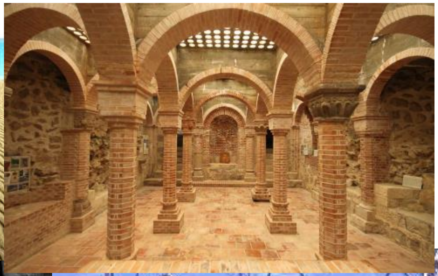
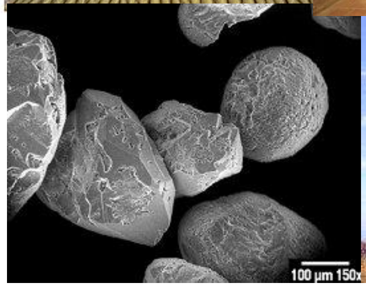
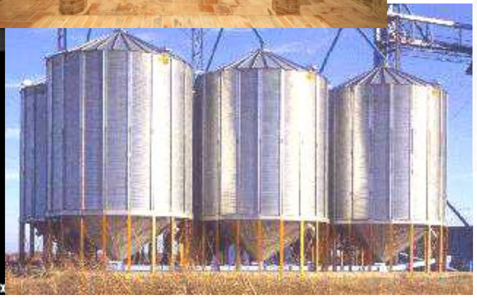
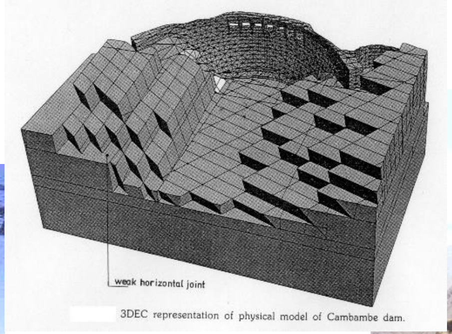
THE DISCRETE ELEMENT METHOD

WHAT IS DEM?

The aim: to model materials or structures having discrete internal builtup

„what does it do if loads are put on it?"


THIS PRESENTATION

→ Non-continuous phenomena:

phenomena from the engineering practice that cannot properly be reflected with continuum mechanics (eg. FEM; FDM)

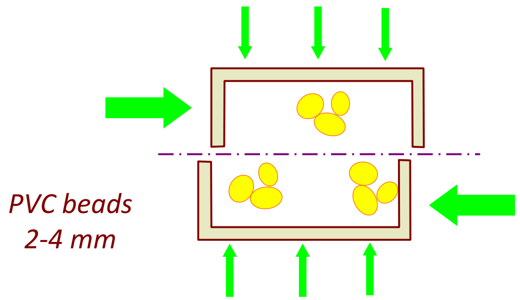
→ What is DEM?

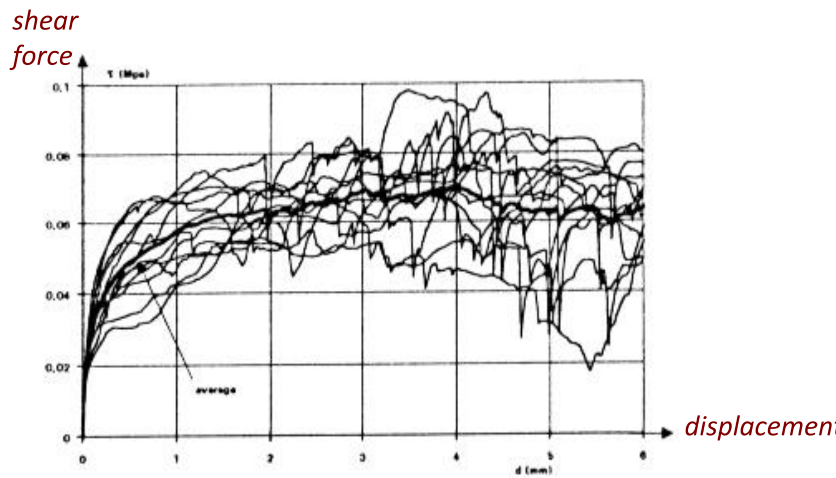
- ⇒ definition
- ⇒ history
- ⇒ example
- ⇒ main steps

NON-CONTINUOUS PHENOMENA

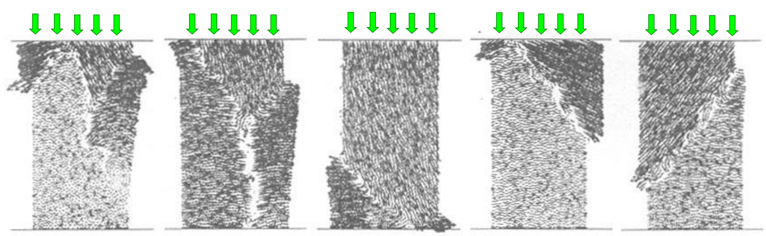
Soil mechanics:

e.g. Large scatter in the measured data:





also for cemented materials!



NON-CONTINUOUS PHENOMENA

Soil mechanics:

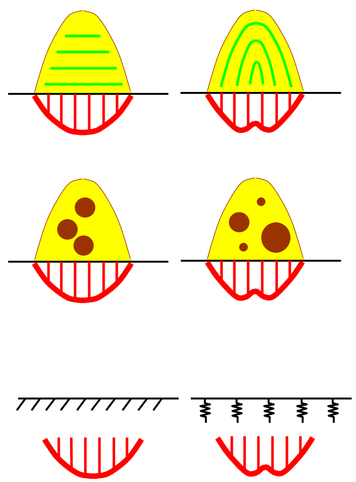
e.g. Stress dip under sand piles:

depends on:

→ deposition technique

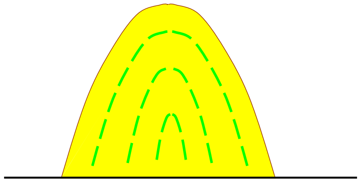
→ grain size distribution

→ stiffness of the subsoil



Microstructual explanation:

„internal arches”



NON-CONTINUOUS PHENOMENA

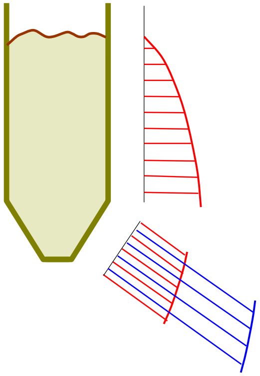
Silos:

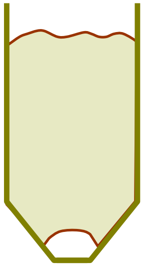
problems e.g.:

→ Pressure acting on the walls?

