

**KANSAS GEOLOGICAL SURVEY
OPEN-FILE REPORT 99-14**

**PRACTICAL GUIDELINES FOR THE DESIGN AND ANALYSIS
OF SLUG TESTS**

by

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J. Healey

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Practical Guidelines for the Design and Analysis of Slug Tests

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Kansas Geological Survey

Presentation to KDHE Personnel
Topeka, Kansas
May 3, 1999

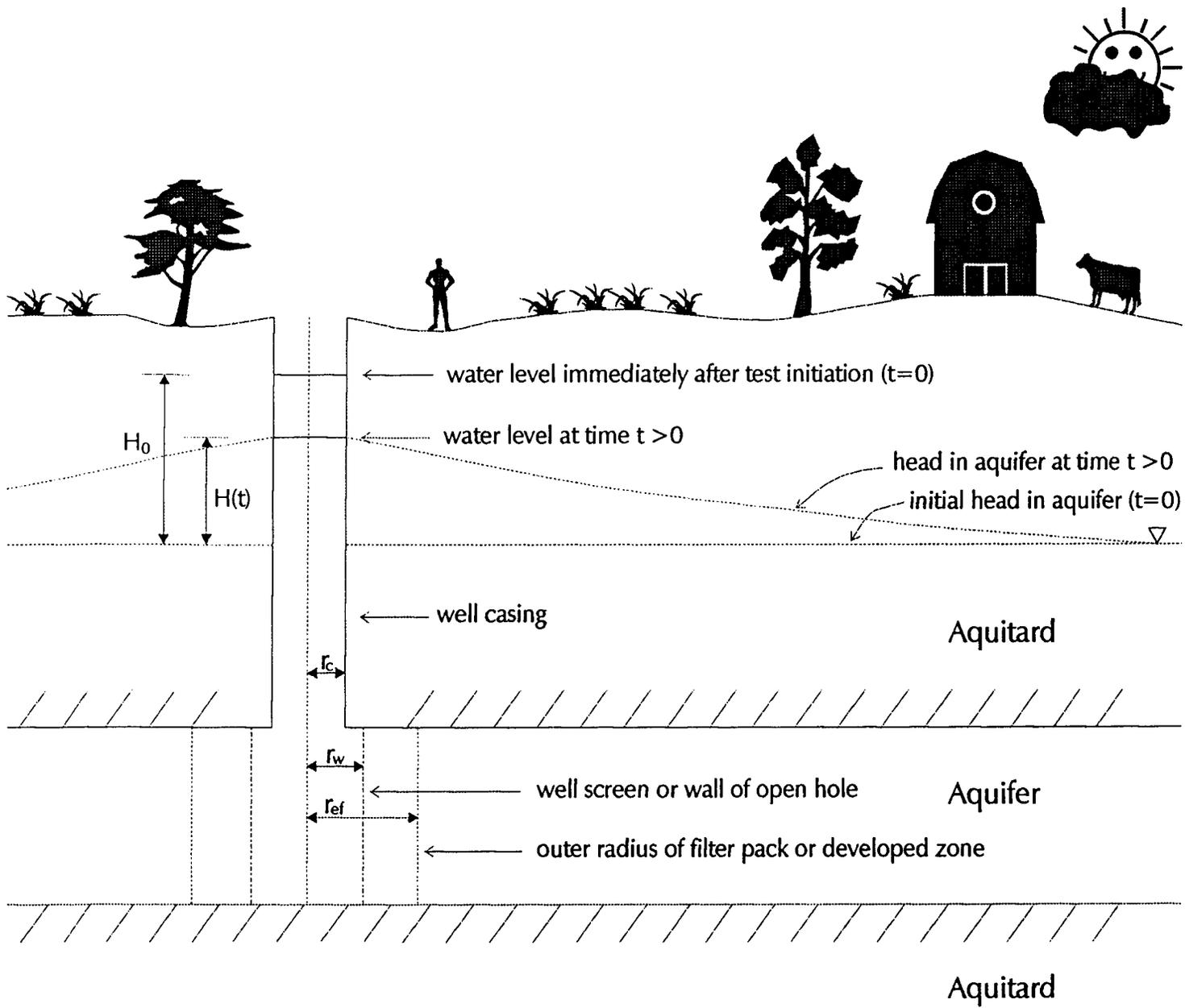
Kansas Geological Survey Open-File
Report 99-14

PRESENTATION OUTLINE

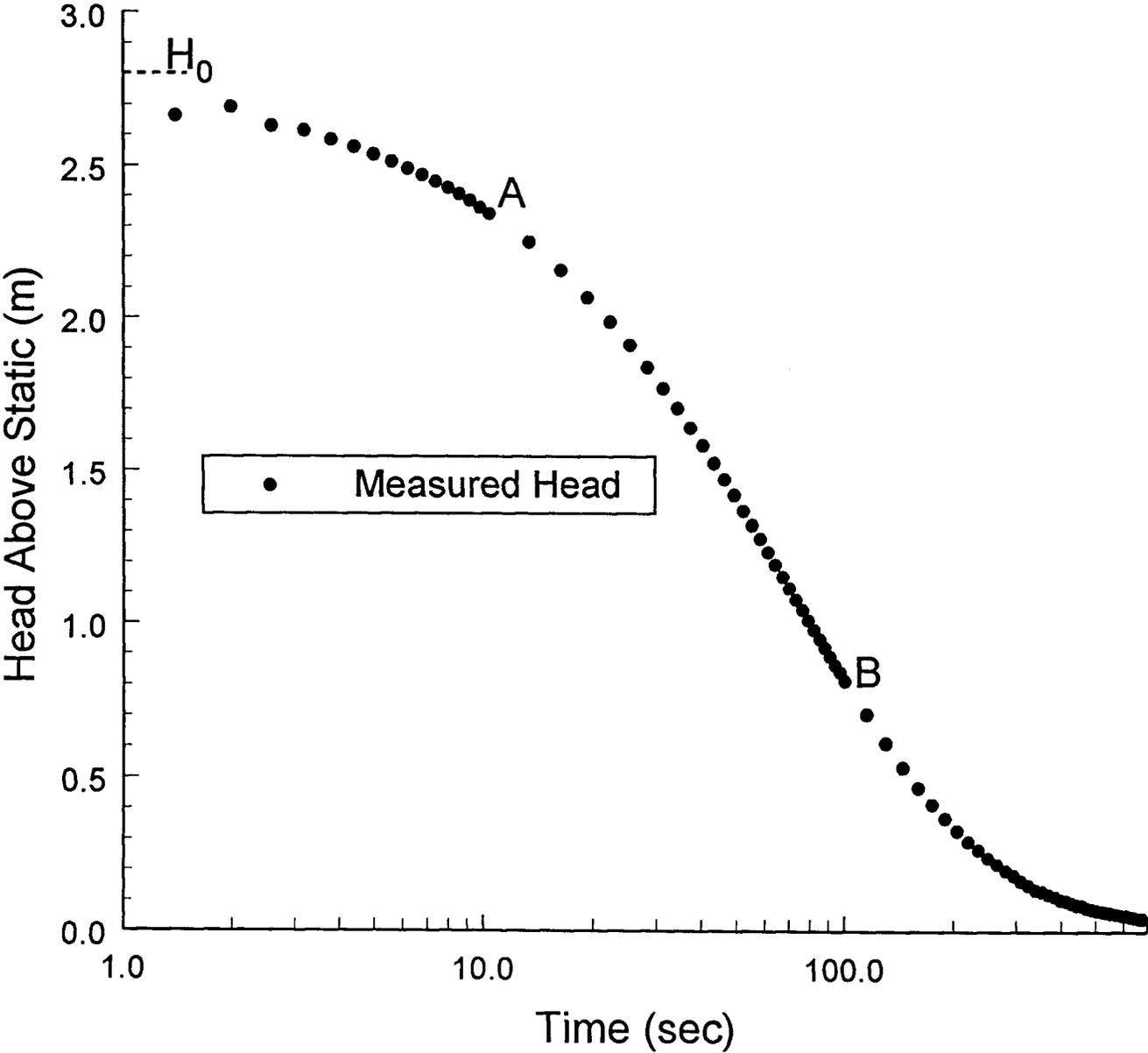
- The Slug Test - An Introduction
- Initiation Mechanisms
- General Design Guidelines
- Design of Tests in Low-K Media
- Design of Tests in High-K Media
- Analysis Design Tree
- Major Methods for Data Analysis
- Data Analysis Strategies
- Conclusions

The Slug Test - An Introduction

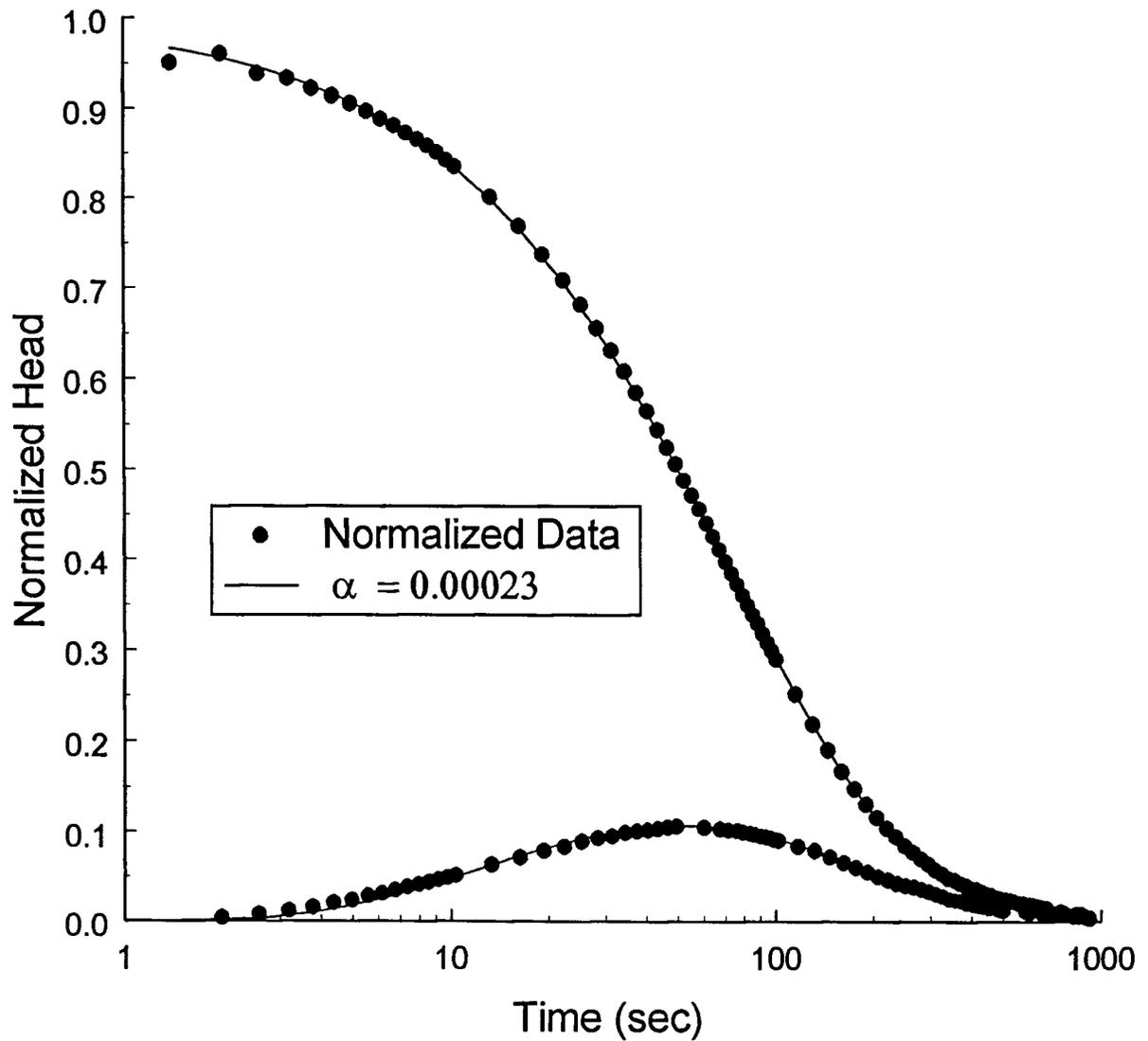
- What?
 - in-situ estimation of hydraulic conductivity (K)
- When?
 - sites of suspected groundwater contamination
- How?
 - sudden change in water level (head)
 - measure return to static conditions



Lincoln County Site - Well Ln-2 6/18/91 Test 2



Lincoln County Monitoring Site
Wells Ln-2 and Ln-3
6/18/91

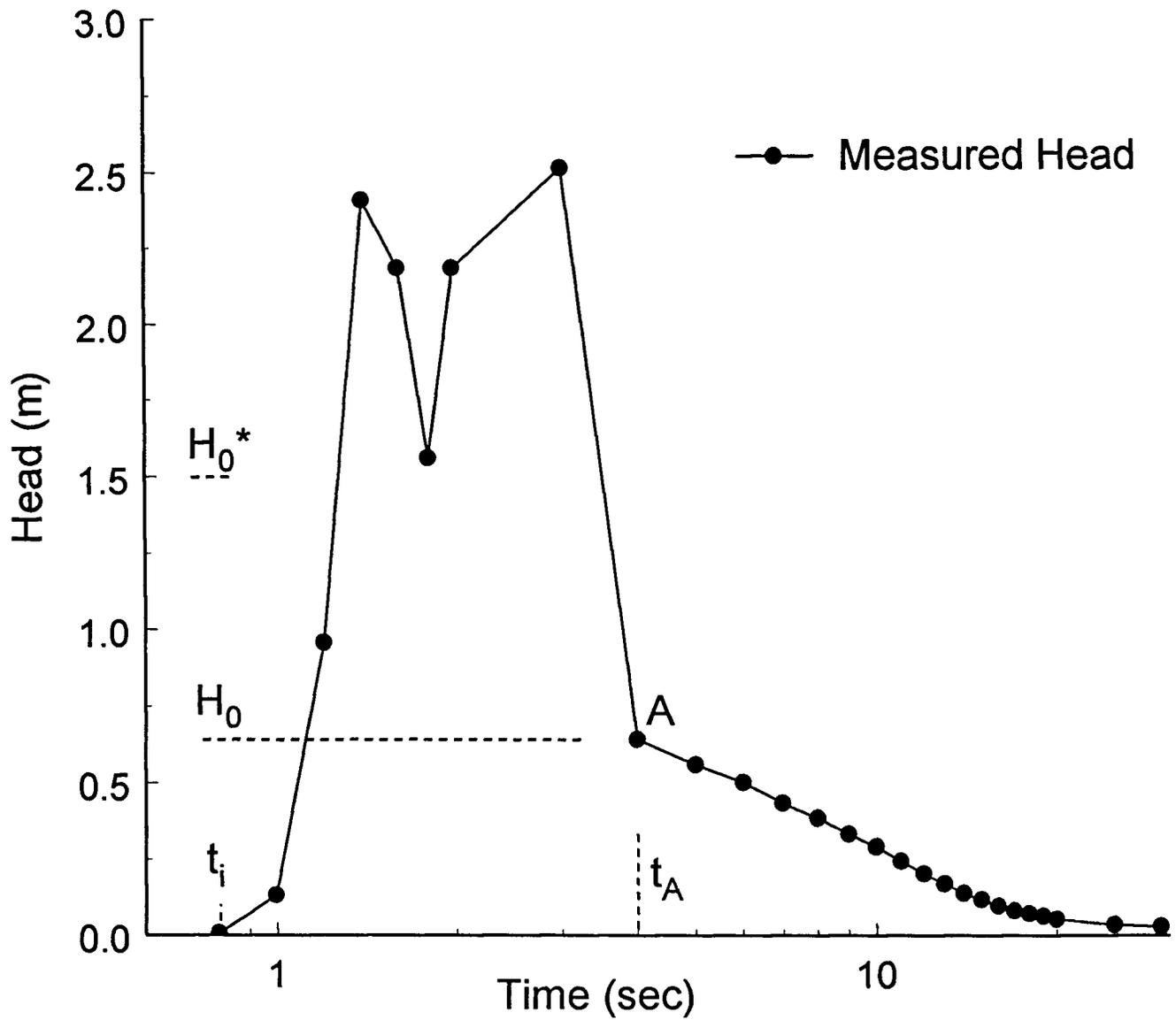


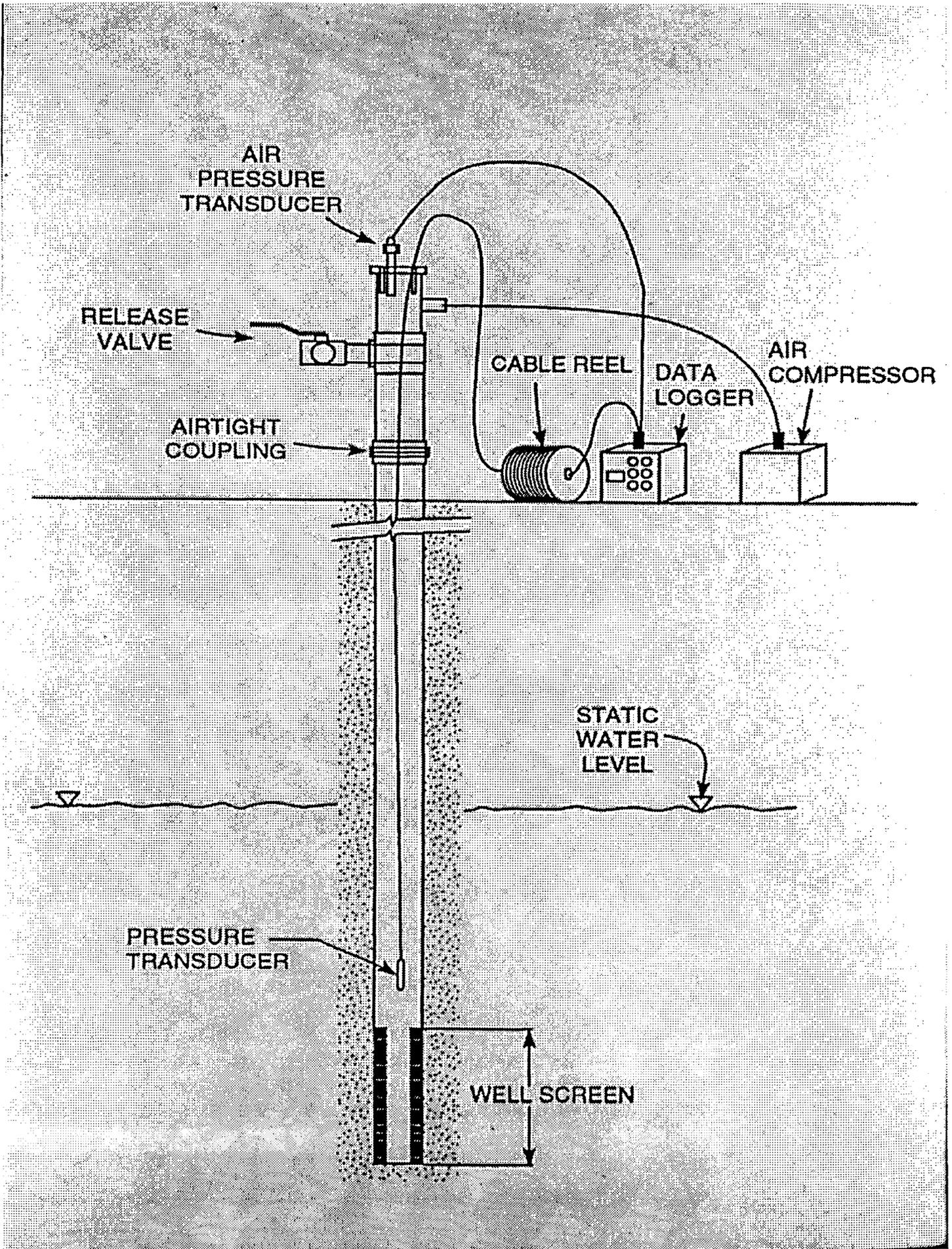
Initiation Mechanisms

- Solid Slug
 - best for shallow depths to water and larger diameter wells
 - data can be very “noisy”
- Pneumatic Method
 - wells of all diameters and depths
 - only transducer below water
- Packer Systems
 - tests in low-K media
 - multilevel slug tests

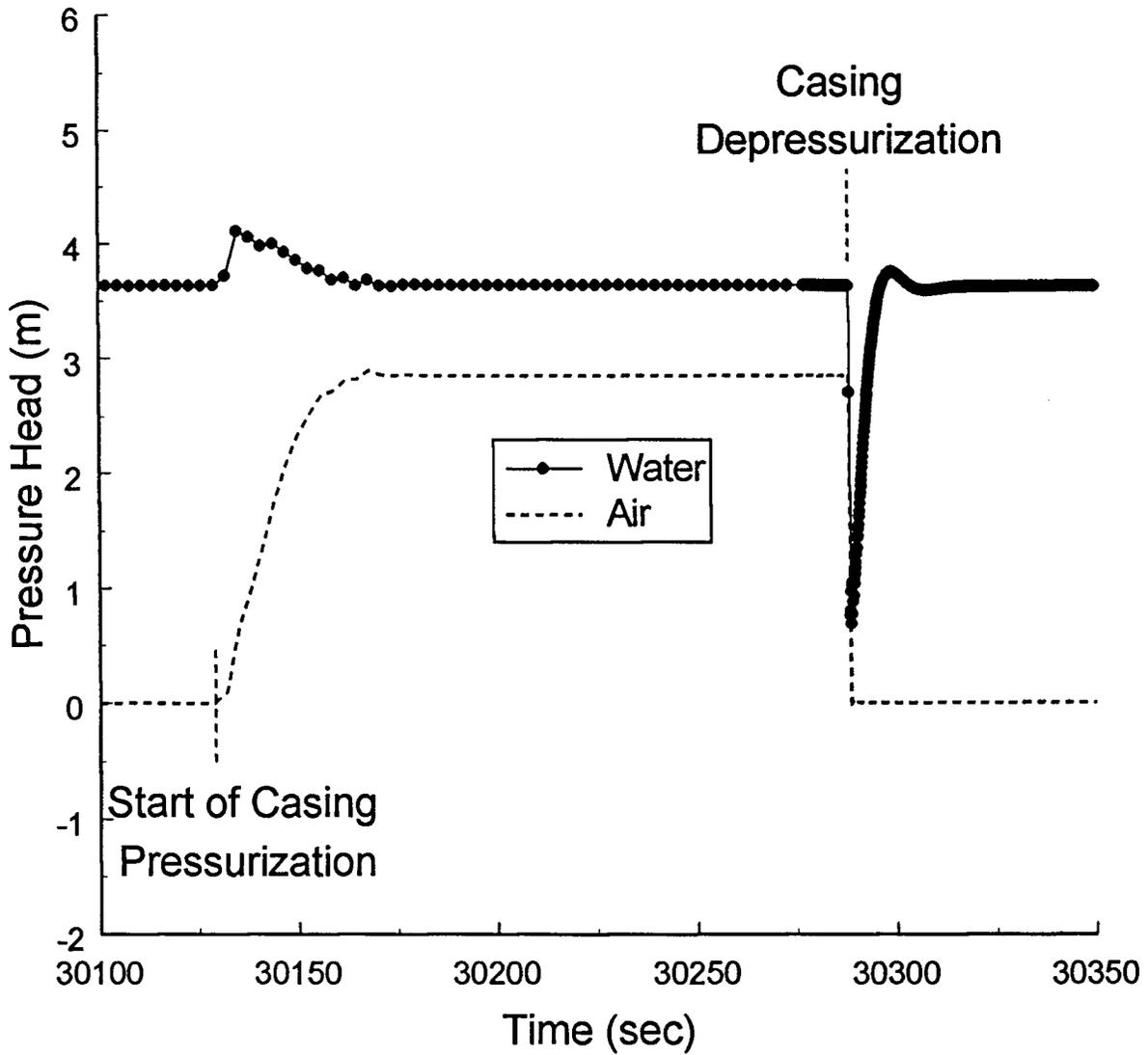
An important advantage of all three of these methods is that no water is added or removed from well for test initiation.

