How Discrete Element Method code can model dynamical phenomena such as saltation transport, multiple collision process and granular avalanches

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Schedule

1. General information for DEM
2. 3D grains interaction with humidity (avalanche)
3. 3D mono shot for Splash function
4. Multi shots for splash function
5. 2D saltation with wind interaction
6. Conclusion
§1: General characteristics of DEM: Molecular Dynamics simulation (soft model)

Compression: \( F_n = K_n \delta - b_n v_n \) (\( \delta \) is the positive overlap)

Tension: \( F_n = 0 \) (if \( \delta \) is negative)

+ external forces: wind, humidity, Electrostatic, ...
+ shape factor: rolling resistance

\[ F_t = K_t \delta_t - b_t v_t \]

and \( F_t \) is controlled by:

\[ F_t = \mu_i F_n \]
Soft sphere interaction

two spheres collision

coordinates with time
§2: 3D Avalanche with humidity
(present everywhere!)

Pendular
Funicular
Capillary

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85 µm glass beads

Force at the contact

Experimental results at FI-UBA

I. Arriarn & I. Ippolito

Tilt box

For humidity control

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500 µm beads

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Maximal angle and repose one (grains 1 mm)
Différence between angles
1st avalanche & following
grains de 1mm

![Graph showing the difference between the angles of the 1st avalanche and following grains de 1mm. The graph plots the maximal angle established (°) against the number of avalanches (nº avalanche). The graph includes lines for 75% repos., 75% etab., 80% etab., and 80% repos., with specific angles marked for ΔΘ_m1 and ΔΘ_m2.](image-url)
Numerical model

- Spring-Dashpot DEM 3D
- non periodic box
- 16000 monosize spheres
- Pré-consolidation des empilements
- Charlaix 's adhesion force
- Rotation by gravity vector
- Measures of angles in box directions
Comparaison déplacement, vitesse, accélération avec ou sans RH

coords X

Vitesses

Accélération
Evolution of velocities
(2 vel. thresholds : 2colors : θ+2indications)
Movie of full sequence
With sphere output
Evolution slopes velocities

The graph shows the evolution of slopes and velocities as a function of angle. The red line represents the velocities (m/s), while the brown line represents the derivative of the slope (°). The x-axis represents the angle in degrees, and the y-axis represents the derivative of the slope and velocities.
Evolution slopes & displacement (2 friction coefficients)

- $\mu=0.4$ (disp)
- $\mu=0.3$ (disp)
- $\mu=0.4$ (slope)
- $\mu=0.3$ (slope)
Sphere disorder effect

Different if higher than 10%

Slope (°) vs. tilting angle (°)

- $\delta=5\%$
- $\delta=10\%$
- $\delta=15\%$
Effects of inclination speed

- 30°/s
- 15°/s
- 2°/s
Evolution of active contacts

Number of active contacts vs Angle (°)

- 70%
- 60%
- 50%
Evolution velocities = $f(RH)$
§2: Conclusions

• Humidity is crucial to understand grains transport
• Humidity is difficult to model
• Correct results up to 70% RH
• Progress:
  – For high humidity rate!!!
  – Multiple capillary bridges!!
§3-4-5 issue: sand transport by saltation

2D LASER slice of 3D sand flow inside a large wind Tunnel

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Experimental Setup

PVC beads
D=6mm
Weight = 0.2g
$e_n = 0.91$
$\mu = 0.19$

Valve 1
Valve 2
Valve 3

Nitrogen
Timer
Vacuum pump

Vacuum cell
Air gun

Incident bead
Rail

Cameras
PC

Projector
3D packing

synchronized Cameras

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Synchronized 3D Film

Possibility to detect the real 3D trajectories
Control Parameters

Froude Number = 1000
Sand diameter ~ 100 μm
Impact velocities: few m/s

Froude number = \[
\frac{\text{Impact kinetic energy}}{\text{Potential energy to reach One diameter high}} = \frac{V_i^2}{gd}
\]

