



First International  
*FLAC/DEM* Symposium

*Determination of Aquifer and Aquitard  
Parameters from Inverse Modeling*



Michael Burlingame, PE  
Bureau of Design and Construction

New Jersey Department of  
Environmental Protection

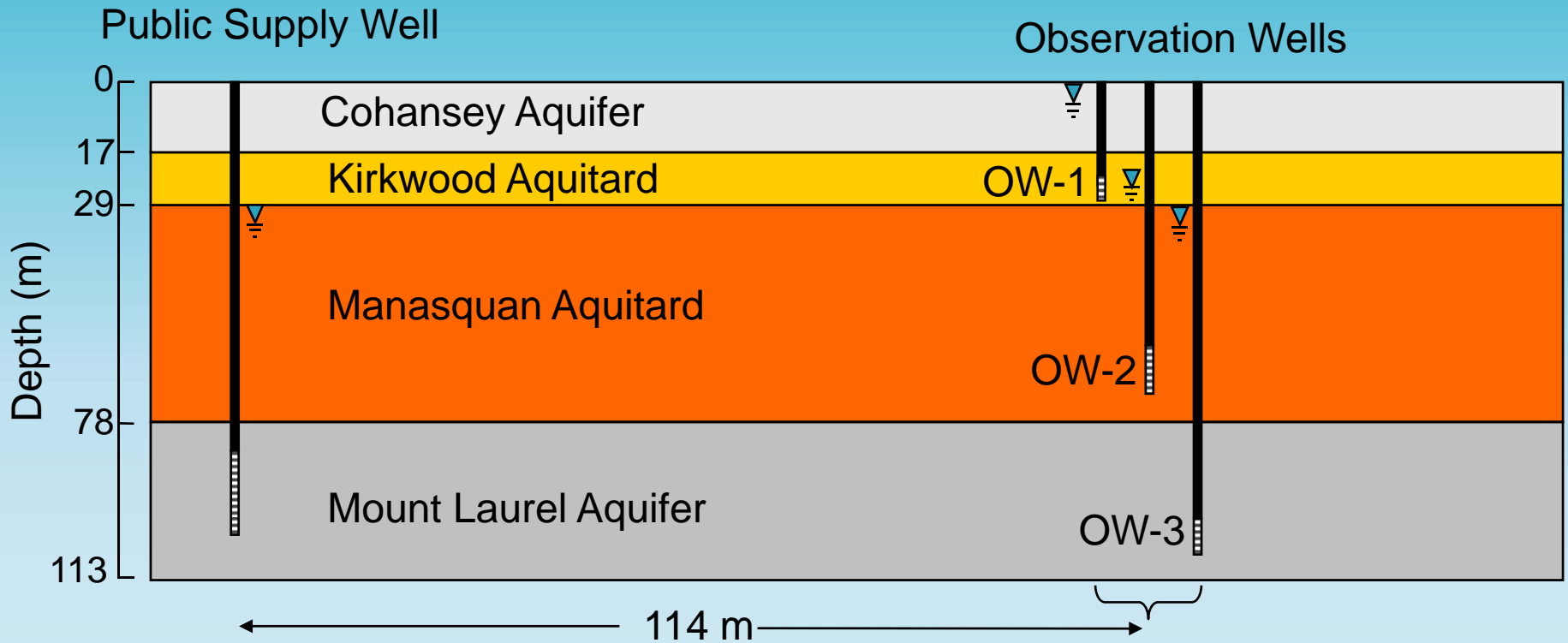
# Landfill with Supply and Observation Wells