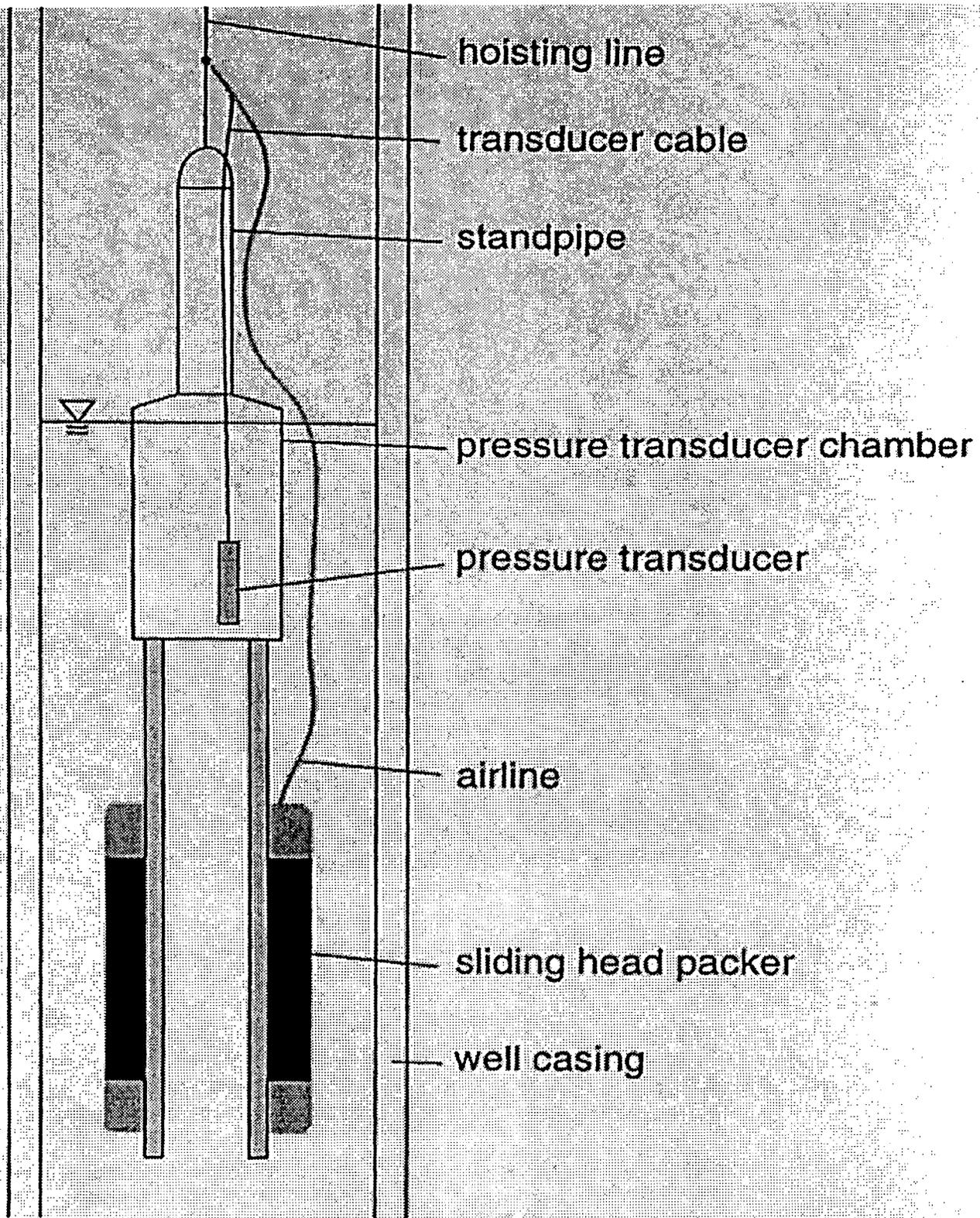
Test Initiated with a Solid Slug





Garden City Site - GCOW1 6/18/98 Slug Test 2



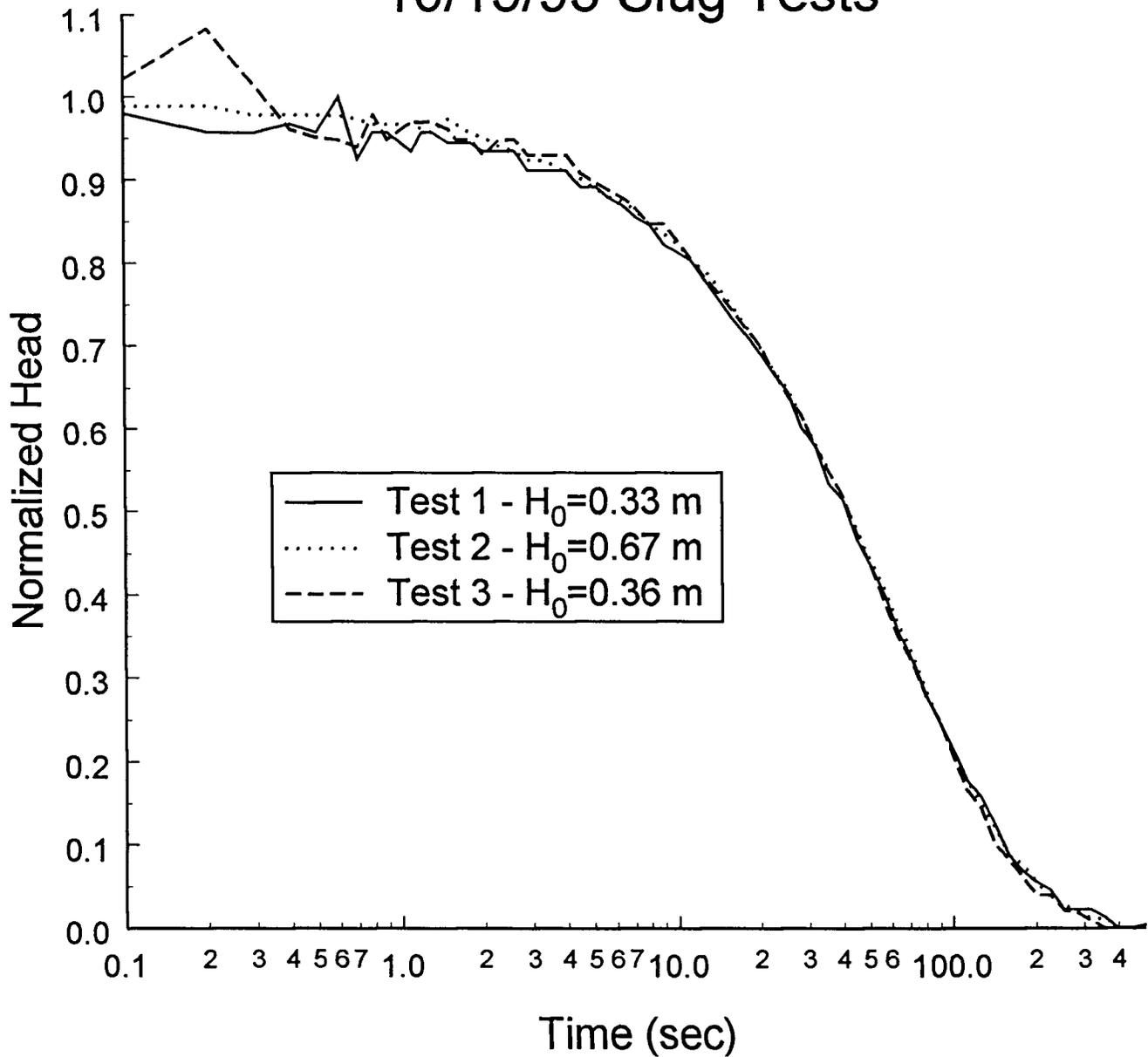


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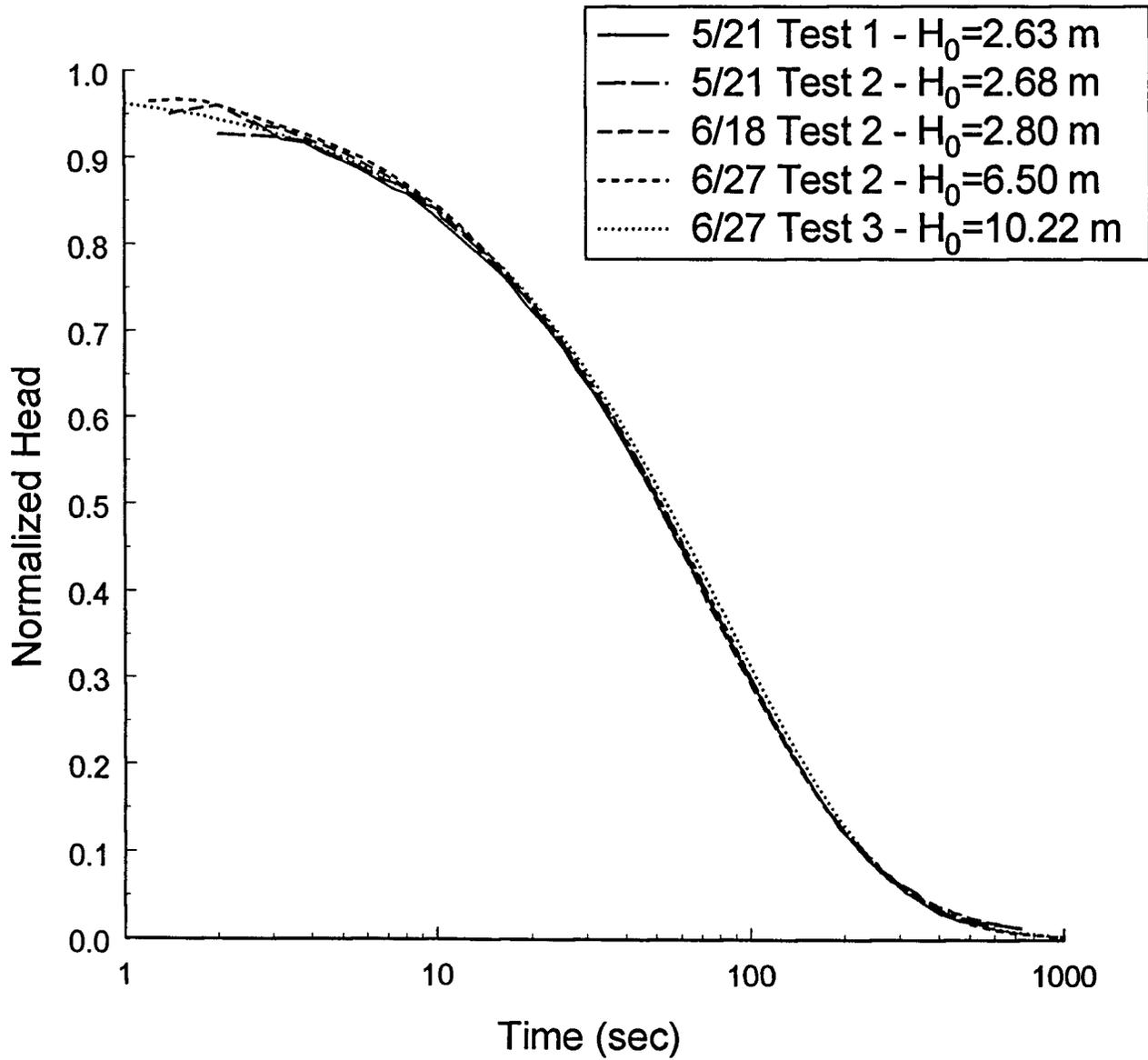
General Design Guidelines

- Overall goal of design guidelines
 - viability of conventional theory
 - effectiveness of well development
- Always perform repeat slug tests
 - vary H_0
 - vary flow direction
- Always compare H_0 values
 - expected versus measured

Pratt County Site 36, Well 4 10/15/93 Slug Tests



Lincoln County Monitoring Site Well Ln-2 1991 Slug Tests



Well Development

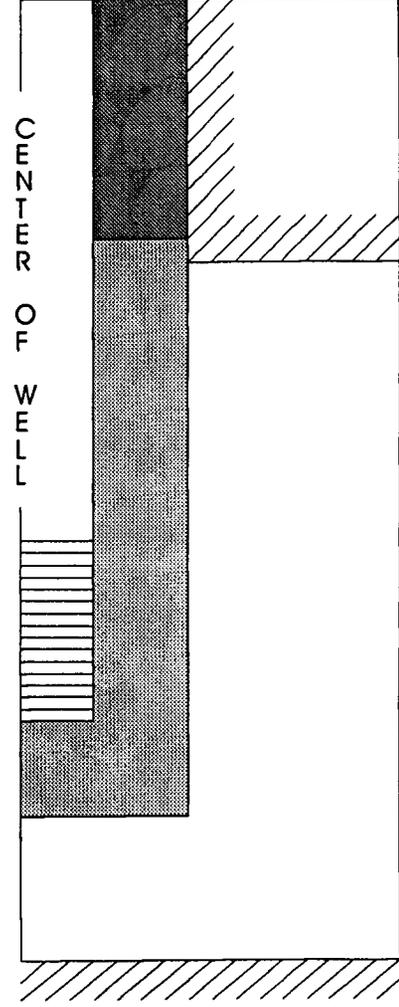
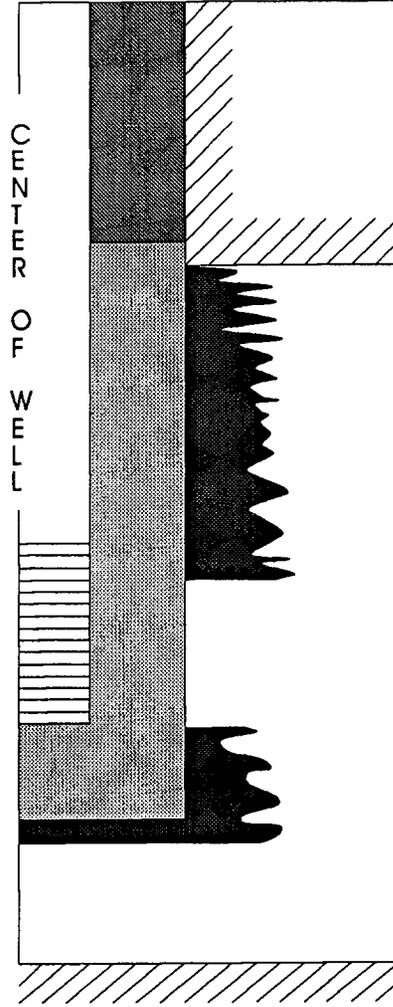
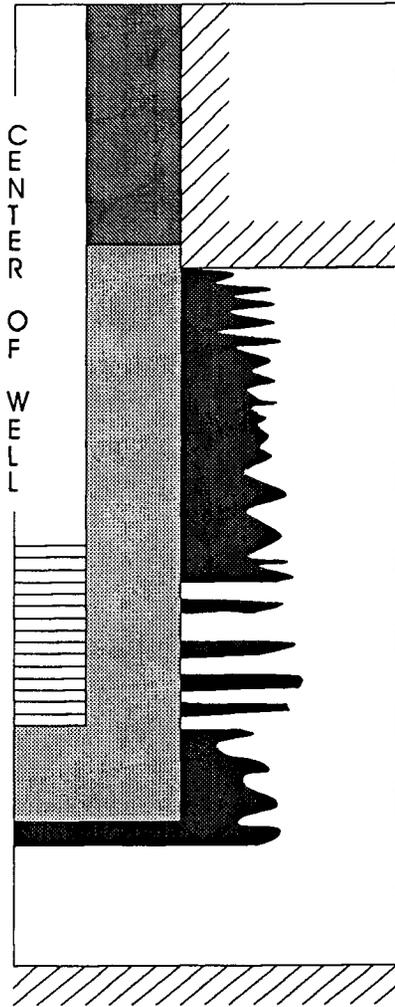
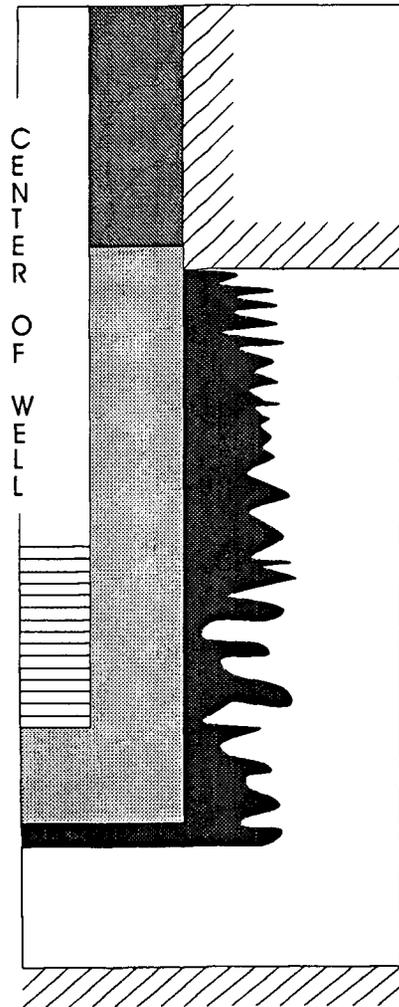
- Well development most critical factor in program of slug tests
- Incomplete well development
 - Skin effects
 - Dynamic
 - Static
 - Directional Dependent
- Slug test $K =$ lower bound on K of formation in vicinity of well

A

B

C

D



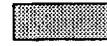
drilling debris



grout



confining bed

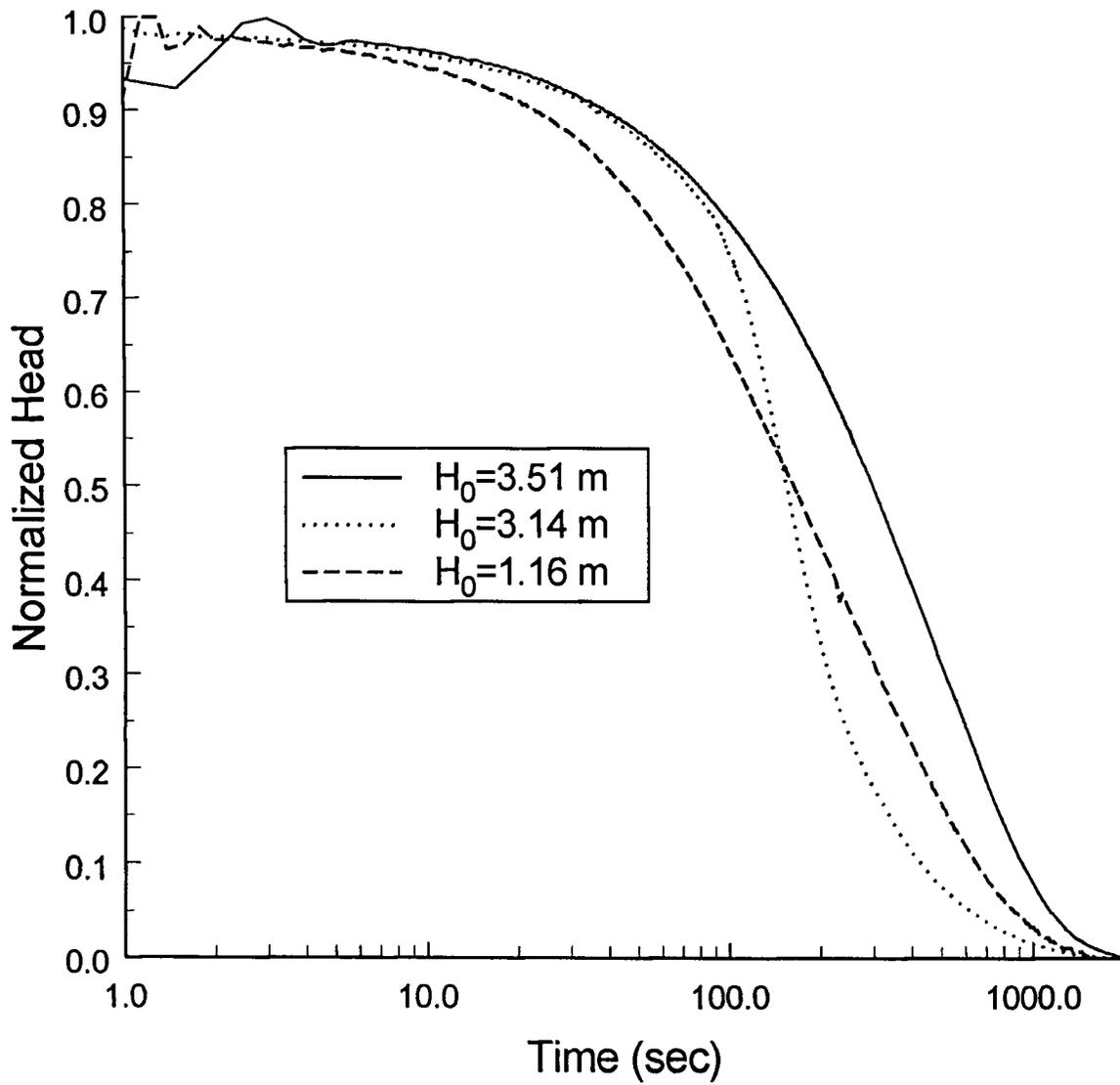


filter pack

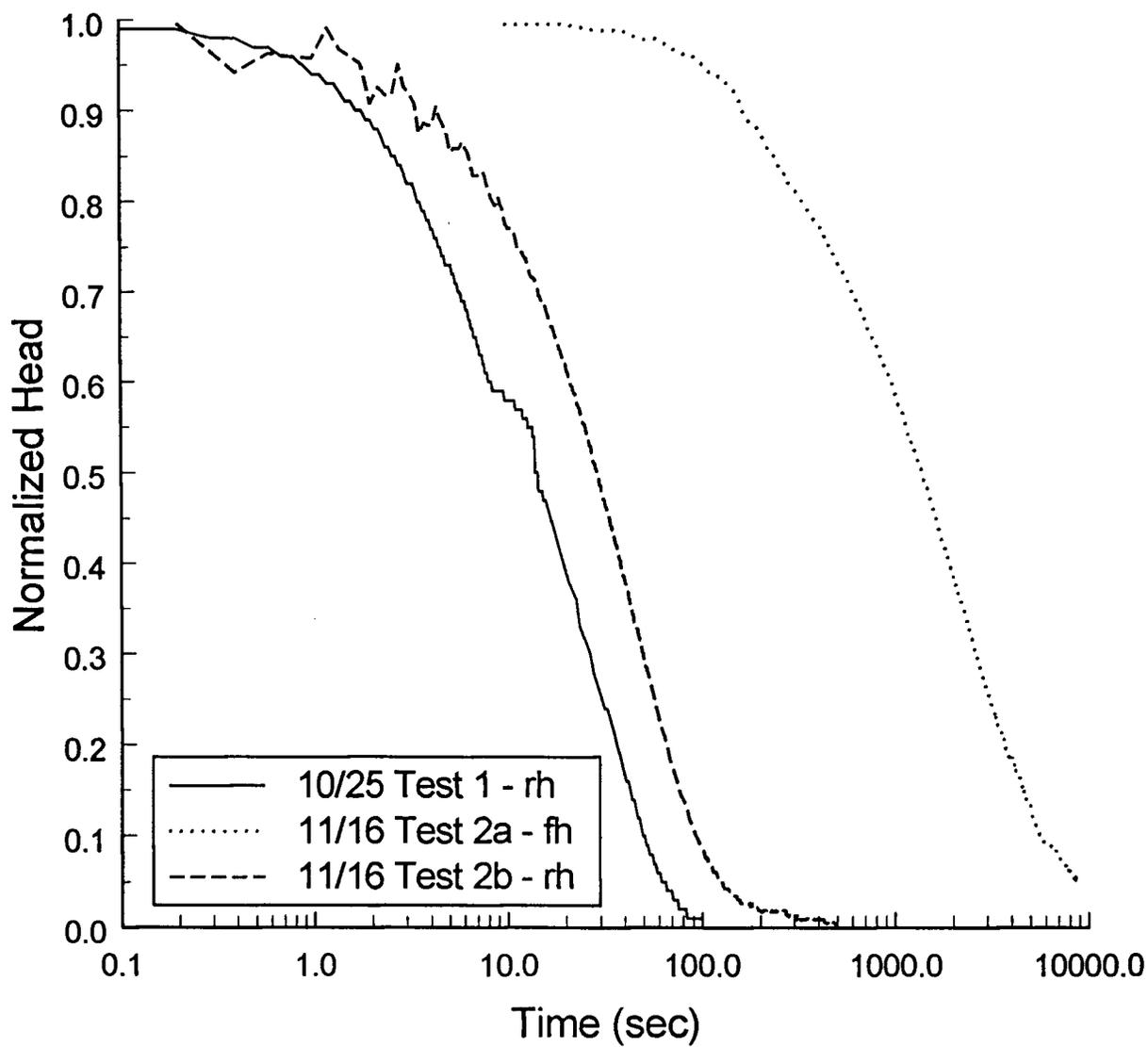


well screen

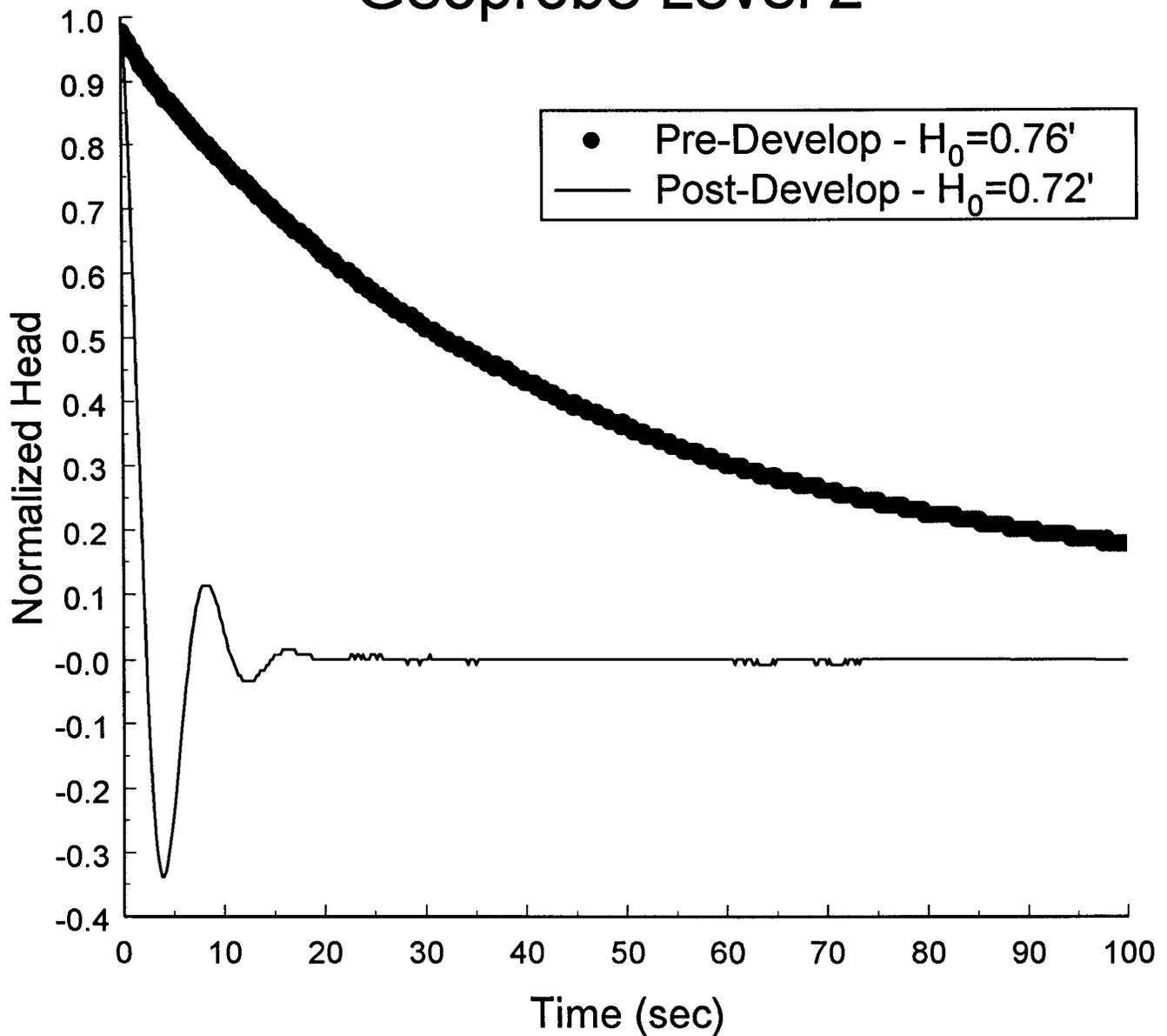
Stafford County Site 18 - Well 1 9/18/95 Tests



