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# Mortandad Canyon Permeable Reactive Barrier Investigation

## Phase 1—Data Evaluation and Work Plan for Future Investigation Activities

Prepared for Los Alamos National Laboratory
Los Alamos, New Mexico

September 29, 2006

**Best Available Copy**

aRc Accelerated Remediation Company

*Daniel B. Stephens & Associates, Inc.*
6020 Academy NE, Suite 100 • Albuquerque, New Mexico 87109

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# 1. Introduction

The Mortandad Canyon Permeable Reactive Barrier (PRB) Demonstration Project is located in Mortandad Canyon in the northcentral part of the Los Alamos National Laboratory (LANL) in Technical Area (TA)-5 (Figure 1). In January and February of 2003, LANL installed the PRB to demonstrate in situ treatment of a suite of contaminants in shallow alluvial groundwater. The barrier was designed to perform in situ removal of the following contaminants of concern (COCs):

- Strontium-90
- Isotopic plutonium (plutonium-238 and plutonium-239,240)
- Americium-241
- Perchlorate
- Nitrate

Due to the variability of these contaminants, no single treatment media was optimal for their removal. Consequently, LANL personnel designed and constructed a multiple-layer permeable reactive barrier (MPRB) that would allow multiple treatment zones arranged in series to sequentially remove each of the specified COCs. For the purposes of this report, the LANL installation is referred to as the Mortandad Canyon PRB.

The Mortandad Canyon PRB employs a funnel-and-gate system with a sequential series of four reactive media cells. The funnel consists of a row of sheet piles driven through the alluvium and into the underlying bedrock, which directs the alluvial groundwater so that it will flow through the four cells. Four reactive media cells, ordered by sequence of contact with the groundwater, are used for contaminant removal:

- Gravel cell: gravel-sized scoria for colloidal removal
- Apatite cell: phosphate rock containing mineral apatite (calcium phosphate) for the removal of metals and radionuclides

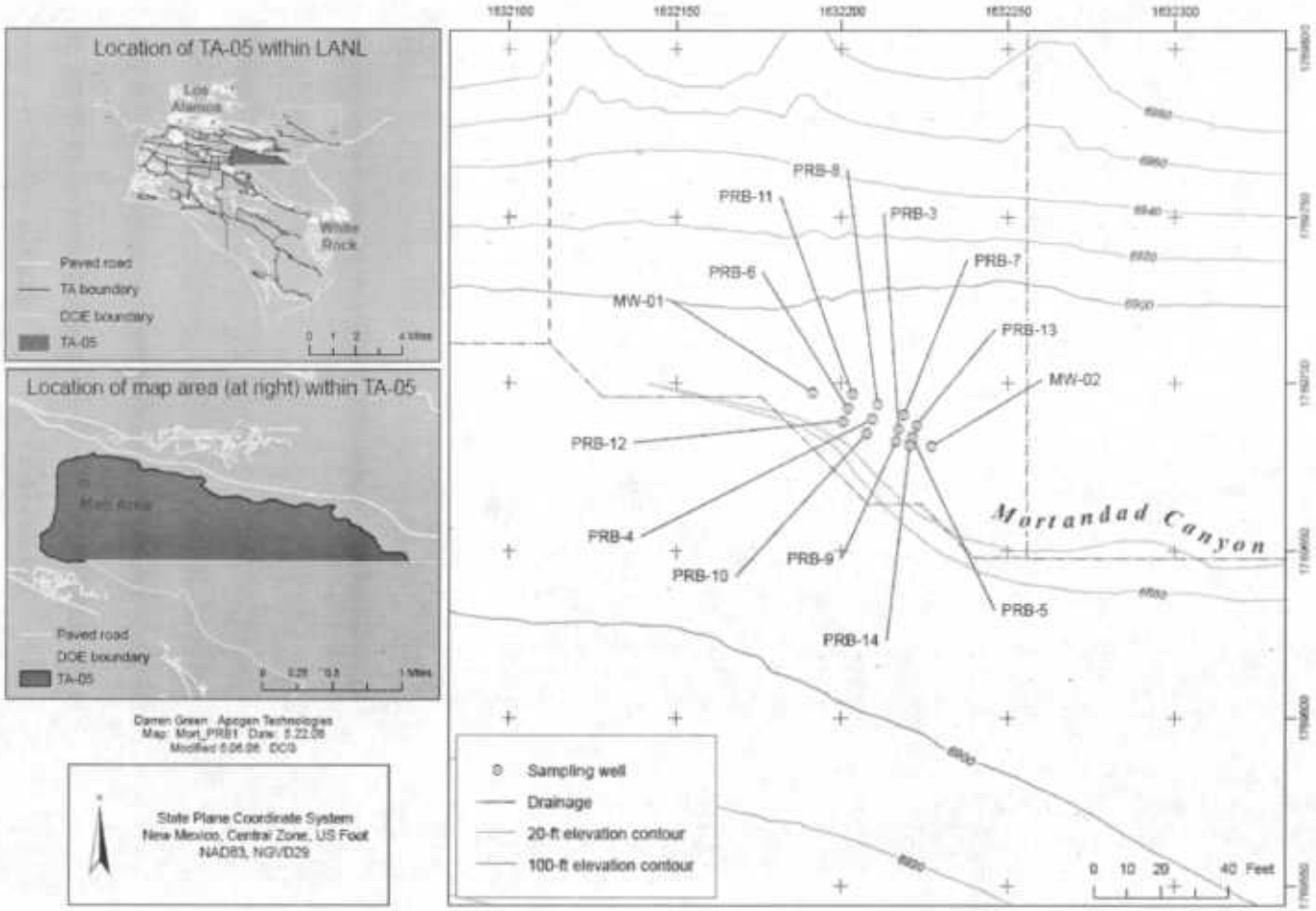


Figure 1

MORTANDAD CANYON PRB INVESTIGATION

**Location of Mortandad Canyon Permeable Reactive Barrier Demonstration Project**

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- Bio-barrier cell: 65 percent pecan shells and 10 percent cottonseed mixed with 25 percent pea gravel to deplete dissolved oxygen and break down nitrate, perchlorate, and any potential organic compounds specified by the Resource Conservation and Recovery Act (RCRA)

- Limestone cell: gravel-sized limestone for pH buffering and anion adsorption

After construction, the performance of the PRB was monitored through the collection of several rounds of groundwater samples between 2003 and 2005. These samples, taken from the PRB sampling ports and nearby alluvial monitor wells, were analyzed for major cations and anions and radionuclides. The resultant data indicated that successful treatment of contaminants occurred in the apatite and bio-barrier cells. However, dissolved concentrations of key contaminants measured in the limestone cell and a downstream monitor well, notably perchlorate, nitrate, and strontium-90, were essentially equivalent to the untreated water quality observed upstream of the PRB. This pattern of chemical behavior was observed initially under very low alluvial saturation levels in 2003, but also during higher saturation levels in 2004. These results are not easily explained without a more detailed investigation of the hydrology and geochemistry of the Mortandad Canyon PRB location.

Settlement of the ground surface overlying the apatite and bio-barrier cells was first documented in July 2003 (Kaszuba, et al., 2003). At that time, the amount of settlement below grade varied from 6 inches at the west end of the apatite cell to 14 inches at the east end of the bio-barrier cell. This was attributed to normal compaction of the initially uncompacted media by Shaw Environmental & Infrastructure, Inc., the design and construction contractor (Shaw, 2003a). In March 2005, a flood overtopped the stream channel adjacent to the PRB and water infiltrated into the top of the PRB. This led to additional subsidence (approximately 1 to 2 feet [ft]) of the surface overlying the apatite and bio-barrier cells. Whether or not this subsidence has significantly compromised the reactive materials in the underlying cells, and thus the hydraulic or geochemical performance of the PRB, is unknown.

This report documents the results of a Phase 1 investigation of the Mortandad Canyon PRB performed by the Accelerated Remediation Company (ARC). The investigation was instigated

by the LANL Water Stewardship Program – Canyons Project for the purpose of initiating a formal evaluation of the PRB and developing plans for further investigation activities. The investigation included the following activities:

- Assembling and assessing all available hydrogeologic and geochemical data
- Reviewing and assessing engineering design and construction issues
- Collecting samples of groundwater and reactive media
- Performing slug tests
- Performing initial hydrologic analysis
- Developing a conceptual model of PRB performance, including alternative hypotheses to explain observed performance issues
- Developing a work plan with recommendations for future investigations that are required to determine lessons learned from the demonstration project

Section 2 provides a list of previous investigations related to the Mortandad Canyon PRB and presents background information on PRBs. The results of the review and analysis of existing data on the Mortandad Canyon PRB and relevant information from other PRB installations is presented in Sections 3 through 5. Section 3 focuses on issues related to the design of the PRB and provides an assessment of this effort, Section 4 reviews and assesses the construction of the PRB, and Section 5 discusses PRB maintenance and monitoring issues, with emphasis on hydrogeologic monitoring and lessons learned from the Mortandad Canyon and other PRB installations. Section 6 presents and discusses data collected specifically for this investigation. A discussion of hydrogeologic and geochemical conceptual models of the Mortandad Canyon PRB, including alternative hypotheses to explain observed performance issues, is provided in Section 7. Finally, Section 8 presents a proposed work plan for future investigation activities.

# 2. Previous Studies and Background Information

A number of studies and investigations have been performed to prepare for the design and installation of the Mortandad Canyon PRB and to document its performance. The data reported by these studies was examined and analyzed during this Phase I evaluation. This section discusses the results of this analysis of existing data and reports as well as relevant information from similar PRB installations and related engineering, construction, and operational issues.

## 2.1 Data Sources

The following project reports were reviewed as part of this investigation:

- *Conceptual design report, multiple permeable reactive barrier (PRB), Mortandad Canyon, Los Alamos, New Mexico* (IT Corporation, 2001a).
- *Demonstration of a multi-layered permeable reactive barrier in Mortandad Canyon at Los Alamos National Laboratory* (Kaszuba et al., 2003)
- *Demonstration of a multiple permeable reactive barrier (multi-barrier) in Mortandad Canyon September 2000* (Conca et al., 2000)
- *Design, installation, and performance of a multi-layered permeable reactive barrier, Los Alamos National Laboratory* (Kaszuba et al., 2004).
- *Field summary report installation of monitoring wells associated with the permeable reactive barrier in Mortandad Canyon July 28th–August 1st FY 2003* (Shaw, 2003b).
- *Field summary report phase I geotechnical and hydrogeologic activities for the multiple permeable reactive barrier Los Alamos National Laboratory Mortandad Canyon, Los Alamos, NM* (IT Corporation, 2001b).

- *Final design report, multiple permeable reactive barrier (PRB), Mortandad Canyon, Los Alamos, New Mexico* (Shaw, 2002).

- *Remediation of nitrate-contaminated groundwater using a bio-barrier* (Strietelmeier et al., 2001a)

- *Use of a unique biobarrier to remediate nitrate and perchlorate in groundwater* (Strietelmeier et al., 2001b).

Kaszuba et al. (2003) presented "as-built" design drawings prepared following the completion of PRB construction.

Water level measurements and analytical chemistry data from several rounds of groundwater samples collected between 2003 and 2005 were also reviewed and analyzed. Also, the data collection process included interviews with key personnel associated with the design and construction of the PRB. The following persons provided additional insights and information with regard to the Mortandad Canyon PRB project:

- Mr. P. Scott den Baars, P.E., the program manager who oversaw the PRB design and construction project for Shaw Environmental & Infrastructure, Inc.

- Mr. Randal S. Johnson, the field construction supervisor for the PRB project

- Mr. John P. Kaszuba; the LANL principal investigator for the PRB project

## 2.2 Background Information on PRBs

A PRB has been defined as "an emplacement of reactive materials in the subsurface designed to intercept a contaminant plume, provide a preferential flow path through the reactive media, and transform the contaminant(s) into environmentally acceptable forms to attain remediation concentration goals at points of compliance" (US EPA, 1997). As of 2005, there were 67 full-scale PRBs installed in 29 states in the U.S.; the Interstate Technology Regulatory Council

(ITRC, 2005) provides a complete listing of these PRB deployments, including site name, location, construction and configuration, installation date, reactive media, contaminants, and reference/contact information. Since 2005, the steady decline in funding for environmental work has significantly slowed the rate of PRB installations.

Several PRBs have used the basic funnel-and-gate design employed in the Mortandad Canyon PRB. However, the only other sequential, multiple-media PRB was built in 1999 at a site on Alameda Island, adjacent to San Francisco Bay, CA. The groundwater at this site contained a mixed organic plume not amenable to treatment with a single reactive media. Consequently, the University of Waterloo and Geosyntec collaborated to design and build a system that combined two in situ treatment technologies. The initial gate segment consisted of granular iron, for the reductive dechlorination of higher chlorinated ethenes in the groundwater. The second segment, the biosparge zone, promoted aerobic biodegradation of petroleum hydrocarbons and any remaining lesser chlorinated compounds. This segment was stimulated by dissolved oxygen (DO) and carbon dioxide ($CO_2$) additions via an in situ sparge system; the $CO_2$ was used to neutralize the high pH produced from reactions in the iron wall.

The Alameda Island funnel-and-gate MPRB was constructed using steel sheet piling installed with conventional emplacement equipment. For the purpose of experimentation, the treatment gate was designed to operate under controlled groundwater flow conditions so that the residence time in the iron wall could be maintained constant. To achieve this, the gate was sealed at its downgradient terminus, and two pumping wells were used to draw groundwater through the gate at a specified flow rate of 0.34 cubic meters per day ($m^3/d$) (Morkin, et al. 2000).

# 3. Design Issues and Assessment

This section provides an overview of various issues and considerations pertaining to the design of the Mortandad Canyon PRB. An overview of factors influencing the conceptual design is followed by discussions of civil engineering, hydraulic, and geochemical considerations. Design-related lessons learned from this and other PRB installations are provided in Section 5.4

## 3.1 Mortandad Canyon PRB Conceptual Design

This section presents an overview of the conceptual design issues relevant to the Mortandad Canyon PRB. These issues include performance criteria, site selection, site characterization, design criteria, and technology selection.

### *3.1.1 Performance Criteria*

The objective of this project was to demonstrate a multibarrier PRB technology for treatment of multiple contaminants. Treatment goals, based on existing federal and state guidelines and standards, were specified to guide the design of the PRB. Table 1 summarizes the treatment goals for the Mortandad Canyon PRB.

**Table 1. Treatment Goals for the Mortandad Canyon PRB**

| Parameter | Treatment Goal |
|---|---|
| Americium-241 | 1.2 pCi/L[a] |
| Nitrate – Nitrogen | 10.0 mg/L[b] |
| Perchlorate | 18 µg/L[c] |
| Plutonium-238 | 1.6 pCi/L[a] |
| Plutonium-239, 240 | 1.2 pCi/L[a] |
| Strontium-90 | 8 pCi/L[d] |

[a] U.S. Department of Energy Drinking Water System Derived Concentration Guide
[b] New Mexico Water Quality Control Commission groundwater limit
[c] Action level proposed by State of California
[d] U.S. Environmental Protection Agency Primary Drinking Water Standard (IT Corporation, 2001b)
pCi/L = Picocuries per liter mg/L = Milligrams per liter µg/L = Micrograms per liter

### 3.1.2 Site Selection

Various criteria were considered during the selection of a site for the PRB. These included the existing need for treatment, geochemical and hydrological conditions, adequate monitoring data and ease of future monitoring. The Mortandad Canyon PRB site was selected for the following reasons:

- The LANL Radioactive Liquid Waste Plant at TA-50 has discharged treated waste effluents into Mortandad Canyon since 1963 (Purtymun et al., 1983). The amount and quality of these discharges and their impact to alluvial and perched intermediate-depth groundwater in Mortandad Canyon are well documented (Broxton et al., 2002; Purtymun et al., 1977; Purtymun et al., 1983; Marty et al., 1997).

- Initial fieldwork for this project (Shaw Corporation, 2001) verified that the flow of alluvial groundwater is constrained by the geology of the canyon. Reactive barriers installed at other U.S. Department of Energy (DOE) sites have failed to perform as expected because of poor hydraulic control of the system.

- A large network of monitoring wells has already been installed along the canyon reach providing an opportunity for performance evaluation over a range of length scales.

- A number of reports and data sets have been published on the geochemistry of the alluvial groundwater (Purtymun et al., 1983; Purtymun, 1995; LANL, 2002), thus documenting the hydrochemistry of the canyon.

Further considerations that favored selection of the Mortandad Canyon PRB site included the historical depth and saturated thickness of the groundwater to be treated, the depth to the aquitard, and the width of the funnel portion of the barrier wall. The depth was limited to approximately 27 ft to ensure the use of conventional excavation equipment; consequently, the barrier was placed as far down the canyon as the depth limitation would allow.

The location of the PRB was a good choice considering the project goals and economic constraints.

### 3.1.3 Site Characterization

To determine if a PRB is an appropriate groundwater remediation technique for a given site, four general subsurface properties should be characterized (US EPA, 1998):

- Plume characteristics
- Hydrogeology
- Geochemistry
- Microbial activity

Knowledge of these subsurface properties is essential to develop design parameters for a PRB installation. Figure 2 shows typical relationships among the parameters that affect PRB design. Major design parameters such as treatment residence time, flow velocity and the corresponding media volume are determined based on performance goals, site characterization data, and laboratory data. Mortandad Canyon PRB designers conducted a comprehensive site characterization and laboratory treatability study prior to completion of the PRB design as documented in the final design report for the Mortandad Canyon PRB (Shaw, 2002).

### 3.1.4 Design Criteria

The design for the Mortandad Canyon PRB was based on the following criteria (Kaszuba et al. 2003):

- Treatment of a diverse contaminant suite comprised of radionuclides (americium-241; plutonium-238, 239, 240; and strontium-90), nitrate, and perchlorate

- Minimum 1-day residence time within each PRB reactive cell

- 10-year lifetime for the PRB

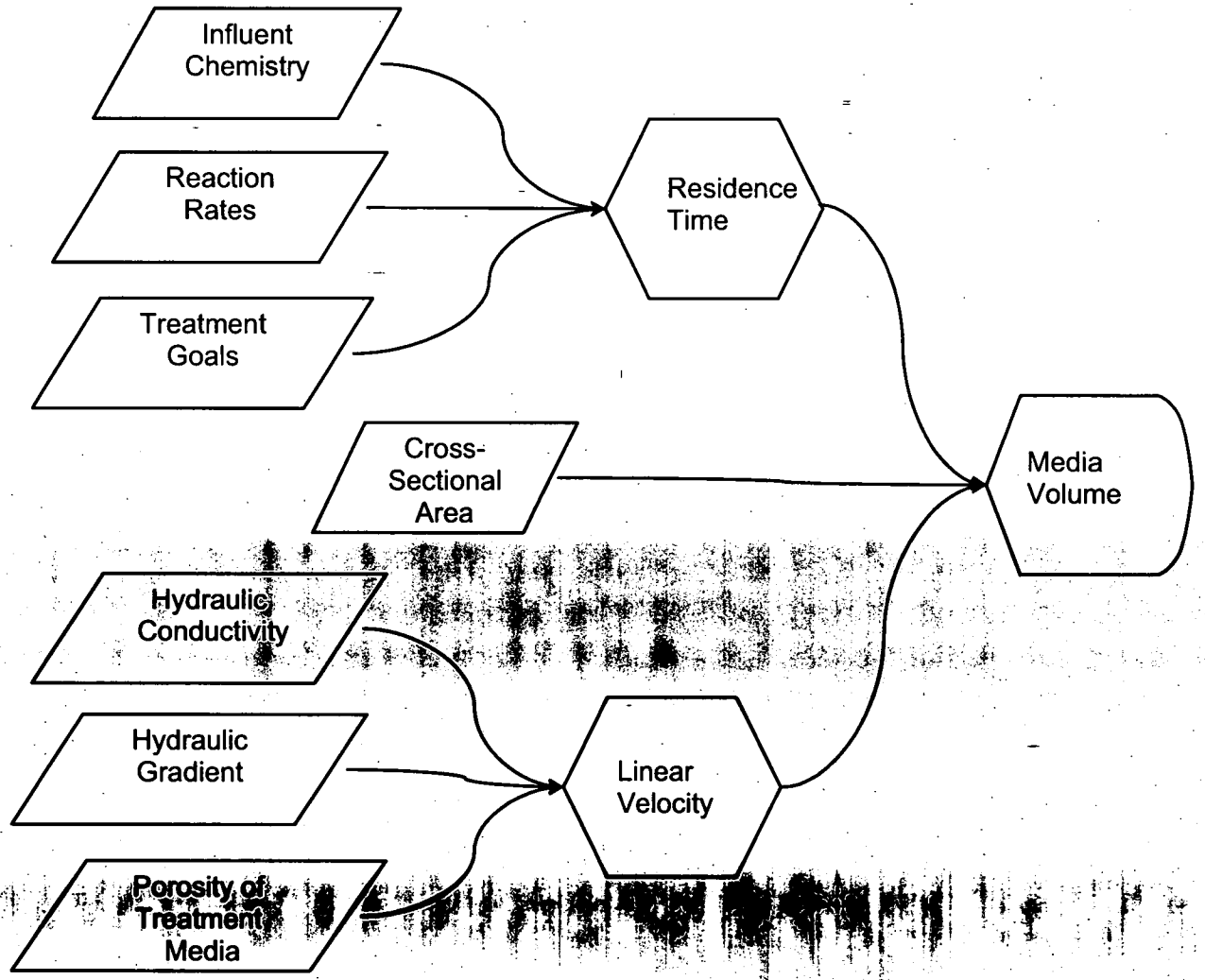


Figure 2

MORTANDAD CANYON PRB INVESTIGATION

**Relationships Among PRB Design Parameters**

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- Minimization of surface water infiltration and erosion
- Optimization of hydraulic capture
- Minimization of excavated material requiring disposal
- Installation of ports in each cell to allow sampling of water and reactive media
- Installation of monitor wells immediately adjacent to the perimeters upgradient and downgradient of the PRB

### *3.1.5 Technology Selection*

In most PRB installations, reactive media has been applied to the subsurface in one of two basic barrier configurations: continuous or funnel-and-gate. Both are applicable for rather shallow plumes (US EPA, 1998). The Mortandad Canyon PRB site was an ideal location for a PRB installation. The subsurface was well characterized and the canyon served as a natural large-scale funnel to assist with capturing and directing the groundwater flow. The site was amenable to either a continuous trench or funnel-and-gate approach; however, according to the US EPA (1998), a funnel-and-gate system using sheet piling for the funnel component may be superior to a continuous trench because excavation and material needs are lower. Although the minimum volume of reactive media needed is independent of the type of barrier configuration used, funnel-and-gate systems may be less expensive because:

- Continuous trenches require media to be spread across the entire plume, while funnel-and-gate systems localize media in the gate area. Less expensive materials, such as sheet piling, are used for the rest of the system. The overall wall system is usually larger for a funnel-and-gate, but the amount of reactive media is less.
- Media is easier to maintain in a localized gate than across a large trench.

- Monitoring costs are lower for the smaller downgradient area created in a funnel-and-gate system.

- Influent contaminant concentration can be homogenized by upstream mixing so that reactive materials are not wasted on areas of low contaminant concentration (IBC, 1999).

The funnel-and-gate design is a well-documented, straightforward approach to capturing groundwater. This design approach was a logical choice for Mortandad Canyon based upon the aforementioned cost considerations, design criteria and site characterization.

## 3.2 Civil Engineering Design Issues

The Mortandad Canyon PRB adheres to a typical funnel-and-gate design composed of impermeable wings walls, approximately perpendicular to the groundwater flow direction, that capture and divert groundwater through the gate or treatment section. This section discusses engineering design considerations specific to the components of this design.

The following general design specifications were applied to the Mortandad Canyon PRB (Shaw, 2002):

- Fabrication and erection work is performed in accordance with American Institute of Steel Construction, Inc. (AISC) specification for structural steel buildings—allowable stress design and plastic design, and the code of standard practice for steel buildings and bridges.

- All welding is performed in accordance with American Welding Society (AWS) D1.1, Structural Welding Code-Steel.

- Structural steel meets ASTM A36 standard.

- Welding electrodes employed meet AWS A5.1 or A5.5 E70XX standards.

- Sheet piling meets PZ-27 ASTM A328 standard or equivalent.
- Sheet piling joints are coated with Adeka Ultra Seal A-50 water stop.
- Grating is rectangular welded steel grating, nonreversible Type V, with 1-1/4 inch × 3/16 inch bearing bars on 1-3/16 inch centers and crossbars on 4 inch centers with 1/2 inch opening wire mesh, 1/16 inch wire, over grating.
- Dividers are constructed of type V steel mesh with 11/16 inch openings to be used for separating the four different media zones within the cofferdam gate.

### *3.2.1 Funnel Design*

The natural formation of Mortandad Canyon acts to funnel water. The designers of the Mortandad Canyon PRB designed the funnel-and-gate structure to take advantage of this natural feature by locating the PRB within a narrow reach of the canyon. The north wing wall ties into the canyon wall while the south wing wall extends beyond the observed southern extent of saturation in the alluvium. The funnel is composed of interlocking steel sheet piling. This design is sufficient to provide excellent lateral hydraulic capture of the flowing groundwater.

### *3.2.2 Gate Design*

In a funnel-and-gate system, the gate is the portion of the PRB that contains the permeable reactive media. Regardless of the construction technique for the funnel wing walls (sheet piling, slurry wall, or other), the gate is generally designed as a braced cofferdam using steel sheet piling internally supported by walers (internal lateral cross supports). Proper design of a braced cofferdam requires knowledge of (1) soil properties such as soil grain distribution, unconfined compressive strength, saturated unit weight, cohesion and angle of internal friction; (2) percentage of clay; (3) groundwater level; and (4) bedrock location and integrity.

To date, the only known problems encountered with a properly installed braced cofferdam designed to confine the treatment media has been the potential for reduced permeability and

consequent flow impedance. This can result at sites that have significant soil clay content. When the sheet piling is driven and removed it heats the soil due to friction and can cause the clay portion of the soil to "shellac," potentially blinding off flow. This same effect has been documented in well installations. Special consideration needs to be given to the percentage of clay in the soil for this reason. Soil characterization at the Mortandad Canyon PRB site indicates that most of the material is coarse-grained alluvium with insignificant amounts of clay. This information reassured designers that the potential for the hydraulic problems due to clay smearing was negligible.

The gate for the Mortandad Canyon PRB is composed of interlocking steel sheet piling. The designers used slug test, soil grain size distribution, and standard penetration test data to estimate the geotechnical properties for the cofferdam location. The footprint and surcharge load of a Caterpillar 300B excavator was also considered when developing lateral soil pressure distribution diagrams. Structural requirements for the gate and internal bracing were determined and cross checked using three different theoretical methods: Rankine, Coulomb, and Terzaghi (Bowles, 1982). The data were modeled using Boussinesq's stress influence charts for lateral strip loading (Bowles, 1982) and further verified using the SPW911 Version 2 computer model (PileBuck, 2001). The modeled results compared well with the manual calculations. The design of the cofferdam was proper and thorough. The cofferdam structure and separation grates will provide structural support and media separation without impeding flow through the cells for the design life of the Mortandad Canyon PRB. Figure 3 shows plan and cross-section schematic views of the cofferdam gate. Table 2 provides the design properties of the Mortandad Canyon PRB.

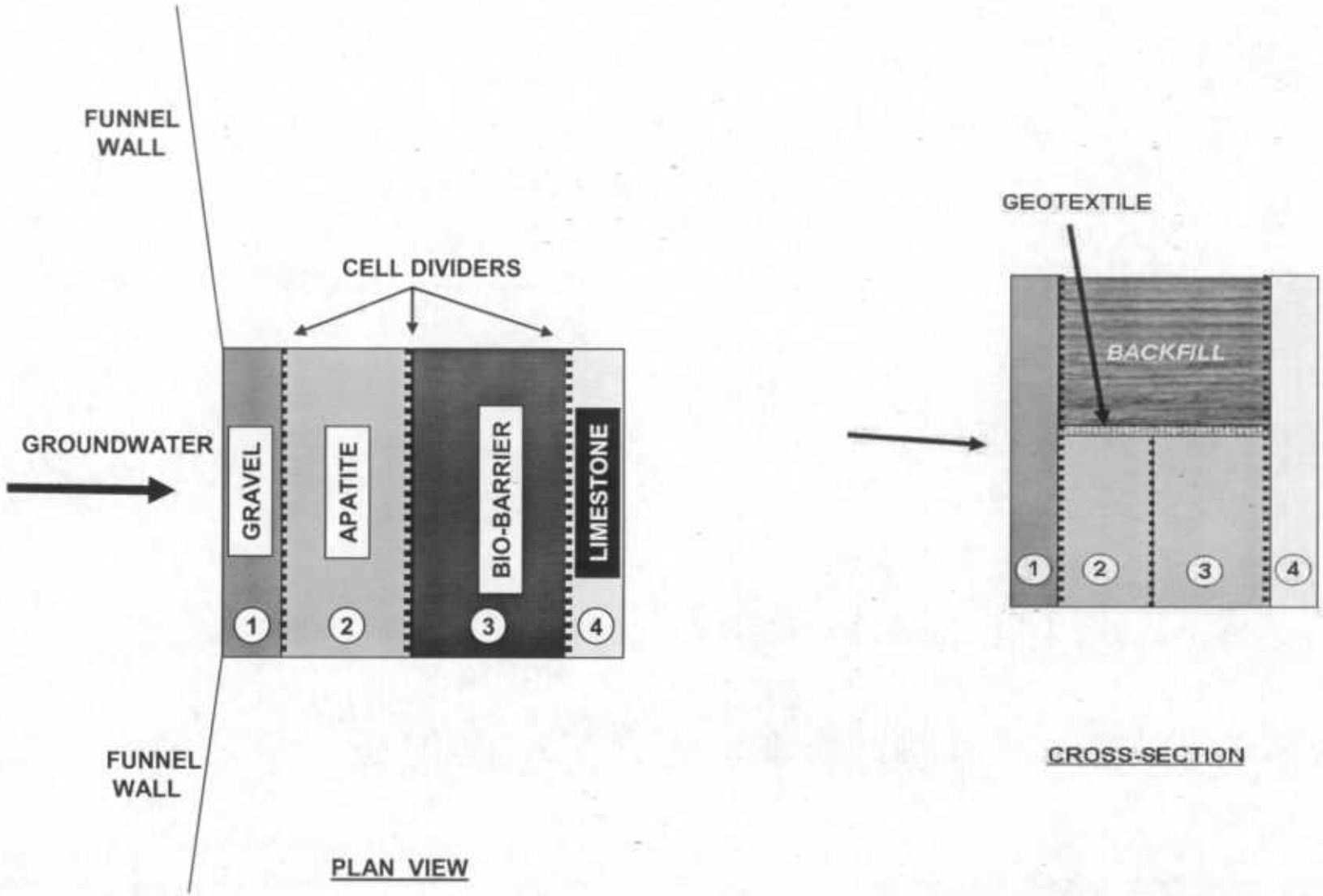


Figure 3

MORTANDAD CANYON PRB INVESTIGATION

**Plan View and Cross Section of Cofferdam Gate**

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**Table 2. Mortandad Canyon PRB Design Properties**

| Cell Number | 1 | 2 | 3 | 4 | Entire Cofferdam |
|---|---|---|---|---|---|
| Media | Gravel | Apatite | Bio-Barrier | Limestone | NA |
| Cell dimensions (ft) | X = 17<br>Y = 3.5<br>Z = 20 | X = 17<br>Y = 7<br>Z = 10 | X = 17<br>Y = 9<br>Z =10 | X = 17<br>Y = 3.5<br>Z = 20 | X = 17<br>Y = 23<br>Z = 20 |
| Volume ($ft^3$) | 1,190 | 1,190 | 1,530 | 1,190 | 7,820[a] |
| Estimated porosity | 0.5 | 0.5 | 0.45 | 0.5 | NA |
| Average velocity (ft/day) | 1.9 | 1.9 | 2.1 | 1.9 | 2.0 |
| Average flow residence time (days) | 1.8 | 3.6 | 4.2 | 1.8 | 11.4 |
| Peak velocity (ft/day) | 2.9 | 5.9 | 6.5 | 2.9 | NA |
| Peak flow residence time (days) | 1.2 | 1.2 | 1.4 | 1.2 | 5.0 |

NA = Not applicable
ft = feet
[a] Includes 2,720 $ft^3$ of soil (backfilled alluvium) cover above Cells 2 and 3.

### *3.2.3 Sampling Ports and Monitoring Wells*

The sampling wells were installed in three transects parallel to the groundwater flow and perpendicular to the media zones. This array provides three water sampling ports within each media zone. In addition, one upgradient and three downgradient monitor wells were installed. The sampling wells located within the PRB consist of 2 inch PVC pipe screened with 0.010 inch slots 10 ft above the base of the gate.

Considering the variable and sometimes very low flow in Mortandad Canyon, multilevel sampling wells would have been more appropriate for evaluating a multimedia barrier. Recent papers have documented the existence of ambient vertical flow within long screened monitoring wells completed in both confined and unconfined aquifer systems (Thomson, 2004). Installation of multilevel samplers and monitoring wells located downgradient of the funnel within and near the gate could provide more discrete monitoring. For example, a PRB installation in Elizabeth City, North Carolina has a total of 147 discrete monitoring points (Puls et al., 1998). This would be excessive for the Mortandad Canyon PRB; however, some additional monitoring points would allow for better assessment of potential preferential flow paths within the gate (media)

and any bypass beneath the gate, through joints, or around the funnel sections. During discussions on permeable reactive barriers at the 2002 Research Technologies Development Forum, it was noted several times that PRB operators should never assume all of the groundwater at a site is being treated, but should perform field studies to determine the extent of the capture zone. A summary report evaluating the economics and performance-based design of monitoring systems for PRBs (Elder et al., 2001) should be referenced by future LANL PRB designs.

## 3.3 Hydraulic Design Considerations

Various aspects of the hydraulic design of the Mortandad Canyon PRB are discussed in this section. These include a discussion of general hydraulic principles affecting the design, as well as an analysis of flow through multiple reactive media materials and the use of divider screens and geosynthetic materials to separate the reactive materials from each other and the overlying backfill.

Understanding the groundwater flow regime is key to the physical design of a PRB system (ITRC, 2005). Sizing for hydraulics constitutes the main design emphasis in PRB engineering. First, a velocity through the media is calculated (Ott, 2000) by applying Darcy's Law:

$$Q = K\,i\,A$$

where

$Q$ = groundwater flow rate
$K$ = saturated hydraulic conductivity
$i$ = the hydraulic gradient
$A$ = the cross-sectional area perpendicular to flow

Using the computed groundwater flow velocity, the design incorporates the physical dimensions and conditions that will allow sufficient residence time within the reactive media to permit the desired reactions to occur. The relatively limited physical extent and natural funneling of

groundwater within Mortandad Canyon minimized the need for designers to understand the groundwater flow patterns, and allowed more focus on the design of the treatment zone hydraulics.

The treatment zone is complex because there are five interfaces between differing materials. There is a clear consensus within the PRB technical community that the vast majority of groundwater constituent removal occurs due to mineral precipitation at the final interface with the permeable reactive media. Although the Mortandad Canyon PRB contains five potential interfaces, it is suspected that most of the precipitation will occur in the gravel zone at the interface with the apatite. However, it remains to be seen whether or not the three additional downgradient interfaces incur significant precipitation.

### *3.3.1 Separation of Reactive Zones*

Shaw designers used filter criteria set forth by Terzaghi and the "Shape Factor – D50Filter/D50Soil" used by the U.S. Army Corps of Engineers (Bowles, 1982) to evaluate the permeability transitions at each interface. Shaw (2002) stated that when treating each media separately as independent layers, the requirements for permeability are not met because the materials are very similar; consequently, the four media were evaluated as a single layer having interfaces only at the gate inlet and outlet. Using this approach, the permeability criteria were met for the upstream interface but not for the downstream interface. Shaw designers concluded that the permeability of the filter will be governed by the seepage through the insitu soil at the gate. They also noted that the limestone layer may become saturated due to low permeability of the in situ soil (Shaw, 2002).

Flow impediment at the limestone/native alluvium interface could result in mounding within or upgradient of the barrier. In fact, significant mounding of the groundwater within the Mortandad Canyon PRB has been observed (see Sections 5.2.3 and 7.3). Some mounding is normal in most reactive barriers, especially funnel-and-gate installations; however, excessive mounding will increase static water elevation pressures against sheet pile joints and aquitard interfaces. In some instances, mounding can even cause water to flow over the top of the barrier, as evidenced at a funnel-and-gate system in Monticello, Utah (personal communication with Stan

Morrison, Roy F. Weston, May 2005). Mounding occurred at that site primarily due to clay smearing effects when the sheet piling was removed from the inlet and outlet of the gate.

### 3.3.2 Hydrologic Modeling

The U.S. Geological Survey (USGS) MODFLOW groundwater flow model (McDonald and Harbaugh, 1988) was used to simulate hydrogeologic conditions in Mortandad Canyon. The model was calibrated to the natural groundwater flow conditions in Mortandad Canyon during June 2001, and subsequently used to simulate flow within the PRB (Kaszuba et al., 2003). Average and peak flow rates in conjunction with required treatment residence times (previously determined in laboratory studies) were used by the designers to size the reactive zones. Due to the fluctuating nature of the groundwater table, the first and last cells (gravel and limestone, respectively) were extended vertically 20 ft over almost the entire alluvial depth of 27 ft in order to promote flow into and from the gate. The two middle cells (mineral apatite and bio-barrier) extended vertically only 10 ft through the lower portion of the alluvium (Shaw, 2002).

The horizontal hydraulic conductivity values used in the groundwater flow modeling are shown in Table 3. These values are based on estimated conductivities determined by slug tests of the alluvium in these wells (Shaw, 2002).

**Table 3. Summary of Estimated Hydraulic Conductivities Used in Mortandad Canyon PRB Groundwater Flow Model**

| Monitoring Well | Hydraulic Conductivity | |
|---|---|---|
| | (ft/day) | (cm/s) |
| MCO-4B | 30.05 | 1.06E-02 |
| MCO-5 | 4.67 | 1.65E-03 |
| PRB-1 | 1.35 | 4.77E-04 |
| PRB-2 | 91.28 | 3.22E-02 |
| PRB-3 | 1.34 | 4.74E-04 |
| PRB-6 | 0.01 | 3.60E-05 |

ft/day = Feet per day cm/s = Centimeters per second

For modeling purposes, the PRB was treated as a single filter zone instead of four separate zones. A saturated hydraulic conductivity of 50 ft/day (0.02 cm/s) was assumed for the PRB. A saturated thickness of 10 ft for average flow and 20 ft for peak flow conditions was assumed. The model was used to calculate the residence times listed in Table 2 for average and peak groundwater flow velocities for each cell; in all cases, these times were greater than the design residence time of 1 day. During peak flow, the residence time was calculated to be approximately 20 percent greater than the design residence time. This relatively small factor of safety raises concerns because the design basis of a 1-day residence time is not well documented.

Typically, when subsurface and barrier properties are heterogeneous, a safety factor should be included when sizing the reactive cell so that fluctuations are accounted for (US EPA, 1998). Some sources recommend that the media's permeability be about ten times that of the aquifer because various events, such as settling of fine-grained particles, solid precipitation, and biofouling, can reduce permeability over time (NATO, 1998).

## 3.4 Geochemical Design Considerations

Geochemistry refers to the native constituents of the groundwater that can affect the short- and long-term performance of a PRB. Geochemistry is an important design consideration because groundwater constituents other than the target contaminants may interfere with a PRB's ability to perform its two main functions (ITRC, 2005):

- Capture groundwater from the targeted portion of the aquifer and provide it with sufficient residence time in the reactive media.

- React with the target contaminants and reduce their concentrations to target cleanup levels.

The designers of the Mortandad Canyon PRB used a deterministic approach to model the geochemical aspects of the PRB design. Average and maximum flow velocities, groundwater constituent concentrations, and reaction rates were used in computer model simulations to

evaluate mineral equilibrium and expected precipitation within the PRB. The desired outcome of the geochemical model should suggest barrier longevity with respect to contaminant removal and permeability. Computer simulations of water passing through the PRB were performed using the EQ3NR/EQ6 (EQ3.6) computer code. The EQ3.6 code is an industry-standard chemical-reaction model that performs solubility, speciation, and reaction-path calculations (Wolery, 1992; Wolery and Daveler, 1992).

The PRB influent composition was based on sample analyses from an upgradient monitor well (MCO-4.5B). The predicted effluent composition from Cell 1 (gravel) was used as input for Cell 2, and so on for all serial cells in the PRB. The final design report prepared by Shaw (2002) contains an appendix with the input and output files for all simulations.

Most PRB installations in the U.S. are designed to remove a single COC. Like many DOE sites throughout the country, Mortandad Canyon has multiple COCs and required a different remedial approach. The concept of treatment trains or serial reactive zones was not new; however, the complexity of the Mortandad Canyon groundwater plume required a more complex approach than had been previously used. Designers conceived a treatment zone containing four in situ cells sequenced to collectively remove the target COCs by means of ordinary physical, chemical, and biological removal mechanisms. These four treatment cells are described below.

### *3.4.1 Cell 1—Gravel*

The primary function of the gravel barrier (Cell 1) is to remove colloids containing americium, plutonium, and strontium. Removal is accomplished by the simple physical adsorption of colloidal material into the void space in the gravel. The high porosity and conductivity of the gravel provides an effective groundwater flow transition from the native soil into the PRB. In addition to colloidal removal, it is anticipated that the gravel zone will promote early precipitation of carbonate and hydroxide complexes, thus improving the ability of Cells 2 and 3 to perform as designed.

Designs that use a permeable gravel or sand layer as the groundwater entry zone have been used at many sites to eliminate permeability problems at the upgradient face of a PRB. The

porous layer allows constituent removal and supports redox conditions without any adverse effects on the primary treatment media. The following are two examples of PRBs that incorporated a porous initial layer (post-startup) after initially experiencing a reduction in permeability at the interface (first 12 inches) where groundwater meets the reactive media:

- Initially, the 903 Mound Site at the Rocky Flats Environmental Technology Site used zero valent iron (ZVI) media in a confined vessel accessible from the surface. After a few months of operation, the flow was severely impeded by precipitation of carbonates and hydroxide salts. The upper 2 ft of media was removed and replaced with gravel. The system has been operational for over six years with no further problems and minimal maintenance.

- The Denver Federal Center installed a 1,200 ft long sheet pile funnel with four 40 ft wide intermediate gates. Mounding due to permeability issues was almost immediate; the reduction in permeability was primarily due to smearing during installation and possibly initial interface precipitation. The mounding was eliminated by the installation of a row of 2 ft diameter auger borings filled with sand and granular iron along the upgradient interface.

Sharp permeability contrasts between emplaced and native media should be avoided whenever possible (IRTC, 2005). The Mortandad Canyon PRB design calculations indicate no permeability, particle piping, or shape issues between the native soil and the gravel zone.

### *3.4.2 Cell 2—Mineral Apatite*

Mineral apatite removes soluble metals and radionuclides via adsorption and co-precipitation. Americium, plutonium, and strontium are primarily removed by the formation of insoluble phosphate complexes which adsorb onto the mineral surfaces; a DOE study (Thomson et al., 2003) concluded that phosphate-based adsorbents have a very high-sorption capacity for americium, plutonium, and uranium at near neutral pH. More specifically, the ability of this natural media to treat thousands of bed volumes of water prior to breakthrough of uranium or plutonium suggests that it may have application in low-cost wastewater treatment systems or for

remediation of groundwater in a permeable reactive barrier system (Thomson et al., 2003). Apatite is an ideal material for long-term containment of contaminants because of its high sorption capacity for actinides and heavy metals, low water solubility (solubility product constant [Ksp] > 10-40), high stability under reducing and oxidizing conditions, availability, and low cost (LeGeros, 1991).

Sources of apatite include synthetic apatite manufactured for use in chromatographic and biomedical applications; bone char from animal processing facilities; fish bones from fish processing plants; and natural phosphate rocks which are mined for fertilizer and other applications (Thomson et al., 2003). According to Robert Moore of Sandia National Laboratories, bone-char is the optimal choice for radionuclide removal (personal communication with R. Moore, 2006); apparently mineral apatite is less than optimal for this purpose. Most of the laboratory treatability work specific to this PRB is based on Apatite II. An examination of the project files indicated that preliminary Mortandad Canyon PRB designs called for the use of Apatite II, a fish bone product; however, the final design used phosphate rock supplied by IMC AGRICO. The apparent lower removal ability of mineral apatite may not be of concern at the relatively low levels of radionuclides found at the Mortandad Canyon PRB, particularly since Cells 3 and 4 (bio-barrier and limestone) should assist with radionuclide removal at the relatively low levels found in this groundwater.

### *3.4.3 Cell 3—Bio-Barrier*

The bio-barrier was designed to biodegrade nitrates and perchlorate. In environmental remediation terms, in situ bioremediation is a biologically mediated process in which microorganisms convert a compound (in this case, the COCs perchlorate and nitrate) to less toxic forms. Microbial degradation of perchlorate and nitrate proceed according to the following anaerobic reduction processes:

$$ClO_4^- \rightarrow ClO_3^- \rightarrow ClO_2^- \rightarrow ClO^- + O_2$$
$$5CH_2O + 4NO_3^- \rightarrow 5CO_2 + 2N_2(gas) + 3H_2O + OH^-$$

A key consideration with an organic bio-barrier is that permeability and performance can be reduced by filtration and accumulation of suspended solids in the pore spaces and by microbial production of gas bubbles during anaerobic degradation. Studies with denitrifying systems have demonstrated that the accumulation of $N_2$ gas bubbles in porous media can significantly reduce the hydraulic conductivity (Scherer et al., 2000). For the Mortandad Canyon PRB, pea gravel was added to increase the porosity of the bio-barrier zone. Designers lowered the porosity estimate by 10 percent (from 50 to 45 percent) to compensate for gas release during remediation. This is a common industry practice in bioremediation.

### *3.4.4 Cell 4—Limestone*

The limestone gravel zone was designed to buffer the pH of the water prior to discharge from the treatment system and provide final polishing through precipitation of soluble plutonium, americium, and metals. The limestone particles are significantly larger than the adjacent soil (alluvium). The contrast in particle size between the limestone and the downgradient soil does not meet the permeability criteria, which suggests a potential for flow impediment at that interface.

