Study of Liquefaction Susceptibility of Granular Soils using Discrete Element Modeling

presented to
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presented by

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Outline

- Background
- Research Objectives
- Shape Characterization and Reconstruction
- Discrete Element Modeling
- Conclusions

Background

- Particle morphology governs micromechanical behavior of granular media
- Traditionally, 2-D DEM analyses adopted in studying influence of particle shapes on mechanical response of cohesionless soil and most analyses are limited to circular or idealized shapes
- Limited knowledge available on 3-D discrete element modeling of highly irregular particle shapes

Background

- Particle shape modeling techniques in 2-D using DEM
  - Circular/spherical discrete elements: Cundall and Strack (1979)
  - Polygonal discrete elements: Barbosa and Ghaboussi (1992)
  - Elliptical discrete elements: Ting et al. (1993)
  - Overlapping discrete element cluster (ODEC): Ashmawy et al. (2003)

- Particle shape modeling techniques in 3-D
  - 3-D ellipsoid-based DEM - ELLIPSE3D: Lin and Ng (1997)
  - Polyhedron-based approach: Ghaboussi and Barbosa (1990)
  - 3-D image-based DEM: Matsushima (2004)

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Research Objectives

- To design and develop automated 3-D tomography reconstruction algorithms applied to shape characterization of sand particles
- To numerically validate the reconstruction method by comparing with 3-D reconstructions obtained from multiple projections of a single particle generated using optical and X-ray methods
- 2-D and 3-D discrete element modeling of particle shape
- Evaluation of influence of particle shape on shear strength of soil

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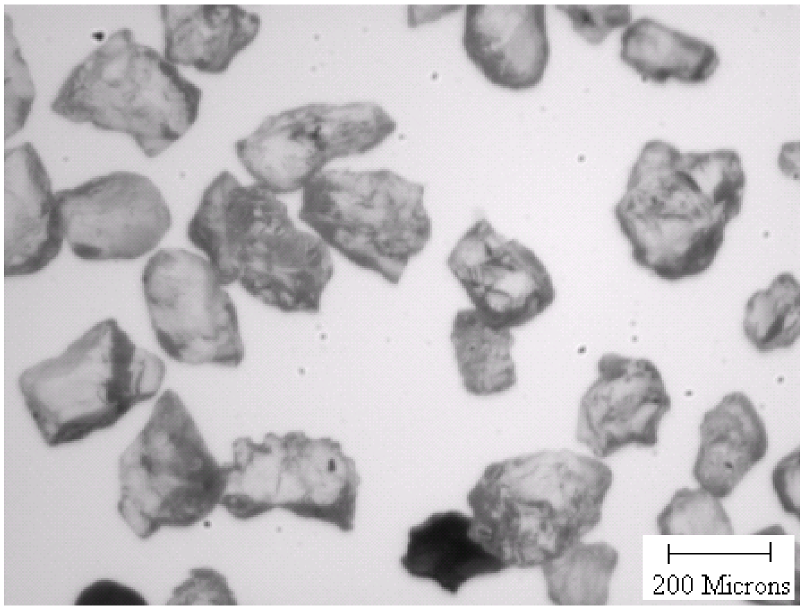
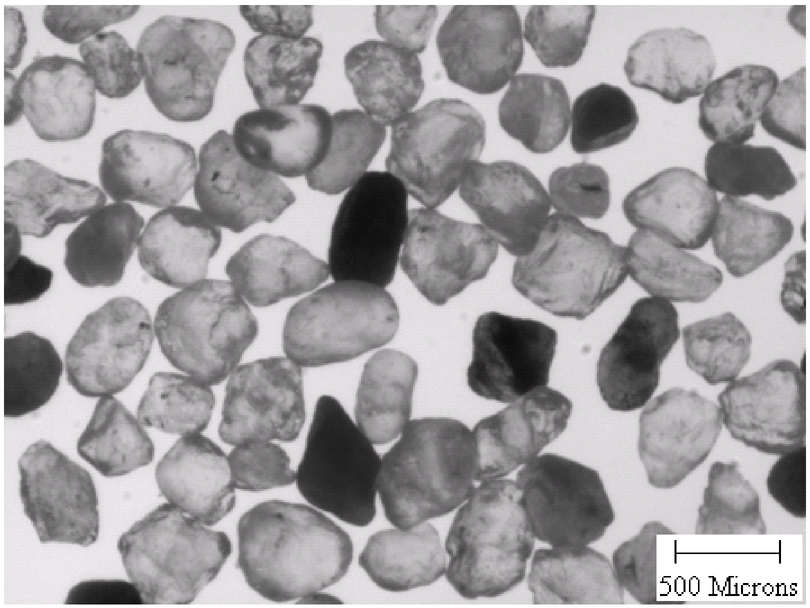
Data Set



Daytona Beach Sand



Michigan Dune Sand

Outline

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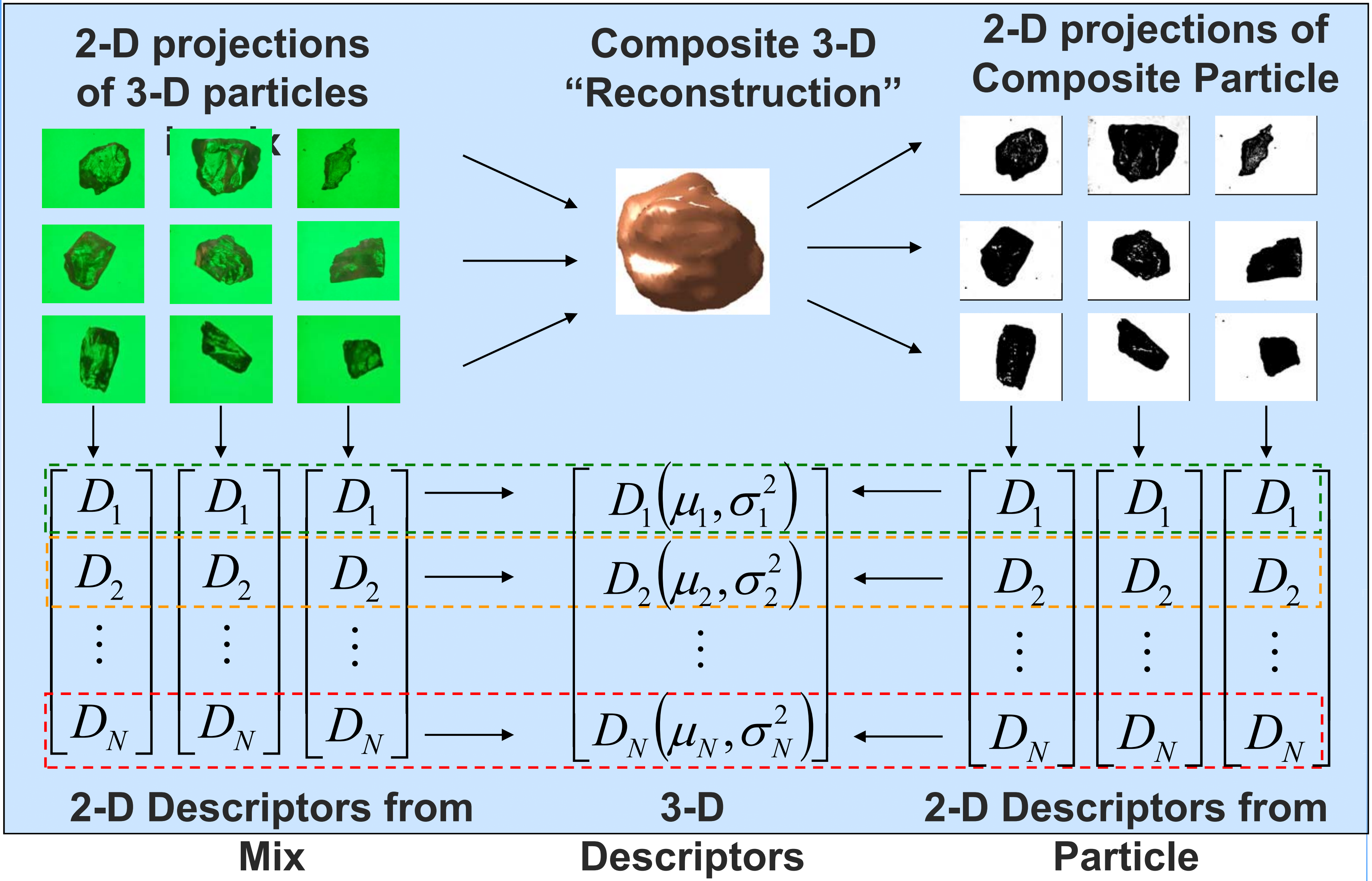
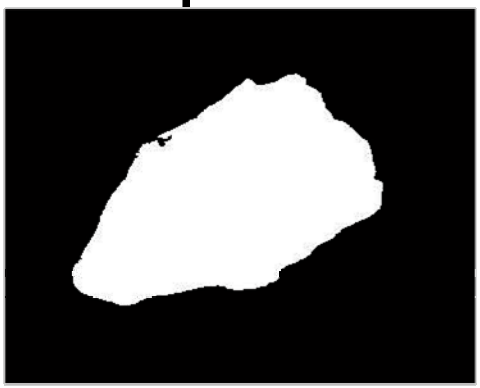
Research Premise

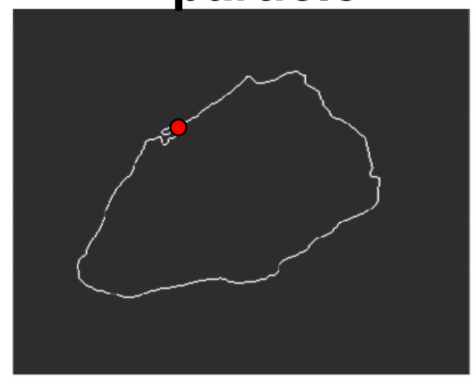


3D Shape Descriptors

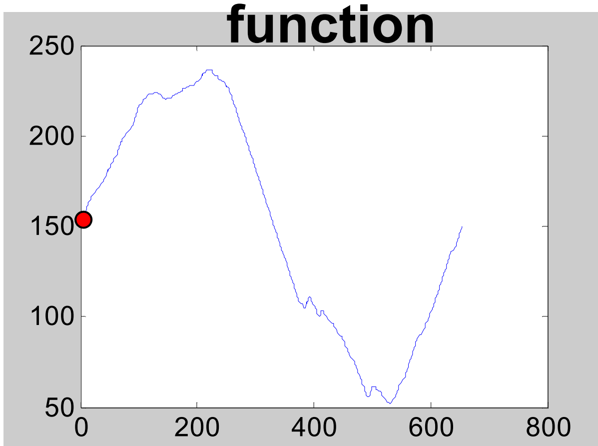
2D projection from a particle



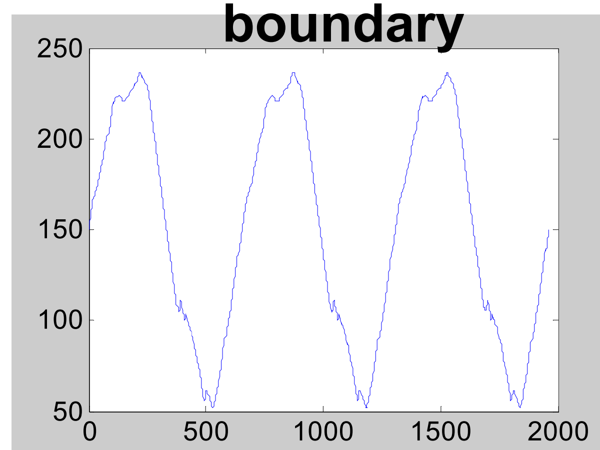
Boundary of the particle



Un-rolled boundary as a function



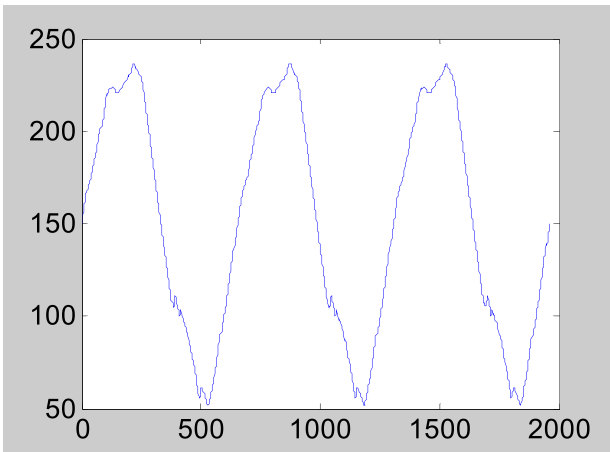
Periodic representation of boundary



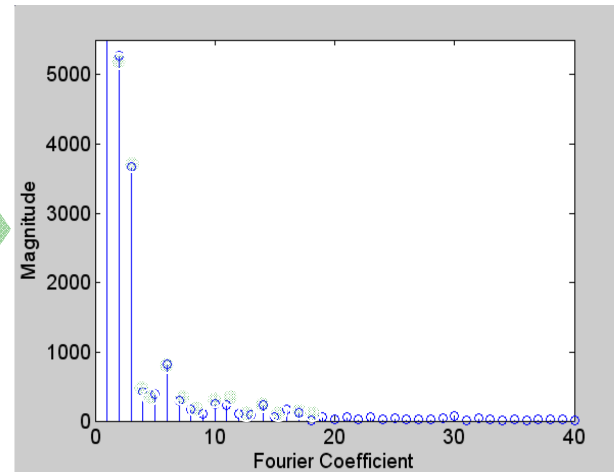
Sebestyn and Benson - "unrolling" a closed outline