Impact speed ~ 10 m/s
Diameter = 6 mm

Incident angle effect:
- Constant speed: 26 m/s
- Variable angle: 0° to 90°

Incident speed effect:
- Constant Angle: 10° (Natural angle for saltation)
- Variable incident speed: 18 m/s et 39 m/s.
Variation of the rebound angle

Velocity 26 m/s

Angle 10°

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Number of ejected beads

Number of ejected beads vs Incident bead angle (°)

- **Velocity 26 m/s**
- **Angle 10°**

Number of ejected beads vs Incident bead velocity $V_i$ (m/s)

- $V_{i}^{th} = 10 \text{ m/s}$
Distribution of the vertical velocity components of ejected beads

Vertical ejection speed $V_z$ (m/s)

PDF*100

Distribution is independent of the angle and the incident velocity
Numerical simulation

• Discrete Element Method
  – Soft sphere model ("Spring-dashpot")
• 30000 spheres for the packing (43x43x16)
• Same physical and mechanical parameter as the real beads:
  – Diameter = 6mm, weight= 0.2g
  – Stiffness= 1.0 E9 N/m
  – Restitution coefficient= 0.75 -0.95
  – Friction coefficient= 0.2-0.4
Visualization of the sphere displacements

Incident bead: angle = 10° and velocity = 50 m/s

Green = displacement higher than 0.25 diameter
Dark blue = displacement higher than 1 diameter
DEM approach
(Discrete Element Method - Soft model)

Colors correspond to different displacement amplitudes

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Analysis of the rebound of the incident bead

![Graph showing the relationship between incident angle and rebounding angle for different speeds.](Image)
Vertical velocity restitution

Werner’s law:

\[ \overline{e_z} (\alpha_i) = \left( \frac{0.320}{\sin(\alpha_i)} - 0.236 \right) \overline{e_z} (15^\circ) \]
Global energy restitution for the incident bead

- $E_{\text{inc}}$
- Incident bead angle (°)
- 60 m/s
- 50 m/s
- 40 m/s
- 30 m/s
Number of ejected beads

\[ N_{ej} \]

\[ \sin(\alpha_i) \]

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Energy of the ejected beads

![Graph showing the energy of ejected beads as a function of incident angle for different velocities.](image-url)

- Global ejected bead restitution coefficient
- Incident angle (°)
- Vectors for different velocities: 30 m/s (diamonds), 40 m/s (squares), 50 m/s (triangles), 60 m/s (crosses).
Comparison between experimental and numerical results

Experimental
- 29 m/s
- 39 m/s

Numerical
- 30 m/s
- 40 m/s

PDF*100

Vertical ejection speed $V_z$ (m/s)
But with different sizes!

- Monosize or binary packing of sphere
- Size of the impactant different (0.5 up to 4)
- Variable velocities and angles
Incident bead

The graph shows the relationship between the angle and the normalized energy restituted. Two sets of data points are shown for different radii (R) of 0.8 and 1.2. The graph indicates a decrease in energy restituted as the angle increases for both radii values.
Same impact velocities, different sizes

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1 symbol = 1 run for 1 velocity

Ejectas energy

Energy given to the bed by the incident bead

R=3
For different size ratio, angle and impact velocities

R 0.5 up to 3
§3: Concluding results on SPLASH function

• Depends on:
  – angle
  – shot velocity
  – Coefficient of restitution of the grains
  – Coefficient of friction of the grains
  – Initial packing fraction of the grain bed
  – And so on...