Trego County Site 10/25 and 11/16/95 Tests



3/16/99 GEMS Slug Tests Geoprobe Level 2





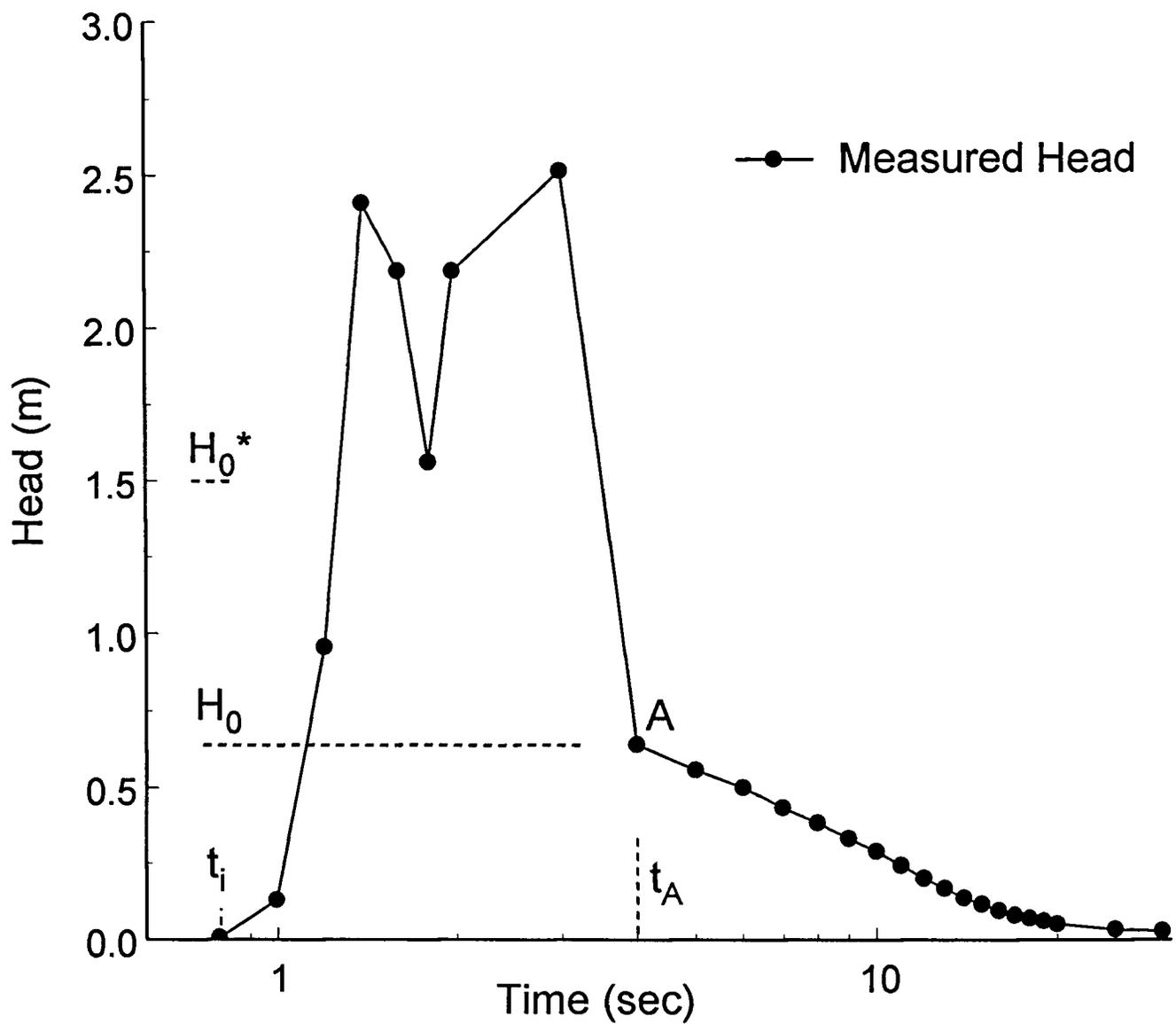
0.4" OD Pressure
Transducer

9" Wire-Wrap
Screen

Expected Versus Measured H_0

- **Noninstantaneous slug introduction**
 - K of media and initiation mechanism
- Effective casing radius = nominal casing radius?
 - drainage of filter pack
 - entrapped air in the filter pack
 - leaky annular seal

Example of Noninstantaneous Slug Introduction

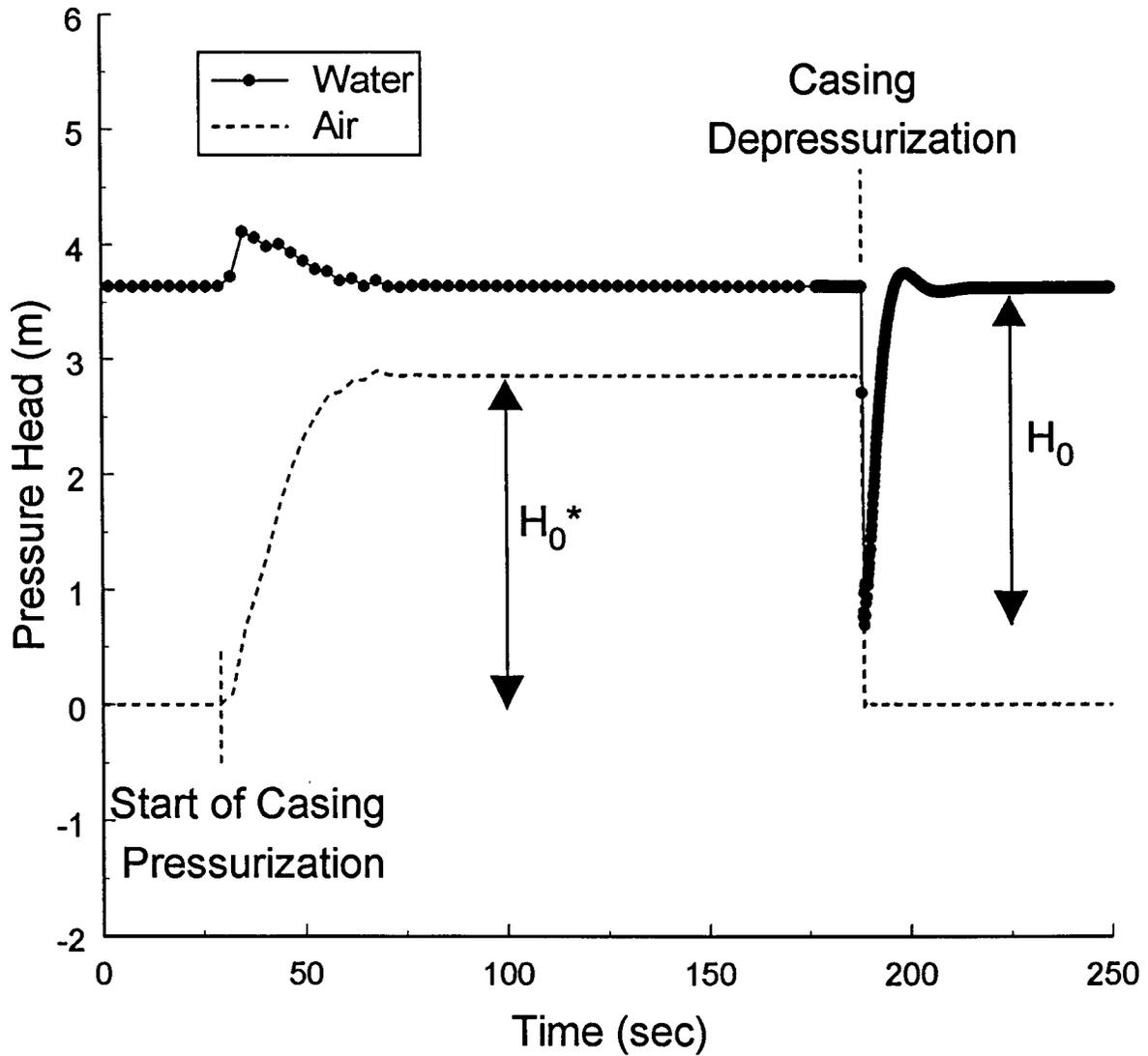


Expected Versus Measured H_0

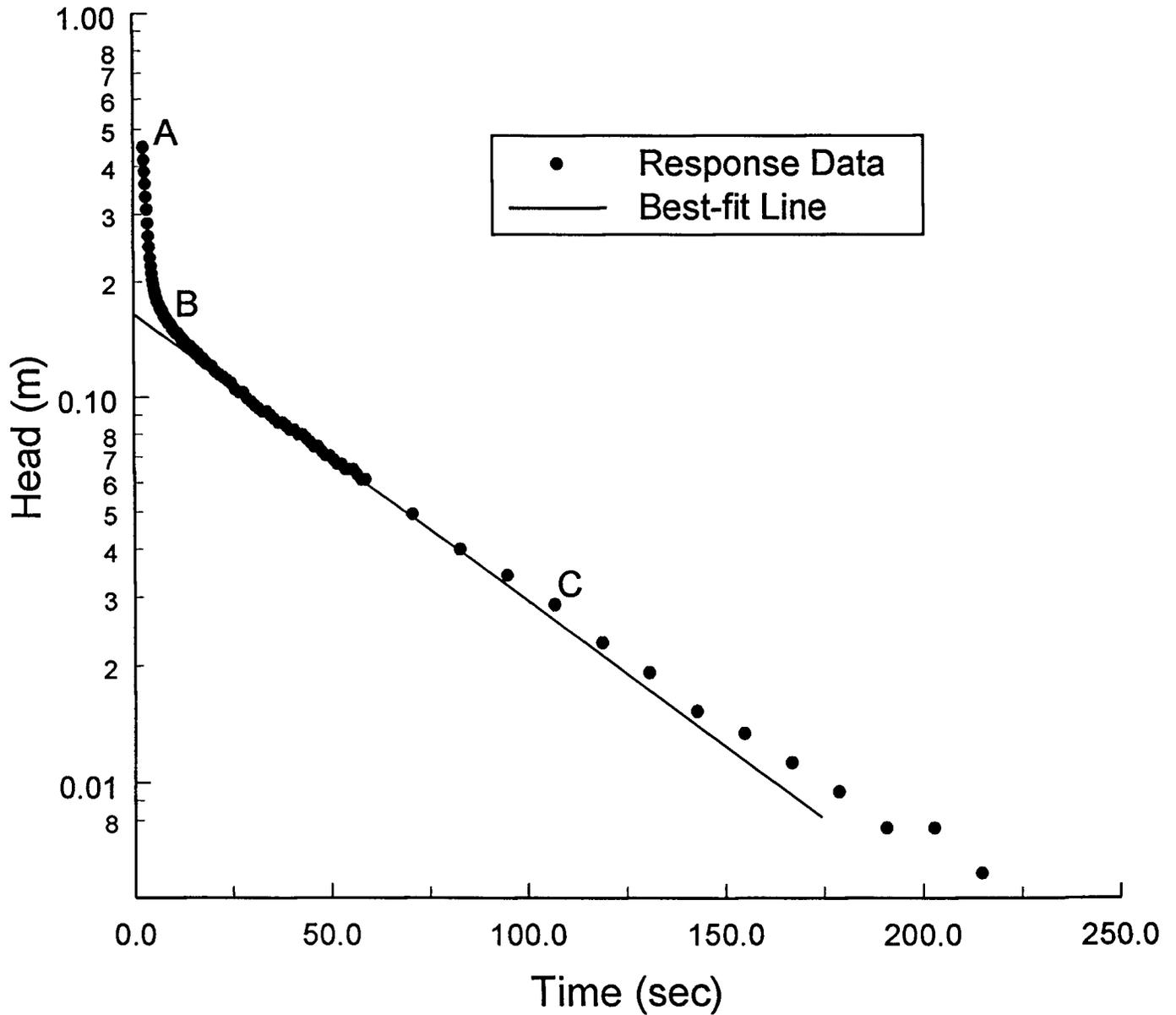
- Noninstantaneous slug introduction
 - K of media and initiation mechanism
- **Effective casing radius = nominal casing radius?**
 - drainage of filter pack
 - entrapped air in the filter pack
 - leaky annular seal

Garden City Site - GCOW1

6/18/98 Slug Test 2



Slug Test in Well Screened Across the Water Table



Calculation of effective casing radius with mass balance

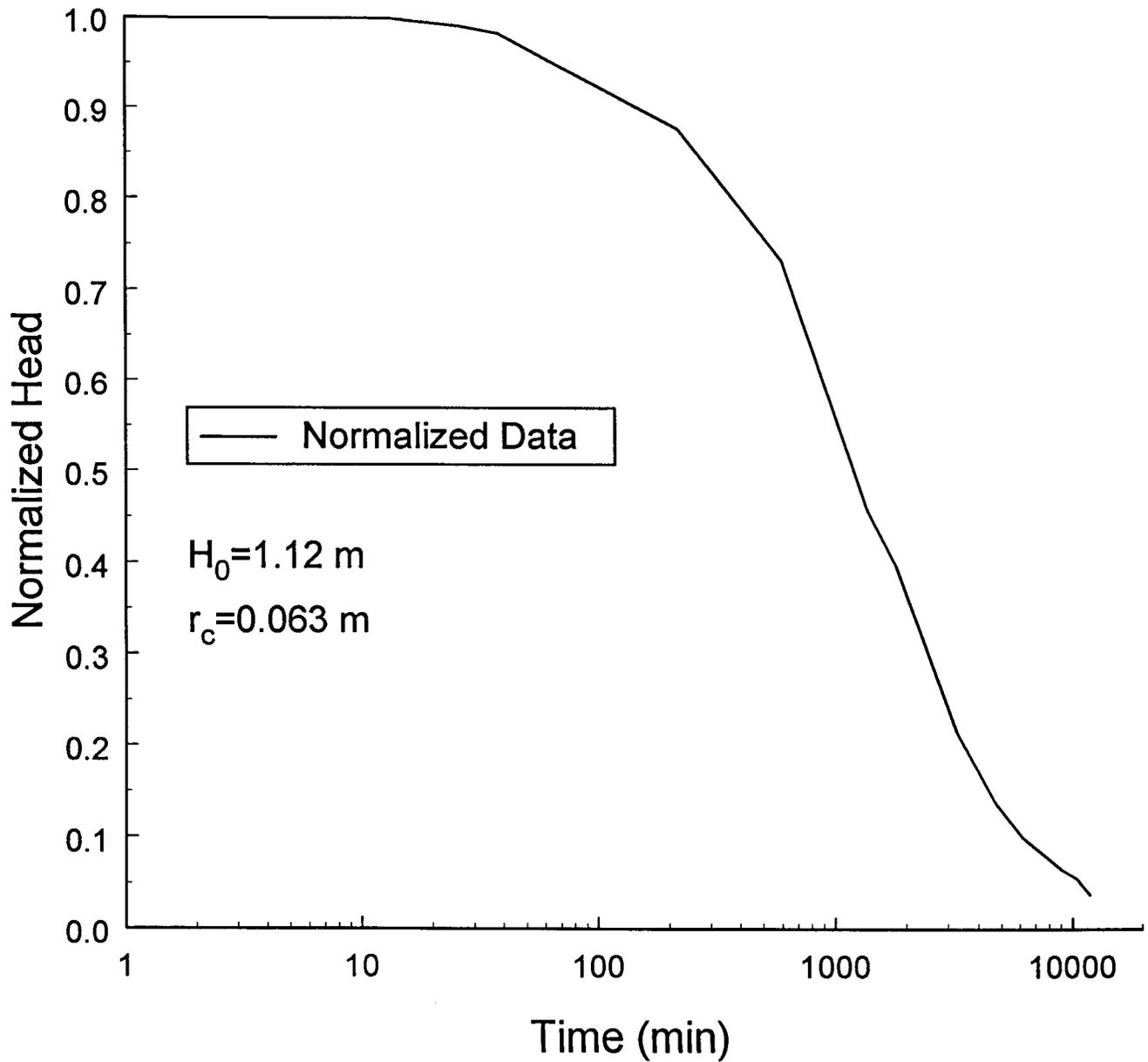
$$\pi r_c^2 H_0 = \pi r_{nc}^2 H_0^*$$

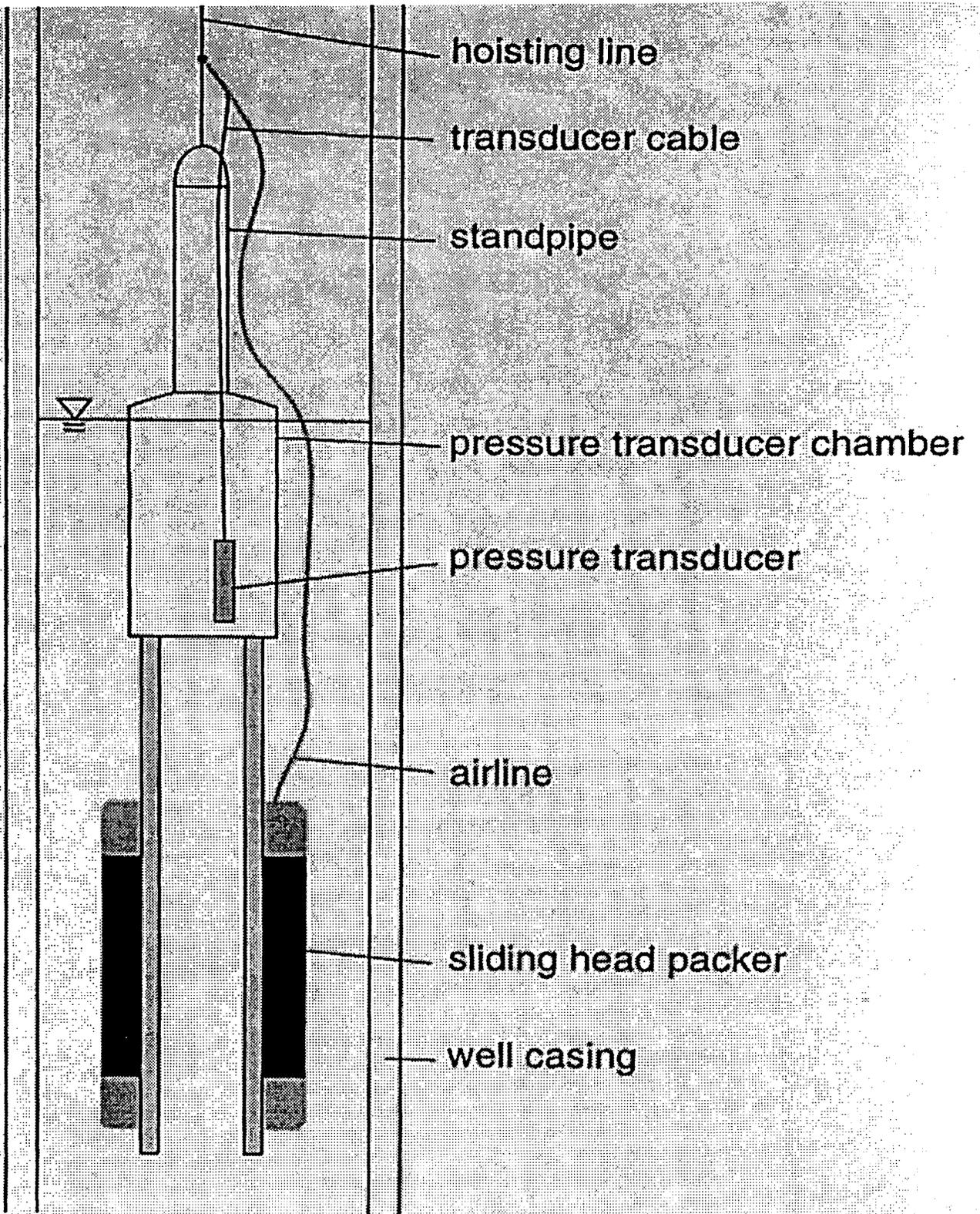
$$r_c = r_{nc} \sqrt{\frac{H_0^*}{H_0}}$$

Design of Tests in Low-K Media

- **Duration - The Big Problem**
 - Packer and Standpipe
 - Shut-In Test
- **Additional Issues**
 - Radius of Investigation
 - Effective Casing Radius
 - Entrapped Air in the Filter Pack