3D Shape Descriptors

- The Fourier Coefficients can then be reduced using principal components analysis (PCA) to a desired set amount



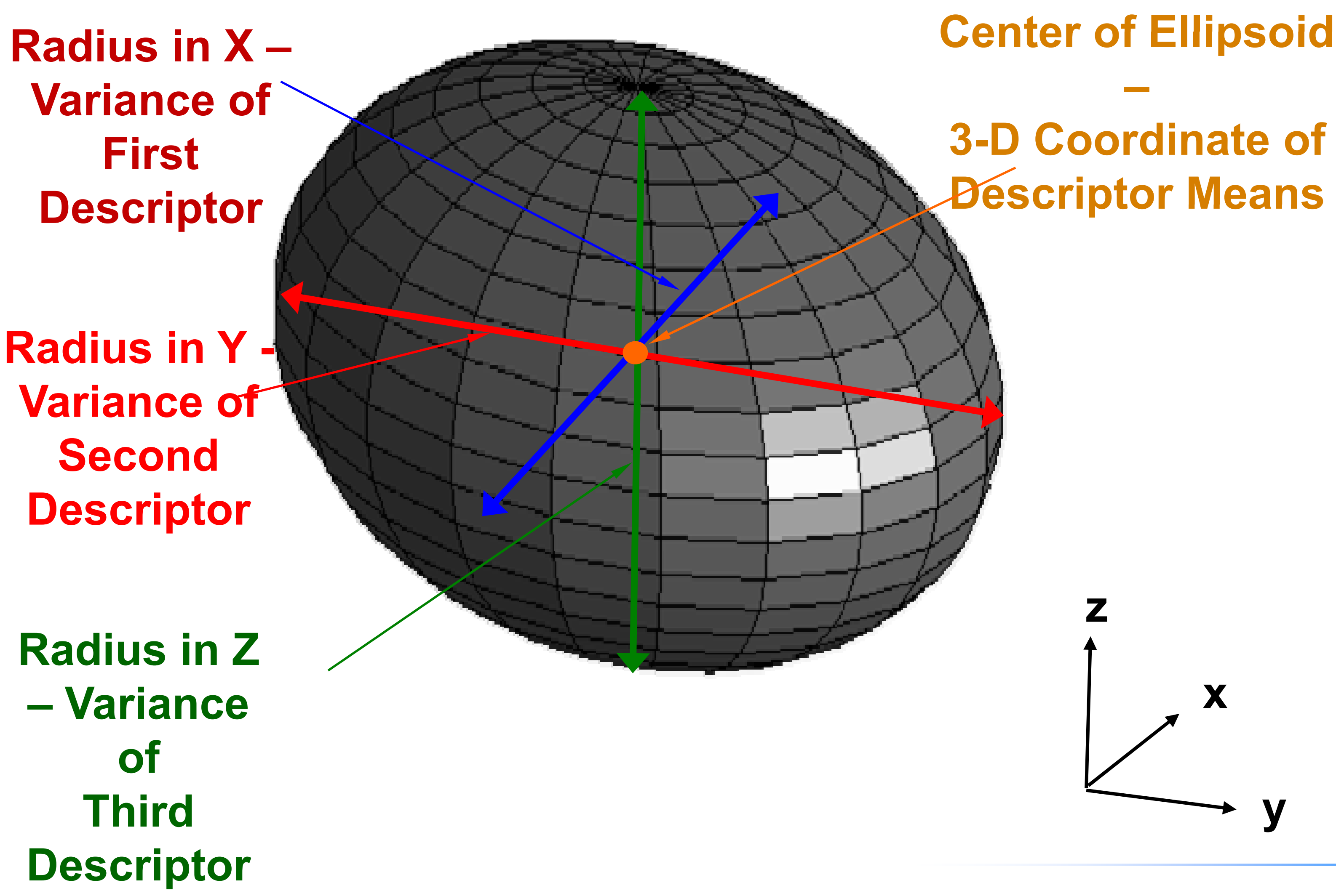
FFT



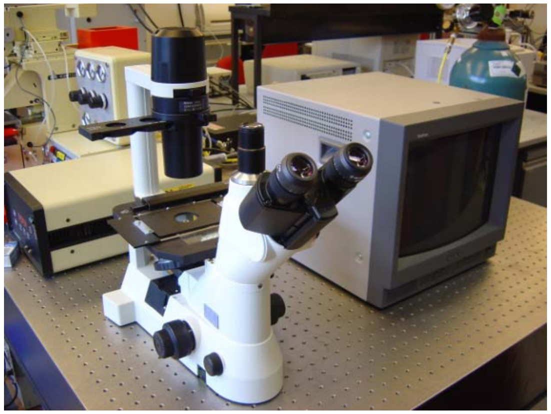
$$\begin{bmatrix} c_1 \\ c_2 \\ c_3 \\ \cdot \\ \cdot \\ \cdot \\ c_n \end{bmatrix} \xrightarrow{\textbf{PCA}} \begin{bmatrix} D_1 \\ D_2 \\ D_3 \end{bmatrix}$$

R. Duda, P.Hart, D. Stork, *Pattern Classification*

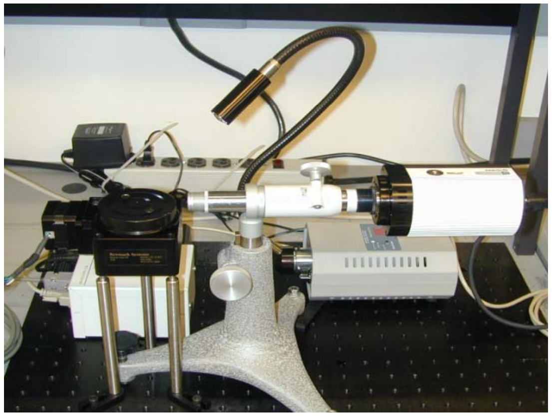
Ellipsoid Model for Illustrating the Performance of the Algorithm



Algorithm and Premise Validation



Validates
Premise

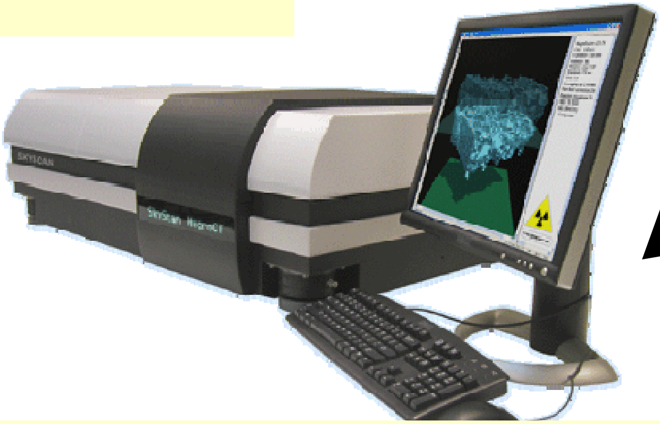


Optical Microscope

Optical Tomography

Multiple views, Multiple Particles

Multiple views, Single Particles

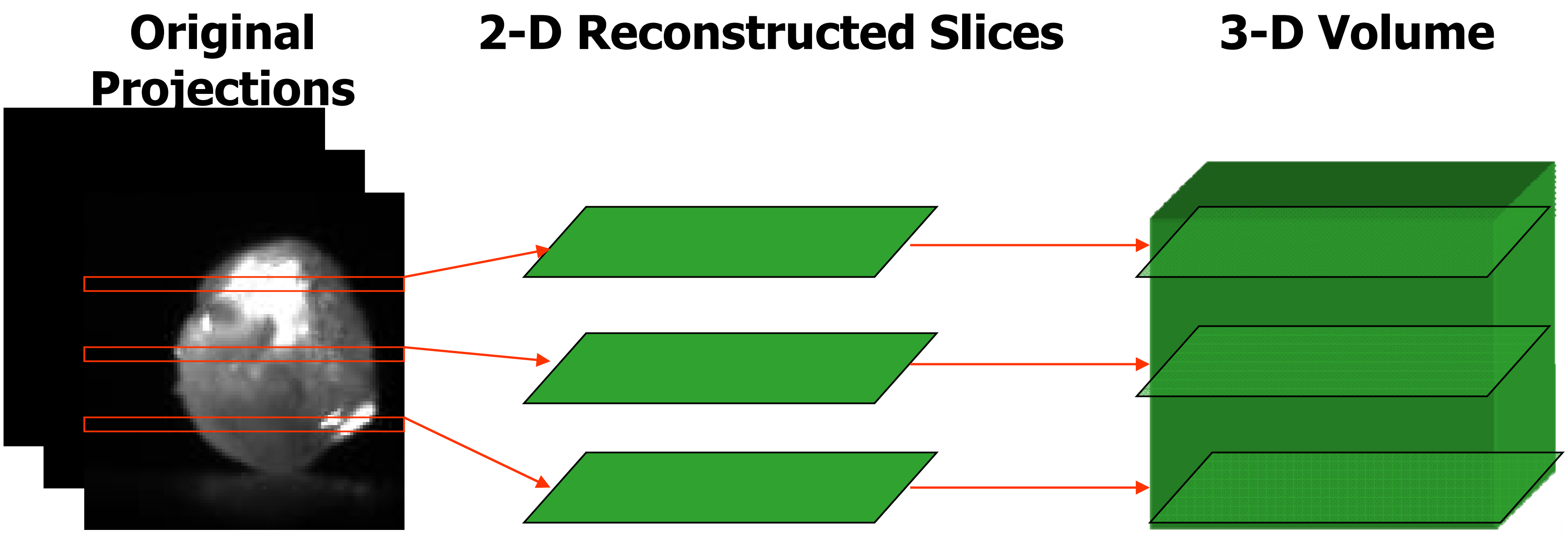


Validates
Algorithm

X-Ray CT System

Multiple views, Single Particle (Most Accurate)

2-D Algebraic Reconstruction Technique for Constructing 3-D Volumes

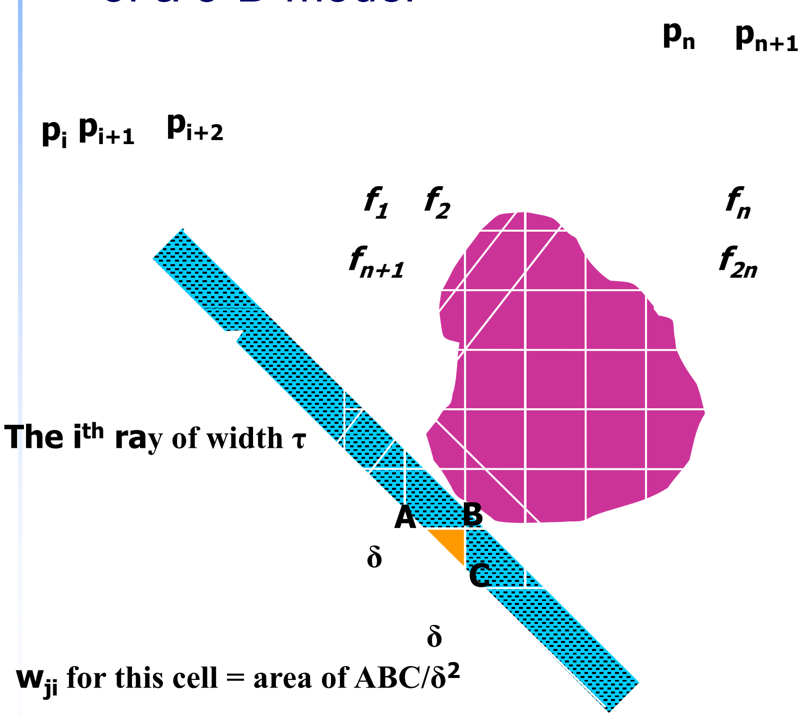


For a set of 2-D projections, each row of pixels is treated as a set of 1-D projections. ART is performed on each set of these 1-D projections and 2-D slices of the 3-D object are created. These slices are then stacked to form the final 3-D object

