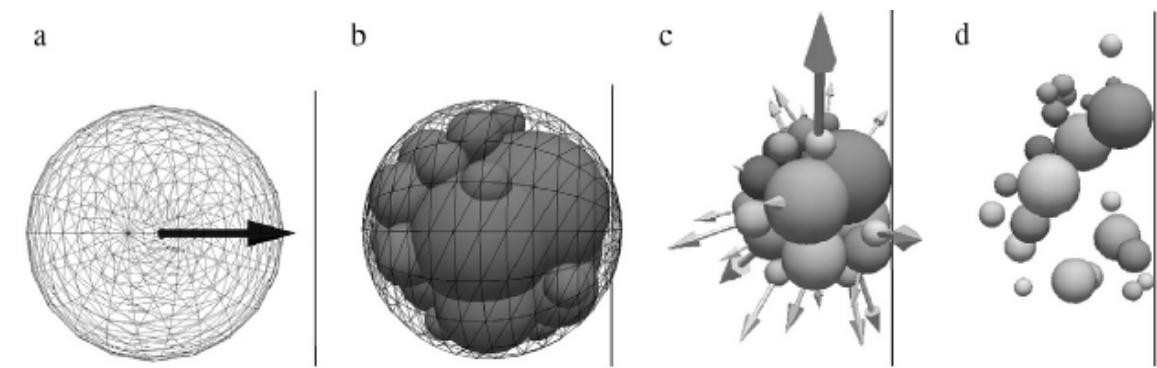


➤ Bonded agglomerates

- Bond parameters instead of breakage criteria
- Limited capture of GSD evolution
- Computationally very demanding

➤ Multigenerational

- Efficient



Multi-generation crushing model

Ciantia et al (2015) Geotechnique 65, No. 2, 91–110

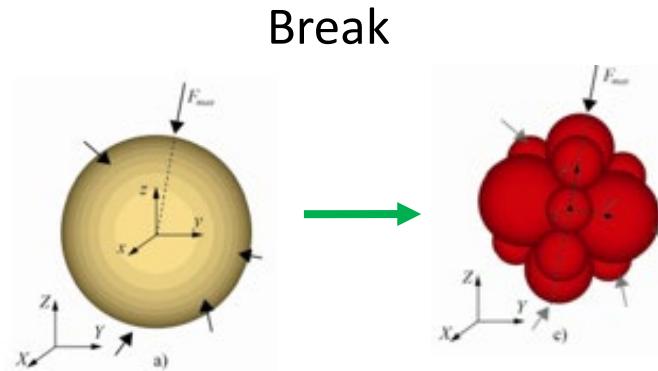
➤ Breakage criterion

$$F_n \leq \sigma_{\lim} A_F$$

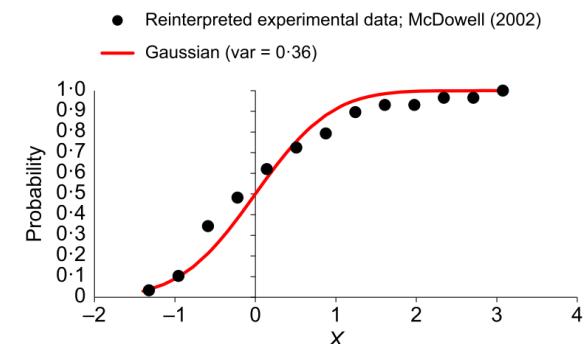
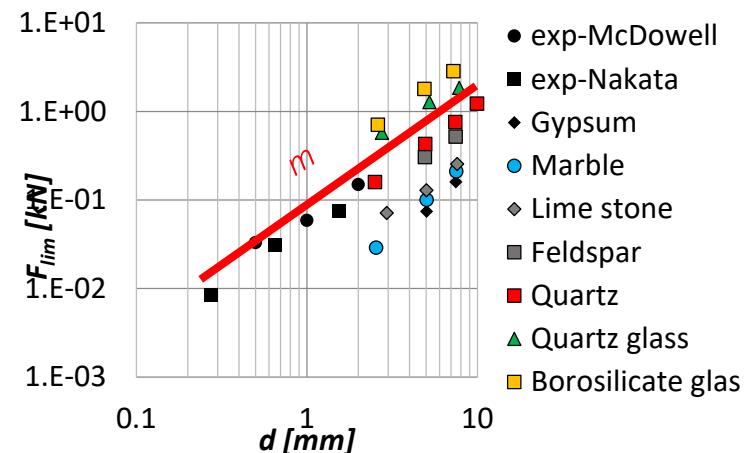
- Crushing strength σ_{\lim}

$$\sigma_{\lim} = \sigma_{\lim,0} f(\text{var}) \left(\frac{d}{d_0} \right)^{-3/m}$$