## 3.5 Assessment of Mortandad Canyon PRB Design

The PRB in Mortandad Canyon is very complex. Granular iron might have been used to simplify the Mortandad Canyon PRB design; however, concerns regarding the University of Waterloo patent for iron media and the associated licensing fees reportedly led the designers to develop the multiple-barrier concept (personal communication with P. Scott den Baars, Shaw Environmental & Infrastructure, August 2006). Without the use of zero-valent iron, multiple media were essential to capture the suite of COCs having dissimilar geochemical properties. The general design logic followed industry standards including adequate site characterization and laboratory treatability studies. Due to the complexity of the PRB design, however, some design concerns arose around the following issues (listed in order of concern):

1. *Potential compaction/consolidation of the bio-barrier and the mineral apatite zones due to soil overburden.* The potential for differential settlement and secondary consolidation

always exists within PRBs; however, this design magnified the potential by placing 17 ft of soil above Cells 2 and 3. In the event of settlement due to consolidation, saturated hydraulic conductivity within Cells 2 and 3 could be reduced causing upgradient mounding of water and potential bypass. For this design, the primary method to minimize secondary consolidation is maintenance of the PRB surface cover to keep water from penetrating the surface. This is normally achieved by maintaining a positive slope to avoid ponding on the PRB surface, and maximizing vegetation and thus evapotranspiration to avoid localized erosion.

2. *Failure of the PRB to pass the permeability criteria ratio (Terzaghi/Bertram Criteria).* The permeability criteria were not met when the PRB cells were considered separately. Even when the PRB was considered as a single filter (instead of four separate filters) in contact with the native soil, the last interface did not meet the permeability criteria. Failure to satisfy the permeability criteria at this juncture could result in upgradient mounding, erratic flow patterns, and possible system bypass.

3. *The choice of mineral apatite as the primary radionuclide filter.* The majority of preliminary laboratory work evaluated Apatite II (fish-bone) as the best form of apatite for radionuclide removal. Relevant literature suggests mineral apatite does not sorb radionuclides as well as the bone form of apatite. There are four distinct sources of apatite: synthetic, animal bone-char, fish bone, and phosphate rock. The literature suggests that all four forms can capture radionuclides; however, synthetic and bone-char apatite's radionuclide sorption capabilities are more favorable with the least potential for leaching of trace metals. Synthetic apatite is relatively expensive while the other forms are cost competitive. However, considering the relatively low radionuclide concentrations in Mortandad Canyon groundwater and the anticipated assistance of the other three filter media in removing radionuclides, the mineral apatite should suffice in this application.

4. *Potential movement of COCs from native soil placed above Cells 2 and 3.* Water can move vertically (either direction) between Cells 2 and 3 and the soil above these cells.

Native soil was used as fill over the two cells; this soil may contain contaminants that can affect sampling results within the PRB.

# 4. Construction Issues and Assessment

The construction field logbook notes were not available for this design review. Instead, field photographs, survey notes, drilling logs, and other site characterization notes and data were examined. These records, combined with interviews of with key project personnel (Section 2.1), were used to fill information gaps.

## 4.1 Civil Structures

As described in Section 3.2, the civil structures in a PRB include the funnel, gate, and monitoring wells. Information related to the construction of these features was obtained and reviewed, as described below.

### *4.1.1 Funnel Installation*

The funnel materials and installation methodology met industry standards. Minimal difficulties were encountered driving sheets to design depths. Interlocking sheet pile joints were sealed with A-50 water stop to ensure joints remain water tight. The design specification called for the sheet piling to be driven to a specified depth into the aquitard (underlying volcanic tuff) or to refusal. Records of penetration depths for all sheet piling were recorded in the construction field log notes; however, this information was not available for this design review. Consequently, assessment of as-built conditions is based on the accounts of construction provided by key personnel.

Each wing wall was tied (interlocked) into the upgradient respective outside corners of the cofferdam gate. All sheet pile was installed in accordance with depth and vertical alignment specification, and no problems were encountered with joint seals. The north end of the north wing wall was completed using a bentonite seal.

A profile drawing (Drawing number 826732-D1, Revision 0, As-Builts (5-21-03), Profile A/C1) showing details of the approximate bottom of sheet piling, top of the tuff aquitard layer, and top of the sheet piling relative to grade can be found in Kaszuba et al. (2003).

### 4.1.2 Gate Installation

The gate materials and installation methodology meet industry standards. Minimal difficulties were encountered driving sheets to design depths and performing required sheet piling removal (at the entry and exit from the gate). The sheet pile installer noted that contact with the aquitard was obvious and all driven sheets met design specifications with respect to verticality and depth (personal communication with R.S. Johnson, 2006). This is critical because the most common failure of a funnel-and-gate design is difficulty associated with keying sheet piling into the aquitard and vertical misalignment due to difficult soil conditions. All sheet pile joints were sealed with A-50 water stop in accordance with the manufacturer's guidelines. Although the southwest and southeast corners of the gate did not close perfectly, this was not an issue because the upgradient and downgradient sheets where the mismatched corners occurred were removed per design. The other two corners, where the gate sides (not to be removed) connected to the funnel wing walls, were sealed properly as shown in Figure 4.

The gate was excavated using a track-hoe capable of excavating to 27 ft. Internal structural braces (walers) were installed as the excavation progressed. Three rows of walers were installed per design. During excavation of the bottom quarter of the gate section, water influx was encountered. Water was removed using trash pumps; however, it was noted that visual observation of the last several feet of the excavation was impaired by mud and water and the bottom of the excavation was never seen (personal communication with R.S. Johnson, 2006). Unfortunately, possibly due in part to the poor visibility, the gate was overexcavated. This occurrence is not well documented. Because of the lack of access to the construction field notes it was necessary to rely on the interviewees' recollections of events. There was consensus among the interviewees that overexcavation of approximately 4.5 ft occurred, primarily in the area of Cells 2 and 3. In addition, the interviewees were unsure of the condition of the bottom of the excavation: that is, was there fracturing of the volcanic tuff aquitard? Was some of the broken-up and over-excavated material left in the bottom? To compensate for the

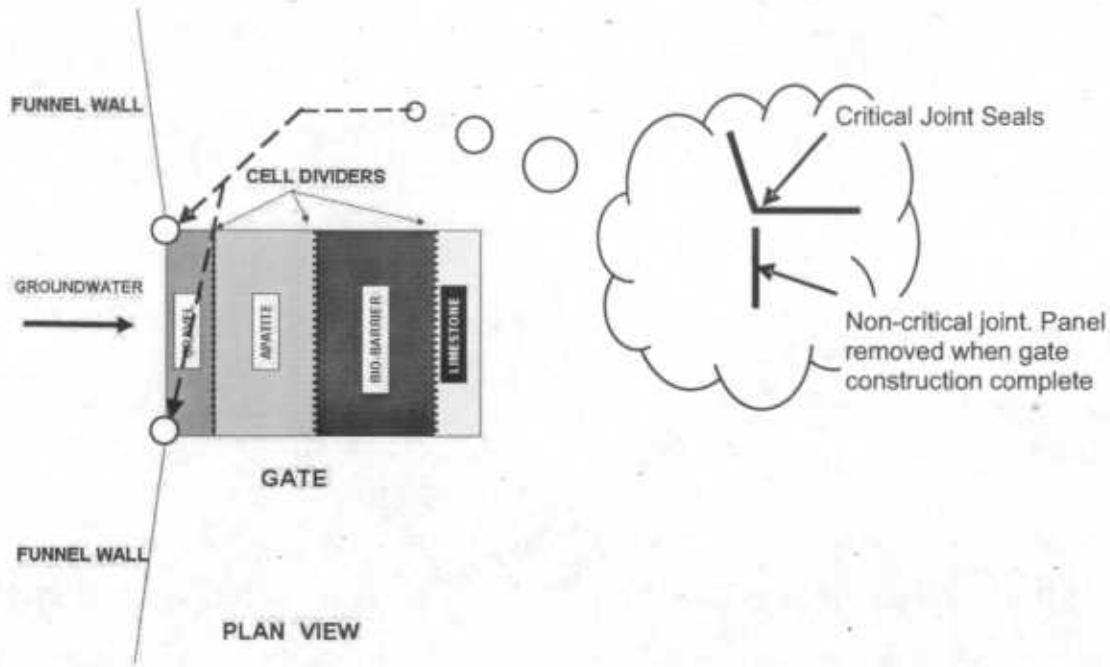


Figure 4

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MORTANDAD CANYON PRB INVESTIGATION

**Schematic Plan View of the PRB**

overexcavation, additional media was procured and used to fill the extra volume to ensure adherence to design elevations for the top surfaces of the reactive cells.

Installation of a 2 ft thick bentonite bottom seal would have mitigated the potential for vertical migration into or out of the permeable reactive zones. Many PRB installations incorporate a bentonite bottom seal because of the unknown effect excavation may have on an aquitard.

The soil above Cells 2 and 3 had to be isolated from the PRB to eliminate the possible mixing of soil and media. Impermeable geosynthetic clay liners (GCLs) were used to separate the vertical portions of Cells 1 and 4 from the soil overburden above Cells 2 and 3. Cells 2 and 3 were separated from the soil above using a permeable geotextile fabric. This type of fabric is designed to separate materials yet allow transmission of water in either direction. While this reduces the potential for a bathtub effect in the event the soil becomes saturated, it does allow any COCs associated with the soil and water to move either direction. Under ideal PRB conditions (i.e., saturated media), the use of geotextile fabric to separate soil overburden from cell media is not an issue; however, when water levels fluctuate between saturated and unsaturated conditions (as is indicated by preliminary site characterization data at Mortandad Canyon), the capillary action between the varying materials can accelerate consolidation and associated settlement.

The final step in construction was the placement of a soil cap. The cap had a gradual slope tapering approximately 2 ft to the surrounding topography overlying the gate section. As-built engineering drawings (Drawing numbers 826732-D1, 826732-D3 and 826732-D5, Revision 0, As-Builts, (5-21-03)) provide profile views showing the details of the gate installation (Kaszuba et al., 2003).

### *4.1.3 Sampling Ports and Monitoring Wells Installation*

Well installations met industry standards and were performed in accordance with the design drawings. Well casings are 2 inch diameter, schedule 40 PVC pipe. Sampling and monitoring wells within the PRB were supported during media installation by connection to the steel cell

dividers and walers. Media was placed in lifts of 1 to 2 ft evenly between cells to avoid any stress on the cell dividers and wells.

Kaszuba et al. (2003) provides a profile section showing well installation details such as well depths, screened intervals, and standard penetration test blow counts for each well installation (Drawing number. 826732-D1, Revision 0, As-Builts (5-21-03), Profile A/C1).

## 4.2 Hydraulic Installations

This section discusses the assessment of the PRB components relevant to hydraulic performance.

### *4.2.1 Groundwater Flow Through Gate*

A permeable reactive barrier is essentially an in situ filter. Darcy's Law applies to flow through porous media such as the soil and treatment media. It is critical that the flow of groundwater through the filter zone(s) is reasonably uniform and there are no flow impediments. Installation of a funnel decreases the cross-sectional area (*A*) for water flow, thereby, increasing the gradient (*i*), while the hydraulic conductivity (*K*) remains constant. As shown in Figure 5, assuming the PRB acts as a single filter, the upgradient flow rate (Q1) and the downgradient flow rate (Q3) are equal for conservation of flow at equilibrium. Because $A_1 >> A_2 = A_3$, and $K_1 i_1 = K_3 i_3$, $K_2 i_2$ must be greater than $K_1 i_1 = K_3 i_3$. To ensure this, the designers selected media with much greater K values than the in situ soil. The potential for a problem occurs at the interface of the limestone and downgradient soil. In a funnel-and-gate system, the outlet from the gate should be sized to accommodate infiltration of the capture of a very large cross-sectional area of water ($A_1$). Most gates neglect this consideration because the permeability transition between the PRB and downgradient soils meets the filter criteria for a smooth transition. Despite this, many PRBs experience moderate mounding of groundwater upgradient or within the PRB. Modeling of the Mortandad Canyon PRB design indicates that the permeability criteria regarding particle size ratios is not met at the outlet interface.

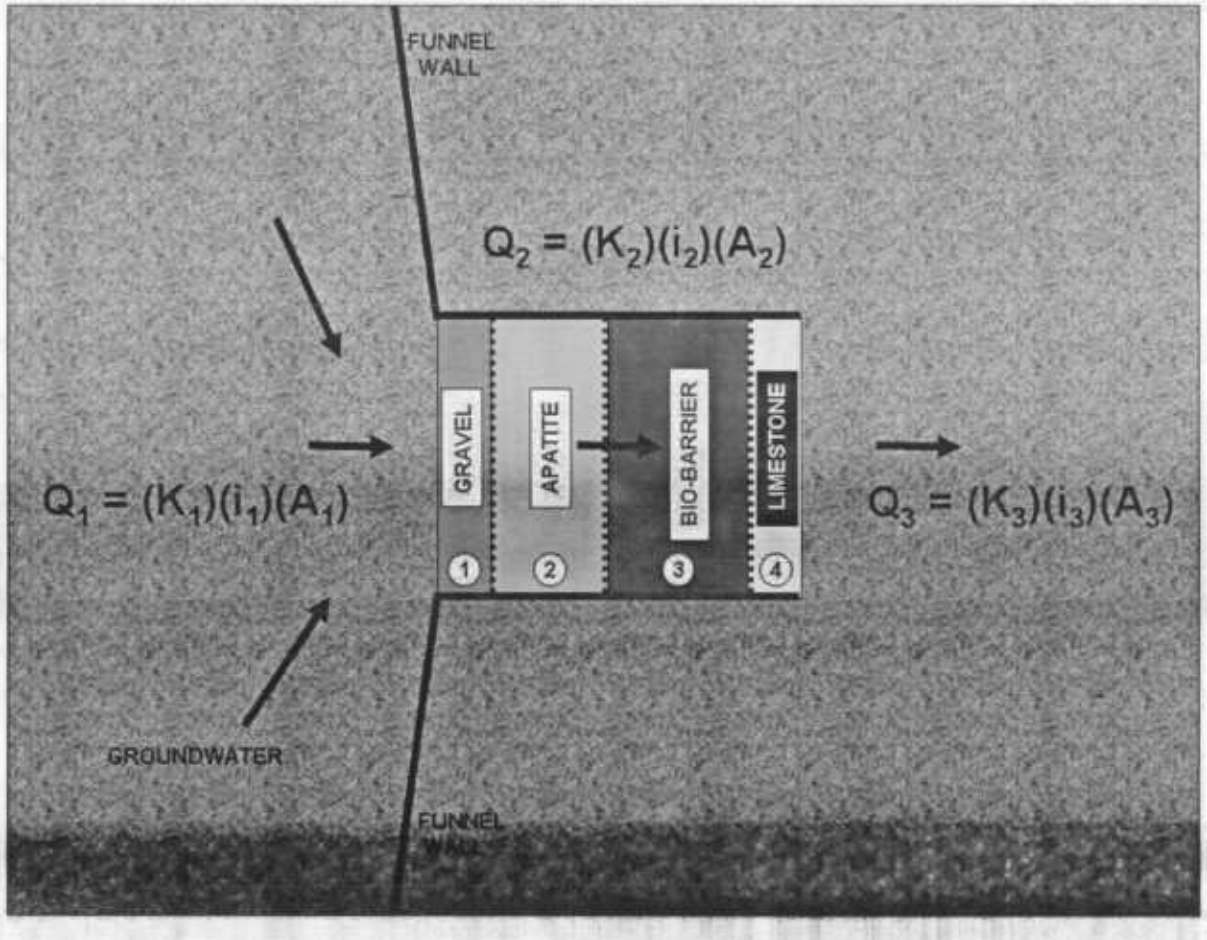


Figure 5

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MORTANDAD CANYON PRB INVESTIGATION

**Schematic Plan View Illustrating Darcy's Law**

### 4.2.2 Material Separation

The divider screen material and installation methodology meet industry standards. Project photos confirm that no problems were encountered during installation. Interviewees stated that the cell divider screens were installed as shown in Drawing number 826732-D1, Revision 0, As-Builts (5-21-03) (Kaszuba et al., 2003).

Project photographs show various stages of installation of the GCL. No information is available regarding the manufacturer specifications of the GCL. Interviewees stated that the GCL was installed as shown in Drawing number 826732-D1, Revision 0, As-Builts (5-21-03) (Kaszuba et al., 2003).

No information is available regarding the manufacturer specifications of the geotextile. Interviewees stated that the geotextile was installed as shown in Drawing number 826732-D1, Revision 0, As-Builts (5-21-03) (Kaszuba et al., 2003).

## 4.3 Geochemical Installations

This section discusses geochemical design aspects relating to the use of different types of reactive media in a single PRB installation.

Four treatment media were installed in accordance with the dimensions shown in Drawing number 826732-D1, Revision 0, As-Builts (5-21-03) Gate Cross Section (Kaszuba et al., 2003). During installation of PRB media, it is important to place the media as uniformly as possible to minimize packing variability which can create preferential flow paths. Differing grain sizes within a media magnifies the potential for this problem. A soil or media particle size is classified in accordance with ASTM standards. The results of particle size tests are graphed as a particle size distribution curve. The Hazen coefficient of uniformity (Cu) is a measure of media uniformity. Table 4 provides Cu values for the four media used in the Mortandad Canyon PRB.

**Table 4. Soil Indexing Parameters of Media Used in PRB Cells**

| Reactive Media | Soil Index Coefficient Cu (Coefficient of Uniformity) Min | Max | Satisfies Criteria (Yes < 5 < No) Min | | Max | |
|---|---|---|---|---|---|---|
| Gravel | 2.8 | 3.3 | < 5 | Yes | < 5 | Yes |
| Mineral Apatite | 2.1 | 2.2 | < 5 | Yes | < 5 | Yes |
| Bio-Barrier | 1.8 | 2.1 | < 5 | Yes | < 5 | Yes |
| Limestone | 1.5 | 1.3 | < 5 | Yes | < 5 | Yes |

All four media satisfy the criteria to be considered uniform in particle size. The bio-barrier media is a three-part mix (cottonseed, gravel, and pecan shells). The three parts were mixed on the surface using a front-end loader (personal communication with R.S. Johnson, 2006). There are no photographs or data regarding the uniformity of the mix prior to emplacement.

All four media were dumped in 1 to 2 ft lifts into the excavated gate using a front-end loader. This method of emplacement was less than ideal. At a minimum, special care should have been allowed for emplacement of the bio-barrier. Separation of the three materials composing the bio-barrier could occur during dumping due to significant differences in the material densities. The use of a tremmie pipe to convey the media to depth would minimize particle separation and variations in compaction density that may be created by dumping media to depths greater than 20 ft.

# 5. Maintenance and Monitoring Issues

The Mortandad Canyon PRB is a field-scale pilot project designed to operate for 10 years from its start-up date in February 2003. One of the design criteria for the project is that surface infiltration and erosion must be minimized through the use of impermeable barriers and riprap/boulders (Kaszuba et al., 2003). The EPA requires maintenance protocol as part of a long-term monitoring plan for PRBs.

The Mortandad Canyon PRB installation agreement with the State of New Mexico Environment Department (NMED) noted a monitoring period of 5 years from start-up, which means that monitoring should continue until February 2008. Minimum maintenance of the PRB during this 5-year period should include the following:

- Minimizing surface infiltration and erosion by maintaining the cap above the gate as stated in the design criteria (Shaw, 2002)
- Ongoing diversion of surface water flows through the designated area away from the gate region
- Protection of well casings above grade (especially PVC well casings)

In March 2005 a major precipitation event in the Los Alamos area resulted in tremendous surface runoff in Mortandad Canyon. The PRB cap was severely altered due to surface erosion. The high-velocity runoff scoured the surface of the gate section eroding the cap and causing what appeared to be channeling or piping of surface water down into the PRB above Cells 2 and 3. The original surface design elevations were never restored, and the result has been substantial subsidence (2 to 3 ft) of the PRB surface, primarily above Cells 2 and 3.

## 5.1 PRB Performance Evaluation

Performance monitoring generally involves measurement of water levels, field parameters (oxidation-reduction potential [Eh or ORP], pH, DO, and conductivity), and inorganic constituents in the groundwater monitoring wells in the PRB and its vicinity (Gavaskar et al., 2000). To assess seasonal variations in a groundwater, the U.S. EPA suggests sampling wells at least every quarter and more frequently if possible. In a funnel-and-gate system, monitoring should include sampling of wells located upgradient, downgradient, and along the wing walls of the PRB. "No set number of monitor wells is required for a funnel-and-gate design; however, as many strategically located many wells as feasible is ideal. If a problem with PRB performance occurs, the solution is usually provided through an analysis of well data; consequently, the more wells, the better. The Mortandad Canyon PRB has a total of 16 sample wells (1 upgradient, 12 within the PRB, and 3 downgradient) used for monitoring the PRB performance. Figure 6 shows the relative locations of water sample ports in the PRB.

### *5.1.1 Monitoring Methodology*

The Mortandad Canyon PRB is a field-scale pilot project based on a multiple media concept and laboratory bench-scale treatability studies. The pilot project was developed as a proof of concept and not as a final corrective measure for Mortandad Canyon. As such, a Quality Assurance Project Plan (QAPP) was not required for this project. The methods used for various aspects of monitoring the PRB are outlined below.

#### *5.1.1.1 Sample Collection*

Traditional sampling methods that involve purging several well-casing volumes of water prior to collection should be avoided when collecting groundwater samples from the reactive cell or gate because such practices may capture water that represents a significantly lower residence time in the reactive cell. Rapid withdrawal of a water sample by any sampling method (e.g., a bailer) may draw water quickly from the upgradient direction, and such water may have been incompletely treated by the reactive medium. Analyzing a mixture of water from locations partially outside of the monitoring well screen could suggest higher levels of the target analytes

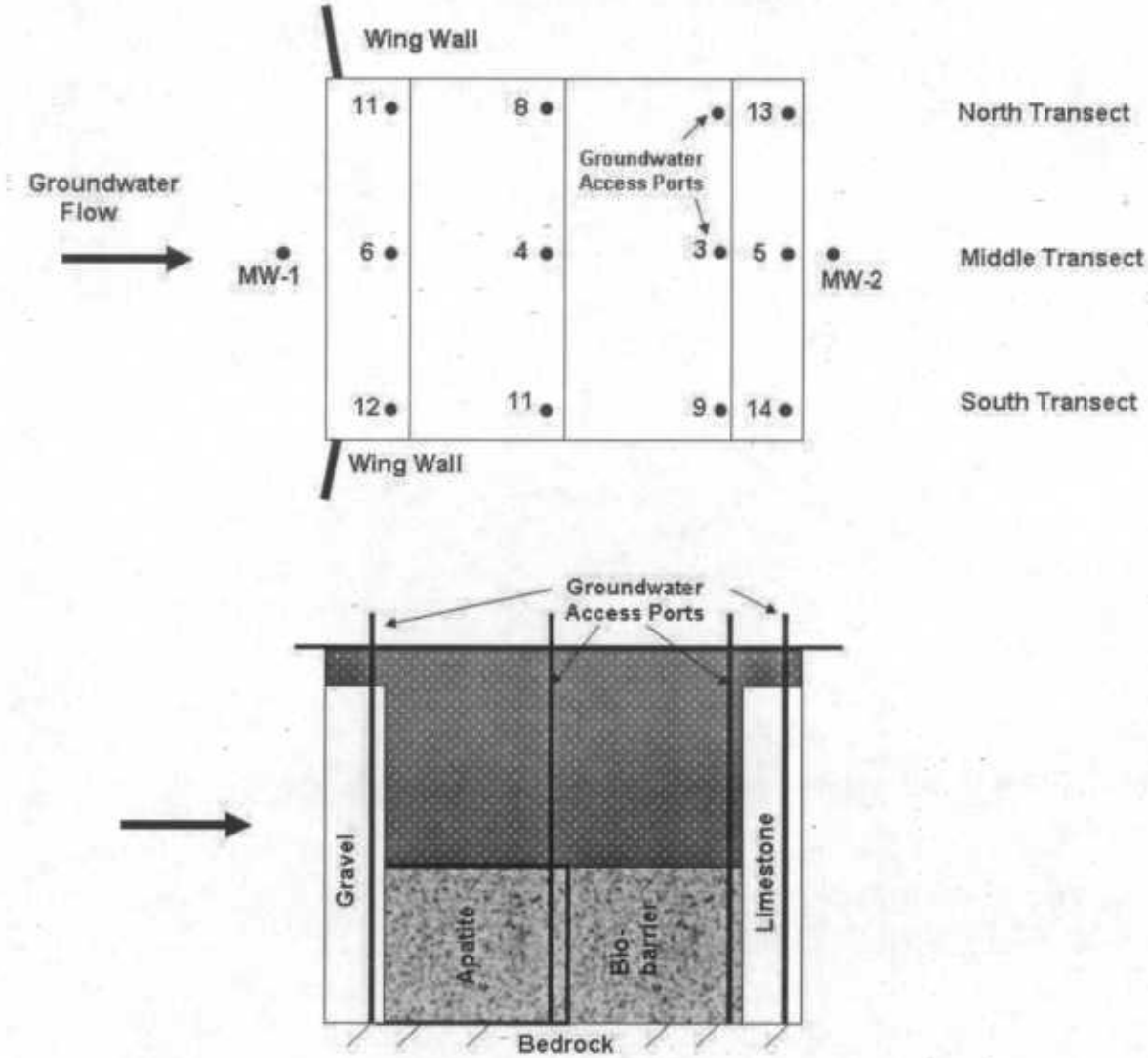


Figure 6

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**Schematic of Water Sampling Wells**

than actually exist (Gavaskar et al., 2000). The main precaution to be observed when obtaining a representative sample is to avoid creating a strong disturbance in the well. This can be caused, for example, by purging with a bailer or inserting a sampling tube repeatedly or too quickly.

An alternative sampling method known as "micropurging" is expected to be suitable for groundwater sampling in the PRB and its vicinity and yield representative water samples; this technique has been discussed by Kearl et al. (1994). Micropurging involves the removal of very small sample volumes at low flow rates to minimize disturbance within the PRB and results in a more representative sample. There are currently no guidelines on the amount or rate at which groundwater should be purged; therefore, these parameters should be determined on a case-by-case basis (ITRC, 2005). In general, flow rates should be less than 1 liter per minute (L/min), and in some cases less than 100 milliliters per minute (mL/min), depending on the transmissivity of the medium (Powell and Puls, 1997).

During all sampling events before 2005, Mortandad Canyon PRB water samples were collected using bailers. A peristaltic pump was used for the single 2005 sampling event. Wells were typically not purged during sampling except for the 2005 sampling event in which pre-purge and post-purge samples were collected. Sample collection using a bailer or standard peristaltic pump at high volume is less than optimal and can have an adverse effect on analysis results. Considering the drought conditions that have existed during much of the project, the hydraulic gradient and corresponding flow rates through the PRB have often been small to nonexistent, likely resulting in stagnant water being sampled at times.

#### *5.1.1.2 Sampling Frequency*

The frequency of sampling is site specific, but in general, samples should be collected at a frequency that captures seasonal and storm-related variations, changes related to installing the PRB, and hydrologic changes within the PRB over time (Liang et al., 2001). Based on this, the Mortandad Canyon groundwater elevations should be measured monthly; field parameters, COCs, and inorganic constituents should be measured quarterly.

#### 5.1.1.3 Sample Analysis

Although sampling parameters for a PRB may differ depending on the monitoring objectives (e.g., compliance vs. performance), sampling parameters generally fall into four broad categories:

- Field parameters
- Inorganic analytes
- Contaminants of concern
- Groundwater levels

Field parameters typically include water level, pH, temperature, redox potential (Eh), DO, alkalinity, specific conductance, turbidity, and salinity (ITRC, 2005). All Mortandad Canyon PRB sampling events measured each of these parameters with the exception of salinity. Field samples were collected, transported to a local laboratory facility and measured using mass spectrometry. Field parameter measurements should be conducted with a flow-through cell and monitoring instruments for continuous measurement to minimize interferences associated with the introduction of oxygen in the sample. Field instruments can also be employed as down-hole probes inside wells for collection of field parameter data (ITRC, 2005).

Sampling also included analysis of all target COCs and a comprehensive suite of inorganic analytes. All analyses were completed in accordance with U.S. EPA sampling guidelines. Periodic groundwater level measurements were performed manually.

## 5.2 Hydrogeologic Analysis

The hydrogeologic analysis of the Mortandad Canyon PRB relied on monitoring data collected from start up in February 2003 through September 2006. The monitoring data consist of periodic measured water levels and the results of slug tests on nearby alluvial monitor wells. Water level data were used to determine the site's piezometric profile and variability as well as to perform an analysis of hydraulic gradients across the PRB. Monitoring data were also

applied to compute estimated groundwater flow velocities both across the site and within segments of the PRB.

### 5.2.1 Hydrogeologic Monitoring

The most common problem with PRB installations is hydraulic plugging and/or bypass. Groundwater level data will clearly indicate the occurrence of hydraulic plugging; however, hydraulic bypass is much more difficult to identify and even more difficult to pinpoint. Potentiometric data is the easiest type of data to obtain that provides an indication of groundwater flow characteristics.

The two major objectives of PRB hydrogeologic monitoring are to determine the following:

- Groundwater flow pattern including velocity, gradient, and direction
- Extent of the groundwater capture zone

These data, along with porosity and hydraulic conductivity information, facilitate calculating groundwater flux and corresponding treated water volume.

Preliminary site characterization data indicated there would be major seasonal fluctuations in the groundwater levels within Mortandad Canyon. Water levels were measured manually on a monthly schedule from May 2003 through September 2003 and approximately weekly from March 2004 through June 2004. After that time, water level measurements occurred sporadically, with the most recent measurements made in September 2006. Figure 7 is a cross section showing the relative locations of the Mortandad Canyon PRB monitoring wells.

Water level data exist for seven of the eleven quarters since PRB start-up. Figure 8 illustrates the seasonal variation of groundwater levels with respect to the elevations of the aquitard and the top of the mineral apatite (Cell 2) and bio-barrier (Cell 3). This water level pattern is synonymous with the surface weather pattern (i.e., dry winters with minimal spring runoff/percolation followed by summer monsoonal rain creating a shallow groundwater level rise). As shown in Figure 8, in 2003, Los Alamos County was in the midst of drought conditions,

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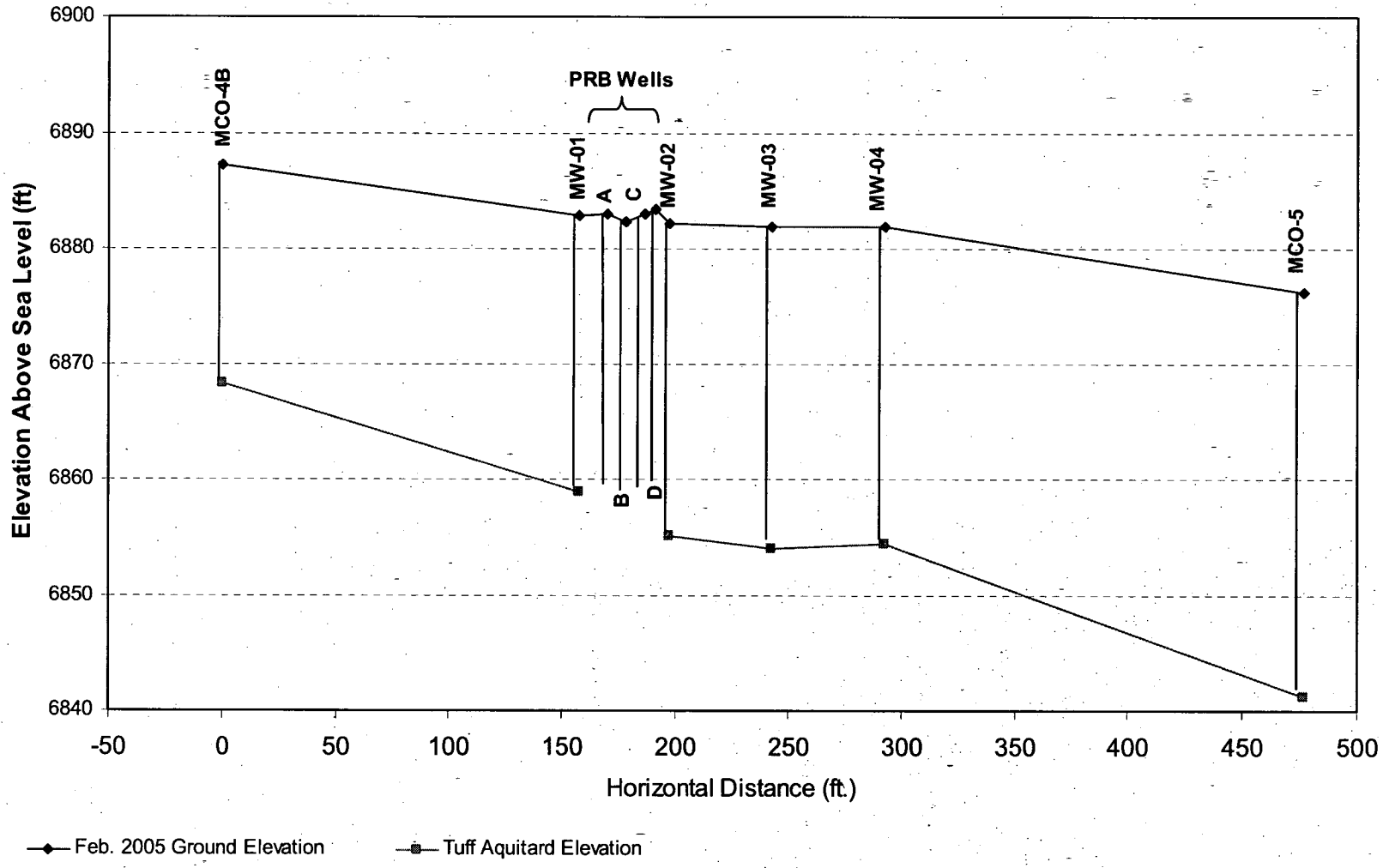


Figure 7

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**Cross Section Showing Well Locations**

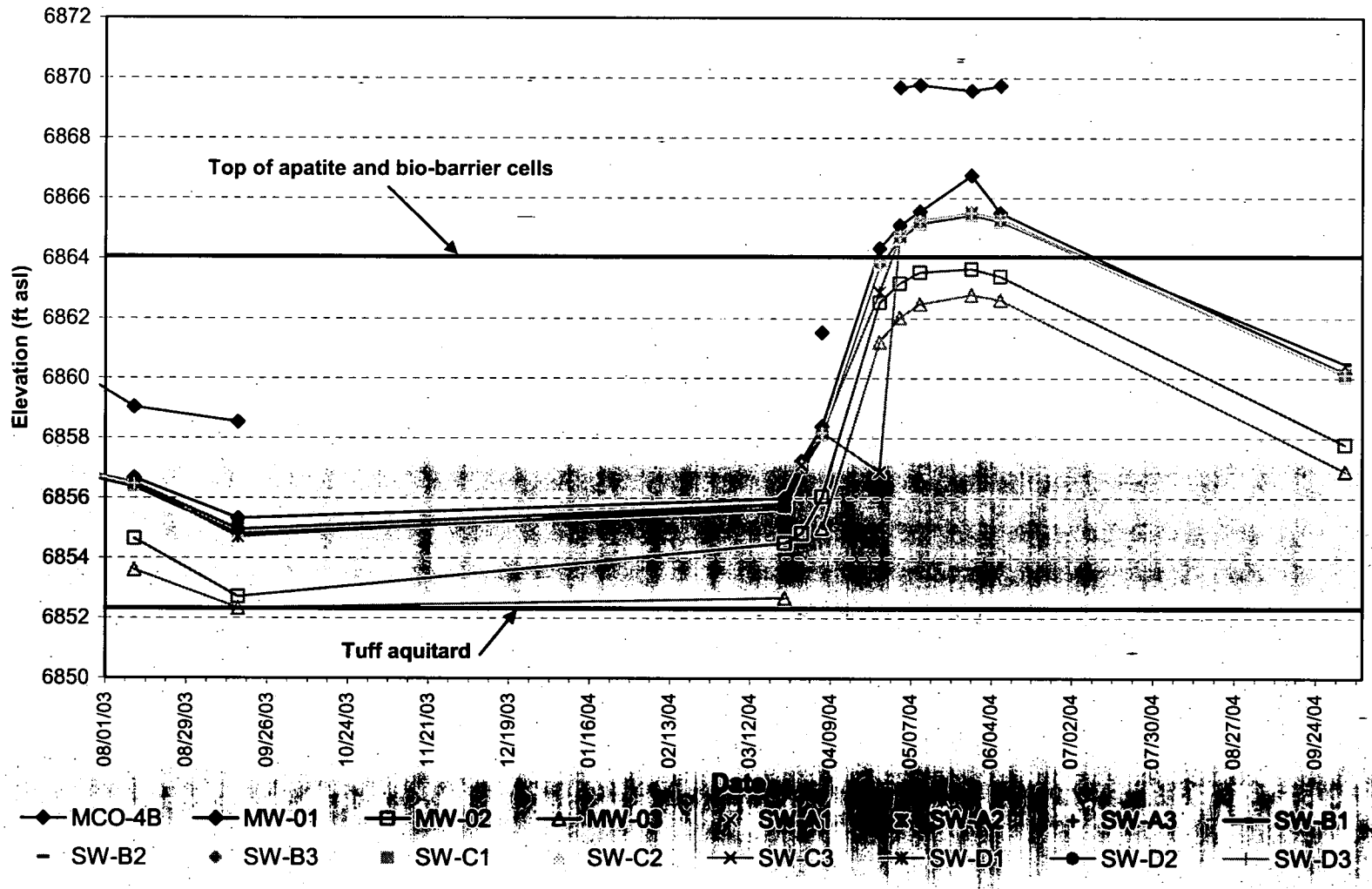


Figure 8

MORTANDAD CANYON PRB INVESTIGATION

**Mortandad Canyon Seasonal Groundwater Fluctuation**

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which resulted in very low groundwater levels and no significant flow through the barrier. By the spring of 2004, Cells 2 and 3 were saturated allowing the PRB to finally operate as designed.

### 5.2.2 Hydraulic Gradient, Velocity, and Flow Rate Across Site

Table 5 includes estimates, based data obtained on several different sampling dates, for the hydraulic gradients (*i*), velocities (*v*), and flow rates (*Q*) between the wells shown in Figure 7. Only those dates between April 2004 and September 2006 were analyzed because the alluvial aquifer had little or no flow during the drought conditions that existed prior to this time. For all dates shown except September 2006, the aquifer formation properties were used to calculate *i*, *v*, and *Q*. The wells measured in September 2006 spanned an area consisting primarily of the PRB; therefore, the PRB properties were used for these calculations.

Interestingly, the hydraulic gradient of the surface (0.023) is similar to the piezometric profiles, but the tuff aquitard is somewhat steeper (i.e., the alluvium becomes thicker down the canyon). From April 2004 to February 2005, the *i*, and thus *v*, and *Q* are consistent, indicating minimal disruption of the Mortandad Canyon shallow aquifer after the installation of the PRB.

Estimating the flow rate of water passing through the barrier is critical in evaluating the performance of a funnel-and-gate PRB. The performance criteria include hydraulic capture effectiveness, COC treatment, and longevity. The calculations shown in Table 5 assume all water flows through the minimum cross-sectional area (*A*) of the PRB (170 $ft^2$). In other words, the canyon groundwater gross flux is the same at any canyon cross section, including the PRB. This assumes there is no leakage through the funnel section or beneath the gate.

Table 6 presents values for horizontal groundwater velocities and corresponding residence times at the Mortandad Canyon PRB. The design criteria for residence time ($T_r$) is from the Mortandad Canyon PRB final design report (Shaw, 2002). LANL laboratory studies indicated that the bio-barrier (Cell 3) was the critical cell for residence time, requiring a minimum $T_r$ of 1 day to ensure remediation of perchlorate and nitrate. Based on this information, Cell 3 was sized to have a $T_r$ of 1.4 days at the highest predicted velocity through the cell.

## Table 5. Hydraulic Gradient, Velocity, and Flow Rate Estimates

| | Existing Surface | Tuff Aquitard | Sampling Date | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | 04/06/04 | 04/26/04 | 5/04 | 06/04 | 10/04 | 02/05 | 09/06 |
| Upgradient Well ID | MCO-4B | MCO-4B | MCO-4B | MW-01 | MCO-4B | MCO-4B | MW-01 | MCO-4B | MW-01 |
| Downgradient Well ID | MCO-5 | MCO-5 | MW-03 | MW-03 | MW-03 | MCO-5 | MCO-5 | MCO-5 | MW-02 |
| Horizontal distance (ft) between wells, *X* | 476.4 | 476.4 | 242.7 | 85.2 | 242.7 | 476.4 | 318.9 | 476.4 | 39.9 |
| Vertical water level fall (ft), *Y* | 11.1 | 27.1 | 6.52 | 3.11 | 7.29 | 13.39 | 9.72 | 16.17 | 4.88 |
| Average hydraulic gradient, $I = Y/X$ | 0.023 | 0.056 | 0.027 | 0.036 | 0.030 | 0.028 | 0.030 | 0.033 | 0.122 |
| Estimated saturated hydraulic conductivity, $K_s$ (ft/day)[a] | NA | NA | 30 | 30 | 30 | 30 | 30 | 30 | 134 |
| Estimated porosity, *n* | NA | NA | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.25 | 0.45 |
| Velocity, *v* (ft/day), where $v = K_s\, i/n$ | NA | NA | 3.2 | 4.4 | 3.6 | 3.4 | 3.7 | 4.0 | 36.4 |
| Cross sectional area, *A* ($ft^3$)[b] | NA | NA | 170 | 170 | 170 | 170 | 170 | 170 | 170 |
| Flow rate, *Q* ($ft^3$/day), where $Q = K_s\, i\, A$[c] | NA | NA | 137 | 186 | 153 | 143 | 155 | 173 | 2786 |

[a] From ESH-18 slug test results
[b] Use cross sectional area of MPRB
[c] Flow rate through MPRB minimum cross section

ft = Feet
NA = Not available
$ft^3$ = Cubic feet

## Table 6. Comparison of Design, Predicted, and Measured (Estimated) Velocity and Residence Time Values

| | PRB Cells | | | | Combined Distances | |
|---|---|---|---|---|---|---|
| | 1 (Gravel) | 2 (Apatite) | 3 (Bio-Barrier) | 4 (Limestone) | Entire PRB | Canyon Reach (MCO-4B to MCO-5) |
| Horizontal distance (ft) | 3 | 7 | 9 | 3 | 22 | 475 |
| Design criteria $T_r$ (days)[a] | 1 | 1 | **1** | 1 | 4 | NA |
| Predicted high flow $v$ (ft/day)[a] | 2.9 | 5.9 | 6.5 | 2.9 | NA | NA |
| Predicted average flow $v$ (ft./day)[a] | 1.9 | 1.9 | 2.1 | 1.9 | NA | NA |
| Predicted high flow $T_r$ (days)[a, b] | 1.2 | 1.2 | 1.4 | 1.2 | 4.6 | NA |
| Predicted average flow $T_r$ (days)[a, c] | 1.8 | 3.6 | 4.2 | 1.8 | 11.2 | NA |
| Estimated $v$ (ft./day)[d] | 2.9 | 3.7 | 3.7 | 2.9 | 2.9 | 3.7 |
| Estimated $T_r$ (days)[d, e] | 1.0 | 1.9 | 2.4 | 1.0 | 6.3 | NA |

[a] Source: Shaw (2002)
[b] Calculated by dividing the horizontal distance by the predicted high flow velocity
[c] Calculated by dividing the horizontal distance by the predicted average flow velocity
[d] Source: Table 5 ( this report)
[e] Calculated by dividing the horizontal distance by the estimated velocity

**Bold** indicates critical design criteria that must be achieved

$T_r$ = Residence time for specified horizontal distance (days)
NA = Not available
v = Velocity (ft/day)

The water level data for all sampling events except September 2006 indicate an average steady-state horizontal groundwater velocity between monitoring wells MCO-4B and MCO-5 of approximately 3.7 ft/day. This estimated velocity is greater than the predicted high velocities for Cells 1 and 4 and would appear to be cause for concern regarding adequate $T_r$ for PRB cells. One consideration, however, is that the hydraulic gradient and corresponding velocity estimates were calculated using saturated hydraulic conductivity ($K_s$) and porosity ($n$) values obtained during site characterization. Even in the relatively homogeneous aquifer at Dover Air Force Base where a pilot-scale funnel-and-gate PRB was installed, hydraulic conductivity varied by more than an order of magnitude from well to well (ITRC, 2005). If, in fact, the velocity through Mortandad Canyon is 3.7 ft/day, this is still less than the predicted high velocity through Cell 3 of 6.5 ft/day and results in a $T_r$ of 2.4 days which is greater than the 1-day design criteria.

However, the 3.7 ft/day velocity is greater than the predicted high velocities for Cells 1 and 4 of 2.9 ft/day. In accordance with Darcy's Law, this is problematic in that any sustained velocity above 2.9 ft/day will result in a bottleneck at Cells 1 and 4. A bottleneck would appear as a drop in elevation from the bottleneck location to the next downgradient sample well creating a groundwater mound within the PRB.