Algebraic Reconstruction Technique

- The following explanation of ART is for the 2-D case, and is how one can reconstruct a single 2-D slice of a 3-D model

$$\sum w_{ij} f_j = p_i, \qquad i = 1, 2, \ldots, M$$



f_j = constant value in the j^{th} cell

w_{ij} = fractional area of the j^{th} cell intercepted by the i^{th} ray

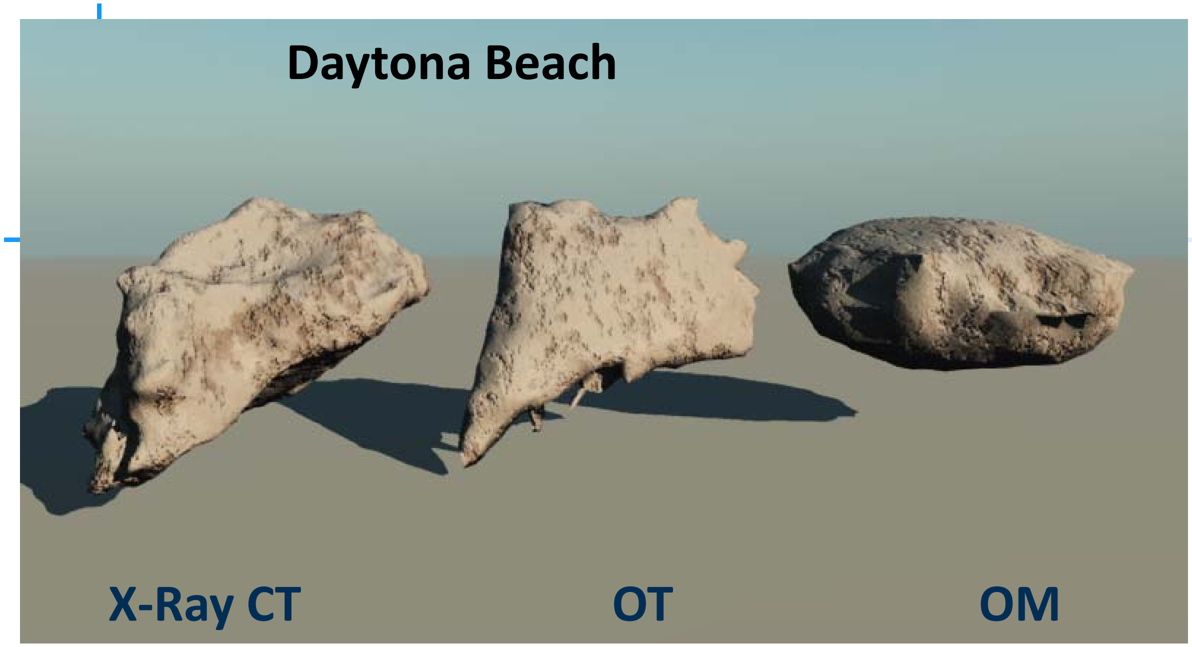
p_i = the ray-sum measured with the i^{th} ray as shown in previous slide

M = the total number of rays in all projections

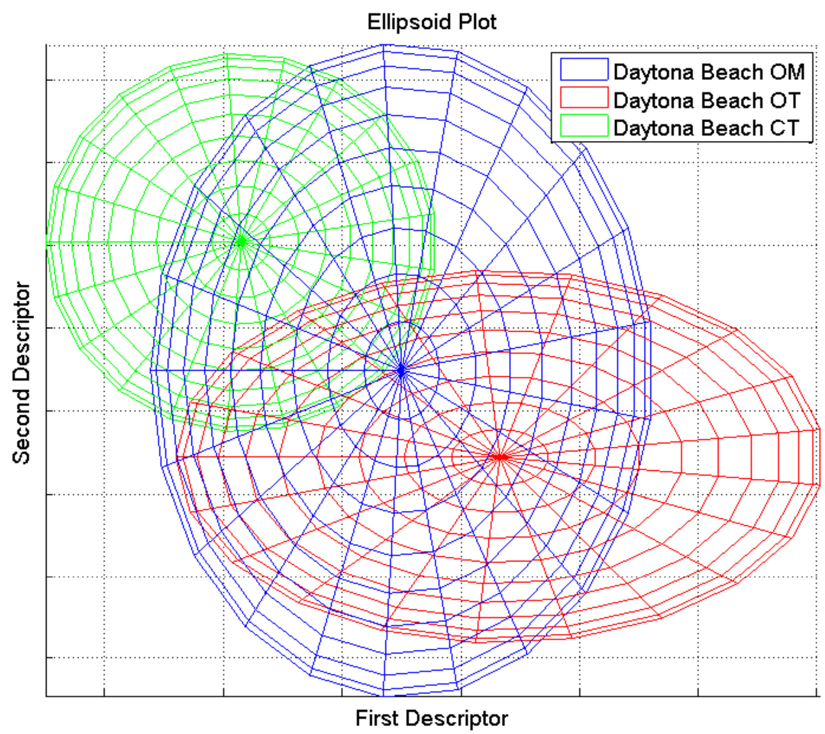
$$w_{11} f_1 + w_{12} f_2 + w_{13} f_3 + \ldots + w_{1N} f_N = p_1$$
$$w_{21} f_1 + w_{22} f_2 + w_{23} f_3 + \ldots + w_{2N} f_N = p_2$$
$$\vdots$$
$$w_{31} f_1 + w_{32} f_2 + w_{33} f_3 + \ldots + w_{3N} f_N = p_3$$

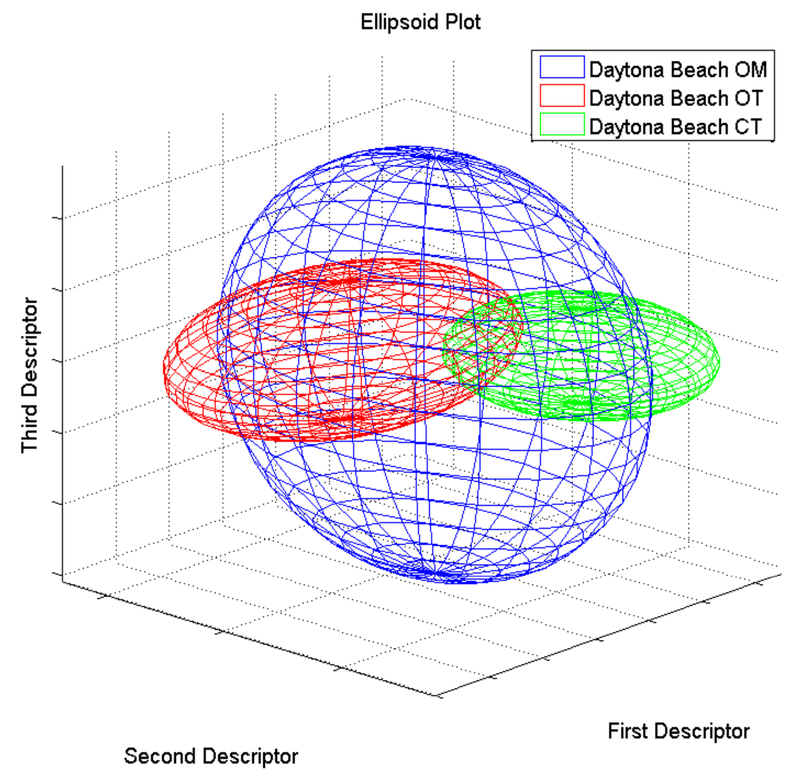
K. Tanabe, "Projection method for solving a singular system"

Synthesis Results (Daytona Beach)