- Contact failure area A_F



- Mass lost but accounted for in tracking grain size distribution



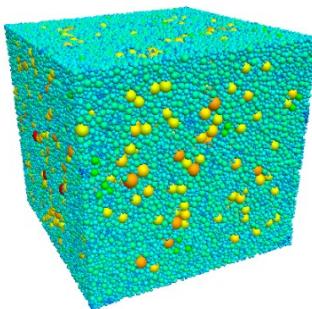
$$A_F = \pi r_H^2 = \pi r' \delta$$

Rough contact model

Implementation of the crushing model

Particle crushing can be implemented by:

- FISH, a loop over all contacts, time-consuming (**previous work**)
- User-defined contact model (UDCM), C++, embedded in force-displacement law, efficient (**this study**)



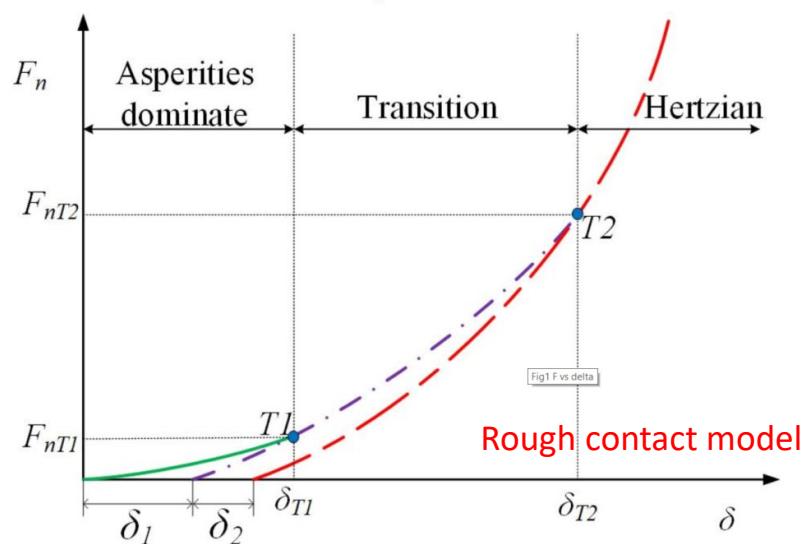
Test-ID	μ_w	E_w	μ_b	E_b	ν	$\sigma_{im,0}$	m	variance	n crush	LR	$N_p,0$	N_p,end	Time*
	[-]	[MPa]	[-]	[MPa]	[-]	[MPa]							[h]
FISH-10	0.4	866	0.4	866	0.3	116	5	0.0	10	0.01	10k	86,388	8:04
UDCM	0.4	866	0.4	866	0.3	116	5	0.0	-	0.01	10k	83,905	3:46

Incorporation of roughness effect into the crushing model

- Hertzian model

$$F_n = \frac{4}{3} E' \sqrt{r'} \delta^{1.5}$$

$$E' = \left(\frac{1-v_1^2}{E_1} + \frac{1-v_2^2}{E_2} \right)^{-1} \quad r' = \left(\frac{1}{r_1} + \frac{1}{r_2} \right)^{-1}$$