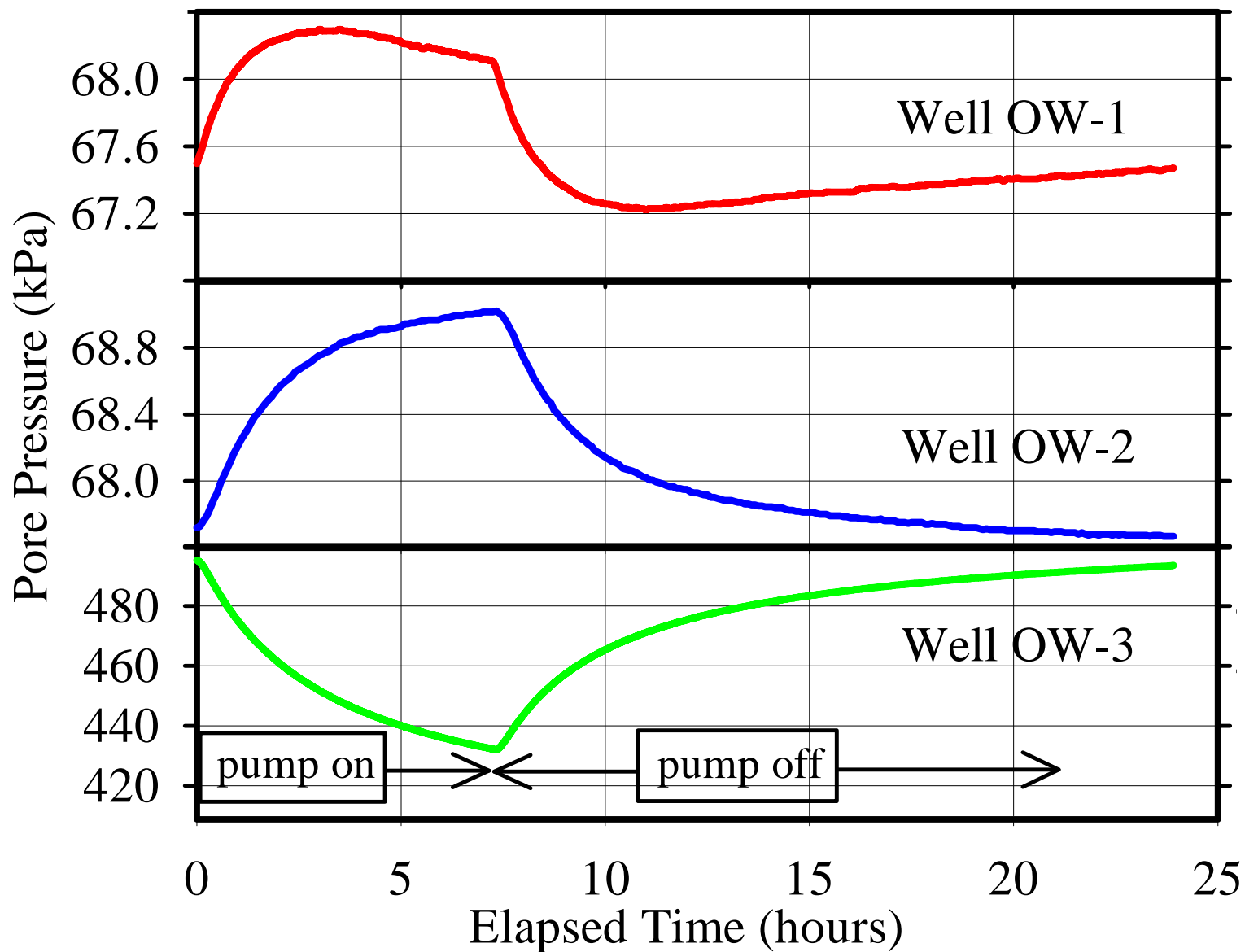
# Supply and Observation Wells



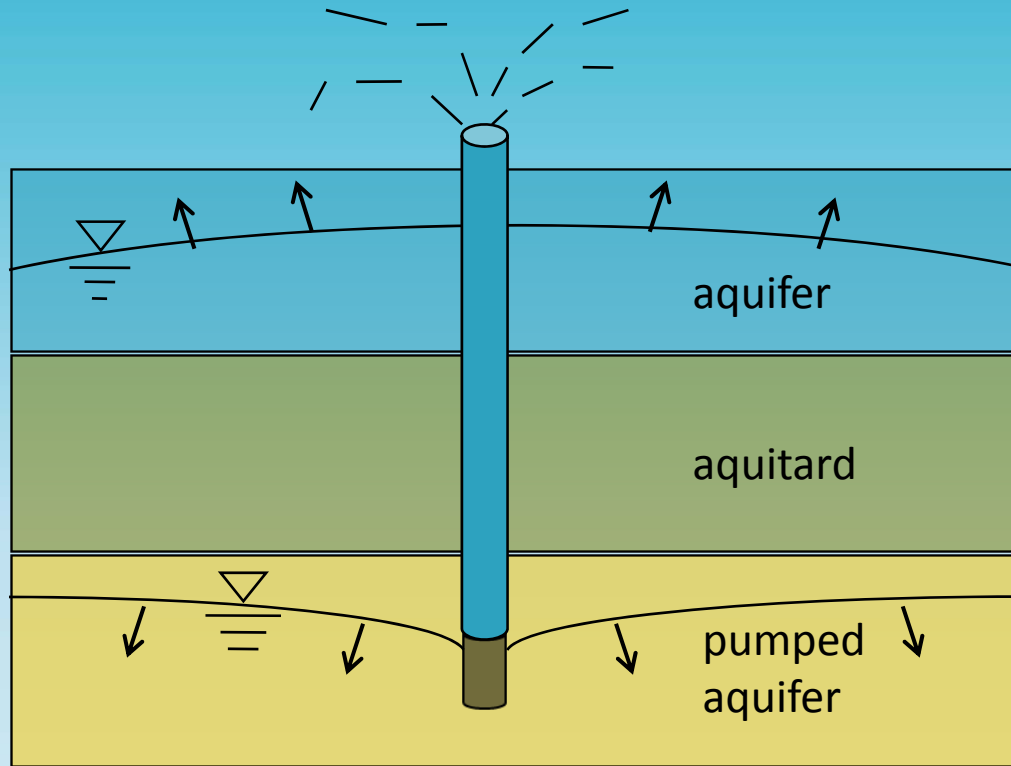
# Conceptual Site Model



# Groundwater Monitoring Data

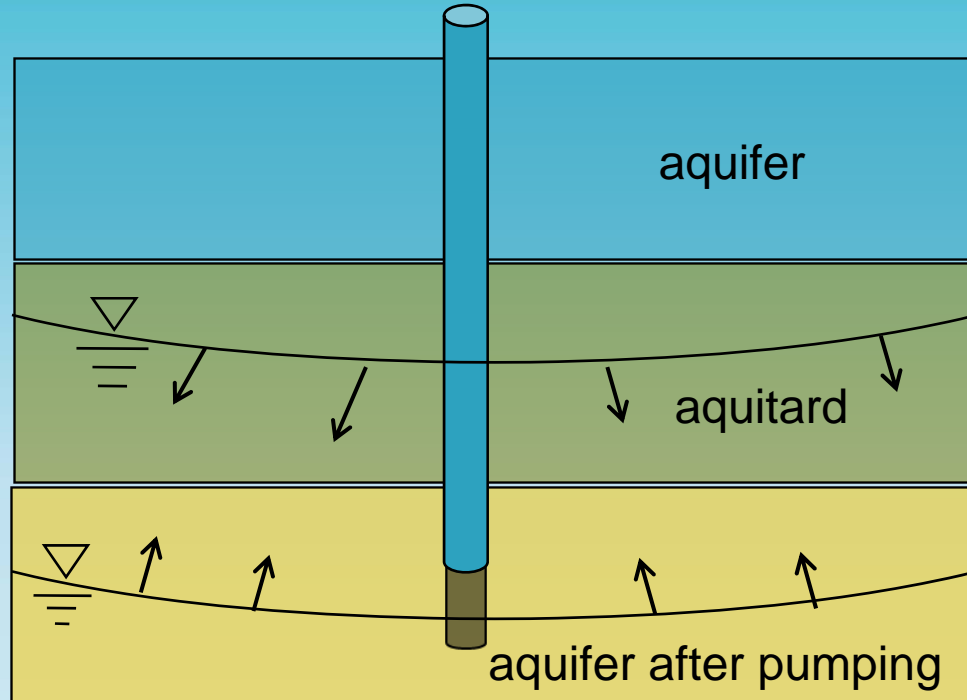


# Reverse Water Level Fluctuations - Noordbergum Effect



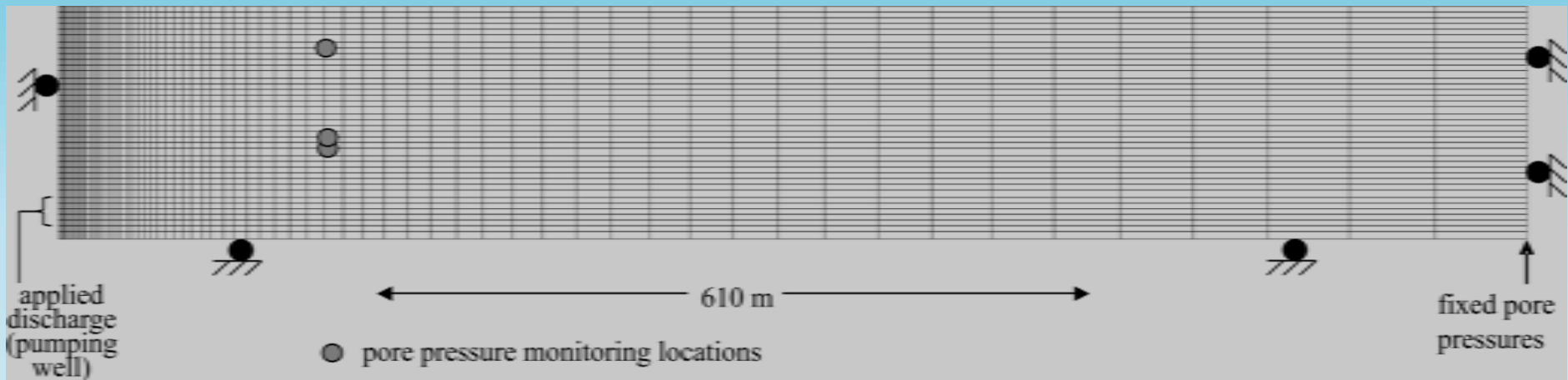
- Shallow aquifer exhibits increasing water level as a lower aquifer is pumped.
- First documented by A. Verruijt, Delft University, who termed it the Noordbergum Effect after a town in the Netherlands where it was observed.

# Reverse Water Level Fluctuations - Rhade Effect



- Aquitard exhibits decreasing water level as a lower aquifer recovers from pumping.
- First documented by Langguth & Treskatis, who termed it the Rhade Effect after a town in Germany where it was first observed.

# FLAC Axisymmetric Grid and Boundary Conditions



# Modeling Assumptions

- Soil strata are horizontal, isotropic, and saturated.
- Groundwater viscosity is constant and soil grains are incompressible.
- Soil porosity and hydraulic conductivity is constant.
- Hydraulic inefficiencies from well screen and sand pack are negligible.
- Impermeable, incompressible layer forms the base of the model.
- Effects of pumping on pore pressures and lateral strains are negligible at the model's limits.

# Governing Equation - Hydromechanical Formulation

In Biot's Theory of 3-D consolidation, pore pressure ( $P$ ) and volumetric soil strain ( $\varepsilon_{kk}$ ) are coupled or covariant. For a FLAC element:

$$\frac{\partial P}{\partial t} = \frac{K_w}{n} \left( \frac{k}{\gamma_w} \nabla^2 P - \frac{\partial \varepsilon_{kk}}{\partial t} \right)$$

where:

$$\varepsilon_{kk} = \varepsilon_{\theta\theta} + \varepsilon_{rr} + \varepsilon_{zz}$$
$$\nabla^2 P = \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial P}{\partial r} \right) + \frac{1}{r^2} \frac{\partial^2 P}{\partial \theta^2} + \frac{\partial^2 P}{\partial z^2}$$
$$\varepsilon_{ii} = \frac{1}{2G} \left( \sigma_{ii} - \frac{\nu}{1+\nu} \sigma_{kk} \right) + \frac{1}{3K} P \quad i = \theta, r, z$$

$k$  is hydraulic conductivity,  $K$  is drained bulk modulus,  $\nu$  is the drained Poisson Ratio,  $G$  is the shear modulus,  $K_w$  is the bulk modulus of water,  $n$  is porosity,  $\gamma_w$  is the unit weight of water,  $\sigma_{kk}$  is the mean normal stress.

# Basic Modeling Strategy

## Run sequence:

- 1) Run in hydraulic mode to establish pore pressure distribution.
- 2) Run in mechanical mode to develop body forces, then set displacements to zero.
- 3) Run in coupled, hydromechanical mode until volumetric strains  $< 10^{-7}$ .
- 4) Apply well discharge.
- 5) Run with Fast-Flow scheme for aquifer and in standard mode for aquitards.
- 6) Work from most highly stressed to least stressed layer.