Stafford County Site 16, Well 1 10/93 Slug Test

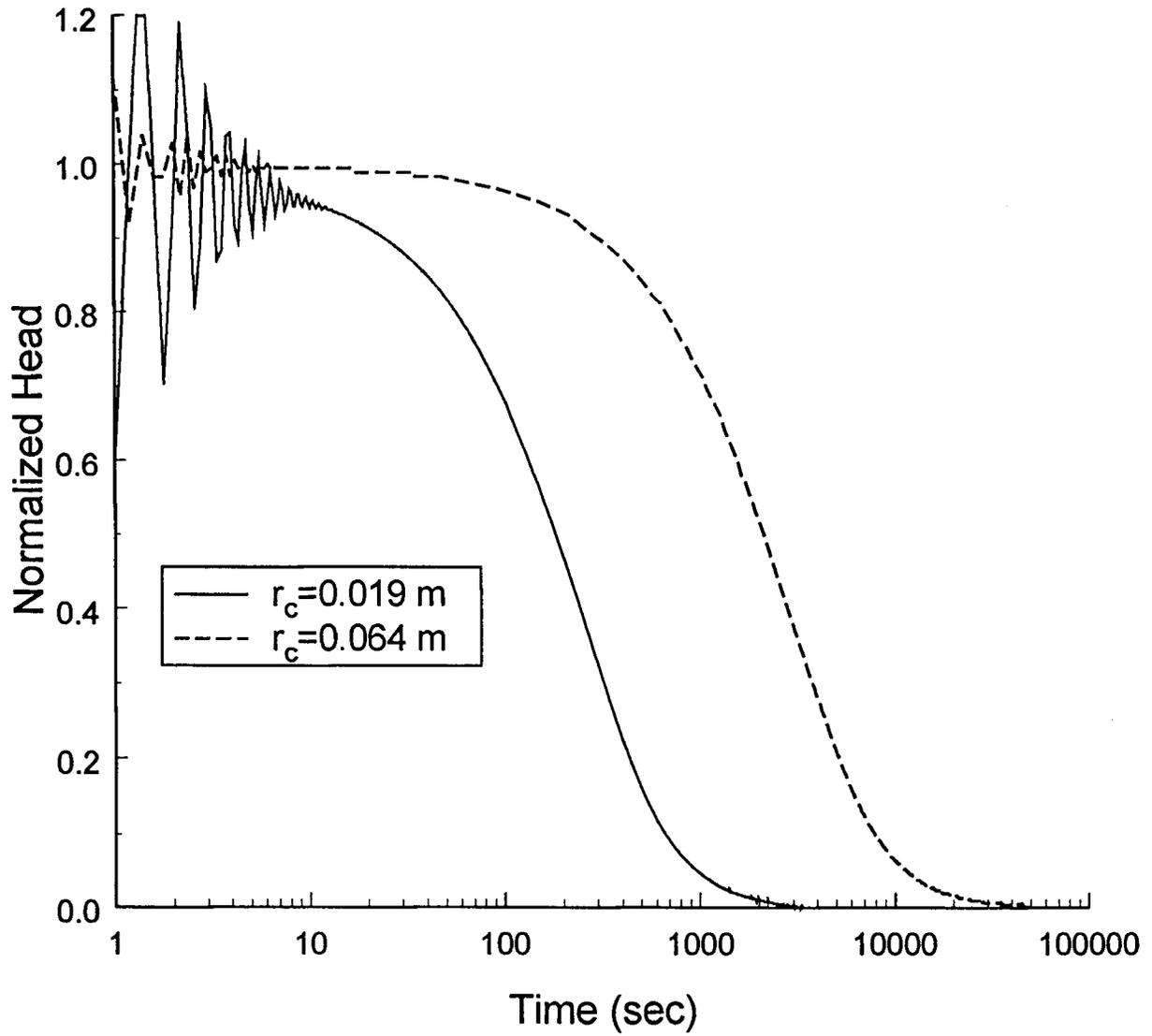




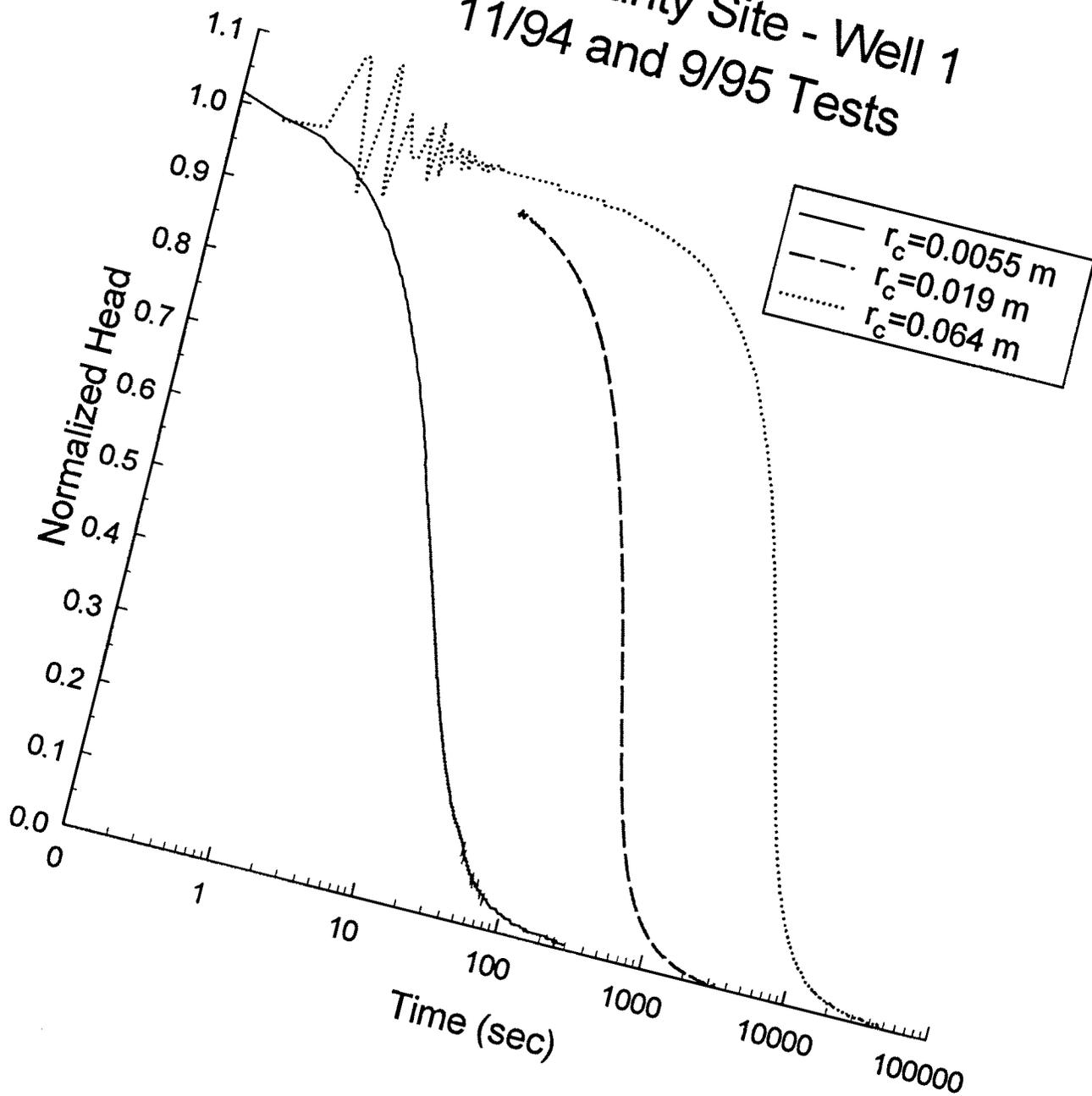
not to scale

Reno County Site - Well 1

9/12 - 9/13/95 Tests



Reno County Site - Well 1 11/94 and 9/95 Tests



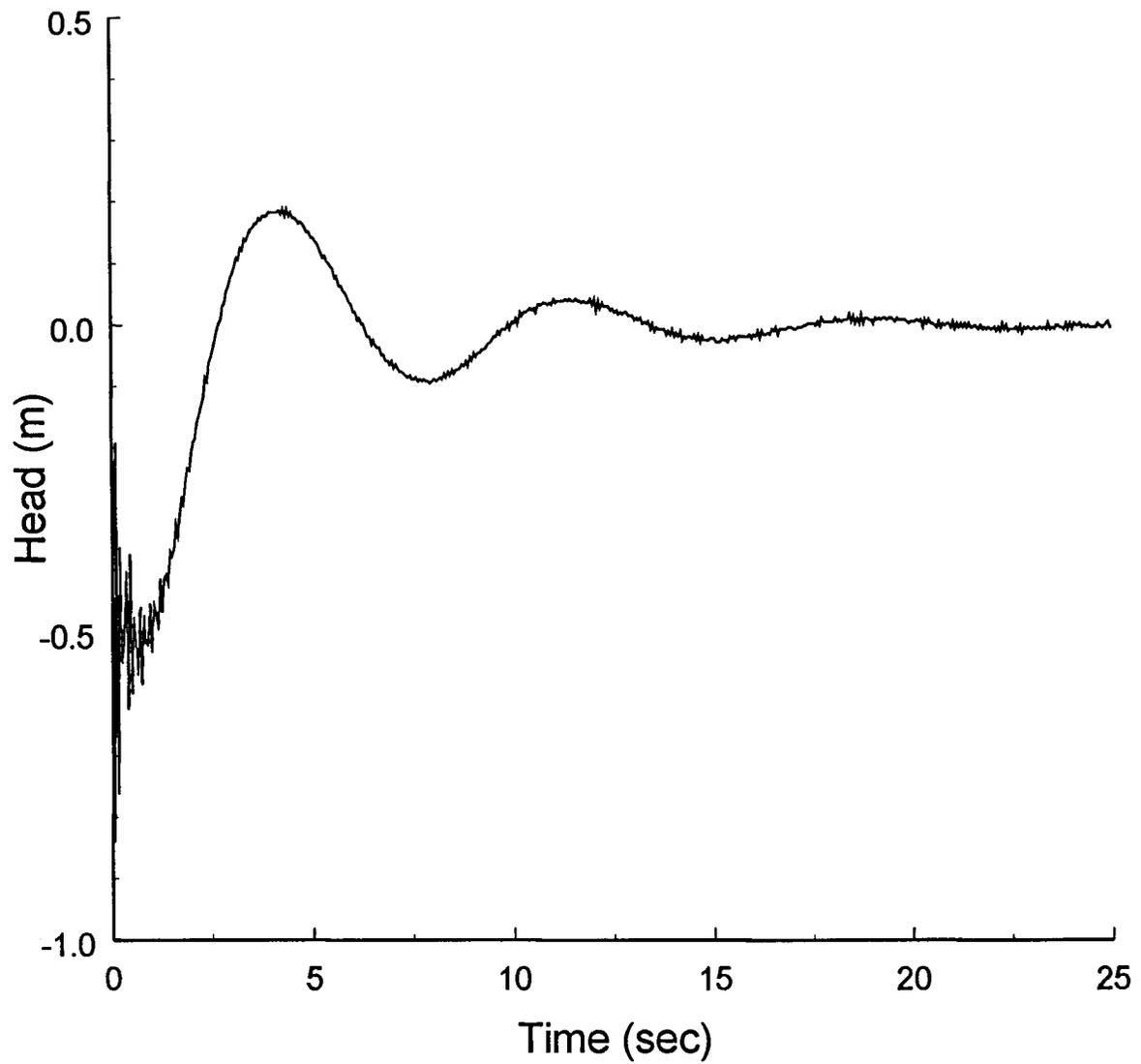
Design of Tests in Low-K Media

- Duration - The Big Problem
 - Packer and Standpipe
 - Shut-In Test
- **Additional Issues**
 - Radius of Investigation
 - Effective Casing Radius
 - Entrapped Air in the Filter Pack

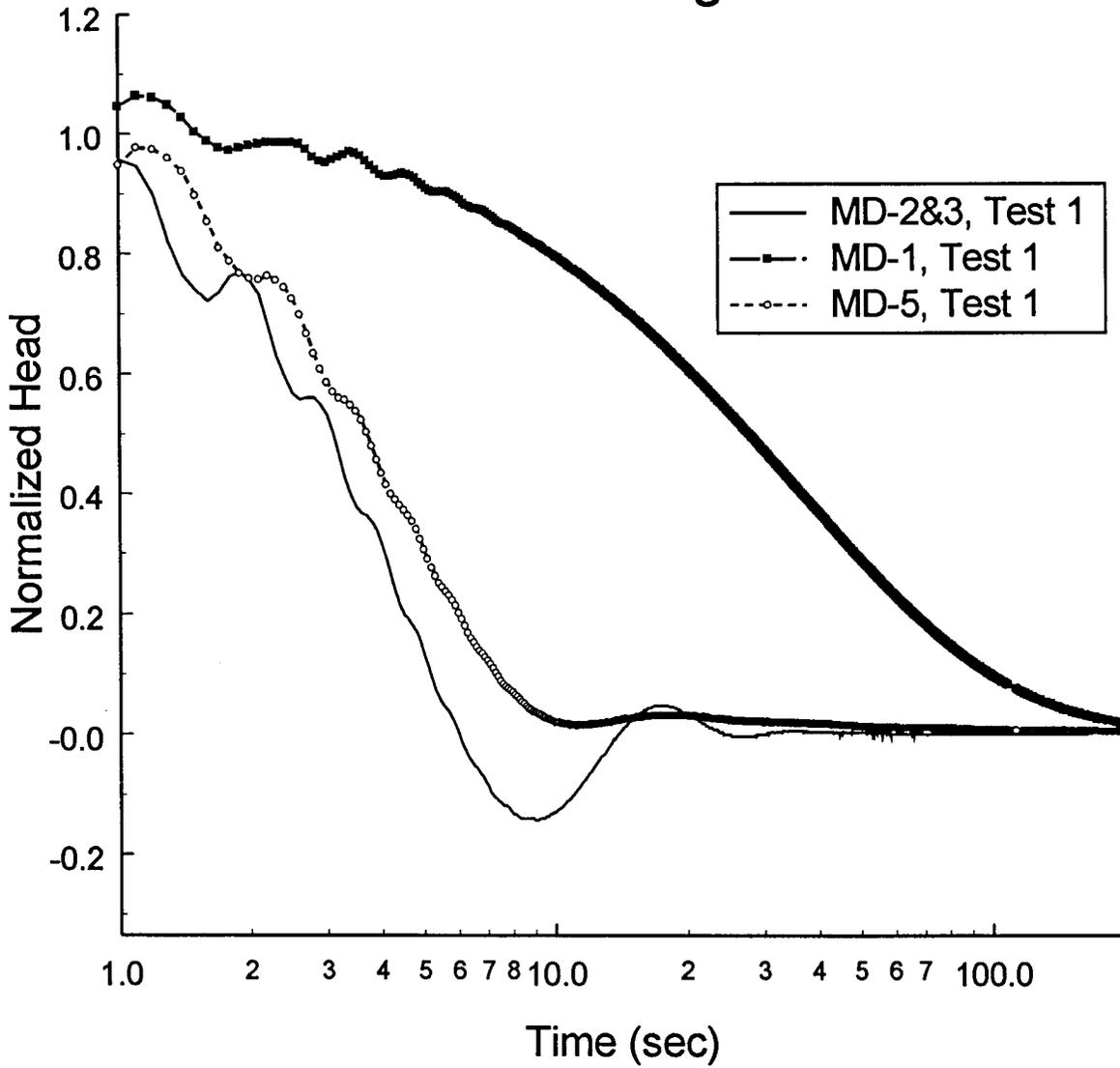
Design of Tests in High-K Media

- **Oscillatory Responses**
 - Underdamped to Overdamped
- The Big Problems
 - Duration
 - Head Dependence

Douglas County - GEMS 00-1
3/18/94 Test 1



Hays Dakota Well Field 6/10/97 Slug Tests

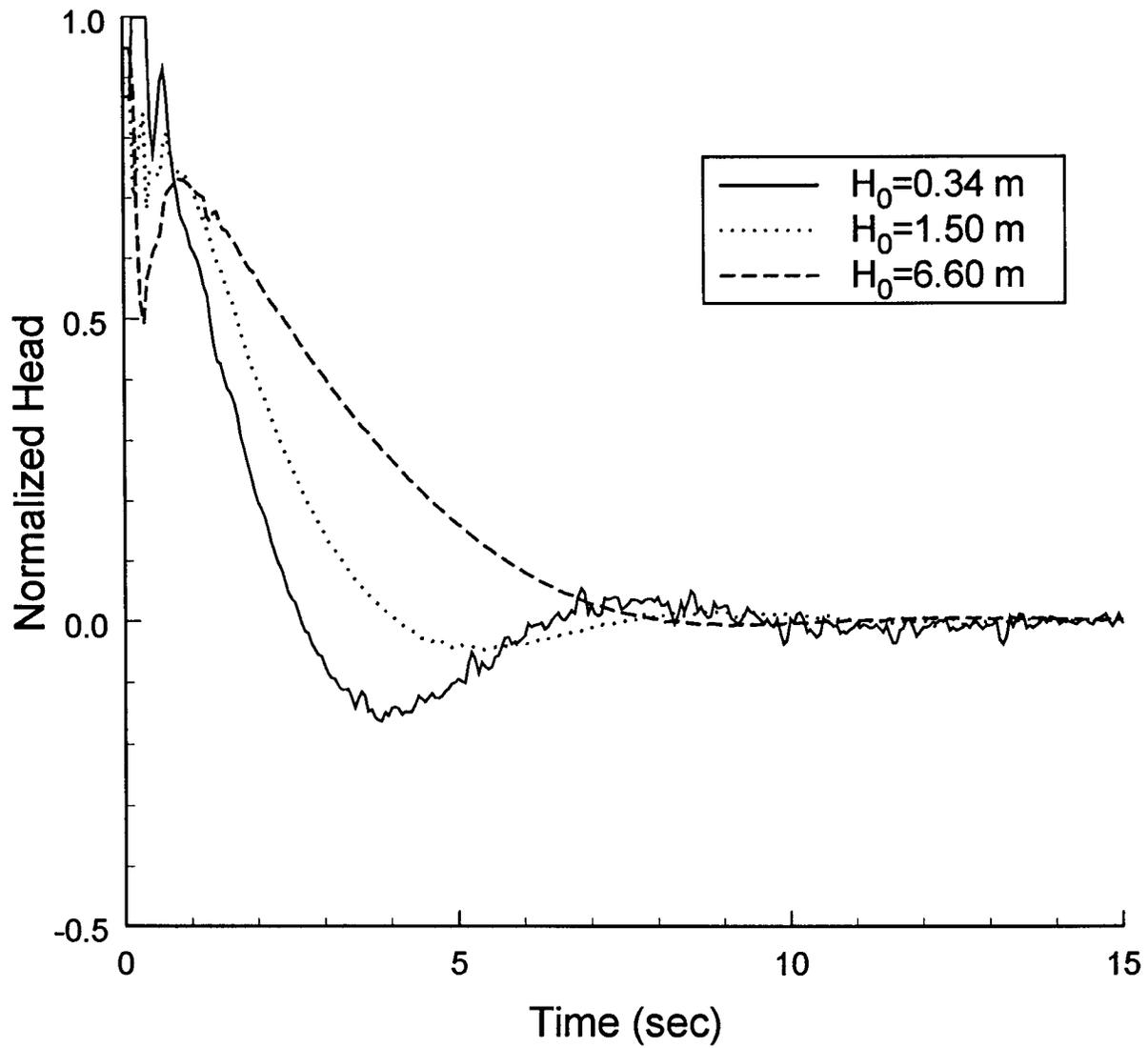


Design of Tests in High-K Media

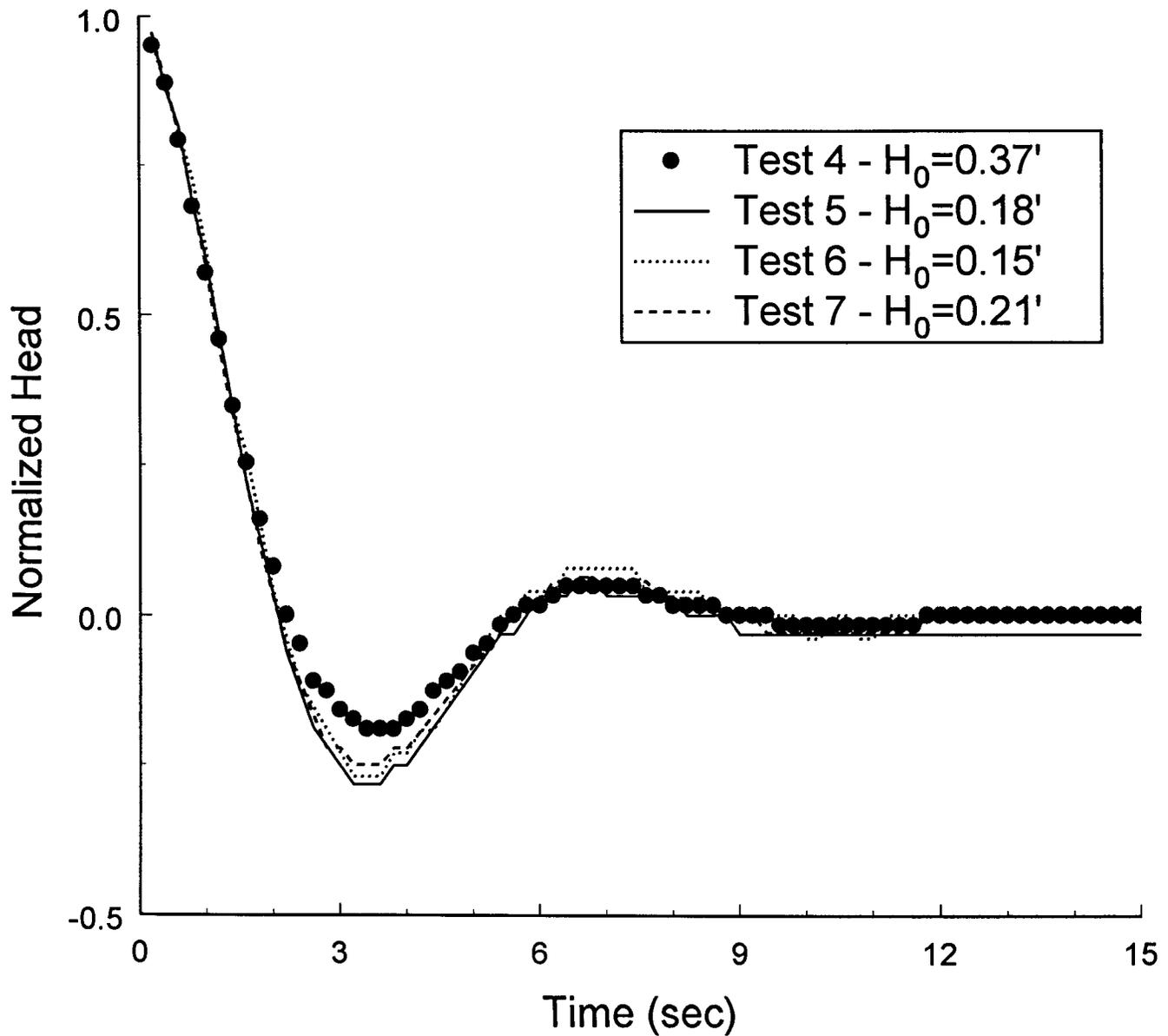
- Oscillatory Responses
 - Underdamped to Overdamped
- **The Big Problems**
 - Duration
 - Head Dependence

Douglas County - GEMS 07

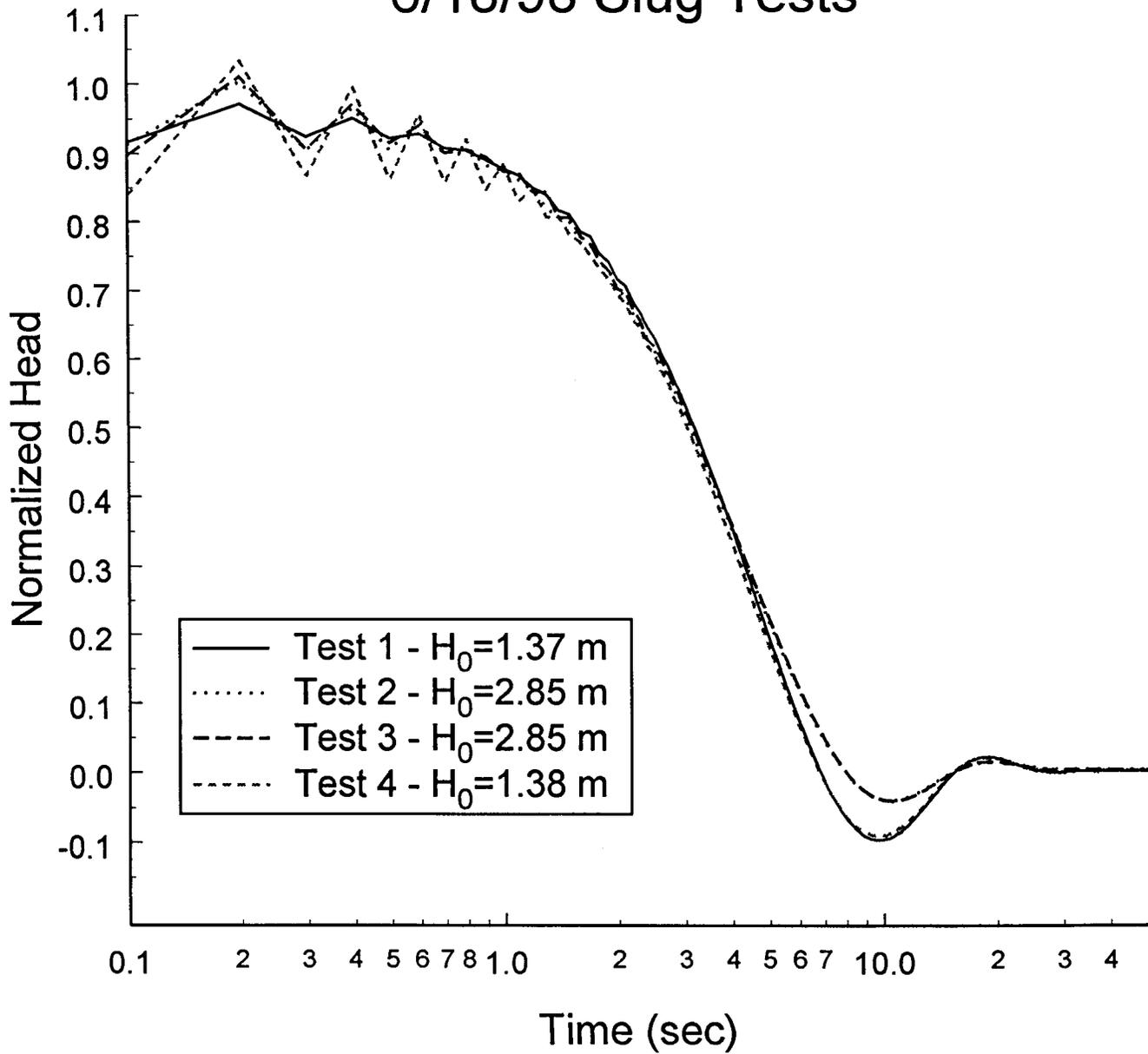
5/3/96 Tests



GEMS 3/16/99 Geoprobe Slug Tests Post-Development Level 1 - Tests 4-7



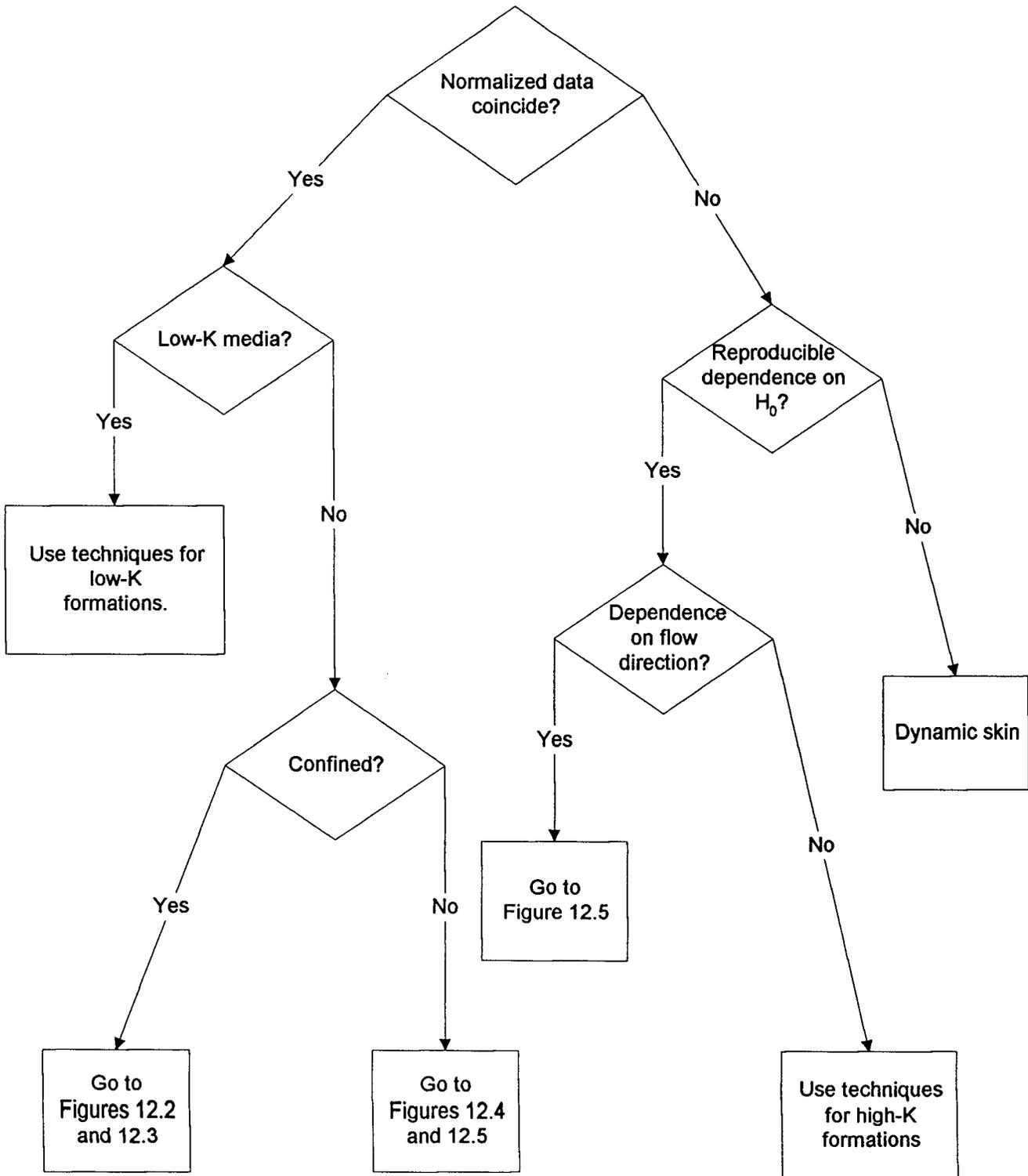
Garden City Site - GCOW1 6/18/98 Slug Tests