- Rough contact model

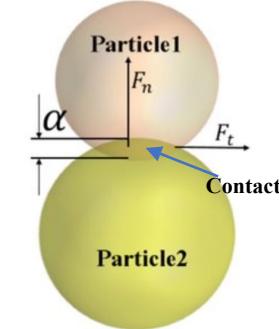
$$F_n = F_{nT1} \left(\frac{\delta}{\delta_{T1}} \right)^c \quad \delta < \delta_{T1}$$

$$F_n = F_{nT2} \left(\frac{\delta - \delta_1}{\delta_{T2} - \delta_1} \right)^b \quad \delta_{T1} \leq \delta < \delta_{T2}$$

$$F_n = \frac{4}{3} E' \sqrt{r'} (\delta - \delta_1 - \delta_2)^{1.5} \quad \delta_{T2} \leq \delta$$

$$b, c, \delta_1, \delta_2, \dots \equiv f(S_q, n_1, n_2)$$

Described in:
Otsubo et al (2017) for the
rough contact model



New variables:
 S_q (measurable),
 n_1, n_2

So, the particle crushing criteria can be written as:

$$F_n = \sigma_{\lim,0} f(\text{var}) \left(\frac{d}{d_0} \right)^{3/m} \pi r' \left(\frac{F_n}{S_q E' \sqrt{2r' S_q}} \right)^{\frac{1}{c}} \left\{ \left(\frac{1}{100} \right)^{1/b} \left[\left(\frac{300 S_q E' \sqrt{2r' S_q}}{4E' \sqrt{r'}} \right)^{2/3} + n_2 S_q \right] + n_1 S_q \right\} \quad F_n < F_{nT1}$$

$$F_n = \sigma_{\lim,0} f(\text{var}) \left(\frac{d}{d_0} \right)^{3/m} \pi r' \left\{ \left(\frac{F_n}{100 S_q E' \sqrt{2r' S_q}} \right)^{\frac{1}{b}} \left[\left(\frac{300 S_q E' \sqrt{2r' S_q}}{4E' \sqrt{r'}} \right)^{2/3} + n_2 S_q \right] + n_1 S_q \right\} \quad F_{nT1} \leq F_n < F_{nT2}$$

$$F_n = \sigma_{\lim,0} f(\text{var}) \left(\frac{d}{d_0} \right)^{3/m} \pi r' \left[\left(\frac{9 F_n^2}{16 E'^2 r'} \right)^{\frac{1}{3}} + n_1 S_q + n_2 S_q \right] \quad F_{nT2} \leq F_n$$

- UDCM

OUTLINE

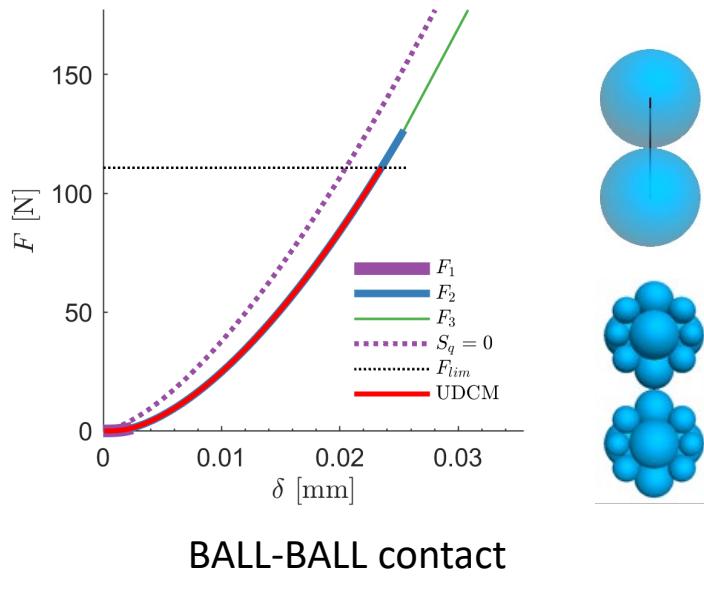
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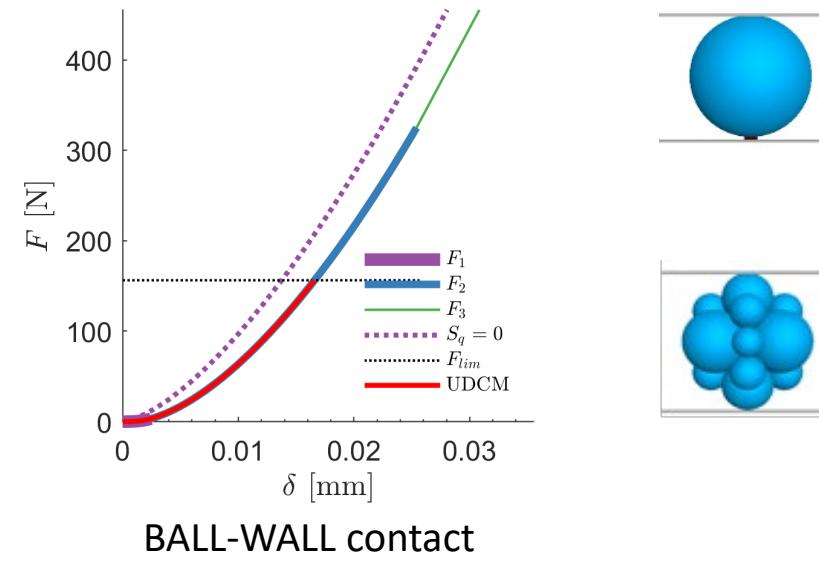
The UDCM implementation is correct?