# Inverse Modeling Strategy

## Sensitivity Analysis:

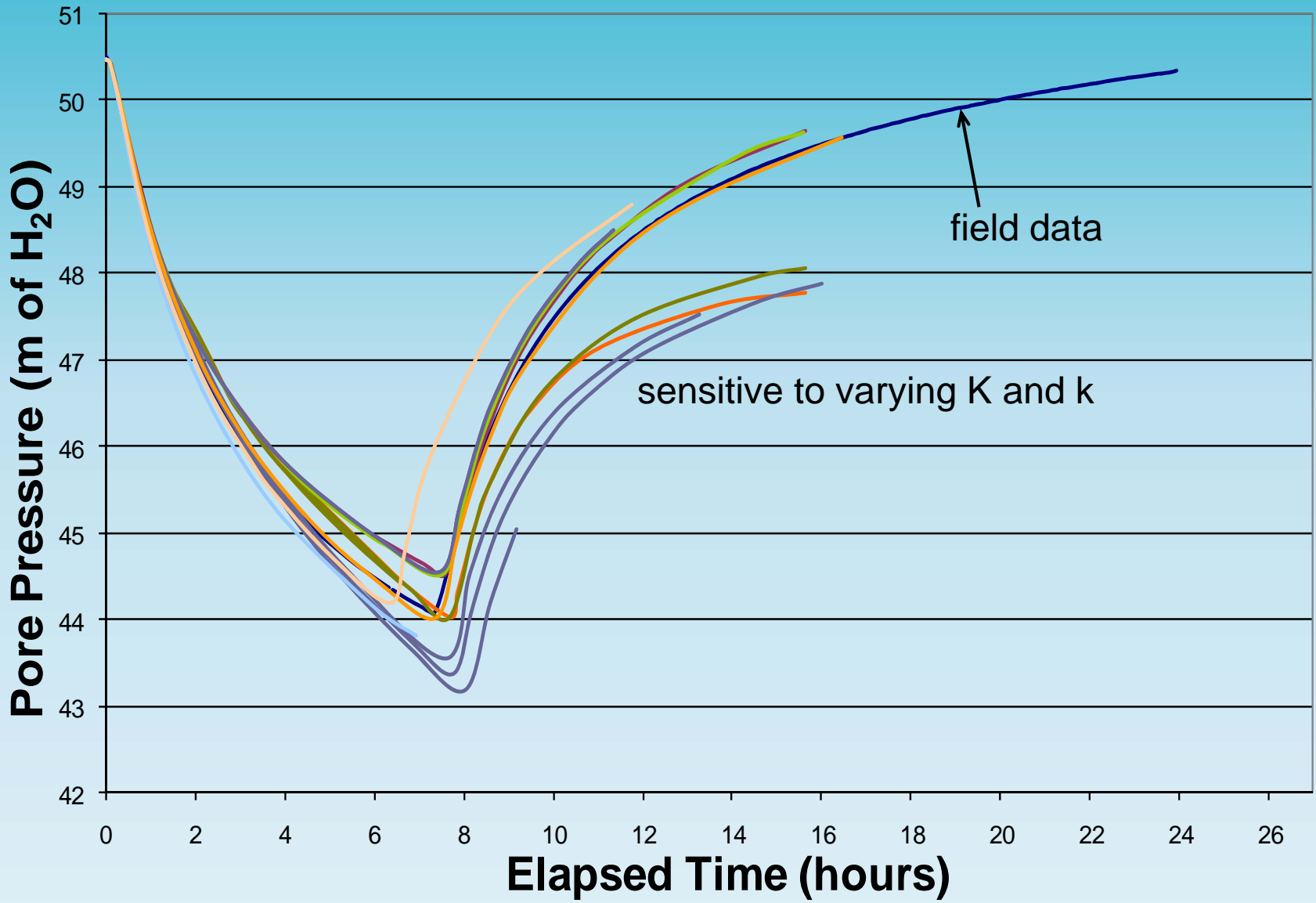
- Examine effects of soil parameters on pore pressure development to narrow down the number of unknowns.
- Examine effects of modeling schemes (equilibration time, fast-flow, explicit/implicit, MC/elastic) on pore pressure development.

## Model Calibration (trial and error assisted by contouring):

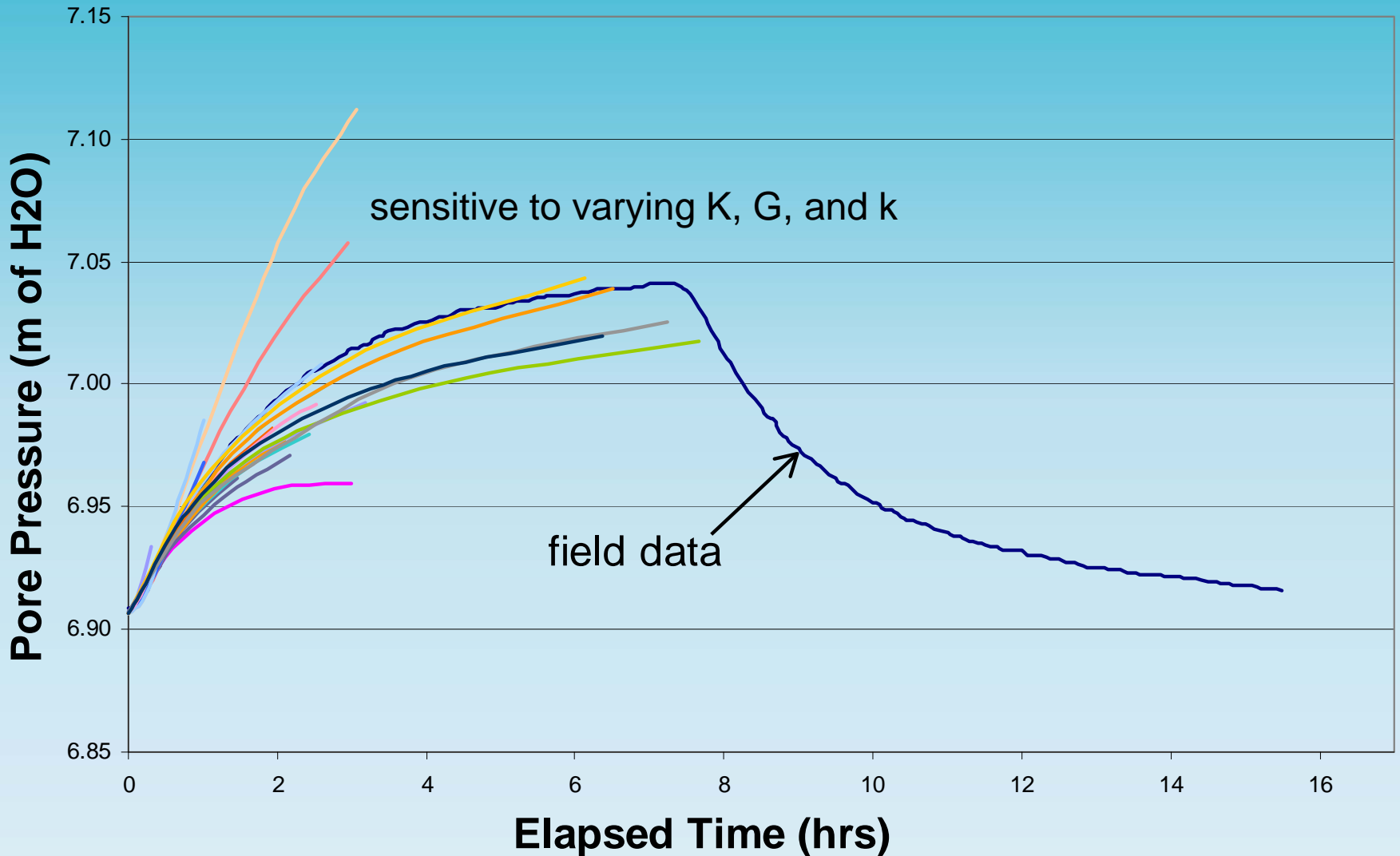
- Use literature values to bound the variables.
- Match modeled pore pressure histories to field data.
- Calibrate each layer then make global runs to adjust for interaction between layers.