Table 7 shows varying average linear velocity flow rates across the site and within the PRB over time. These rates were computed by using gradients determined from water level measurements and applying Darcy's Law with hydraulic conductivity values and assumed porosity values obtained from various sources as noted. The equation for computing average linear velocity, based on Fetter (1994), is as follows:

$$V_x = \frac{K}{n_e}\frac{dh}{dl}$$

where

$V_x$ = average linear velocity of groundwater flow

$K$ = hydraulic conductivity

$n_e$ = effective porosity

$dh/dl$ = the hydraulic gradient

## Table 7. PRB Vicinity Average Linear Velocity Rates

| Canyon Reach | Velocity Rate (ft/day) [a] | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 2003 | | | | | 2004 | | | | | | | | | 2006 |
| | May | Jun | Jul | 8/11 | 9/16 | 3/24 | 3/30 | 4/6 | 4/26 | 5/3 | 5/10 | 5/28 | 6/7 | 10/4 | 9/6 |
| MCO-4B to MW-01 | --- | --- | --- | --- | 3.6 | --- | --- | 3.5 | --- | 5.1 | 4.7 | 3.2 | 4.7 | --- | --- |
| MW-01 to SW-A1 | --- | --- | --- | 2.8 | 6.1 | 3.4 | 2.6 | 3.6 | 8.2 | 6.7 | 6.1 | 23.8 | 3.6 | 0.7 | 4.1 |
| MW-01 to SW-A2 | --- | --- | --- | 3.1 | --- | --- | 2.7 | 3.7 | 8.6 | 6.9 | 6.3 | 24.5 | 3.7 | 0.9 | 4.3 |
| MW-01 to SW-A3 | --- | --- | --- | 2.5 | 5.3 | 3.0 | 2.1 | 3.2 | 7.7 | 6.0 | 5.6 | 22.6 | 3.2 | 0.6 | 3.8 |
| SW-A1 to SW-B1 | 5.9 | 5.5 | 4.9 | 4.9 | 6.5 | 5.2 | 4.9 | 5.2 | 4.2 | 3.3 | 2.9 | 2.6 | 3.3 | –10.7 | 1.6 |
| SW-A2 to SW-B2 | 3.8 | 2.5 | 2.2 | 1.8 | --- | --- | 1.8 | 2.2 | 2.2 | 2.2 | 2.2 | 2.5 | 2.8 | 1.8 | 1.8 |
| SW-A3 to SW-B3 | 2.7 | 2.7 | 2.7 | 2.3 | 4.7 | 2.7 | 2.7 | 2.7 | 2.7 | 3.4 | 2.7 | 2.3 | 3.0 | 2.7 | 1.0 |
| SW-B1 to SW-C1 | –2.4 | –2.4 | –2.0 | –1.6 | –2.0 | –2.4 | –2.7 | –2.4 | –0.5 | 0.2 | 0.9 | 0.9 | 0.9 | 15.8 | 2.0 |
| SW-B2 to SW-C2 | –2.9 | –1.8 | –1.4 | –1.1 | –1.4 | –1.1 | –1.8 | –1.4 | –1.8 | –1.4 | –1.8 | –2.1 | –1.8 | –1.1 | –1.8 |
| SW-B3 to SW-C3 | –2.0 | –2.0 | –2.0 | –1.7 | –2.0 | –2.4 | –2.7 | –2.0 | --- | –2.7 | –2.0 | –1.7 | –2.0 | –2.7 | –0.7 |
| SW–C1 to SW–D1 | –64.6 | –3.4 | –3.4 | –4.0 | --- | –4.0 | – | –3.4 | 56.0 | –4.6 | –6.4 | –4.6 | –5.2 | –4.6 | –8.3 |
| SW–C2 to SW–D2 | –62.0 | 1.9 | 1.3 | 1.3 | 0.6 | 1.3 | --- | 1.3 | 0.6 | 0.6 | 0.6 | 1.3 | 0.6 | 0.0 | –1.9 |
| SW–C3 to SW–D3 | 2.4 | 3.0 | 3.0 | 3.0 | --- | | --- | 2.4 | --- | 1.0 | –1.0 | 0.3 | 0.3 | 2.4 | –0.3 |
| SW–D2 to MW–02 | --- | --- | --- | 66.4 | --- | 46.8 | --- | 76.6 | 48.6 | 56.2 | 60.9 | 66.8 | 68.2 | --- | --- |
| MW–02 to MW–03 | --- | --- | --- | 5.3 | --- | 9.4 | --- | 5.4 | 6.7 | 5.9 | 5.4 | 4.4 | 4.0 | --- | --- |

[a] Velocity computations assume the following:

K upgradient of PRB is the avgerage of the MCO–4B slug test and PRB–2 slug test results; PRB interior parameters as defined below; downgradient K = PRB–2 slug test results.
Porosity of alluvium = 0.25 (estimated); Porosity of barrier materials (gravel, apatite, limestone) = 0.5 (Shaw, 2002); Porosity of barrier materials (bio) = 0.45 (Shaw, 2002)
Aquifer max K (PRB–2) =2.05E–02 cm/s = 58.11 ft/day (Shaw, 2002); Aquifer min K (PRB–6) = 6.47E–05 cm/s = 0.18 ft/day (slug test results; IT Corp, 2001)
K for barrier materials = 4.75E–02 cm/s = 134.65 ft/day (Spitz and Moreno, 1996 [App. B, low range of K for gravel])
MCO–4B K = 1.06E–02 cm/s = 30.05 ft/day (ESH–18 slug test results)

--- = Not measured
Shading indicates negative velocities.

Negative velocities indicate zones within the PRB where negative gradients result in computed velocities indicating groundwater flow in the upstream direction, diametrically opposed to the normal direction of flow. This reverse flow condition is indicative of hydraulic problems within the PRB that result in irregular and preferential flow patterns rather than a continuous through-flow pattern as envisioned in the PRB design. Table 7 shows that this situation is persistent throughout the period of record between Cell 2 (apatite) and Cell 3 (bio-barrier) in rows 2 and 3 (the middle and southern transects). Some of the 2003 and early 2004 data may be suspect because of extremely low water levels due to drought conditions. After the water levels rose in April 2004, normal groundwater flow conditions should exist. After May 2004, it is interesting to note that reverse flow persists in rows 2 and 3 of Cell 3, but downstream flow begins to occur in row 1 (the northern transect) and persists thereafter.

These data suggest that preferential flow is occurring along the northern edge of the bio-barrier cell and normal flow is blocked off in the center and southern parts of the cell. Remarkably though, at the transition between Cell 3 (bio-barrier) and Cell 4 (limestone), reverse flow seems to be most persistent in row 1 while normal downstream flow usually is observed in rows 2 and 3. However, the most recent measurements in September 2006, which occurred under fully saturated conditions, show reverse flow occurring in all three rows at the interface between the bio-barrier and the limestone cell. These data indicate problems with hydraulic performance within the PRB, mostly associated with the transitions to and from the bio-barrier cell. The fact that these abnormal flow patterns are persistent throughout the data record suggest that they have not been affected by the subsidence event that occurred in March 2005.

### *5.2.3 Piezometric Profiles*

Figures 9, 10, and 11 are graphical representations of the 2003, 2004, and 2005–2006 groundwater hydraulic profiles, respectively, in the vicinity of the Mortandad Canyon PRB. These figures show groundwater level cross sections of the middle longitudinal well transect shown in Figure 6. Groundwater levels in the northern and southern transects are very similar.

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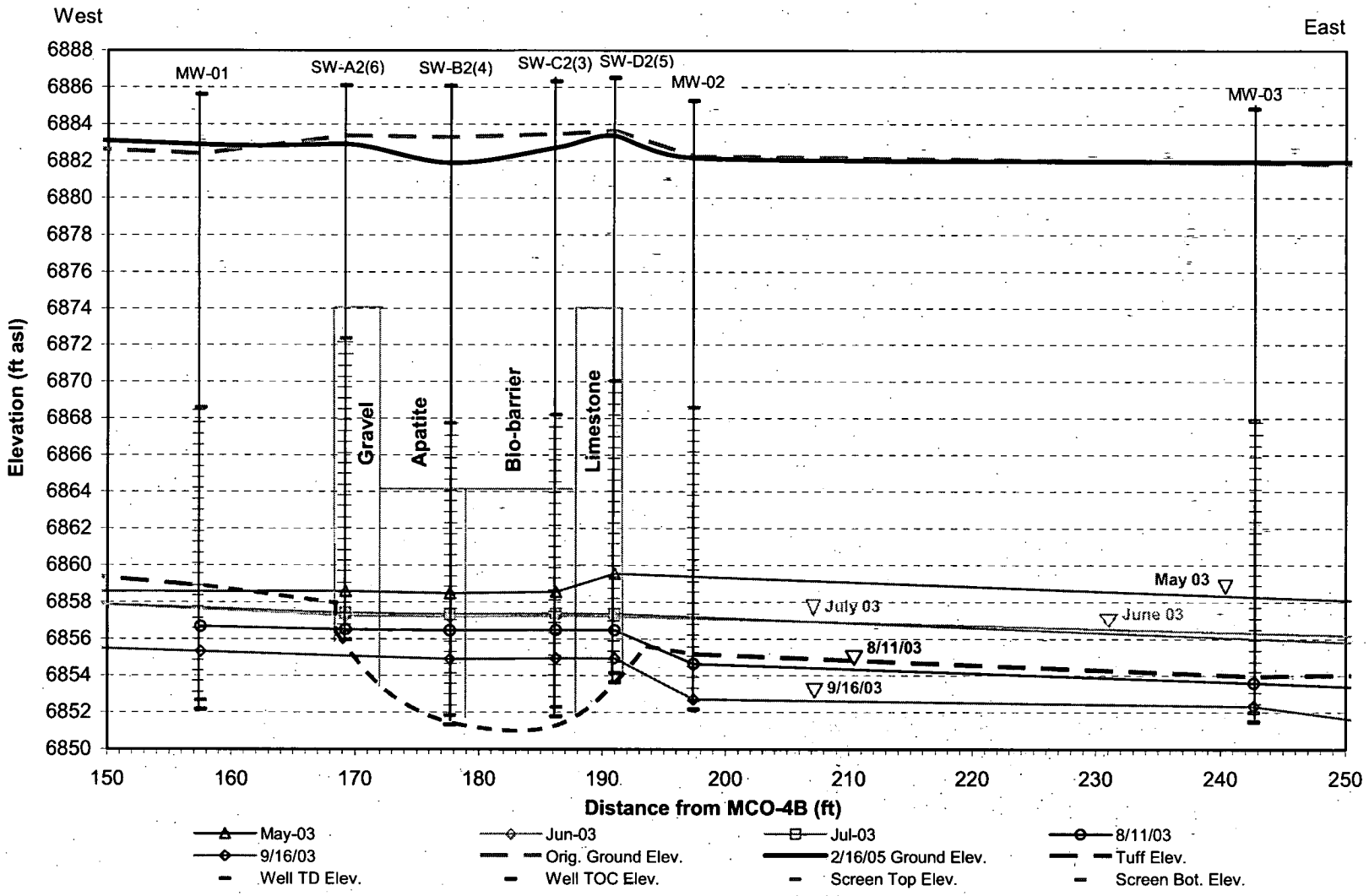


Figure 9

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**2003 PRB Water Levels**

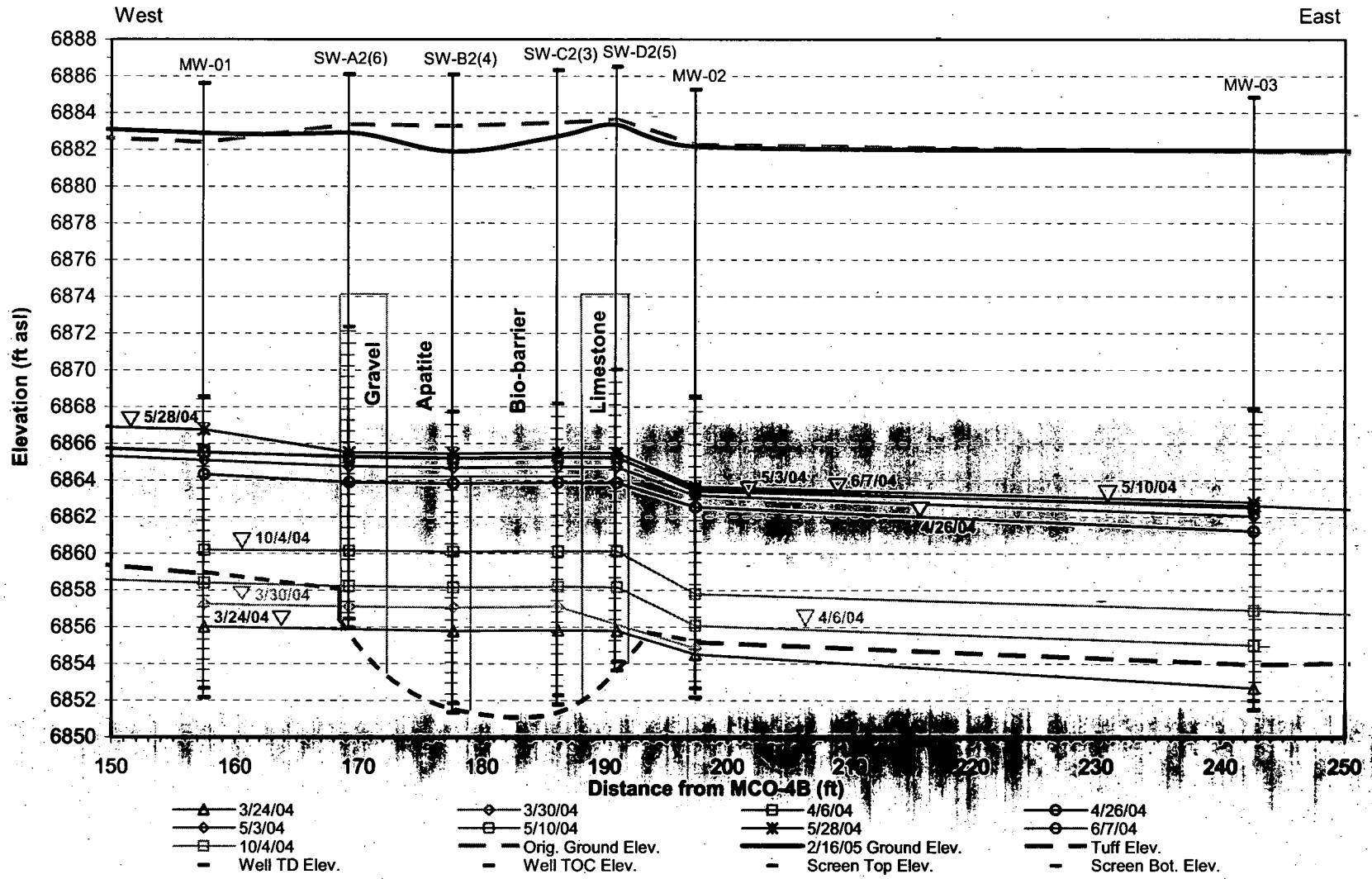


Figure 10

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MORTANDAD CANYON PRB INVESTIGATION

**2004 PRB Water Levels**

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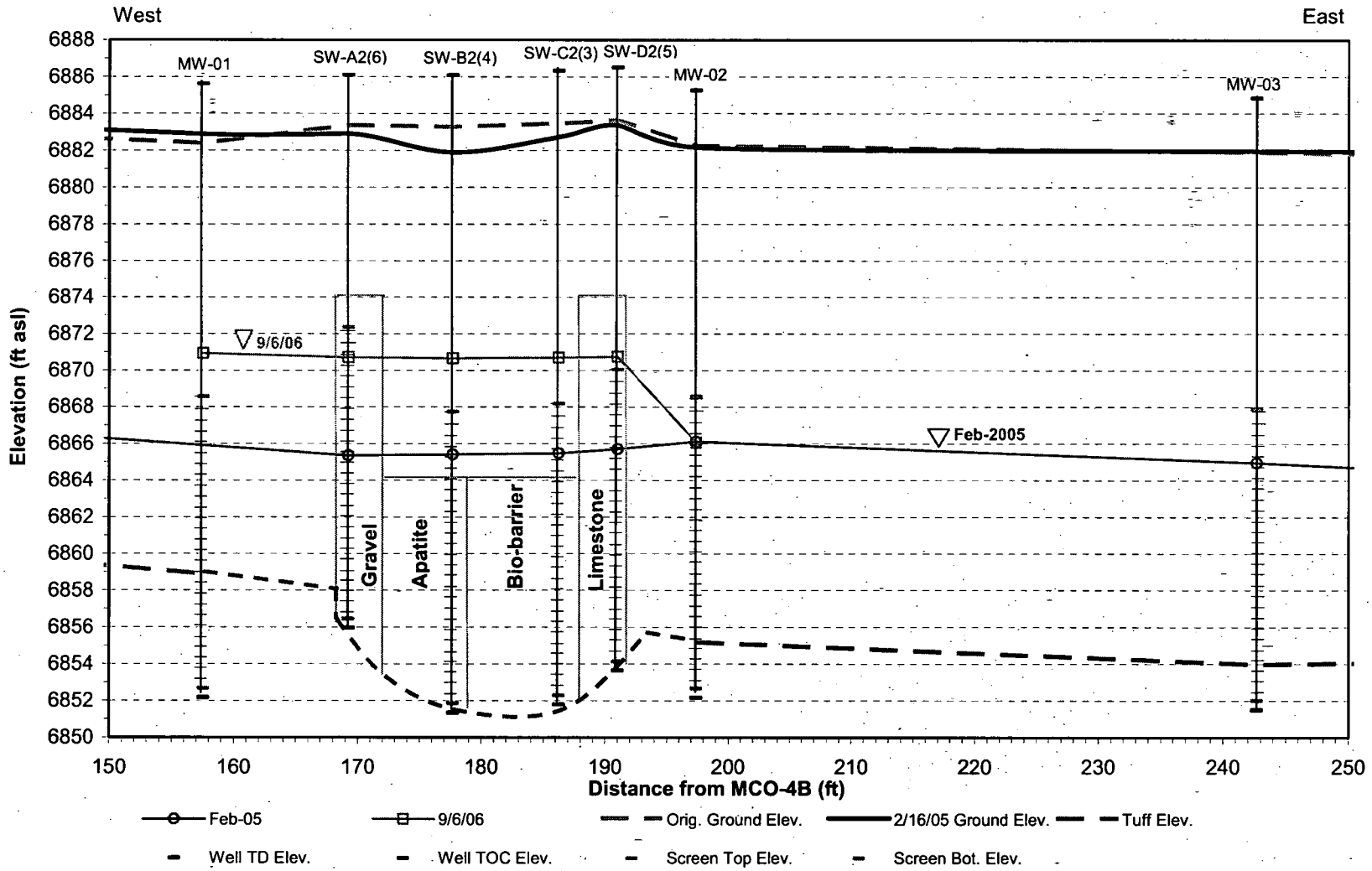


Figure 11

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MORTANDAD CANYON PRB INVESTIGATION

**2005–2006 PRB Water Levels**

The water levels for 2003 sampling dates shown in Figure 9 begin to show a notable drop in elevation head (1.9 ft) from sample port 5 (SW-D2) in Cell 4 (limestone) to the next well downgradient of the PRB, MW-02. This indicates mounding of water within the PRB. The 2004 water levels (Figure 10) show a rising water table with a flat gradient across the PRB followed by a similar drop in groundwater elevation between sample port 5 and MW-02, again signifying some mounding within the PRB. The water level continued to rise in 2005 (Figure 11); however, the trend in elevation drop from Cell 4 to MW-02 disappeared. Following a very wet summer season in 2006, Figure 11 shows a further rise in the water table and a considerable drop in groundwater elevation of 4.7 ft from sample port 5 to MW-02. With the exception of the February 2005 sampling event, there is a consistent pattern of flat hydraulic gradients across the PRB followed by an elevation drop downgradient of the PRB. This elevation drop appears to increase over time.

Some mounding is expected in funnel-and-gate PRBs because of the narrowing of the cross-sectional flow area. As previously mentioned, the potential problems associated with mounding groundwater include the following:

- Higher upgradient water level increases the pressure head across funnel joints and bottom seals.
- Water levels that rise into the soil above Cells 2 and 3 can induce/increase settlement and transport contaminants downward into the PRB when water levels subside.
- Short circuiting of water can occur from Cell 1 to Cell 4 via the soil above Cells 2 and 3.
- Preferential flow paths through the media can be induced by higher pressures.
- A worst case scenario could result in groundwater surfacing upgradient or above the PRB.

The initial impact of the PRB installation to Mortandad Canyon groundwater flow appears minor. The canyon hydraulic gradient is affected only slightly in the PRB vicinity. In 2003, a slight mounding of water in the PRB occurred, likely due to the transition from Cell 4 to the downgradient native alluvium. During the next 2 years, the water table rose steadily during the spring/summer seasons and showed slight declines during the fall. Table 5 shows the estimated hydraulic gradients in the PRB vicinity at various groundwater levels during 2004 through 2006.

The early (2003) drought conditions, coupled with the limited amount of data collected to date, makes it difficult to assess the PRB performance. The Mortandad Canyon PRB was designed to operate under saturated conditions, but it was not until the summer of 2004 that water levels finally increased enough to begin saturating Cells 2 and 3. Fluctuating groundwater levels will have only minor impacts on Cells 1, 2, and 4; however, Cell 3 operation requires sustained saturation. As a bio-reactor, Cell 3 relies on microorganisms to degrade the nitrate and perchlorate. The microorganisms need an anaerobic environment to survive. More specifically, the microorganisms cannot survive with fluctuating temperature and oxygen levels caused by oscillating saturated and unsaturated conditions.

## 5.3 Assessment of COC Removal Effectiveness

As contaminated groundwater moves through the PRB, changes in the native inorganic species in the groundwater can indicate trends in the groundwater geochemistry. Most PRBs constructed to date use ZVI media; consequently, the literature focuses on geochemical changes due to ZVI treatment. Because of its design, the Mortandad Canyon PRB will affect groundwater geochemistry differently than ZVI-based PRBs; however, the basic treatment principles are the same. Groundwater constituents are removed by ordinary physical, chemical and/or biological means. The Mortandad Canyon PRB uses all three removal mechanisms. Details regarding the geochemical and biological processes expected to occur within each of the Mortandad Canyon PRB media were discussed in Section 2.6.1.

The goal of the Mortandad Canyon PRB is to lower the COCs to acceptable levels. Table 8 provides a summary of the groundwater data and treatment goals in Mortandad Canyon.

**Table 8. Summary of COCs in Mortandad Canyon Groundwater**

| Constituent | Contaminant of Concern Level[a] | | |
|---|---|---|---|
| | Measured | DOE Action Level | LANL Treatment Goal |
| Strontium-90 | 80 | 8 | [illegible] |
| Plutonium-238 | 1.182 | 1.6 | 1.0 |
| Plutonium-239, 240 | 0.61 | 1.2 | 0.2 |
| Americium-241 | 1.53 | 1.2 | 1.2 |
| Nitrate (N) | 5.7[b] | 10[b] | 10.0 |
| Perchlorate | 120–150[c] | 4[c] | 10 |

[a] Given in picocuries per liter (pCi/L) unless otherwise noted.
[b] Milligrams per liter (mg/L)
[c] Parts per billion (ppb)

A comparison of upgradient and downgradient COC levels indicates if the barrier is working; further analysis of the canyon groundwater chemistry can provide more insight into PRB operation and longevity. As groundwater moves through the PRB, changes in inorganic species and field parameters such as pH, DO, and conductivity can be compared to modeling results. Core sampling can be used to verify precipitate forms and levels.

The locations of the sample ports in each cell are near the downgradient interface with the next cell; consequently, an important consideration when analyzing the data in graphical form is the potential influence of the downgradient media on the results. For example, a sample taken from the port in Cell 2 might inadvertently draw in water from Cell 3. This problem is magnified when the hydraulic gradient is flat or negative, as was often observed in the Mortandad Canyon PRB based on water level data. As discussed earlier, sampling methods that rely on the use of bailers or peristaltic pumps could also draw water from the downgradient cell.

Figure 12 shows changes in pH across the barrier through the middle transect. The pH decreases from more than 7.5 to almost 6 in Cells 2 and 3, then rises back to 7.5 in the

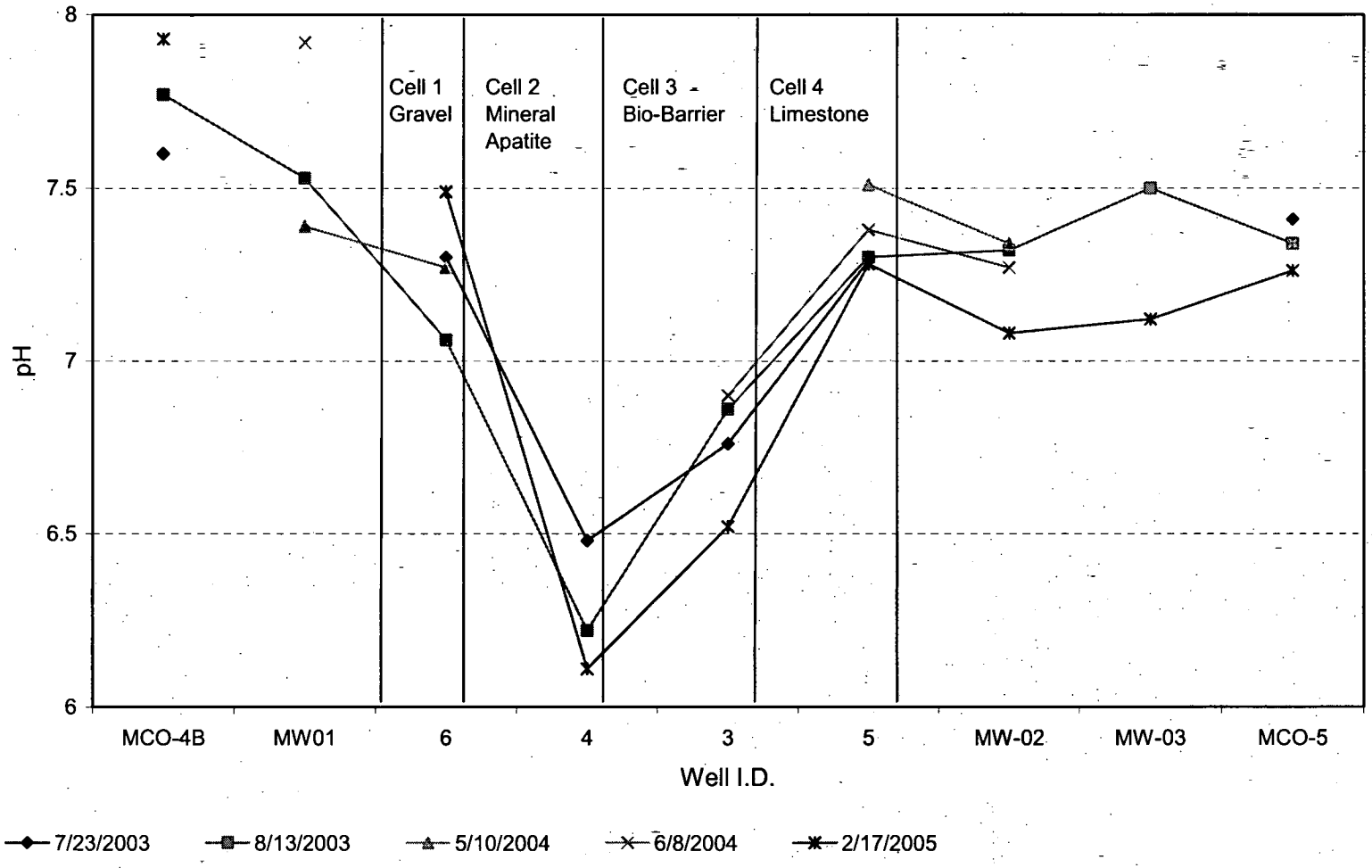


Figure 12

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MORTANDAD CANYON PRB INVESTIGATION

**Change in pH Across the PRB**

limestone cell (Cell 4). A drop in pH in Cell 3 (bio-barrier) was expected as a result of the formation of mild organic acids due to biological activity; however, it was anticipated that the pH in Cell 2 (apatite) would be buffered by the calcium phosphate rock and thus would not decline. It seems likely that water from the bio-barrier (Cell 3) was inadvertently collected during the sampling of sample port 4 in Cell 2, thus causing the low pH reading. Considering the proximity of sample port 4 to the bio-barrier zone and the flat, sometimes negative hydraulic gradients within the PRB, this is very plausible. After the groundwater passes through the bio-barrier, the pH is increased to near-neutral by Cell 4 (limestone), as designed.

Figure 13 shows a steep decline in DO across Cells 2 and 3 followed by a return to upgradient DO levels in Cell 4. As the groundwater flows past the apatite and bio-barrier, redox becomes more reducing and oxygen is consumed in the process. Most of the DO consumption is likely due to the bio-barrier region becoming anaerobic, as designed. Decreased pH and DO levels indicate that microbial reduction of perchlorate and nitrate is occurring. This is illustrated in Figures 14 and 15, which show the removal of nitrate and perchlorate across the PRB for various sampling events.

During the reduction of nitrate the release of ammonium ion ($NH_4^+$) and nitrogen gas ($N_2$) byproducts occurs. Nitrogen gas was not measured; however, Figure 16 shows the increase in $NH_4^+$. The highest ammonium ion level is associated with Cell 2 (apatite), which reaffirms the influence of sampling procedure and/or the occurrence of flat and negative flow gradients within the PRB. The high level of $NH_4^+$ in sample port 4 is attributable to the reactions occurring in Cell 3, the bio-barrier.

Another measure of the presence of microbial degradation conditions is the total organic carbon (TOC) level. Figure 17 shows the increase in TOC related to the bio-barrier. This is another positive sign that organic carbon is readily available for the microorganisms to assist with $NO_3$ and $ClO_4$ degradation. The highest TOC concentration appears to occur in Cell 2, but again this is likely the result of inadvertent sampling of downstream water.

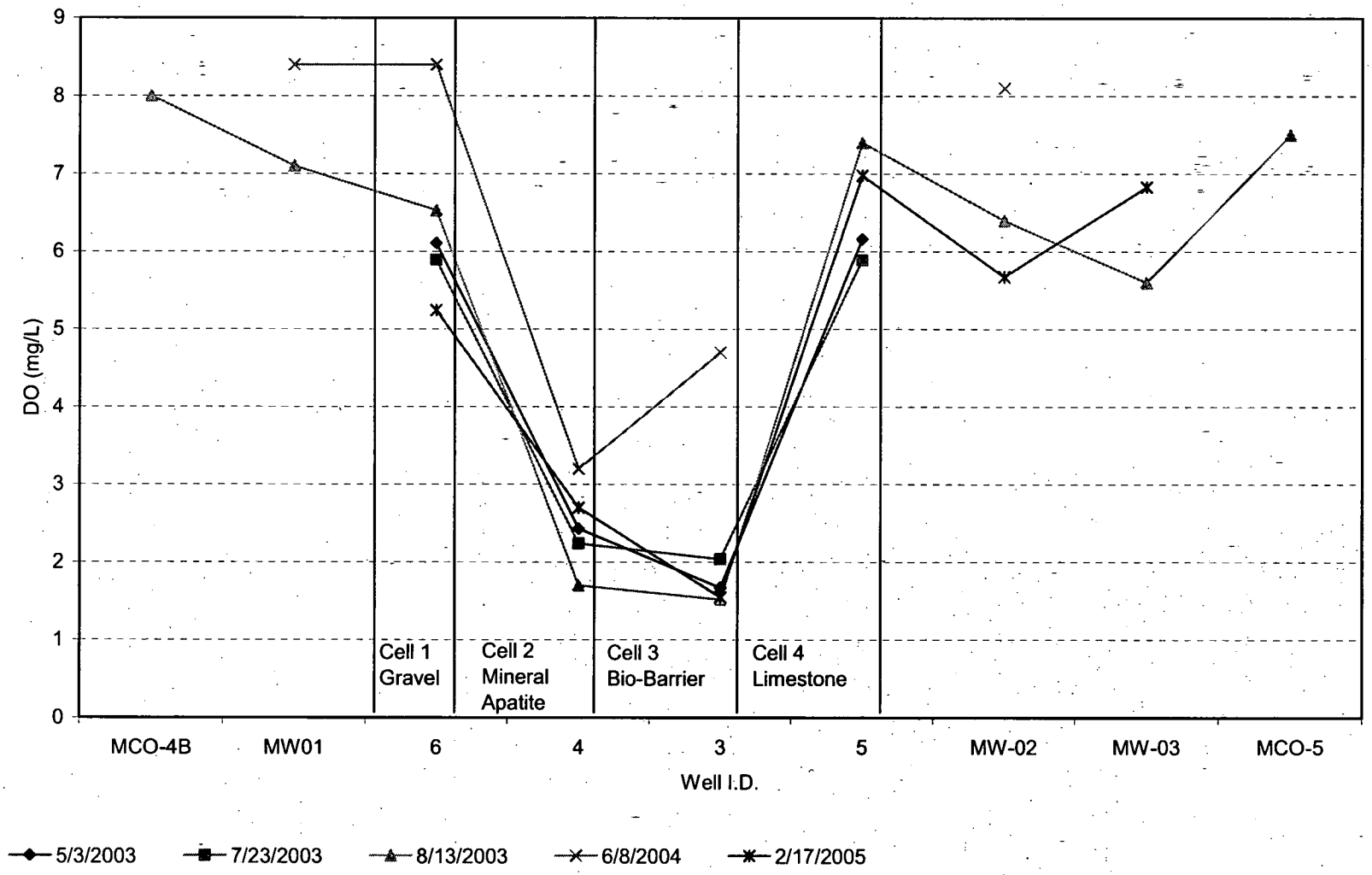


Figure 13

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**Dissolved Oxygen Across the PRB**

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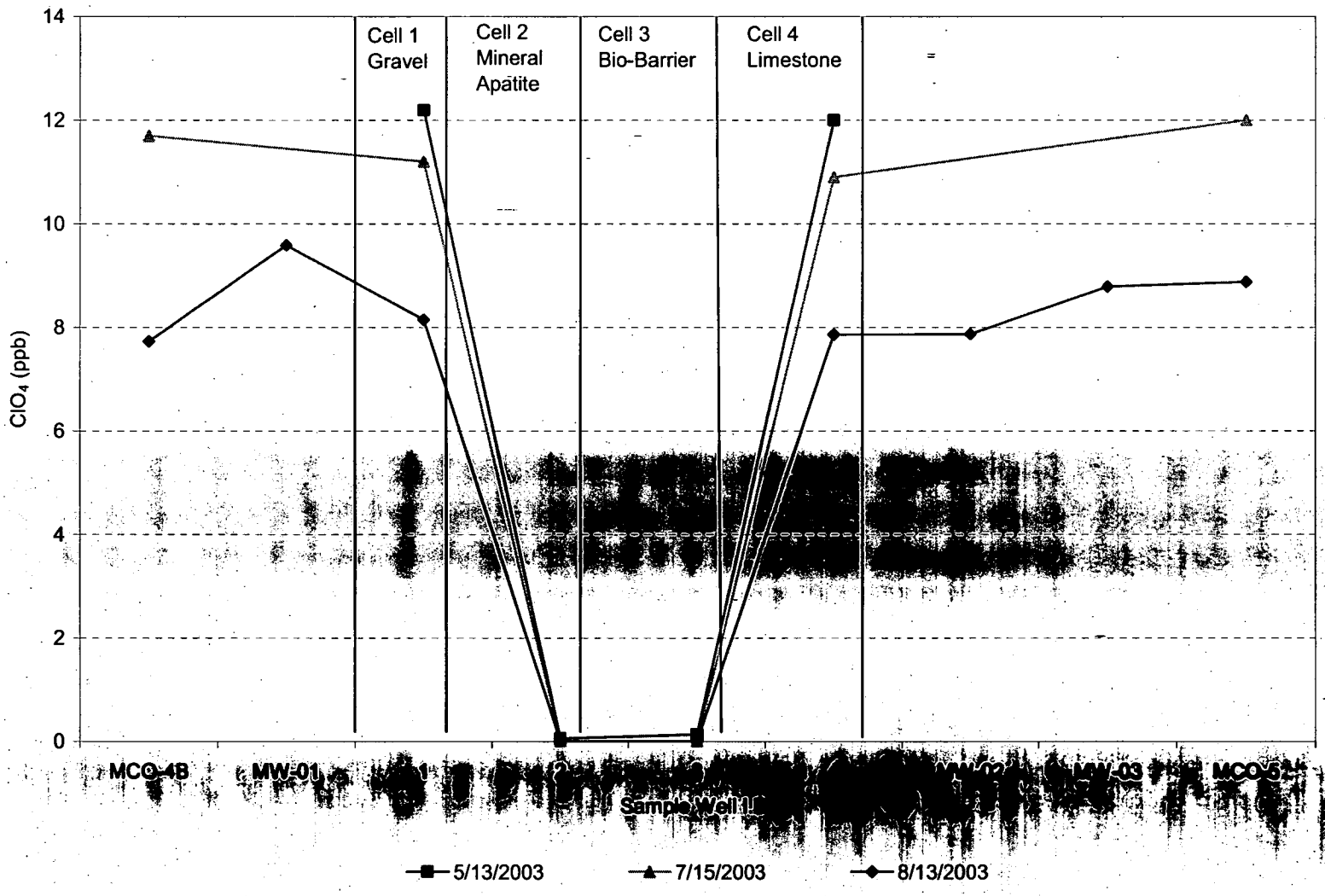


Figure 14

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**Nitrate Across the PRB**

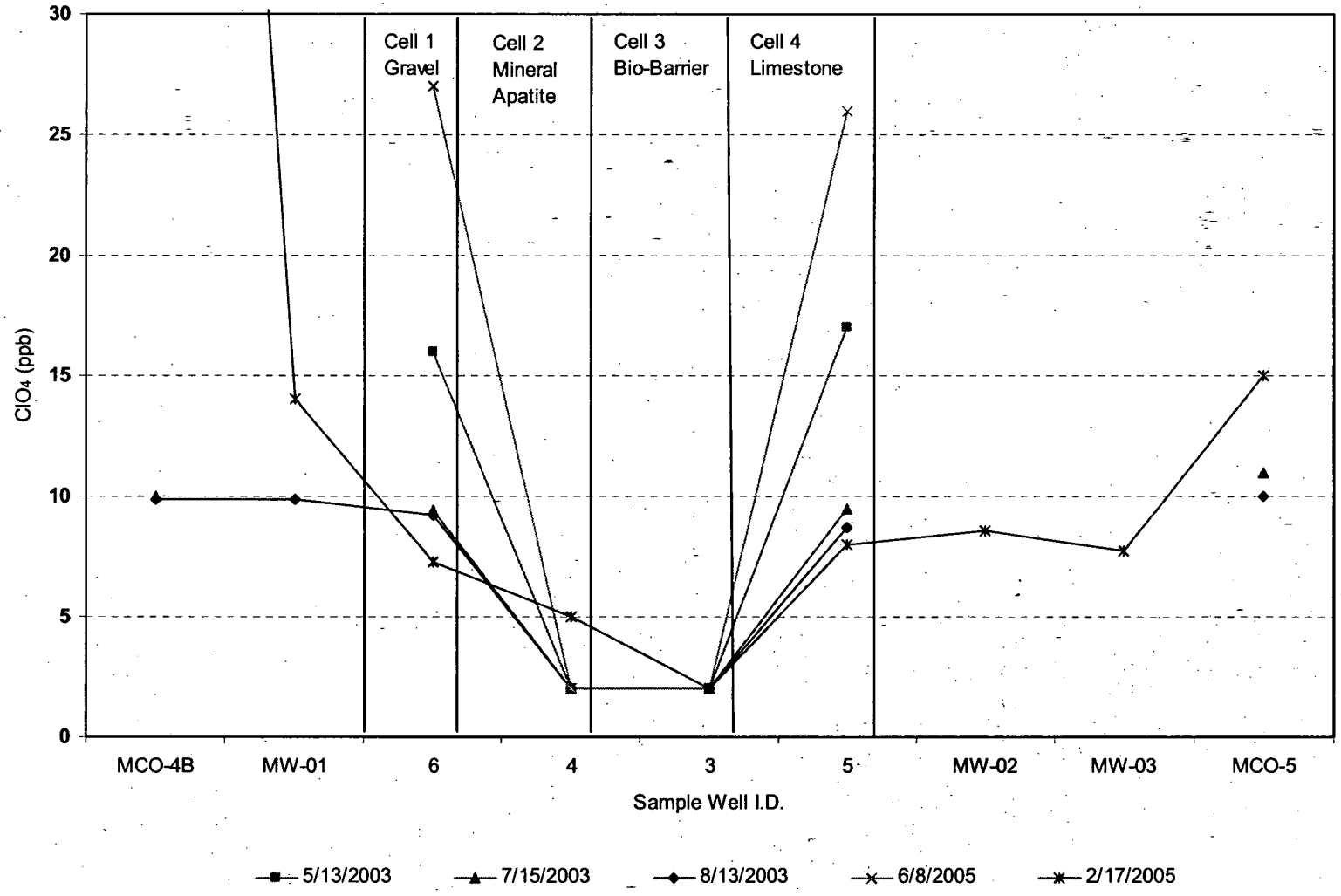


Figure 15

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MORTANDAD CANYON PRB INVESTIGATION

**Perchlorate Across the PRB**

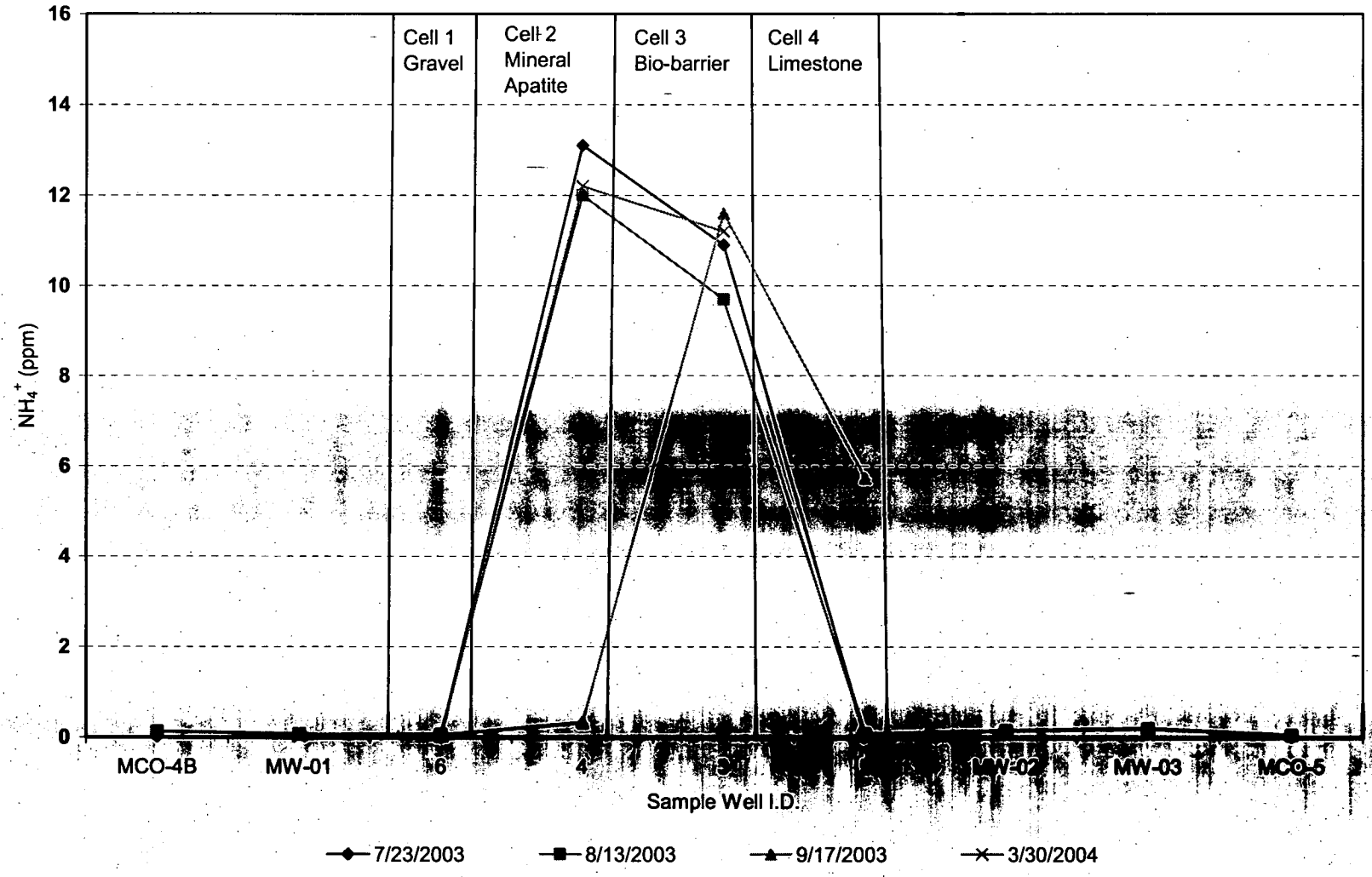


Figure 16

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**Ammonium Ion Across the PRB**

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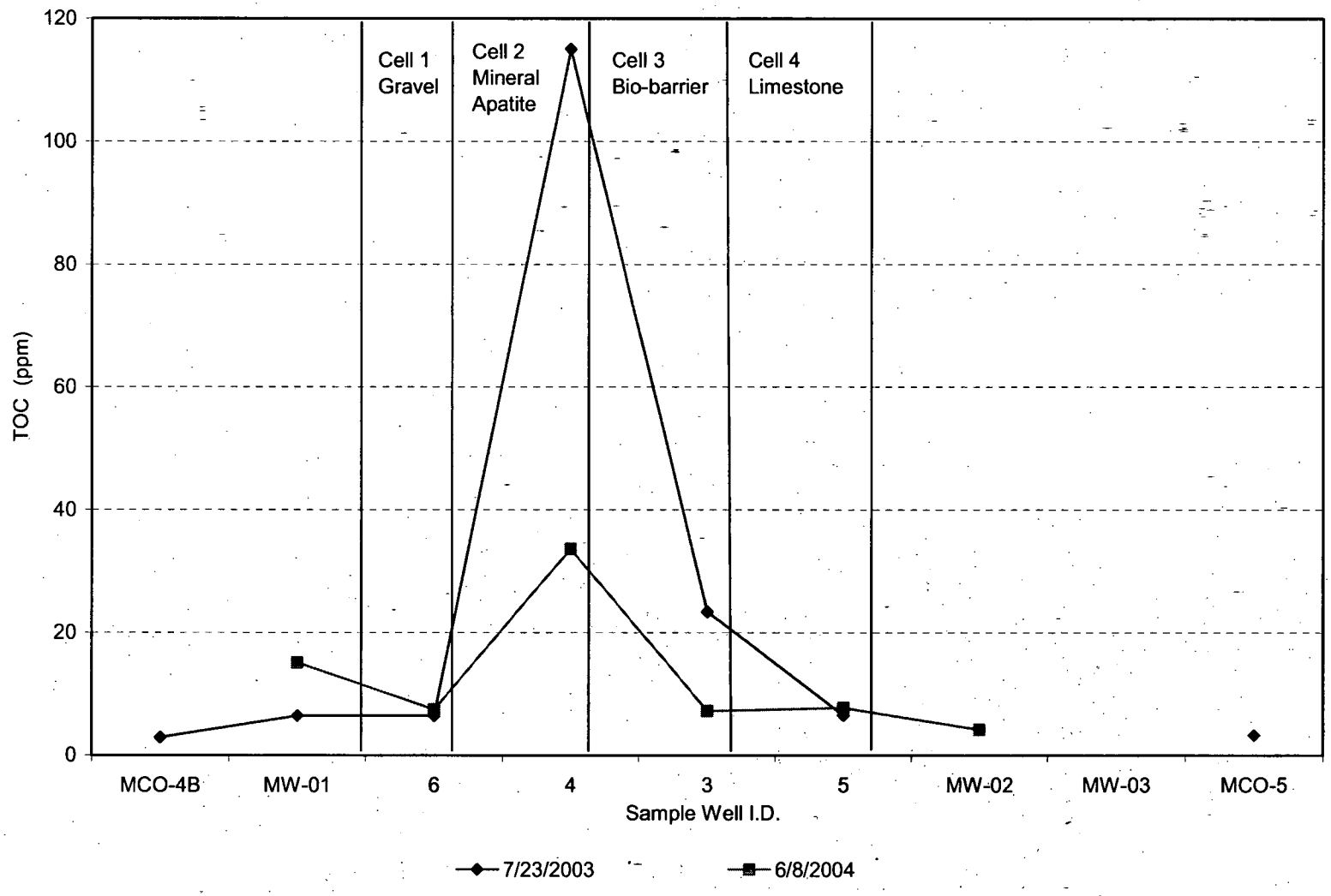


Figure 17

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MORTANDAD CANYON PRB INVESTIGATION

**Total Organic Carbon Across the PRB**

Anaerobic biodegradation of perchlorate proceeds as follows:

$$ClO_4^- \rightarrow ClO_3^- \rightarrow ClO_2^- \rightarrow Cl^- + O_2$$

Because chlorite ($ClO_2$) is toxic to bacteria, the key to bacterial growth using chlorate ($ClO_3$) and perchlorate ($ClO_4$) is the presence of chlorite dismutase, a nonrespiratory enzyme that catalyzes the disproportionation of chlorite to $O_2$ and $Cl^-$. Rates of chlorite disproportionation by chlorite dismutase are greater than chlorate reduction by chlorate reductase and oxygen utilization by cytochromes; the slowest step is perchlorate reduction. As a result, no intermediates ordinarily accumulate in solution during perchlorate biodegradation (Logan, 2001).