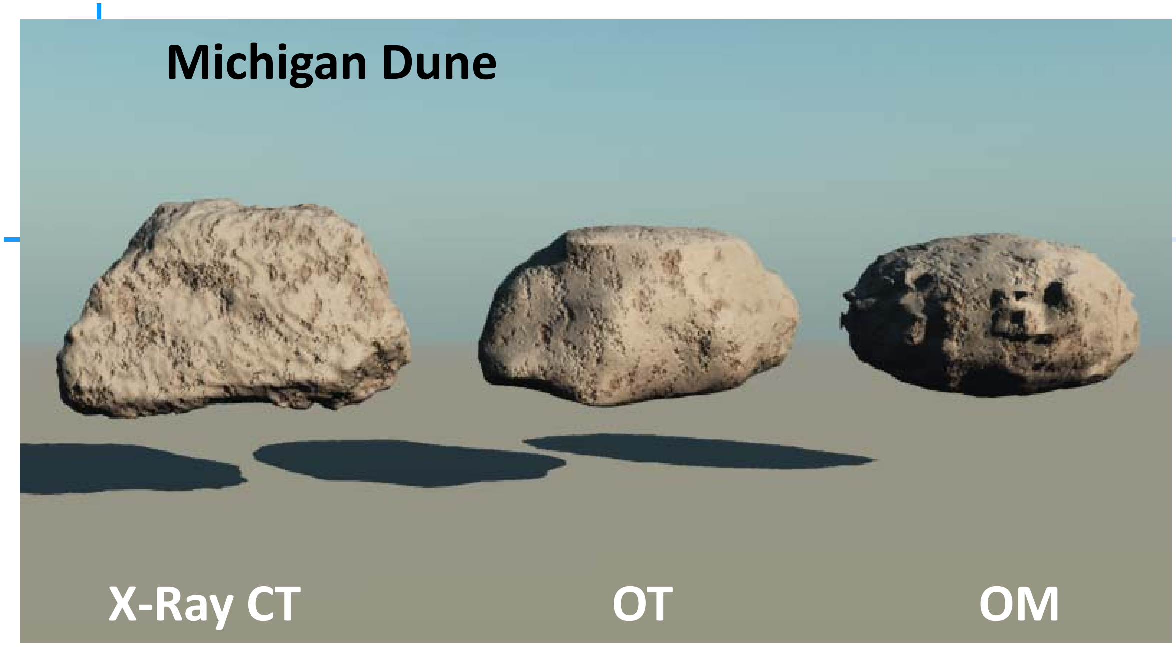


Green	X-ray CT
Red	OT
Blue	OM

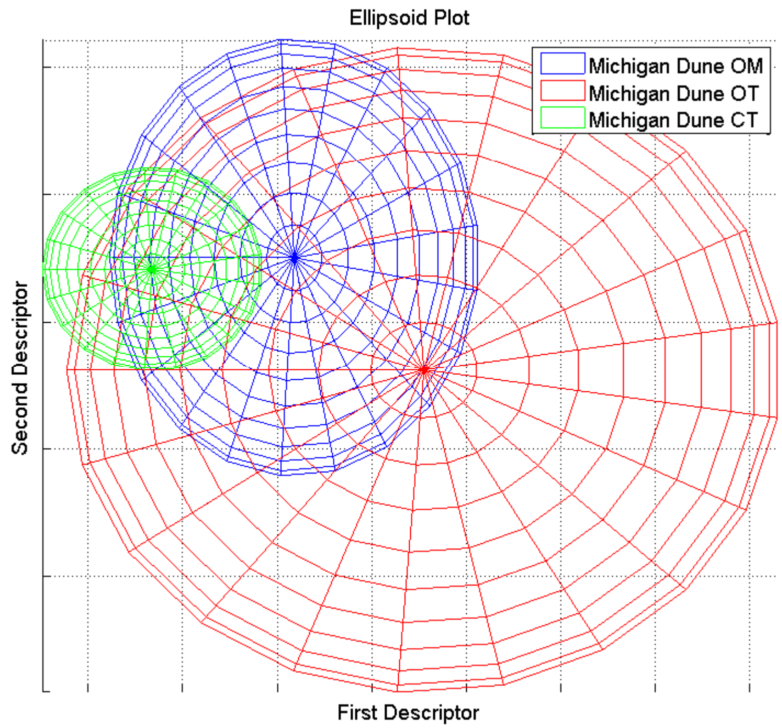


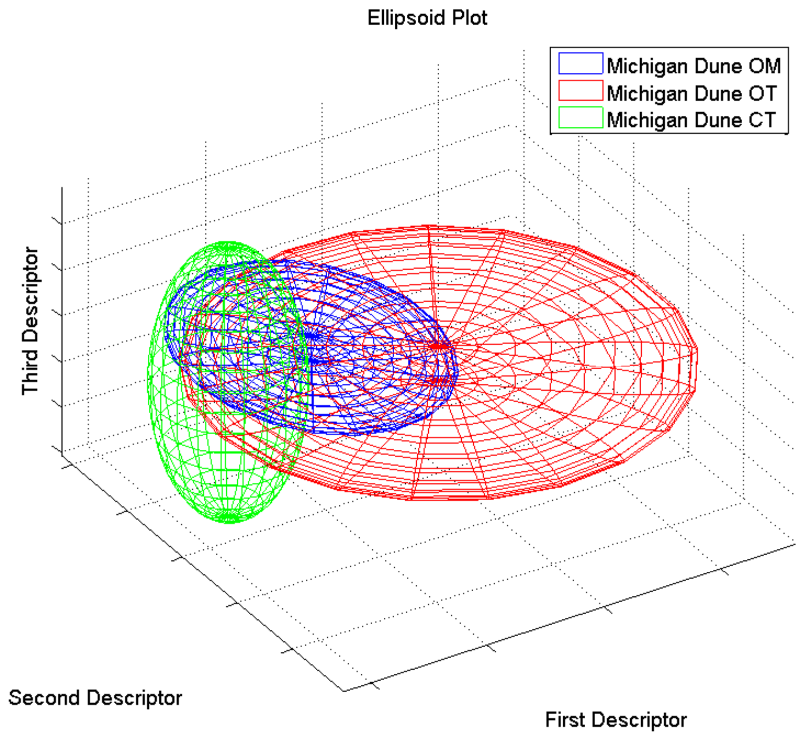


Synthesis Results (Michigan Dune)

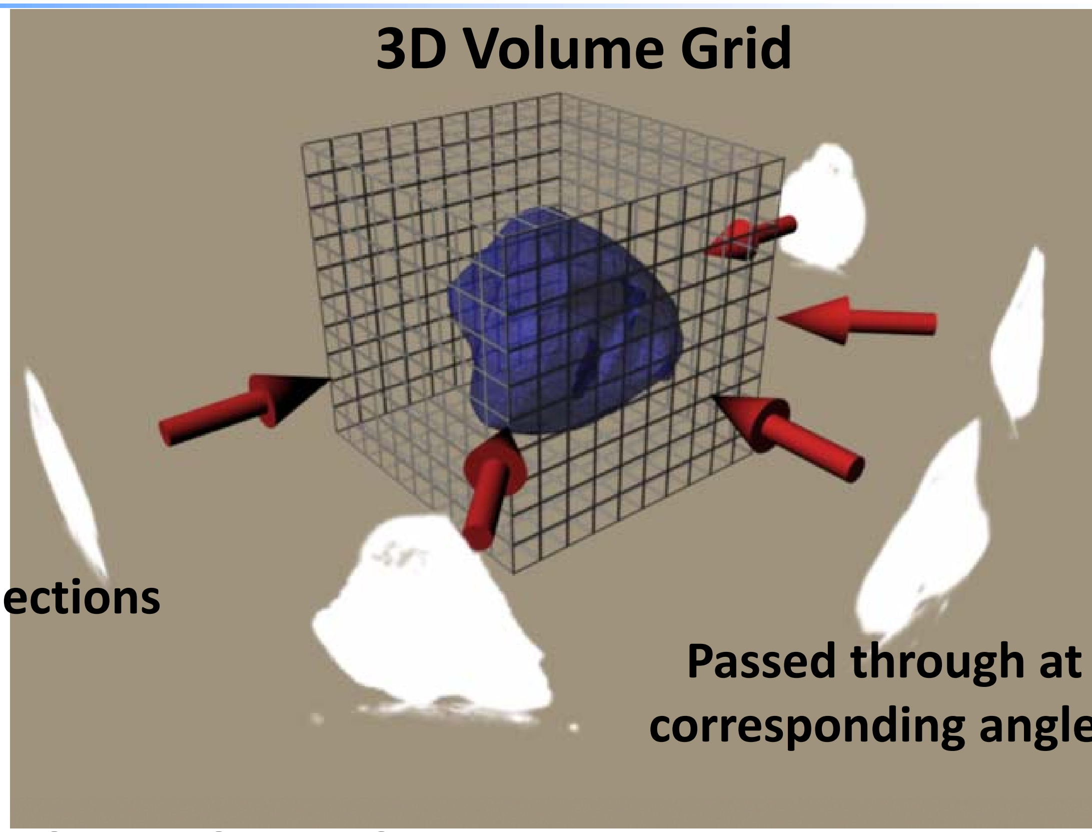


Green	X-ray CT
Red	OT
Blue	OM



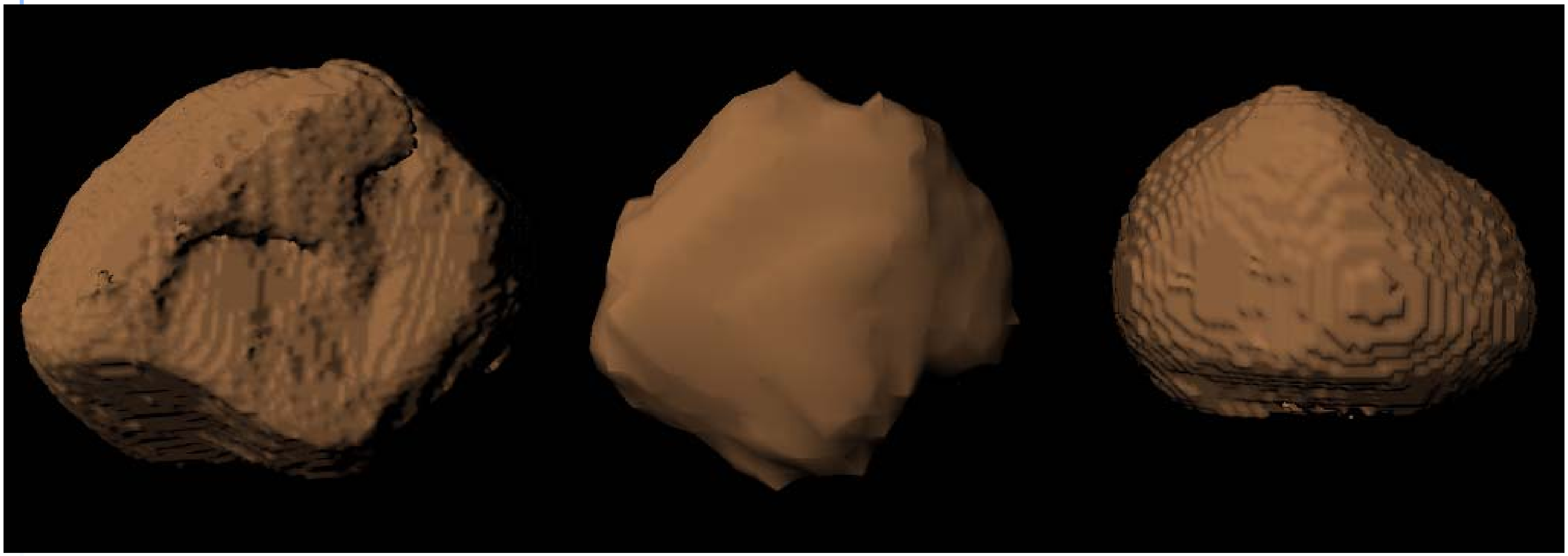


New ART Algorithm



In the new algorithm, the entire projection is passed through a 3D array, creating a bank of summed values, which are used for reconstruction

Michigan Dune Sand reconstruction using new algorithm



CT **Old OT** **New OT**

Online database

http://www.rowan.edu/colleges/engineering/clinics/shreek

[*] = Number of Particles

- Online geomaterial database
  - Computed Tomography
    - X-ray tomography
      - Michigan Dune [8]
      - Standard Melt [7]
      - Dry #1 [6]
      - Rhode Island [7]
      - Ala Wai Beach [5]
      - Kahala Beach [7]
      - Daytona Beach [5]
    - Optical tomography
      - Michigan Dune [8]
      - Standard Melt [7]
      - Dry #1 [6]
      - Rhode Island [7]
      - Ala Wai Beach [5]
      - Kahala Beach [7]
      - Daytona Beach [5]
  - Optical Microscopy
    - Michigan Dune [293]
    - Standard Melt [391]
    - Dry #1 [382]
    - Daytona Beach [299]

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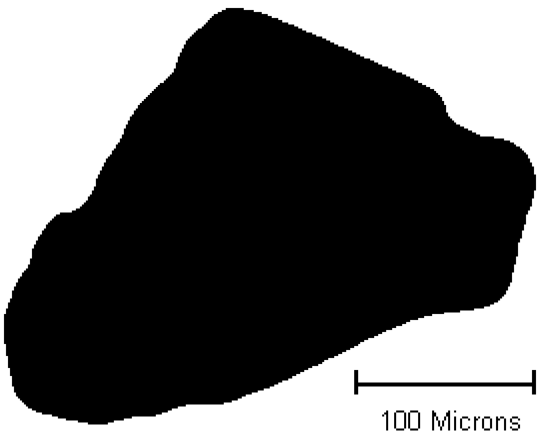
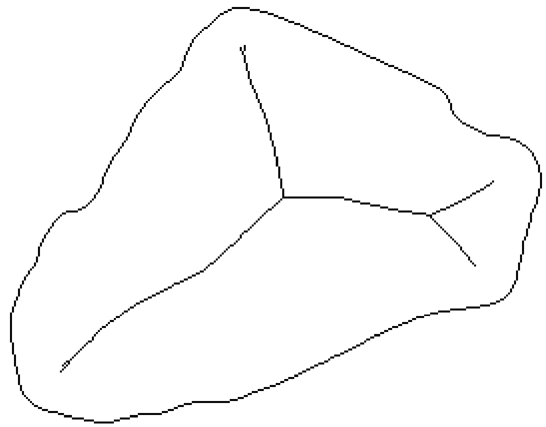
Research Methodology:
Particle Shape Modeling in Two Dimensions

Skeletonization



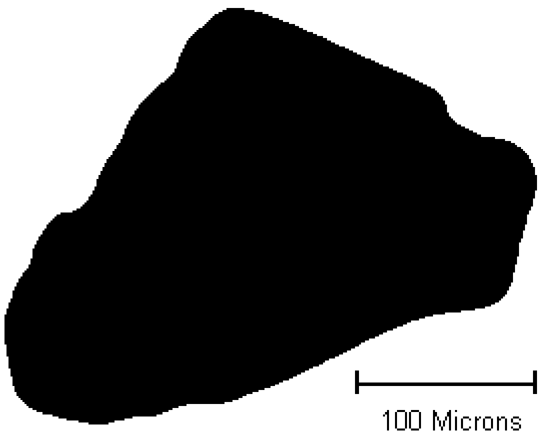
Daytona Beach Sand Grain



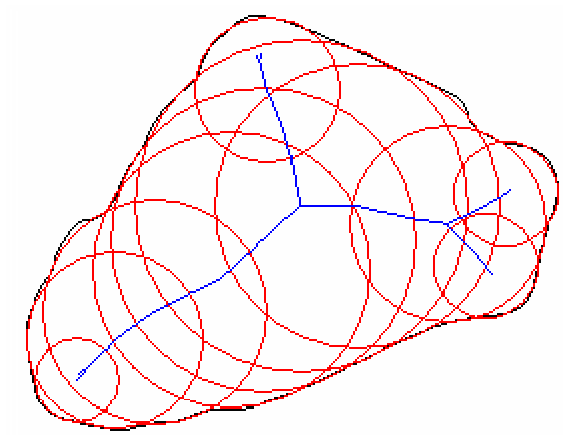
Skeleton

Research Methodology:
Particle Shape Modeling in Two Dimensions

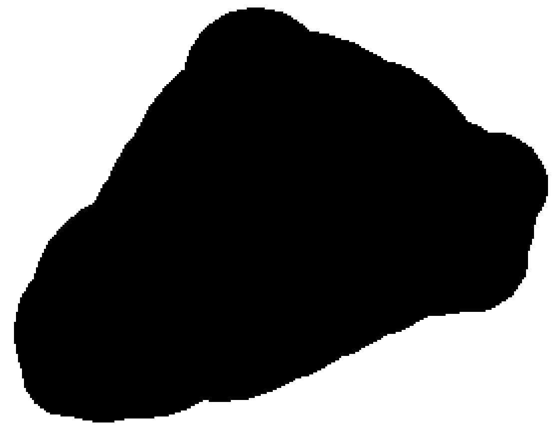
Overlapping Discrete Element Cluster Algorithm: ODEC-2D