# Well OW-3 - Mount Laurel Aquifer

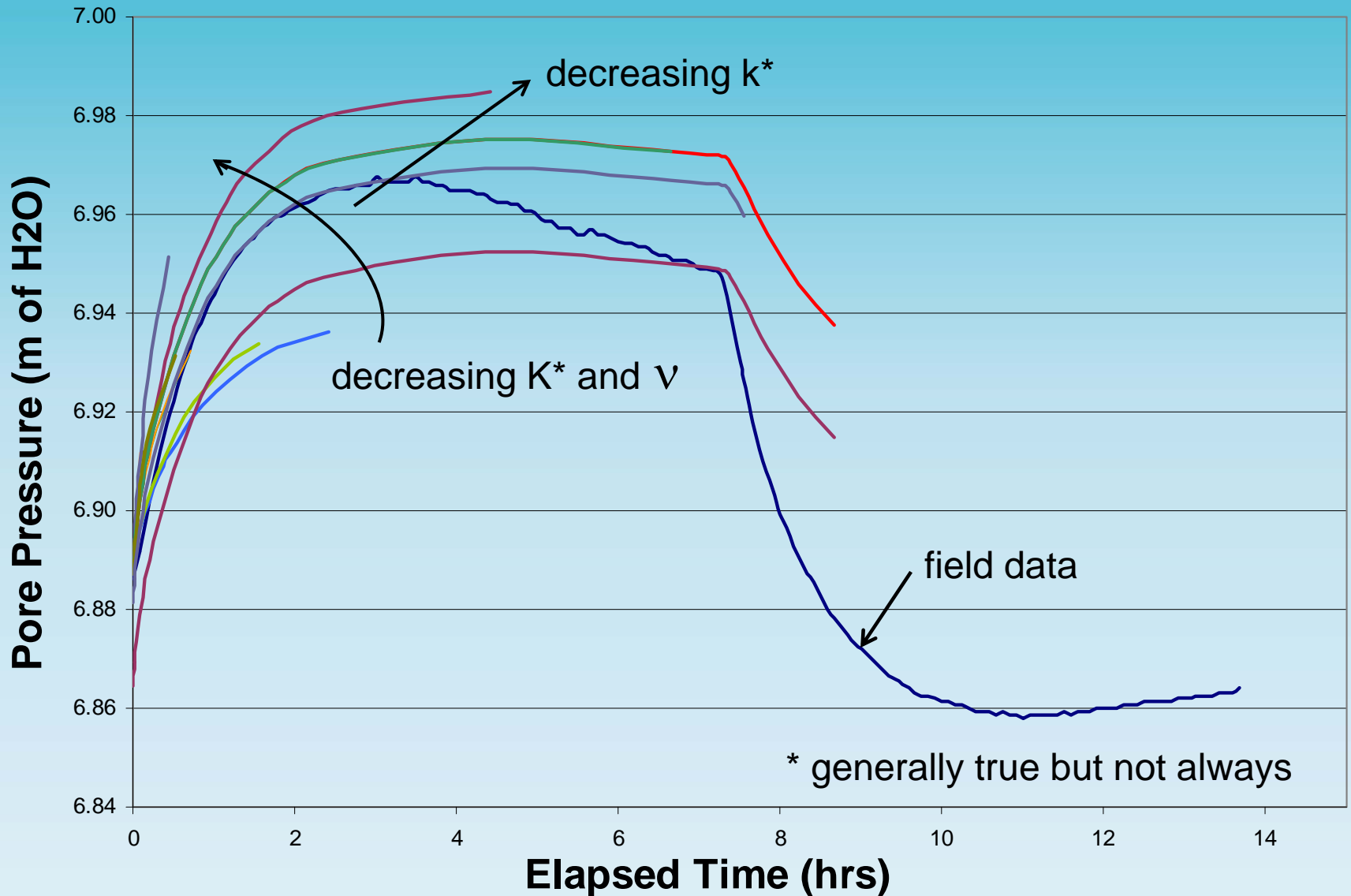
## Curve Matching of Pore Pressure Histories



# Well OW-2 Manasquan Aquitard Curve Matching of Pore Pressure Histories



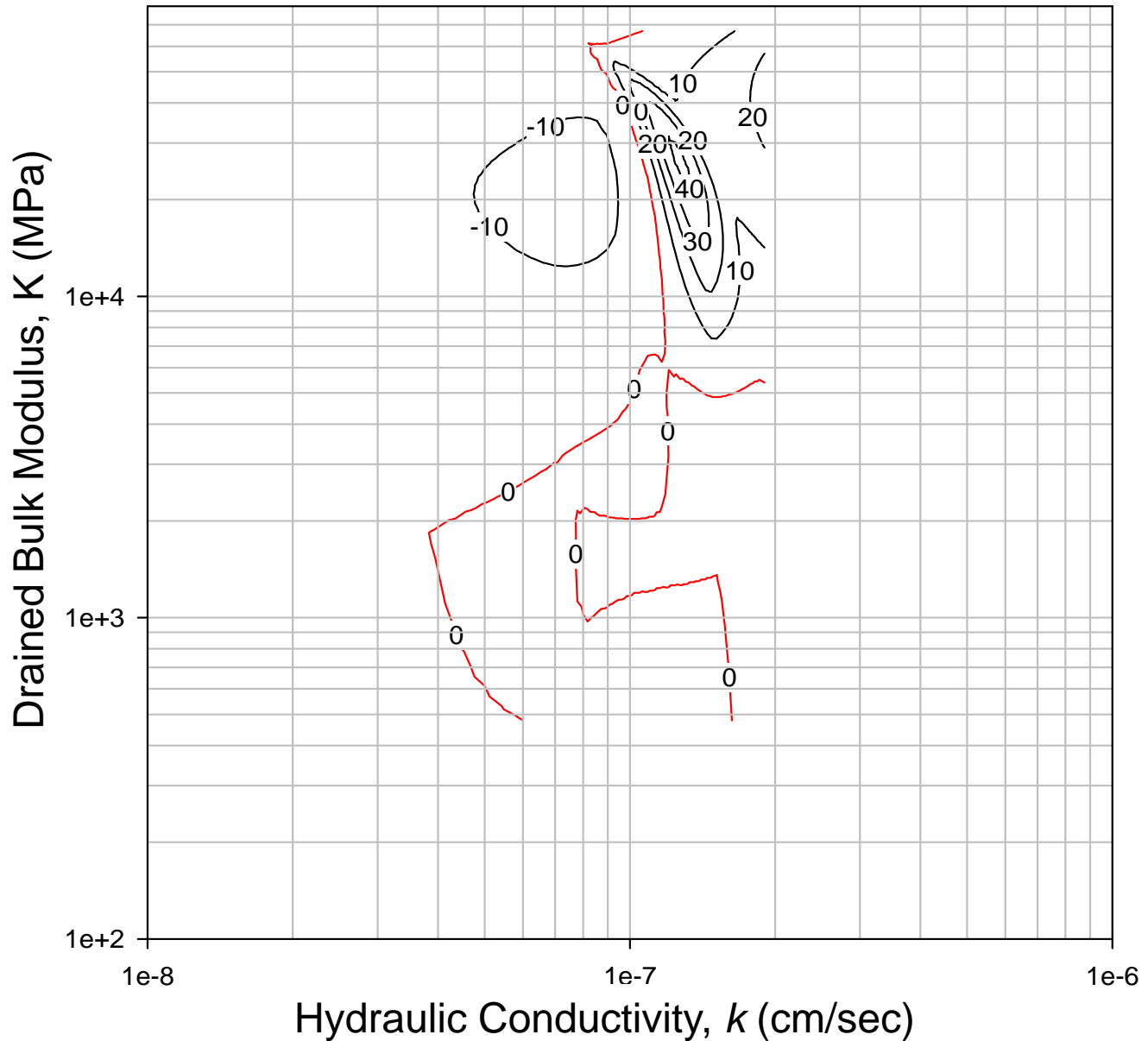
# Well OW-1 Kirkwood Aquitard Curve Matching of Pore Pressure Histories