→ Emptying: sudden large forces

→ arching ☹

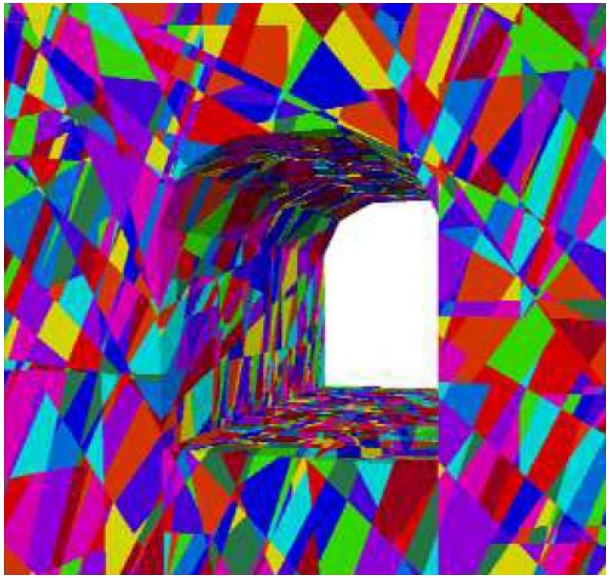




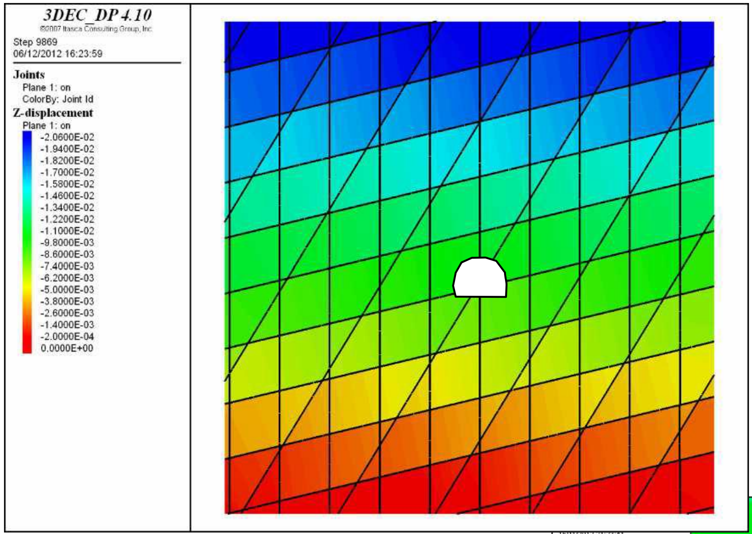
Reason: The stored material is not a continuum!

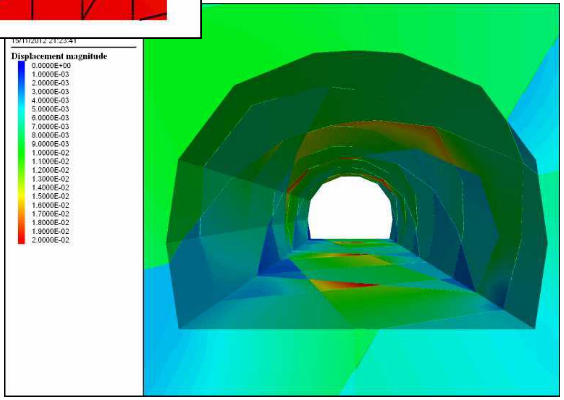
NON-CONTINUOUS PHENOMENA

Tunnels in fractured rock soils:



Futai et al (2017)

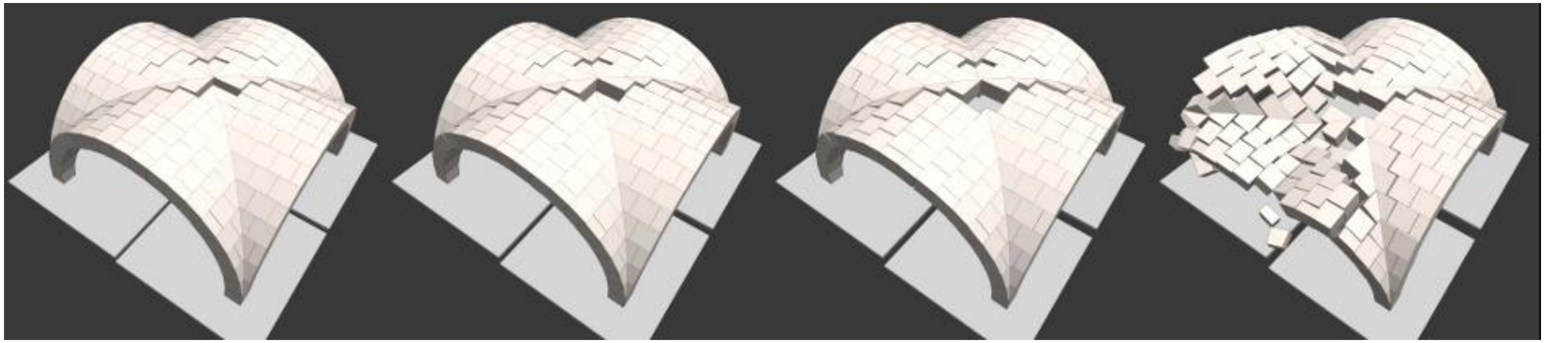


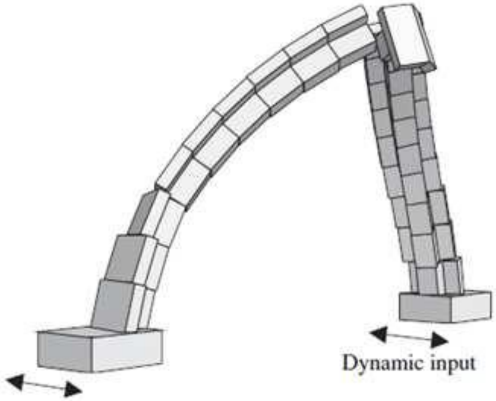


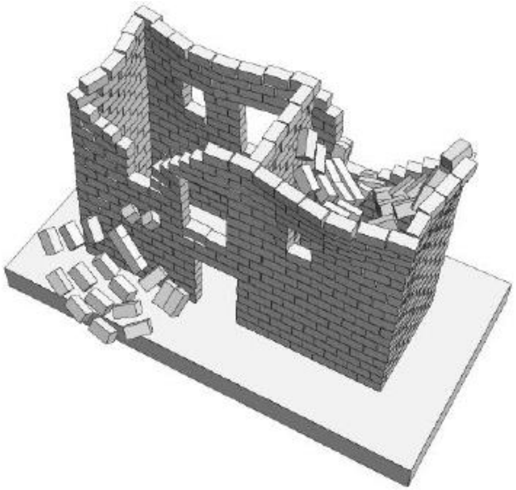
D. Borbély, MSc Thesis

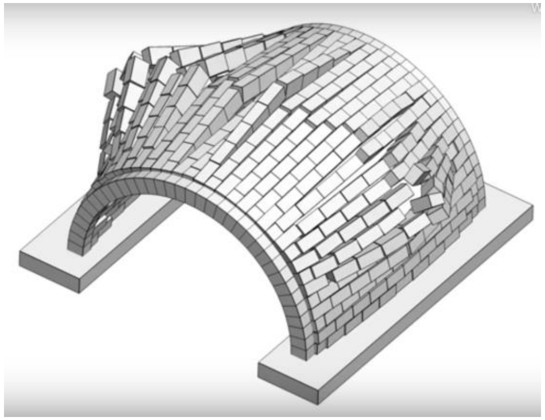
NON-CONTINUOUS PHENOMENA

Collapse of masonry structures:



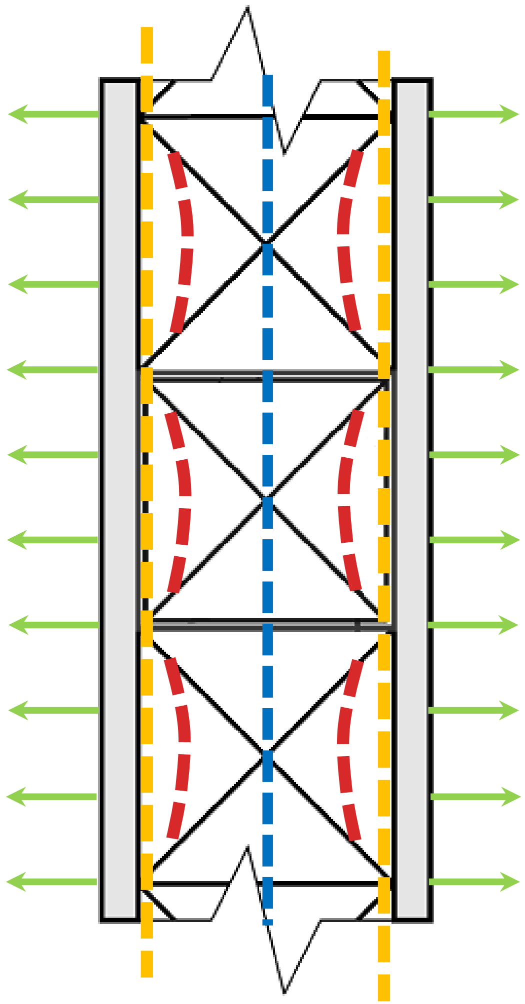


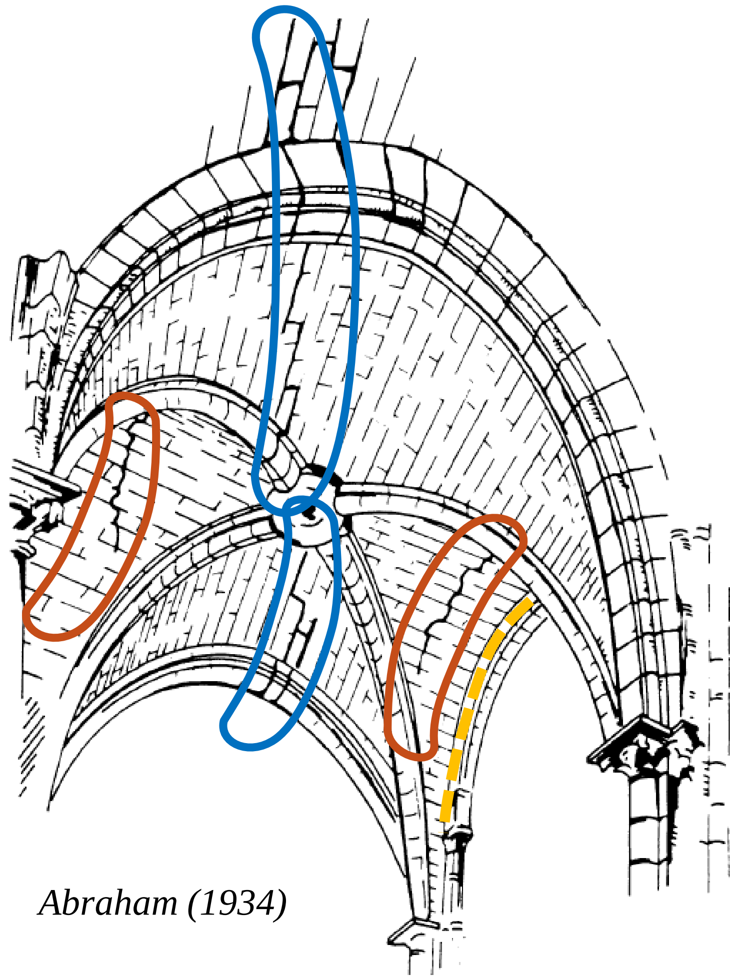




NON-CONTINUOUS PHENOMENA

Cracking of masonry structures in service state:





Abraham (1934)

NON-CONTINUOUS PHENOMENA

Microgravity circumstances:

Here on Earth: during earthquakes:

~~$g = 9.81\ m/sec^2$~~

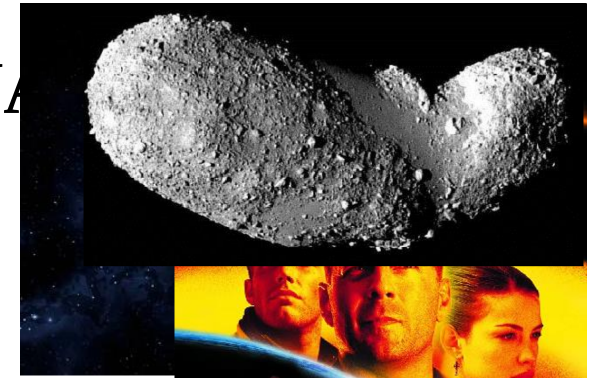
≈ „fluidized"

San Francisco, 1989

NASA, in different space shuttle missions:

? behaviour of granular assemblies at nearly-zero gravity ?

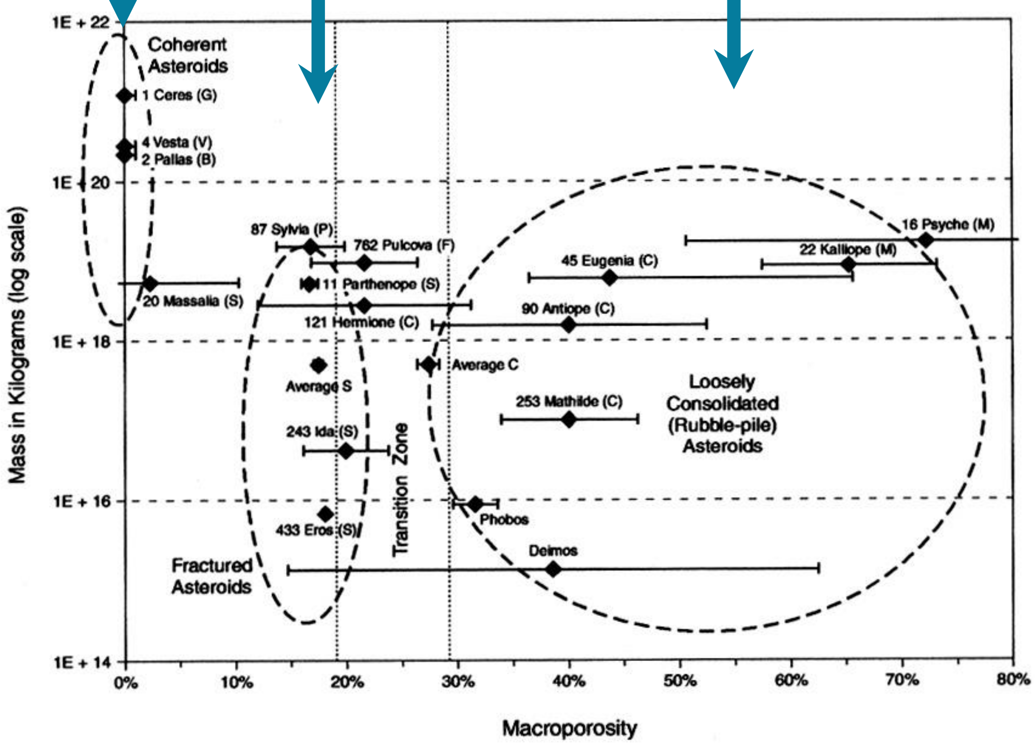
NON-CONTINUOUS PHENOMENA



Microgravity circumstances:

How to predict behaviour of „rubble pile" asteroids?

solid ***fractured*** ***rubble-pile***

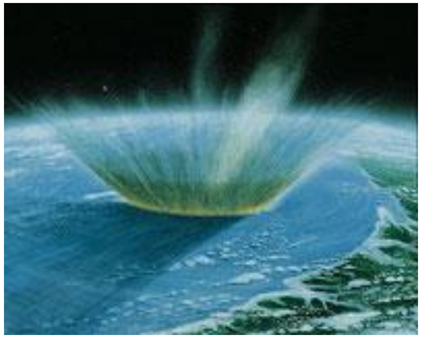


„rubble pile"-type:

porosity > 30%

e.g. Tunguska event (?), 1905, Siberia

NON-CONTINUOUS PHENOMENA



Microgravity circumstances:

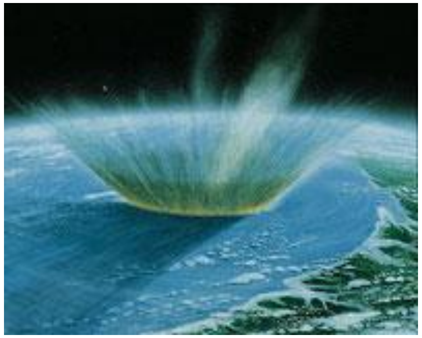
How to predict behaviour of „rubble pile” asteroids?

Bennu:

2nd most dangerous near-Earth object, ≅ 500 m, **? 2175 ?**

NASA, OSIRIS-REx

NON-CONTINUOUS PHENOMENA

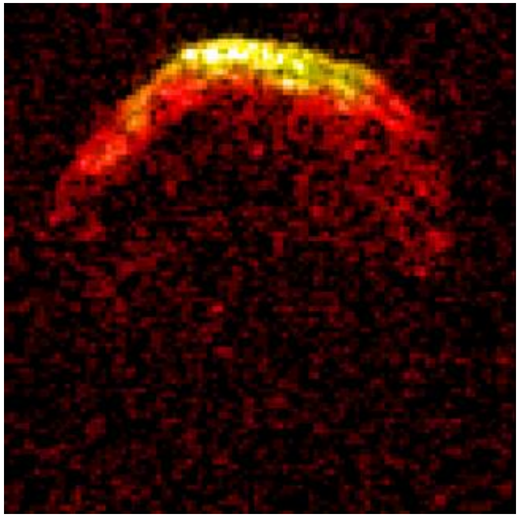


Microgravity circumstances:

How to predict behaviour of „rubble pile” asteroids?

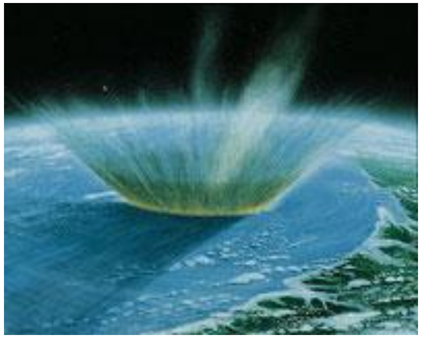
1950 DA:

1st most dangerous near-Earth object, ≅ 1100 m, **? 2035 ?**



http://neo.jpl.nasa.gov/1950da /radar_bw_scale.gif

NON-CONTINUOUS PHENOMENA



Micrograviy circumstances:

How to predict behaviour of „rubble pile” asteroids?

$\Rightarrow$ protection against them: can they be „pushed away”?

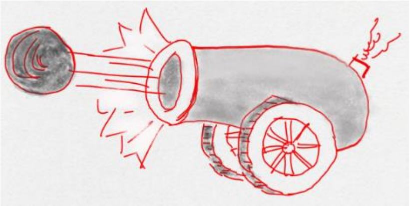
NO !!!

microstructural explanation: huge energy dissipating capacity

[friction/collisons between grains]

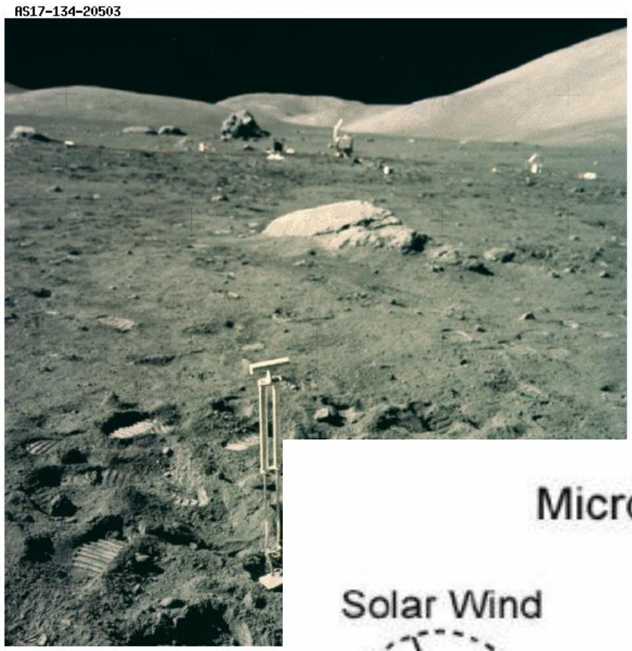
NON-CONTINUOUS PHENOMENA

Traditional application of the huge energy-dissipating capacity:



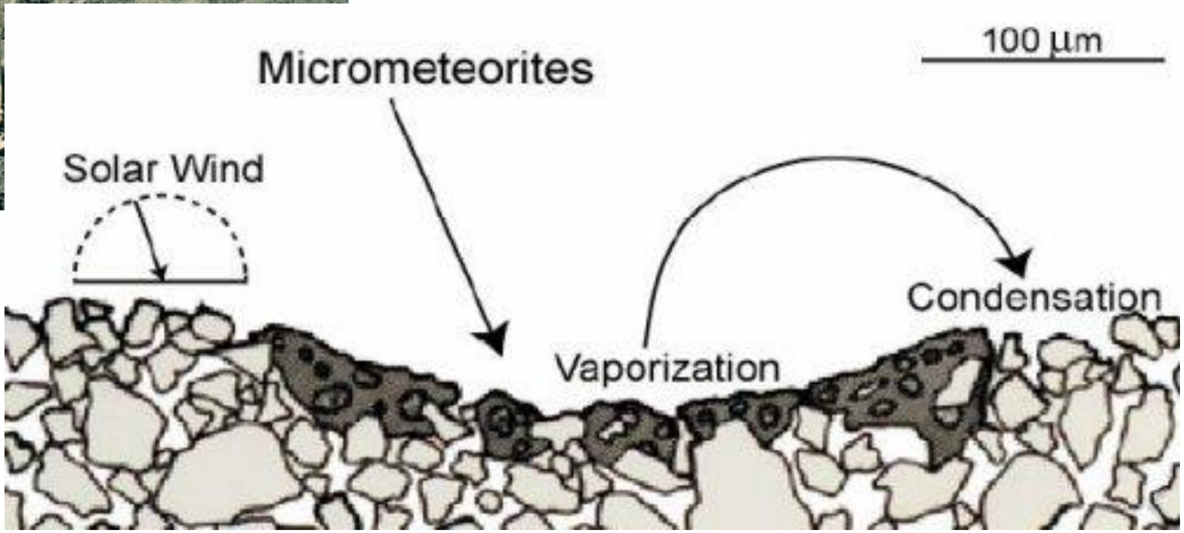
NON-CONTINUOUS PHENOMENA

Taking advantage of the huge energy-dissipating capacity:



← *surface of the Moon*

„regolith”:



NON-CONTINUOUS PHENOMENA

Taking advantage of the huge energy-dissipating capacity:

Circumstances on Moon to cope with:

→ dense meteorite bombardment (10 … 30 km/sec)

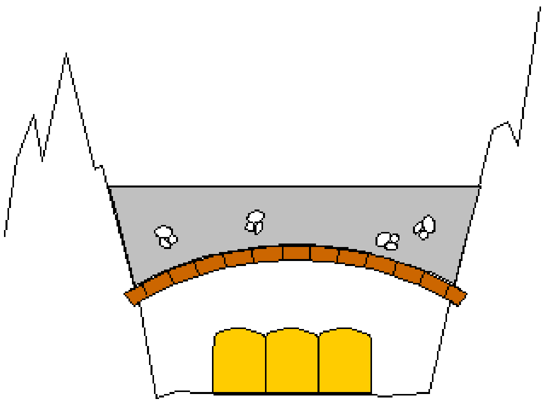
→ temperature extremities (+120 … -150 °C)

→ radiation

→ powder ☹

„volcanic caves” would provide protection;

BUT: we don’t know where & how they are



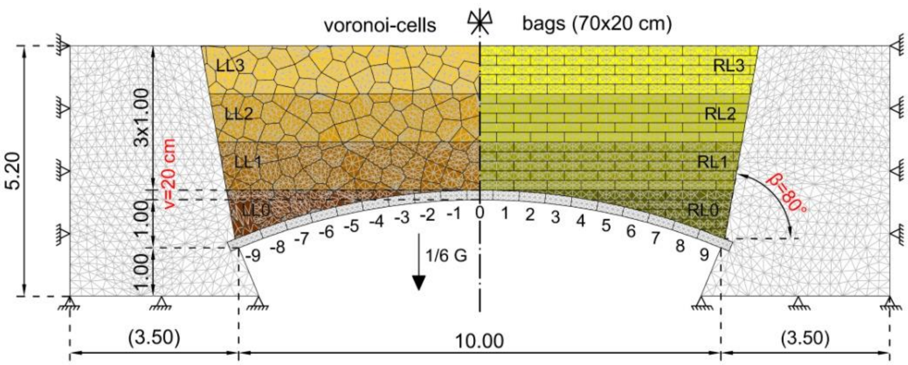
A possible solution:

Boldoghy et al, 2006

Calculation:

Tóth & Bagi, 2010,

J. Aerospace Eng.



NON-CONTINUOUS PHENOMENA

„There are no good continuum models, only good curve fits."

/unknown soil mechanican
from the XXth century/

THIS PRESENTATION

→ Non-continuous phenomena:

phenomena from the engineering practice that cannot properly be reflected with continuum mechanics (eg. FEM; FDM)

→ What is DEM?

- ⇒ definition
- ⇒ history
- ⇒ example
- ⇒ main steps

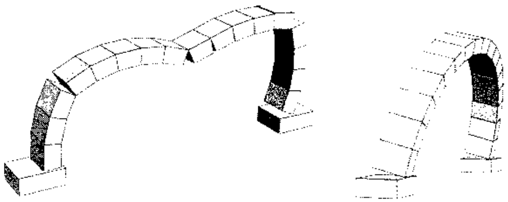
WHAT IS DEM?

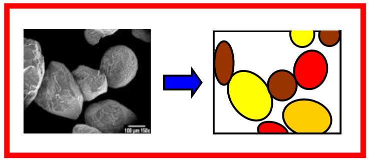
The aim: to model materials or structures having discrete internal builtup

„what does it do if loads are put on it?”

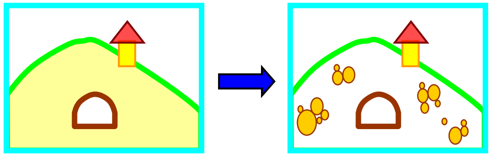
The components of the model:

separate elements + their contacts





or



- mechanical models for the material of the elements: → rigid
  → deformable
- contacts: → they have to be recognized
  → they have to be mechanically modelled:
  → non-deformable
  → deformable: e.g.point-like, deformable
  e.g. finite size, deformable } e.g. frictional, e.g. cemented

WHAT IS DEM?

Definition:

A discrete element model is a numerical model which satisfies the following conditions:

→ consists of clearly separated finite-sized elements, and the contacts between them;

→ the elements have their own independent degrees of freedom e.g. translational, rotational, deformational (→← FEM: „C0-continuous”, „C1-continuous”)

→ the displacements are finite (i.e. „large”)

→ elements can be separated and new contacts can be formed between them, so that the creation of new contacts are automatically recognised (→← frame models, FEM fracture models: no new contacts)

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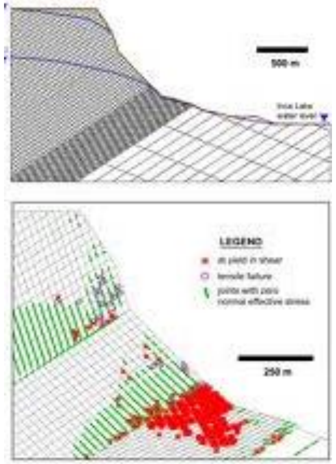
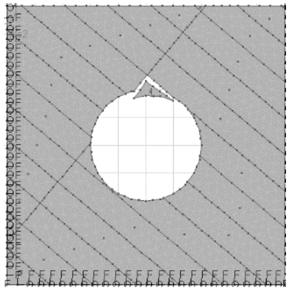
WHAT IS DEM?

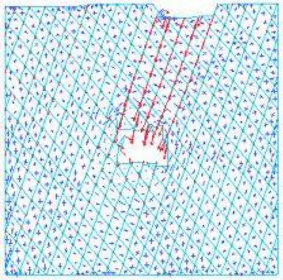
History overview

→ end of 1960ies:

Peter A Cundall,
Imperial College:
UDEC
(„Uniform Distinct Element Code")

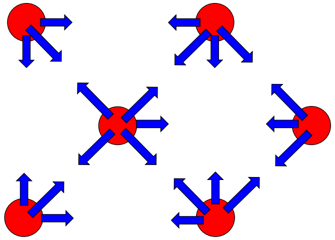






model for fractured rocks

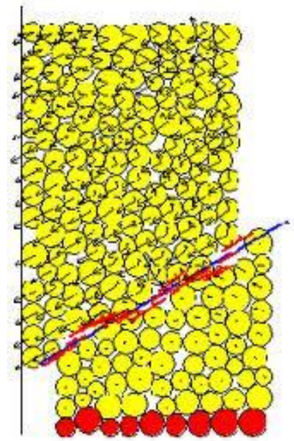
→ 1970ies: Molecular Dynamics methods, physics literature
point-like objects: not really DEM



WHAT IS DEM?

