Nonlocal contact evolution and curvature correction in confined granular systems

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**Motivation**
- Powder compaction is a highly popular manufacturing process and the core of many major industries, especially pharmaceuticals and powder metallurgy.
- Predictive modeling of the macroscopic behavior of confined granular systems is essential for optimizing the process and increasing its efficiency and productivity.

**Modeling Approach**
- Particle mechanics strategies (models individually describe all particles in the powder bed)
- Experimentally assisted multi-scale modeling (particle scale models and protocols for characterizing particle properties)

**Particle Mechanics Strategies**
- Predictive constitutive models of inter-particle interactions for a variety of physical mechanisms:
  - Elastic deformations
  - Plastic deformations
  - Bonding
  - Strain-rate mechanisms
  - Friction and fracture
  - Water intake and swelling
- Complex behavior at the granular scale can be simplified by studying three symmetric loading configurations of single particles.
- Predictability of particle mechanics approaches relies on the contact formulation being employed.

**Theoretical Framework (Plastic Deformations)**
- For elastic particles, formulation is an extension of Hertz Theory
- For plastic particles, formulation could be an extension of Storakers Law

**Theoretical Framework (Elastic Deformations)**
- Dominant mechanisms:
  - Elastic deformations
  - Plastic deformations
  - Bonding
  - Strain-rate mechanisms
  - Friction and fracture
  - Water intake and swelling
  - Nonlocal contact evolution and curvature correction

**Theoretical Framework (Elastic Deformations)**
- Nonlocal contact formulation (Soriano and Castro 2012)
- Relaxes the assumption of independent contacts by considering deformations due to multiple contact forces on the particle
- Applicable to small deformations and low relative velocities
- Dominant mechanisms: Elastic deformations, Plastic deformations, Bonding, Strain-rate mechanisms, Friction and fracture, Water intake and swelling
- Nonlocal contact formulation (Storekers 1997)
- Contact formulation for confined granular systems
- Applicable to small deformations and low relative velocities

**Curvature Correction**
- Current Formulation:
  \[ E_i = R_i - \sqrt{R_i^2 - z_i^2} \]
- New Formulation:
  \[ E_i = R_i - \sqrt{R_i^2 - z_i^2} + \frac{1}{2} \left( \frac{z_i}{R_i} \right)^2 \]

**Nonlocal Contribution to Contact Radius**
- The nonlocal contribution to contact radius, denoted by \( \Delta r_{NL} \), is given by
  \[ \Delta r_{NL} = \frac{1}{2} \left( \frac{z_i}{R_i} \right)^2 \]
- The nonlocal contribution to contact radius is a function of the nonlocal parameter \( \Delta r_{NL} \).

**Simulation Results**
- Simulations were performed for spherical rubber particles with \( E = 1.85 \text{ MPa}, v = 0.48 \) and \( R = 10 \text{ mm} \).

**Conclusions and Future Work**
- A new, improved version of the nonlocal contact formulation for elastic particles was developed by introducing curvature correction and nonlocal contact evolution.
- Good agreement was obtained between the predictions of finite-element model and nonlocal contact formulation for evolution of force and contact area with deformation.
- Nonlocal contribution to contact radius and curvature correction were found to improve the prediction of contact impingement.
- Extension of nonlocal formulation to finite plastic deformations remains a topic of future research.

**References**