# Manasquan Aquitard

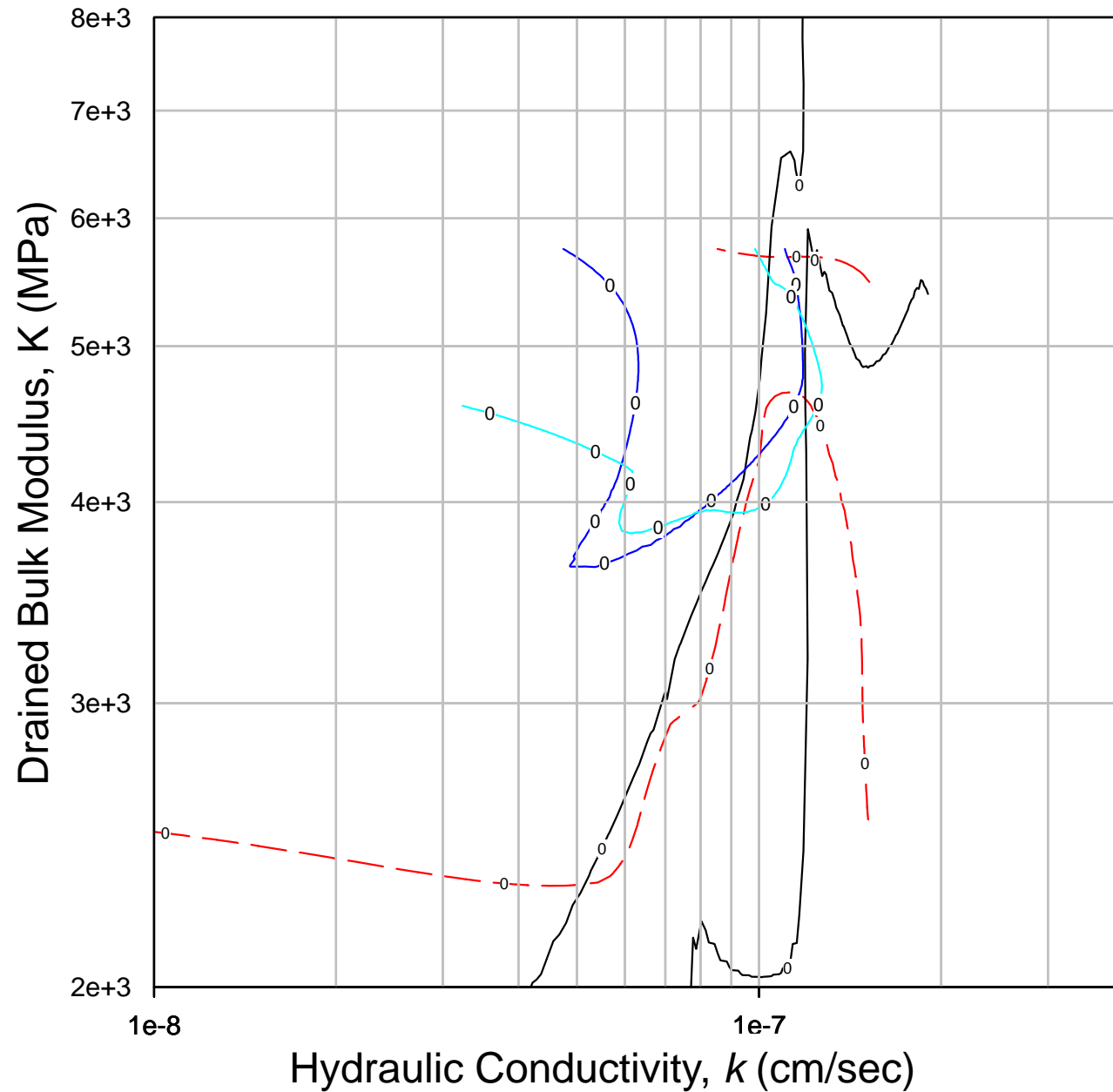
Contours of  $P_{\text{modeled}} - P_{\text{actual}} \times 10^{-2}$  (Pa)

Flow Time = 3000 secs



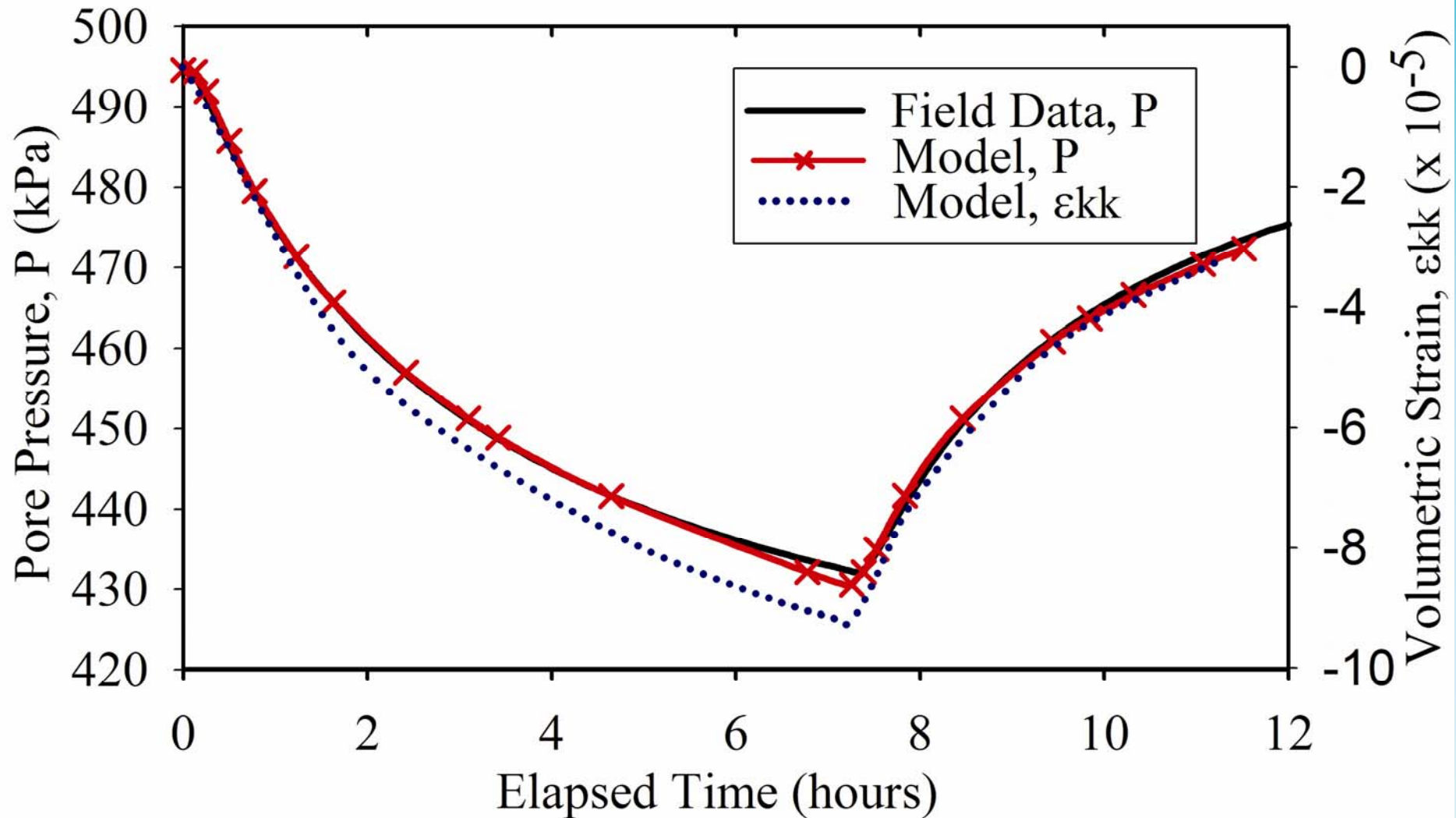
# Manasquan Aquitard

## Zero Difference P Contours at Various Times



# Mount Laurel Aquifer

## Pore Pressure and Volumetric Strain Histories



# Simplified Diffusion Equation for Pumping Test Analysis

Commonly, for pumping test analysis, the change in pore pressure is uncoupled from mechanical strain:

assume....  $\partial P \cong \partial \sigma_{kk}$  or in terms of strain.....  $\partial P/K \cong \partial \varepsilon_{kk}$

so that:

$$\frac{\partial P}{\partial t} = \frac{K_w}{n} \left( \frac{k}{\gamma_w} \nabla^2 P - \frac{1}{K} \frac{\partial P}{\partial t} \right)$$

rather than Biot's more correct formulation:

$$\frac{\partial P}{\partial t} = \frac{K_w}{n} \left( \frac{k}{\gamma_w} \nabla^2 P - \frac{\partial \varepsilon_{kk}}{\partial t} \right)$$

# Hydraulic Conductivity of Aquifer by Various Methods

<b>Formation</b>	<b>Test Method</b>	<b>Solution Method</b>	<b><i>k</i> (cm/sec)</b>
<b>Mt. Laurel</b>	<b>Pump Test*</b>	<b>Hantush &amp; Jacob, 1955 (confined)</b>	<b><math>2.1 \times 10^{-3}</math></b>
	<b>Pump Test*</b>	<b>Hantush, 1961 (semi-confined)</b>	<b><math>2.3 \times 10^{-3}</math></b>
	<b>Pump Test**</b>	<b>Hantush &amp; Jacob, 1955 (confined)</b>	<b><math>2.1 \times 10^{-3}</math></b>
	<b>Pump Test*</b>	<b>FLAC 2D, Ver. 5.1 (fast-flow)</b>	<b><math>5.0 \times 10^{-3}</math></b>

\* Kimball, 2006    \*\* Sammon, 1993

Conclusion for aquifer:

$k$  (hydromechanical)  $\approx 2 \times k$  (uncoupled)

The difference is due in large part to how volumetric soil strain is handled.