The disturbing trend noted in Figures 14 and 15 is the increase in $NO_3$ and $ClO_4$ concentrations in Cell 4 (limestone). Possible explanations for this include the following:

- The inadvertent collection of untreated water from outside the PRB (downgradient) during the sampling of port number 5 in Cell 4 (due to sample collection methods and/or possible negative hydraulic gradient within the PRB)

- Hydraulic bypass of Cells 2 and 3

This trend is also evident in the removal of many other constituents. To help identify the cause of this trend toward increased COC levels in Cell 4, it is suggested that (1) future sampling is performed using the micropurging sample method described in Section 5.1.1.1 and (2) additional observation/monitor wells are installed and a tracer test is performed after their installation.

Whatever the cause of the increased constituent levels in Cell 4, it is evident from the samples retrieved from Cells 2 and 3 that nitrate and perchlorate removal is occurring in Cell 3. The $NO_3$ and $ClO_4$ levels in samples from Cells 2 and 3 are below the DOE Action Levels and LANL Treatment Goals (Table 7).

The mineral apatite in Cell 2 provides the primary removal zone for americium, strontium, and plutonium. Removal is accomplished via the formation of phosphate complexes containing the actinides. The increased availability of soluble phosphate as the groundwater passes through Cell 2 is evident in Figure 18. The apatite cell also introduces bicarbonate into the water, increasing the alkalinity of the water, as shown in Figures 19 and 20, respectively. The increased level of these minerals in the water is also reflected in an increase in total dissolved solids (TDS), which can be measured in the field as conductance. Figure 21 shows the increase in conductivity as the groundwater travels through Cell 2.

Figures 22 through 25 show the radionuclide COC levels across the PRB. The levels of plutonium-238, plutonium-239, 240 and americium upgradient of the PRB are already below the LANL action levels (Table 7). Nearly all radionuclide levels are significantly reduced by the mineral apatite in Cell 2; however, the radionuclide content increases in Cell 4 to approximately upgradient levels. This pattern of increased levels in Cell 4 is similar to that observed for other constituents. Only one of the four sample locations for strontium-90 showed levels lower than the LANL Treatment Goal and DOE Action Level.

## 5.4 Lessons Learned from Evaluation of Existing Data

This section presents lessons learned from other PRB installations as well as those specific to the Mortandad Canyon PRB pilot project.

### *5.4.1 Lessons Learned from Other PRB Installations*

In general, the suggestions for improvements from different PRB installations nationwide are similar. A summary of the lessons learned, based on the consensus of various PRB experts, is provided below:

- A thorough understanding of site characteristics is required for the design and installation of PRBs (ITRC, 2005).

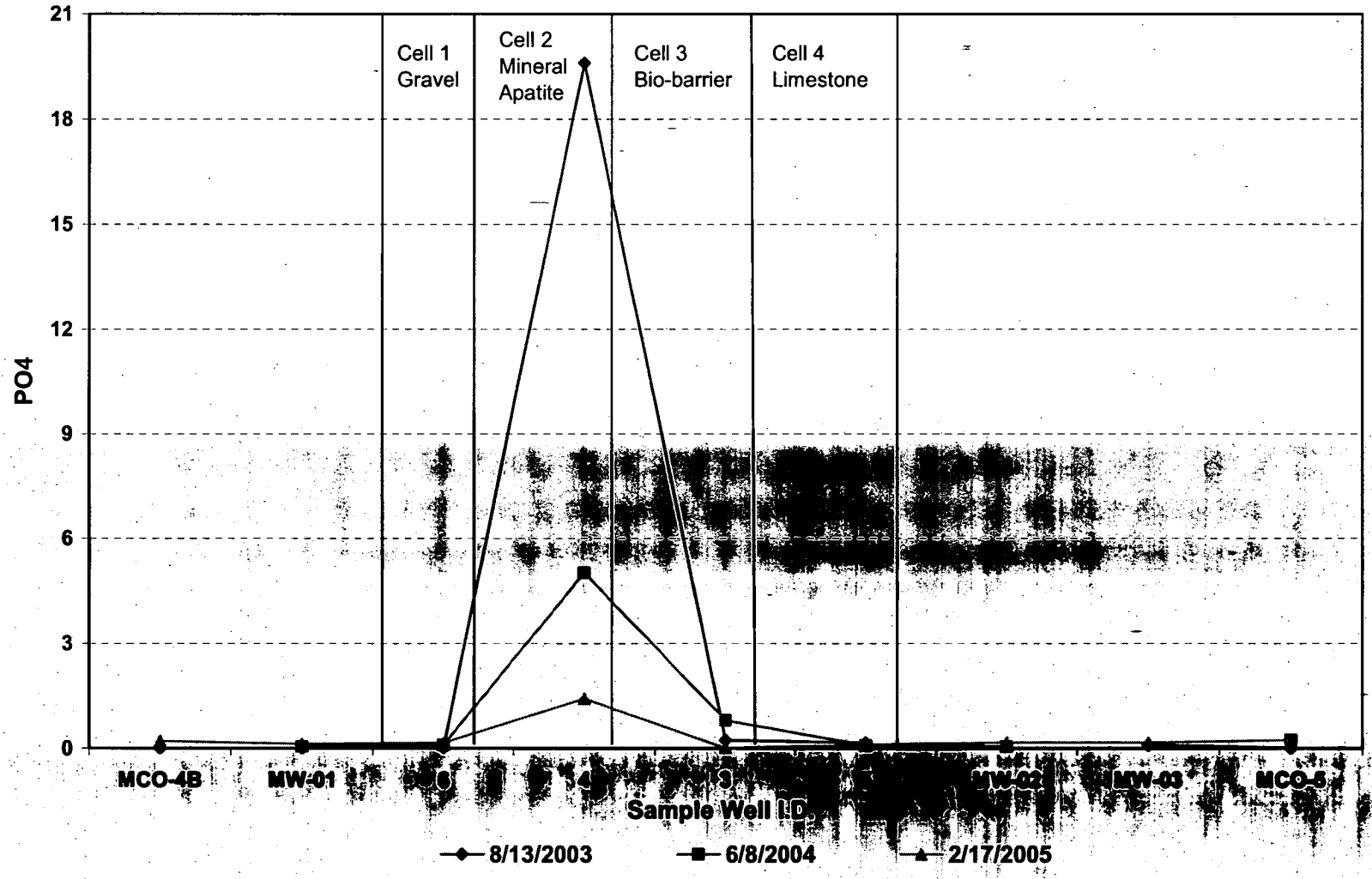


Figure 18

MORTANDAD CANYON PRB INVESTIGATION

**Phosphate Levels Across the PRB**

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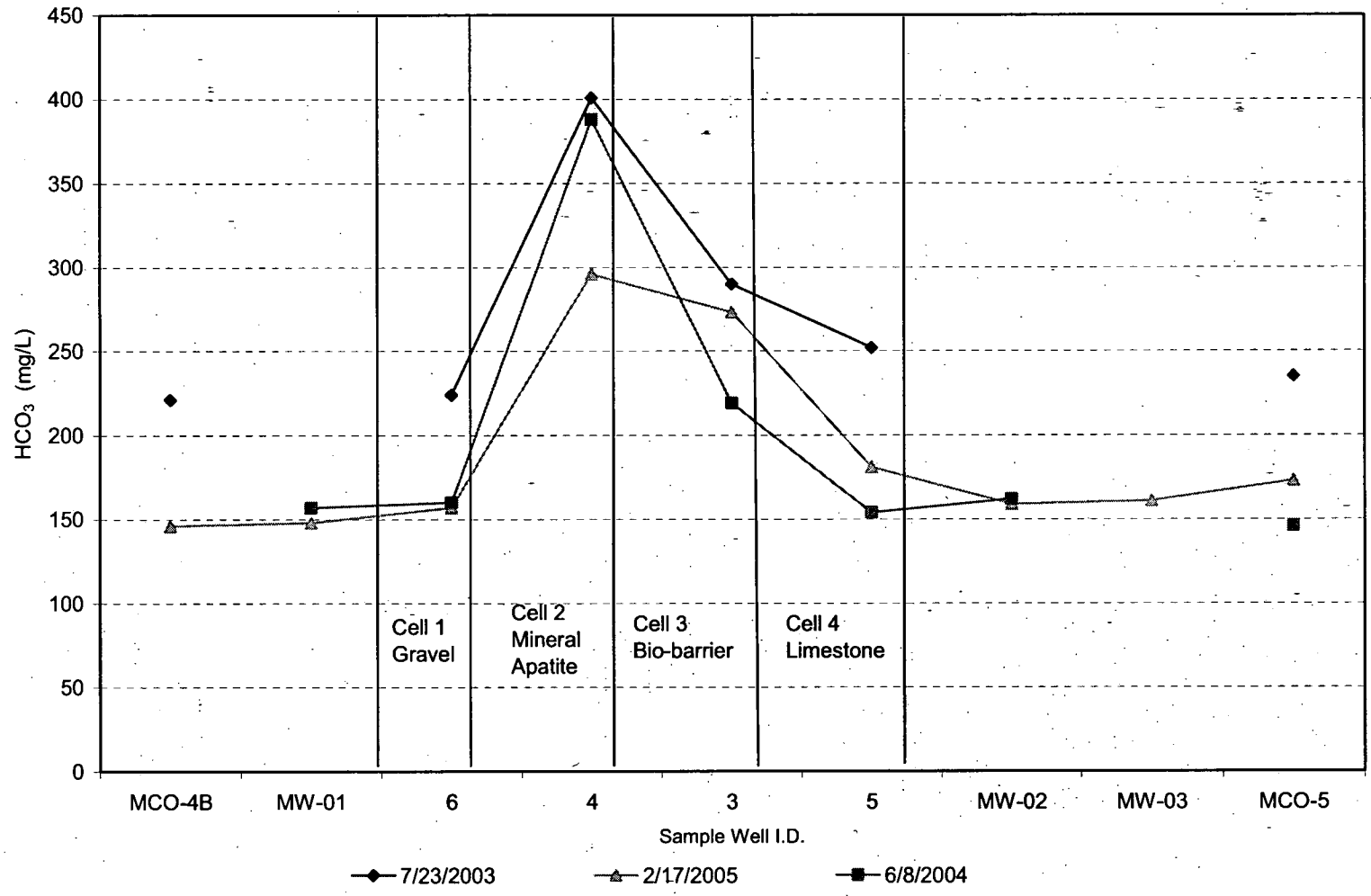


Figure 19

MORTANDAD CANYON PRB INVESTIGATION

**Bicarbonate Across the PRB**

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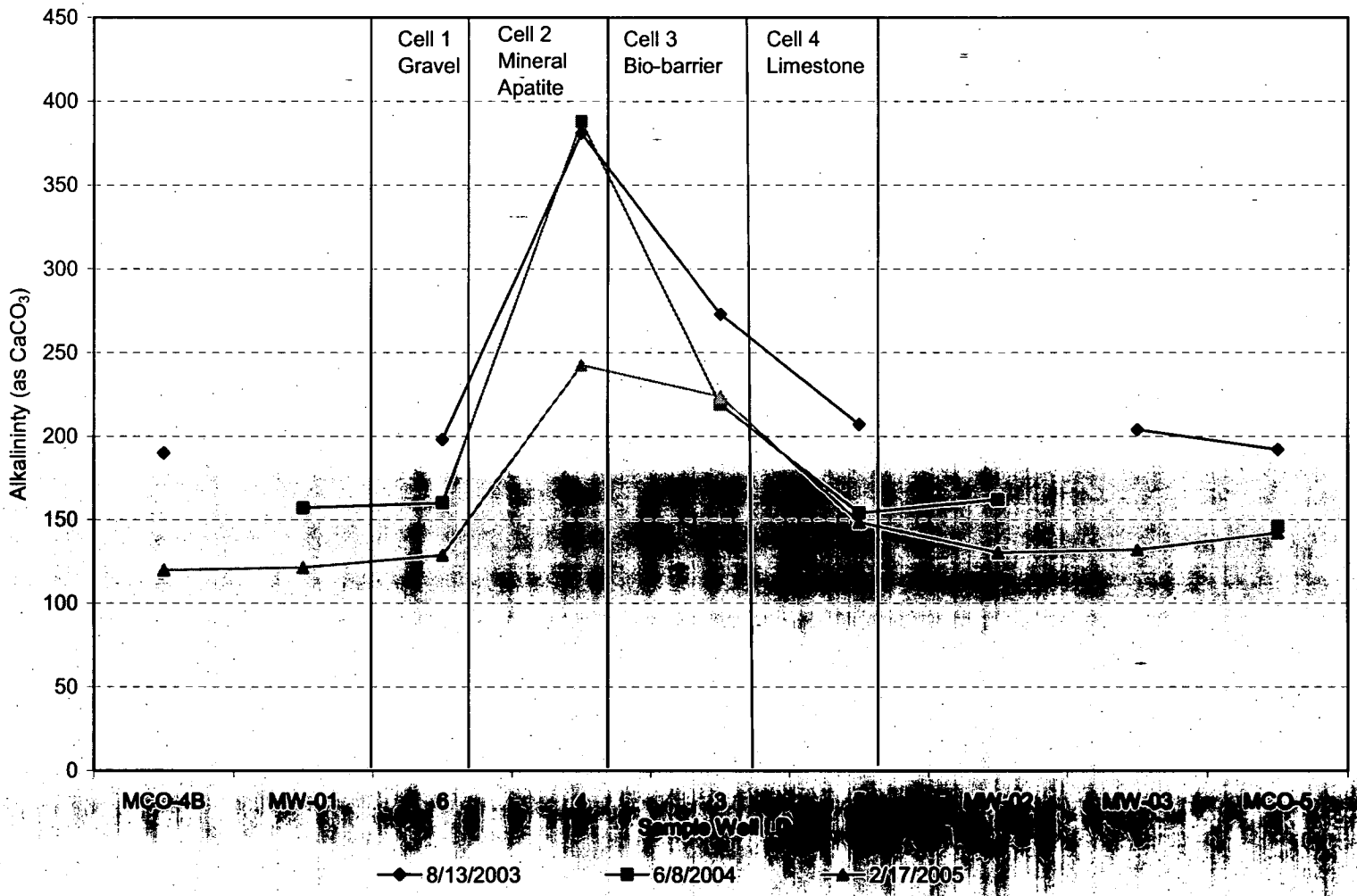


Figure 20

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MORTANDAD CANYON PRB INVESTIGATION

**Alkalinity Across the PRB**

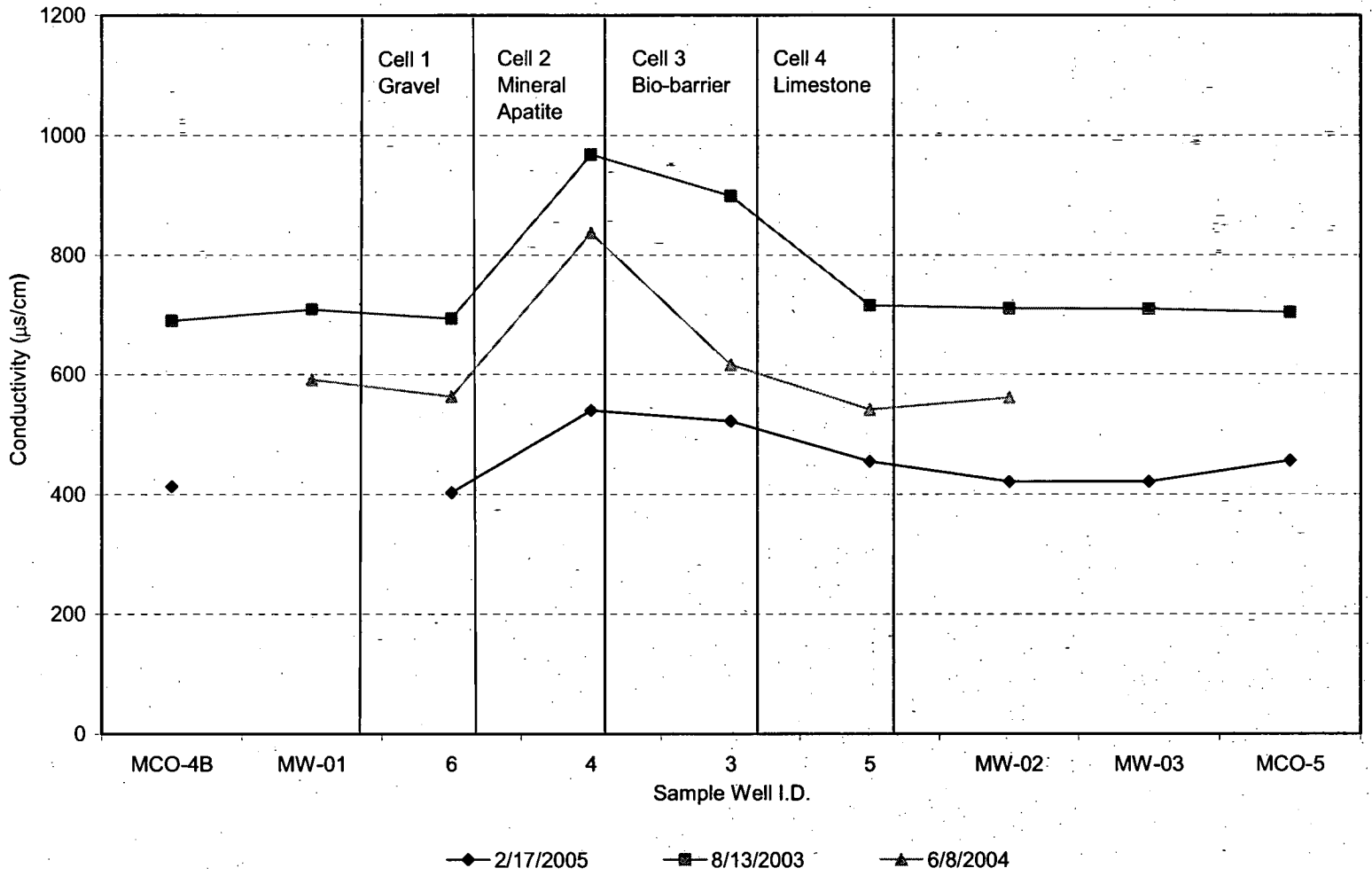


Figure 21

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MORTANDAD CANYON PRB INVESTIGATION

**Conductivity Across the PRB**

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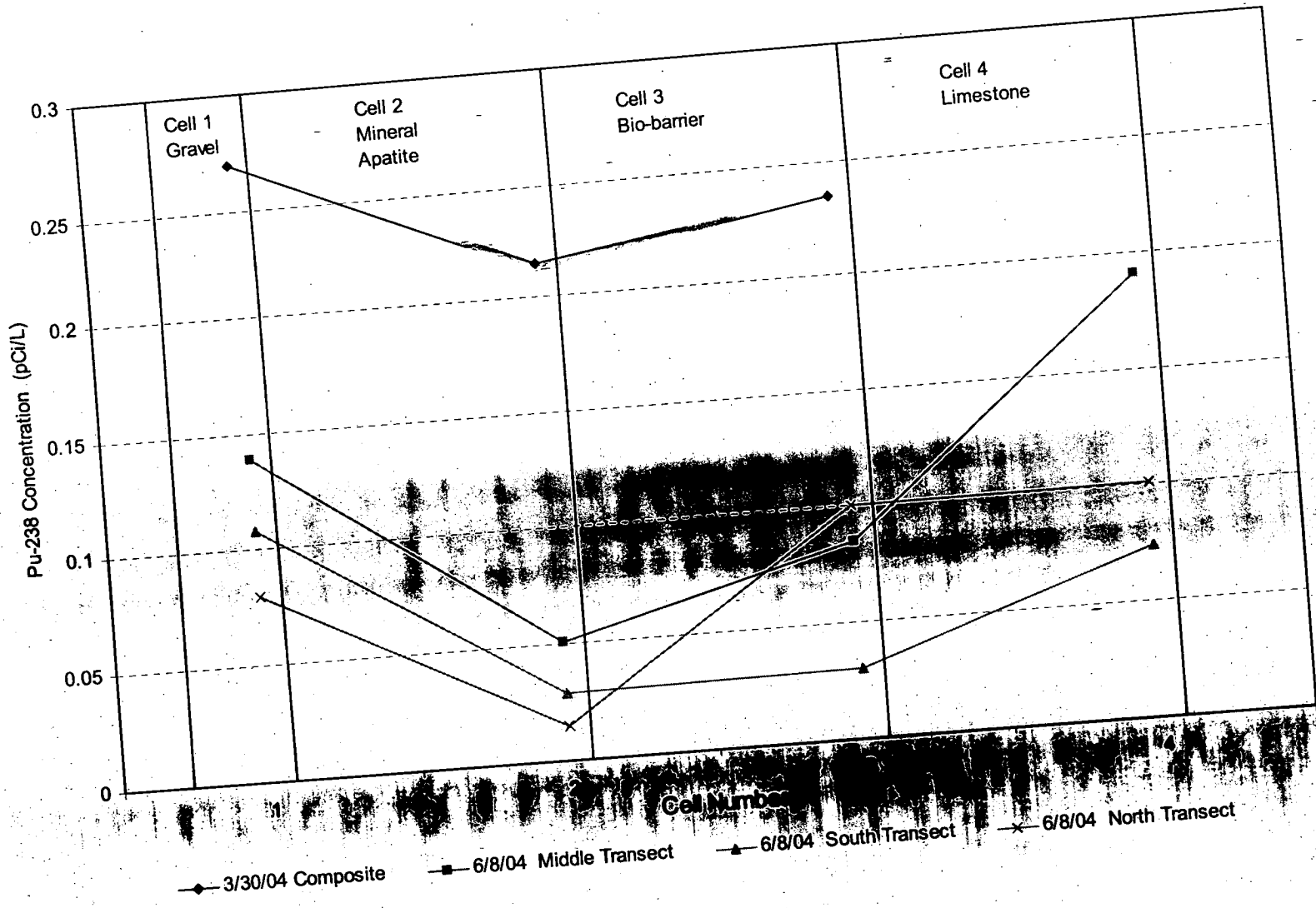


MORTANDAD CANYON PRB INVESTIGATION

**Plutonium-238 Across the PRB**

Figure 22

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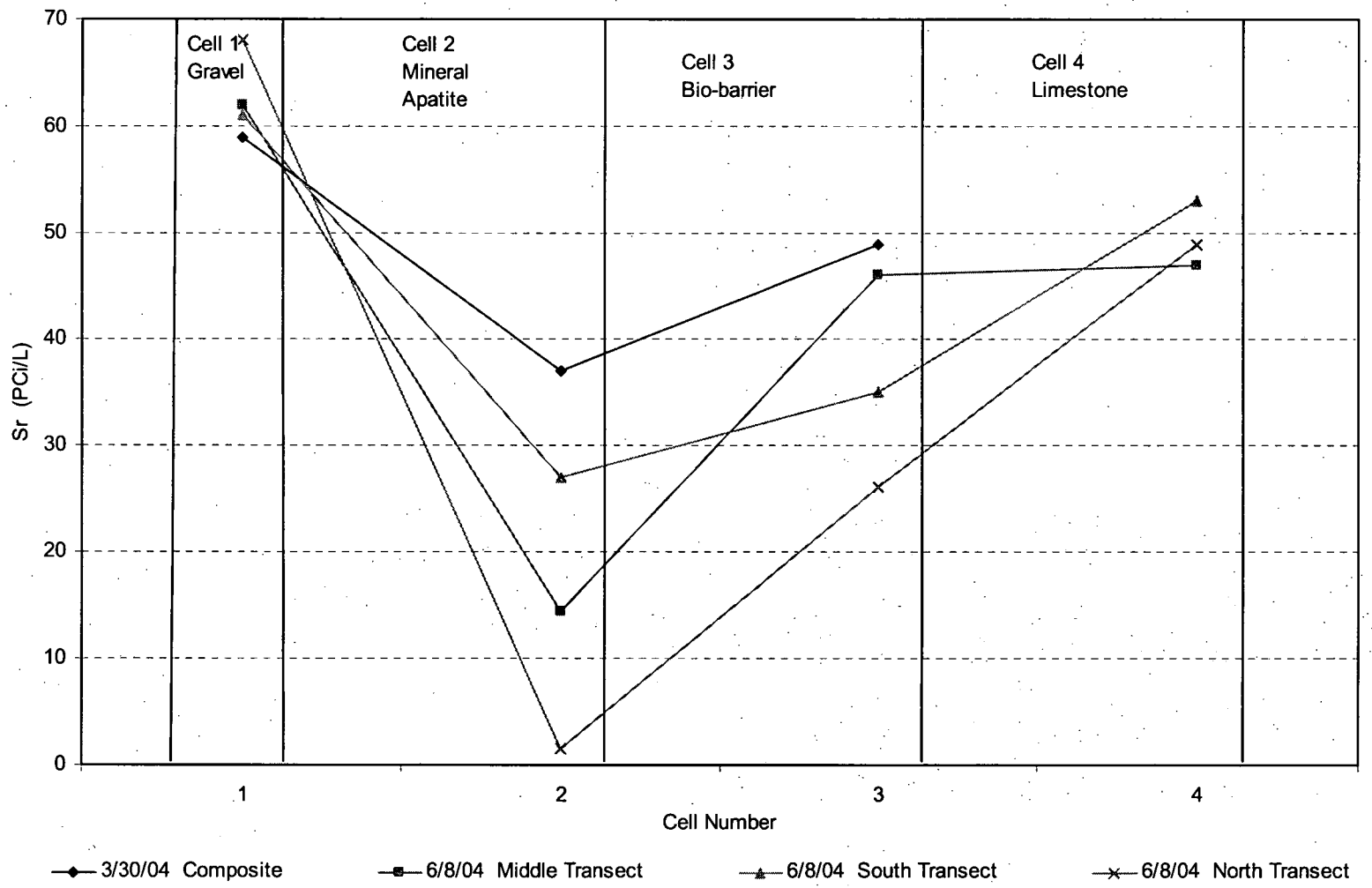


Figure 23

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MORTANDAD CANYON PRB INVESTIGATION

**Strontium-90 Across the PRB**

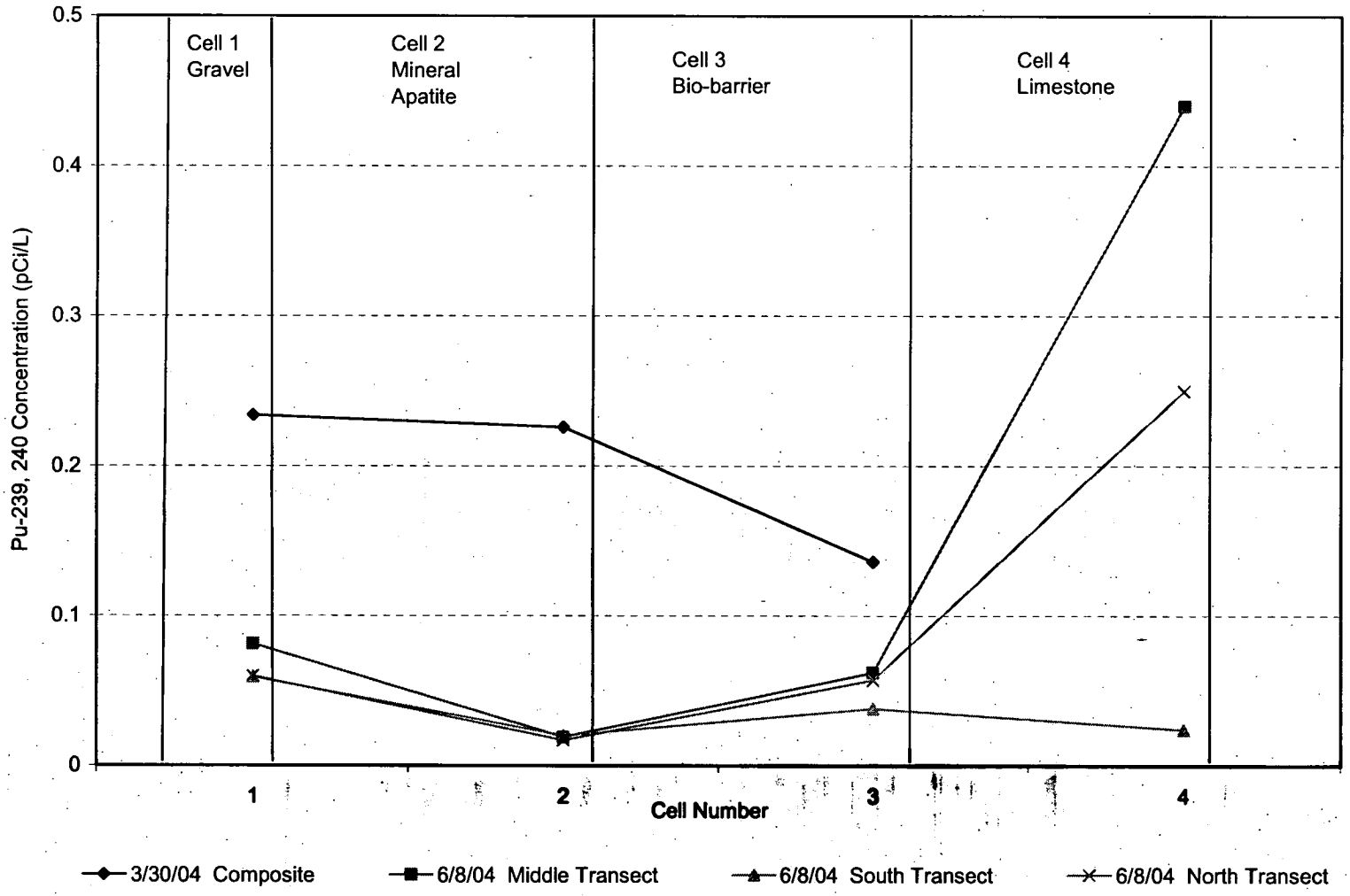


Figure 24

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**Plutonium-239,240 Across the PRB**

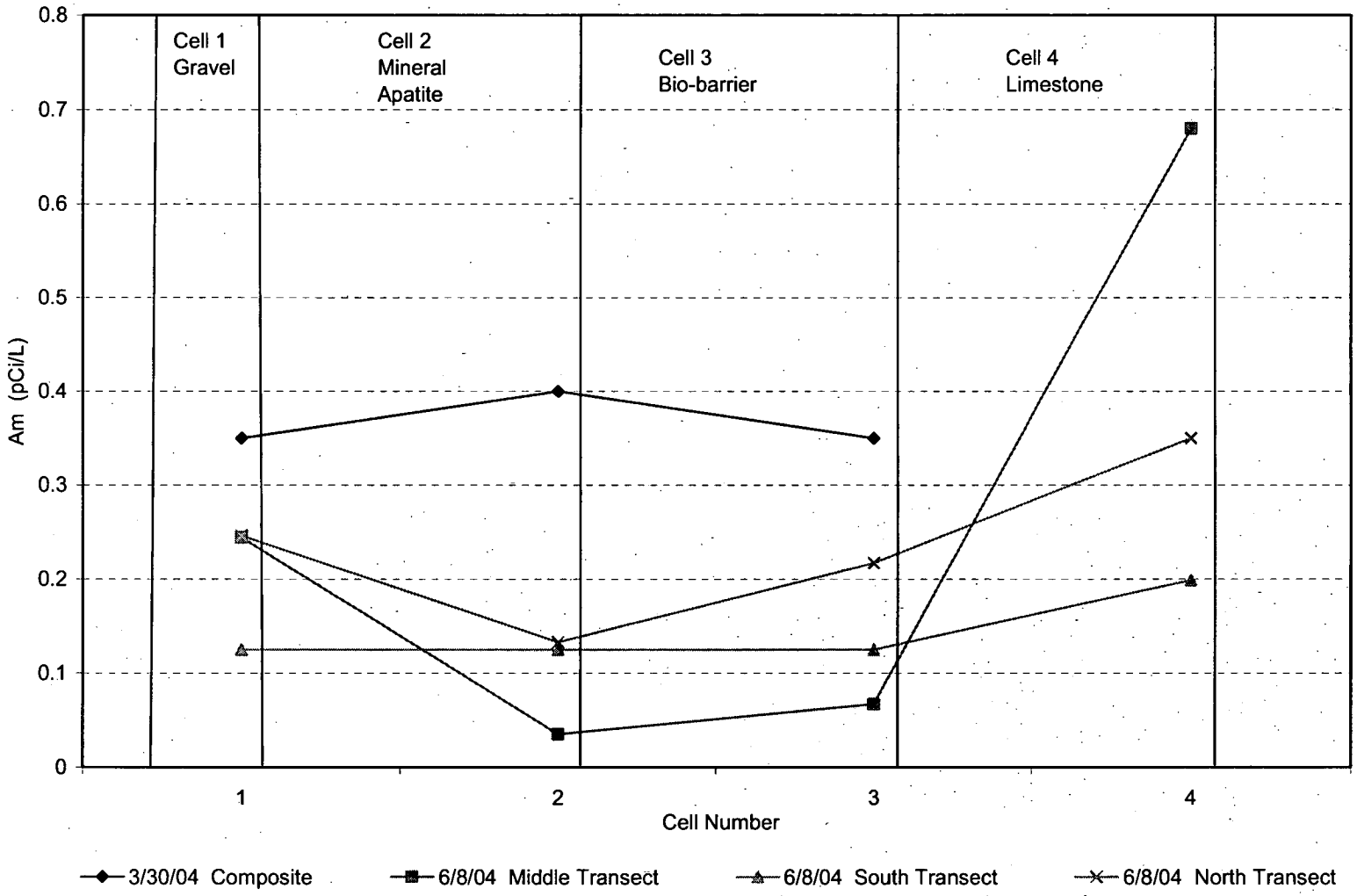


Figure 25

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MORTANDAD CANYON PRB INVESTIGATION

**Americium-241 Across the PRB**

- The flow-through thickness of a barrier should be designed for constituent levels representative of the core of the contaminated groundwater plume (Morkin et al., 2000).

- If the groundwater used in the design treatability study does not contain contaminant concentrations representative of the core of the plume, additional contaminant should be added to the groundwater so that rate constants are calculated using maximum field concentrations (Morkin et al., 2000).

- To properly identify areas of high contaminant concentrations or the location of the plume core, the initial site characterization must be sufficiently detailed. Multilevel samplers are recommended for this purpose as the exclusive use of fully screened wells tends to obscure high concentrations as a result of mixing and dilution in the standing water (Morkin et al., 2000).

- PRBs typically take advantage of ambient flow conditions. Promoting active flow through siphoning or limited pumping may be desirable in some cases (ITRC, 2005).

- Once installed, a PRB is difficult to modify or adjust. This places a greater emphasis on ensuring a successful PRB design, which is dependent on an accurate site characterization (ITRC, 2005).

- Seasonal variations in groundwater flow and temperatures can affect the performance of the PRB and need to be accounted for in the design (ITRC, 2005).

- Preventing zones of reduced permeability during construction and minimizing the variability in packing of the reactive media are critical to PRB operation. Zones of reduced permeability or deflected flow can result from the use of sheet piling in incompatible geologic conditions, improper maintenance of biopolymer, and improper placement of reactive material through the biopolymer (ITRC, 2005).

- Research has shown that ZVI PRBs can be expected to last an estimated 10 to 30 years, depending on the rate of flow through the system and the levels of the total dissolved solids (ITRC, 2005).

- Use of low-flow and passive sampling methods to monitor the PRB is recommended to minimize disruption in the groundwater flow field (ITRC, 2005).

- Despite its limitations, the most effective tool for monitoring the hydraulics of the PRB system is the use of accurate groundwater head measurements (ITRC, 2005).

- Tracer tests provide the best flow information but are difficult and expensive to conduct (ITRC, 2005).

- When a PRB is located within the contaminant plume, it may be difficult to determine performance due to the residual downgradient contamination. Monitor wells should be installed within or close to the downgradient side of the reactive media to facilitate monitoring (ITRC, 2005).

- Given the time lag in achieving downgradient water quality improvements, regulators and site owners should also consider establishing a temporary compliance point within the reactive media at or near the downgradient edge of the PRB. This would enable better evaluation of the PRB's ability to treat groundwater contaminants to established regulatory standards. The location of the compliance points can be reevaluated as the downgradient residual contamination dissipates (ITRC, 2005).

- The use of iron for source zone treatment is finding increased acceptance for site remediation (ITRC, 2005).

- PRBs offer cost incentives due to the passive nature for the technology that adds to the reduced operation and maintenance costs. The one cost factor that is difficult to estimate is replacement or replenishment of the reactive media (ITRC, 2005).

### 5.4.2 Lessons Learned from the Mortandad Canyon PRB

The lessons learned regarding the Mortandad Canyon MPRB can be divided into four areas:

- Design
- Construction
- Operation
- Maintenance

Specific recommendations are listed below:

#### 5.4.2.1 Design Lessons Learned

The more simple the design, the less likelihood for problems during construction and operation. Specific design points to consider include:

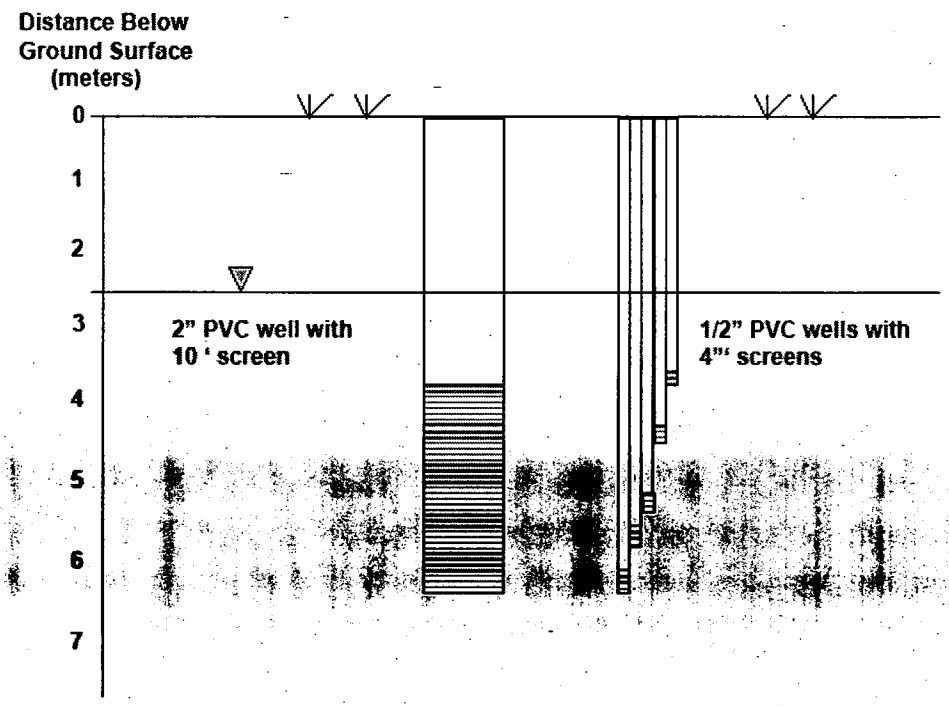
- In a multimedia PRB, the bottom and top elevations of each media should be the same.
- The design residence time should be increased by a factor of safety. There are no specific guidelines for determining an appropriate safety factor; such a factor will be based on site specific data and should be incorporated into the design by the time the 30 percent review is made.
- A single media should be used whenever possible.
- Adherence to porosity, particle size, and permeability criteria is critical for smooth horizontal flow; failure to meet any one of these criteria can impede flow through the PRB, resulting in a multitude of additional problems.
- Additional strategically placed sample wells would help identify groundwater flow patterns and potential leakage around, through or beneath the gate and funnel sections, and also provide more information on COC removal performance.

- Sampling wells should be multilevel to allow for better determination of flow patterns. Screening wells at varying depths across the sample zone minimizes the effects of vertical variations in the formation or PRB permeability. A major concern in PRBs is potential channeling through high conductivity zones; multilevel sample wells can provide high vertical spatial resolution to help evaluate this potential effect.

- Smaller diameter wells (e.g., 3/4 inch internal diameter) or even bundled tubes with short screens (<1 ft screens), as shown in Figure 26, are often preferred for performance monitoring purposes. Proper location of the screened intervals in three dimensions is important for monitoring different vertical zones within the PRB. It also helps provide coverage for different flow paths and allows estimation of degradation or transformation rates as the contaminants pass through the system. These same monitoring points can be used for tracer tests to evaluate changes in permeability. The placement of monitoring points for flow path analysis requires prior detailed site characterization to determine flow path direction, flow velocities and system heterogeneities (US EPA, 1998).

- A Quality Assurance Project Plan (QAPP) outlining the sampling protocol should be included as part of any design, regardless of the project scale (pilot vs. full-scale). A QAPP aims to assist with achieving project goals by providing a written, organized, defensible protocol. A QAPP written for a PRB should cover preliminary site characterization, PRB construction, and PRB monitoring. The QAPP can be developed in phases as the project evolves. Essentially, it needs to include quality assurance/quality control requirements and reporting requirements as determined by project-specific data quality objectives.

- The U.S. EPA has developed a quality control methodology called Triad that provides a logical approach to environmental investigation planning, execution, and evaluation (ITRC, 2005). Triad emphasizes three components. The first is better preparation for investigations including systematic project planning and development of a conceptual site model (CSM) that incorporates existing site knowledge and identifies the data




MORTANDAD CANYON PRB INVESTIGATION

**Bundled Tubes with Short Screens for Performance Monitoring**

**Source: U.S. EPA, 1988**

Figure 26

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needed to achieve project goals. The second is to allow greater flexibility while performing fieldwork. This component emphasizes a dynamic work plan centered on field activities that is designed to allow the project team to update the CSM with real-time data and make decisions in the field on subsequent activities. The third component focuses on gathering and analyzing real-time data to support real-time decision making. Further information on this concept is available in *Technical and Regulatory Guidance for the Triad Approach: A New Paradigm for Environmental Project Management* (ITRC, 2003).

- Media should be selected based on sufficient laboratory treatability studies.

- When a media that contains multiple components is specified, procedures for mixing and placement should be included in the design review.

- When a PRB is placed in a shallow, seasonally fluctuating aquifer, preliminary laboratory treatability studies should evaluate the effects of wetting/drying and temperature changes on the media performance.

- Pilot and full-scale PRB installations should identify a compliance treatment point in the design review. A flexible approach should be maintained to allow adjustment of the compliance location as the project and treatment goals progress.

*5.4.2.2 Construction Lessons Learned*

Specific points to consider regarding construction issues include the following:

- During excavation of the gate section in a funnel-and-gate design PRB, an impermeable bottom barrier should always be installed to mitigate any possibility of water flowing beneath the reactive zone.

- The use of tremmie piping to emplace media at depths would improve media uniformity, especially for media composed of multiple materials with different characteristics (e.g., the bio-barrier material).

- Adequate lateral support must be provided for PVC monitoring wells during installation and media backfilling to ensure wells remain vertical.

*5.4.2.3 Operation Lessons Learned*

Specific points to consider regarding PRB operation issues include:

- A QAPP should be developed that documents sampling goals, procedures, and analysis. For a pilot-scale installation where regulatory compliance is not essential, a shortened QAPP can be used; however, it should still specify the basic sampling objectives and corresponding protocol.

- Samples should be collected using low-flow techniques. Low flow, which refers to the velocity with which water is withdrawn from the aquifer, is usually defined as 0.1 to 0.5 L/min, depending upon site-specific hydrogeologic conditions. The sampling effectiveness is intimately linked with proper screen location, screen length, and well construction and development techniques (U.S. EPA, 1998).

- The reestablishment of natural flowpath equilibrium in both the vertical and horizontal directions following disturbance of the water in the well and prior to sampling are important for correct interpretation of the data. Oftentimes, purging is needed only because the sampling device has been passed through the overlying casing water, which causes mixing of these stagnant waters and the dynamic waters within the screened interval. These disturbances and impacts can be avoided by using dedicated sampling equipment set within the screened interval, which precludes the need to insert the sampling device prior to purging and sampling (Powell and Puls, 1993). For high resolution sampling needs, screens less than 1 meter (m) in length should be used. Isolation of the screened interval water from the overlying stagnant casing water may be accomplished using low-flow minimal drawdown techniques. If the pump intake is located within the screened interval most, if not all, of the water pumped will be drawn directly from the formation with little mixing of casing water or disturbance to the sampling zone.

- Polyethylene diffusion bag (PDB) samplers are increasingly being used during monitoring and sampling for volatile organic compounds (VOCs). PDB samplers are low-density bags containing deionized water that are used to collect water samples in groundwater wells for laboratory analyses of VOCs. They are passive devices, relying on the movement of groundwater from the aquifer or water-bearing zone through the screen or open interval of a well. VOCs in groundwater diffuse across the bag material until concentrations within the bag reach equilibrium with those in the surrounding groundwater (ITRC, 2005). PDB samplers are not appropriate for sampling metals and other inorganic compounds.

- Samples should be collected at least once/quarter. Sampling frequency should be based on the hydrogeologic character of the aquifer. Mortandad Canyon water velocity merits quarterly sampling.

*5.4.2.4 Maintenance Lessons Learned*

The soil/vegetative cover above the gate section of a PRB must be maintained to ensure proper functioning of the barrier. Specific considerations include maintaining the elevation and slope, ensuring the presence of vegetation to minimize erosion, and providing for the diversion of surface runoff to prevent erosion.