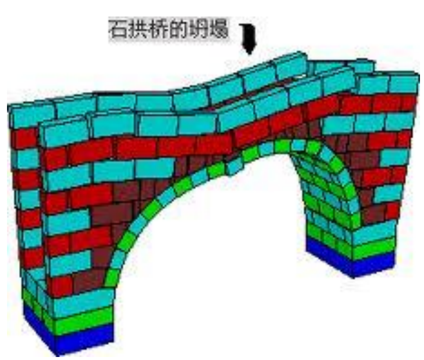
History overview

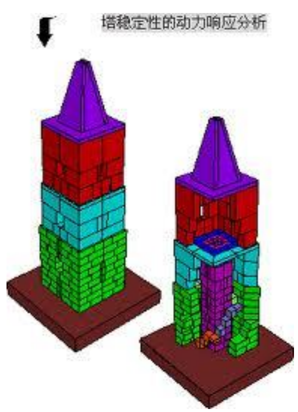
→ end of 1970ies: Cundall & Strack, 1979:
„**BALL**”

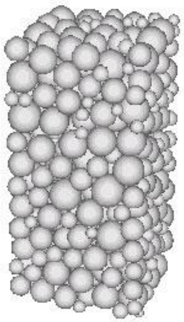


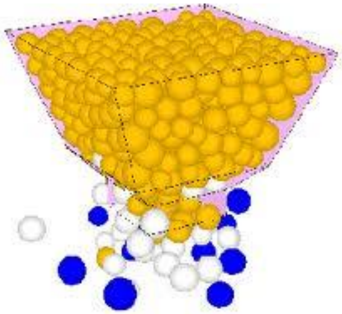
→ from the 1980ies:
- → several new codes, already in 3D
- → general element shapes
- → different mathematical tools

→ from the 1990ies: practical applications in engineering









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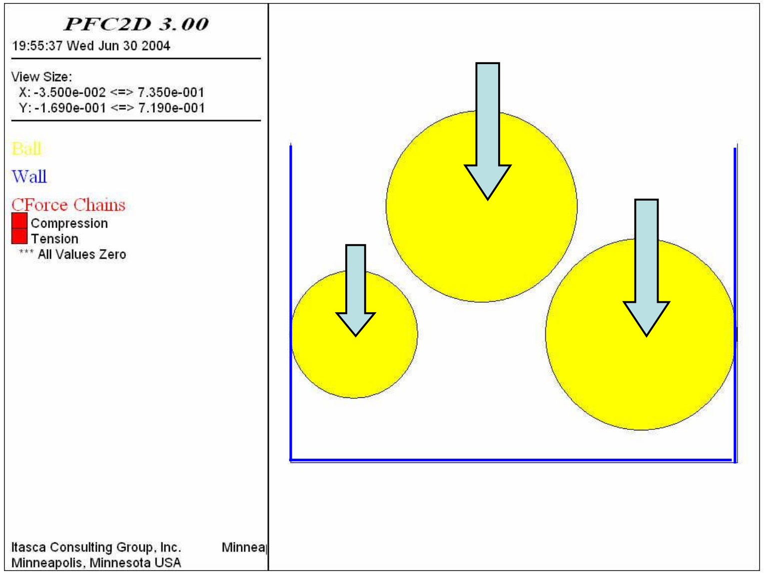
EXAMPLE

1. Define the geometry:

ball id 1 x 0.10 y 0.20 rad 0.10
ball id 2 x 0.55 y 0.20 rad 0.15
ball id 3 x 0.30 y 0.40 rad 0.15
wall id 1 nodes 0.0 0.0 0.7 0.0
wall id 2 nodes 0.7 0.0 0.7 0.5
wall id 3 nodes 0.0 0.5 0.0 0.0



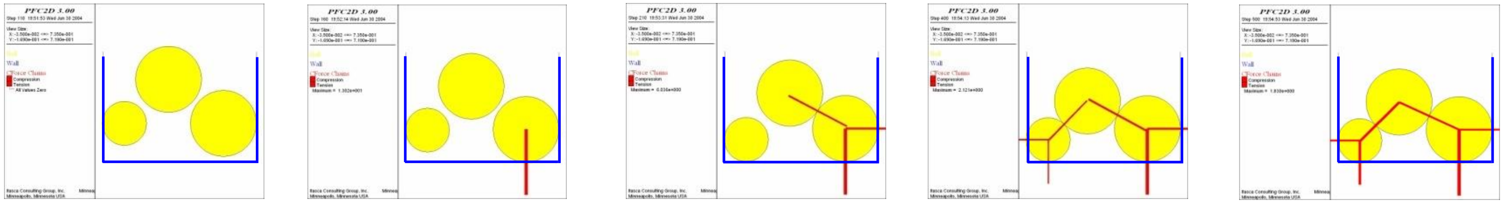
2. Specify the material parameters:

property density 10.0
property kn 1.e4 ks 0.5e4 friction 0.2
wall id 1 kn 1.e12 ks 0. friction 0.
wall id 2 kn 1.e12 ks 0. friction 0.
wall id 3 kn 1.e12 ks 0. friction 0.

3. Specify the loads:

set gravity 0.0 -9.81

From them, calculate the displacements: [series of small increments]



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⇒ definition

⇒ history

⇒ example

⇒ main steps

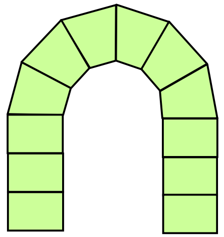
Step 1: Geometry

Step 2: Material characteristics

Step 3: Determine the displacement increments

WHAT IS DEM?

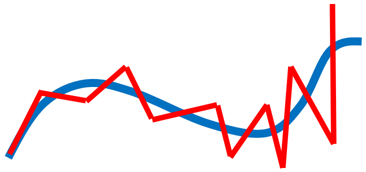
<u>Main steps of the analysis of an engineering problem:</u>



- the model: collection of separate elements ('**discrete elements**')
  {1 body ↔ 1 element} or {several bodies ↔ few elements}
  <u>Step 1.:</u> define the initial geometry

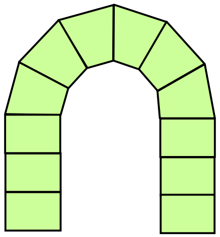
- rigid or deformable ***elements***; rigid or deformable ***contacts***
  <u>Step 2.:</u> specify the material characteristics

- the loading process:
  (e.g. external forces acting on the elements; e.g. prescribed displacements)
- calculation of the state changing: ***series of small increments, based on*** „ **f** = m**a** "
  <u>Step 3.:</u> calculation of the actual displacement increments



WHAT IS DEM?