# Empirical Determination of Aquifer's Shear Modulus

Use Richart's (1977) empirical equation for the small strain shear modulus,  $G_{max}$ , for clean, round-grained sands as:

$$G_{max} = 700 \frac{(2.17 - e)^2}{1 + e} \left( \frac{\sigma_{kk}}{3} \right)^{0.5}$$

where:

$e$  is void ratio, for  $e < 0.80$  or  $n < 0.44$ , and for soil shear strains  $< 10^{-4}$

Get  $\sigma_{kk}$  from the FLAC model and  $e$  from laboratory tests.

# Aquifer Shear Modulus: Model and Empirical Equation

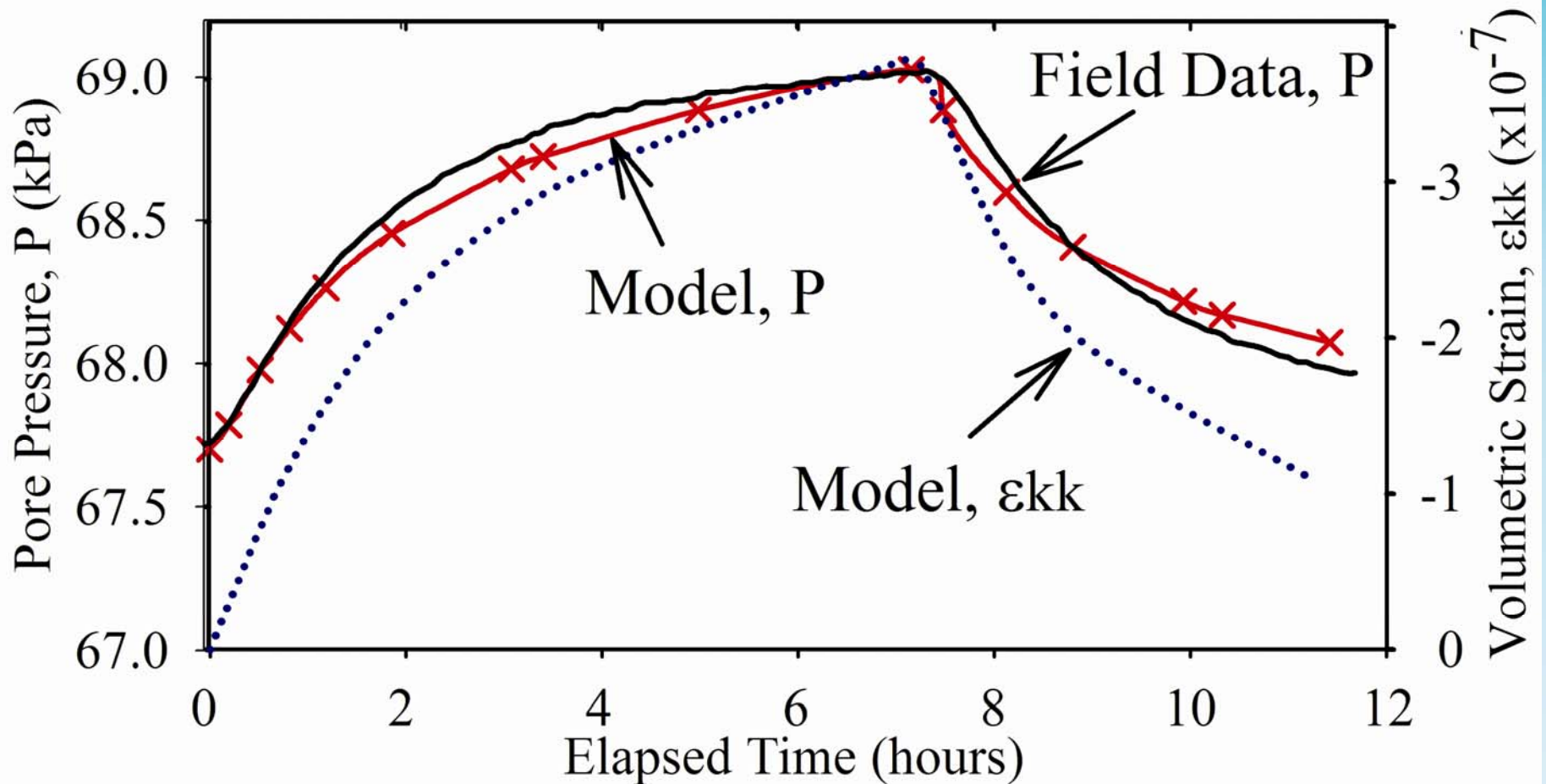
Formation	$\nu$	$n$	Density (kN/m <sup>3</sup> )	$K$ (MPa)	$G$ (FLAC) (MPa)	$G_{max}$ (MPa)
Mt. Laurel	0.2000	0.40	17.28	335.2	251.4	207.0

## Conclusion for aquifer:

$G$  (FLAC Model) is 21% of  $G_{max}$  (Richart Equation).

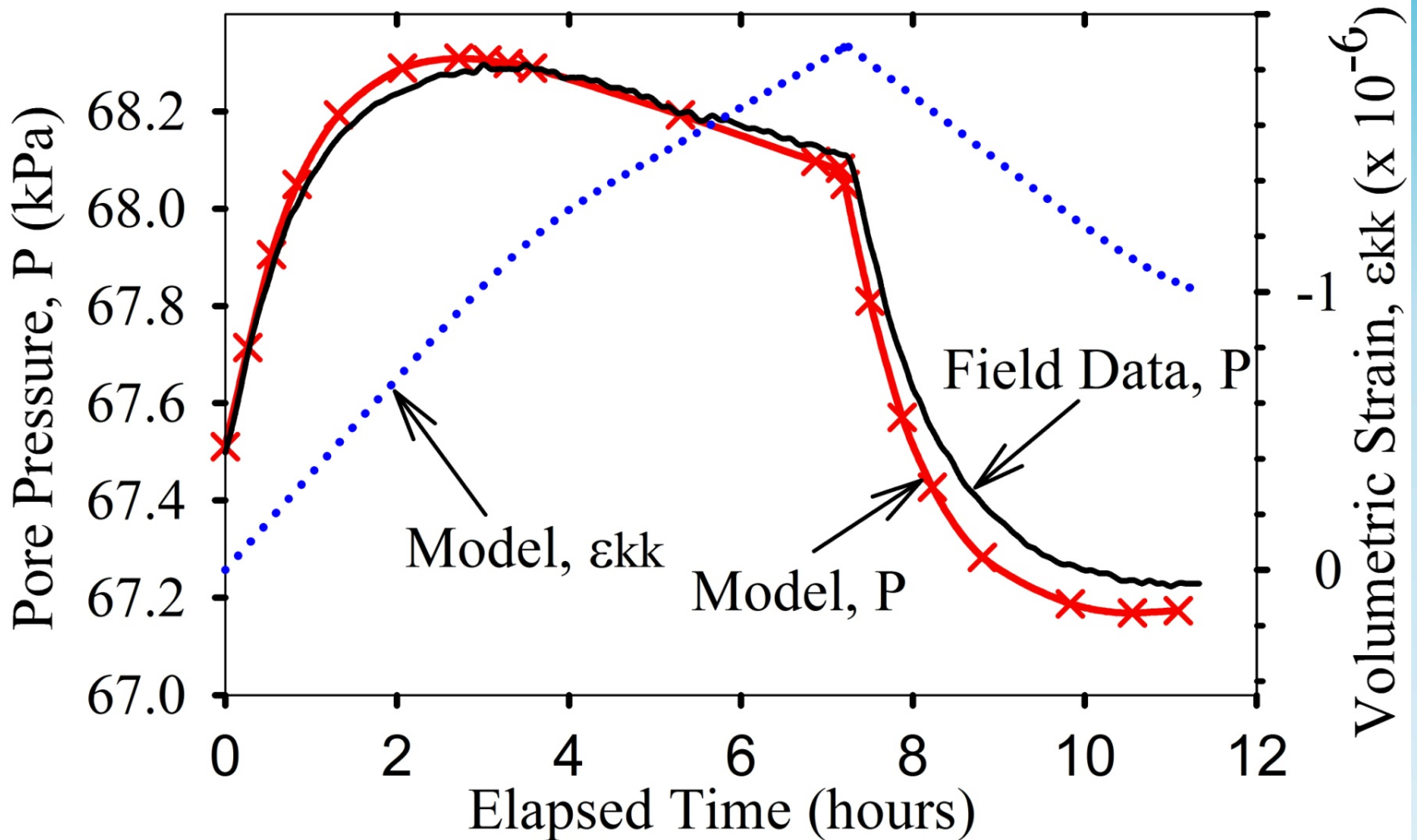
Very good agreement even though the aquifer response is not very sensitive to  $\nu$  and  $G$  !

