Model Development for Three-Dimensional Land Movement Simulation due to Groundwater Pumping from an Aquifer System

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Land Subsidence due to G.W withdrawal

Dr. J. Poland,
Father of Land Subsidence,
USGS, 1977

Dr. Donald C. Helm and Dr. Sheng
Earth Fissures due to G.W. Withdrawal

Front Sight fissures
Pahrump Valley, Nevada

Photo by Greg Doyle
Land subsidence Complicated by Hurricanes (Katrina in 2005)

A subsidence map for the city, generated from space-based synthetic-aperture radar measurements, which reveals that parts of New Orleans underwent rapid subsidence in the three years before Hurricane Katrina struck in August 2005. Dixon et al. (2006)
Rising sea levels expose low-lying coastal areas to increased flooding, saltwater intrusion, and erosion, which can further increase their vulnerability to the effects of storms. The Mississippi River Delta along coastal Louisiana is particularly sensitive to sea level rise, as the river-driven geology causes the land to sink, amplifying local sea level rise.
The city of New Orleans pictured at dawn, Saturday, Sept. 3, 2005 as fires continue to burn and water still stands in many areas of the city. New York Times / Vincent Laforet
Super storm Sandy and Sea Level Rise (2012)


- Twenty-three of the 25 most densely populated U.S. counties are on the coast.
- Roughly a foot of sea level rise in the New York City area in the past century
- Land subsidence in the New York City area has been roughly 3-4 inches per century

Cynthia Rosenzweig, NASA Goddard Institute for Space Studies.

Escalator under Water @ South Ferry, MTA
Subsidence due to G.W. Withdrawal

• Land subsidence due to ground water withdrawal is a worldwide problem.
• Land Subsidence:
  • 10.0 m in Mexico City, MEXICO (population: 22 million)
  • 9.0 m in Long Beach, CA, US (population: 0.5 million)
  • 9.0 m in San Joaquin Valley, CA, US (population: 0.7 million)
  • 4.3 m Eloy, AZ, US (population: 0.01 million)
  • 3.1 m in Tianjin, CHINA (population: 11 million)
  • 2.4 m Huston, TX, US (population: 2.0 million)
  • 2.1 m in Shanghai, CHINA (population: 25 million)
  • 1.6 m in Las Vegas, NV, US (population: 0.5 million)
  • 0.8 m in Bangkok, THAILAND (population: 6.5 million)
  • Others counties: Japan, Netherlands, Australia, etc.
Subsidence due to G.W. Withdrawal, Shanghai, CN

Subsidence: up to 8.8 ft by 1965
Losses: $45 billion in 2005
Subsidence: 9.3 ft by 2030
Subsidence: 9.8 ft by 2050
Scientific research indicates sea levels worldwide have been rising at a rate of 0.14 inches (3.5 millimeters) per year since the early 1990s. The trend, linked to global warming, puts thousands of coastal cities, like Venice, Italy, (seen here during a historic flood in 2008), and even whole islands at risk of being claimed by the ocean.

Photograph by Andrea Pattero/AFP/Getty Images
Shale gas

Source: Energy Information Administration (EIA, 2011)

Well, Hydrated
Water going into and out of a typical shale-gas well in the Marcellus shale

80,000 gallons
Water needed for drilling

3.8 million gal.
Water needed for hydraulic fracturing

1 million gallons
Fracking water that returns to the surface

200
Trucks needed to transport one million gallons

Source: Department of Energy

Source: British Geological Survey
Groningen gas fields - the Dutch earthquake zone

By Anna Holligan
BBC News, The Netherlands

As earthquakes become more intense and more frequent in the north of the Netherlands, there is mounting pressure on the government to reduce the amount of gas being extracted there.

It is a curse for thousands of inhabitants having to cope with the effects of living amid the Groningen gas fields - the largest in Europe.

There exists a consensus among all parties - including the gas companies - that the process of extracting the gas is causing earthquakes, but the country is thriving on the proceeds.

In 2012 the Dutch government made about 14bn euros (£12bn, $16bn) from the Groningen gas fields. Without these revenues, the Netherlands' deficit would be similar to that of crisis-struck Cyprus (6.3%).

"It comes rumbling towards you, louder and louder and louder," says Daniella Blanken, who runs the Groningen Ground Movement.

Klaas Kester and Jannette Schoof show a crack in the wall of their home in Middelstum.

222 waargenomen bevingen M ≥1.5
Groningen gasveld, periode 1995 t/m 2013

Royal Netherlands Meteorological Institute (KNMI)
Land Subsidence near Oil and Gas Fields, Houston, TX
The USGS Modular Three-dimensional Finite-Difference Ground-Water Flow Model: The Modular Model

By Michael G. McDonald and Arlen W. Harbaugh
USGS report 83-875

Cover image from McDonald & Harbaugh (1983)

MODFLOW-88, 96, 2000, 2005
Three Subsidence Packages in MODFLOW: Vertical Compaction

1. **Interbed-Storage** package
2. **Subsidence and Aquifer-System Compaction** package
3. **Subsidence and Aquifer-System Compaction Package for Water-Table Aquifers** package
Aquifer movement in terms of Darcy-Gersevanov Law

\[ q_b = (1 - n)v_s + n v_w = q + v_s \]
\[ q = n(v_s - v_w) = -K \nabla h \]
\[ v_s = q_b - q = q_b + K \nabla h = -K \nabla (h_s - h) \]