Ongoing performance assessment of the Mortandad Canyon PRB would be greatly improved by the following activities:

- Installation of additional strategically located wells to facilitate more comprehensive monitoring of the funnel-and-gate system integrity

- Core sampling and analysis to compare actual mineral precipitation to geochemical model predictions, and bed volumes of groundwater treated—a strong correlation provides an excellent predictive tool for barrier longevity

- Measuring the velocity and direction of groundwater in PRB vicinity wells using a borehole probe

# 6. 2006 Investigation Activities and Results

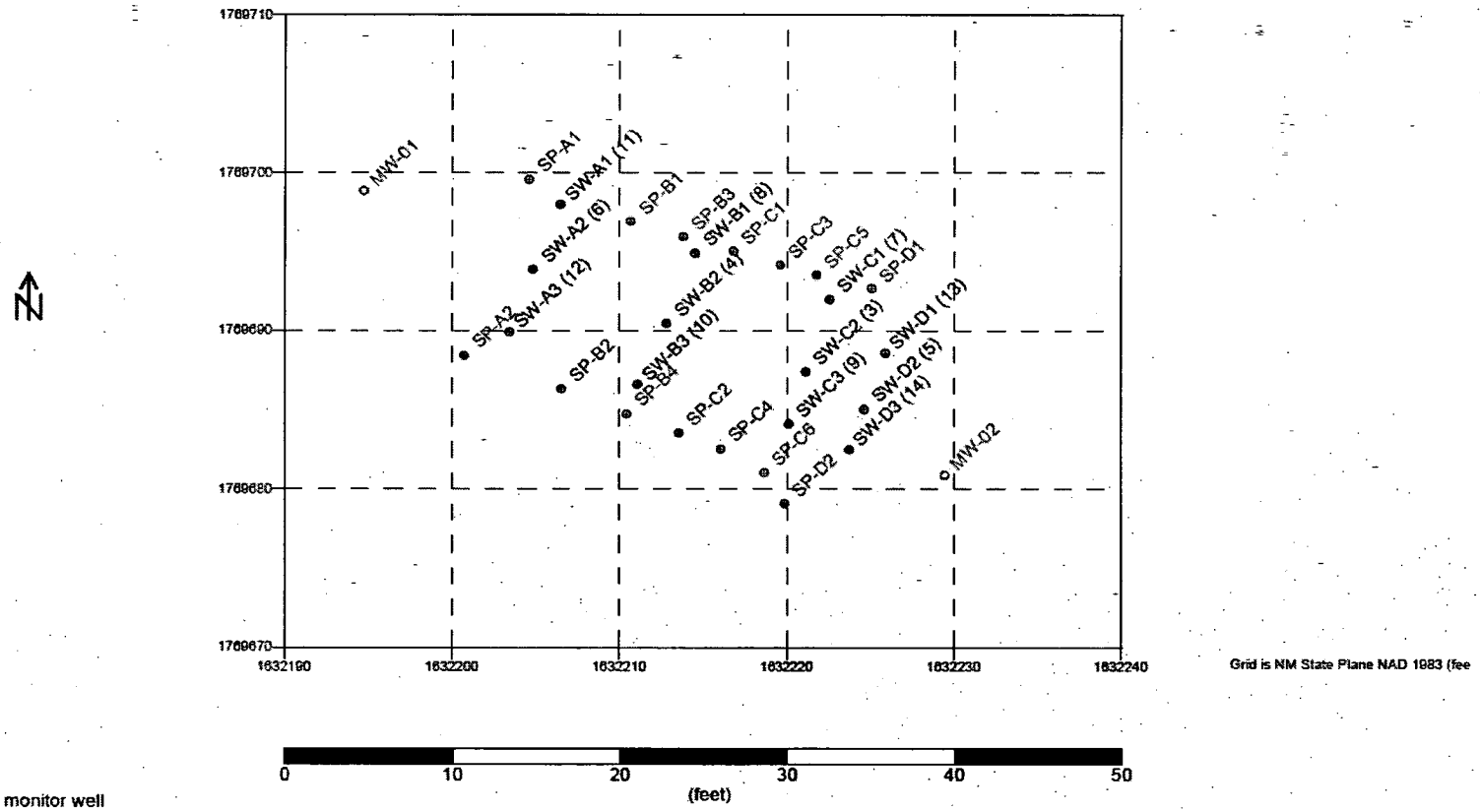
This section presents a description of the field investigation activities conducted during September 2006 and results obtained from analysis of the data collected during the field investigation, where available. These activities were undertaken to make an initial assessment of the possible impact that subsidence may have had on PRB performance.

## 6.1 Subsidence Mitigation

Health and safety concerns led to access restrictions to the area within the PRB fence after the March 2005 subsidence event. The need for access to the PRB interior to conduct field investigation activities required mitigation of potential hazards related to possible instability of the ground surface overlying the PRB. The solution employed to mitigate the possible hazards was emplacement of a safety net draped over the ground within the PRB and secured to a steel cable encircling the steel fence posts. In addition, half-inch plywood was placed above a few spots where erosional holes had developed during the flood event. It should be noted that once access inside the PRB fence was attained and field personnel were able to move around within the interior of the PRB fence, there were no issues with any ground instability. The ground surface is in fact quite stable.

## 6.2 Groundwater and Reactive Media Sampling

Groundwater samples were collected on September 7 and 8, 2006 from each of the 12 water sampling ports located within the PRB and from 1 upgradient alluvial monitor well (MW-01) and 1 downgradient alluvial monitor well (MW-02) (Figure 27). These samples were collected for the purpose of comparing the current geochemical behavior of the PRB to that observed in previous sampling rounds and thus evaluate possible impacts to PRB performance that may have been caused by the flooding and subsidence event in March 2005. Table 9 shows the samples collected information and analytical suites for the water samples.




MW = monitor well

SW = PRB water sampling port

SP = PRB reactive media sampling port

Figure 27

MORTANDAD CANYON PRB INVESTIGATION

**Mortandad Canyon PRB Sampling Port and Well Locations**

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## Table 9. PRB Groundwater Samples

| Location | Description | Location ID | LANL Water Quality Division Sample ID[a] | Sample Date | Sample Time |
|---|---|---|---|---|---|
| PRB-SW-A1 | Mort PRB Gravel Cell 11 (north) | MO-22545 | GF06090PBG1101 | 9/7/2006 | 1145 |
| PRB-SW-A2 | Mort PRB Gravel Cell 6 (center) | MO-22546 | GF060900PBG601 | 9/7/2006 | 1215 |
| PRB-SW-A3 | Mort PRB Gravel Cell 12 (south) | MO-22547 | GF06090PBG1201 | 9/7/2006 | 1245 |
| PRB-SW-B1 | Mortandad PRB Apatite Port 8 (north) | MO-22548 | GF060900PBA801 | 9/7/2006 | 1300 |
| PRB-SW-B2 | Mortandad PRB Apatite Port 4 (center) | MO-22549 | GF060900PBA401 | 9/7/2006 | 1320 |
| PRB-SW-B3 | Mortandad PRB Apatite Port 10 (south) | MO-22550 | GF06090PBA1001 | 9/8/2006 | 950 |
| PRB-SW-C1 | Mortandad PRB Bio Port 7 (north) | MO-22551 | GF060900PBB701 | 9/8/2006 | 1015 |
| PRB-SW-C2 | Mortandad PRB Bio Port 3 (center) | MO-22552 | GF060900PBB301 | 9/8/2006 | 1035 |
| PRB-SW-C3 | Mortandad PRB Bio Port 9 (south) | MO-22553 | GF060900PBB901 | 9/8/2006 | 1100 |
| PRB-SW-D1 | Mortandad PRB Limestone Port 13 (north) | MO-22554 | GF06090PBL1301 | 9/8/2006 | 1145 |
| PRB-SW-D2 | Mortandad PRB Limestone Port 5 (center) | MO-22555 | GF060900PBL501 | 9/8/2006 | 1205 |
| PRB-SW-D3 | Mortandad PRB Limestone Port 14 (south) | MO-22556 | GF06090PBL1401 | 9/8/2006 | 1230 |
| PRB-MW-01 | MW-01, well upgradient of PRB | MO-22544 | GF06090PBW101 | 9/8/2006 | 1310 |
| PRB-MW-02 | MW-02, well downgradient of PRB | MO-22557 | GF06090PBW201 | 9/8/2006 | 1330 |

[a] Filtered sample IDs shown (ID nos. for filtered samples have a prefix of GF; unfiltered samples have a prefix of GU).

Analyses requested:

Radionuclides (isotopic Pu, isotopic U, Am-241 by Alpha-spec, Cs-137 by Gamma-spec, Gross A/B/G, tritium by liquid scintillation, strontium-90)

General Inorganics (total alkalinity, total organic carbon, bromide, chloride, fluoride, sulfate, perchlorate, TKN, nitrate/nitrite)

Total Metals (ICP/MS EPA 6020); Anions (EPA 9056/8321M/415.2); SVOCs (EPA 8270-C); PCBs (EPA 8082); TCLP Organics (EPA 1311/8260-B & 1311/8270-C);

Gamma Spectroscopy (EPA 901.1); Organic Pesticides (EPA 8081-A); Organic Herbicides (EPA 8151-A; Cyanide (EPA 335.2/SW846 9012A/SW846 9010B)

Samples of the reactive media were collected on September 8 through 11 and September 19 through 20, 2006 from the media sample ports (Figure 27) using a hand augur with a 1½ inch augur bucket. Reactive media samples were collected from multiple ports in each cell and combined into single composite samples, one for each of the four PRB cells. These samples were collected for the purpose of evaluating the condition of the reactive media after three and one-half years of operation of the PRB and for characterization of the potential future waste stream that would be generated during excavation and deconstruction of the PRB. Table 10 shows the samples collected information and analytical suites for the media samples. All samples were processed by the LANL Sample Management Office (SMO) for submittal to General Engineering Laboratory for analysis. Because of the timing of the sampling, analytical results are not available at the time of the preparation of this report. Table 11 shows the values of the field parameters measured with a downhole probe prior to collection of the water samples.

**Table 10. PRB Reactive Media Samples**

| Location [a] | Description | ER Sample ID | Sample Date | Sample Time |
|---|---|---|---|---|
| SP-A1,A2 | Mortandad PRB gravel cell media ports | CAMO-06-72644 | 9/20/2006 | 1222 |
| SP-B1,B2,B3,B4 | Mortandad PRB apatite cell media ports | CAMO-06-72642 | 9/14/2006 | 1515 |
| SP-C1,C2,C4,C6[a] | Mortandad PRB bio-barrier cell media ports | CAMO-06-72641 | 9/12/2006 | 1601 |
| SP-D1,D2 | Mortandad PRB limestone cell media ports | CAMO-06-72643 | 9/19/2006 | 1325 |

[a] Sample ports C3 and C5 could not be sampled due to obstructions in the ports.
Analyses Requested:
Radionuclides (isotopic Pu, isotopic U, Am-241 by Alpha-spec, Cs-137 by Gamma-spec, Gross A/B/G, tritium by liquid scintillation, strontium-90)
General inorganics (total alkalinity, total organic carbon, bromide, chloride, fluoride, sulfate, perchlorate, TKN, nitrate/nitrite)

## 6.3 Water Level Measurements

Water levels were measured in each of the water sampling ports and monitor wells MW-01 and MW-02 on September 6 and September 20, 2006. The top of casing (TOC) stick-up heights and total depths were also measured on September 20. These data are shown in Table 12. The water level data show that substantial recharge to the Mortandad Canyon alluvial aquifer during the historically wet summer of 2006 has created a water table only 10 to 11 ft below the

## Table 11. Groundwater Field Parameters

| Location | Description | Date | Time | pH | SC (µS/cm) | Temp (C°) | ORP (mv) | DO (mg/L) | Turbidity (NTU) [a] |
|---|---|---|---|---|---|---|---|---|---|
| SW-A1 | Mortandad PRB Gravel Cell 11 (north) | 9/6/2006 | 1229 | 6.62 | 299 | 10.32 | 89 | 2.67 | 23.2 |
| SW-A2 | Mortandad PRB Gravel Cell 6 (center) | 9/6/2006 | 1234 | 6.46 | 303 | 11.91 | 189 | 3.03 | 11.5 |
| SW-A3 | Mortandad PRB Gravel Cell 12 (south) | 9/6/2006 | 1239 | 6.42 | 308 | 9.70 | 107 | 2.72 | 41.4 |
| SW-B1 | Mortandad PRB Apatite Port 8 (north) | 9/6/2006 | 1309 | --- | --- | --- | --- | --- | 30.2 |
| SW-B2 | Mortandad PRB Apatite Port 4 (center) | 9/6/2006 | 1311 | 6.31 | 503 | 13.11 | -32 | 0.51 | 12.8 |
| SW-B3 | Mortandad PRB Apatite Port 10 (south) | 9/6/2006 | 1314 | 6.31 | 477 | 11.42 | -43 | 0.77 | 9.5 |
| SW-C1 | Mortandad PRB Bio Port 7 (north) | 9/6/2006 | 1257 | 6.70 | 539 | 10.28 | -144 | 0.60 | 56.4 |
| SW-C2 | Mortandad PRB Bio Port 3 (center) | 9/6/2006 | 1302 | 6.28 | 550 | 10.26 | -51 | 0.67 | 40.2 |
| SW-C3 | Mortandad PRB Bio Port 9 (south) | 9/6/2006 | 1306 | 6.38 | 447 | 10.05 | -80 | 0.24 | 16.6 |
| SW-D1 | Mortandad PRB Limestone Port 13 (north) | 9/6/2006 | 1246 | — | — | — | — | — | 92.1 |
| SW-D2 | Mortandad PRB Limestone Port 5 (center) | 9/6/2006 | 1249 | 6.44 | 373 | 11.29 | 154 | 0.53 | 31.6 |
| SW-D3 | Mortandad PRB Limestone Port 14 (south) | 9/6/2006 | 1253 | 6.49 | 343 | 11.06 | 157 | 2.39 | 29.3 |
| MW-01 | MW-01, well upgradient of PRB | 9/6/2006 | 1220 | 7.15 | 253 | 14.25 | 190 | 6.48 | 17.0 |
| MW-02 | MW-02, well downgradient of PRB | 9/6/2006 | 1223 | 6.69 | 327 | 10.95 | 53 | 4.39 | 14.5 |

SC = Specific conductance
Temp. = Temperature
ORP = Oxidation reduction potential
mg/L = Milligrams per liter
NTU = Nephelometric turbidity units
µS/cm = Microsiemens per centimeter
C° = Degrees Celsius
mv = Millivolts
DO = Dissolved oxygen
— = No parameter collected due to port obstruction

[a] Turbidity measured during groundwater sampling; see Table 9 for time and date of parameter collection.

ground surface beneath the PRB site. This high water level is indicative of saturated conditions extending approximately 7 ft above the reactive media in Cells 2 and 3 (Figure 11). The September 6 measurements were incorporated into the flow velocity analysis presented in Section 2.13 (Table 7).

Table 12 also shows a comparison of the TOC stick-ups with TOC measurements made on February 16, 2005 prior to the flood and subsequent subsidence that occurred in March 2005. The differences between these measurements indicate the amount of additional subsidence that occurred after the March 2005 flood. These data show that the minimum amount of subsidence (0.4 to 0.6 ft) occurred over the limestone cell while the maximum amount of subsidence (2.03 ft and 1.96 ft) occurred above the centers of the apatite and bio-barrier cells respectively. Subsidence above the gravel cell was about 0.7 to 1.0 ft, subsidence above the bio-barrier cell ranged from about 1.2 to 2.0 ft, and subsidence above the apatite cell ranged from about 1.3 to 2.0 ft.

**Table 12. Water Level and Well Measurements**

| Location | Depth to Water (ft below TOC) | | | Measured TOC Stickup (ft ags) | | Amount of Subsidence (ft) from 2/16/05 to 9/20/06 |
|---|---|---|---|---|---|---|
| | 9/6/2006 | 9/20/2006 | Total Measured | 9/20/06 | 2/16/05 | |
| PRB-SW-A1 | 15.63 | 14.73 | 32.96 | 3.95 | 2.93 | 1.02 |
| PRB-SW-A2 | 15.38 | 14.48 | 30.18 | 3.58 | 2.72 | 0.86 |
| PRB-SW-A3 | 15.56 | 14.67 | 32.94 | 3.75 | 3.10 | 0.65 |
| PRB-SW-B1 | 13.03 | 12.13 | 31.72 | 2.25 | 0.98 | 1.27 |
| PRB-SW-B2 | 15.42 | 14.53 | 34.79 | 4.82 | 2.79 | 2.03 |
| PRB-SW-B3 | 13.29 | 12.40 | 30.37 | 2.3 | 0.98 | 1.32 |
| PRB-SW-C1 | 15.19 | 14.30 | 32.99 | 3.9 | 2.61 | 1.29 |
| PRB-SW-C2 | 15.62 | 14.74 | 34.40 | 4.82 | 2.86 | 1.96 |
| PRB-SW-C3 | 15.06 | 14.17 | 32.84 | 3.71 | 2.55 | 1.16 |
| PRB-SW-D1 | 16.00 | 15.10 | 32.01 | 3.65 | 3.10 | 0.55 |
| PRB-SW-D2 | 15.77 | 14.88 | 32.74 | 3.5 | 2.86 | 0.64 |
| PRB-SW-D3 | 16.04 | 15.15 | 30.96 | 3.72 | 3.35 | 0.37 |
| PRB-MW-01 | 14.68 | NA | 33.09 | NA | NA | NA |
| PRB-MW-02 | 19.21 | NA | NA | NA | NA | NA |

ft = Feet TOC = Top of casing ags = Above ground surface NA = Not available

## 6.4 Slug Tests

Slug tests were performed in each of the water sampling ports and in monitor wells MW-01 and MW-02 during September 13 to 18, 2006 in accordance with LANL standard operating procedure SOP-07.03, Rev. 1 -Slug Tests. The following equipment was used in slug testing:

- In-Situ Level TROLL 700-15 PSIG transducer with accompanying software
- Laptop computer
- PVC slugs of different lengths (6.02 ft, 8.03 ft, and 9.98 ft)

The volumes of the three slugs were 0.42, 0.56 and 0.70 gallons respectively. The slugs were constructed of 1-5/16 inch diameter capped PVC pipe filled with play sand and suspended on twine.

At least two falling head and rising head tests were attempted with the 9.98 ft slug in each sampling port and well. If the sampling ports did not allow for full immersion of the 9.98 ft slug in the port due to obstruction, the 8.03 ft or 6.02 ft slug was utilized. Slug tests could not be performed in sampling ports B1 and D1 due to unknown obstructions in the port (likely the casings were bent to the extent that the slugs could not pass by the deformed section). Care was taken to smoothly insert and extract the slugs into the ports and monitoring wells to reduce splashing the water table. Whenever possible, the PVC casing stickups were temporarily removed (unscrewed) from the ports to allow smooth insertion and extraction of the slugs.

Plots of the water level response from each slug test and the results obtained from the analyses of one test in each of the four media cells in the PRB and one test in each of the monitoring wells are included in Appendix A. The majority of the slug tests show an oscillatory response due to the inertial effects in the highly conductive material that comprises the PRB cells. The high conductivity of the reactive media produced extremely small water level responses in the sampling ports (<0.15 ft) while the responses in the monitoring wells were moderately small (< 1.2 ft). Changes in barometric pressure due to changing weather conditions were likely recorded during the recovery from these small responses; hence, according to the transducer

data, some wells apparently did not recover to static water level. In fact, according to field measurements, the wells did recover to static and the pressure transducer had to be recalibrated between each test to correctly record the small responses.

Analysis was completed for the best test in each of the four media cells and the monitoring wells using AQTESOLV for windows. The Hvorslev (1951) solution method for unconfined aquifers was applied to the data. Assumptions included effective porosities of 0.46 for the filter pack material in the monitoring wells, 0.45 for the media in Cell 3 (bio-barrier), and 0.50 for the media in Cells 1, 2, and 4. Due to the oscillatory responses, the time-drawdown data did not plot on a straight line for a majority of the tests; thus, only rough estimates of the media's hydraulic conductivity could be calculated. The calculated hydraulic conductivity of the media in the PRB and alluvium is shown in Table 13.

**Table 13. Slug Test Analysis Results**

| Location | Saturated Zone | K (cm/s) |
|---|---|---|
| MW-01 | Alluvium | 1.35E-2 |
| MW-02 | Alluvium | 1.48E-2 |
| SP-A2 | Scoria | 1.12E-2 |
| SP-B3 | Apatite | 1.69E-2 |
| SP-C1 | Bio-barrier | 1.29E-2 |
| SP-D2 | Limestone | 1.48E-2 |

Because of the extremely small water level responses induced in the PRB water sampling ports by injecting and pulling the slugs, it is likely that those results are unreliable. In fact, the conductivities required to virtually eliminate the effect of injecting a 10 ft slug in less than 5 seconds, as was observed, may be as much as an order of magnitude higher than the values depicted in Table 13. Literature values for the hydraulic conductivity of a medium gravel range from 0.313 to 1.04 cm/s (Spitz and Moreno, 1996). Another possible explanation for the lack of response in the apatite and bio-barrier cells might be that settling and compaction of the media may have created open void spaces adjacent to the well screens, thus allowing water to move very quickly in and out of the screens.

# 7. Conceptual Models of PRB Performance

This section presents several alternate hypotheses for conceptual models to explain the observed performance of the Mortandad Canyon PRB. These are primarily conjectural hypotheses; further investigations are necessary to confirm or disprove them.

## 7.1 Non-Representative Sampling

Issues affecting the ability to collect representative groundwater samples include:

- *Locations of sampling wells*. As shown in Figure 6, the water sampling ports are located very close to the downstream edge of each barrier cell. Locating the sampling wells so close to the media interfaces makes it difficult to get a representative sample without inadvertently pulling in water from the adjacent media.

- *Sampling methods*. The possibility of pulling water from an adjacent cell during sampling was likely enhanced by the sampling methods (bailing and pumping at a presumably relatively high rate) employed.

The observed lowered pH in the apatite wells (Figure 12) shows that these samples were actually water from the downstream bio-barrier cell where lower pH should occur, whereas there is no reason why low pH should be created in the apatite cell. The lack of optimal sampling procedures (i.e., the use of micropurging technique) and less than optimal well locations to obtain water samples may have resulted in unreliable chemistry data from the Mortandad Canyon PRB. For example, the samples collected from the limestone cell that show high COC concentrations may actually represent water from the alluvium directly downstream of the PRB. This possibility notwithstanding, problems with sampling issues do not explain the persistent presence of unremediated groundwater observed immediately downstream from the PRB.

## 7.2 Preferential and Reverse Flow

The apparent preferential flow paths and reverse gradients observed in the bio-barrier may be caused by a few different possibilities:

- Compaction of the media may be responsible for erratic flow patterns (the bio-barrier media had the highest original porosity and was the most likely to compact). Density variations due to non-uniform compaction very likely could cause channeling though the higher porosity areas. Mixing of the pecan shells, cottonseed, and gravel was not well documented, and emplacement by a front end loader dumping at depths up to 27 ft was likely to cause segregation due to density and particle shape variations, further leading to irregular, non-uniform placement. Preferential flow is likely to develop along zones of higher porosity due to potential irregular placement of the bio-barrier media. Reduced permeability due to compaction is a likely contributor to flow impediment within the PRB leading to reverse gradients observed in the bio-barrier.

- There is potential for bio-fouling to occur in the bio-barrier where excessive bacterial growth accumulates additional biomass that clogs the matrix (Katsutoshi et al., 2006). Bacterial growth occurs in areas where nutrients are available (e.g. preferential pathways). This growth would continue in such locations until they plugged up due to the biomass buildup, then flow would have to be redirected elsewhere until the pattern was repeated. Flow that occurs along preferential pathways does so at greater velocities, which leads to lower residence times. Thus, the water may not be adequately treated before moving past the bio-barrier. Clogging due to bio-fouling may also contribute to flow impediment and reverse gradients.

- Nitrogen and methane gas formation from denitrification and methanogenesis may also lead to clogging, preferential pathways, and flow impediment.

## 7.3 Groundwater Mounding

The presence of groundwater mounding within the PRB has been persistent since 2004, becoming more significant over time. Some mounding was expected by the designers of the Mortandad Canyon PRB, but excessive mounding causes hydraulic stresses that may affect PRB performance. Issues that likely contribute to the groundwater mounding in the PRB include:

- The contrast in permeabilities due to particle size differences between Cell 4 and the downgradient alluvium caused the PRB design to fail the permeability criteria used in the design (filter criteria as set forth by Terzaghi and the "Shape Factor = D50Filter/D50Soil" used by the U.S. Army Corps of Engineers; Bowles, 1982). The PRB designers acknowledged this in Shaw's final design report (2002) and noted that this would likely cause the limestone to become saturated. This is a likely contributor to the observed groundwater mounding in the PRB.

- Fluctuating water levels leading to groundwater mounding above the reactive media cause further compaction within the PRB reactive media due to secondary consolidation of the media that occurs during repeated wetting and drying processes. Compaction of the media reduces its permeability, creating less efficient through-flow and favors development of preferential flow paths with consequent lowered residence time and reduced operational efficiency.

## 7.4 Potential for Hydraulic Bypass

Several alternatives are possible for hydraulic bypass to occur:

- Potential bypass may be occurring beneath the reactive media along a rubble zone in the overexcavated area. The PRB designers assumed that the tuff contact was impermeable. However, the inadvertent overexcavation into the tuff by several feet beneath Cells 2 and 3 likely caused some fracturing of the bedrock. Also, the fact that

the bottom of the excavation was submerged and located 27 ft deep made it impossible to observe the condition of the bottom of the excavation and difficult to ensure that any broken rock was fully removed. Thus, without an impermeable seal at the base of the PRB, the likelihood of a preferential pathway beneath the media in Cells 2 and 3 exists; this would allow most groundwater to flow directly into the limestone cell in an untreated condition.

- A possible pathway for hydraulic bypass over the top of the reactive media could exist through a potential gap that may have developed between the GCL lining the inside faces of the portions of Cells 1 and 4 that extend above the reactive media in Cells 2 and 3 and the geotextile liner overlying Cells 2 and 3. Reportedly, the two liner materials had about 2 ft of overlap where they meet; however, this is not documented. With observed total settlement of as much as 4 ft or more, this overlap could have been compromised creating a pathway for flow to move directly from Cell 1 through the gap bypassing over the top of Cells 2 and 3 and into Cell 4 without treatment.

- Possible leakage through the funnel wing walls could provide a pathway for groundwater flow to bypass the gate altogether. This, in conjunction with a poorly developed flow field and reverse gradients in the PRB, could explain the observations of untreated water chemistry at the downgradient end of the gate. The lack of availability of field notes made verification of the depth of sheet piling installation impossible to determine during data assessment. Reportedly, the specification was 3 ft or refusal, whichever came first. However, this detail is not shown in the as-built drawings or documented elsewhere. It was also noted that the as-built drawings are not correct with respect to downgradient well placement. Additional monitor wells would be necessary to verify whether or not leakage is occurring through the wing walls.

# 8. Work Plan for Future Investigation Activities

This section provides a work plan including several investigation activities that should be undertaken to address unresolved questions regarding the performance of the Mortandad Canyon PRB.

## 8.1 Collect Core Samples Within the PRB

The major subsidence of the ground surface over the PRB occurred above the central portion (Cells 2 and 3). This subsidence is attributable to some combination of compaction of the reactive media plus compaction of the backfill overburden overlying Cells 2 and 3. Whether the compaction occurs primarily in the reactive media or the overburden or is equally distributed between them is unknown.

In order to determine the geometry of the contact between the overburden and the reactive media, samples of overburden and reactive media materials will be obtained using a Geoprobe® or comparable direct push rig or a compact sonic drill rig. The core samples obtained from these borings will also be used to select samples to be submitted for laboratory testing of hydraulic and physical properties plus geochemical and biological testing. Continuous cores will be collected from the borings for four wells proposed in the interior of the apatite and bio-barrier cells and from four additional borings proposed near the interface of the gravel and apatite cells and the interface of the bio-barrier and limestone cells. Geochemical testing will be focused on samples near the cell wall interfaces, where reactive processes are likely to be concentrated.

A hydrogeologist and an engineer experienced in PRB construction and design will be on-site during the drilling program to select the sample intervals for testing. At least one sample each from the apatite cell and bio-barrier cells will be analyzed for saturated hydraulic conductivity, porosity, and specific density. If visual observations of the core indicate apparent differences in material density within a cell, multiple samples may be tested. Likewise, at least one sample each from the apatite cell and bio-barrier cells will be analyzed for major cations and anions,

metals, and radionuclides. If visual observations of the core indicate apparent differences in appearance that may be attributable to chemical precipitation, additional samples may be analyzed. In addition, at least one sample from the bio-barrier will be analyzed for a microorganism survey. Recommended locations for borings within the PRB are shown in Figure 28. Sampling will be performed in accordance with current LANL Standard Operating Procedures.

## 8.2 Install Additional Monitoring Wells

Several additional sampling wells will be installed preparatory to conducting a tracer test. Ten wells with 6 inch screens are proposed in the interior of the PRB. These wells would be screened below the reactive media in order to assess the capability of this zone to provide a bypass route for fluid flow beneath the PRB. Eight wells with 10 ft screens are proposed adjacent and downgradient of the wing walls and near the periphery of the PRB to assess potential leakage through the funnel walls and from the sides and corners of the PRB gate. Locations of proposed monitoring wells are shown in Figure 28.

### *8.2.1 Well Development*

Well development activities will be performed in accordance with LANL SOP-05.02, Rev. 2 - Well Development. Purge water will be contained and handled as appropriately characterized waste in accordance with current LANL Standard Operating Procedures or discharged on site under an approved Notice of Intent to discharge.

### *8.2.2 Well Sampling*

Groundwater samples will be collected from the new monitor wells located within the PRB as well as the original PRB sampling ports and wells and upgradient and downgradient monitor wells for geochemical and biological analyses. The purpose for these analyses is to characterize PRB geochemistry from a set of baseline samples prior to conducting a tracer test. Specific analyte suites will be determined prior to sampling in consultation with the LANL

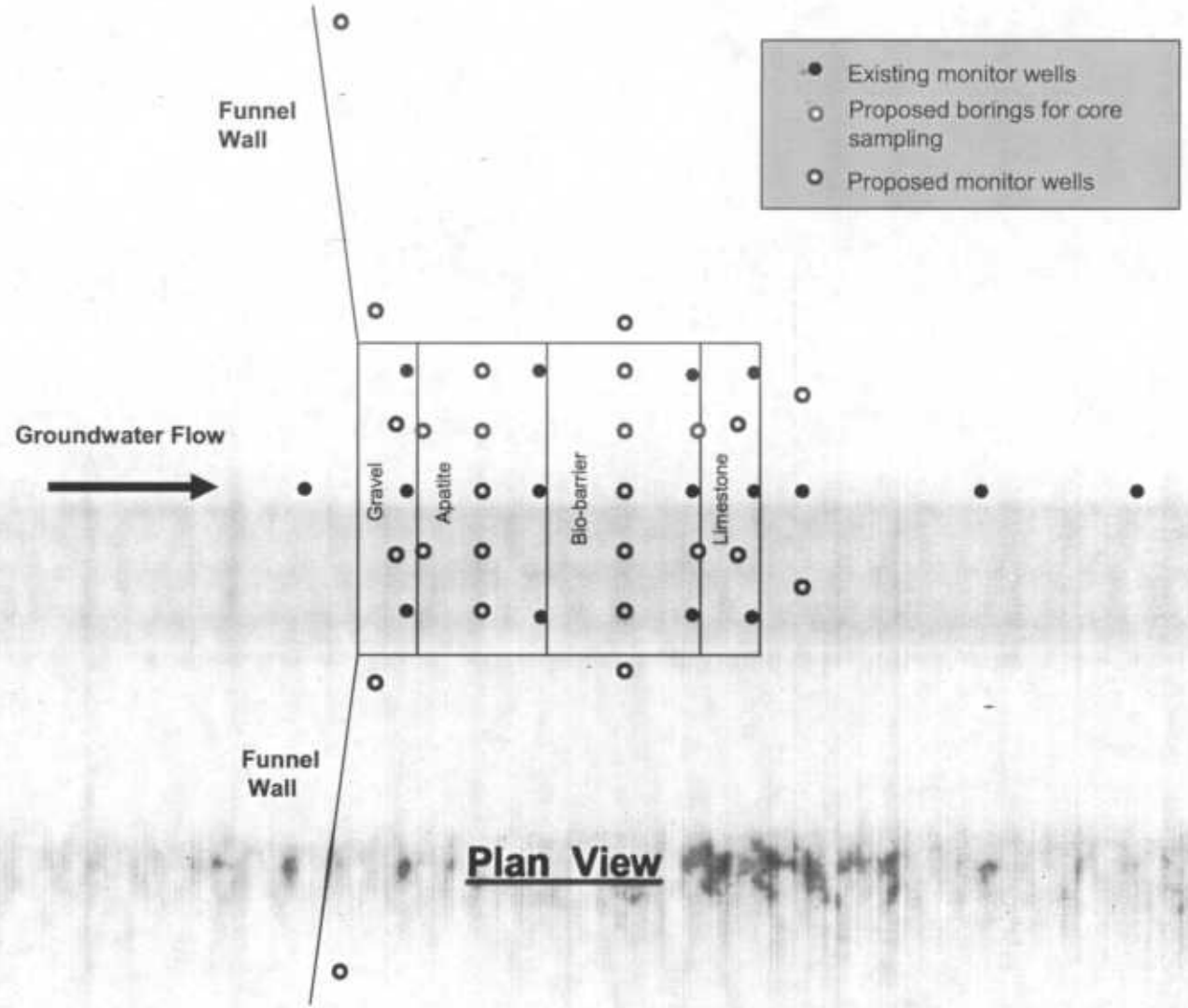


Figure 28

MORTANDAD CANYON PRB INVESTIGATION

**Locations of Proposed Borings and Monitor Wells**

*Daniel B. Stephens & Associates, Inc.*

9/29/06

Principal Investigator (PI). Water samples will be collected from a total of 24 wells including the 12 pre-existing sampling ports in the PRB interior, the 10 new wells installed in the PRB interior, and 1 upgradient and 1 downgradient well. Sampling will be conducted in accordance with current LANL Standard Operating Procedures with the exception that purging prior to sampling will not be performed in wells in the PRB interior. In those wells, a micropurging technique will be employed as per the discussion presented in Section 2.12.

## 8.3 Flowmeter Measurements

Flowmeter measurements will be performed in each of the 12 existing water sampling ports within the PRB, the 10 new wells installed within the PRB, and in each of the 8 new wells installed near the funnel wing walls and PRB gate as well as in 1 upgradient well and 1 downgradient well. Measurements of groundwater flow direction and velocity will be performed at discrete depths (up to three) within the screened interval of each port or well using packers to seal off each discrete zone. These measurements will be performed with a Model 40 Geoflo® horizontal heat-pulse groundwater flowmeter. The collected data will provide quantitative measurements of groundwater flow patterns within the PRB to determine whether preferential flow paths exist within the PRB that could affect geochemical treatment efficiency, and will provide information on flow velocities which may be compared to design criteria.

## 8.4 Conduct Tracer Test

A tracer such as potassium bromide or potassium iodide or a similar inert chemical will be injected upstream of the PRB and its movement through the PRB will be monitored. The purpose of the tracer test is to evaluate the hydraulic performance of the PRB and investigate the location of potential preferential flowpaths within and surrounding the PRB that may result in flow bypassing the reactive media. The additional monitoring wells described in Section 8.2 must be completed prior to conducting the tracer test.

### 8.4.1 Inject Tracer

The tracer injection will be accomplished by pumping the tracer solution into monitor well MW-1 located upgradient of the PRB gate. The appropriate volume and concentration of the tracer will be determined in consultation with the LANL PI.

### 8.4.2 Sample Ports and Wells

Each sampling port and well will be sampled daily for the duration of the test. If possible, two samples per day may be collected, but a minimum of one sample per day will be collected from each port or well. A total of 32 ports and wells will be sampled during the study (18 new wells, 12 sampling ports, the upgradient injection well and the downgradient well. A micropurging technique will be employed in wells located within the PRB interior. A minimum of one casing volume of water will be purged from wells screened in the alluvium outside of the PRB prior to sampling.

A field team comprised of three technical staff is required; two of which will be sampling full time and the third member will assist with sampling and transporting samples to the bench-top analysis lab which will be set up in town. This third member will also be available to assist with the analysis subtask as needed. In order to generate analysis results in near-real time, the standard LANL SOPs for sample management and handling will not be followed. Samples will be transported directly to the bench-top analysis lab with a frequency adequate to maintain a constant supply of samples ready for analysis. Processing through the SMO will not be required.

### 8.4.3 Tracer Analysis

Sample analysis for tracer content will be performed with an ion selective electrode (ISE) and bench-top ISE meter. The required equipment and supplies include the following:

- A bench-top ISE meter such as an Orion 720A or comparable instrument

- Either a combination electrode specific to the tracer ion employed in the test or an ion specific electrode and reference electrode pair

- Multiple standard solutions of the tracer chemical at varying concentrations for instrument calibration. A 3- to 5-point calibration is preferable for enhanced accuracy.

- Beakers, gloves, and safety glasses

- Carboys or plastic drums for waste storage

The bench-top analysis lab will be close enough to the PRB site so that samples may be quickly transported and analyzed within a day of sample collection. This will allow the progress of the tracer through the PRB to be monitored in near-real time. The sampling will be conducted daily for a minimum of one month or until breakthrough in the downgradient well is observed, whichever comes first. Afterward, monitoring of tracer progress will continue on an expanded schedule to be determined in consultation with the LANL PI. Once tracer concentrations have significantly declined from peak levels in all wells where it was detected, the monitoring can be stopped.

## 8.5 Dismantle the PRB

The PRB will be systematically deconstructed as a final step to assess PRB performance and possible causes for performance impairment and/or hydraulic bypass. The deconstruction process will be carefully documented and overseen by a qualified engineer with experience in the design and construction of PRBs employing the funnel and gate design and the placement of sheet piling.

### *8.5.1 PRB Excavation*

Excavation of the PRB should be undertaken after the monsoon season to minimize the threat of flooding in the canyon. Systematic excavation of the PRB will be performed with a backhoe while detailed observations are made and documented by the field team. Excavation will be in 1

to 2 ft lifts followed by visual examination, documentation of observations (written and photographic), and sampling of materials as recommended by the senior staff on hand. Field measurements of soil density will be performed with a nuclear density gauge. The field team will consist of two staff-level geologists with oversight by a senior scientist and a senior engineer/PRB expert. The proposed general sequence of work will be as follows:

1. Determine the best course of action to reduce groundwater flow through the PRB during excavation and propose the final solution to the LANL PI. Possible approaches include installation of sheet piling at the upstream entrance to the PRB gate and pumping of excess water to holding tanks or a retention basin.

2. Excavate and stockpile the backfill overlying the central apatite and bio-barrier cells down to the geomembrane overlying the gravel, apatite, bio-barrier, and limestone cells.

3. Inspect and remove the geomembrane.

4. Excavate the top half of the gravel cell down to the level of the top of the apatite and bio-barrier cells.

5. Excavate the top half of the limestone cell down to the level of the top of the apatite and bio-barrier cells.

6. Remove the top half of the steel grates that separated the upper portions of the gravel and limestone cells from the backfill so that a level surface over all 4 cells is created.

7. Excavate the lower portion of the gravel cell.

8. Excavate the apatite cell.

9. Remove the steel grate that separated the gravel and apatite cells.

10. Excavate the bio-barrier cell.

11. Remove the steel grate that separated the apatite and bio-barrier cells.

12. Excavate the lower portion of the limestone cell.

13. Remove the steel grate that separated the bio-barrier and limestone cells.

14. Perform visual inspection/documentation of gate construction and integrity and bedrock floor.

Table 14 shows the in-place volumes of the materials to be excavated from the interior of the PRB. These volumes are based on information provided in Kaszuba et al. (2003) and the design drawings provided in Shaw's final design report (2002).

**Table14. Excavated PRB Material Volumes**

| Material | Length (ft) | Width (ft) | Height (ft) | Volume | |
|---|---|---|---|---|---|
| | | | | ($ft^3$) | ($yd^3$) |
| Upper sand and gravel backfill cap (above all 4 cells) | 24 | 17 | 7 | 2,856 | 105.8 |
| Lower sand and gravel backfill (above apatite and bio-barrier cells) | 16 | 17 | 10 | 2,720 | 100.7 |
| Gravel cell (volcanic scoria) | 3.5 | 17 | 20 | 1,190 | 44.1 |
| Apatite cell (mineral calcium phosphate) | 7 | 17 | 10 | 1,190 | 44.1 |
| Bio-barrier cell (10% cottonseed meal, 65% pecan shells, 25% pea gravel) | 9 | 17 | 10 | 1,530 | 56.7 |
| Limestone gravel | 3.5 | 17 | 20 | 1,190 | 44.1 |
| Total | | | | 10,676 | 395.4 |

ft = Feet  $ft^3$ = Cubic feet  $yd^3$ = Cubic yards

Although efforts to seal it off are planned, some water leakage through the gate is likely and will require pumping to control. It is anticipated that the steel grates that provide the inlet to and outlet from the PRB gate and separate it from the upgradient and downgradient alluvial sediments will be kept in place. Additional shoring of these grates may be necessary to ensure safe conditions for performing the visual inspections and photographic documentation within the excavated vault. Instruments to monitor potentially explosive gases such as hydrogen and

methane from the bio-barrier will be employed during the excavation. Radiation monitoring of excavated materials will also be performed. Excavated materials will be contained and handled as appropriately characterized waste in accordance with current LANL Standard Operating Procedures.

### 8.5.2 Site Restoration

The removal and disposition of the PRB gate structure and wing walls would add to both logistics and expenses and a significant volume of wastewater could be generated if the wing walls are perforated to restore groundwater flow through the alluvium. Consequently, it is proposed that these structures be left in place and not modified beyond the deconstruction activities described in Section 8.5.1. The planned restoration activities will result in groundwater flow continuing to be funneled through the PRB gate.

### 8.5.3 Backfill

The PRB gate will be backfilled with inert materials having hydraulic properties similar to the alluvial sediments. Backfill materials will also be used to bring the surface up to the surrounding grade. Previously excavated overburden will be used to the extent possible. If all of the previously excavated backfill is used, an additional backfill volume requirement of approximately 250 cubic yards is anticipated. This will likely consist of either crushed tuff or quarried sand and gravel from a local supplier. The backfill material will be placed in 1 to 2 ft lifts that will be mechanically compacted if it is determined that a compactor can safely enter the excavation.

### 8.5.4 Site Restoration

Site restoration activities will consist of grading the site and revegetation with native grasses.