Easy to analyse on single shot
§4: Dry saltation problem

If 3D analysis:

• Too CPU consuming (i.e. too many particles)
• Problems for the periodic boundary
• Definition of the impact zone too wide

If 2D analysis:

• CPU time reasonable
• Periodic boundary on one direction
• Impact zone clear
2D saltation model assumptions

Horizontal boundary conditions
Full progressive dumping \((v_x \text{ et } v_y)\) in depth on \(SP = 20 \times \text{Rayon}\)
Upper perfect mirror (at \(H = 250 \times \text{Diameter}\))

Defined initial shot Angle \((10^\circ)\)
One defined shot velocity for a given run \((E_c = \text{cste})\)
Random horizontal position for the shot \((X = \text{random}(0,L), \ Y = \text{Cst})\)
Interval between shots: \(T_{\text{mean}} + \text{random}(0,1) \cdot \Delta t\)

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Run Conditions

• up to 62 000 disks in 350 disks on X direction and 180 disks on Y direction
• Mirror at $Y_{\text{max}} = 250$ disks
• restitution Coefficient = 0.8
• Shot Angle $= 10^\circ$
• Disk diameter $= 250\mu m$ (sable)
• Shot velocities between 10 and 25 m/s
• Time interval between shots : 25 µs to 200 µs
• Dumping-factor($a=0.4$ & $SP=25xR$)
  $$DF = 1 - \{a(1-y/SP)^3 + (1-a)(1-y/SP)^6\}$$
Continuous movie of sequential shots
Force network inside the bead bed
Packing fraction

Graph showing the packing fraction vs. height (radius unit) at different times:
- Green line: \( t = 0.2 \) seconds
- Red line: \( t = 0.1 \) seconds
- Blue line: Init

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Evolution of the moving disk amount

Number of moving disks

Energy input (A.U. = nb shoots)

mean time between consecutive shots increase

Slope

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Moving disks

mean time between consecutive shots decreases
Energy restitution efficiency

![Graph showing the relationship between slope energy transfer and MeanTime interval (s) for different velocities: v=25 m/s, V=14 m/s, and V=13 m/s.](image)

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§4: conclusions

• The analysis of the saltation process cannot be deduced from the classical results of the 3D “Splash function”

• The initial saltation process needs a large amount of energy to mobilize the upper layer of the dune

• The conservation of the moving saltation region needs less energy than the initiation regime
§5: with wind interaction
Practical conditions

- Initial shot of N given disks at a given initial velocities and angles and variables time intervals.
- Given initial wind velocity profiles according to Creyssels et al (JFM 2010)

After a given number of time steps: equilibrium time

- Calculus of the real grain pressure profile
- Wind velocities profiles according to the grain pressure
Granular temperature

Graph showing the granular temperature (in arbitrary units) over height (1/radius) for different times: t = 13ms, t = 43ms, and t = 100ms.
Pressure vs height

- Height (1/radius)
- Pressure (a.u.)

- Green line: t = 8 ms
- Blue line: t = 32 ms
- Red line: t = 100 ms

Dumping zone
Constant wind velocity profile

Threshold for established flux $\rightarrow$ possible calculi of wind coupling
Profile at different times

Height (Radius unit)

- $t=0.003s$
- $t=0.45s$
- $t=0.82s$
$V_{up}$ & $V_{down}$ when stabilized

$v_{down}$

$v_{up}$

Height (radius unit)
Calculus of the pressure

Height (radius unit) vs. $\sigma$ (dimensionless value)

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One full run for 16000 disks, restitution coefficient=0.4
Variable wind velocities

![Graph showing variable wind velocities over time with different rest coefficients.](image-url)
Variable restitution coefficient

Number of moving disks vs Time (s)

- e=0.8
- e=0.7
- e=0.5

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Conclusions

• The saltation process can be modeled from the classical DEM code with a simple wind grain interaction and no artificial parameters.

• The initial saltation process needs 'some' energy to mobilize the upper layer of the dune but the conservation of the moving saltation region can be controlled classically by the grain characteristics and the wind velocities.

• Improvements: local calculi of the wind profile
Conclusions for §3-5

• Good correspondence between experimental and numerical results are possible

• We can and we do use the real mechanical and physical parameters of our granular problems to make a correct numerical and experimental comparisons

• some improvements can be made by adding extra effects such as:
  • Humidity
  • Electrostatic forces
  • roundness of the grains (rolling resistance)
  • and so on…