- Single particle crushing test

Parameters	d / mm	G / GPa	ν	φ	m	$\sigma_{lim,0} / \text{GPa}$	S_q / m	n_1	n_2
Values	2	32	0.2	0.275	7.5	3	1e-6	1	2



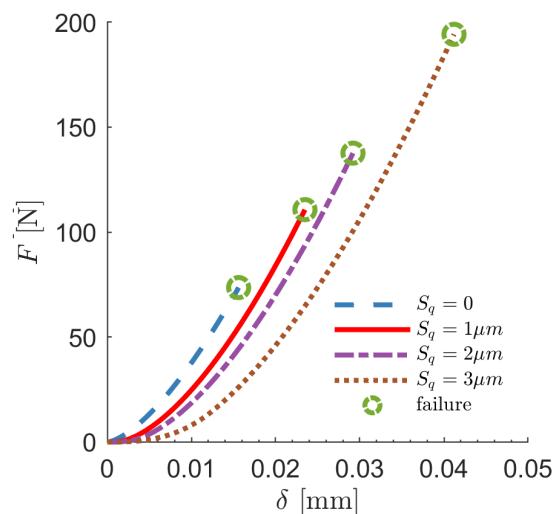
BALL-BALL contact
Analytical



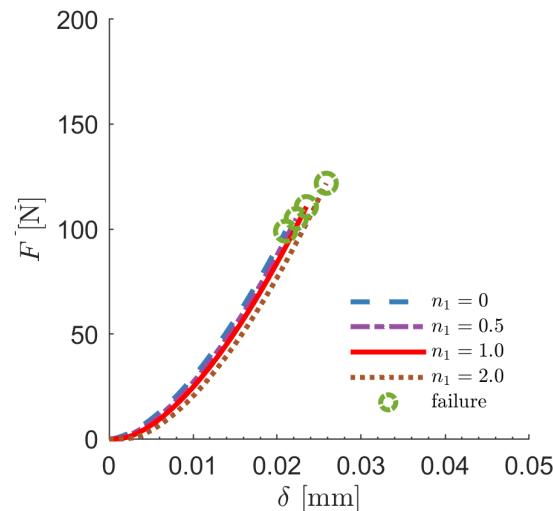
BALL-WALL contact
Analytical

Effect of contact roughness on single particle breakage

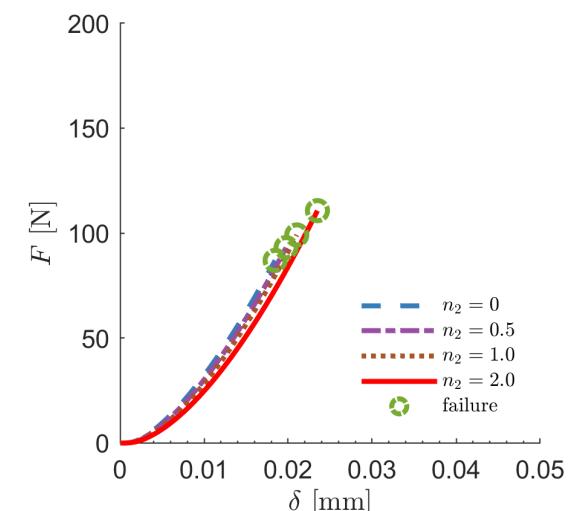
- Parametric study over three new parameters (S_q , n_1 , and n_2) in the crushing model