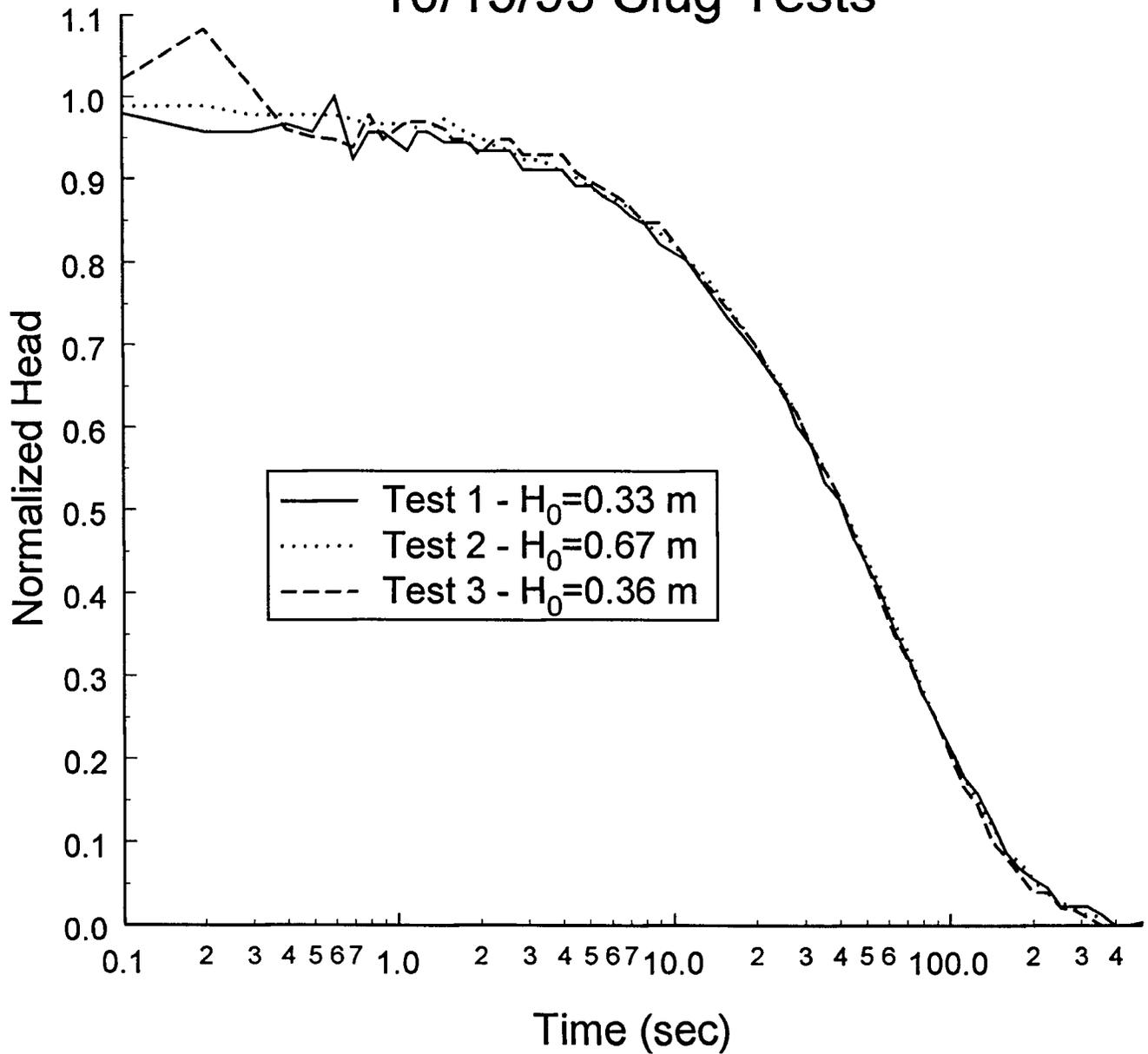
Analysis Design Tree

- Selection of general class of methods to use for analysis of slug-test data
- Assess appropriateness of conventional theory
- Assess appropriateness of well development

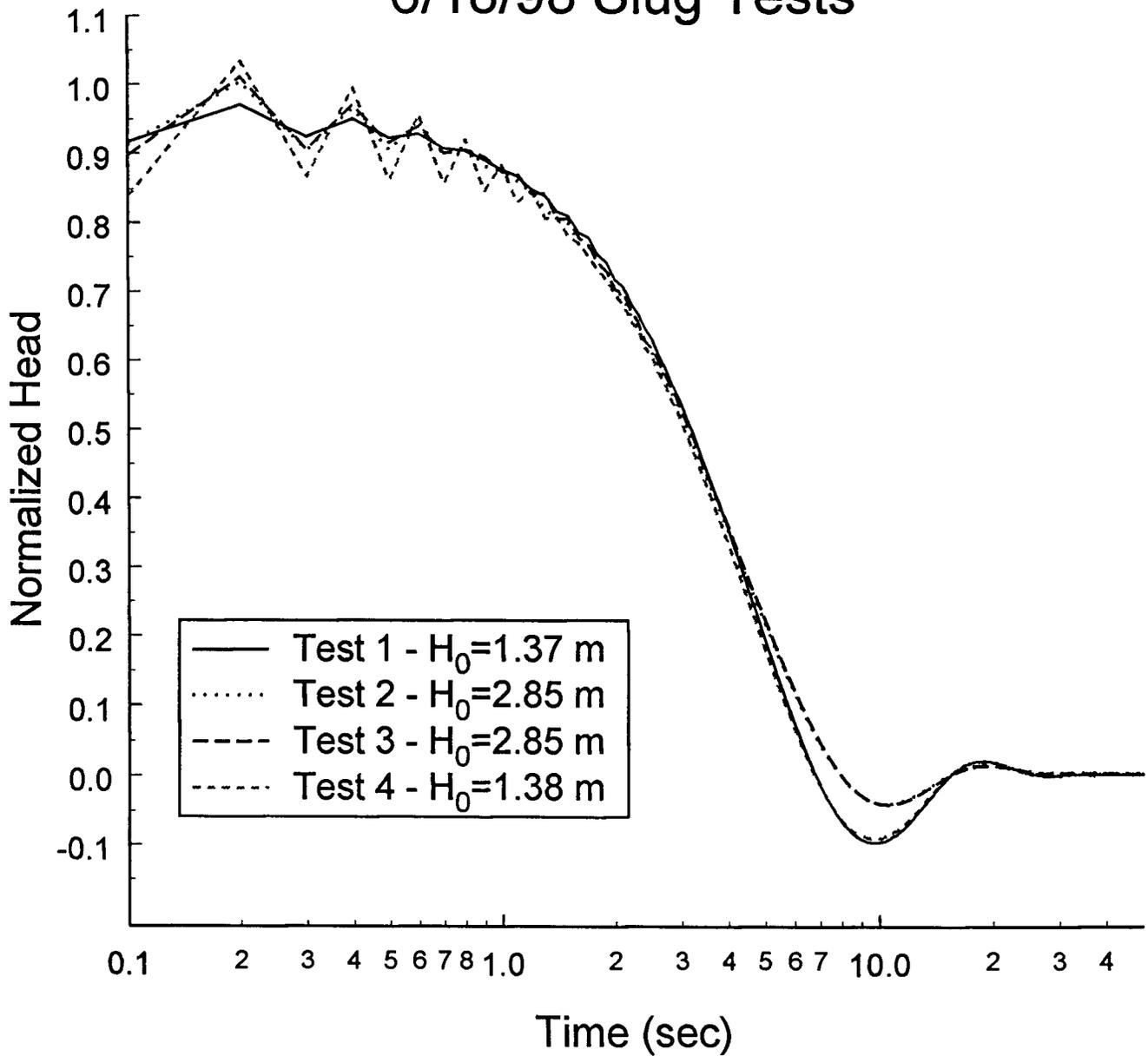
Analysis Design Tree



Pratt County Site 36, Well 4 10/15/93 Slug Tests

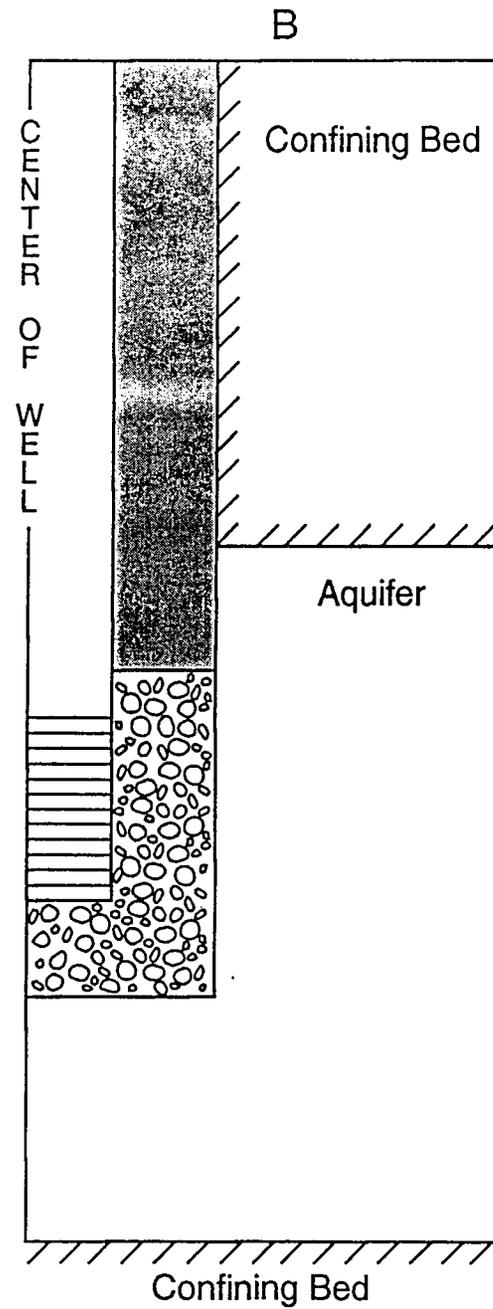
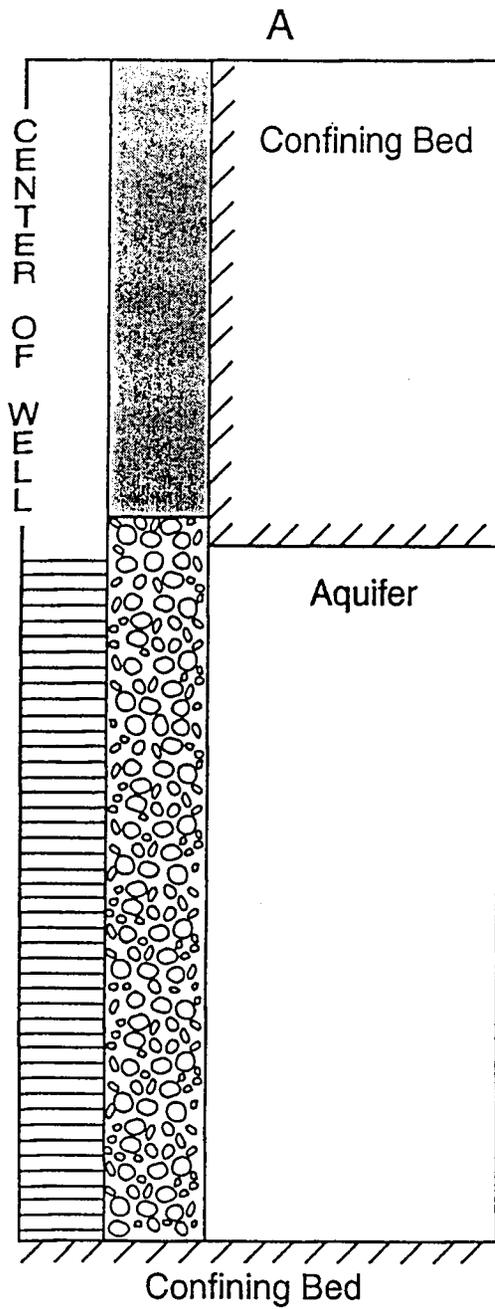


Garden City Site - GCOW1 6/18/98 Slug Tests



Major Methods for Data Analysis

- **Confined Formations**
 - Cooper et al. Model
 - Hvorslev Model
 - KGS Model
- **Unconfined Formations**
 - Bouwer and Rice Model
 - KGS Model



grout

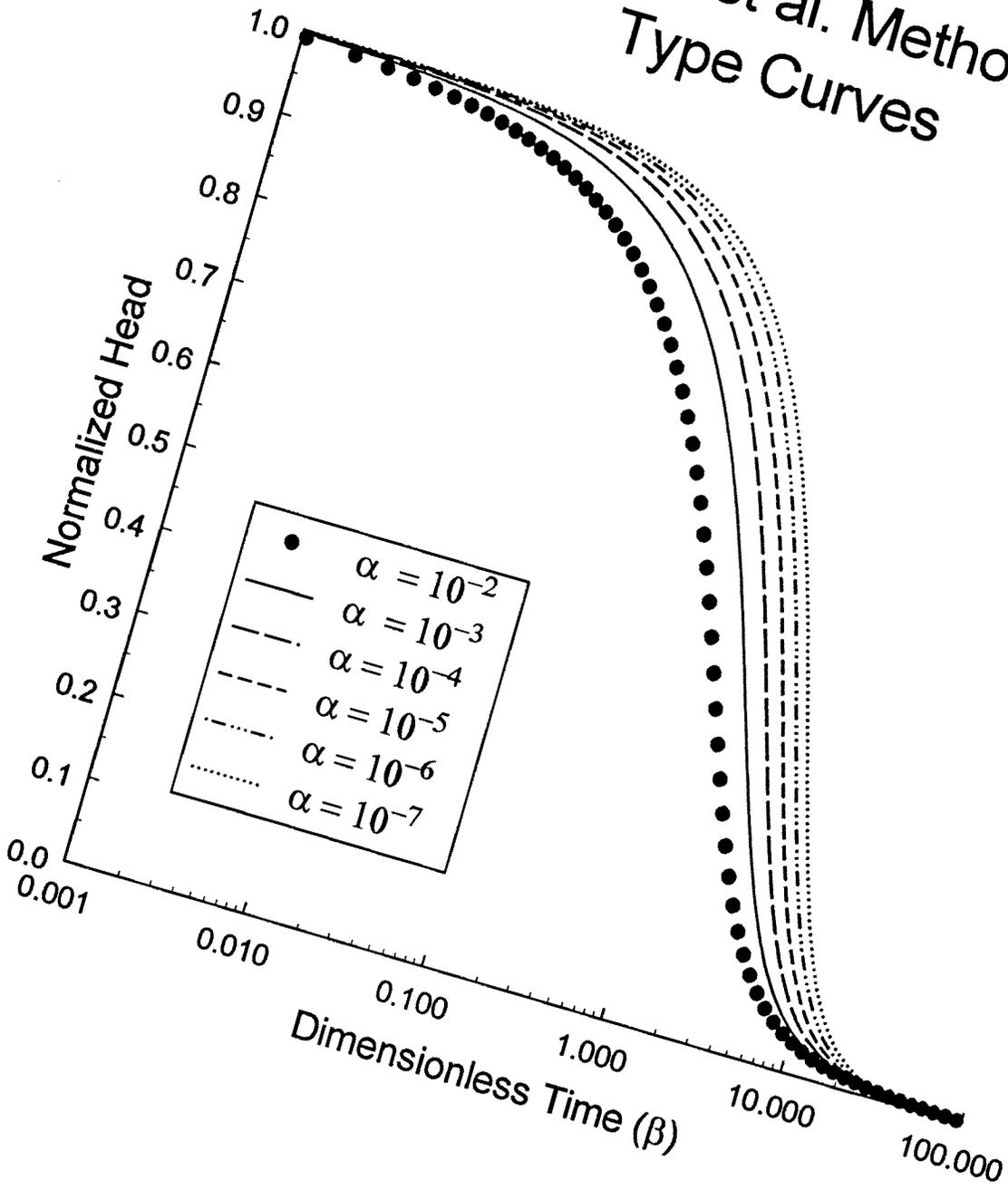


filter pack

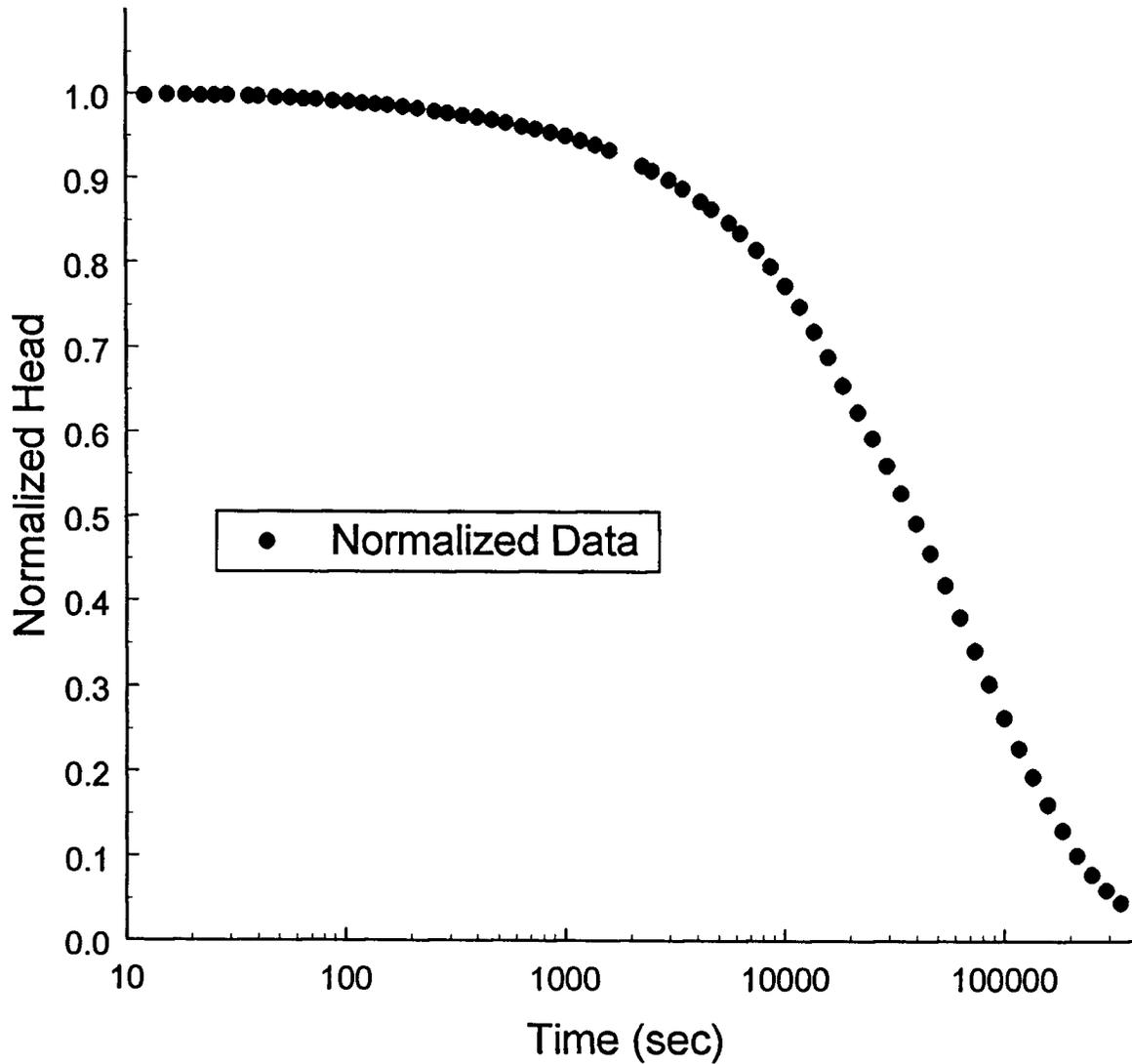


screened interval

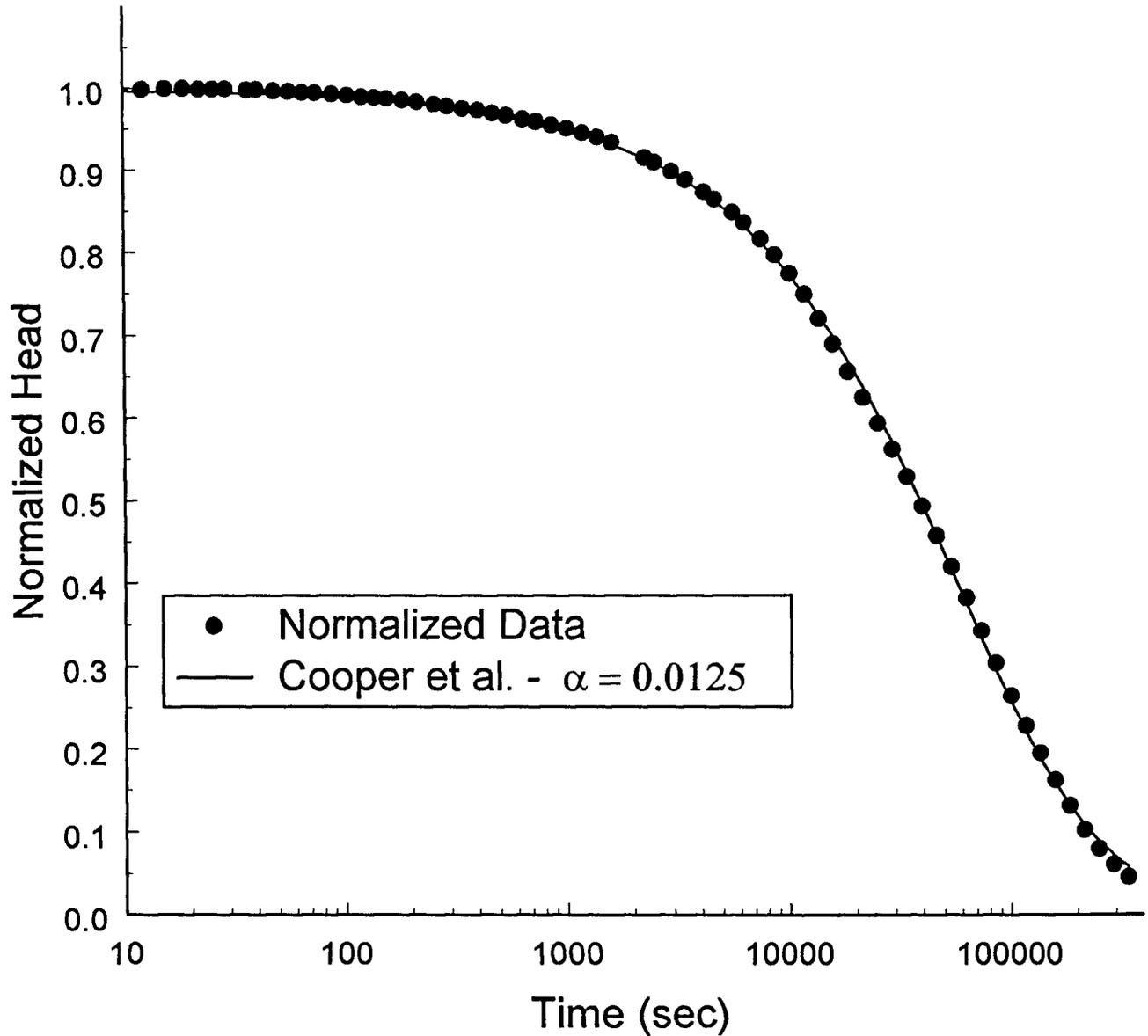
Cooper et al. Method Type Curves



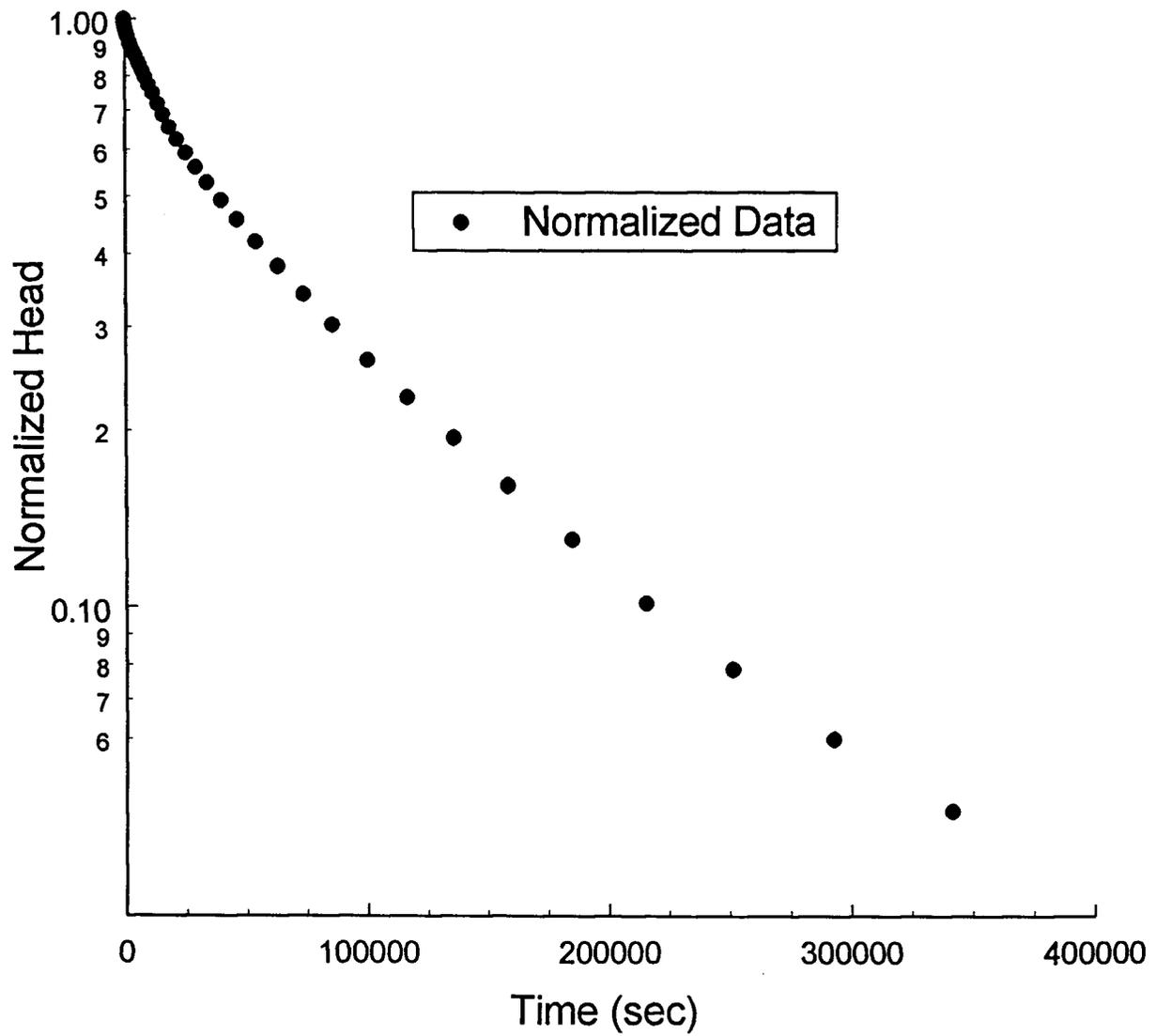
Lincoln County Monitoring Site
Well Ln-1
6/14/91 - 6/18/91