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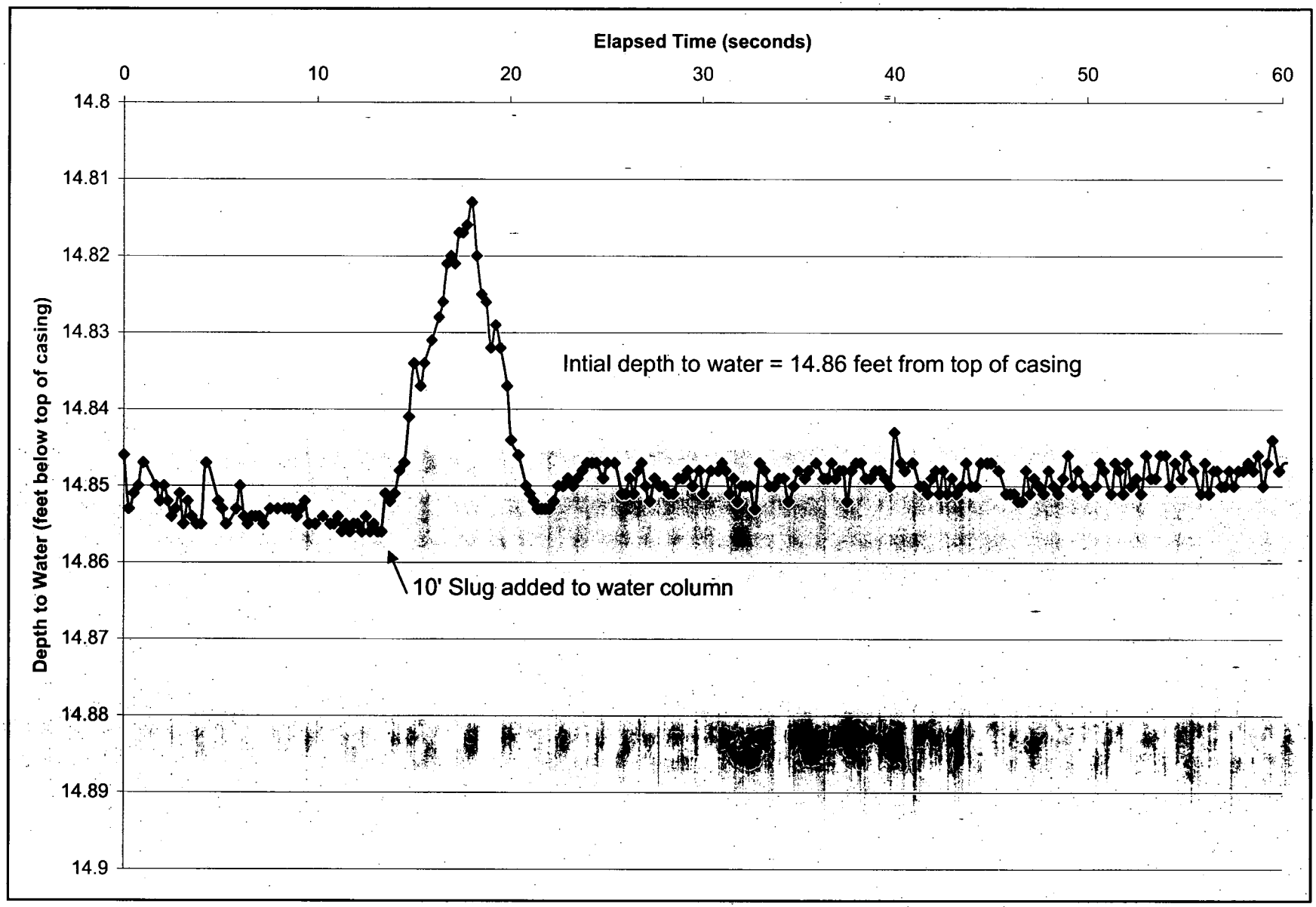
# Appendix A

# Slug Test Data

## PRB SW-A1 Falling Head Test #1




P:_ES06-121\PRB-Eval.9-06\Appx A\Appendix A-slug test plots.xls SW-A1 FH1 Chart

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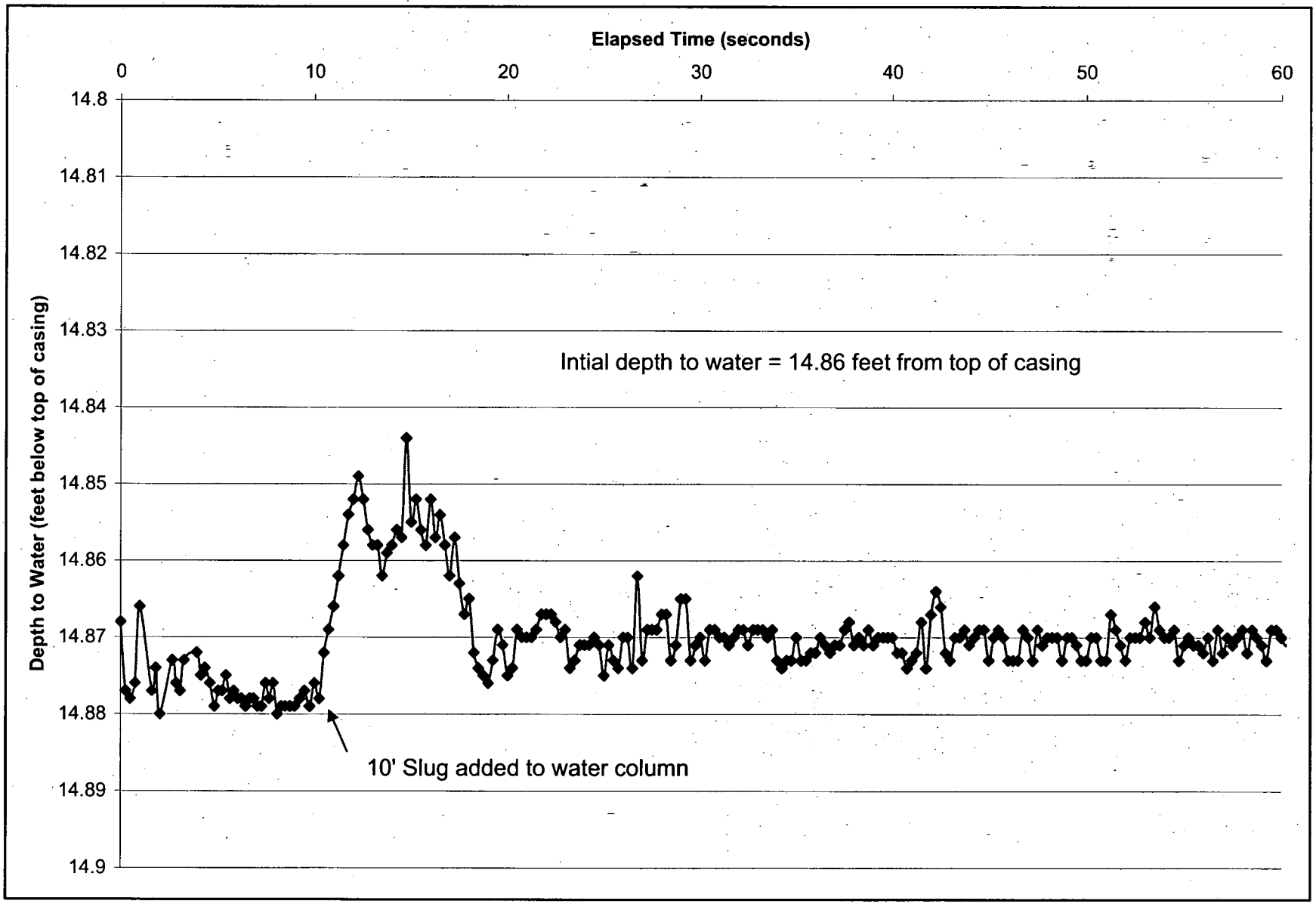


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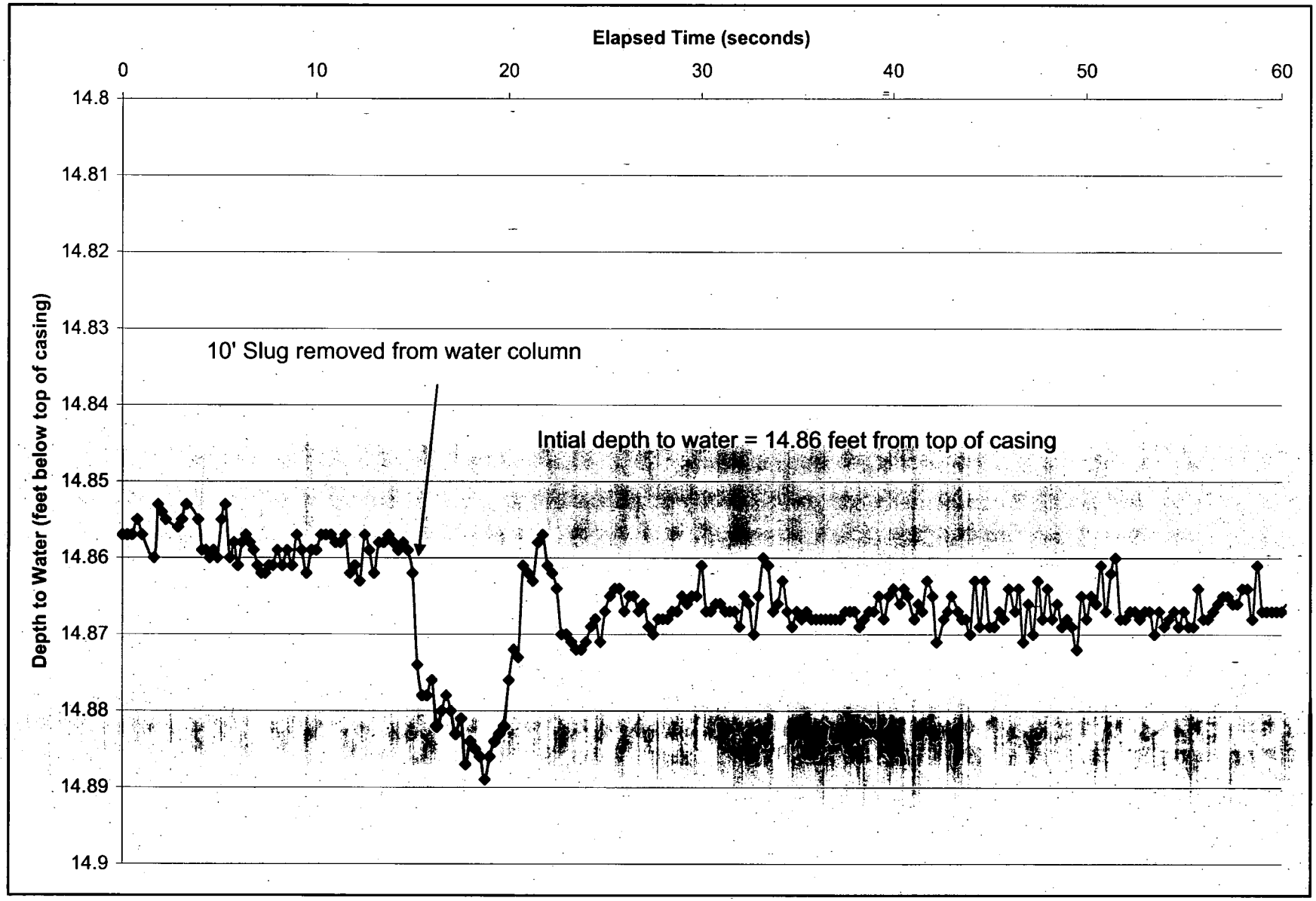


P:_ES06-121\PRB-Eval.9-06\Appx A\Appendix A-slug test plots.xls SW-A1 RH1 Chart

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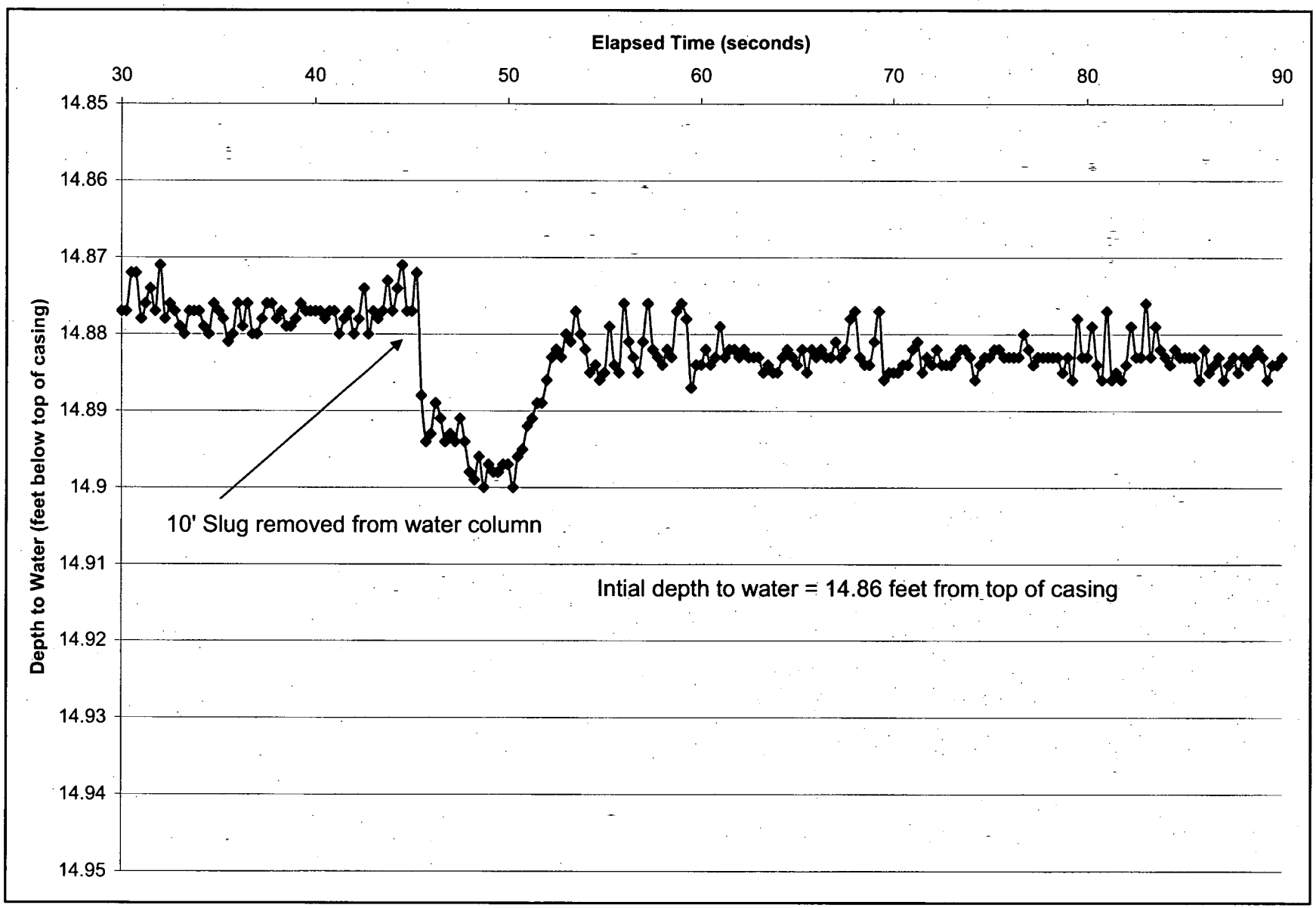


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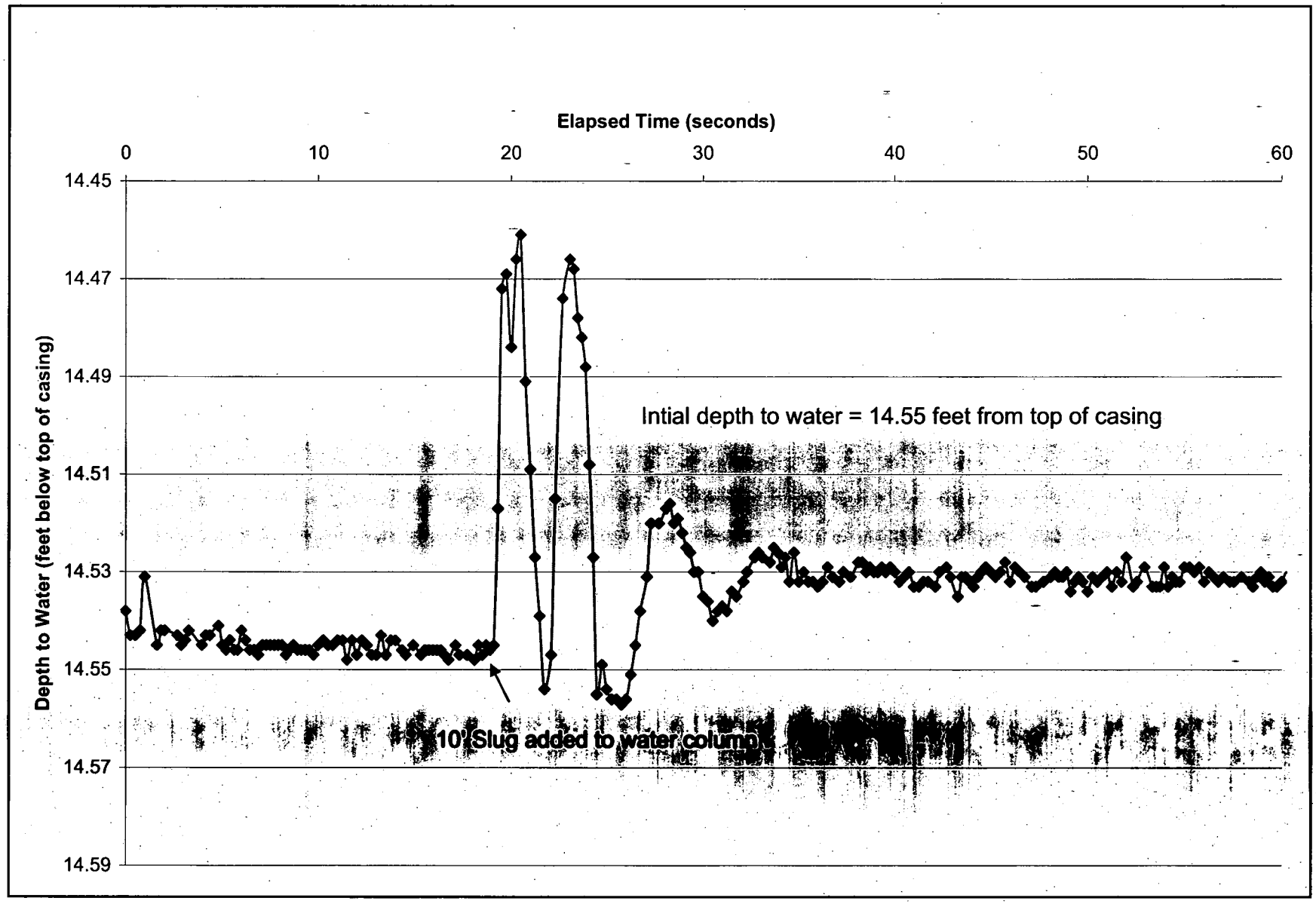


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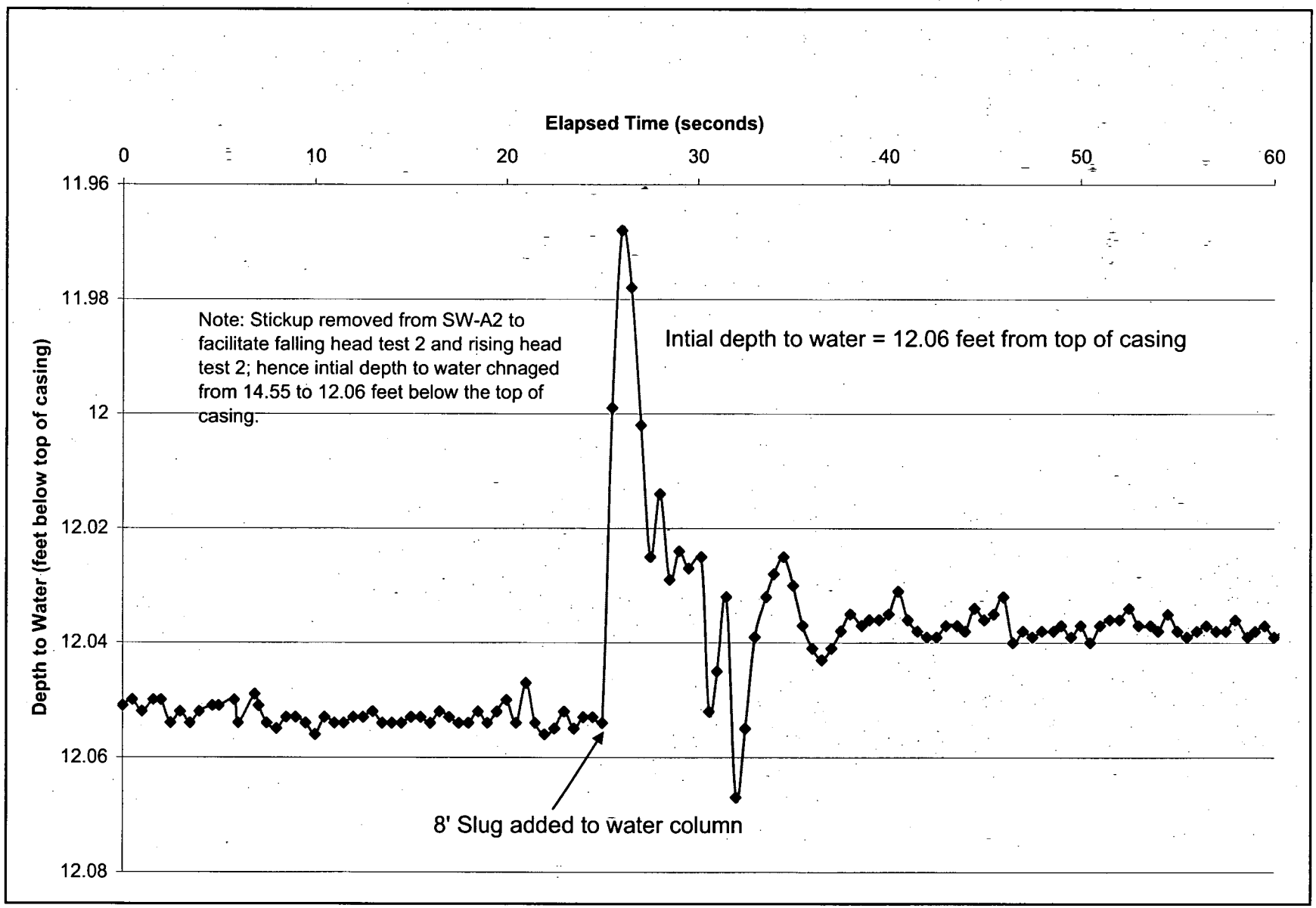


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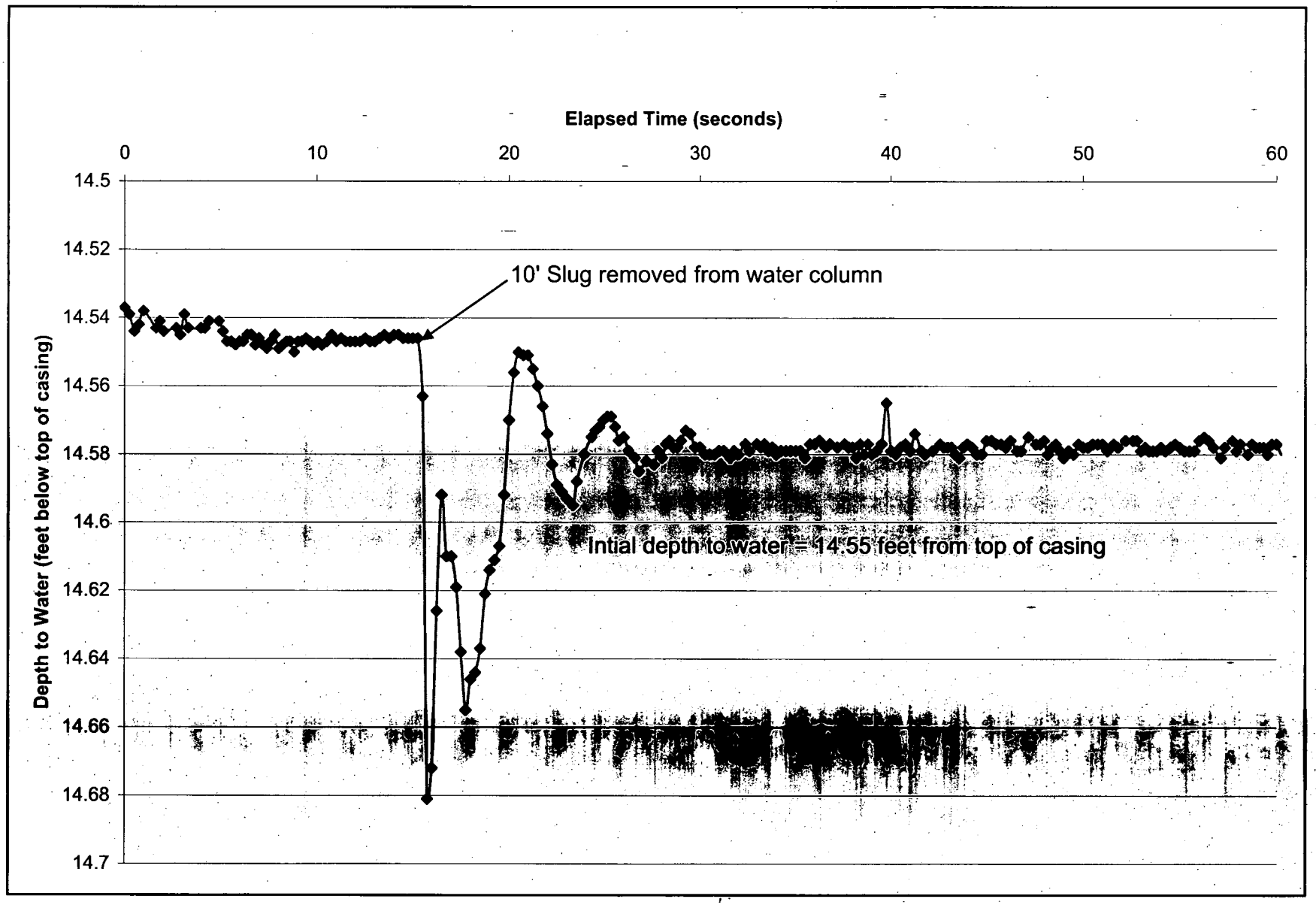


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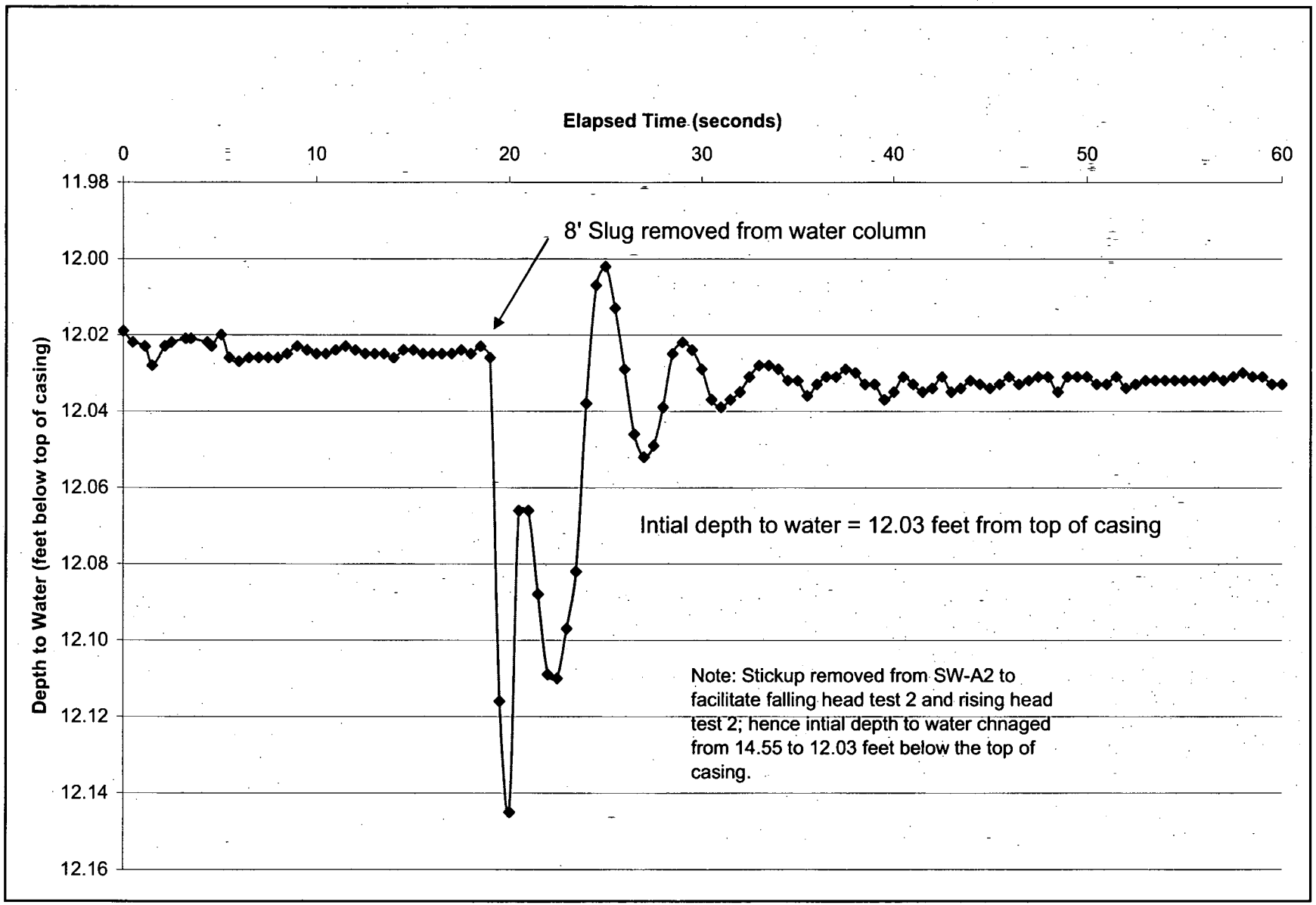


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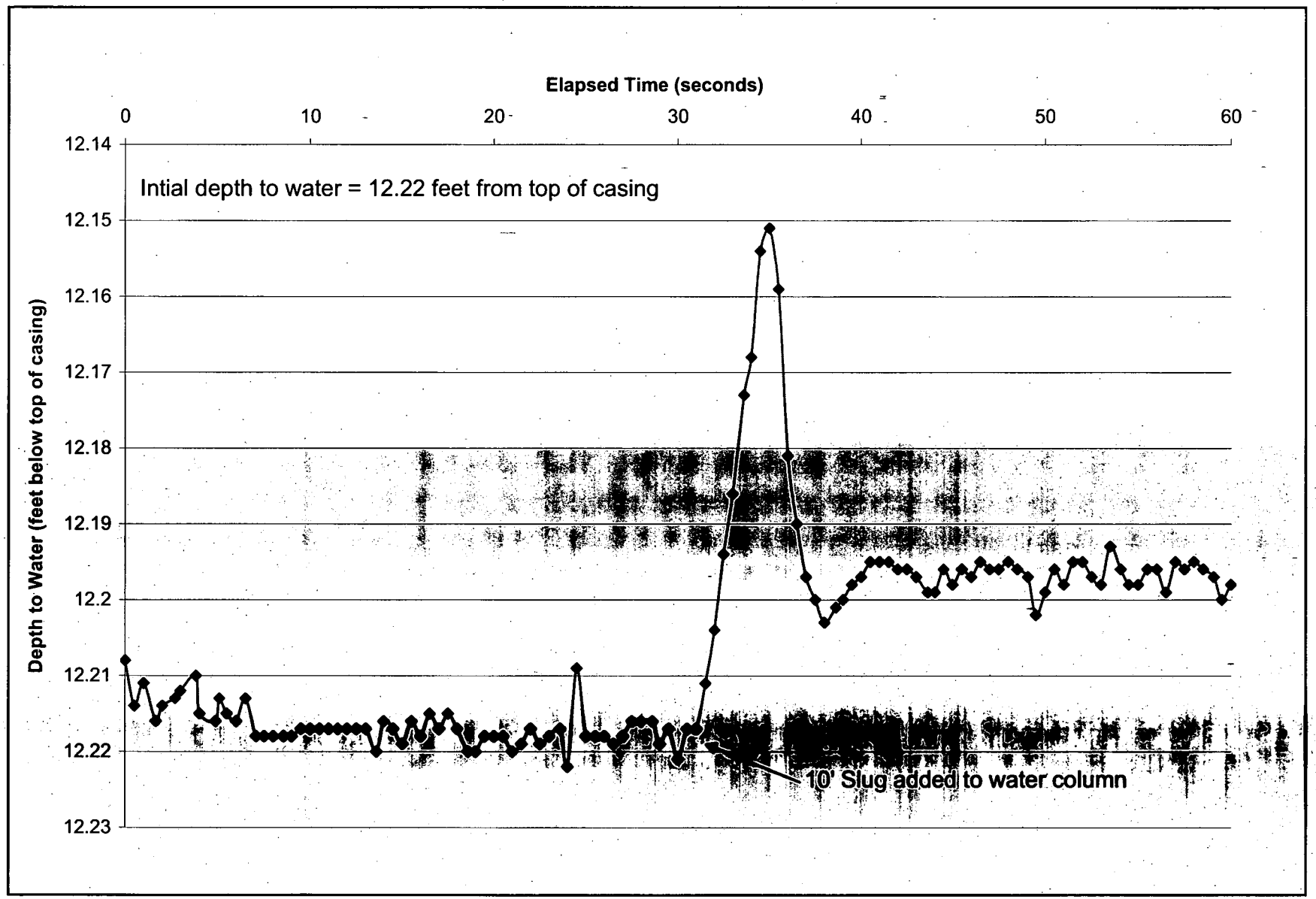


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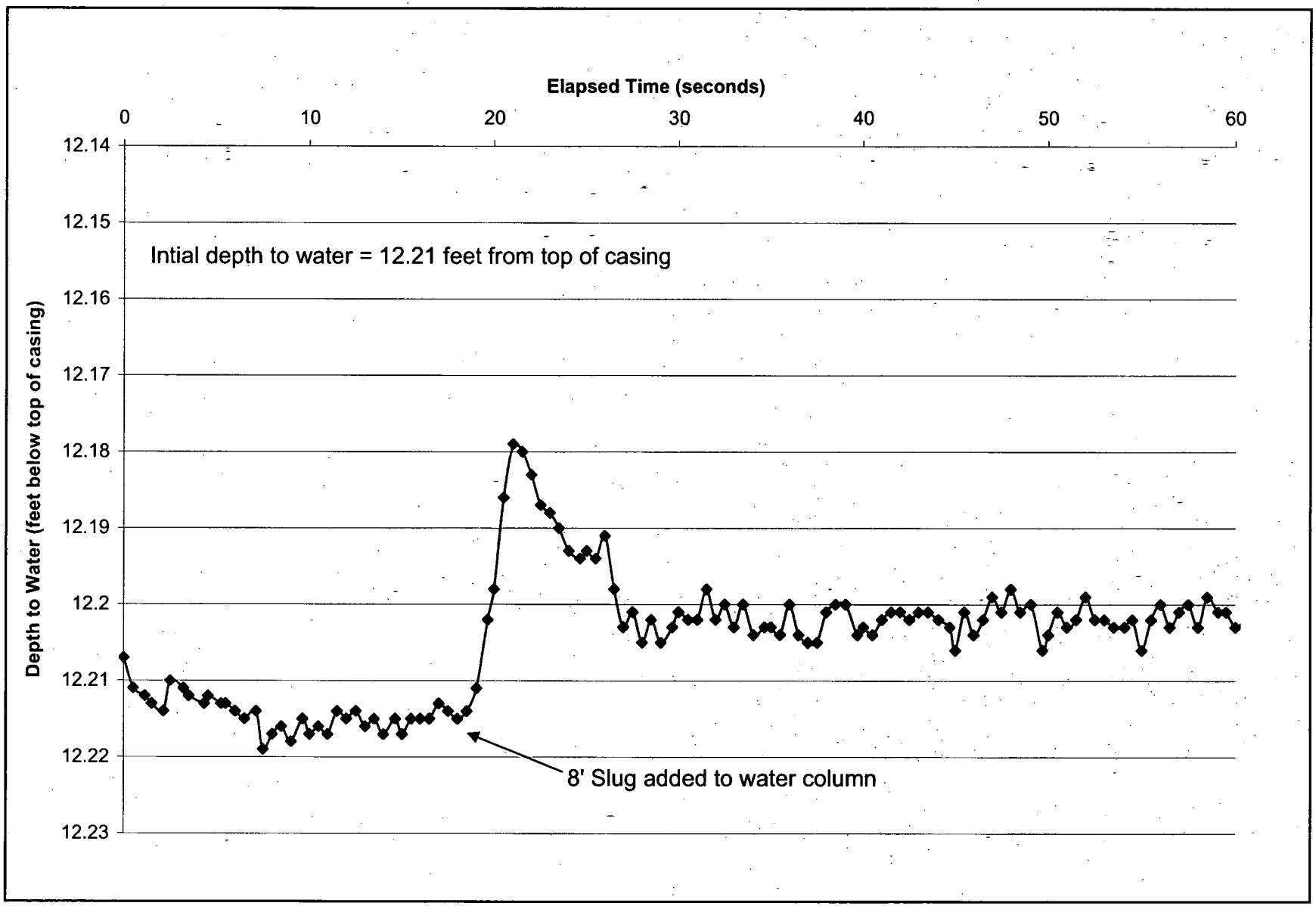


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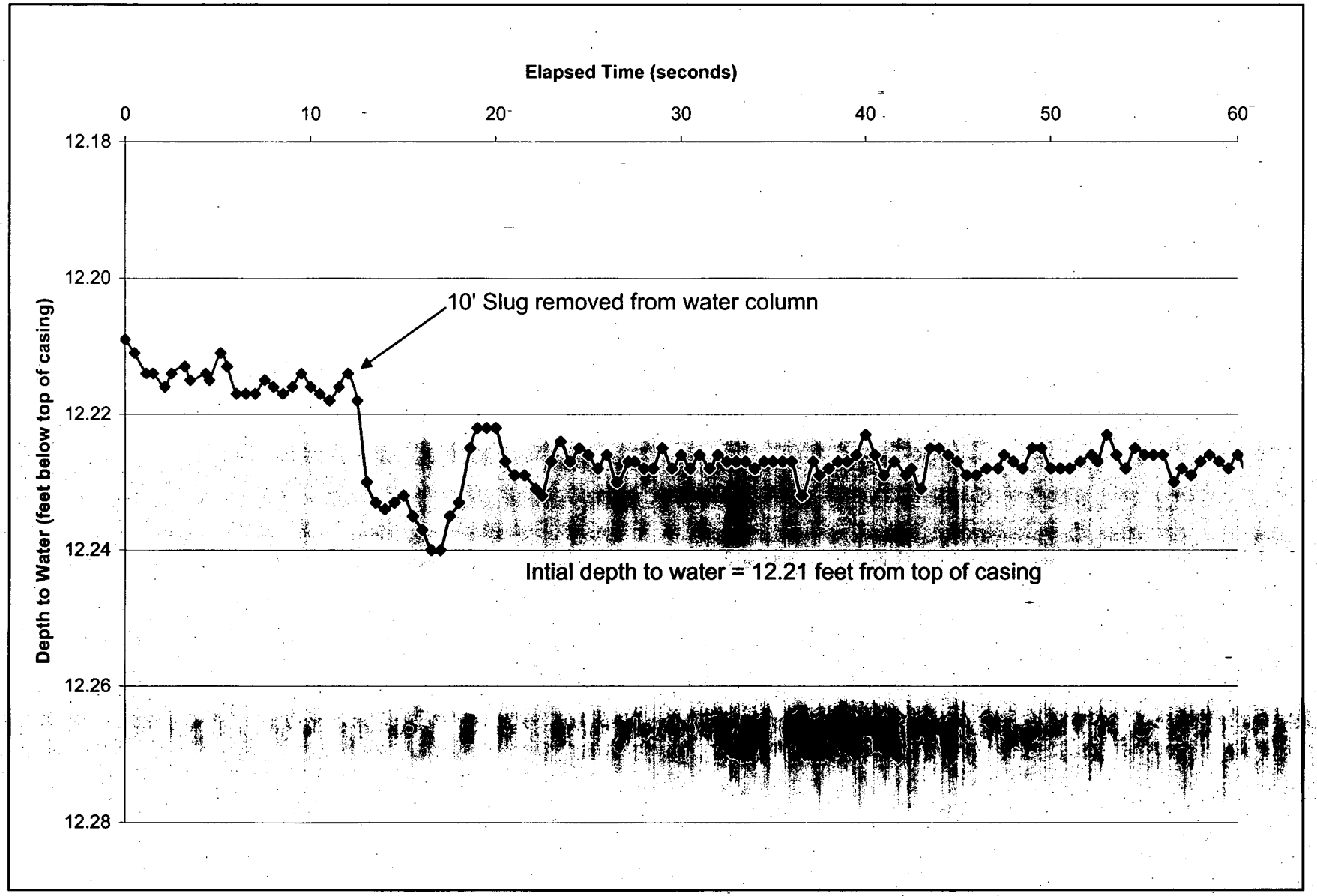
## PRB SW-A3 Rising HeadTest #1

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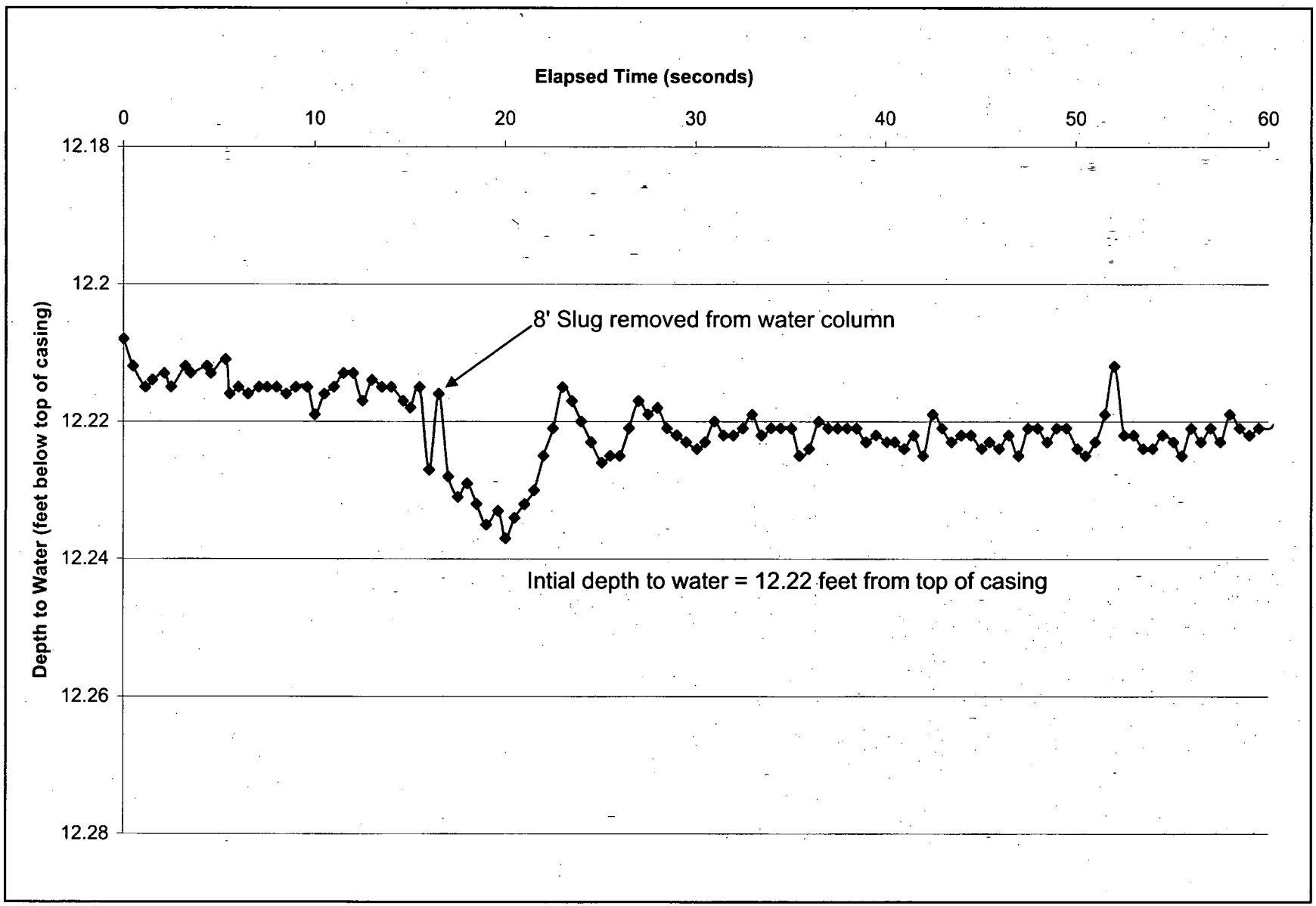


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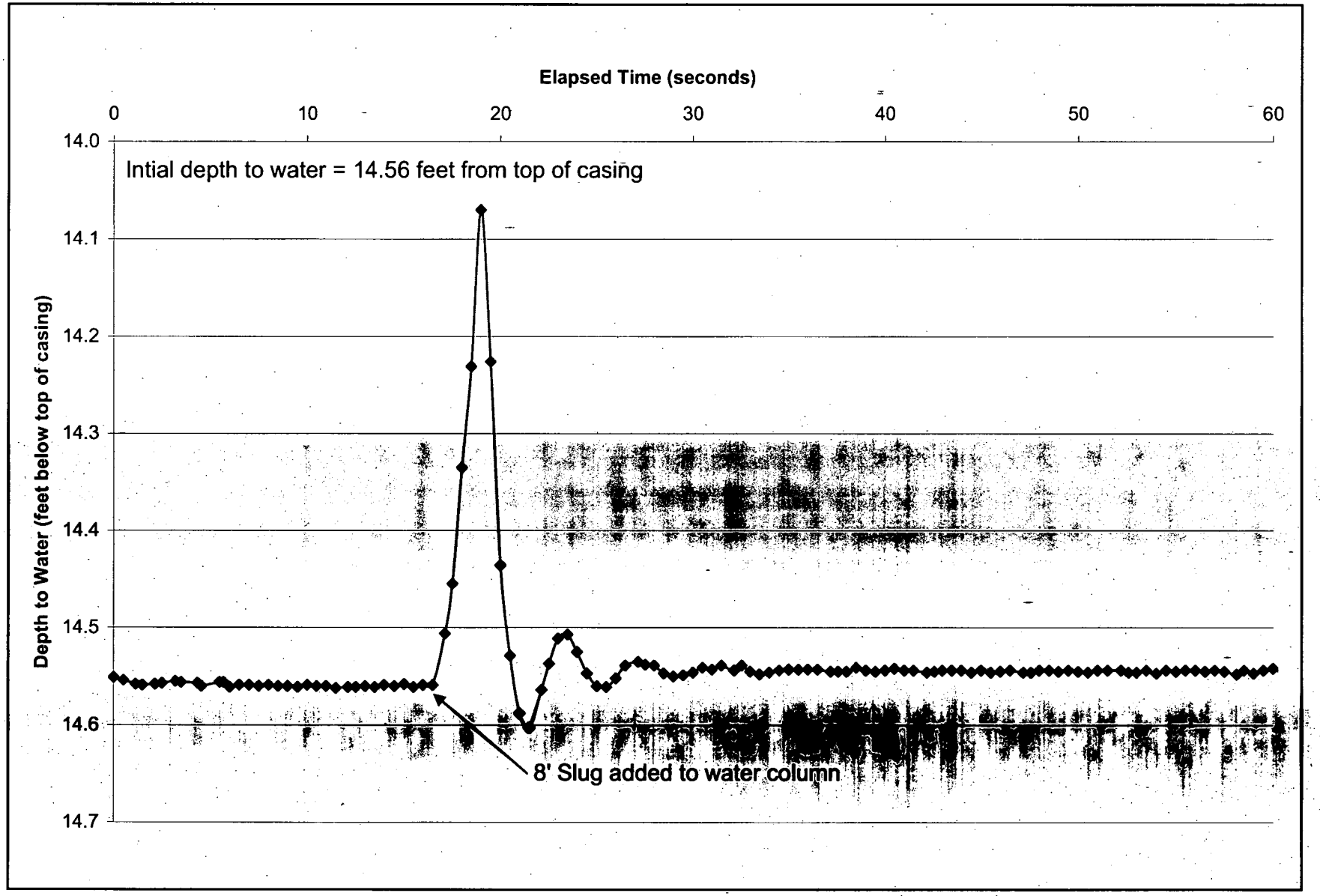


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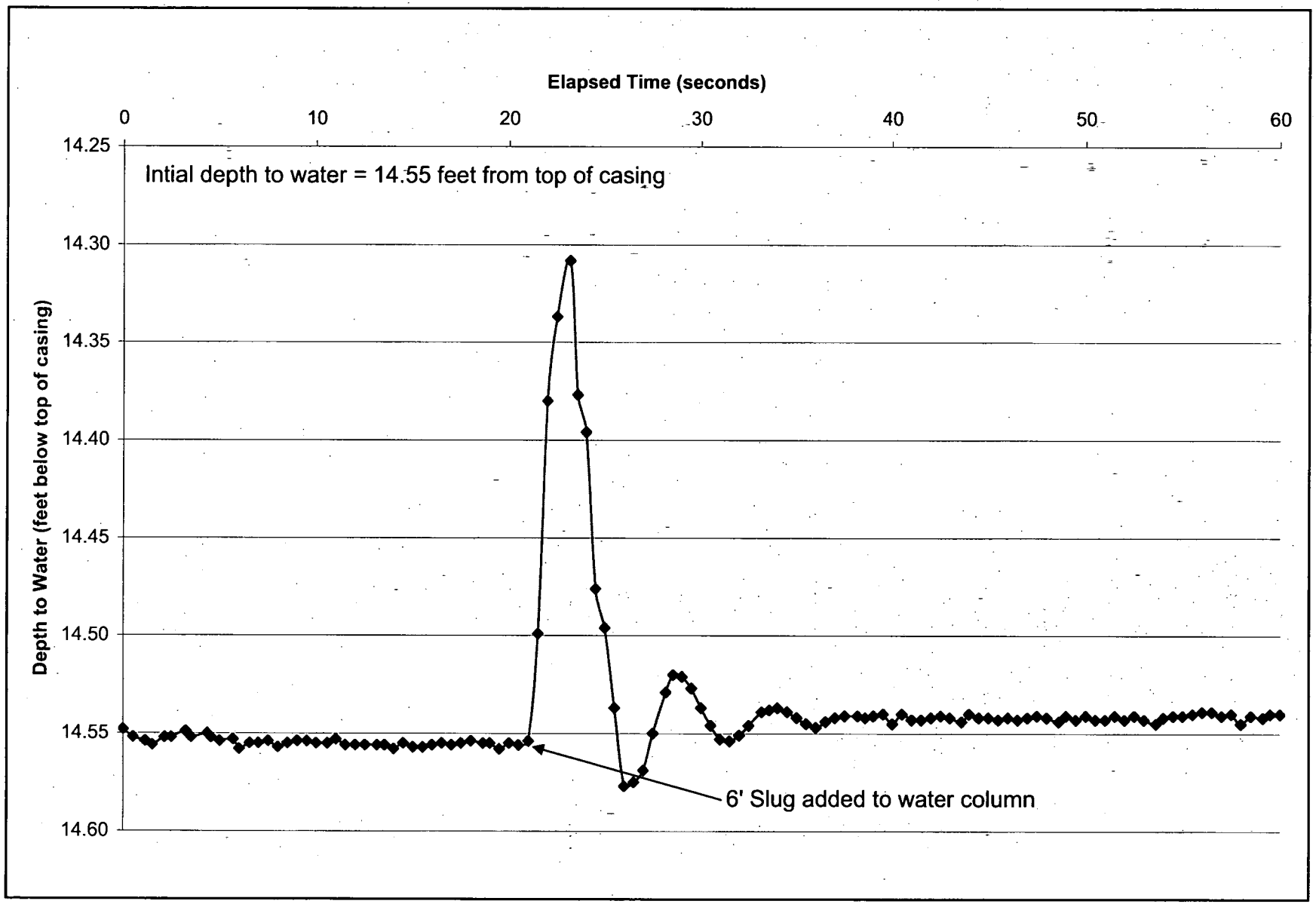