S_q



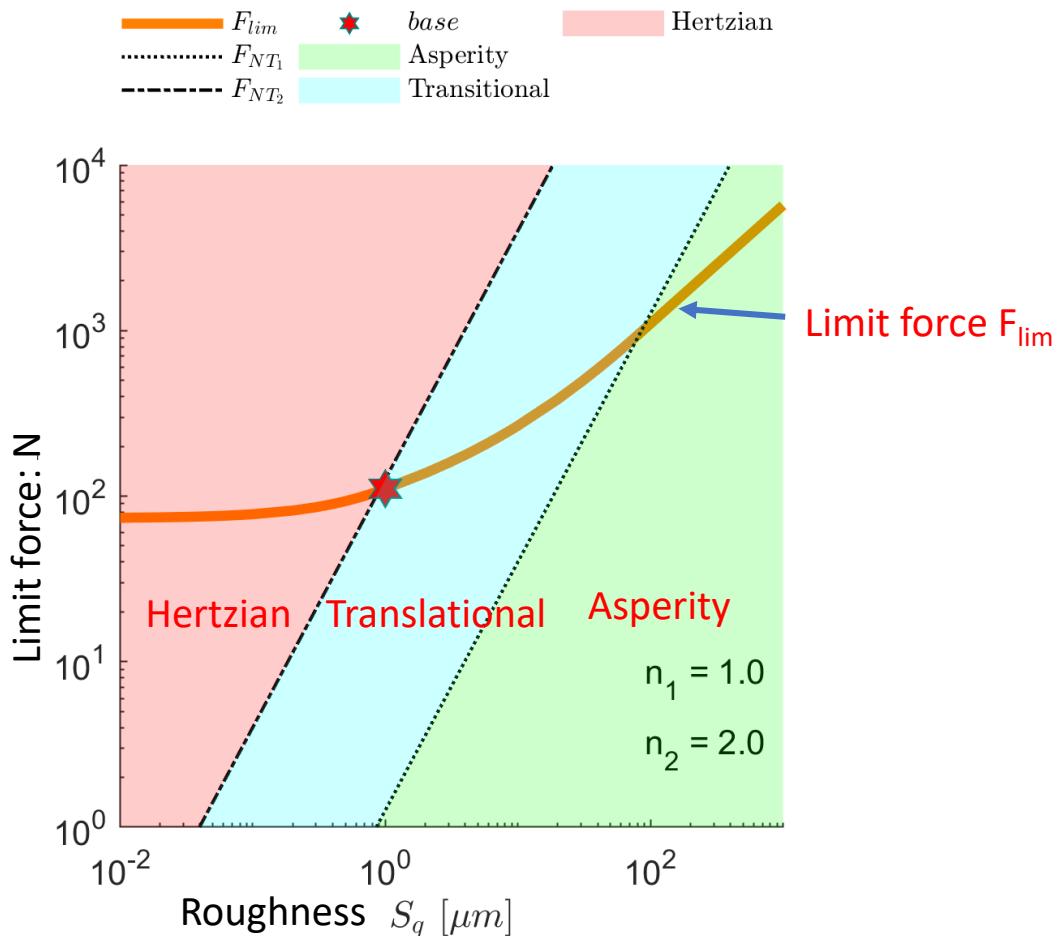
n_1



n_2

Effect of contact roughness on single particle breakage

- **LARGER** range of S_q



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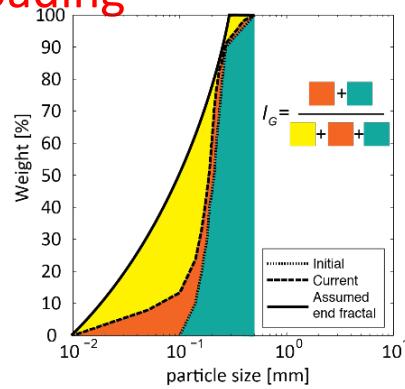