Daytona Beach Sand Grain



Skeleton & ODEC



Model Particle

Number of circles needed to capture the shape = 10
Area uncovered < 1%

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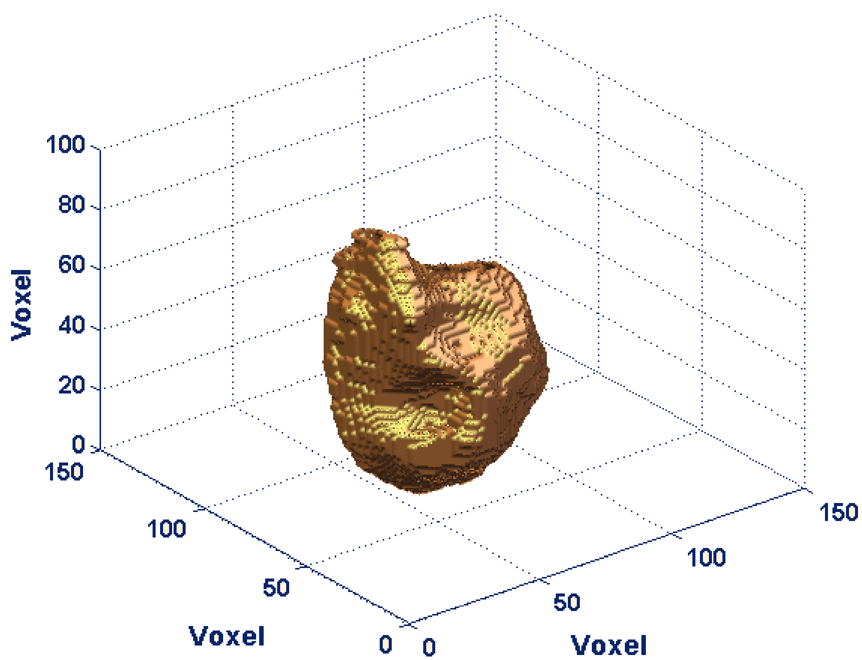
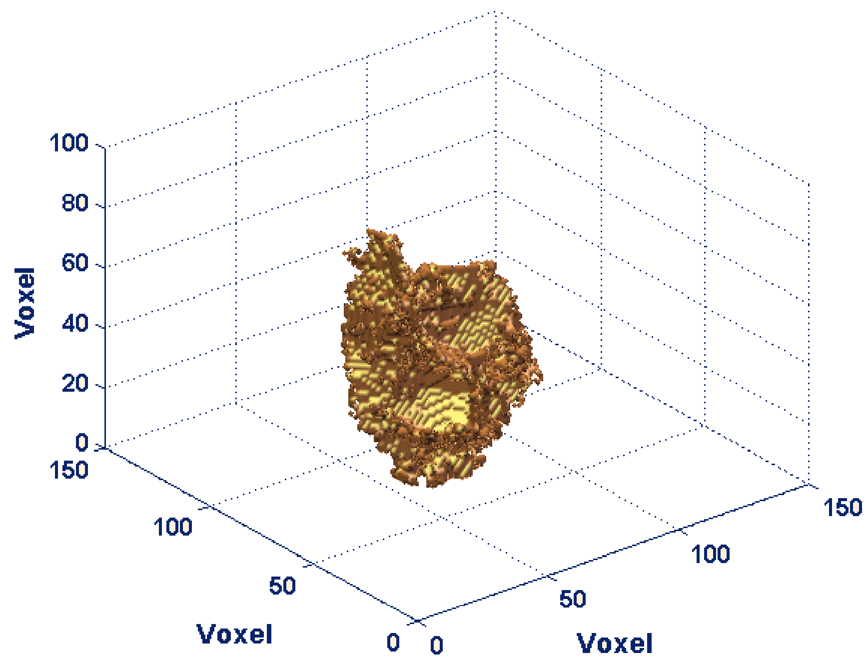
Research Methodology: Particle Shape Modeling in Three Dimensions

Skeletonization



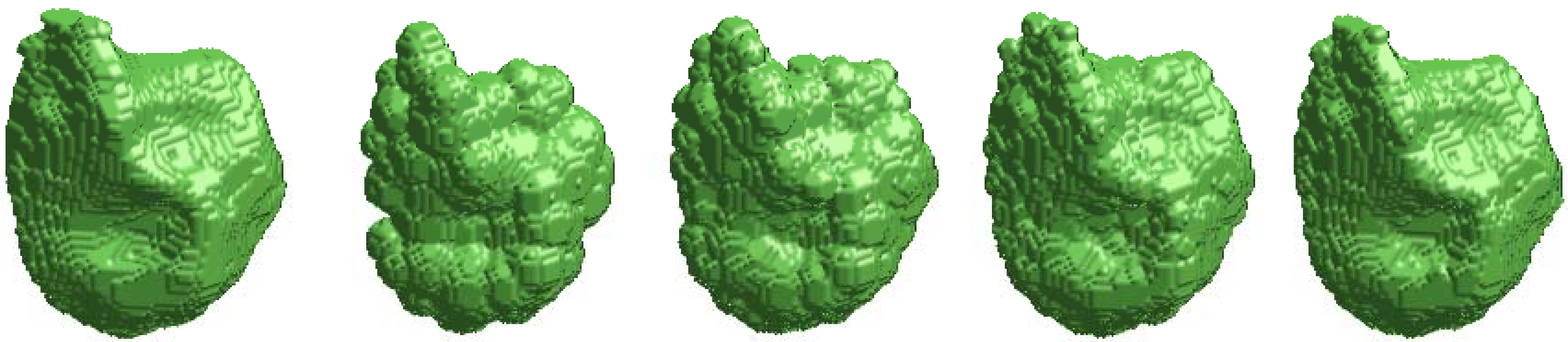
Daytona Beach Sand
(Grain 1)



Surface Skeleton

Research Methodology:
Particle Shape Modeling in Three Dimensions

Overlapping Discrete Element Cluster: ODEC-3D



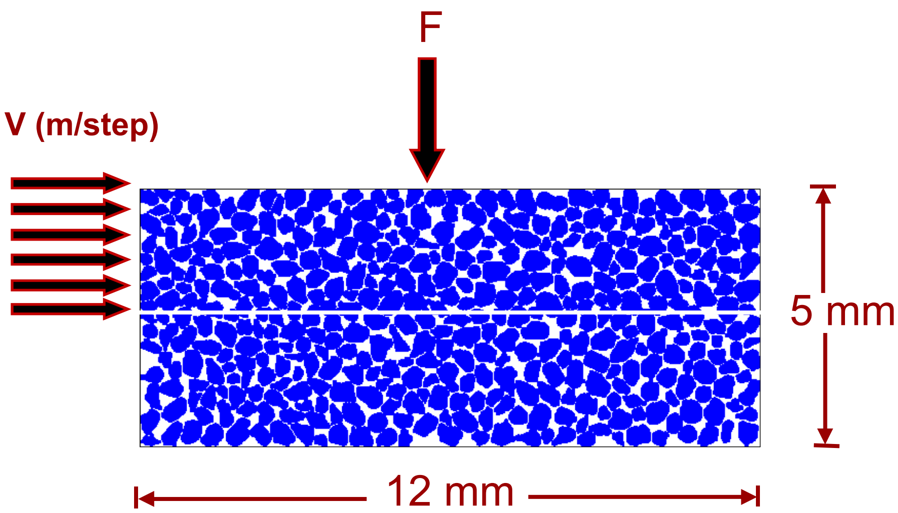
Daytona Beach Sand Grain | 85% Covered | 90% Covered | 95% Covered | 98% Covered

Research Methodology: Particle Shape Modeling in Two and Three Dimensions

Area / Volume Covered	Number of Discs 2-D	Number of Spheres 3-D
98%	9 – 14	251 - 296
95%	4 – 8	123 - 133
90%	3 – 6	61 - 62
85%	2 - 4	35 - 39

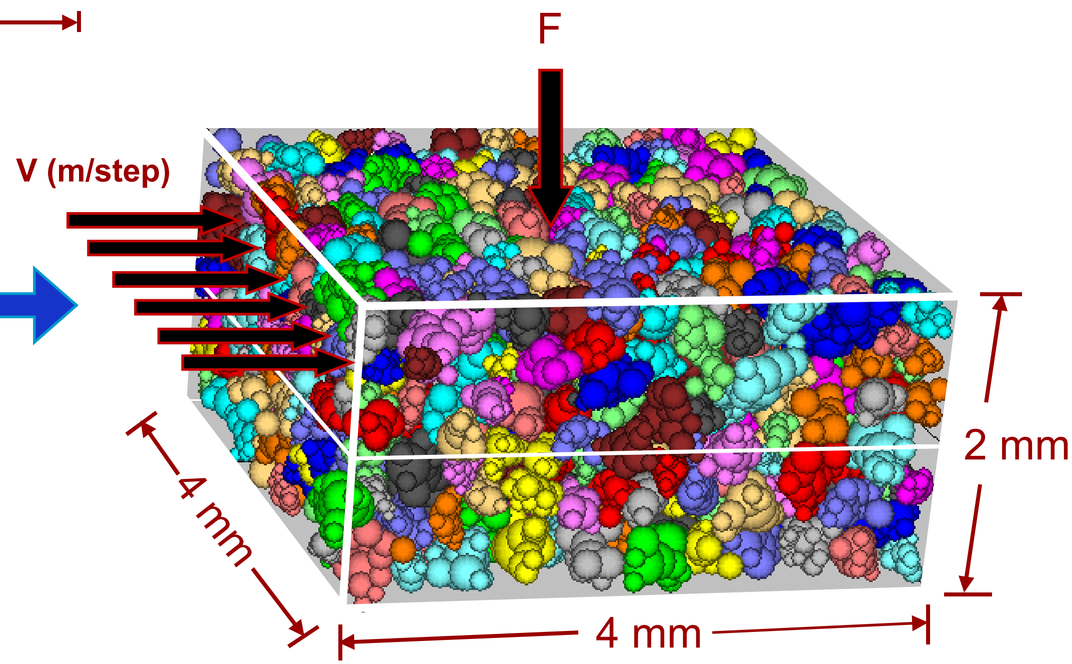
Research Methodology: DEM Simulation of Direct Shear Test