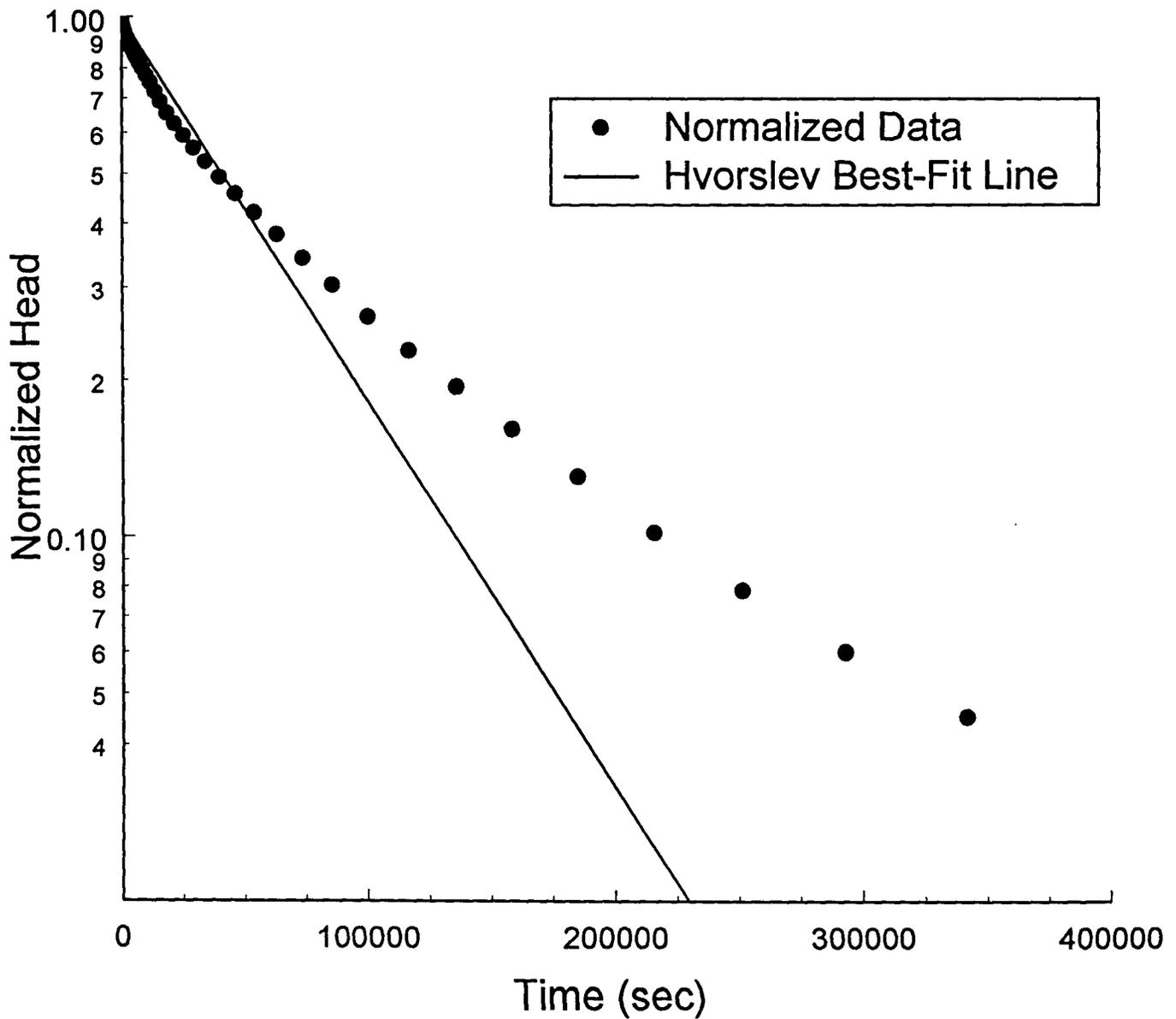
Lincoln County Monitoring Site
Well Ln-1
6/14/91 - 6/18/91



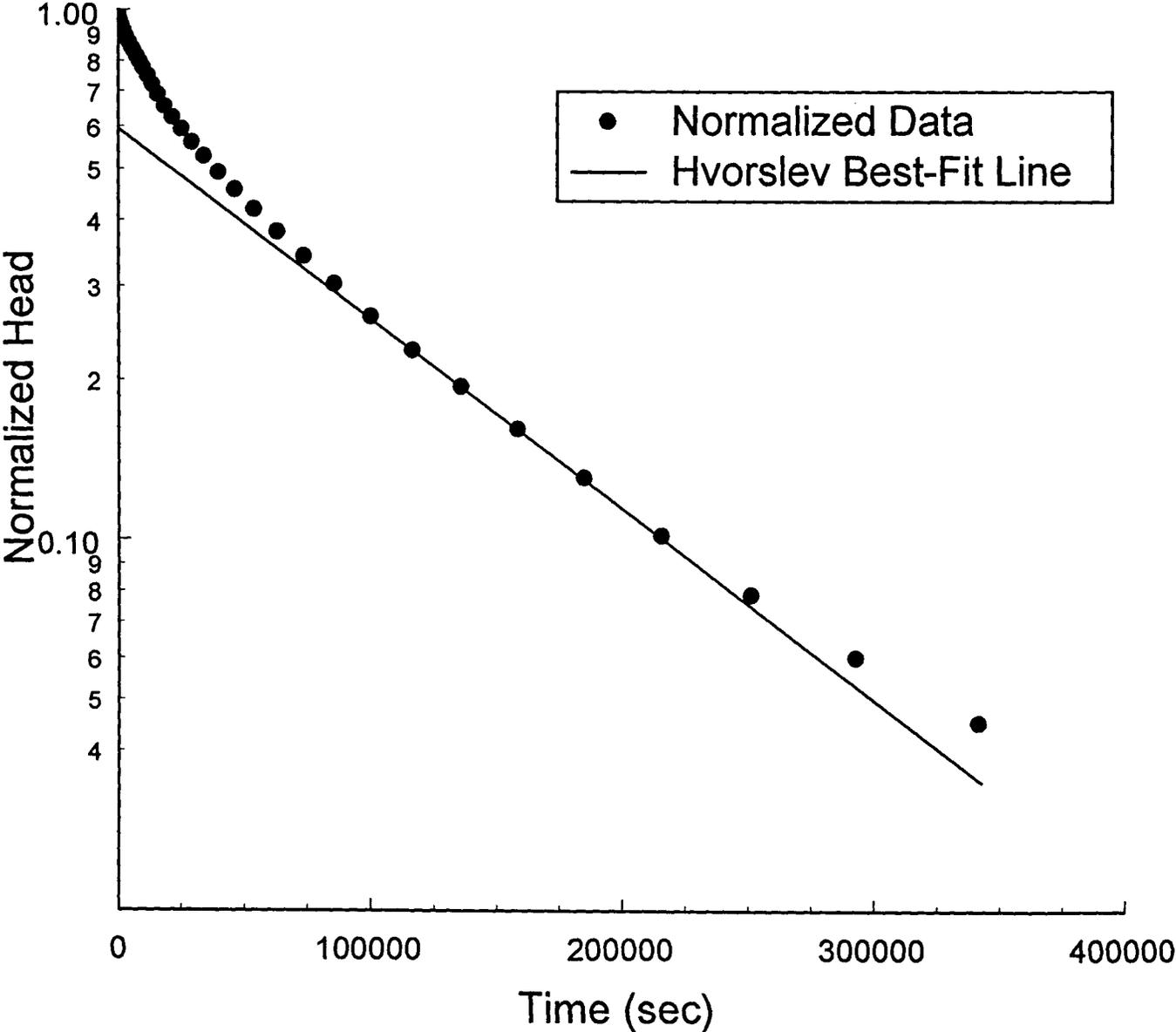
Lincoln County Monitoring Site
Well Ln-1
6/14/91 - 6/18/91



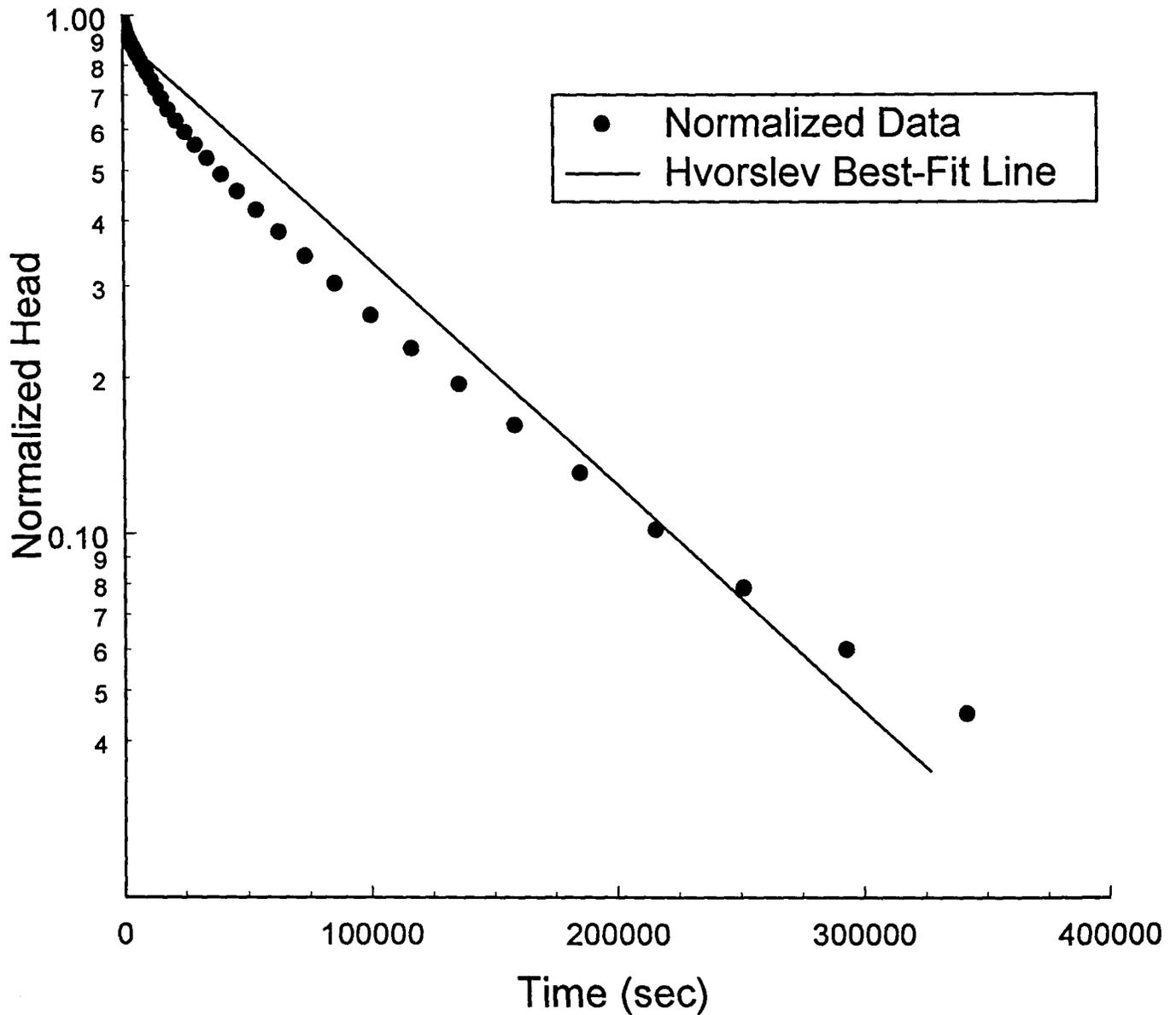
Lincoln County Monitoring Site
Well Ln-1
6/14/91 - 6/18/91

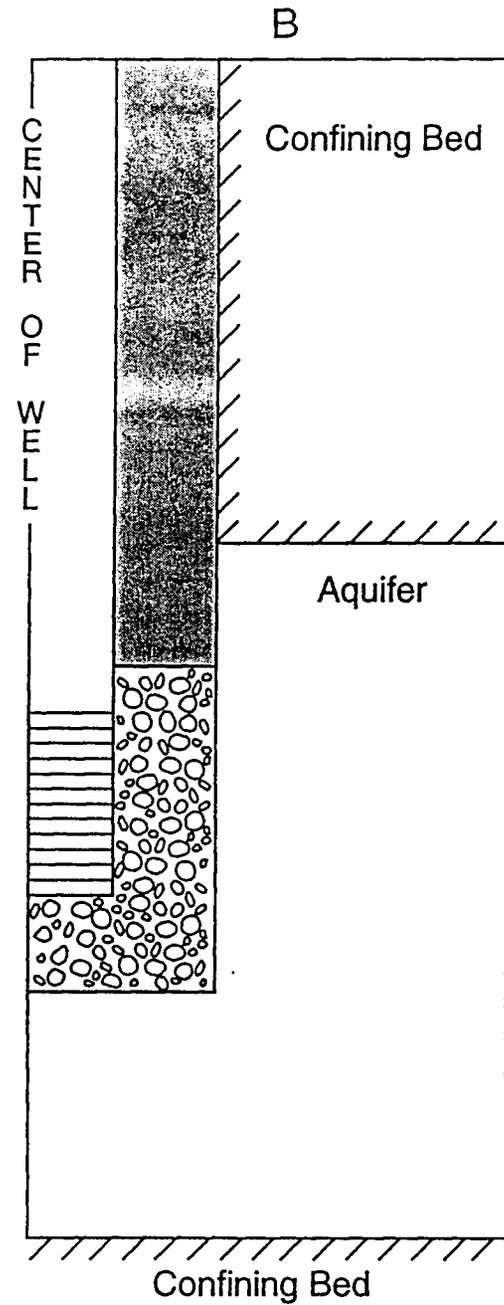
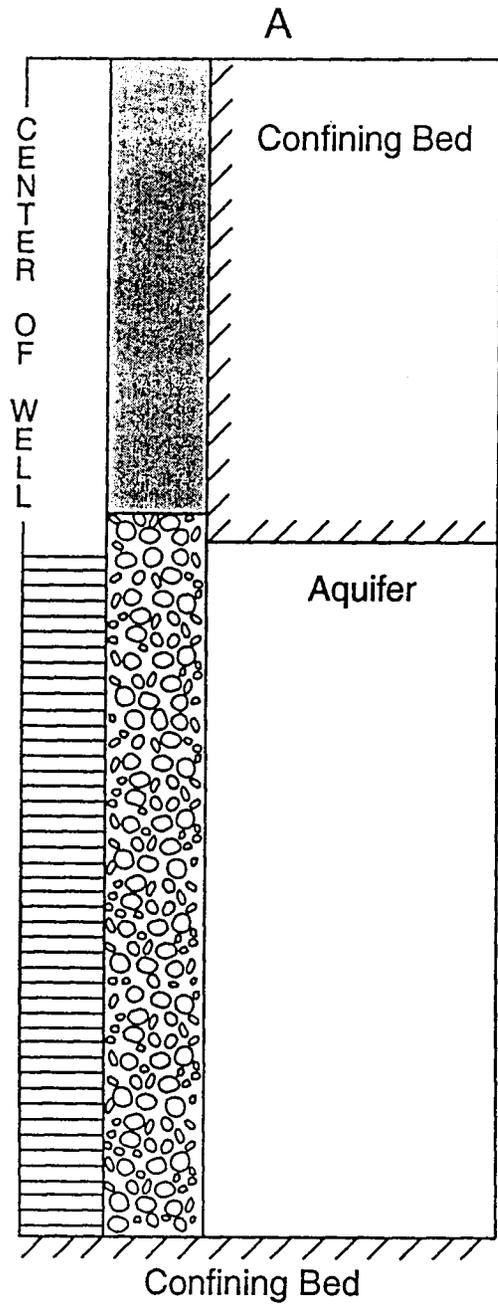


Lincoln County Monitoring Site
Well Ln-1
6/14/91 - 6/18/91



Lincoln County Monitoring Site
Well Ln-1
6/14/91 - 6/18/91

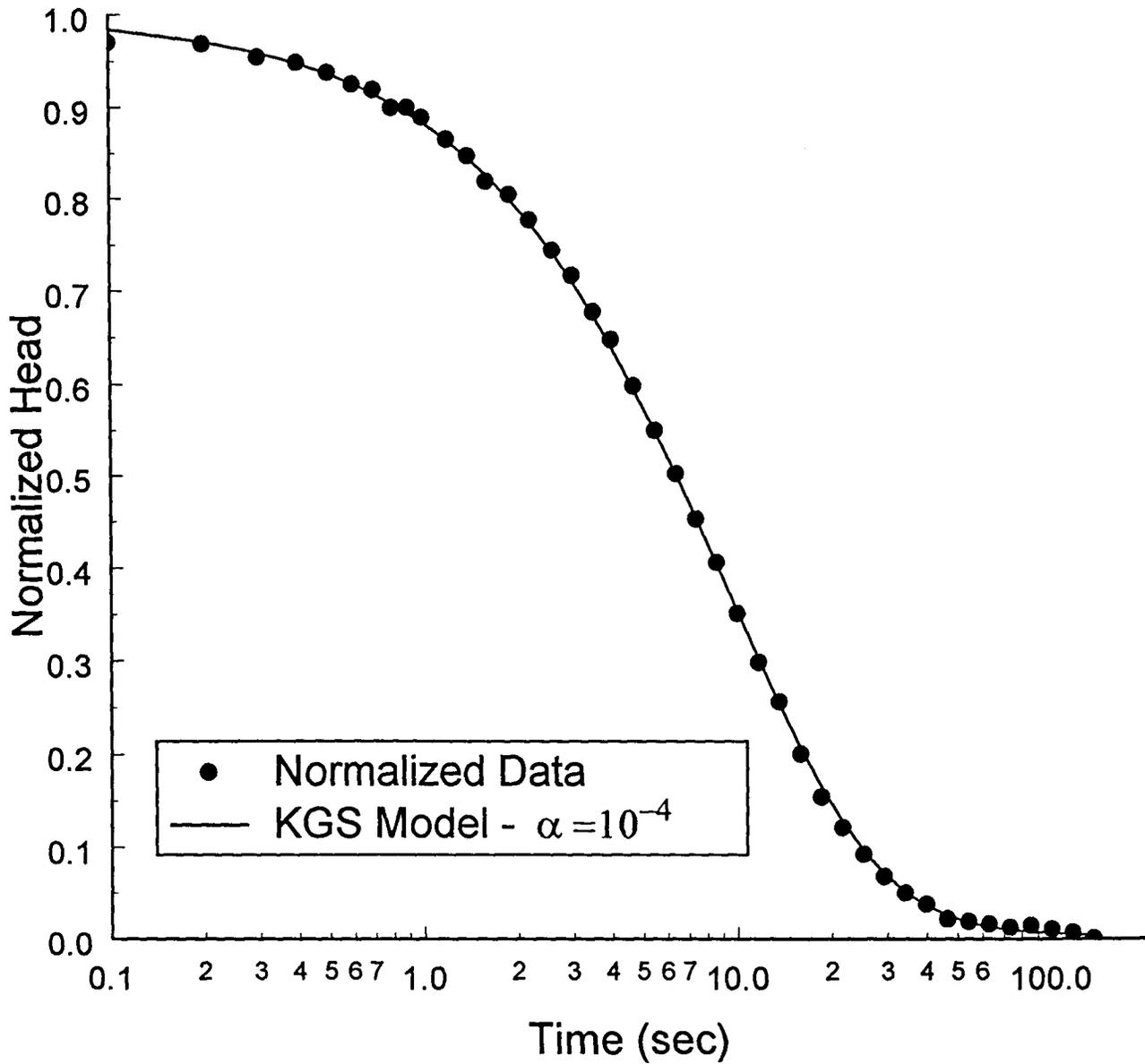




	grout		filter pack		screened interval
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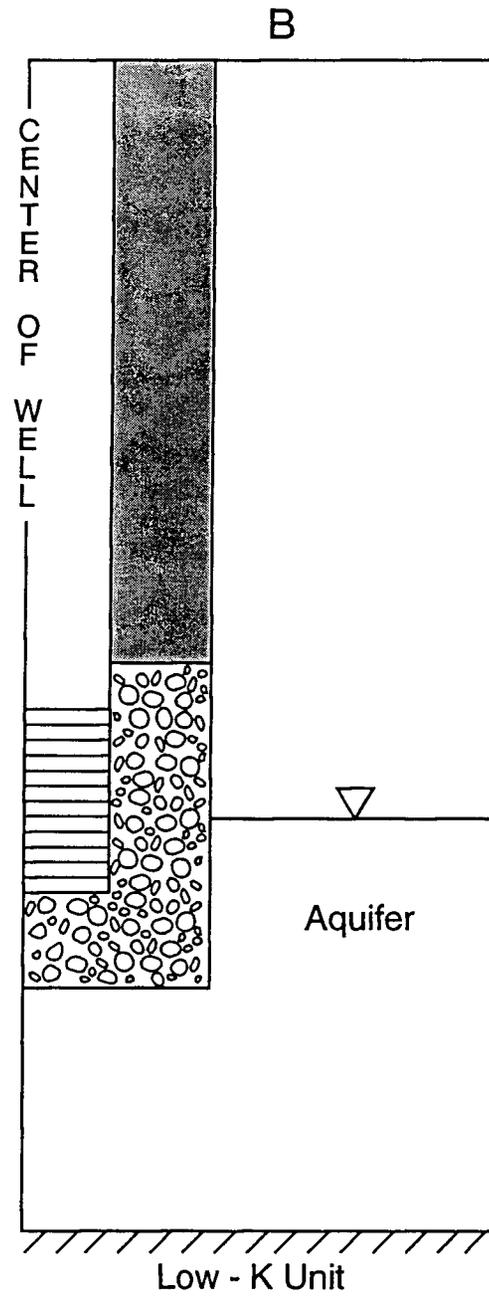
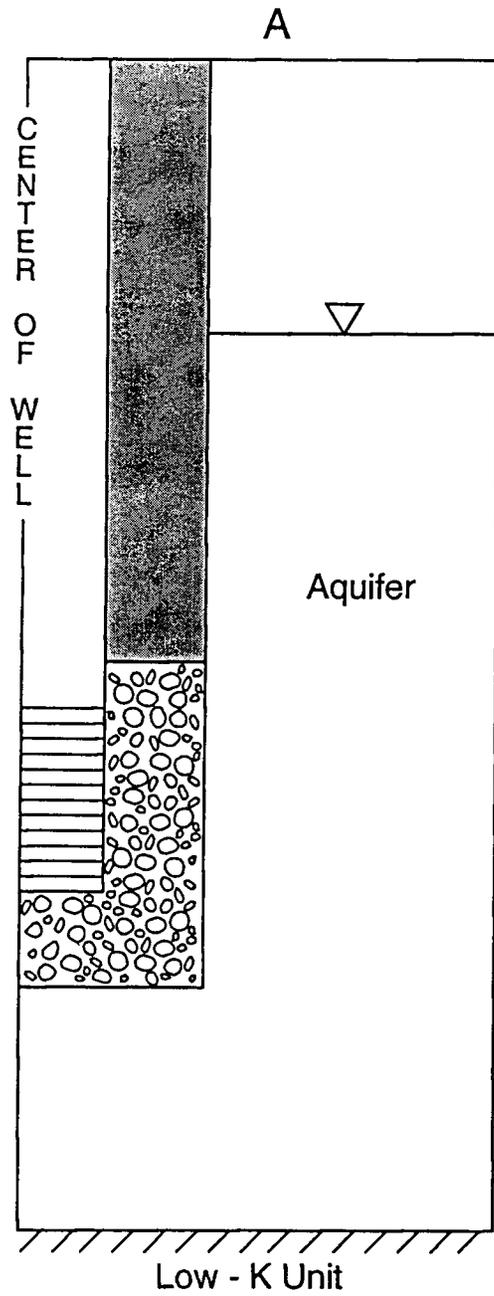
Deerfield Site - Well #5