Limitations of smooth particles

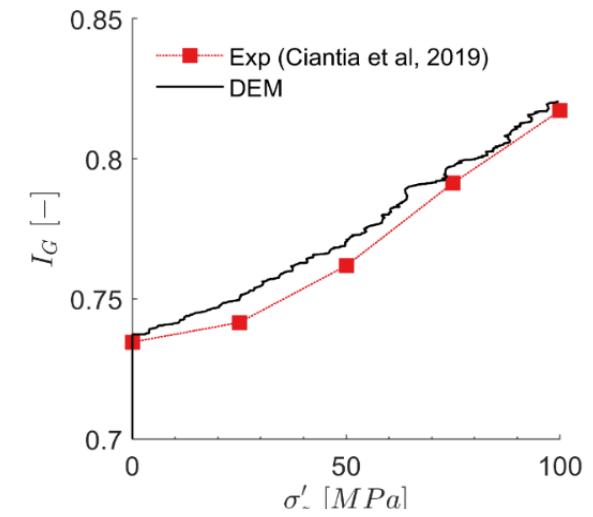
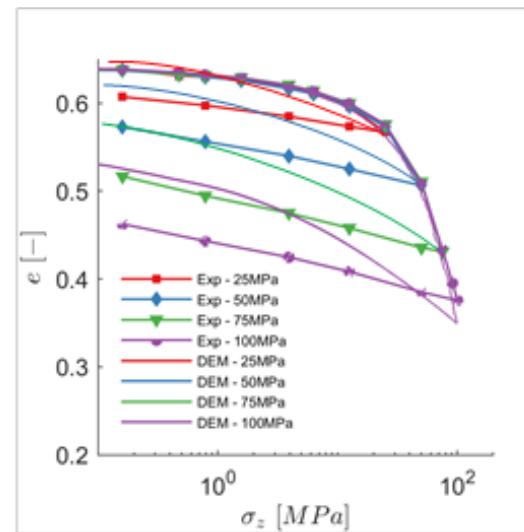
Oedometer test of Fontainebleau (silica) sand

Ciantia et al (2019)

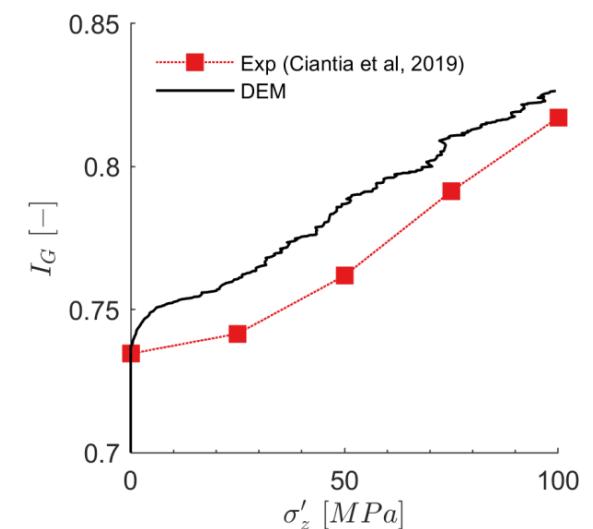
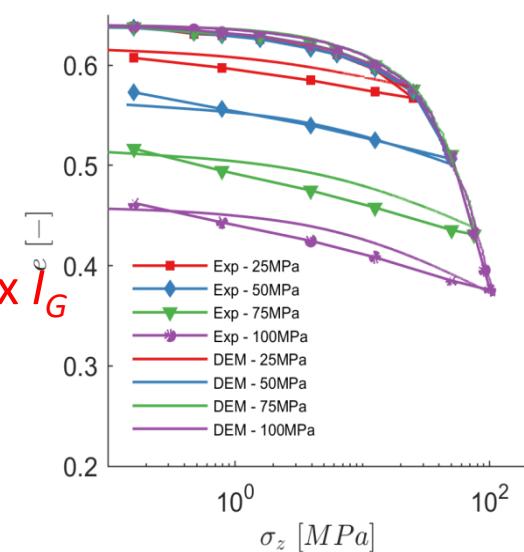
- $G=9$ Gpa, unrealistic
- Good I_G and loading
- But poor unloading