Displacement components

\[ u_s = \int_{t_0}^{t} v_s \, dt + u_{s0} \]

Steady State –QBC, QBR, QBV

\[ (q_{i,j,k}^b)_{\text{right}} = CR_{i,j+1,k} \left/ (\Delta c_i \Delta v_k) \right. (h_{i,j+1,k}^{ss} - h_{i,j,k}^{ss}) \]

Transient : QBTC, QBTR, QBTV

\[ (q_{i,j,k}^m)_{\text{right}} = CR_{i,j+1,k} \left/ (\Delta c_i \Delta v_k) \right. (h_{i,j+1,k}^m - h_{i,j,k}^m) \]

Velocity components

\[ (v_{i,j,k}^m)_{\text{right}} = (q_{i,j,k}^b)_{\text{right}} - (q_{i,j,k}^m)_{\text{right}} \]

Displacement components

\[ (u_{i,j,k}^m)_{\text{right}} = \sum_{m=1}^{M} (v_{i,j,k}^m)_{\text{right}} \Delta t_m \]
Nonlinear stress-strain relations

**Exponential Model**: Li and Ding 2013

\[ \delta \sigma'_v = \sigma'_v \left[ e^{2.3 \left( 1 + \varepsilon_0 \right) \delta \varepsilon_v} - 1 \right] \]

\[ S_s(\sigma'_v) = \alpha \gamma_w = \frac{\partial \varepsilon_v}{\partial \sigma'_v} \gamma_w = \alpha_0 \frac{\sigma'_v}{\sigma_v} \gamma_w = S_s0 \frac{\sigma'_v}{\sigma_v} \]

\[ S_s(h) = S_s0 \frac{\sigma'_v}{\sigma_v - \gamma_w(h-z)} \]

**Hyperbolic Model**: Li et al., 2014

\[ \delta \varepsilon_v = \frac{\delta \sigma'_v}{(a+b \delta \sigma'_v)} \]

\[ S_s(\sigma'_v) = \frac{\partial \varepsilon_v}{\partial \sigma'_v} \gamma_w = S_s0 \frac{1}{(1+\delta \sigma'_v b/a)^2} \]

\[ S_s(h) = S_s0 \frac{1}{[1+(\sigma_v - \gamma_w(h-z)b/a)^2]} \]
SPECIFIC DISCHARGE

- Calculate flow from storage
- Calculate flow from constant head cells
- Calculate flow between adjacent cells in three passes: across columns, across rows, and across layers
- Calculate and save displacements for transient flow between adjacent cells in each direction
  - Transient: QBTC, QBTR, QBTV
- Save steady-state flow between adjacent cells
  - Steady State: QBC, QBR, QBV
Basic input conditions

- 3 LAYERS,
- 37 ROWS,
- 37 COLUMNS

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2000 m$^3$/day

Unconfined Aquifer (30.2m)
- $K_h=6$ m/day, $K_v=3$ m/day

Confined Aquifer (30.2m)
- $K_h=5$ m/day, $K_v=2.5$ m/day

Aquitard (5.3m)
- $K_h=0.006$ m/day, $K_v=0.004$ m/day

The total number of elements equals 4107 (= 37 x 37 x 3).

Variable grid spacing to improve the accuracy

The column located at row 19 and column 19 in Layer 3
Comparison of the linear, exponential, hyperbolic models

Settlement at each layer

Cumulative subsidence
Model Sensitivity by Various Parameters

**Deformation vs. pumpage**

- **Linear**
  \[ y = 0.0023x + 0.0695 \]
  \[ R^2 = 0.999 \]

- **Exponential**
  \[ y = 0.0019x + 0.1715 \]
  \[ R^2 = 0.999 \]

- **Hyperbolic**
  \[ y = 0.0017x - 0.3212 \]
  \[ R^2 = 0.998 \]

**Displacement vs. aquifer thickness**

- **Exponential**
  \[ y = -0.035x + 3.647 \]
  \[ R^2 = 0.972 \]

- **Linear**
  \[ y = -0.0283x + 3.1142 \]
  \[ R^2 = 0.981 \]

- **Hyperbolic**
  \[ y = -0.0297x + 2.4673 \]
  \[ R^2 = 0.921 \]
Total Earth Fissure

![Graph showing Earth Fissure over Distance]

- Linear - 10 day
- Exponential - 10 day
- Hyperbola - 10 day
- Linear - 100 day
- Exponential - 100 day
- Hyperbola - 100 day

July 22, 2012
SUMMARY AND CONCLUSION

• Both the linear and two nonlinear models were embedded in MODFLOW-96 that was modified to simulate the 3-D land movements.

• A new hyperbolic model has been introduced and comparison of a linear model to two nonlinear models (i.e., exponential and hyperbolic models) has been carried out.

• A linear model may produce a higher velocity and larger displacement than that of the two nonlinear models do. This suggests that the magnitude of land subsidence predicted by a linear model is likely overestimated when compared to that done by a nonlinear model.

• The exponential mode results in a larger aquifer deformation than the hyperbolic model does.

• A linear model is more sensitive to both the changes in pumping rates and aquifer thickness than the two nonlinear models are.
CURRENT WORK
COMPARISON NDIS vs MODFLOW 2005 SUB PACKAGE
ACKNOWLEDGMENTS

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QUESTIONS!