6/17/98 Slug Test 4



Major Methods for Data Analysis

- Confined Formations
 - Cooper et al. Model
 - Hvorslev Model
 - KGS Model
- **Unconfined Formations**
 - Bouwer and Rice Model
 - KGS Model



grout

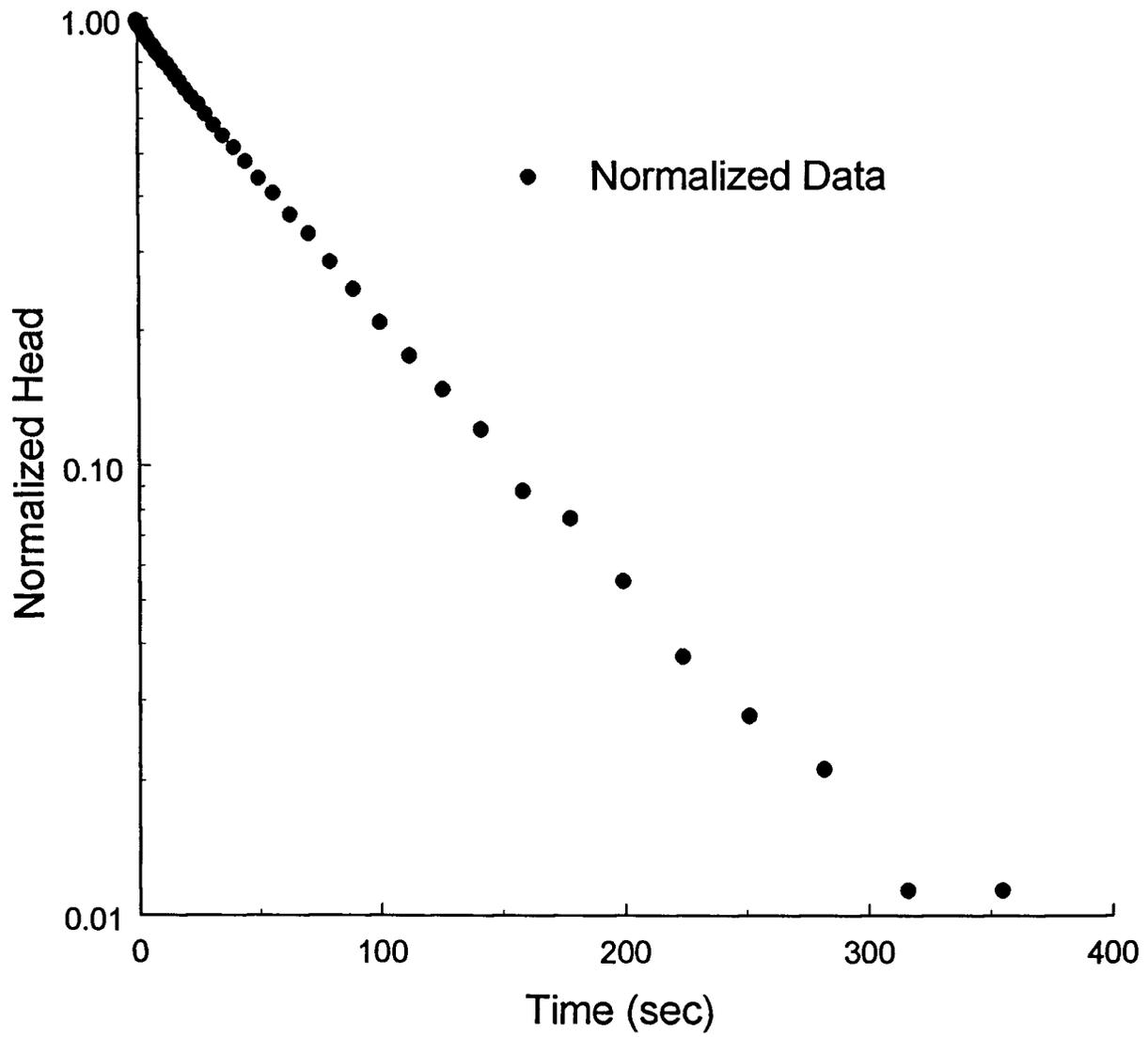


filter pack

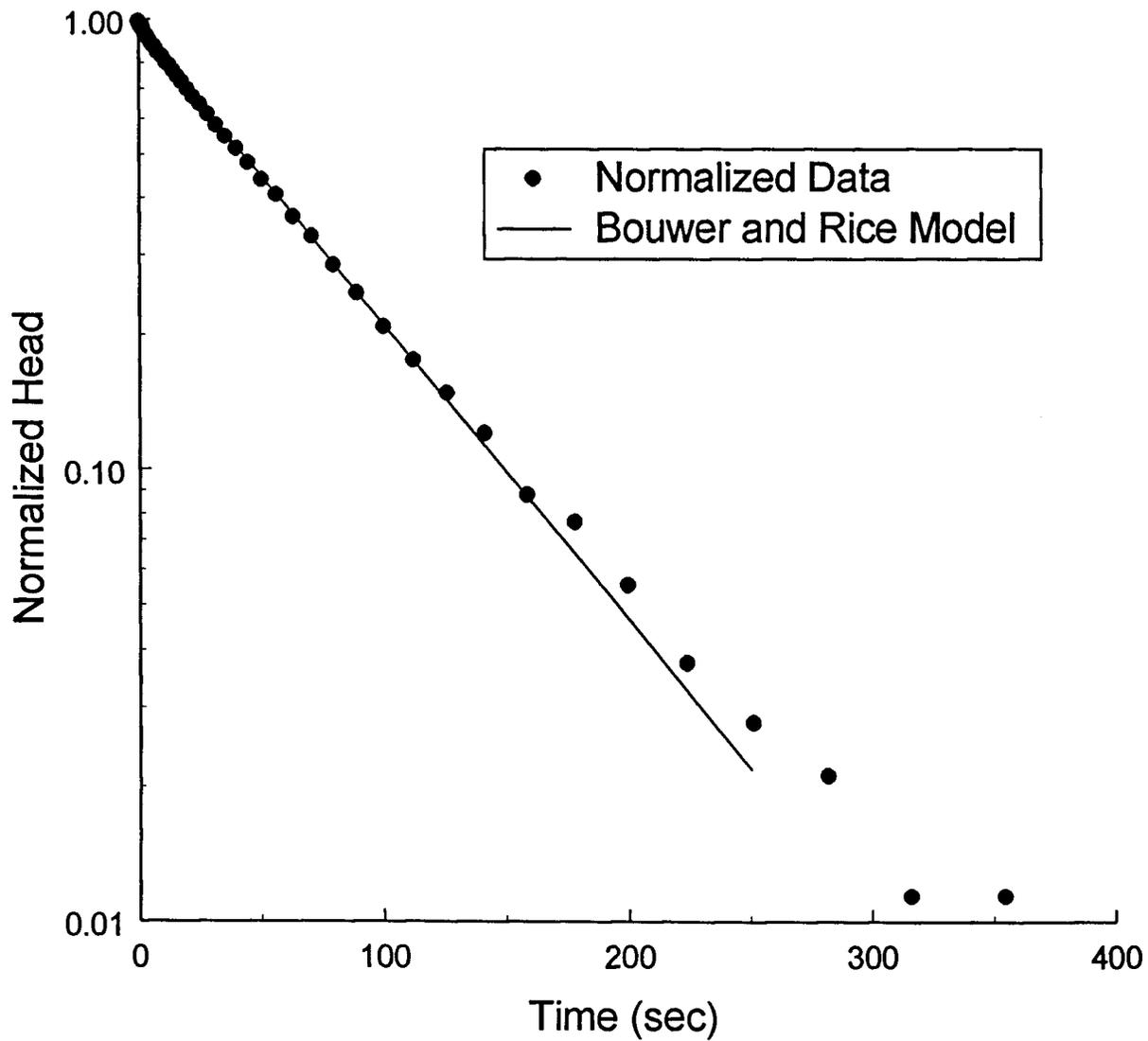


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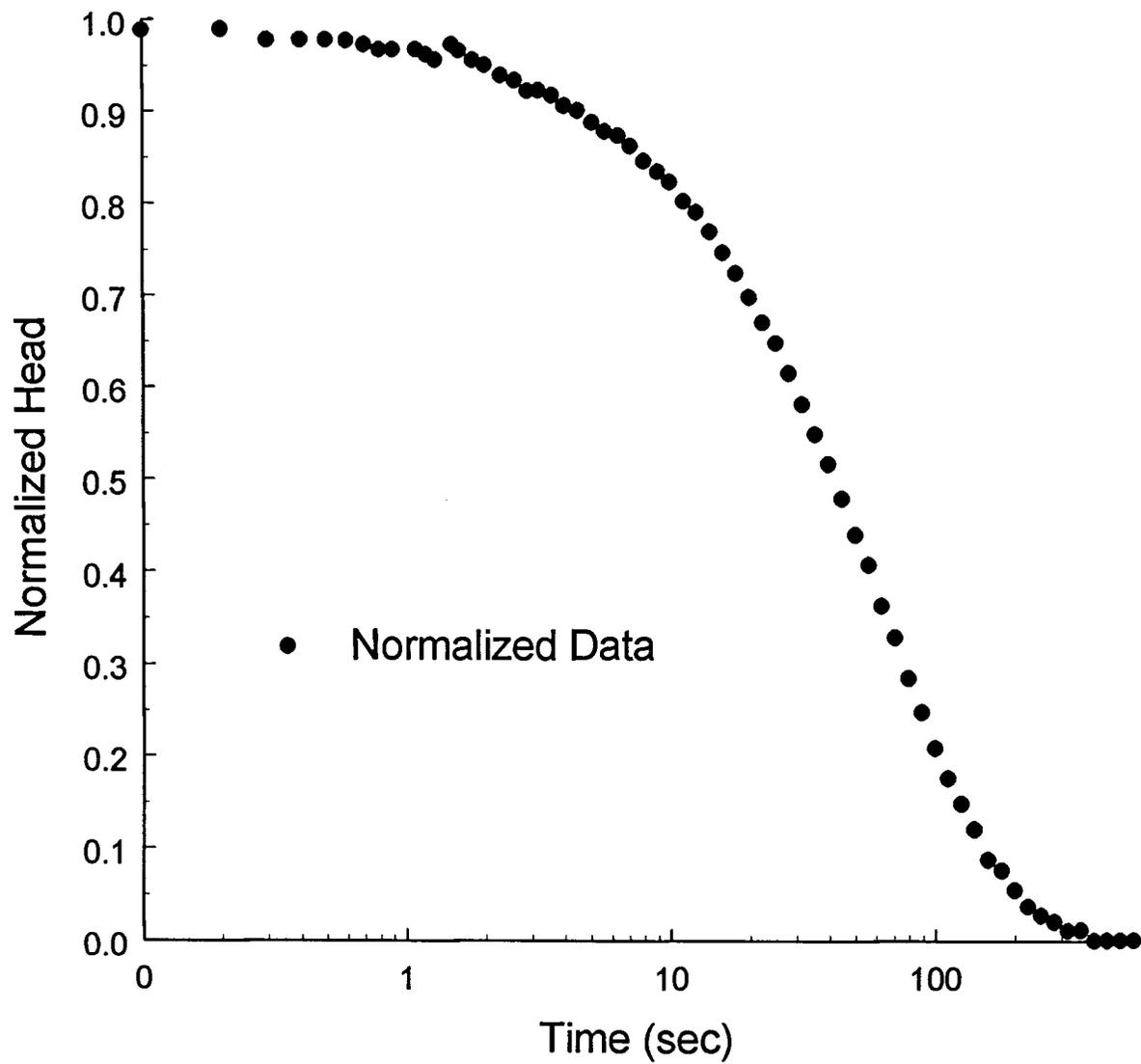
Pratt County Monitoring Site 36 Well #4 - 10/15/93



Pratt County Monitoring Site 36 Well #4 - 10/15/93

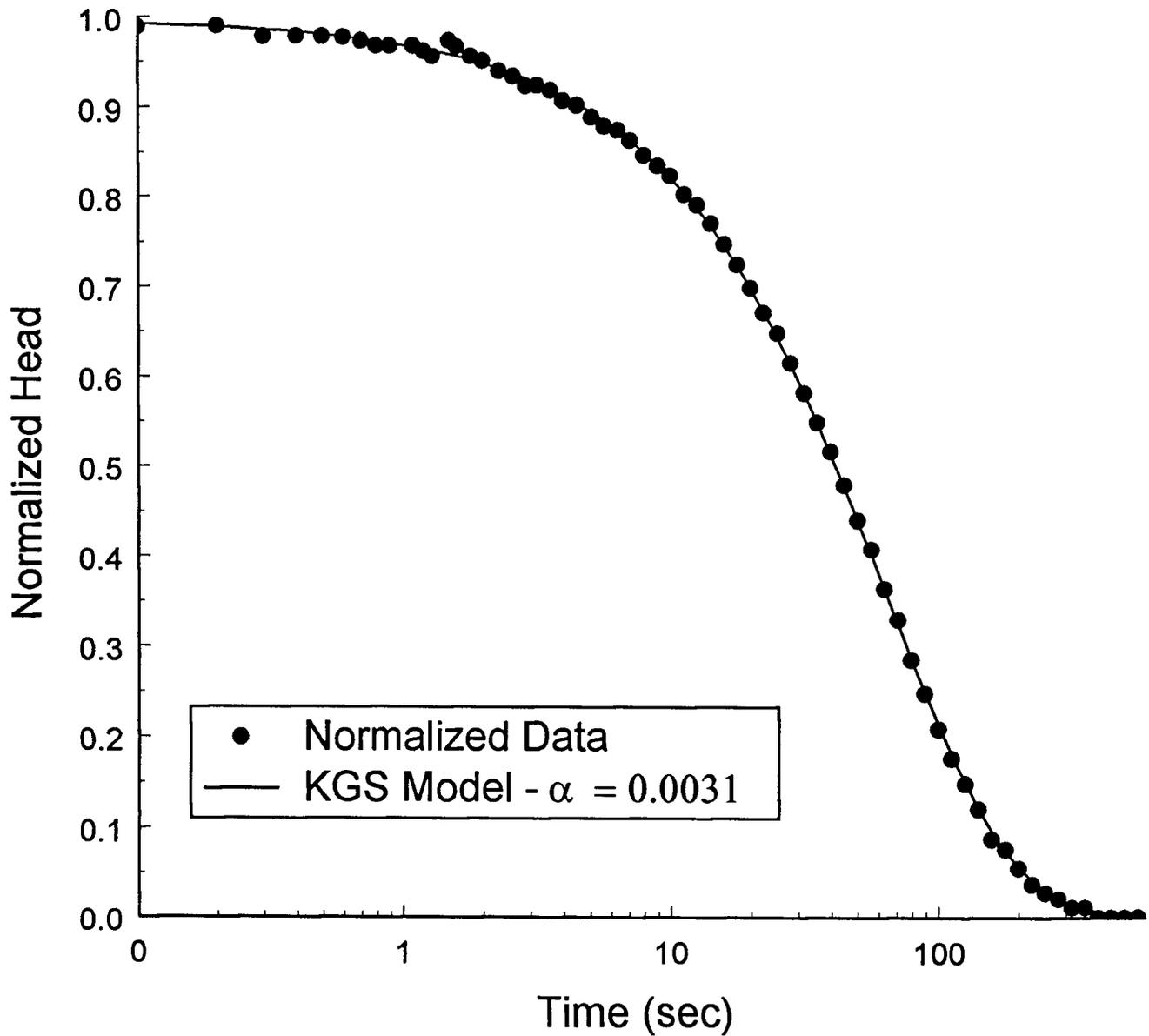


Pratt County Monitoring Site 36 Well #4 - 10/15/93



Pratt County Monitoring Site 36

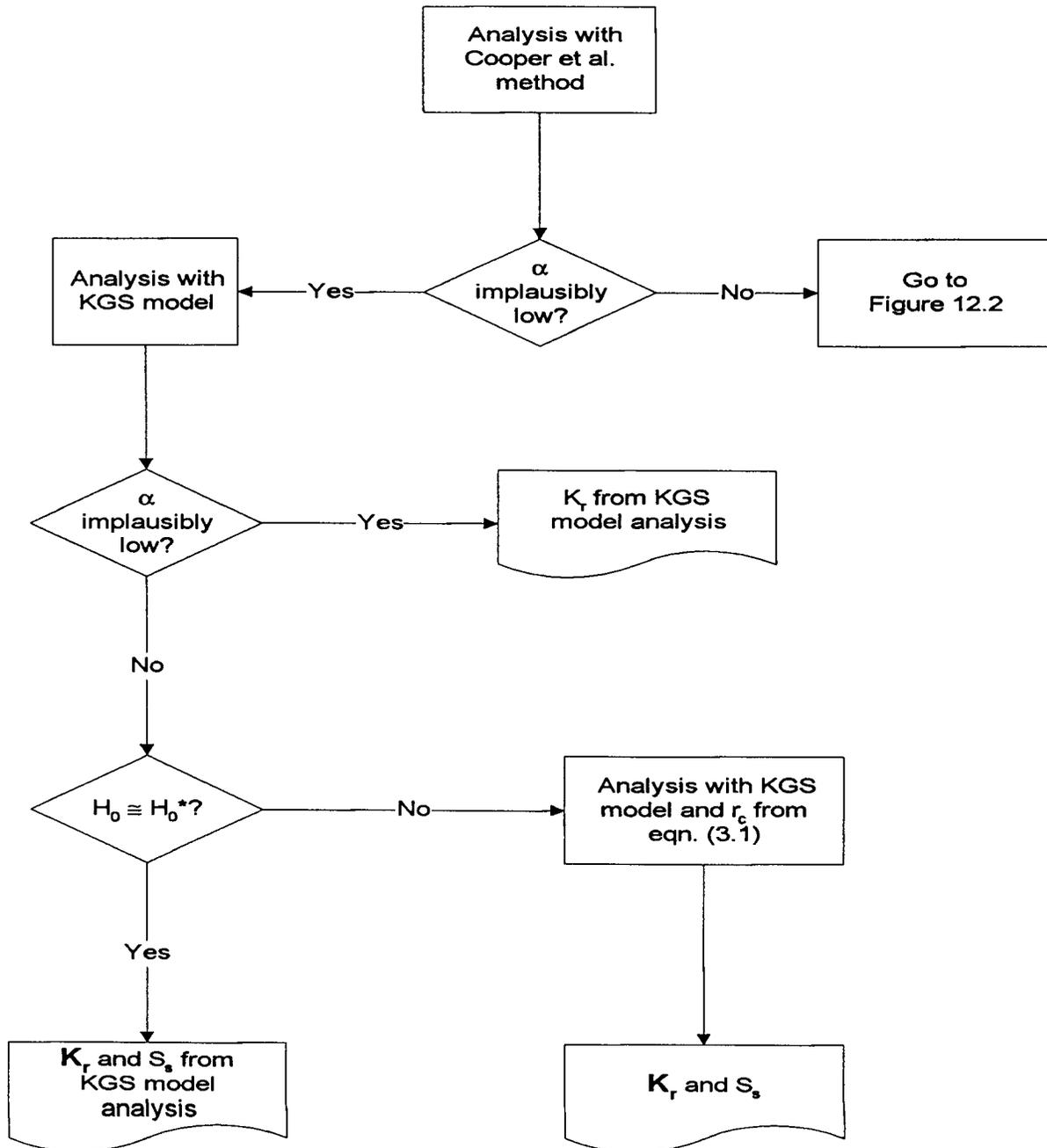
Well #4 - 10/15/93



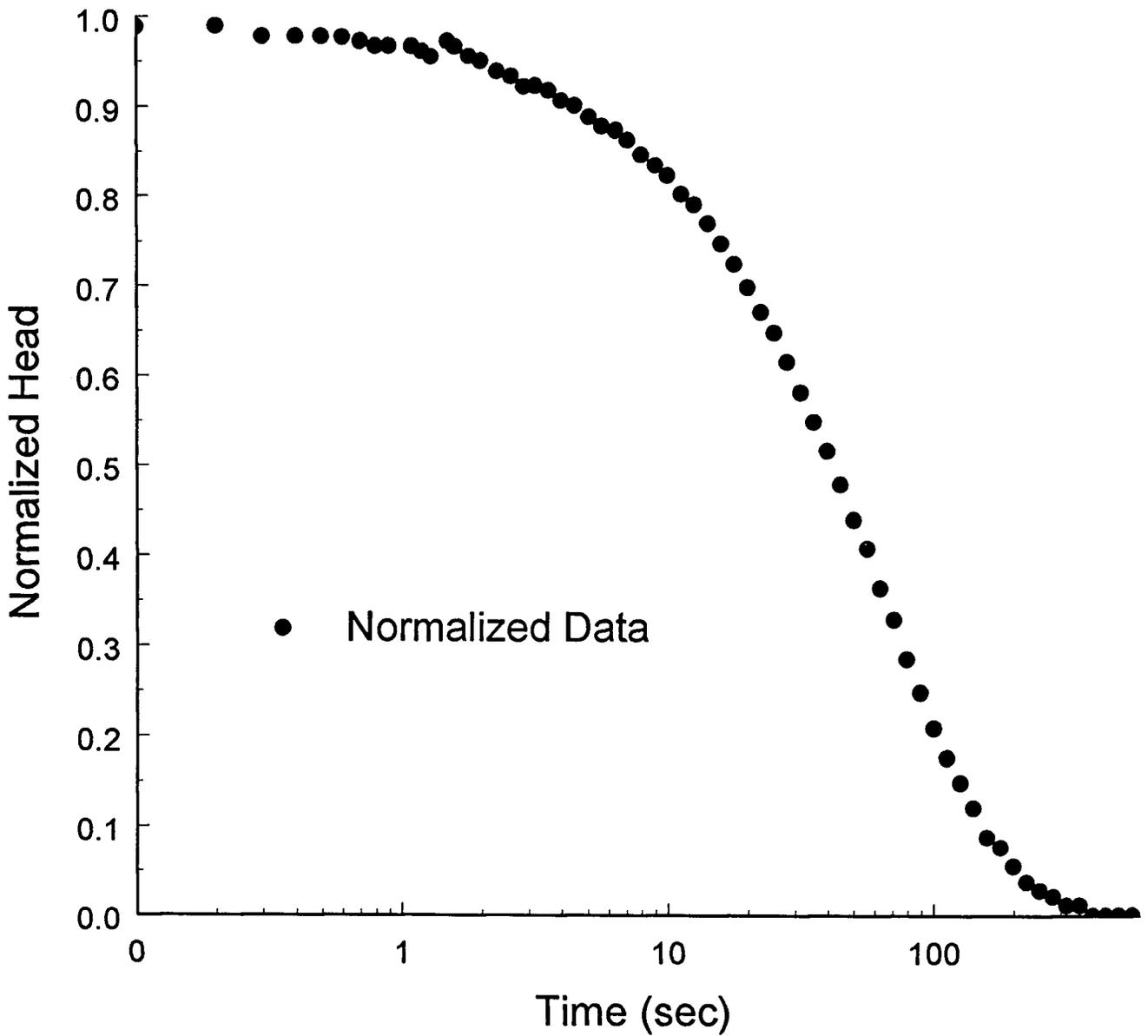
Data Analysis Strategies

- Use Flow Charts
 - Configuration Specific
 - Analysis Design Tree
- Use Screening Analyses
 - Vertical Anisotropy
 - Static Skin
 - Qualitative Reliability
- Should not solely depend on Bouwer and Rice or Hvorslev methods

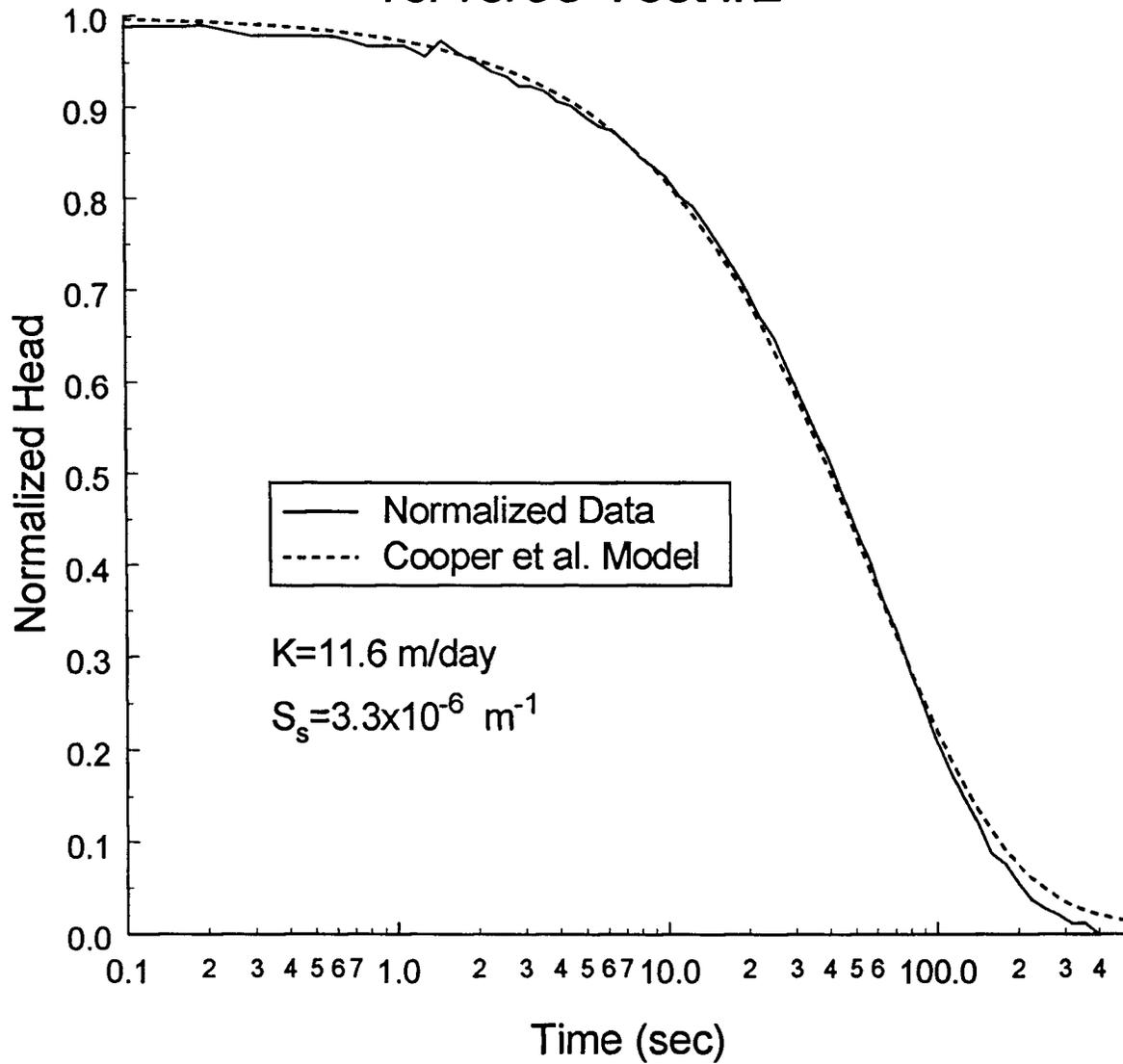
Partially Penetrating Well - Screened Below the Water Table



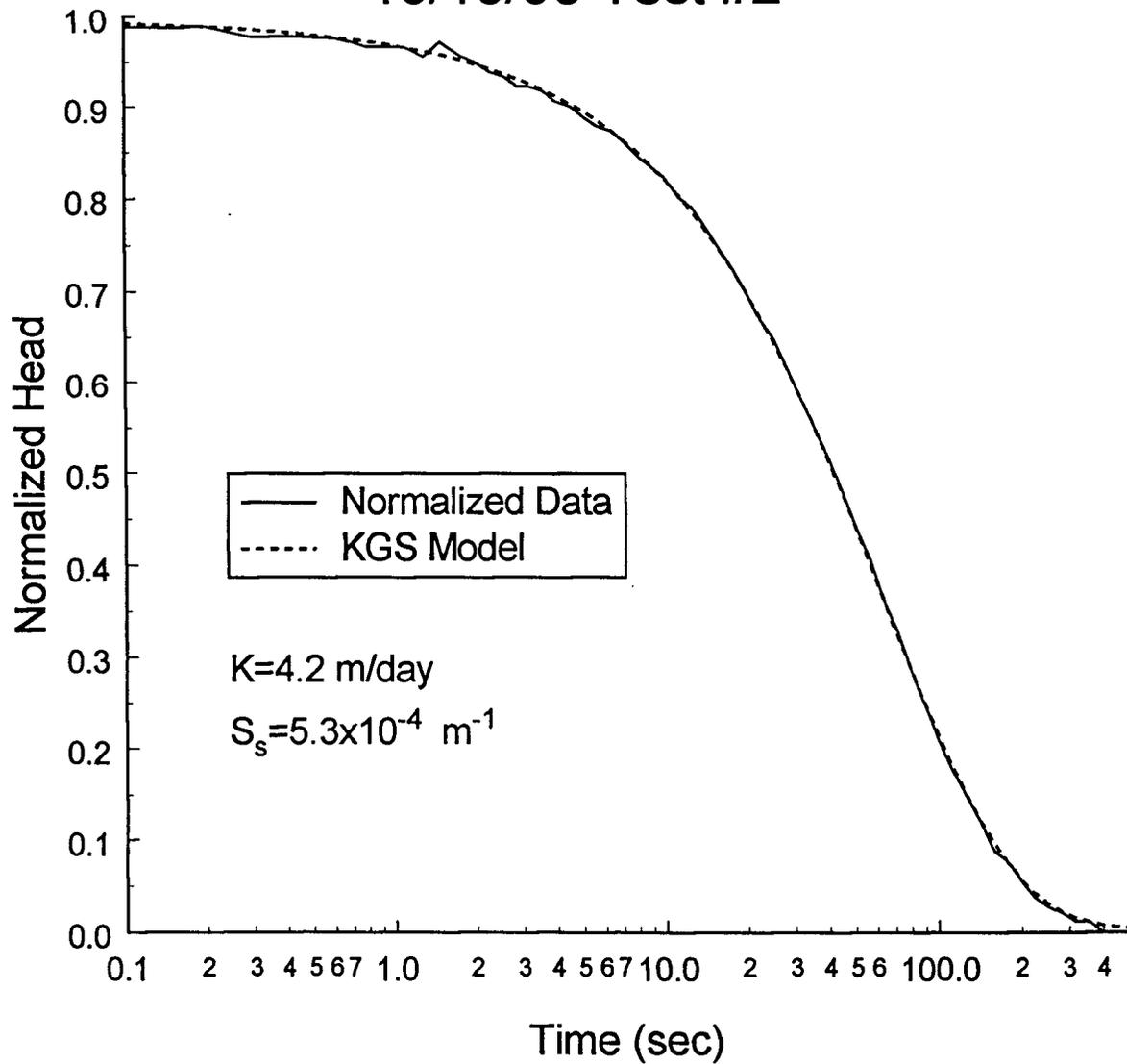
Pratt County Site 36, Well 4 10/15/93 Test #2