# Manasquan Aquitard Pore Pressure and Volumetric Strain Histories



# Shallow Kirkwood Aquitard

## Pore Pressure and Volumetric Strain Histories



# Hydraulic Conductivity of Aquitards by Various Methods

Formation	Test Method	Solution Method	$k$ (cm/sec)
Manasquan	Lab Test* **	Falling Head Tests (Darcy)	$0.3-2.9 \times 10^{-7}$
	Lab Test *	Flex Wall Perm. Tests (Darcy)	$0.6-3.6 \times 10^{-7}$
	Lab Test *	Consolidation Tests (Terzaghi)	$0.5-1.5 \times 10^{-7}$
	Pump Test*	FLAC 2D, Ver. 5.1 (double-precision)	$5.7 \times 10^{-9}$
Kirkwood	Lab Test**	Constant Head Test (Darcy)	$32.0 \times 10^{-6}$
	Lab Test *	Flex Wall Perm. Tests (Darcy)	$7.5 \times 10^{-6}$
	Pump Test*	FLAC 2D, Ver. 5.1 (double-precision)	$6.7 \times 10^{-6}$

\* Kimball, 2006, 2008    \*\* Metcalf & Eddy, 1993

## Conclusion for aquitards:

$k$  (hydromechanical) <  $k$  (Darcy and Terzaghi) by 2 orders of magnitude in the Manasquan Aquitard, but 1 order or less in the Kirkwood Aquitard.

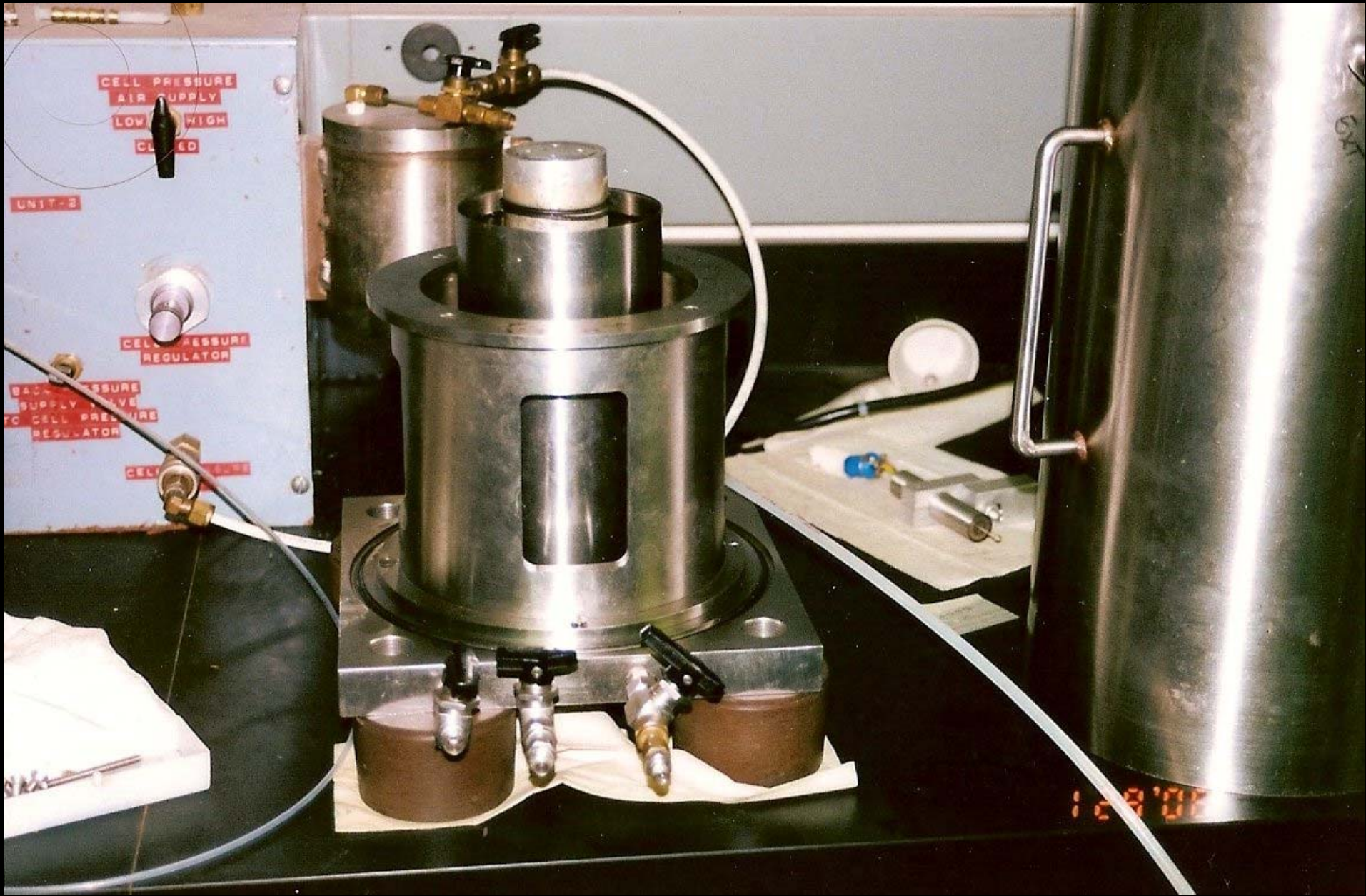
# Denison Sampler for Aquitard (Stiff Silt & Clay)



