Lattice Boltzmann Methods Applied to Three-Dimensional Virtual Cores Constructed from Digital Optical Borehole Images of a Carbonate Karst Aquifer

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Karst

~11 m$^3$ s$^{-1}$

~100 m

7.5 cm

30 cm

17 m

1.7 m

http://research.gg.uwyo.edu/kincaid/
Modeling/wakulla/wakcave2.jpg
Objectives

• Project objectives:
  – Simulate virtual 3-D renderings of Biscayne aquifer macropore network based on borehole image data
  – Simulate 3-D fluid flow through macropores
  – Measure intrinsic permeability of 3-D aquifer renderings at meter-plus scales

• Long-term objective:
  – Develop LBM groundwater models for non-Darcian fluid flow through karst macroporous networks
Prior Work

  - Consider conduit density in 200 x 200 m blocks
- Tilke, P.G., D. Allen, and A. Gyllensten, 2006, Quantitative analysis of porosity heterogeneity: application of geostatistics to borehole images, Mathematical Geology 38:2, 155-173:
  - “We assume here that …there is no vertical variation in formation properties… This assumption fails in the presence of bed boundaries. Fortunately, this is not a common occurrence in the studied borehole.”
Geology to model parameters
Tools

• WellCad
  – borehole imagery
• MatLab
  – RGB/grayscale/geometric
• SGeMS geostatistical software
  – map, measure, and simulate 3-D distribution of macropores and rock matrix
• 3-D LBM integrative tool: compute
  – Permeability, hydraulic conductivity
  – Scale effects
  – Non-Darcy effects
Borehole Imagery
(almost 6 M points, ~2 mm resolution)
RGB Data Manipulation

- Pixel RGB values from WellCad
  - RGB converted into grayscale (standard)

\[ Gray = 0.3R + 0.59G + 0.11B \]

- Threshold applied to grayscale image to obtain a black and white matrix/pore rendering
Radius interpolation and 3-D coordinate computation

- Caliper data at lower resolution
- Borehole radius computed for every pixel z coordinate
- $x, y$ coordinates calculated:
  \[
  x = r \sin \theta \\
  y = r \cos \theta
  \]
Variogram Data

- Randomly sample 1% of original data
- 600,000 points = $1.8 \times 10^{11}$ pairs!
Borehole Indicator Variograms

\[ 2\gamma(h) = \frac{1}{n(h)} \sum_{i=1}^{n(h)} [z(x + h) - z(x)]^2 \]
Biased Variograms

- Nominal diameter
- 0.2 m
- 0.4 m

- Semivariance
  - Vertical
  - North-South
  - East-West
  - Model

- Lag (m)

- Semivariance values:
  - 0
  - 0.05
  - 0.1
  - 0.15
  - 0.2
  - 0.25
  - 0.3

- Plot with data points and curves for different directions.
Simulation Variograms

Semivariance

Vertical
North-South
East-West
Horizontal Model
Vertical Model

Lag (m)

Semivariance

Vertical
North-South
East-West
Horizontal Model
Vertical Model

Lag (m)
Rock Simulation

- Sequential indicator simulation
- Data honored
- Parallelepiped domain, 0.005 m resolution
Results

0.2 m

2.5 m
Results

1.85 m
Results

\[ q = \frac{k}{\rho \nu} \frac{\Delta p}{L} \]

\[ k_{\text{physical}} = k_{\text{LBM}} \left( \frac{L_{\text{physical}}}{L_{\text{LBM}}} \right)^2 \]

\[ K = k \frac{g}{\nu} \]

Result: 100 m/s

(much of Biscayne listed as >1000 ft/d (>0.003 m/s) (Fish and Stewart, WRI-90-4108)
Preliminary Conclusions

• Need much longer horizontal correlation length some places
  – “Non-stationary”
• Medium simulations roughly capture character of rock
• Hydraulic conductivity very high at 100 m/s