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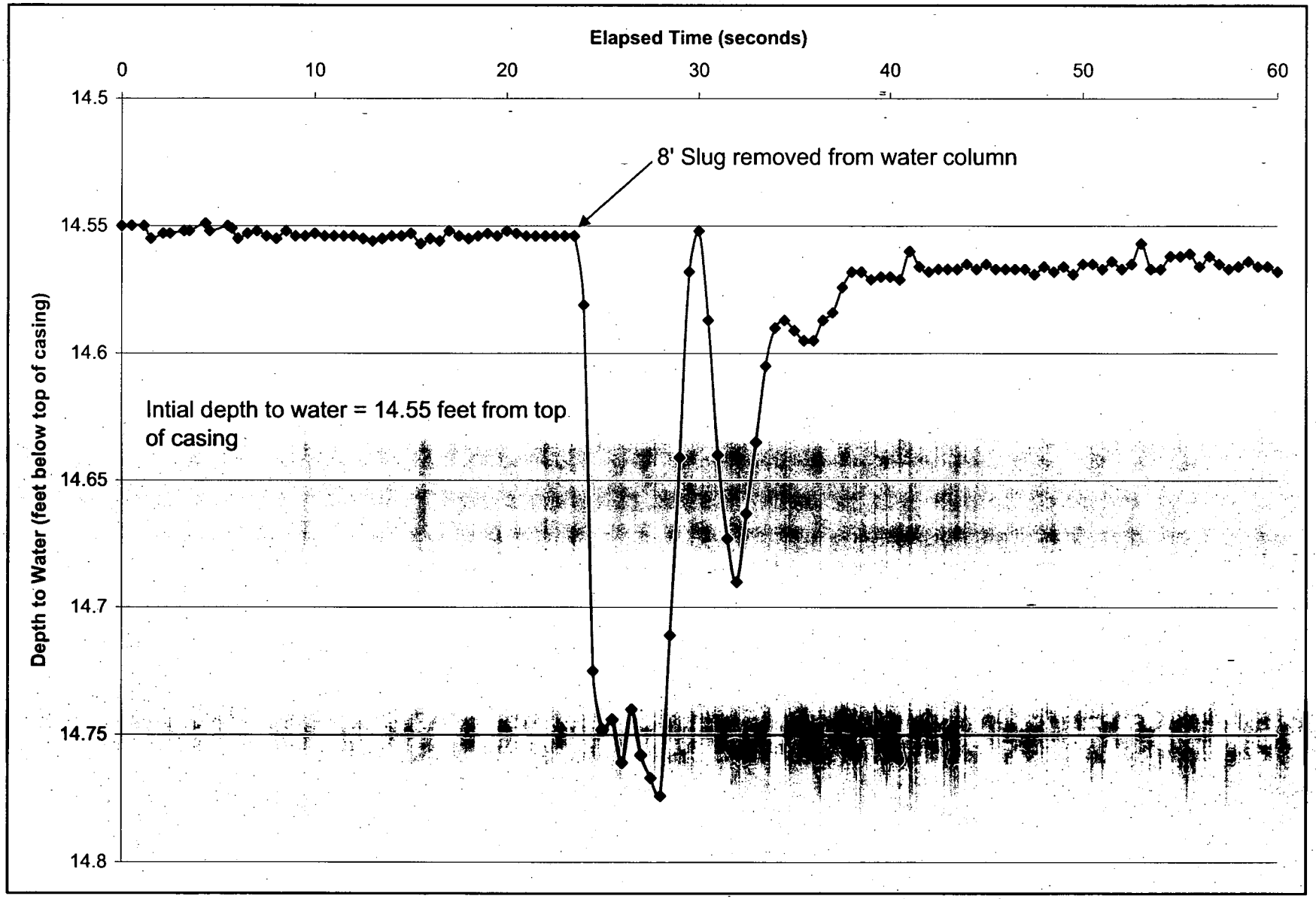


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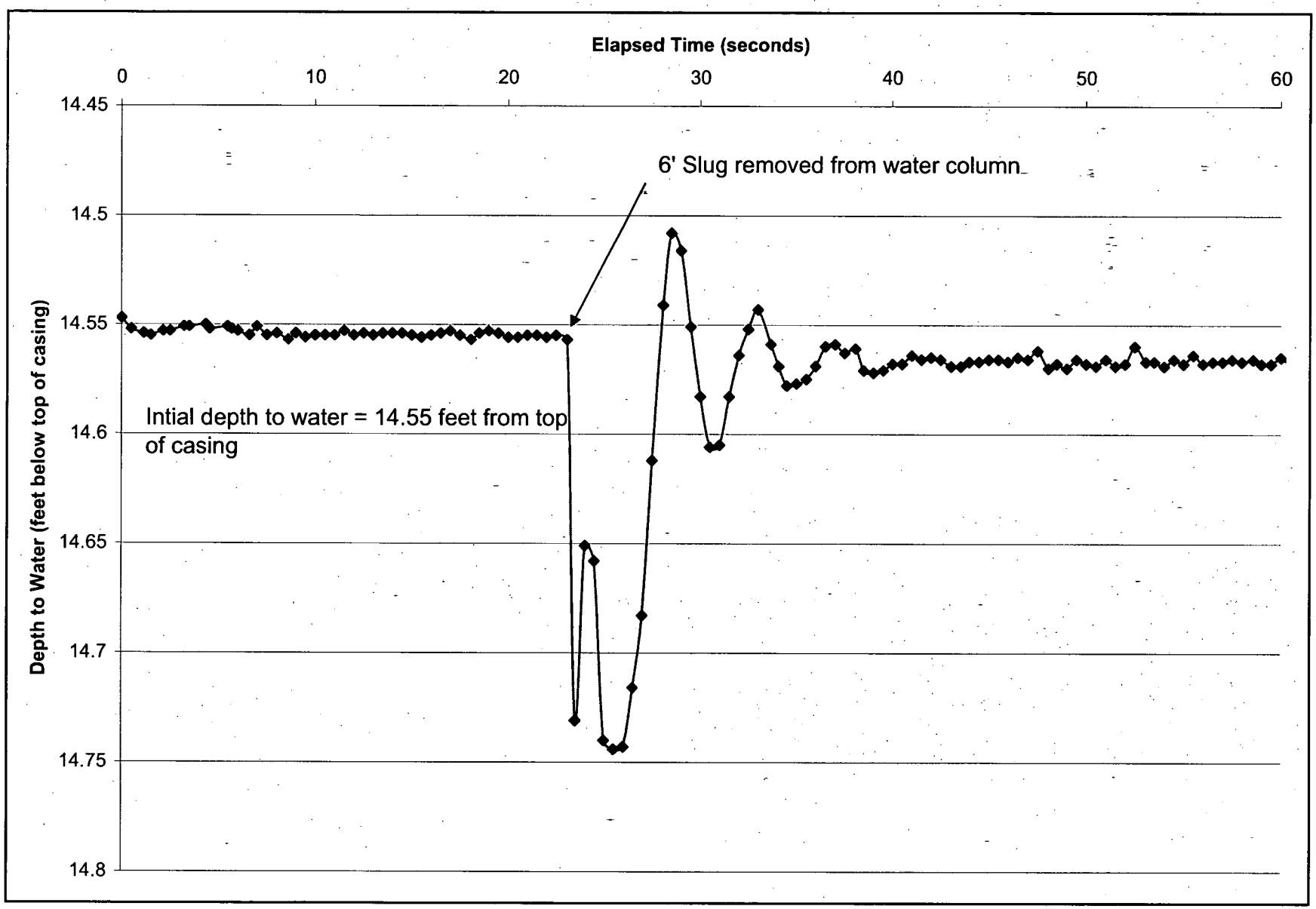


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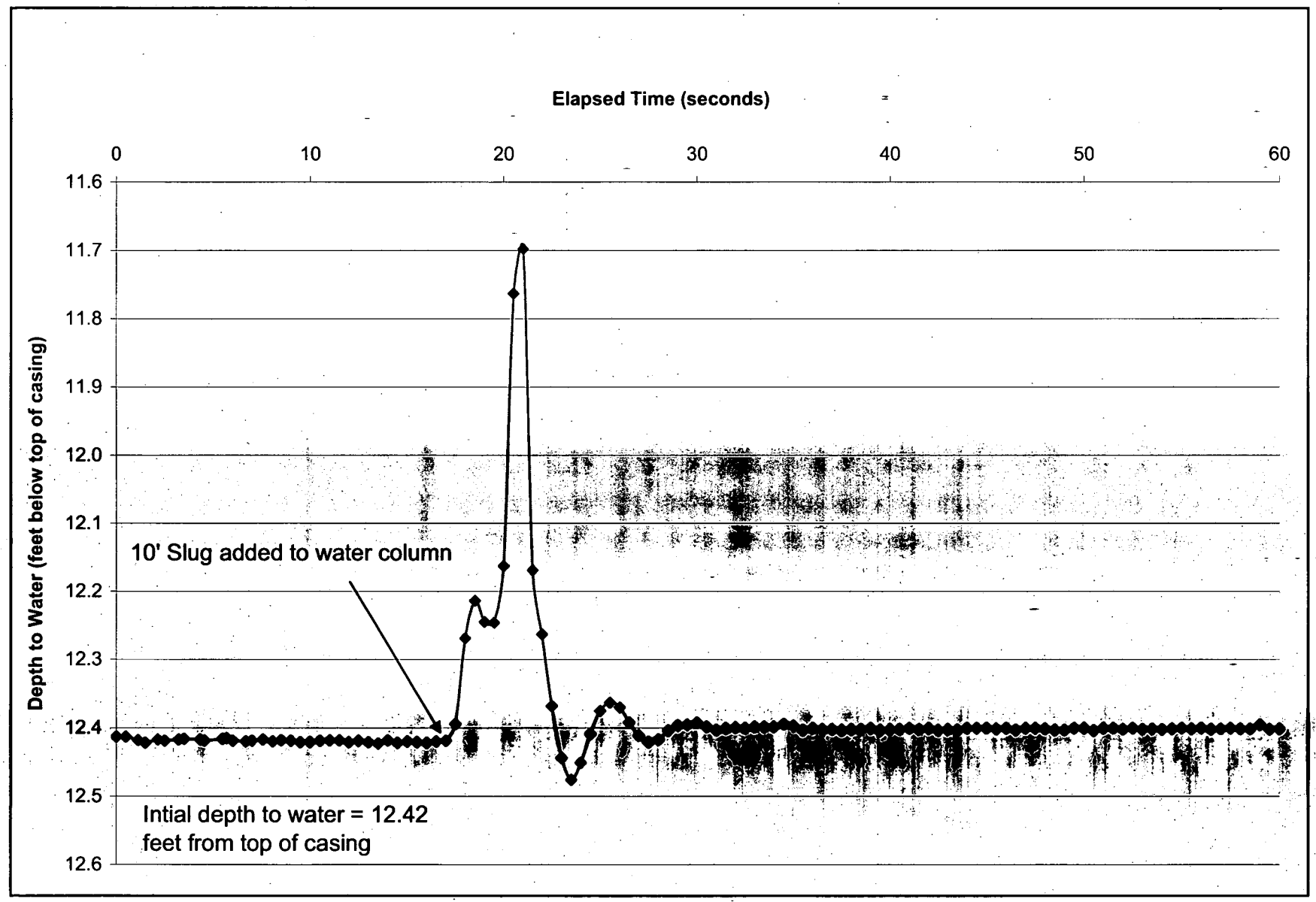


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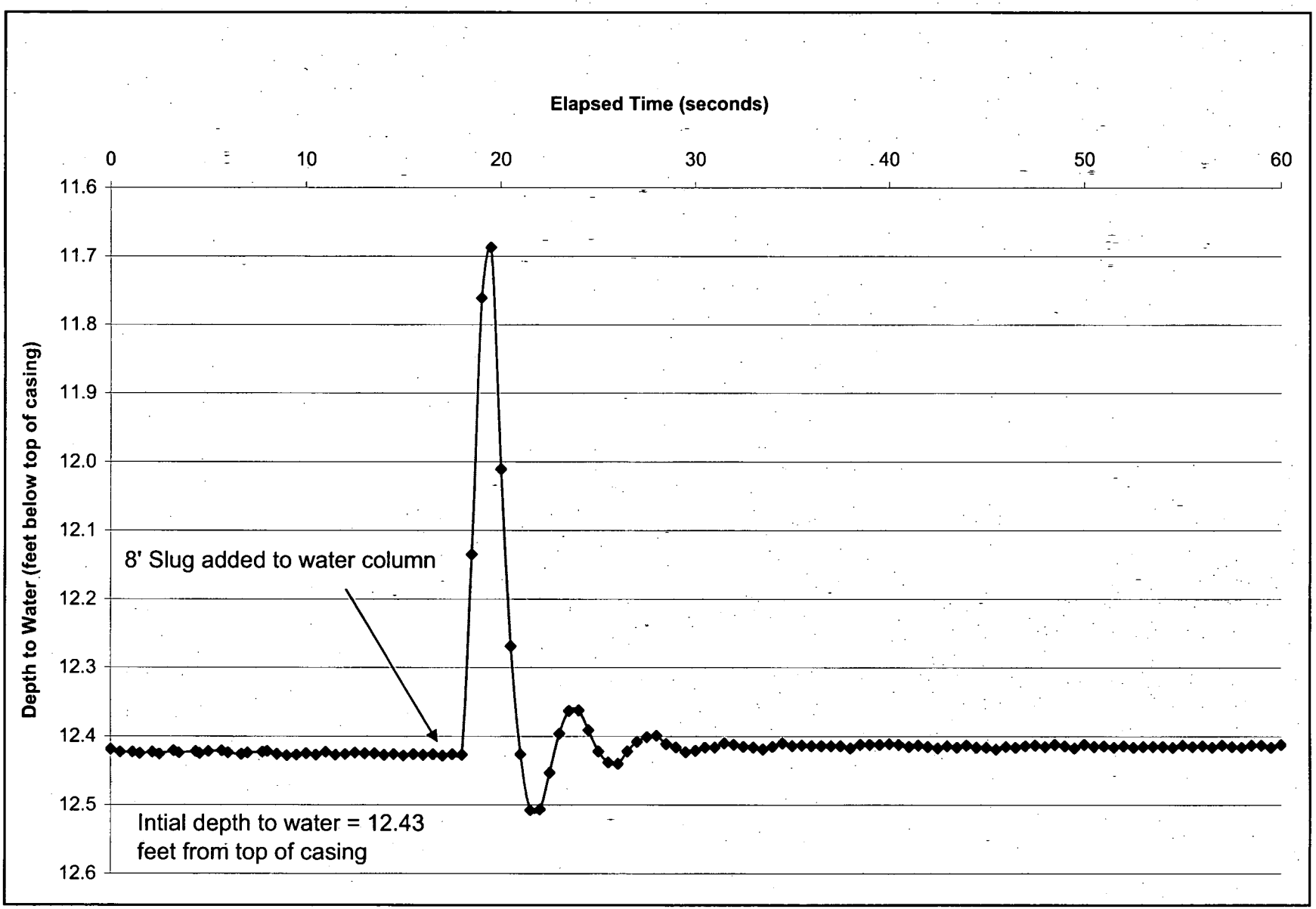


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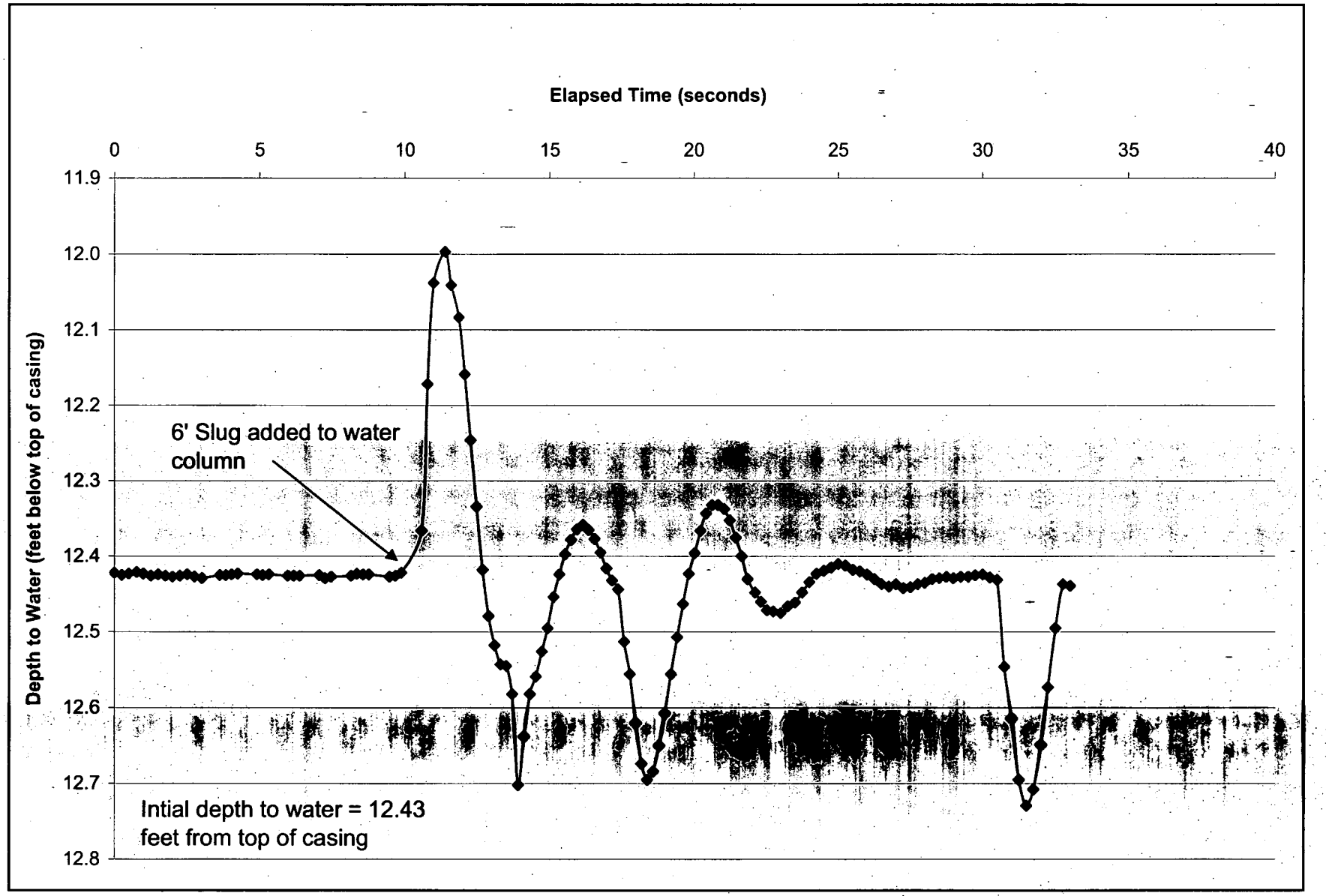


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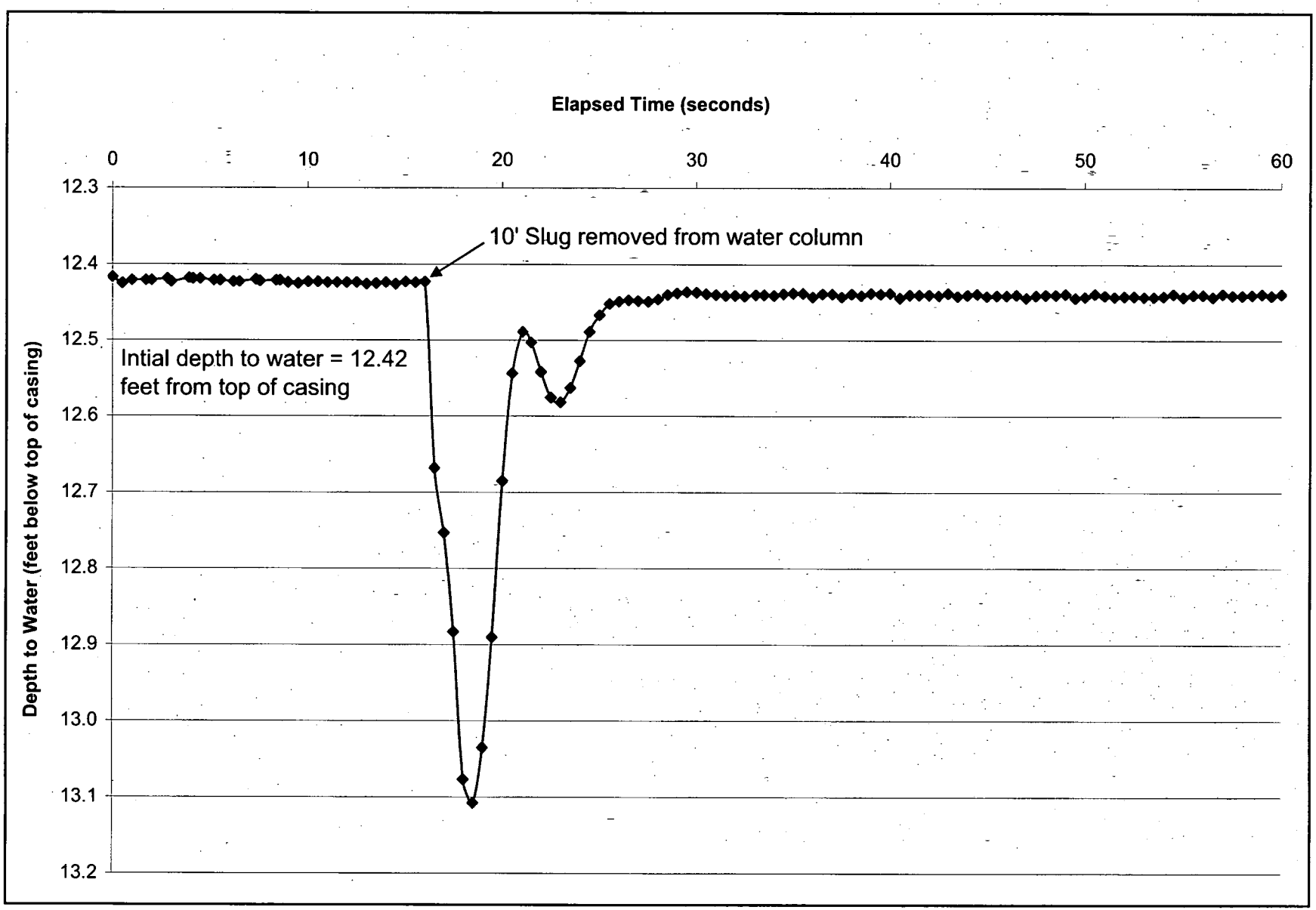
## PRB SW-B3 Rising Head Test #1

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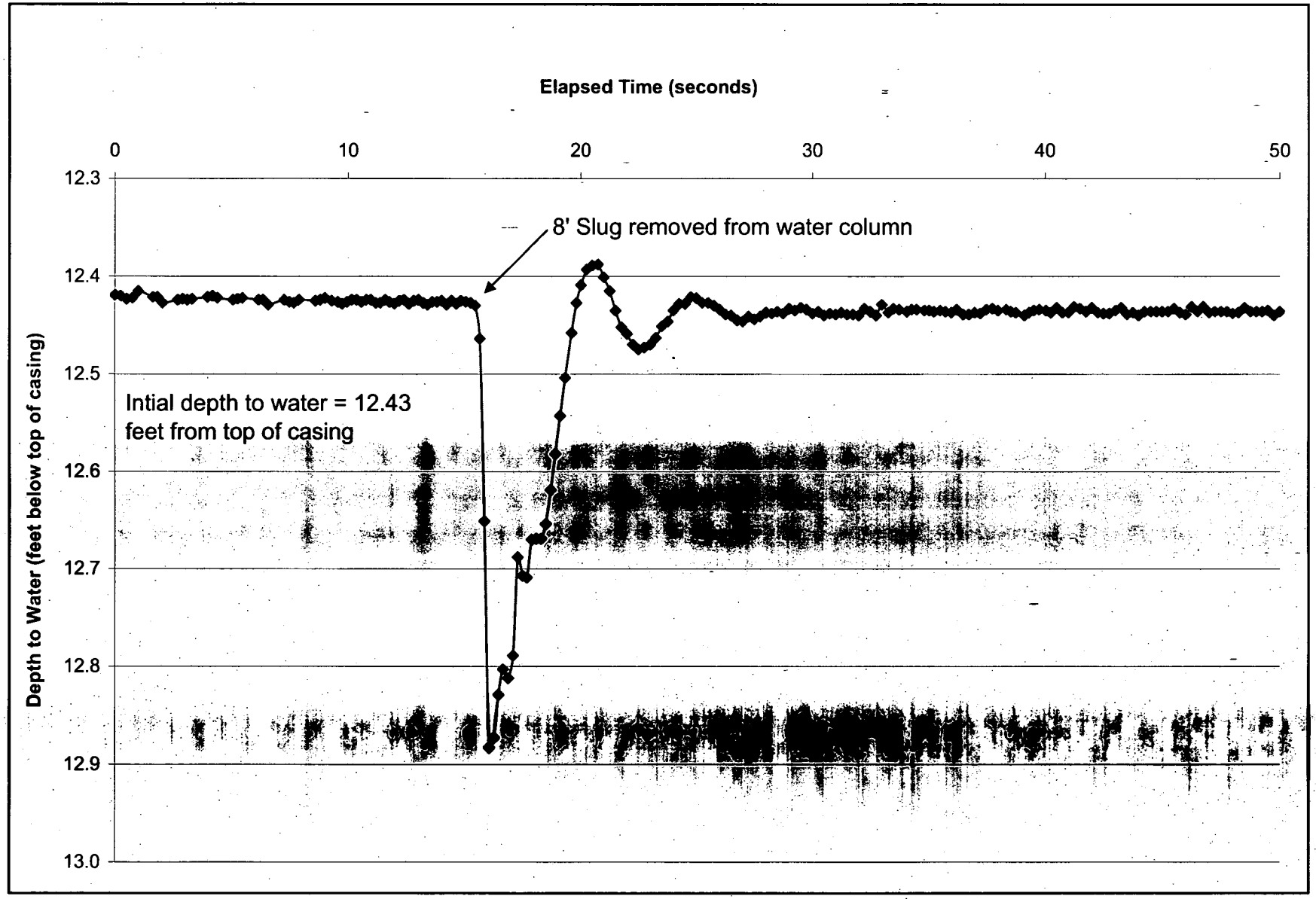


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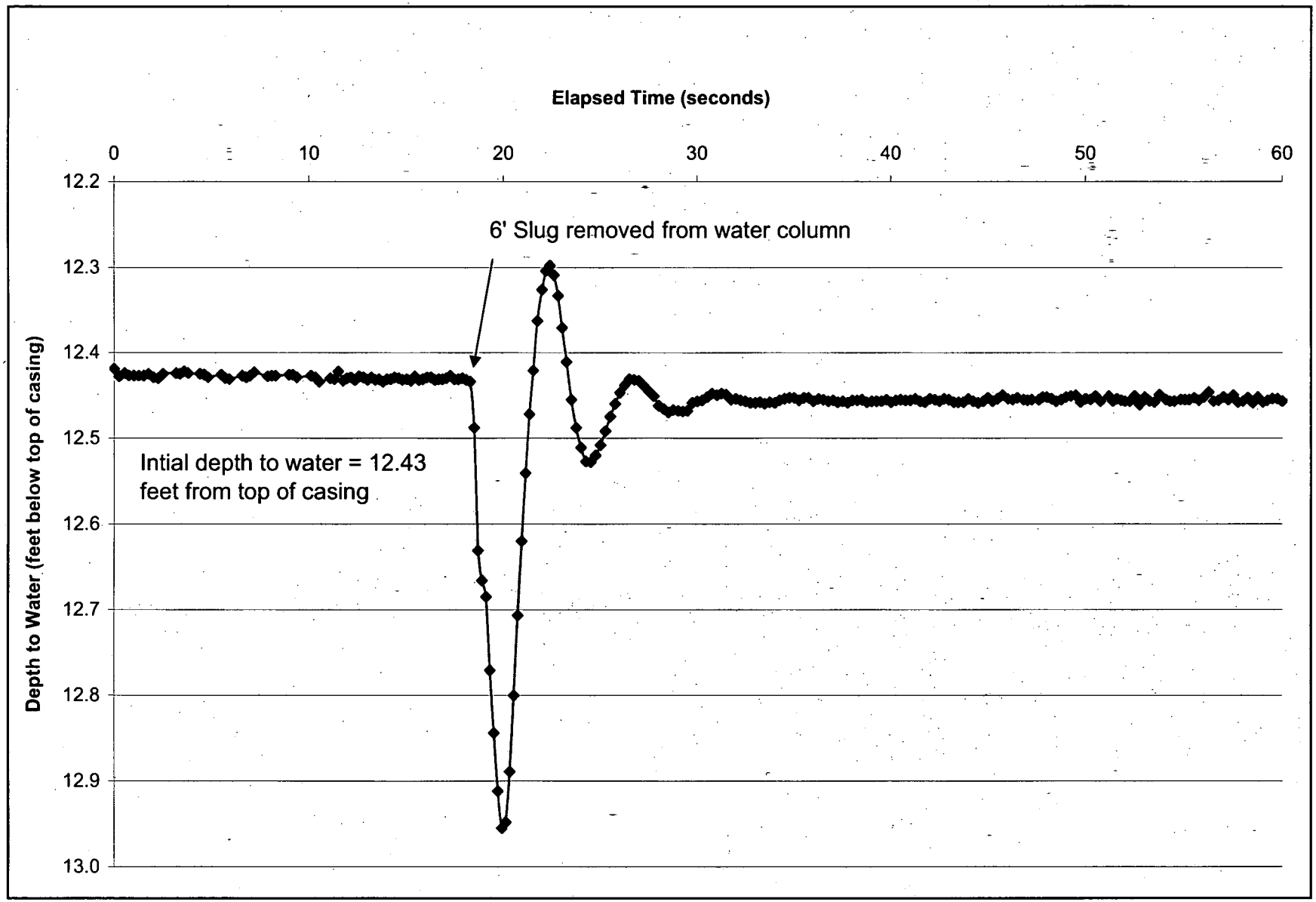
## PRB SW-B3 Rising Head Test #3

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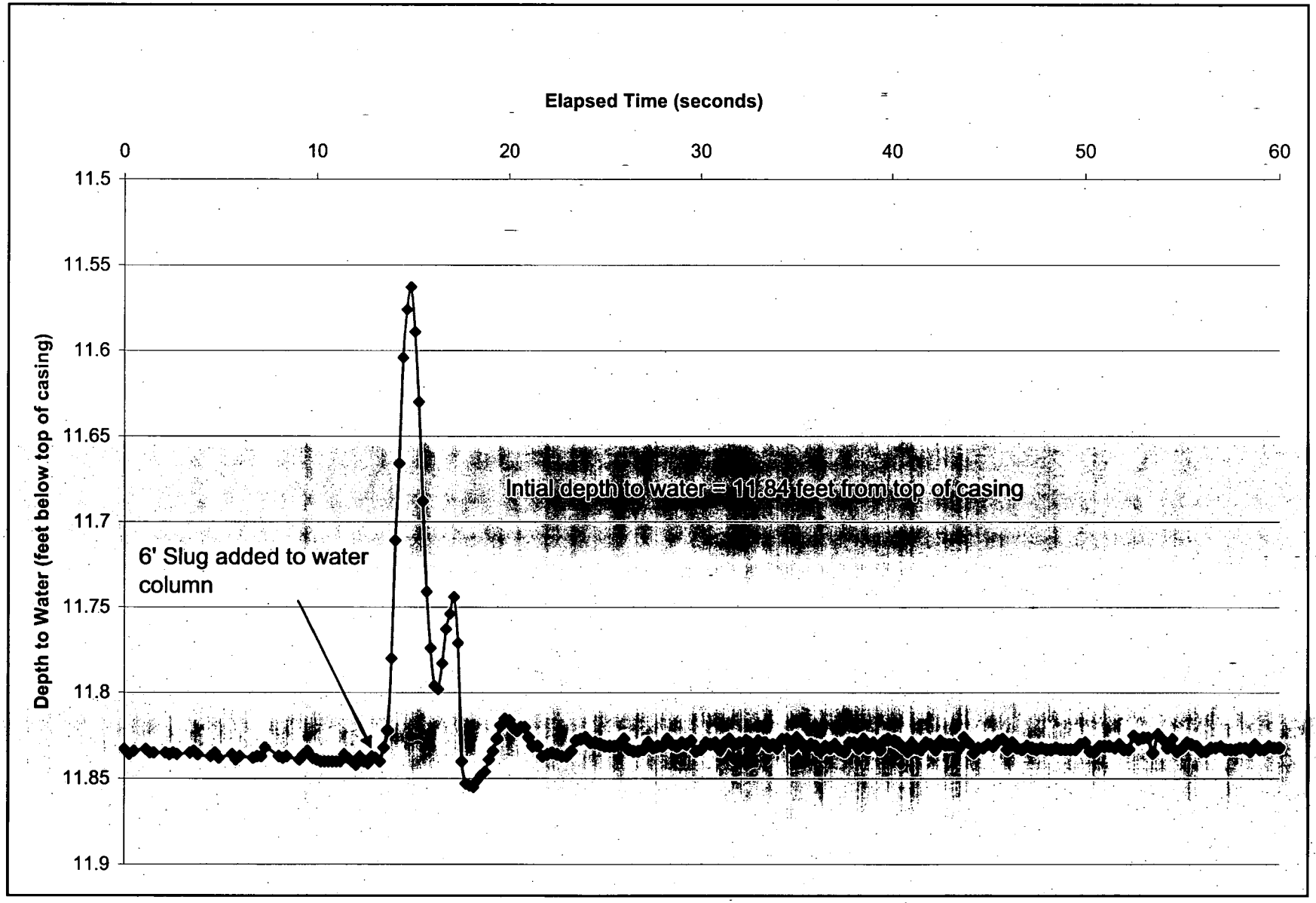
*PRB SW-C1 Falling Head Test #1*

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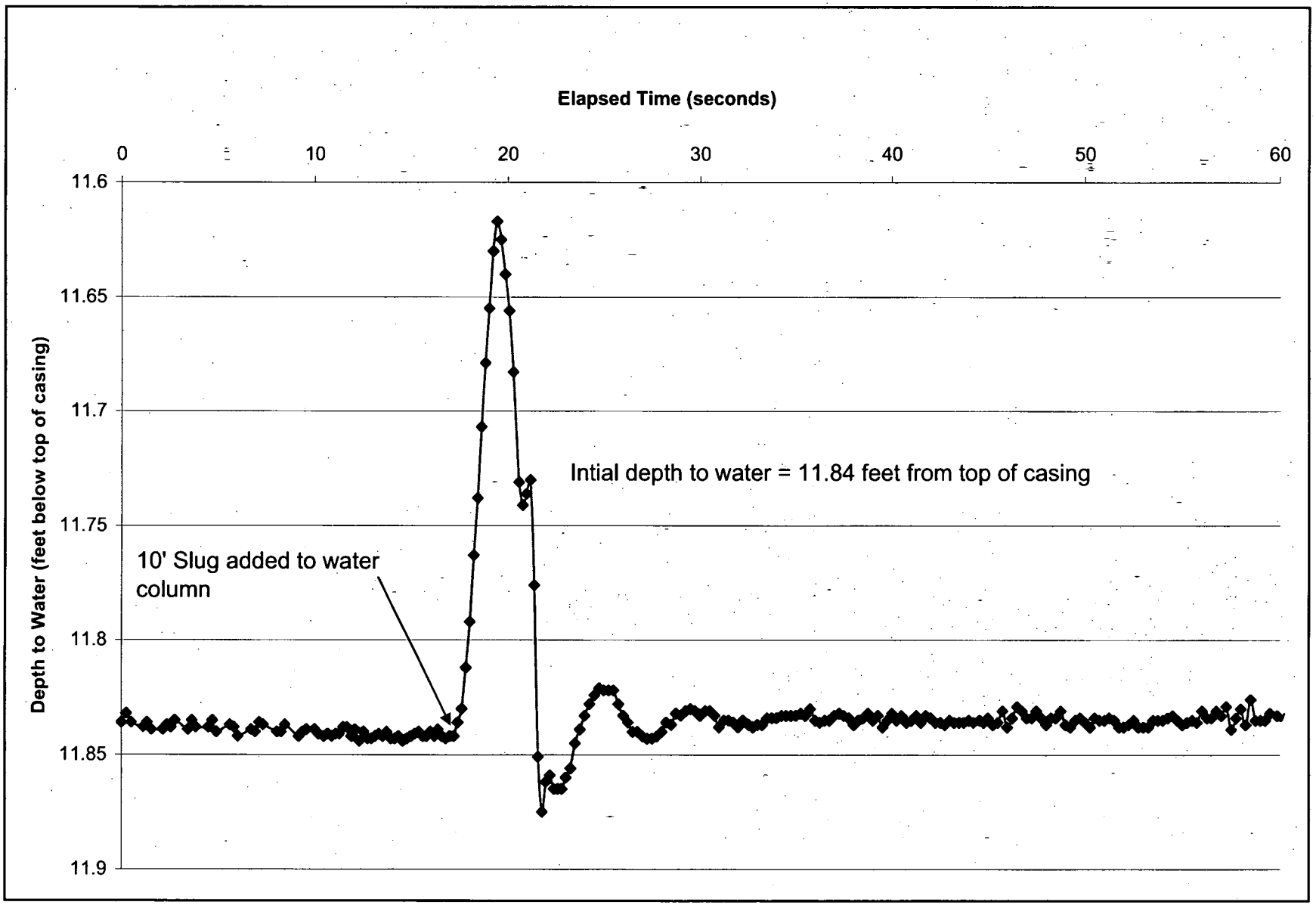
## PRB SW-C1 Falling Head Test #2

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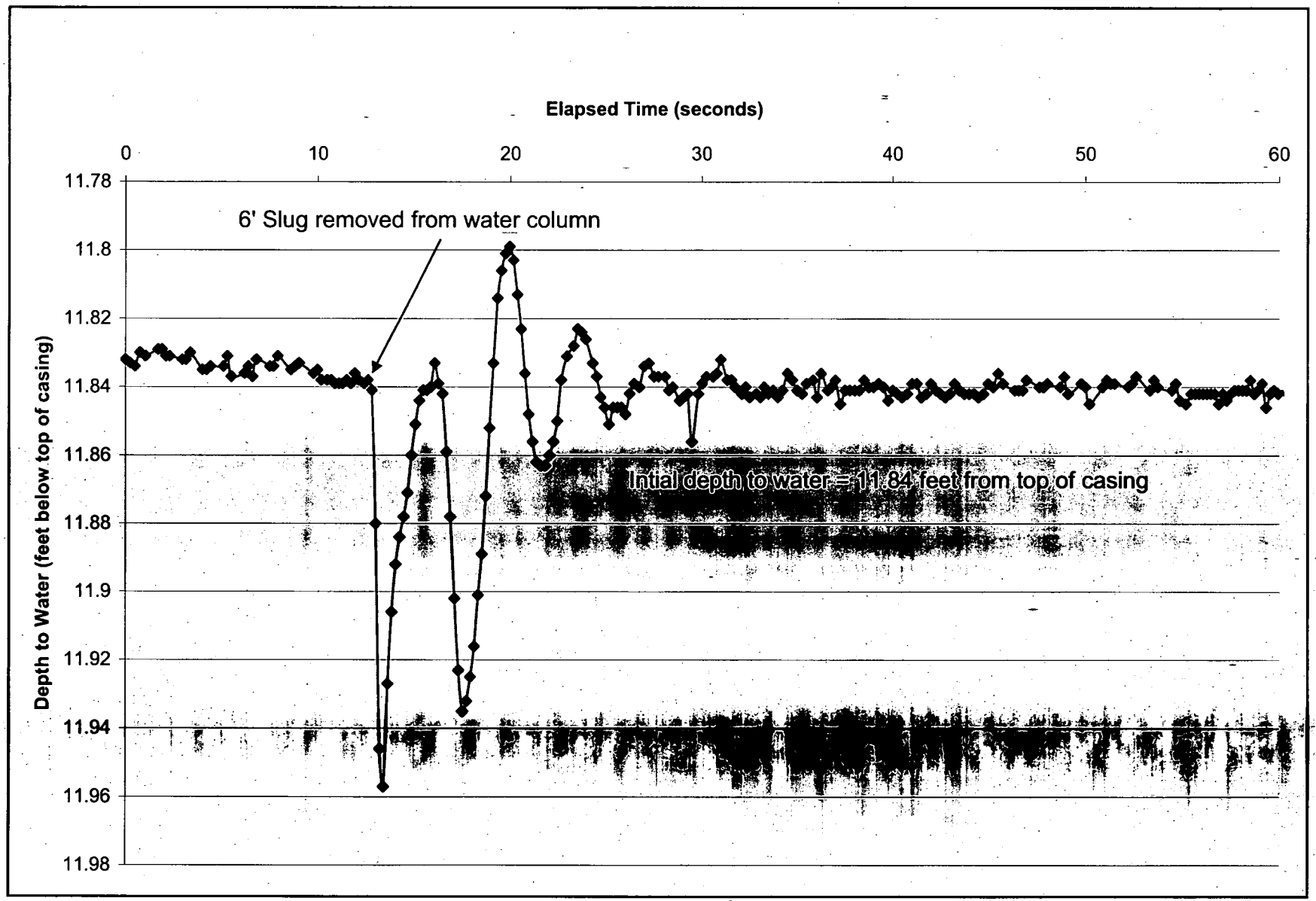
## PRB SW-C1 Rising Head Test #1

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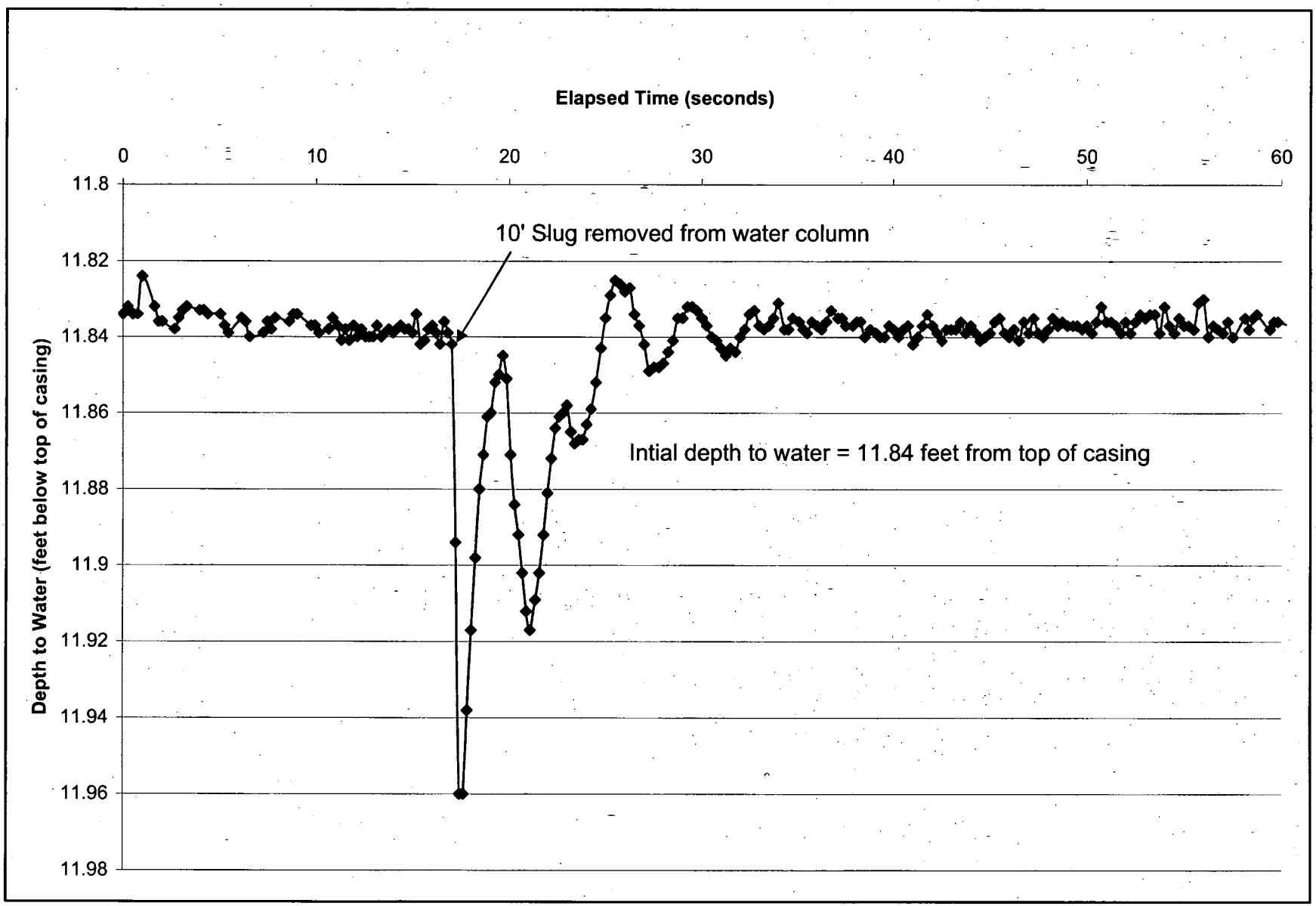
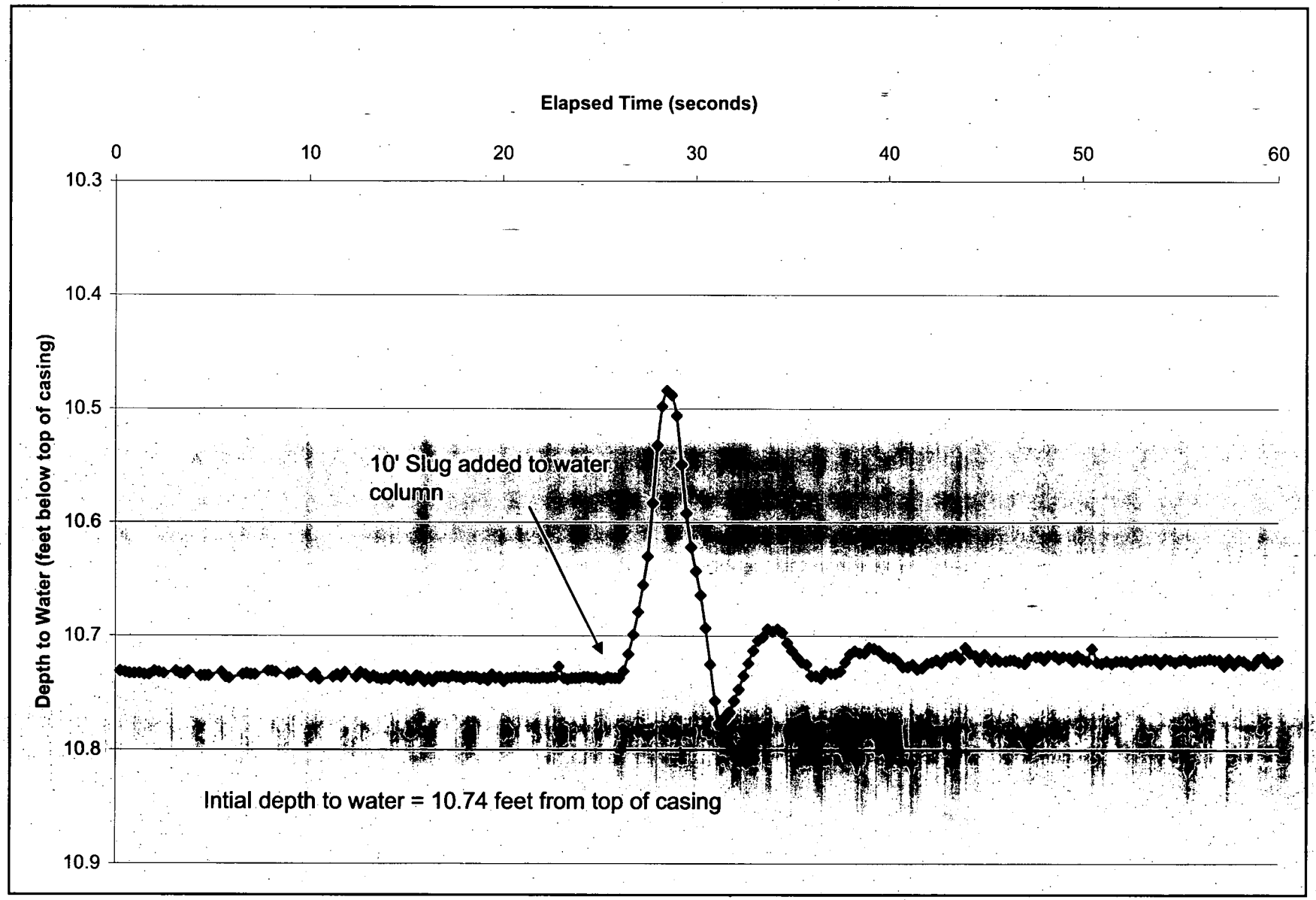
## PRB SW-C1 Rising Head Test #2