Sample: Daytona Beach Sand

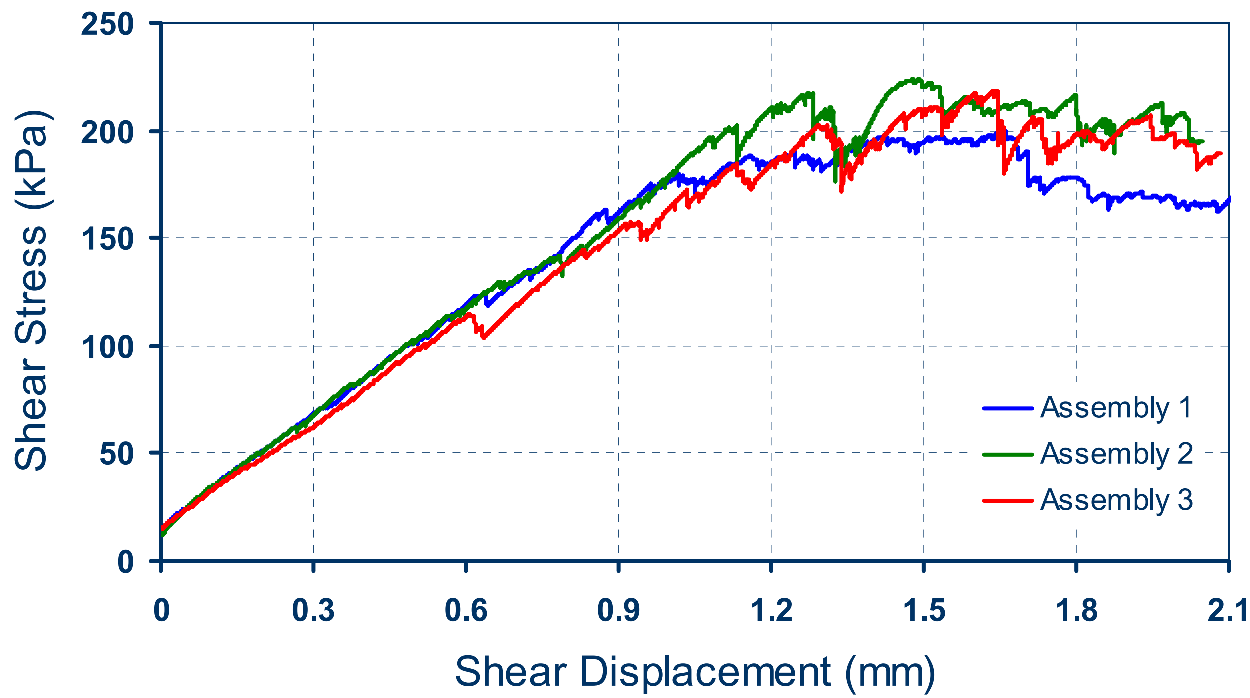


Angular Equivalent of 2-D Circular Particles

Angular Equivalent of 3-D Spherical Particles



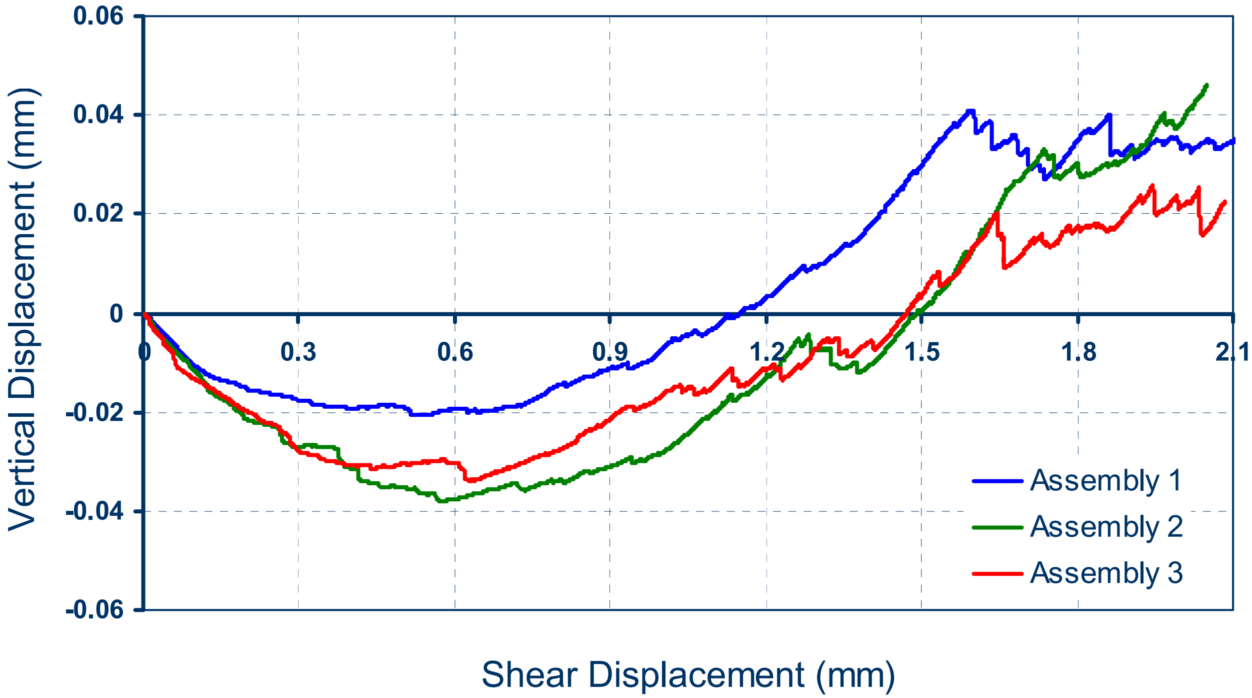
DEM Simulation in Three Dimensions of Daytona Beach Sand



Direct Shear Test on Daytona Beach Sand

(σ = 250 kPa)

DEM Simulation in Three Dimensions of Daytona Beach Sand



Direct Shear Test on Daytona Beach Sand

(σ = 250 kPa)

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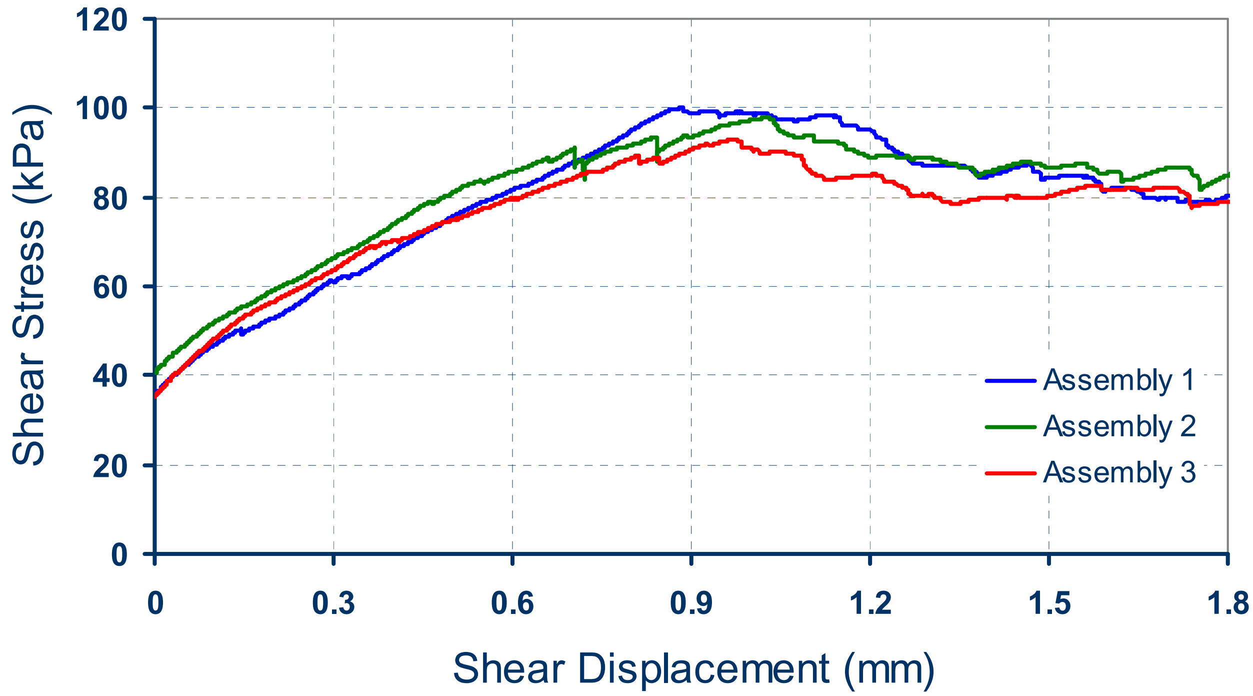
DEM Simulation in Three Dimensions of Glass Beads



Direct Shear Test on Spherical Particles

(σ = 200 kPa)

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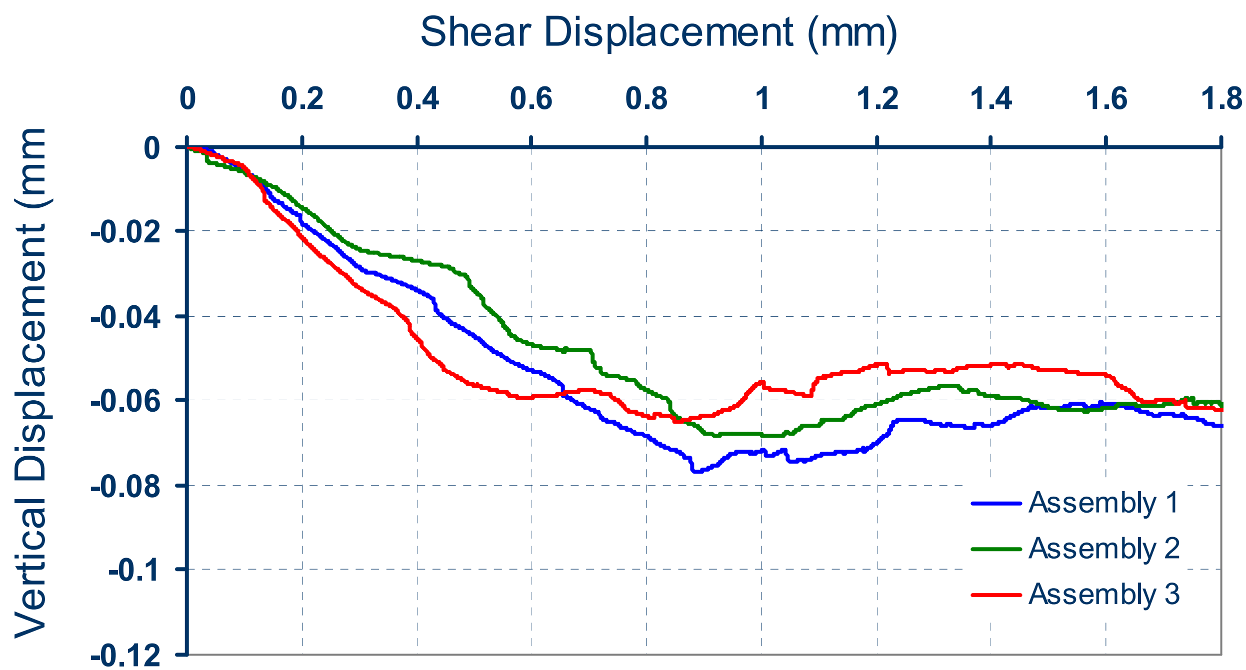
Research Methodology:
DEM Simulation in Three Dimensions



Direct Shear Test on Spherical Particles

(σ = 200 kPa)

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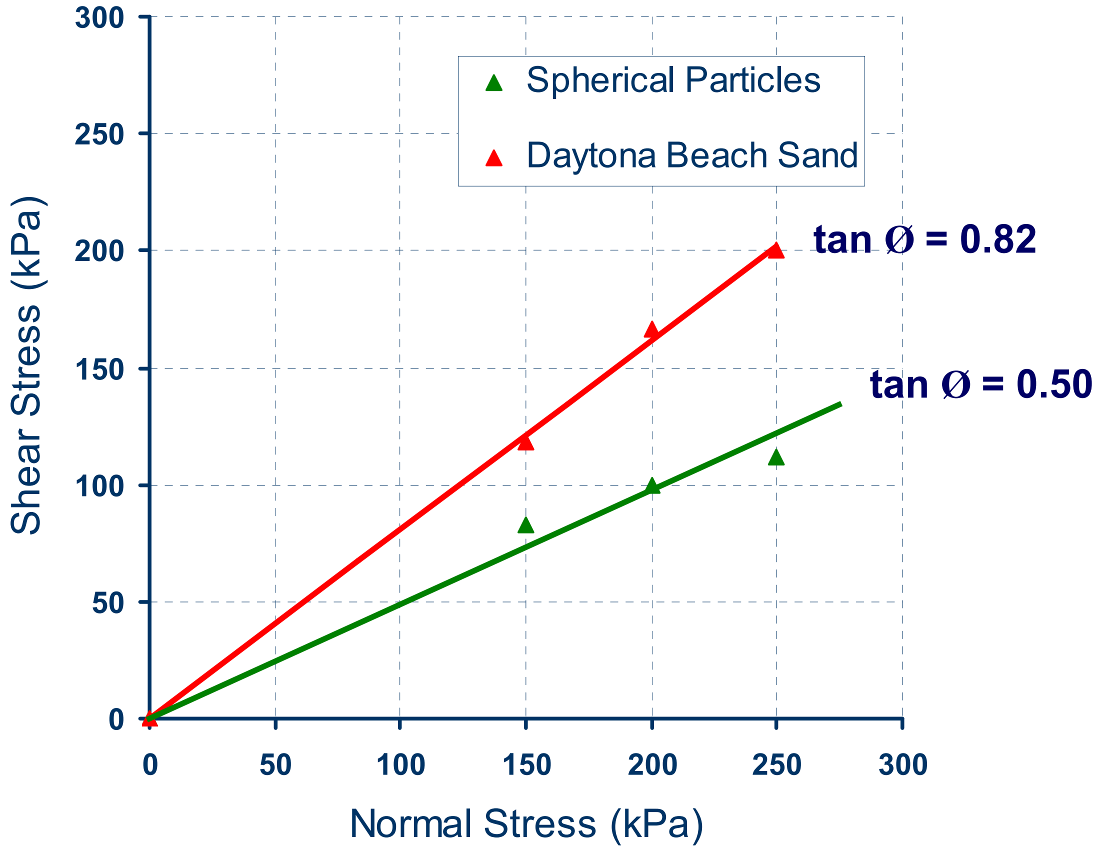
Research Methodology:
DEM Simulation in Three Dimensions