Main steps of the analysis of an engineering problem:



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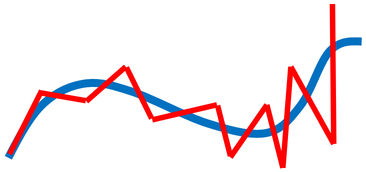
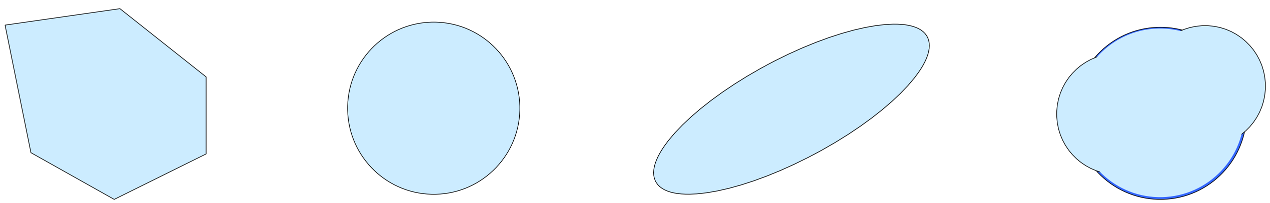


THE GEOMETRY

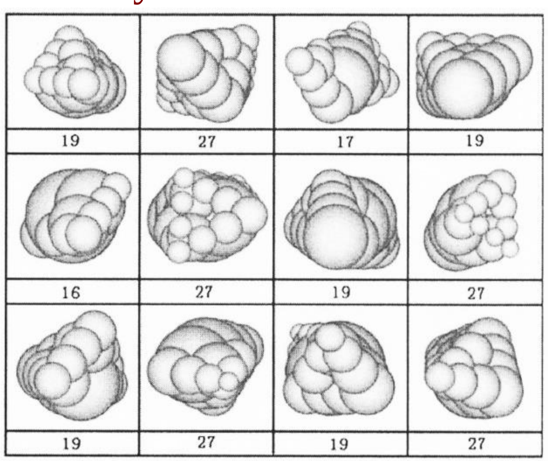
Element shapes:

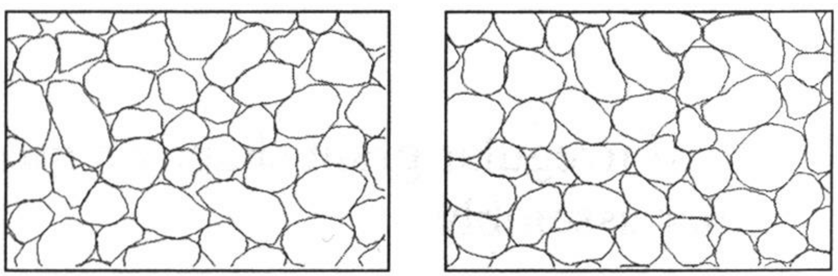


polygon, polihedron   circle, sphere   ellipse, ellipsoid   complex shapes

Matsushima, 2005:

e.g. Lu & McDowell, 2007, PFC-3D:
Railway ballast

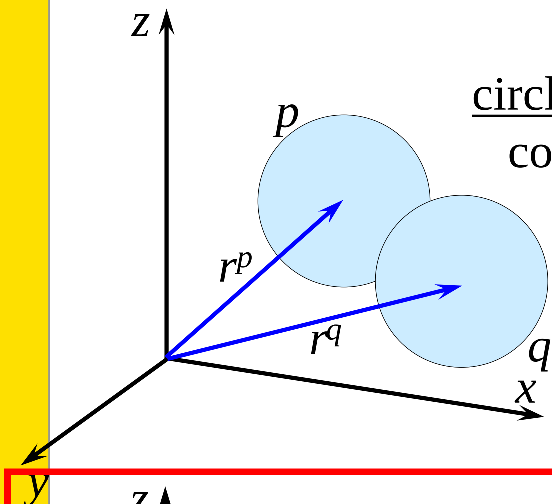




(a) Toyoura sand model   (b) Ottawa sand model

THE GEOMETRY

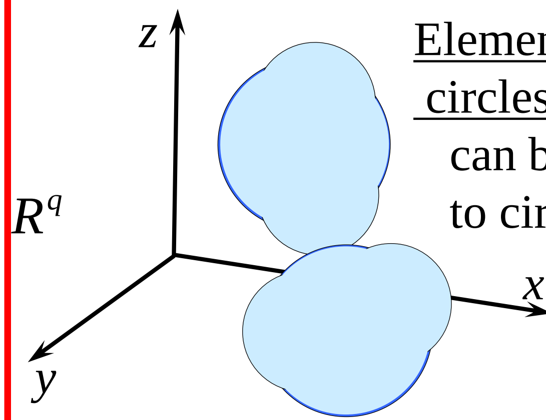
Contact recognition: a point of an element is in the interior of another element



circles/spheres:

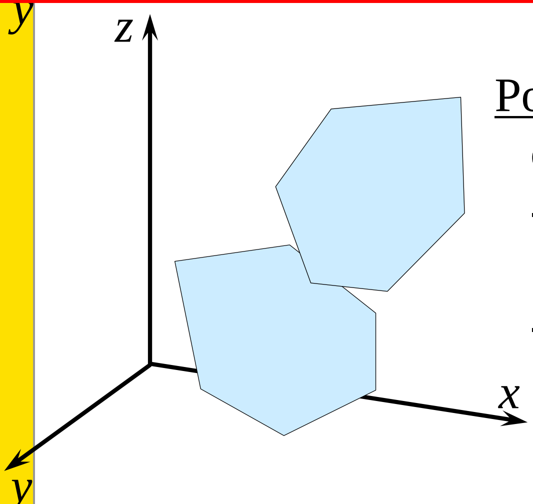
contact if:

$$\left|\mathbf{r}^q - \mathbf{r}^p\right| \le R^p + R^q$$



Elements composed of circles/spheres:

can be treated similarly to circles/spheres

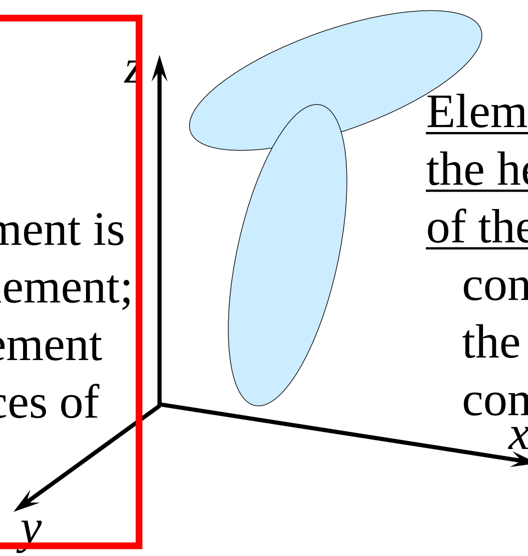


Polygons/polyhedra:

contact if :

-- a node of an element is inside another element;

-- an edge of an element intersects the faces of another element



Elements defined with the help of the equation of their surface:

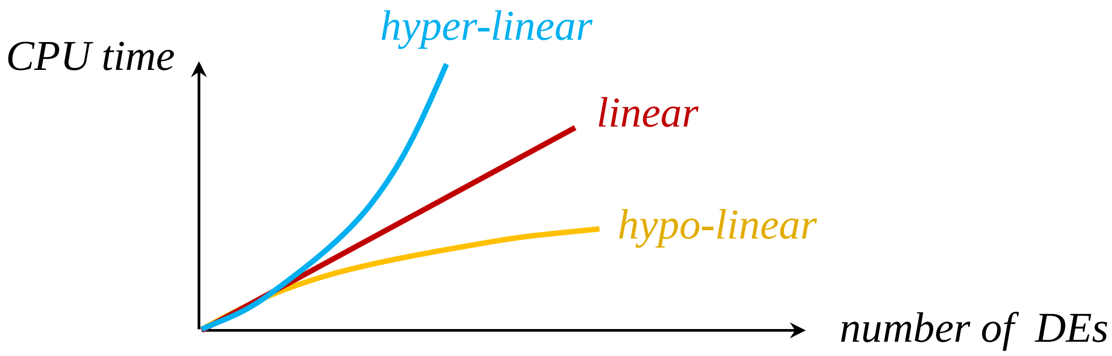
contact if:

the two equations have common solutions

THE GEOMETRY

Contact recognition: several different algorithms exist; its speed basically determines the computational efficiency of the whole DEM code!

the time consuming part: to check the existence of a contact with exact calculations



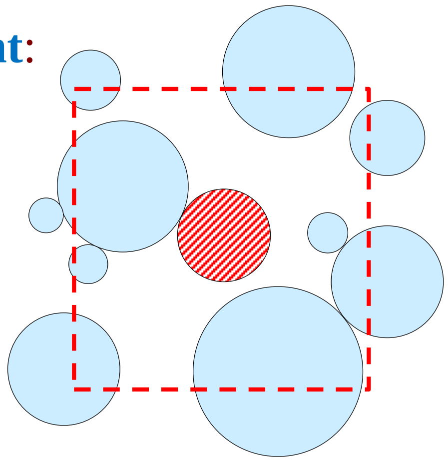
THE GEOMETRY

<u>Contact recognition:</u> several different algorithms exist; its speed basically determines the computational efficiency of the whole DEM code!

<u>the time consuming part:</u> to check the existence of a contact with exact calculations

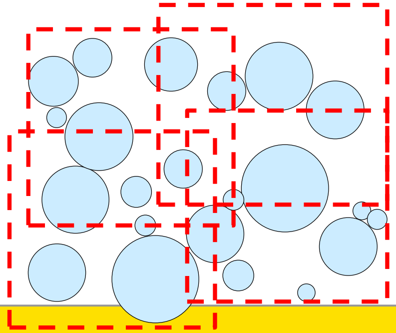
Aim: **avoid checking <u>every</u> element with <u>every other</u> element**:

Trick #1: **apply windows**



→ „body based search” technique:
consider only those others which are in the vicinity of the analyzed element;
then take the next element to analyze, …

→ „space based search”:



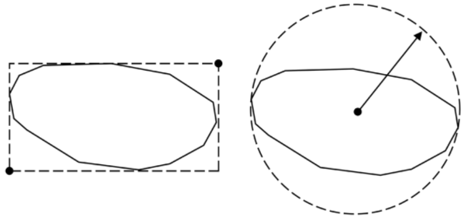
divide the domain into „windows” (overlapping);
collect which elements are in which windows;
analyze those pairs only where both elements belong to the same window

THE GEOMETRY

<u>Contact recognition:</u> several different algorithms exist; its speed basically determines the computational efficiency of the whole DEM code!

<u>the time consuming part:</u> to check the existence of a contact with exact calculations

Aim: **avoid checking <u>every</u> element with <u>every other</u> element**:



Trick #2:

Simple **surrounding domains** checked first
(instead of the elements having complicated shapes)

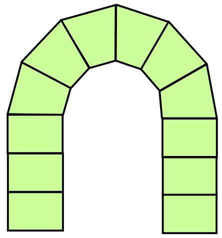
the idea: „surrounding domain" assigned to each element
(simple shape: a brick; a sphere)

→ Phase 1.: **intersection** beween the **surrounding domains**? (fast)

→ if necessary: Phase 2.: detailed, **exact** calculations (slow)

WHAT IS DEM?

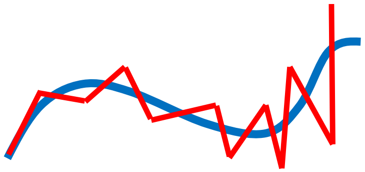
<u>Main steps of the analysis of an engineering problem:</u>



- the model: collection of separate elements('**discrete elements**')
  {1 body ↔ 1 element} or {several bodies ↔ few elements}
  <u>Step 1.:</u> define the initial geometry

- rigid or deformable ***elements***; rigid or deformable ***contacts***
  <u>Step 2.:</u> specify the material characteristics

- the loading process:
  (e.g. external forces acting on the elements; e.g. prescribed displacements)
- calculation of the state changing: ***series of small increments, based on*** „ **f** = m**a** ”
  <u>Step 3.:</u> calculation of the actual displacement increments

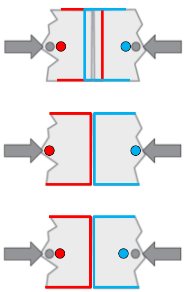


MECHANICAL PROPERTIES

Constitutive model of the elements:

task: ***to specify how to calculate the stresses from the deformations of the elements***

Elements basic types:



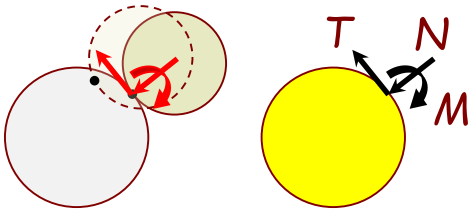
→ perfectly rigid elements: deformability concentrated into the contacts

→ deformable elements:

stress-strain-relations have to be specified

[e.g. E, μ, …]

Constitutive model of the contacts:



task: ***to specify how to calculate the contact forces from the relative displacements at the contact***

Contacts basic types:

→ usually: „deformable" contacts (relative displ. at the contact regions)

[e.g. „ $\Delta T = k_T \cdot \Delta u_T$ but $T \leq - f \cdot N$ "]

→ sometimes: infinitely rigid contacts: no overlap or any other deformation

QUESTIONS

1. What are the **four conditions** to consider a numerical technique a **discrete element model**?

2. The following numerical methods are not DEM. **Why**? Give reason for both.

→ molecular dynamics method

→ FEM 3D continuum model with contact elements

3. What are the **three main steps** of discrete element modelling?

4. What does it mean that a contact detection algorithm is **hyper-linear**?

5. Introduce the aim and the basic idea of the **body-based technique**. Introduce the aim and the basic idea of the **space-based technique**.

6. What is the task of the constitutive model of the **elements**? From the point of view of constitutive mechanical behaviour, what **basic types of elements** are used in the different DEM models?

7. What is the task of the constitutive model of the **contacts**? From the point of view of constitutive mechanical behaviour, what **basic types of contacts** are used in the different DEM models?