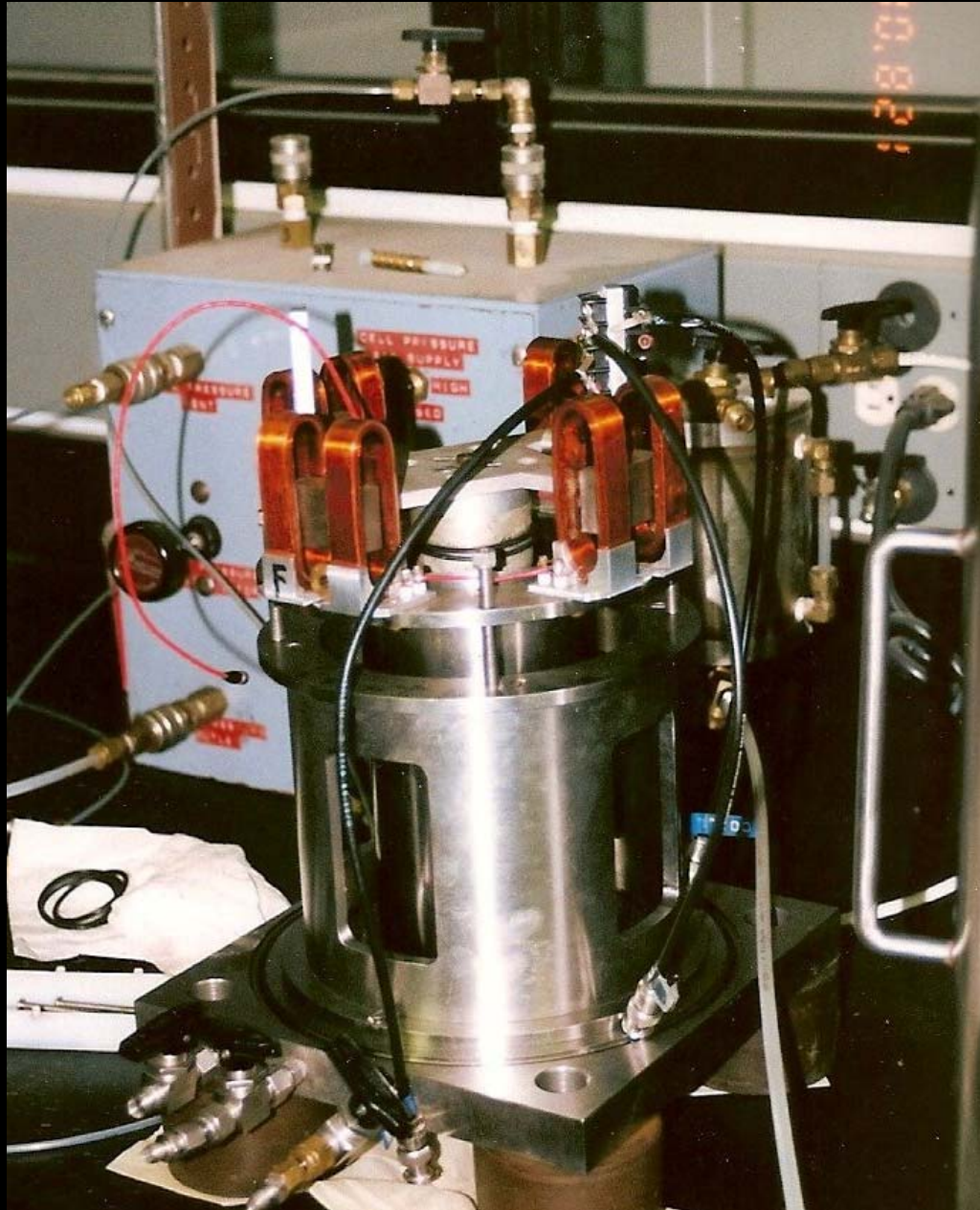
# Denison Sample in 0.6 m Long Plastic Tube



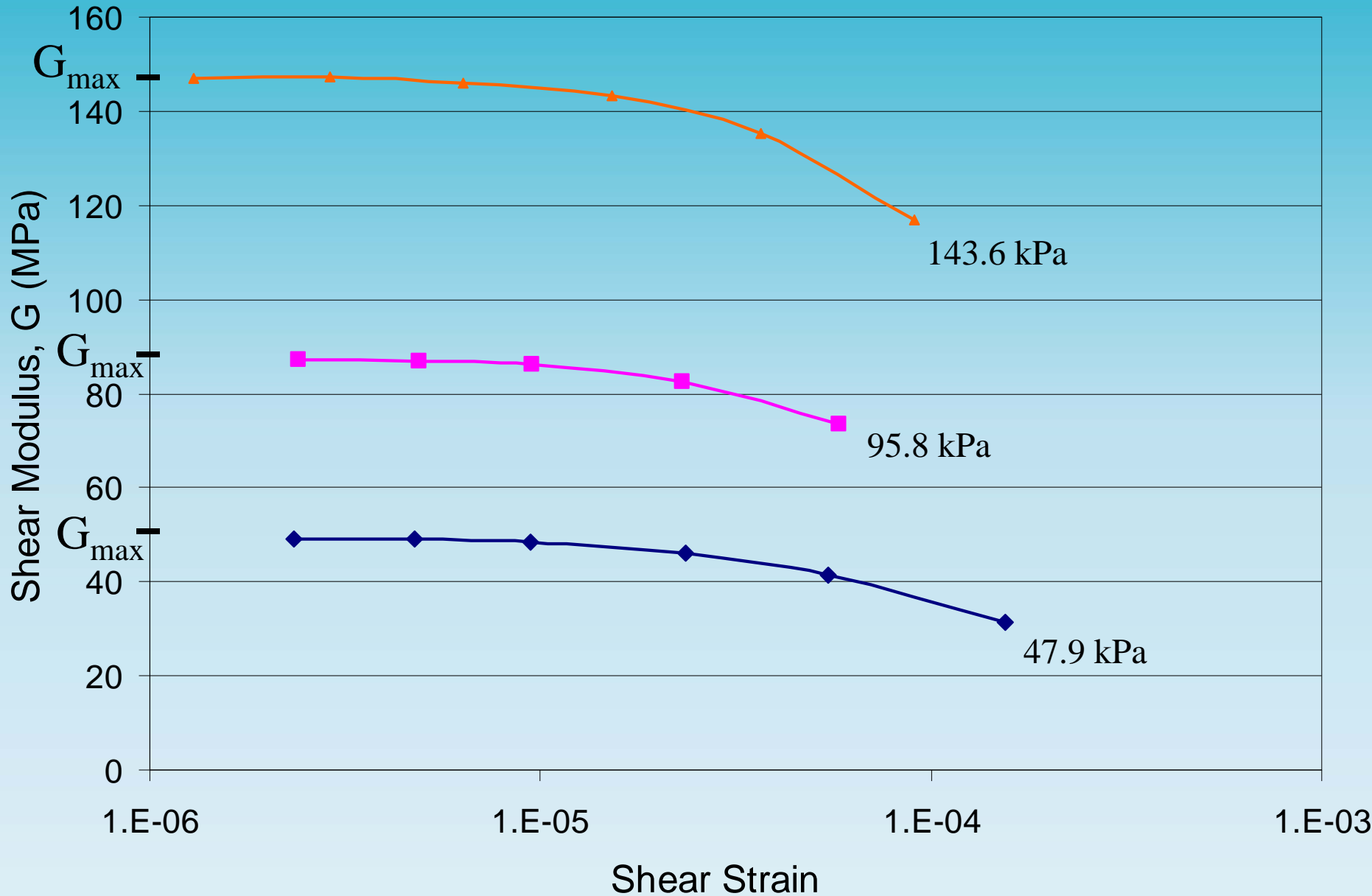
# Resonant Column Testing - Testing Chamber



# Resonant Column Testing Electromagnetic Drive Causes Torsion



# Resonant Column Testing Results - Manasquan Aquitard



# Aquitards' Shear Moduli: Model and Resonant Column Tests

Aquitard	$\nu$	$n$	Density (kN/m <sup>3</sup> )	$K$ (MPa)	$G$ (FLAC) (MPa)	$G_{max}$ * (MPa)
Manasquan	0.4945	0.55	11.62	4788.0	52.7	28.3 and 400.0
Kirkwood	0.4800	0.57	16.34	1197.0	48.4	74.9

\* Resonant Column Testing by URS, 2008

## Conclusion:

$G$  (FLAC Model) is between an order of magnitude and 35% of  $G_{max}$  (Resonant Column).

# Conclusions

- **IN-SITU AQUITARD PROPERTIES:** Modeling of reverse water level fluctuations allows estimation of aquitard properties from a pumping test.
- **TIME CONSUMING AND DIFFICULT:** More than 200 runs, each taking more than 8 hours (need faster processors and software).
- **STRAINS:** Fully-coupled modeling is more important as soil modulus and permeability decrease. FLAC is able to account for both solid-fluid stresses and strains.
- **APPROXIMATION:** Order of magnitude precision is considered possible without perfectly matching the field data.
- **AUTOMATION:** Use of calibration codes, such as UCODE, in a FISH subroutine may be practical for aquifers but very difficult for aquitards due to the ill-posed, non-linear response.
- **FLAC TRICK (fully-coupled modeling):** Use of FLAC's implicit scheme, with a time step as per the FLAC Manual, was up to 4X faster than the explicit scheme without much loss of accuracy.

Nandri      Xie xie      Toda      Baniha      Grazie  
Efcharisto      M goi      Dziekuje      Gracias  
Spasibo      Merci      Jag tackar      Thank  
Hvala vam      Danke schön      Arigato      You

### Acknowledgements:

- ✓ Mr. Juan Salguero, L. Robert Kimball & Associates, designed and conducted the pumping test.
- ✓ Dr. Herb Wang, University of Wisconsin-Madison, provided an independent interpretation of the data.
- ✓ Mr. Greg Thomas, URS, conducted resonant column testing.
- ✓ Dr. Christine Detournay, Itasca Consulting Group, gave helpful guidance on modeling and some words of encouragement.
- ✓ The Symposium's peer review committee made valuable comments.