Research Methodology:
DEM Simulation in Three Dimensions

Angle of Internal Friction from 2-D and 3-D Simulation

Material	2-D Simulation	3-D Simulation	Experiments
Daytona Beach Sand	27°	39° – 43°	37.4°
Rounded Particles	17.2°	25° - 26.6°	24.4° – 27° *

* O'Sullivan et al. (2004); Phillips et al. (2006)

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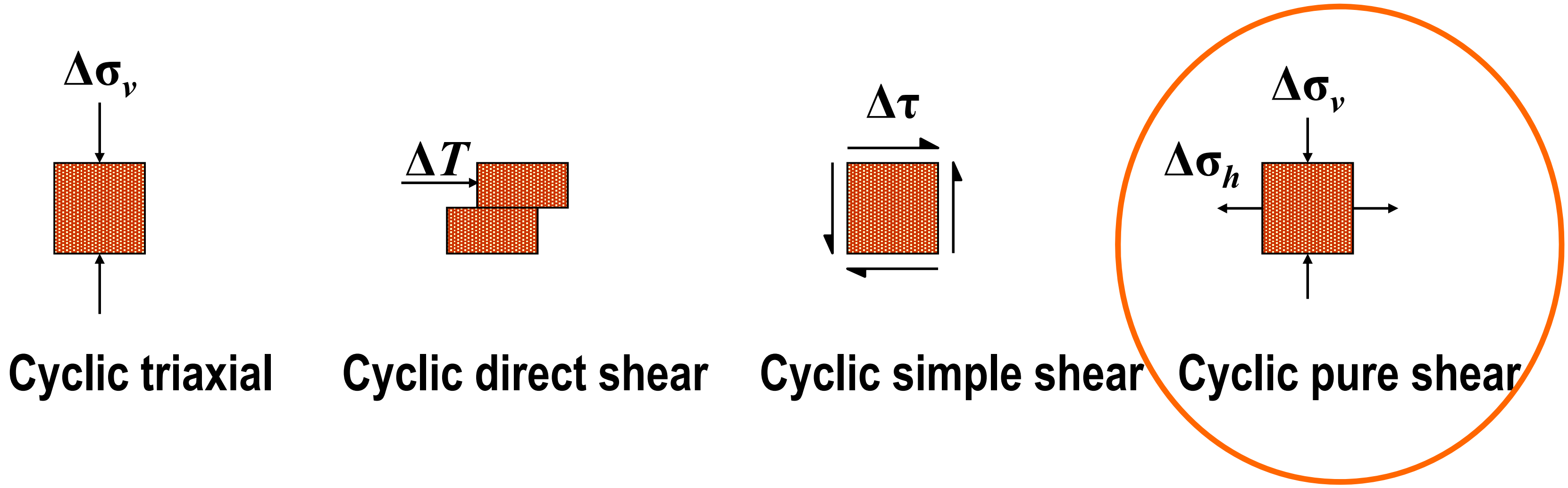
Liquefaction Studies using DEM

Materials

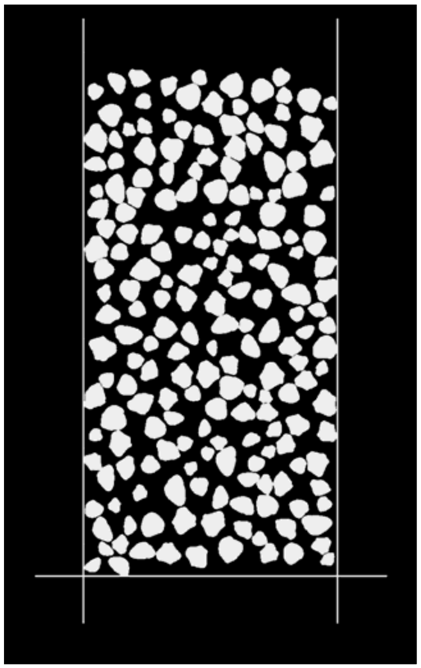
Material	D_{50} (mm)	C_u	SF %	AF %
Rounded Glass Beads	1.18	1.0	0	0
Michigan Dune Sand	0.33	1.5	32	9
Syncrude Tailings Sand	0.18	2.5	45	27
Daytona Beach Sand	0.23	1.4	42	19
Ottawa Angular Sand	0.27	2.2	51	29
Ottawa Rounded Sand	0.53	2.4	30	7

Modeling of Water Pressure

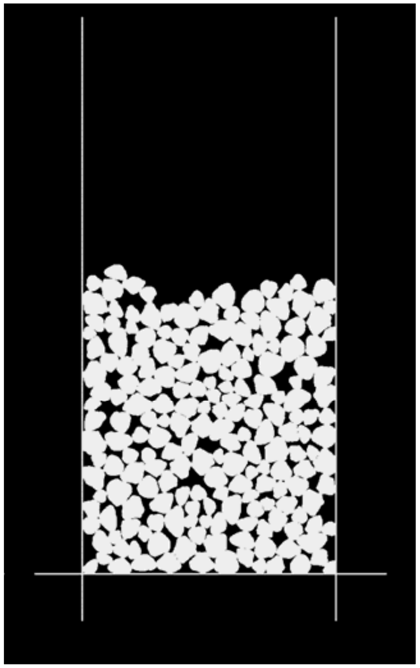
- Undrained conditions were simulated by restricting the volume of the particle assembly (Ng and Dobry, 1994)
- The difference between boundary stresses and initial confinement are attributed to buildup of pore water pressure under cyclic loading



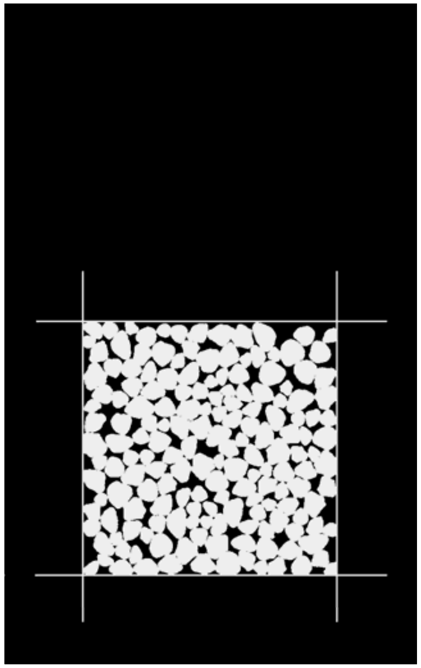
Sample Preparation - Dry Pluviation



Step 1
Granular assembly is generated

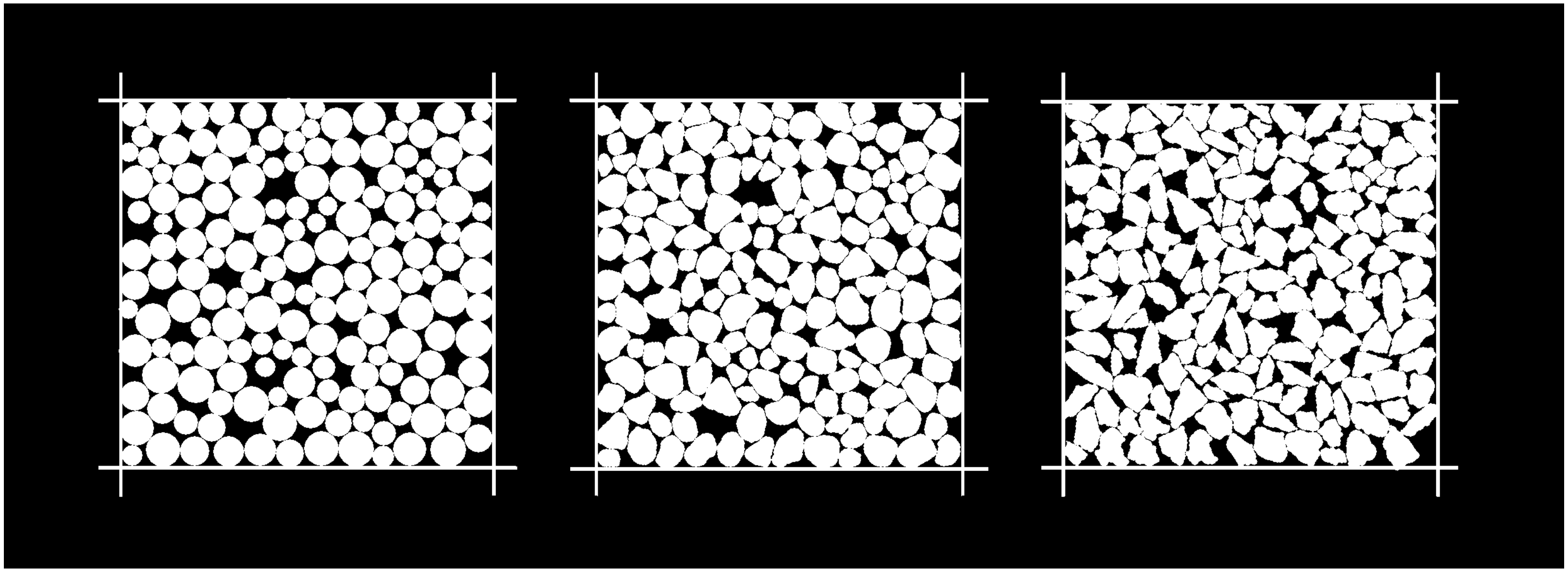


Step 2
Grains are allowed to settle under gravity



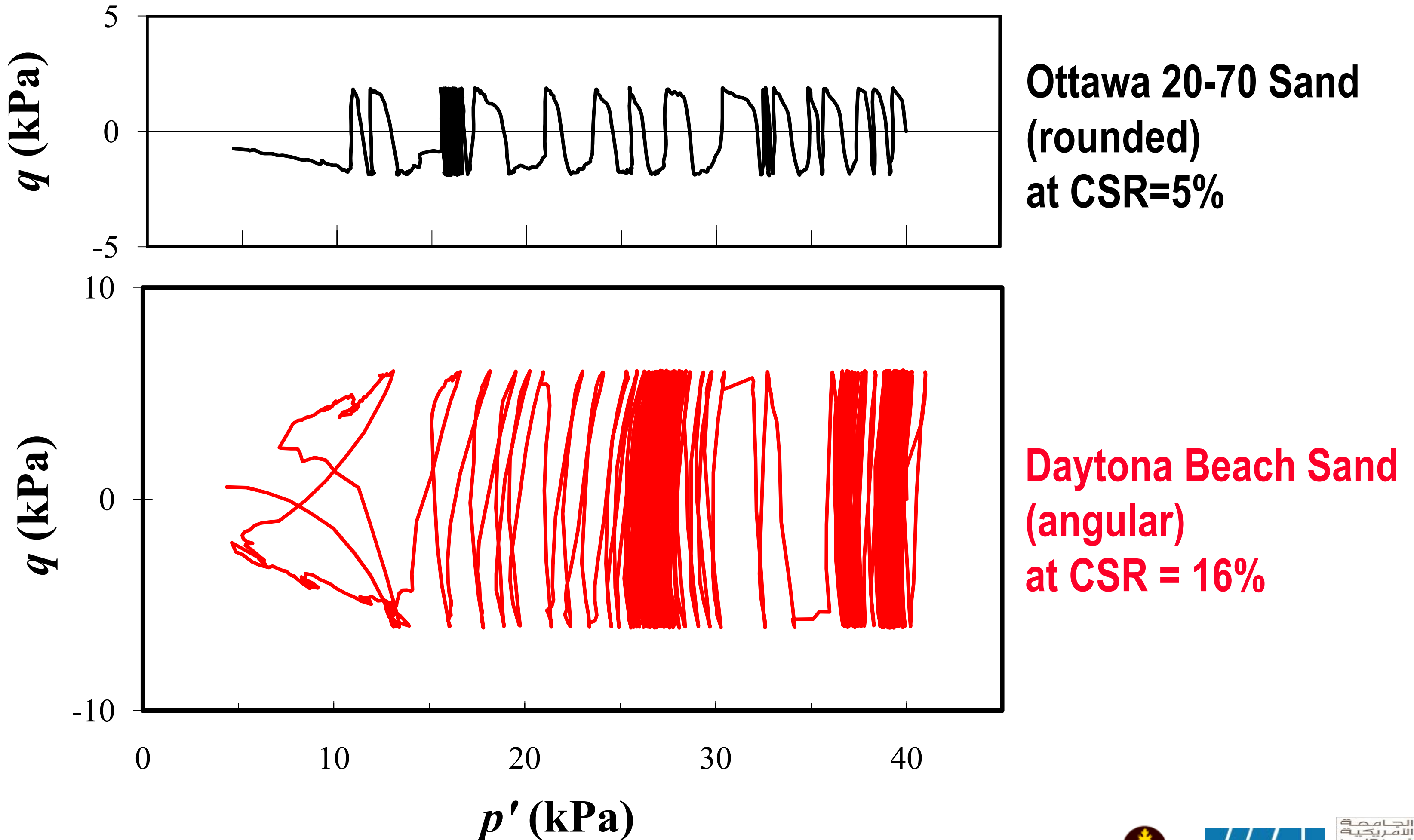
Step 3
Excess grains are cropped at the top