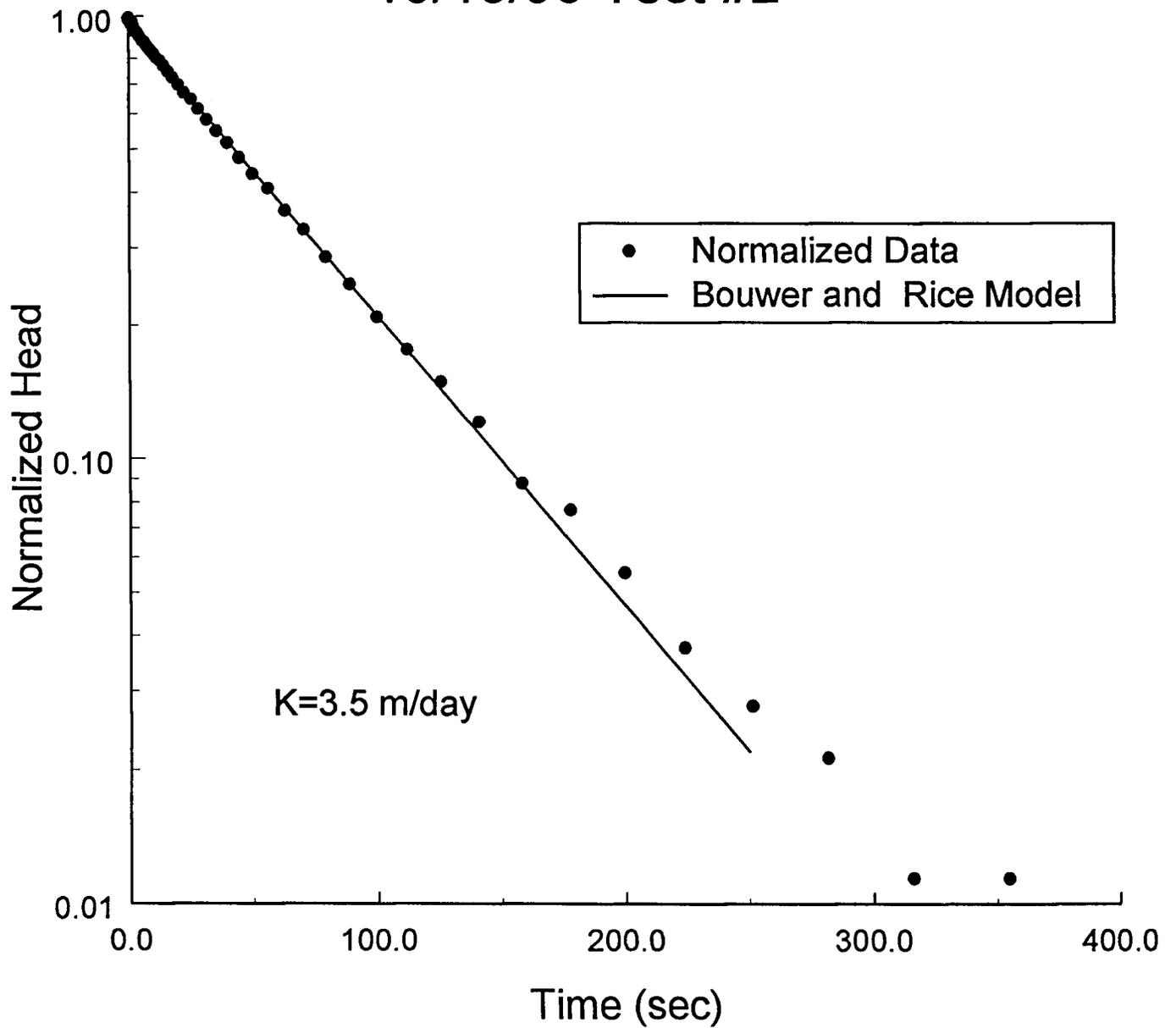
Pratt County Site 36, Well 4
10/15/93 Test #2



Pratt County Site 36, Well 4
10/15/93 Test #2



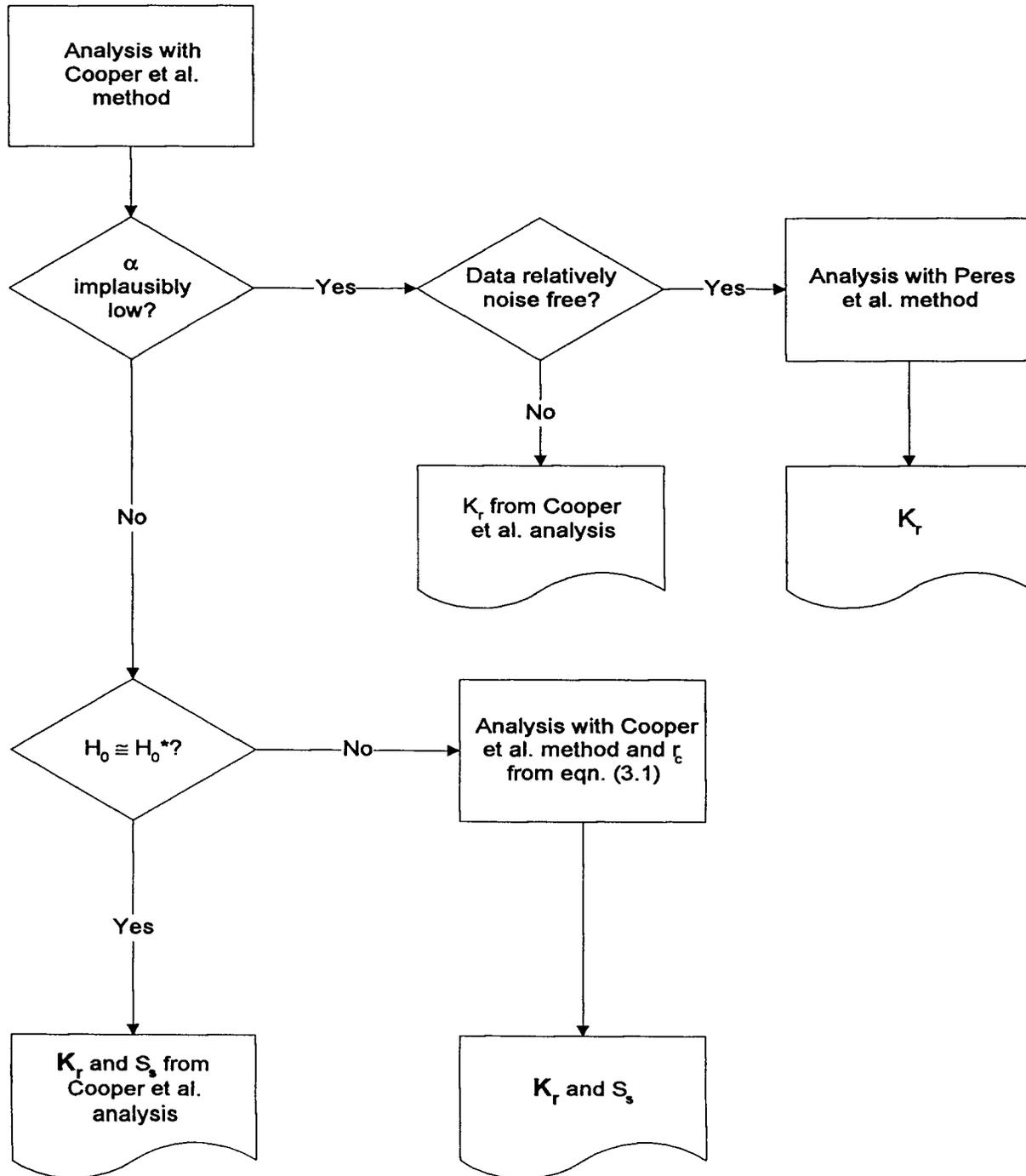
Pratt County Site 36, Well 4 10/15/93 Test #2



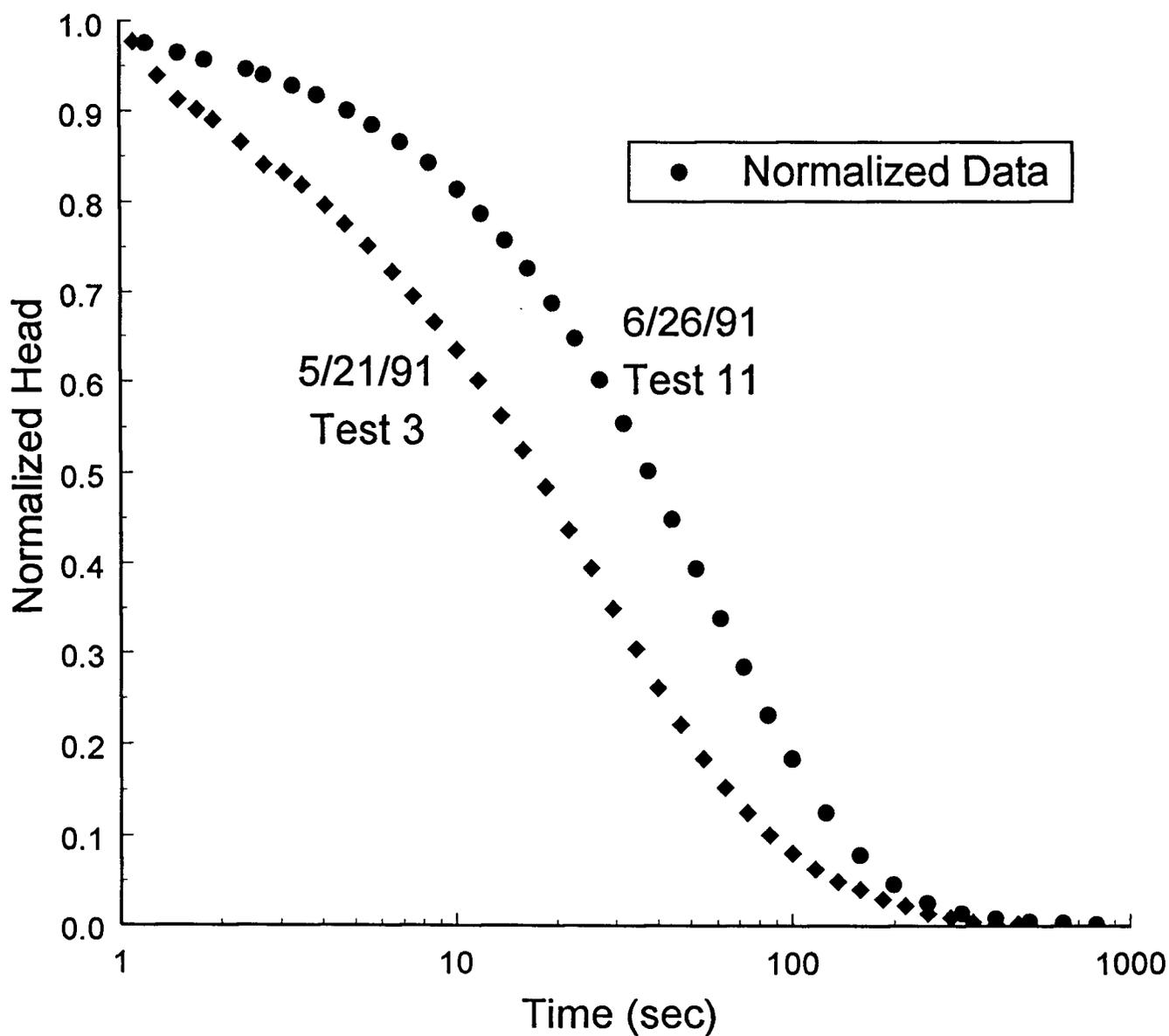
Pratt County Site 36, Well 4 Slug Test Estimates

- Cooper et al. $K = 11.6$ m/day
 $S_s < 3.3 \times 10^{-6}$ m⁻¹
- KGS Model $K = 4.2$ m/day
 $S_s = 5.3 \times 10^{-4}$ m⁻¹
- Bouwer and Rice $K = 3.5$ m/day

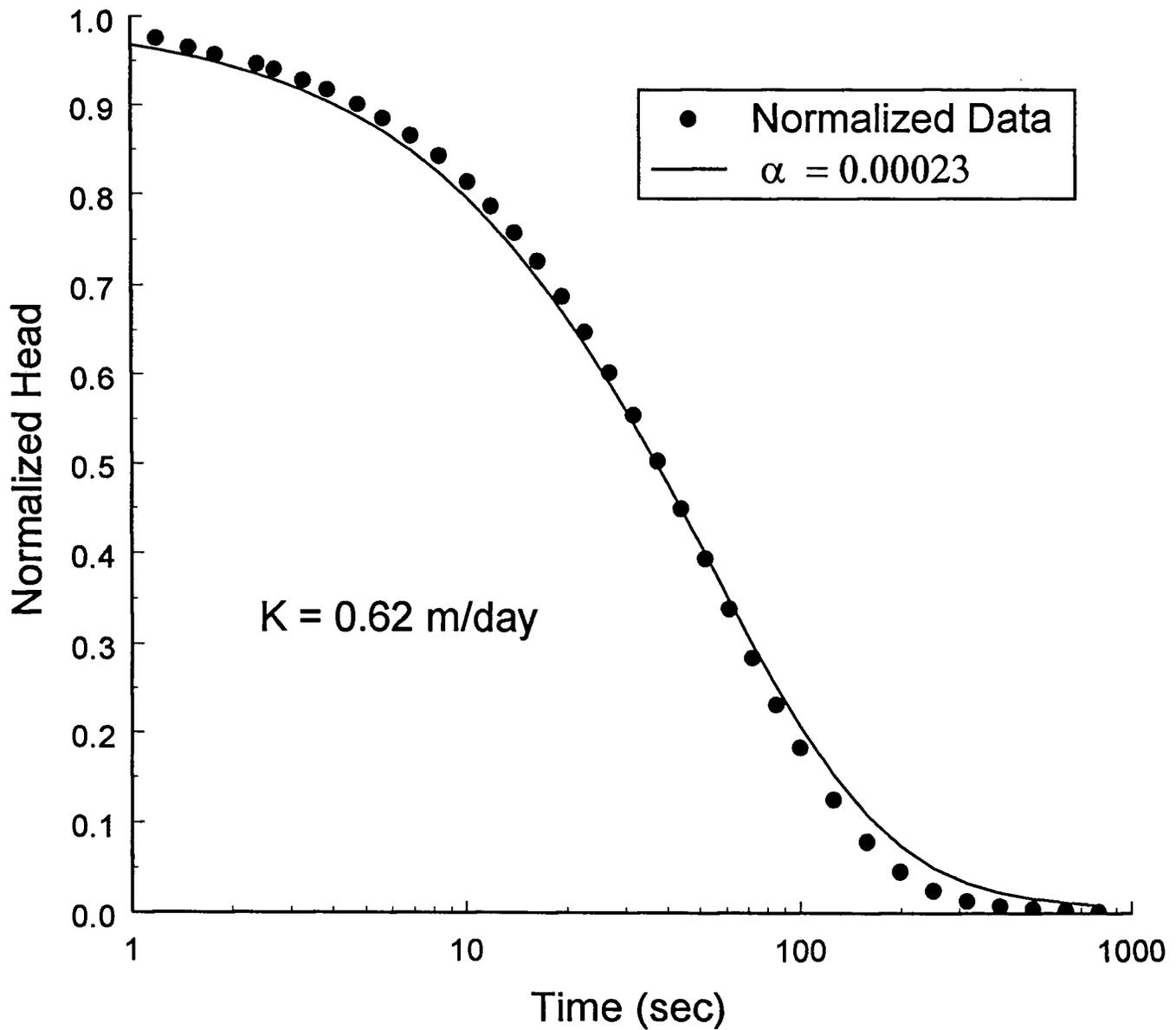
Fully Penetrating Well - Confined Formation



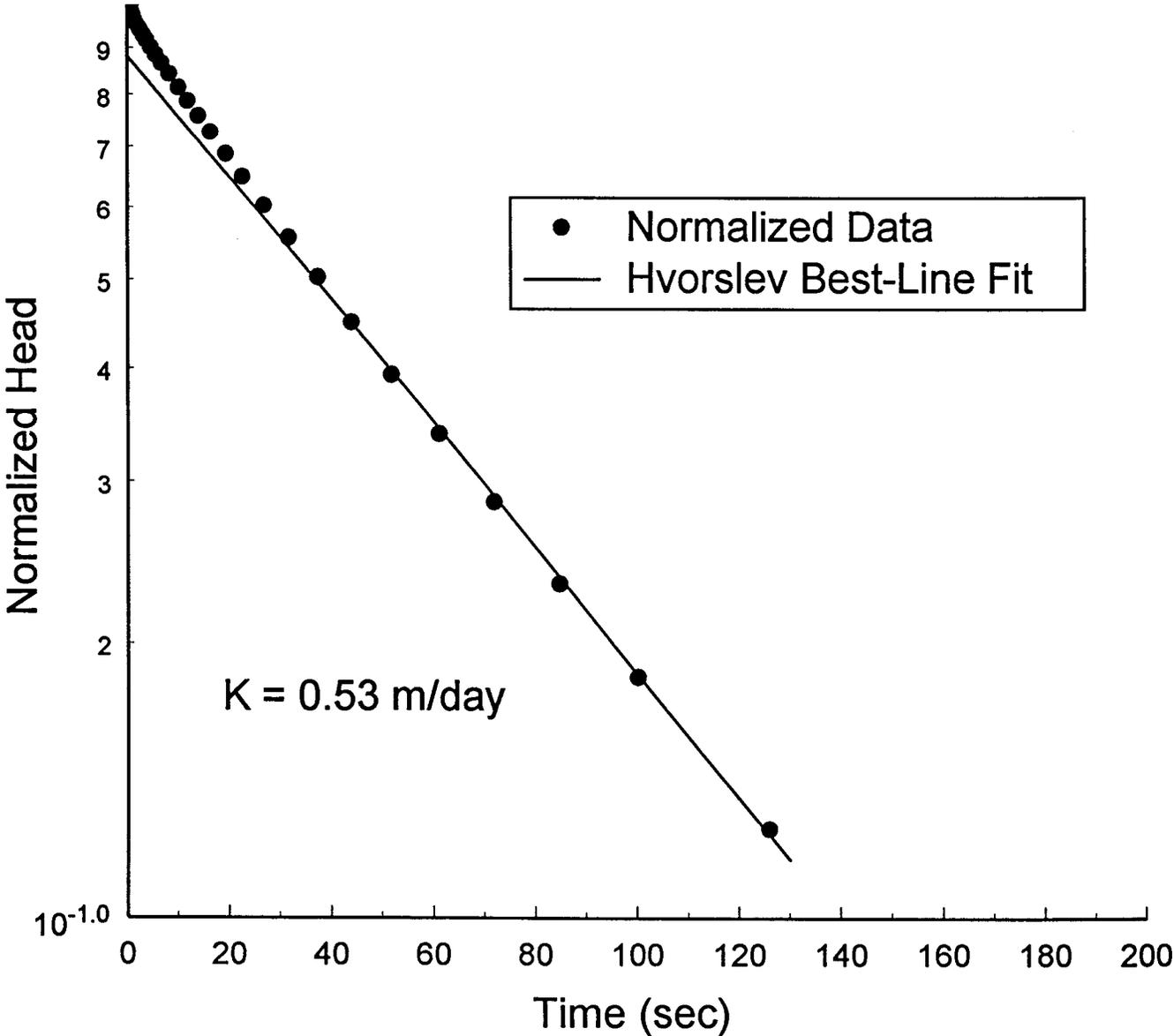
Lincoln County Monitoring Site Well Ln-3 1991 Slug Tests



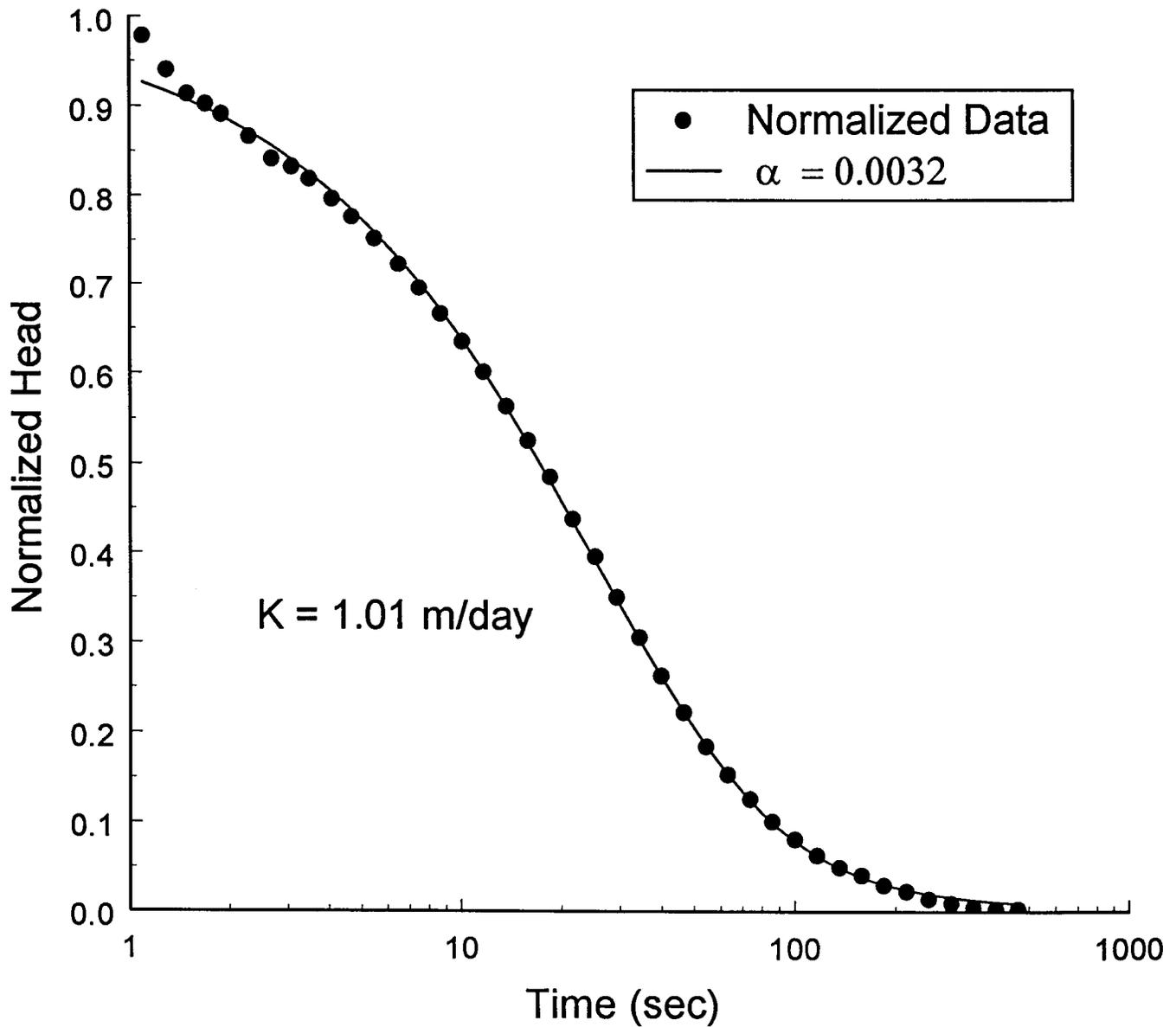
Lincoln County Monitoring Site Well Ln-3 6/26/91 Slug Test 11 Cooper et al. Analysis



Lincoln County Monitoring Site Well Ln-3 6/26/91 Slug Test 11 Hvorslev Analysis



Lincoln County Monitoring Site Well Ln-3 5/21/91 Slug Test 3 Cooper et al. Analysis



Lincoln County Monitoring Site

Well Ln-3

Slug Test Estimates

- 6/26/91 Test 11
 - Cooper et al. $K = 0.6$ m/day
 - Hvorslev Model $K = 0.5$ m/day

- 5/21/91 Test 3
 - Cooper et al. $K=1.0$ m/day

Conclusions

- The Need for Care
 - Design
 - Assess Well Development
 - Class of Analysis Methods
 - Performance
 - Appropriate for Expected K
 - Effective Casing Radius
 - Analysis
 - Flow Charts
 - Move Beyond Hvorslev and Bouwer and Rice
- Lower Bound on K
 - Incomplete Well Development

New!

**"Excellent...a significant milestone in slug test technology
and, for that matter, groundwater hydrology."**

—Herman Bouwer, USDA Water Conservation Laboratory

The Design,
Performance,
and Analysis of
Slug Tests

James J. Butler, Jr.

The Design, Performance, and Analysis of Slug Tests

James J. Butler, Jr.

Kansas Geological Survey, University of Kansas, Lawrence

Available for 30-Day Examination

Addresses practical problems involved in using slug test data



Lewis Publishers

The slug test is currently the most common method for the *in situ* estimation of hydraulic conductivity at sites of suspected groundwater contamination. However, inappropriate procedures in one or more phases of a slug test can introduce considerable error into the resulting parameter estimates. This book remedies this problem by answering virtually every question regarding the design, performance, and analysis of slug tests. This is the first book to provide detailed information on the practical aspects of the methodology of slug tests.

All major analysis methods are described in *The Design, Performance, and Analysis of Slug Tests*. Each analysis method is outlined in a step-by-step manner and illustrated with a field example. The major practical issues related to the field application of each technique are also discussed. This book will help the reader get more reliable parameter estimates from slug tests and increase the utility of slug test data.

Features

- Flow charts make it easy to select analysis methods most appropriate for particular applications
- Methods are illustrated using field examples, demonstrating how the reader should use each method to analyze field data
- Major results are summarized in each chapter in the form of practical guidelines that allow readers to easily grasp the key points of that chapter
- Mathematical models underlying all major techniques are presented, providing a thorough understanding of the analysis methods
- Step-by-step descriptions of analysis methods help readers apply and understand techniques

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