Grading state index I_G



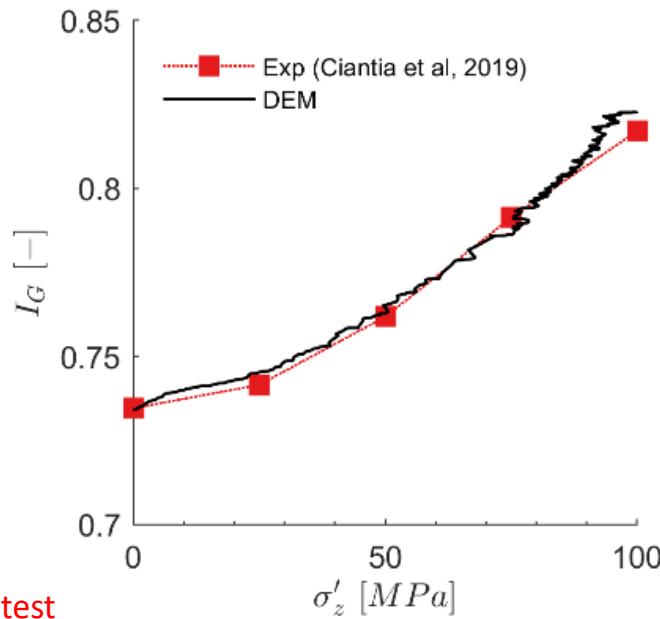
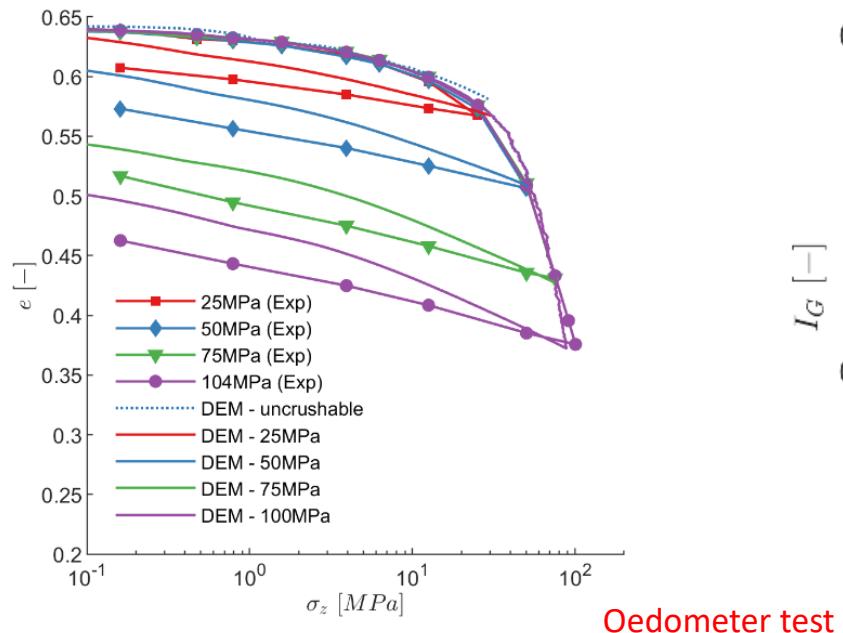
- $G=29$ Gpa, realistic
- Good unloading and loading
- But poor I_G



Rough contact crushing model may be able to solve the problem!

Recalibration of parameters

Sets	G / GPa	v	μ	m	$\sigma_{\text{lim},0} / \text{GPa}$	var	$S_q / \mu\text{m}$	n_1	n_2
Ciantia model-low G	9	0.2	0.275	10	1.9	0.36	-	-	-
Rough-crushable model	32	0.19	0.275	12	3.75	0.38	0.6 0.05 5		



- Satisfactory results in loading, unloading and I_G evolution

Conclusions

This contribution documents the incorporation of particle surface roughness into a DEM model for crushable sands using a UDCM. The effect of contact roughness on single particle breakage has been investigated via parametric studies. The model parameters for a discrete analogue of a representative quartz sand have been recalibrated. The main findings are:

- The parametric study shows that increasing either roughness or the n_i ratios results in larger crushing forces and less stiff contact behaviour;
- The effect of roughness S_q is more significative than those of the n_i ratios.
- The recalibrated parameters including realistic values of surface roughness (using realistic values of elastic bulk properties for the sand grains) enable to correctly capture both load-unload behaviour and particle size distribution evolution of high pressure oedometric tests.
- Roughness is then a model refinement that may result in simpler and more objective DEM calibrations.



To acknowledge:

Professor Marcos Arroyo, Antonio Gens and Dr Matteo Ciantia

ITASCA, Sacha Emam

Thank you for your
attention!