Sample Preparation - Constant Void Ratio



A single assembly is generated, and particles are transformed to equivalent angular shapes, resulting in a similar fabric/arrangement for all materials

Simulated Effective Stress Path - Cyclic Shear



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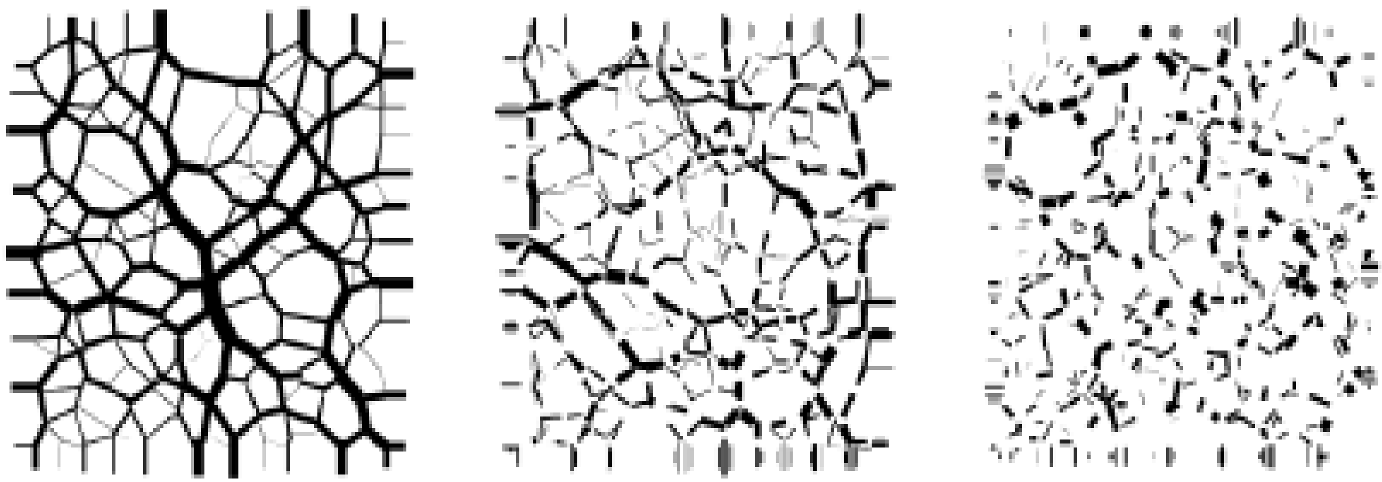
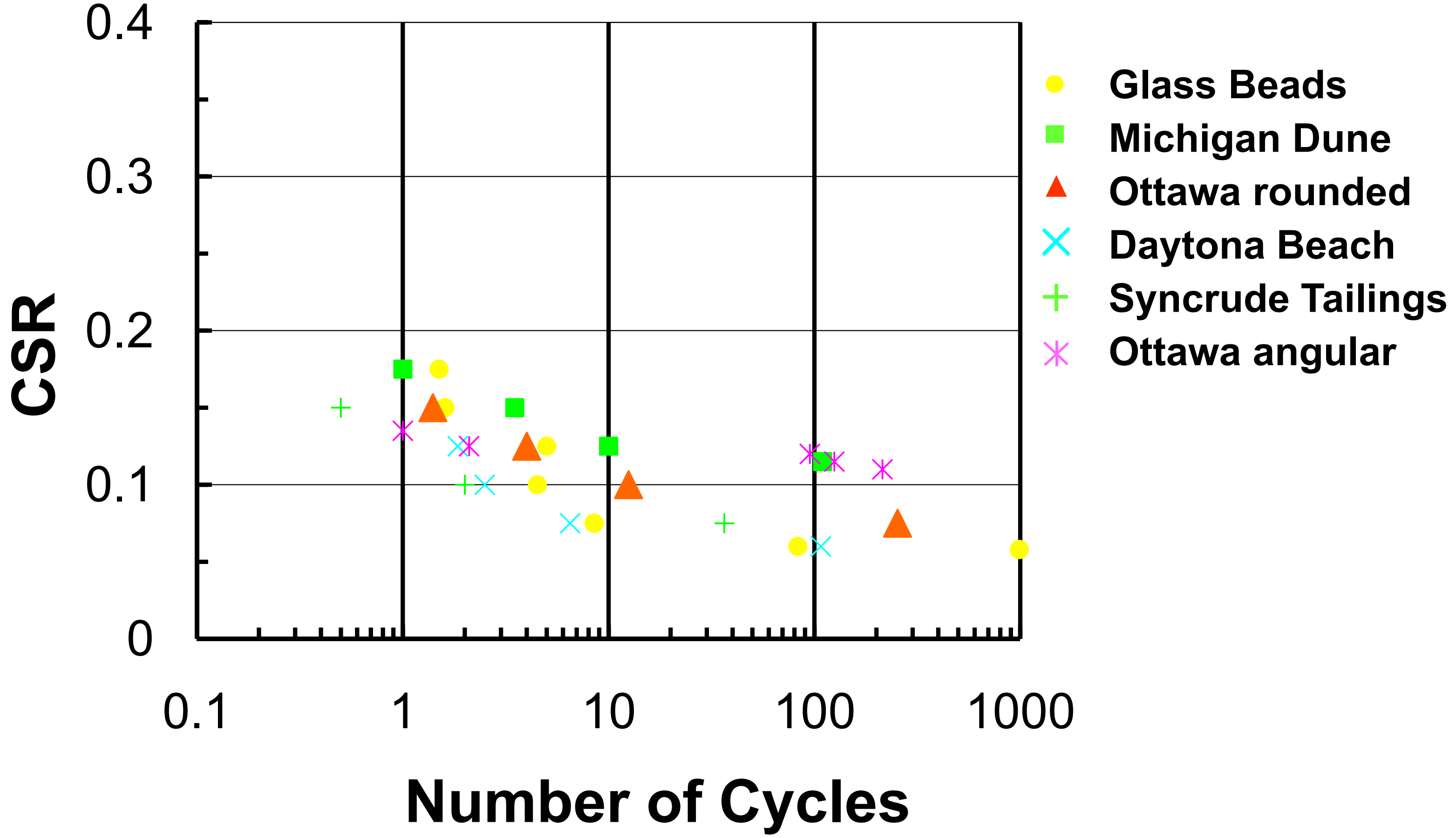
Dependence of contact forces and coordination numbers on particle shape



(a) **Glass Beads** (b) **Ottawa rounded** (c) **Ottawa angular**

CSR vs Number of Cycles – Dry Pluviation



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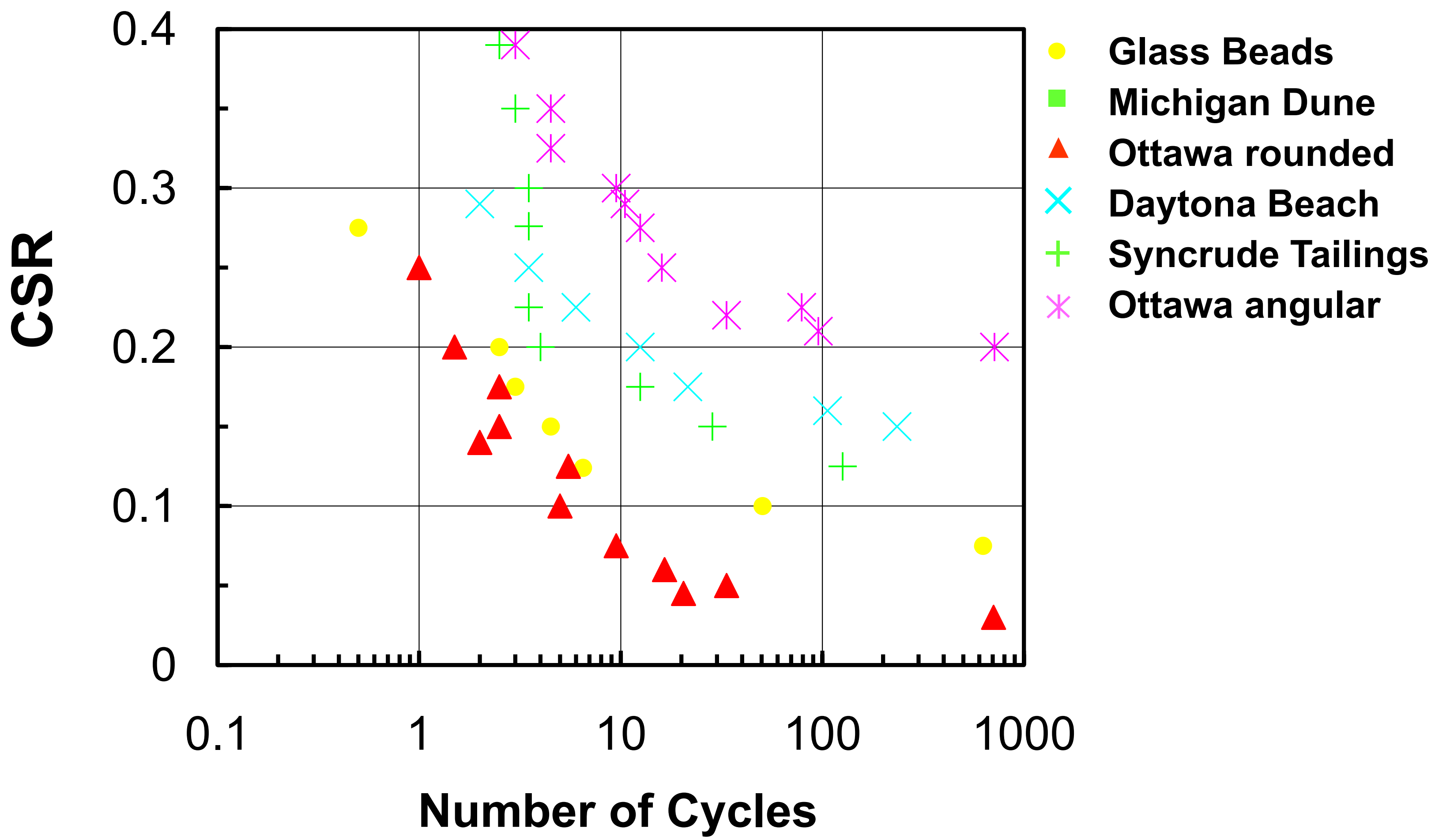
CSR vs Number of Cycles - Constant Void Ratio



Summary

- Individual particles from six natural, processed, and manufactured granular materials were digitized and stored in a software library for DEM modeling
- Simulations of cyclic shear tests were carried out on a representative volume
- At the pluviated void ratio, the susceptibility to liquefaction is independent of particle shape
- At constant void ratio, the influence of particle morphology on liquefaction susceptibility is significant
- Further studies are underway to numerically evaluate the influence of particle shape on other engineering properties

Conclusions

- ODEC2D and ODEC3D algorithms can model irregular 2-D and 3-D particle shape with desired accuracy
- Stress-strain and volumetric behavior of simulated material followed typical soil behavior of angular and rounded particles
- The angles of shearing resistance obtained using three different fabrics in 3-D simulation are very close to each other for both Daytona beach sand and rounded spheres
- Angularity and particles interlocking resulted in more shearing resistance in Daytona Beach sand compared to rounded material

Acknowledgments

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Award # 0324437 Civil & Mechanical Systems

Award # 0324518 Civil & Mechanical Systems

Award # 0421000 Electrical & Communications Systems