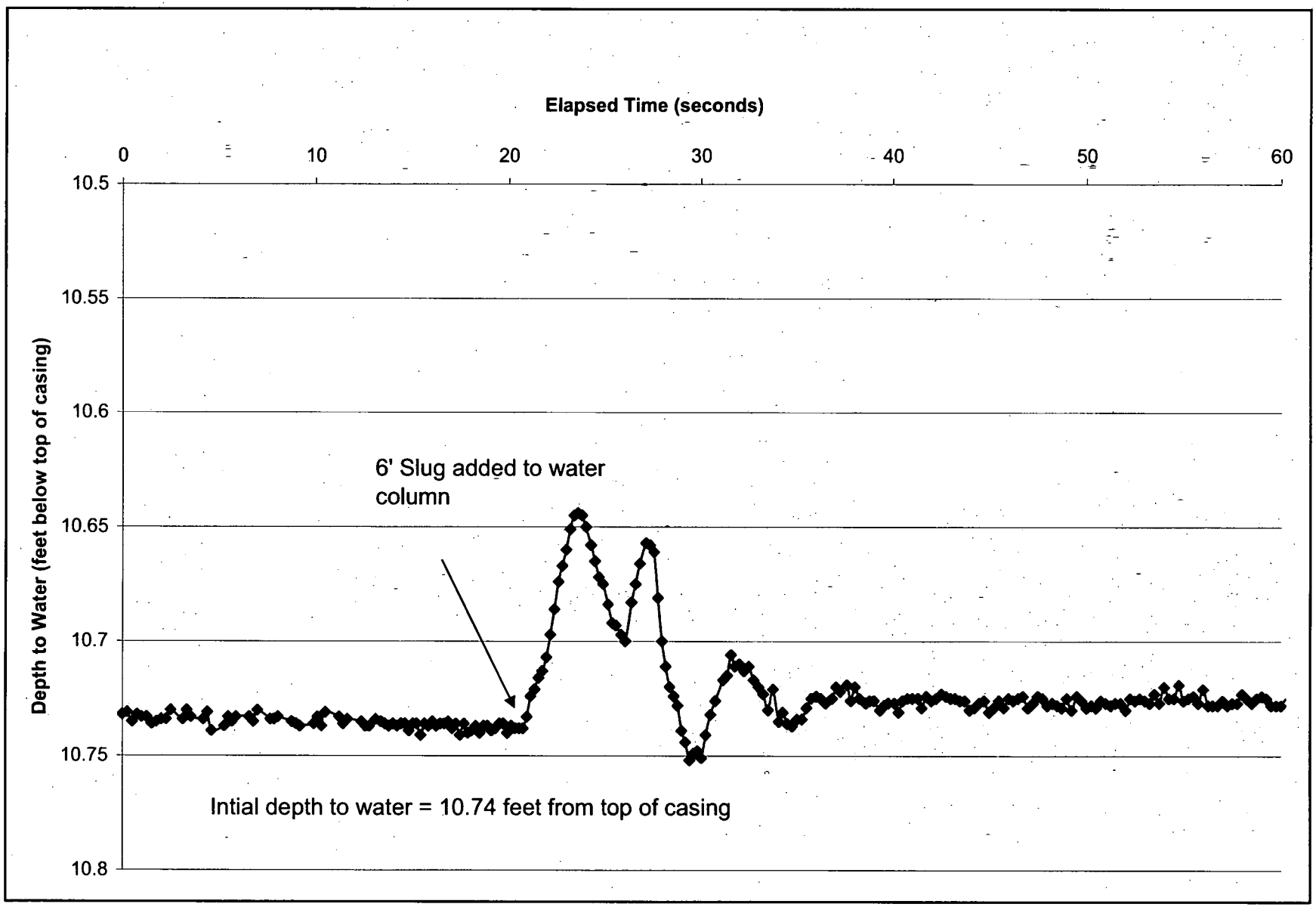

P:_ES06-121\PRB-Eval.9-06\Appx A\Appendix A-slug test plots.xls SW-C1 RH2 Chart

## PRB SW-C2 Falling Head Test #1



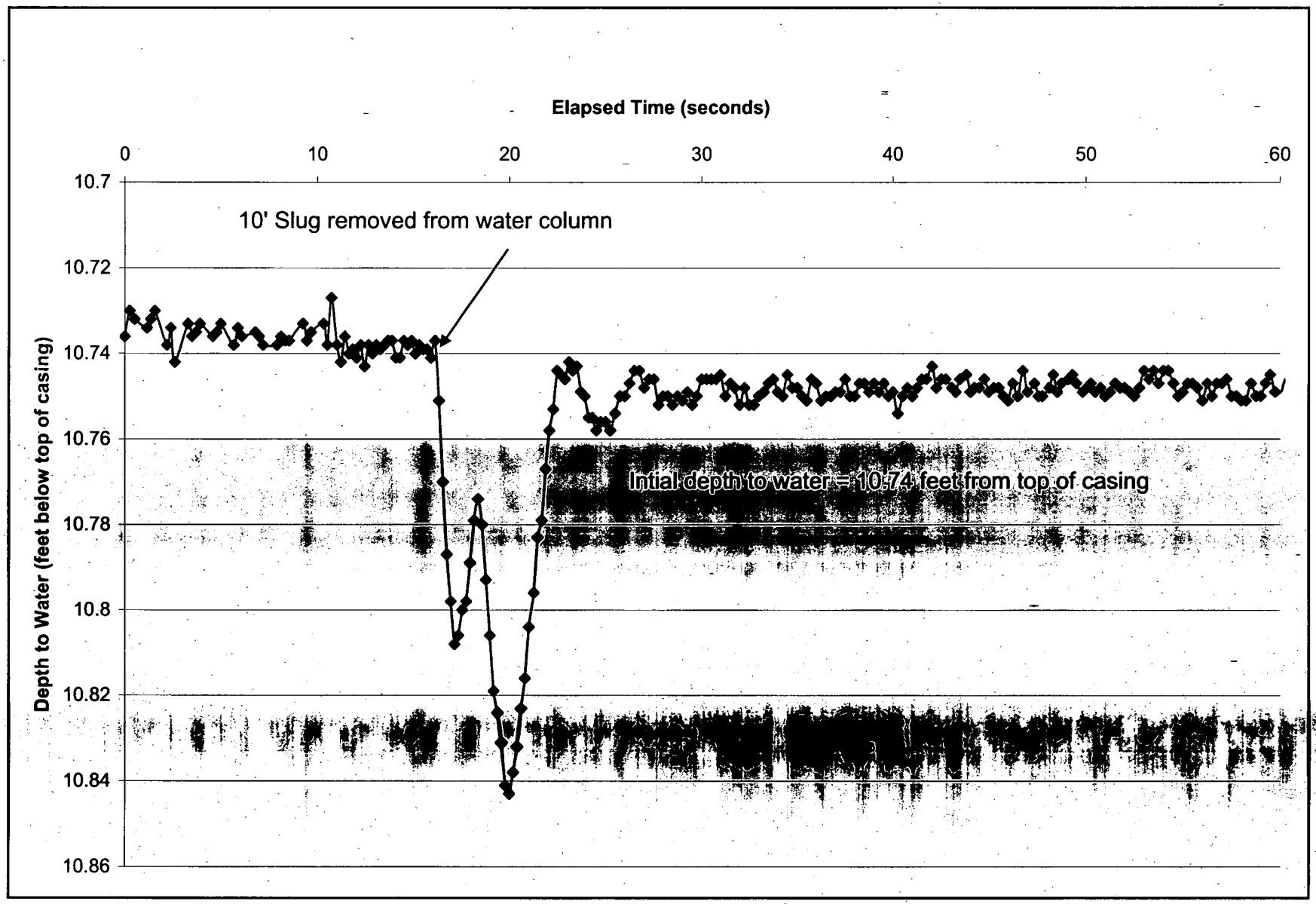

P:_ES06-121\PRB-Eval.9-06\Appx A\Appendix A-slug test plots.xls SW-C2 FH1 Chart

## PRB SW-C2 Falling Head Test #2



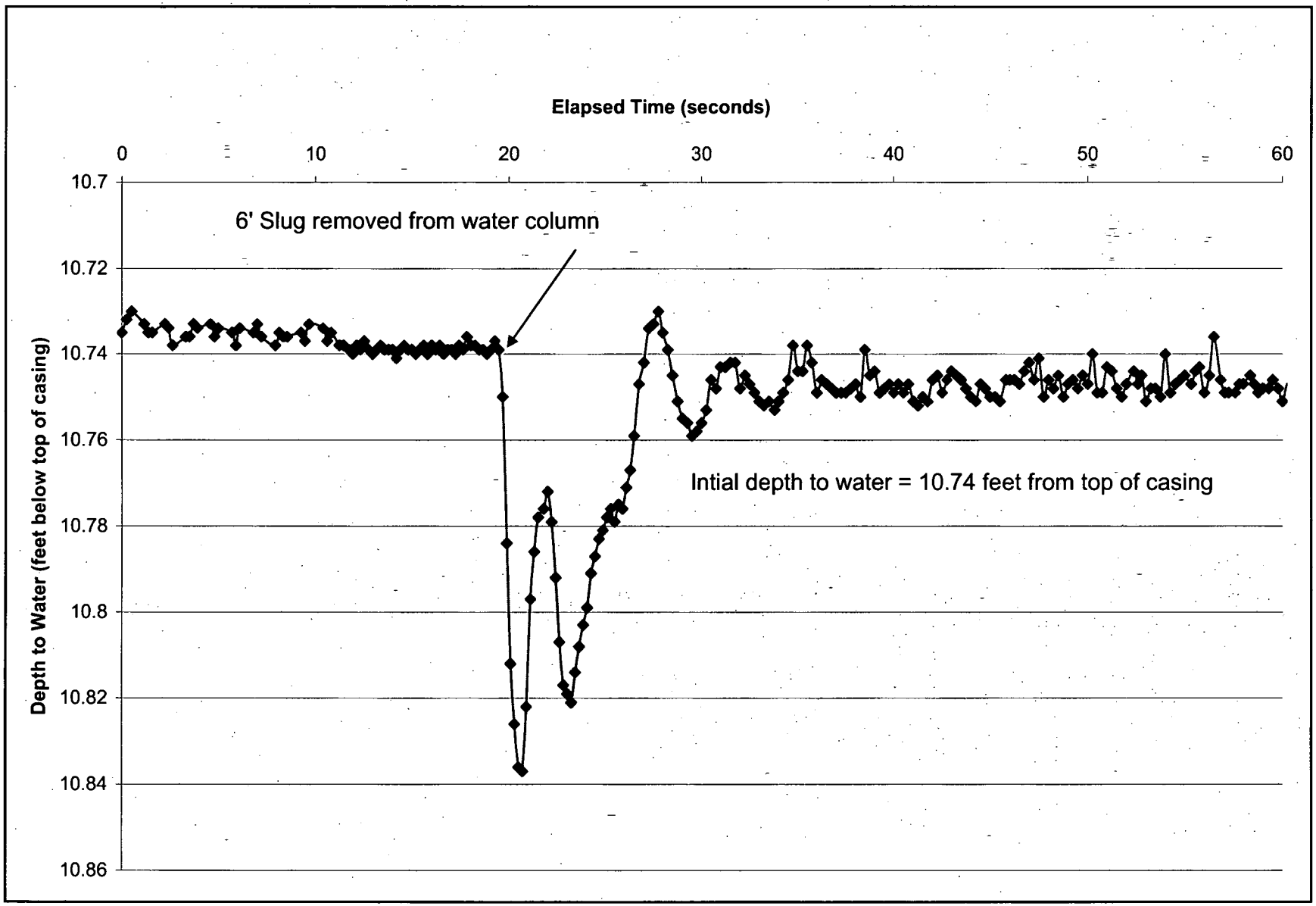

P:_ES06-121\PRB-Eval.9-06\Appx A\Appendix A-slug test plots.xls SW-C2 FH2 Chart

## PRB SW-C2 Rising Head Test #1



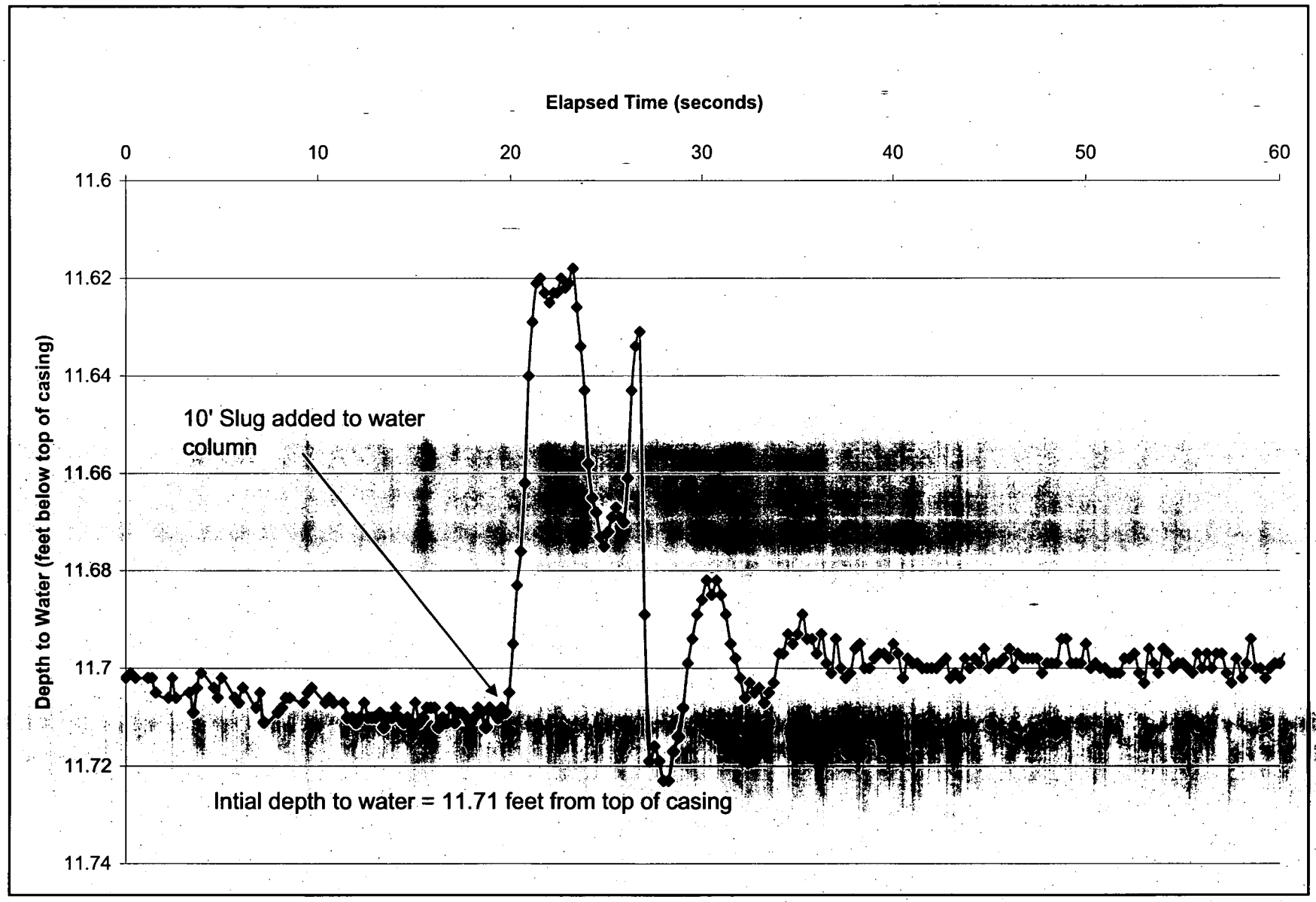

P:_ES06-121\PRB-Eval.9-06\Appx A\Appendix A-slug test plots.xls SW-C2 RH1 Chart

## PRB SW-C2 Rising Head Test #2



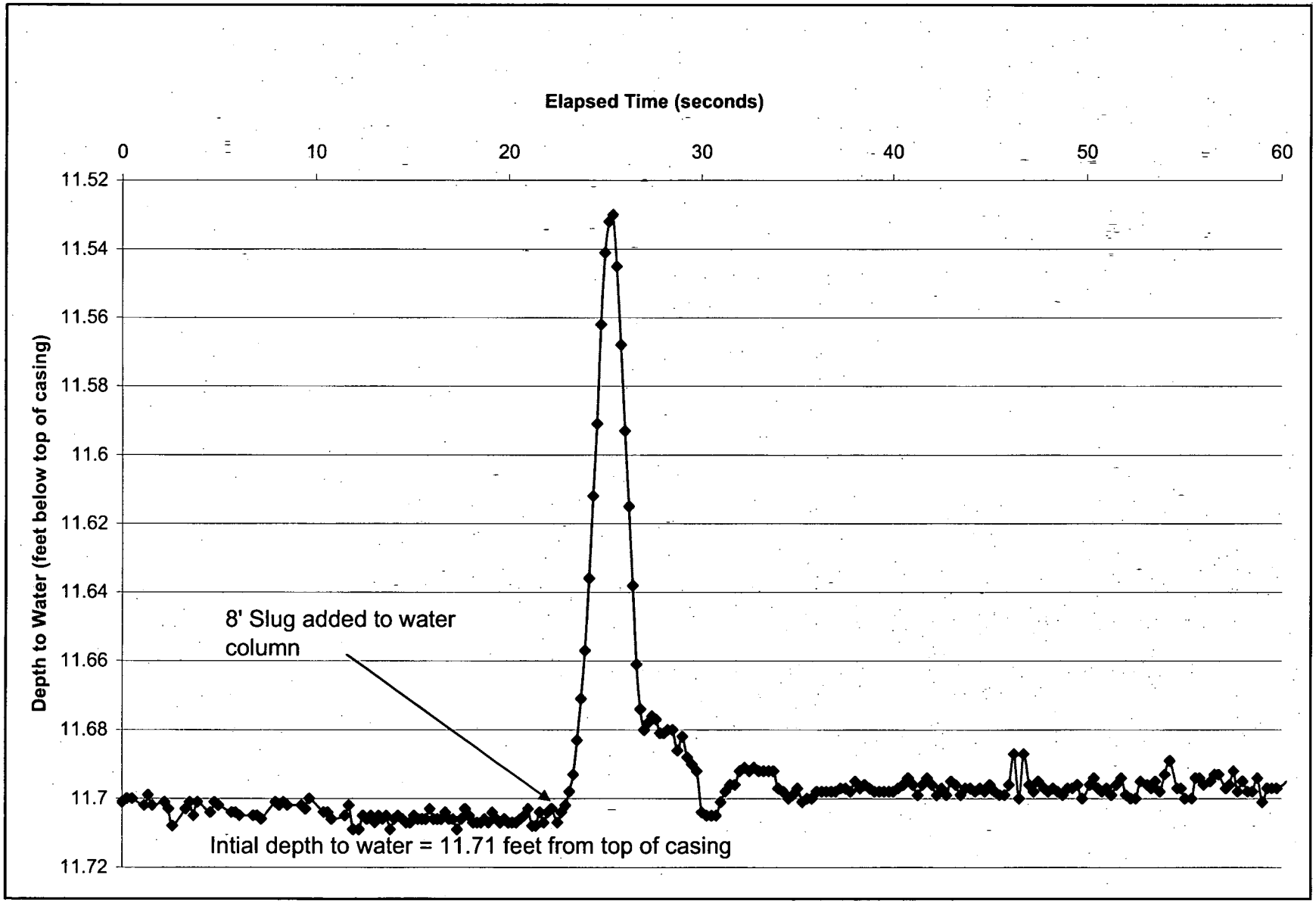

P:_ES06-121\PRB-Eval.9-06\Appx A\Appendix A-slug test plots.xls SW-C2 RH2 Chart

## PRB SW-C3 Falling Head Test #1



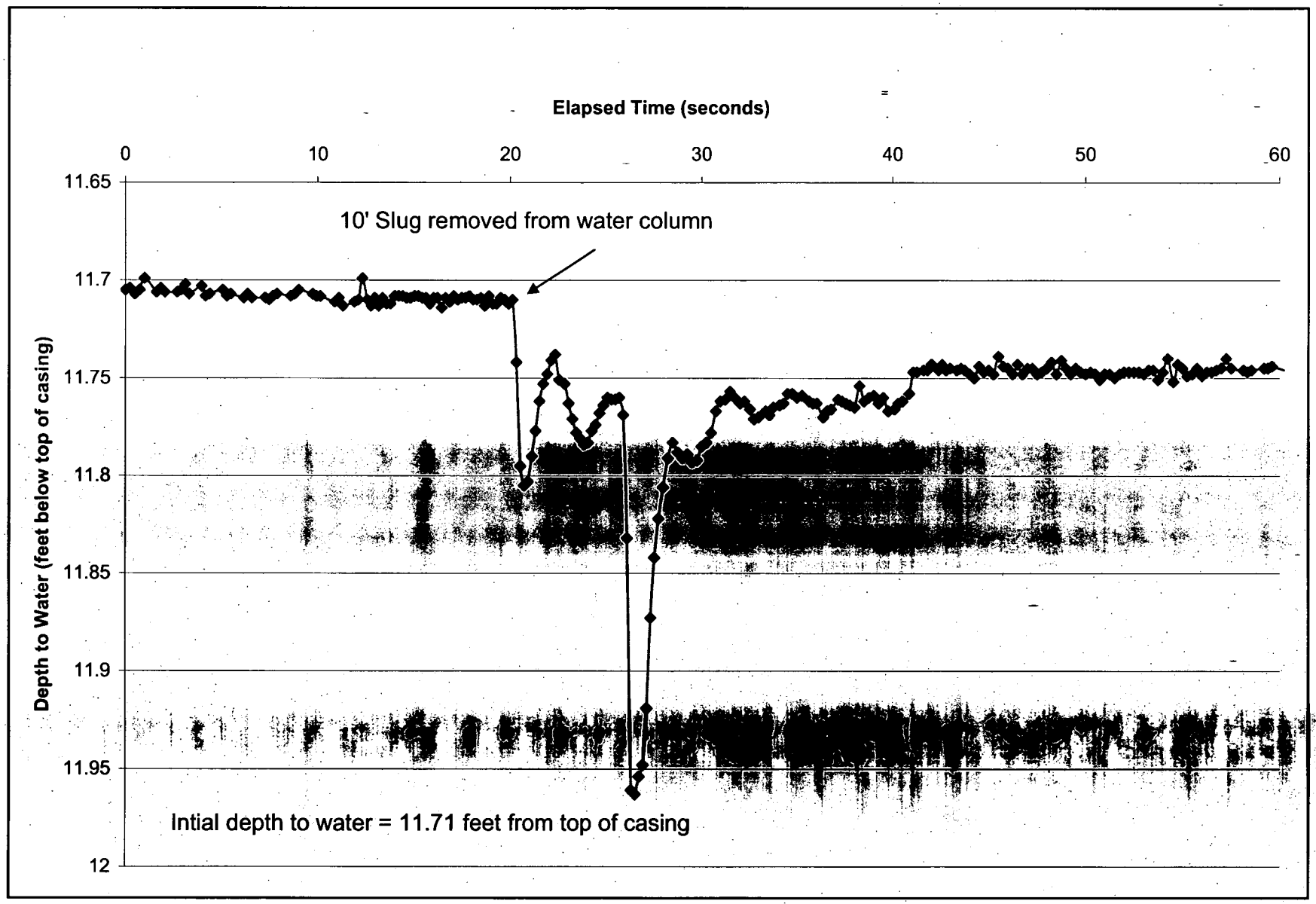

P:_ES06-121\PRB-Eval.9-06\Appx A\Appendix A-slug test plots.xls SW-C3 FH1 Chart

## PRB SW-C3 Falling Head Test #2



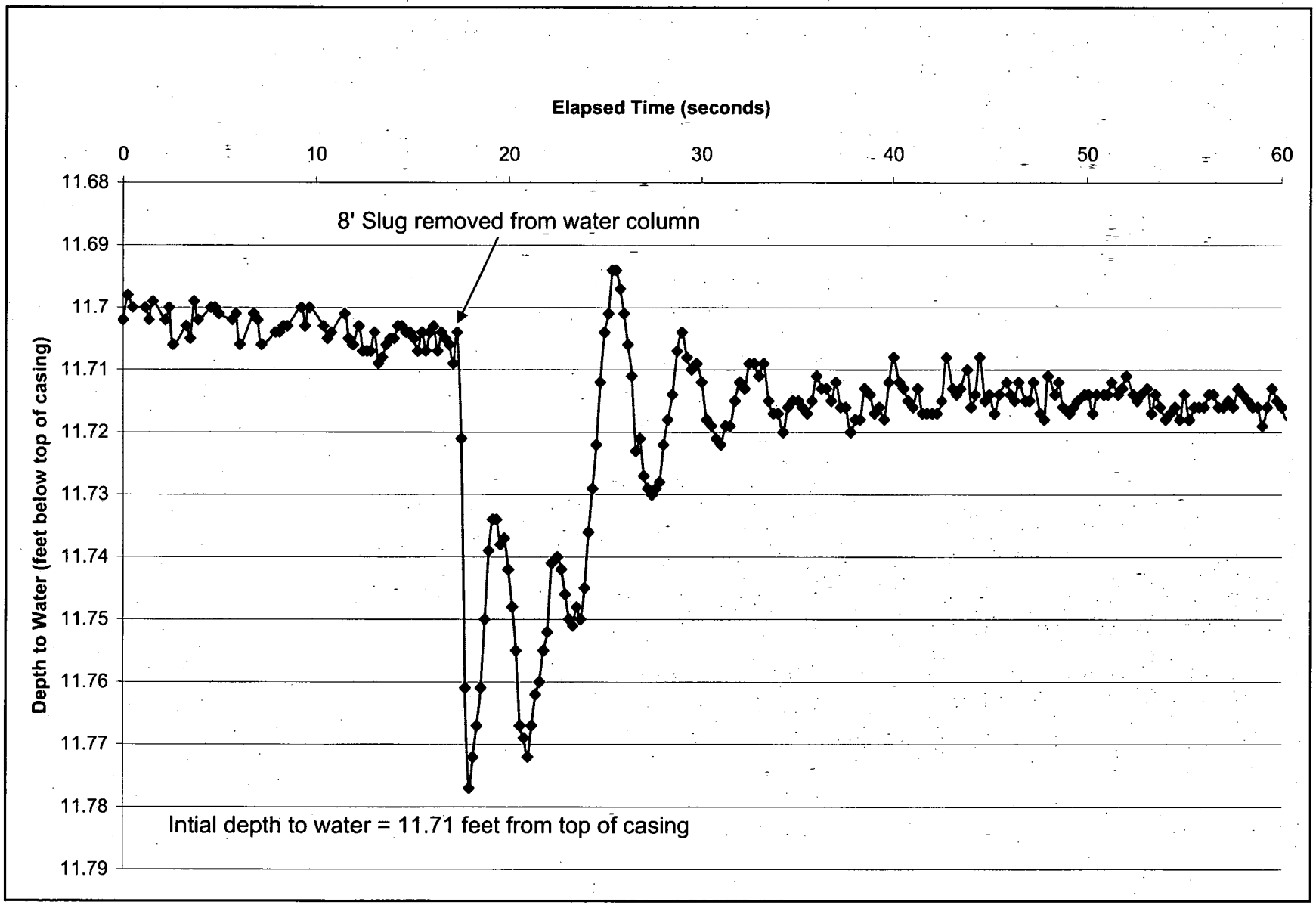

P:_ES06-121\PRB-Eval.9-06\Appx A\Appendix A-slug test plots.xls SW-C3 FH2 Chart

## PRB SW-C3 Rising Head Test #1



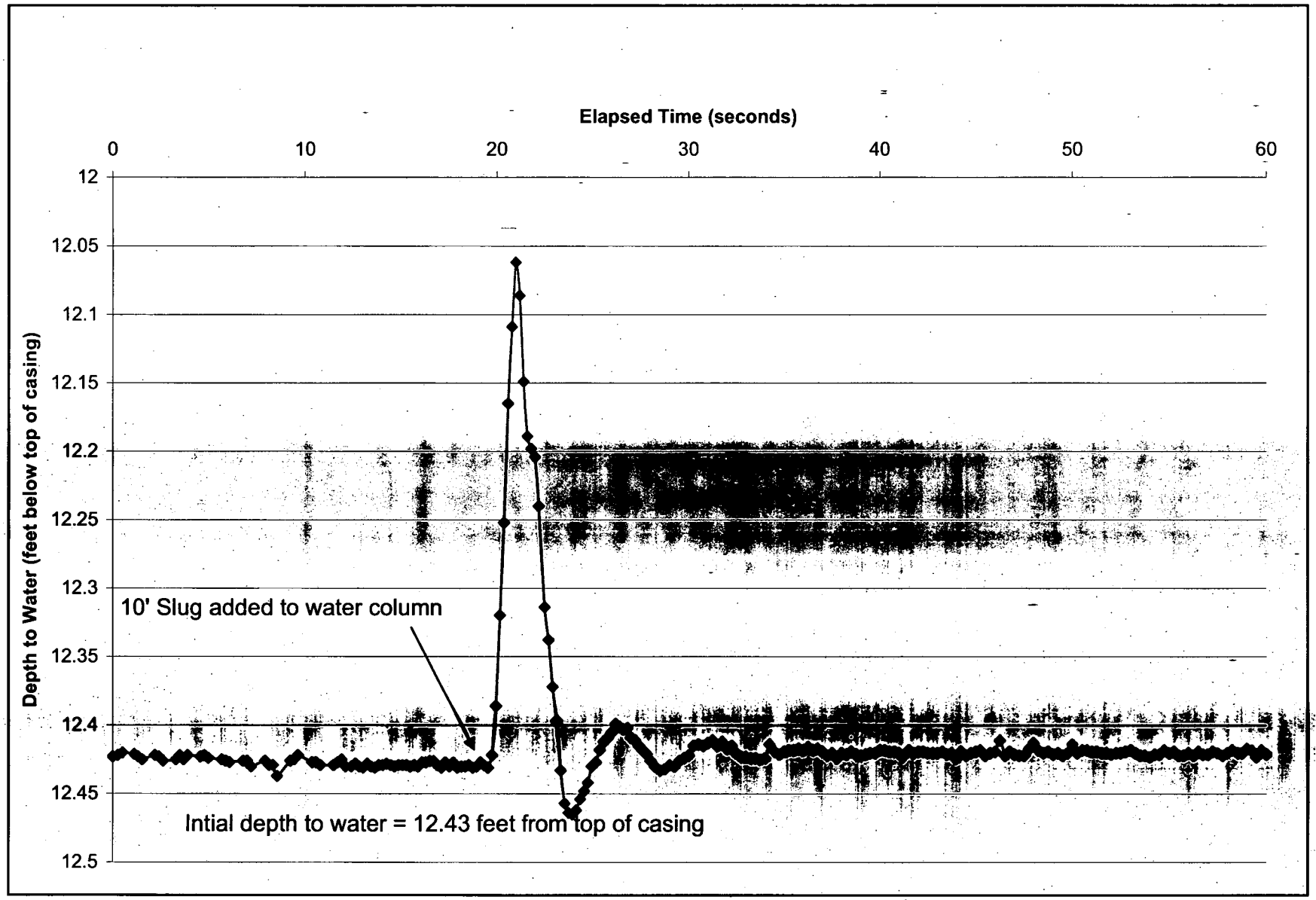

P:_ES06-121\PRB-Eval.9-06\Appx A\Appendix A-slug test plots.xls SW-C3 RH1 Chart

## PRB SW-C3 Rising Head Test #2



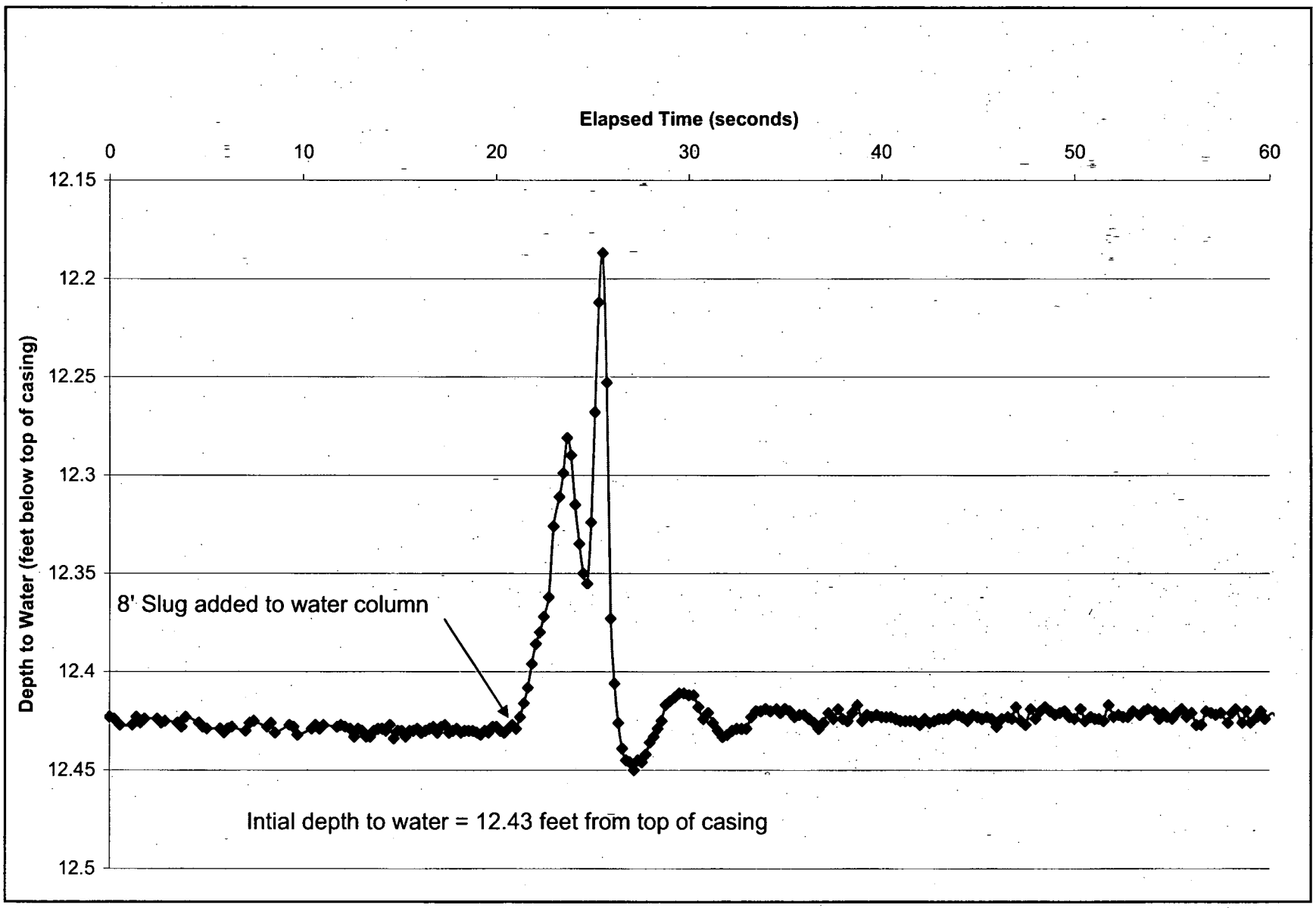

P:_ES06-121\PRB-Eval.9-06\Appx A\Appendix A-slug test plots.xls SW-C3 RH2 Chart

## PRB SW-D2 Falling Head Test #1



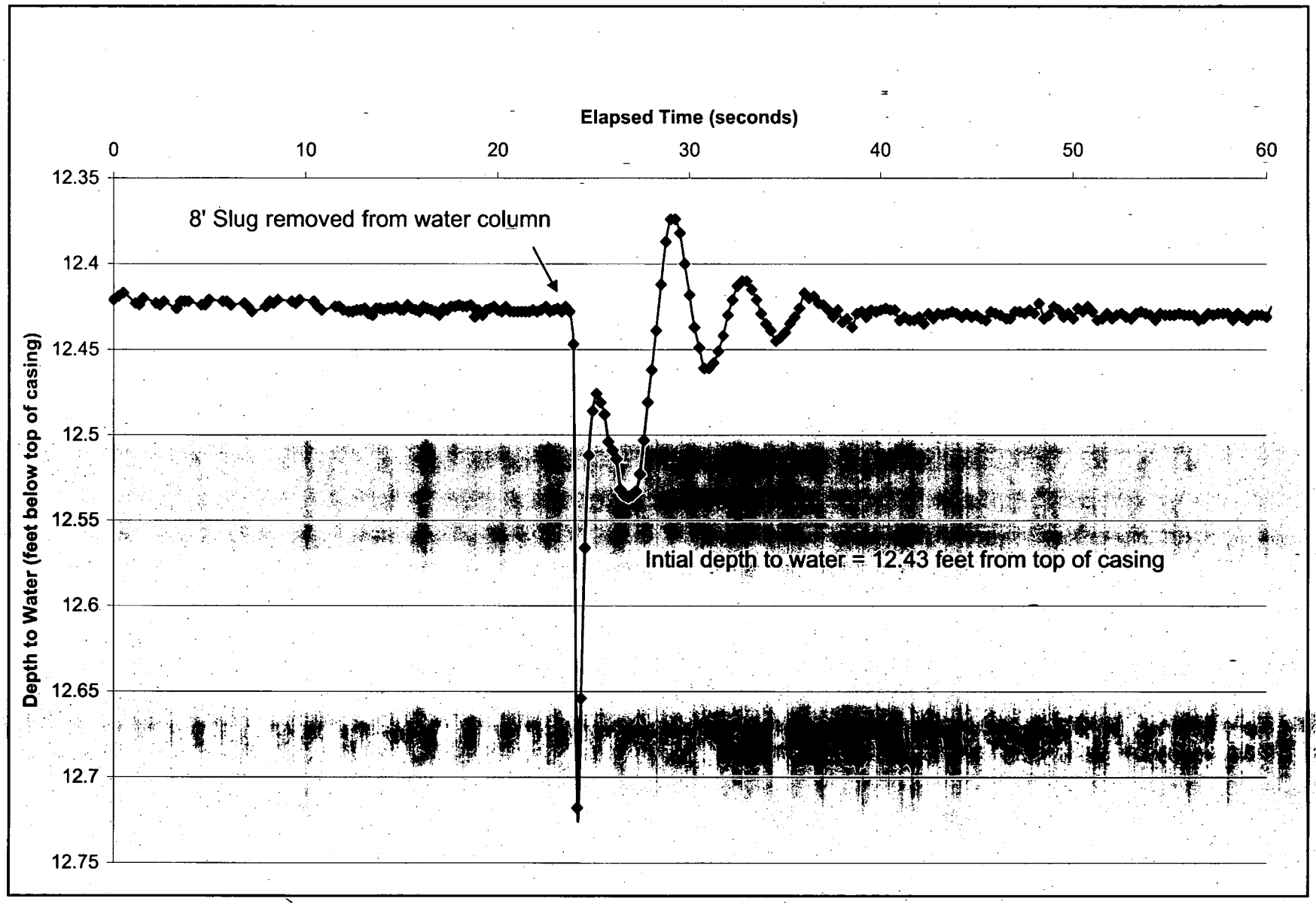

P:_ES06-121\PRB-Eval.9-06\Appx A\Appendix A-slug test plots.xls SW-D2 FH1 Chart

## PRB SW-D2 Falling Head Test #2



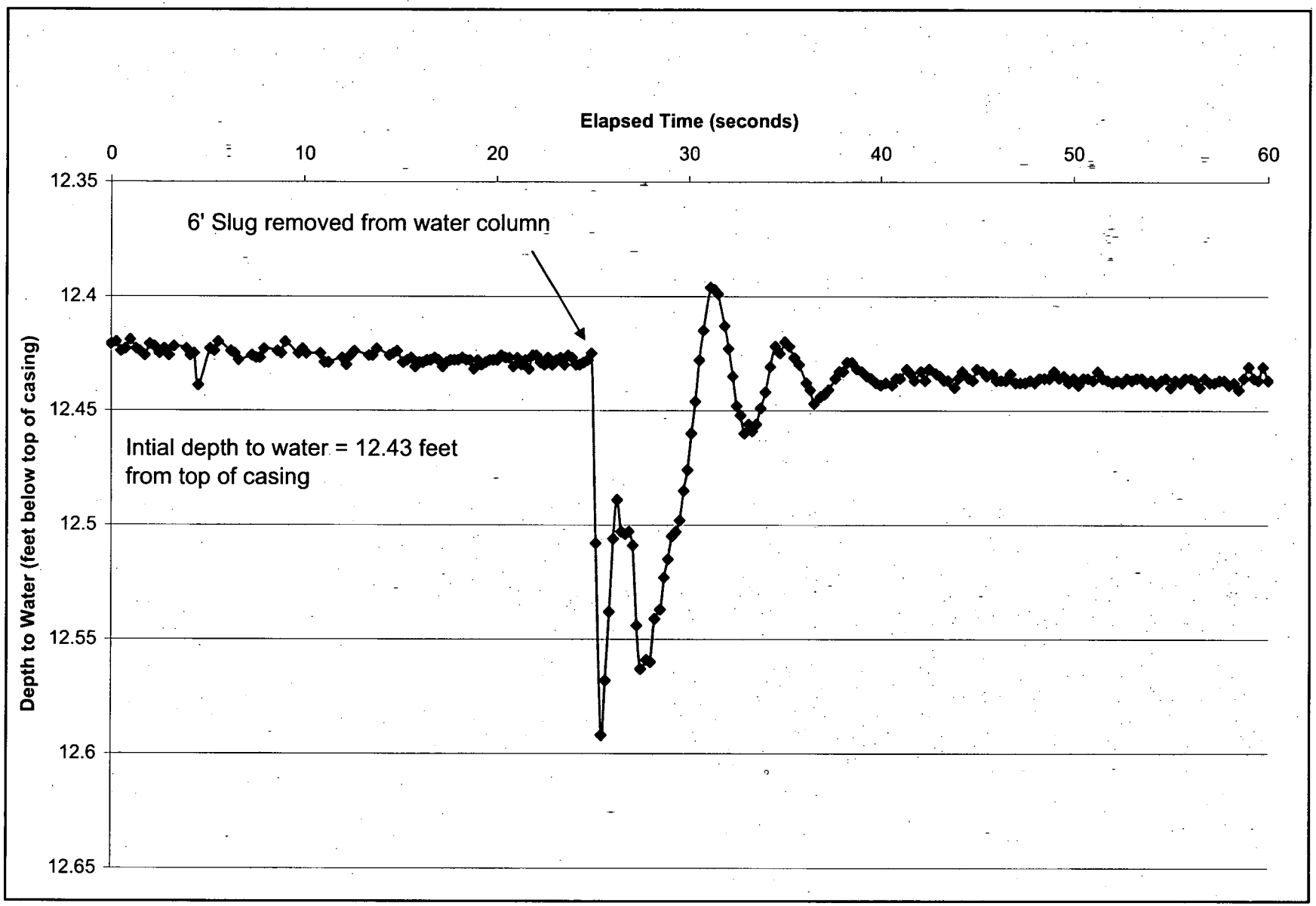

P:_ES06-121\PRB-Eval.9-06\Appx A\Appendix A-slug test plots.xls SW-D2 FH2 Chart

## PRB SW-D2 Rising Head Test #2



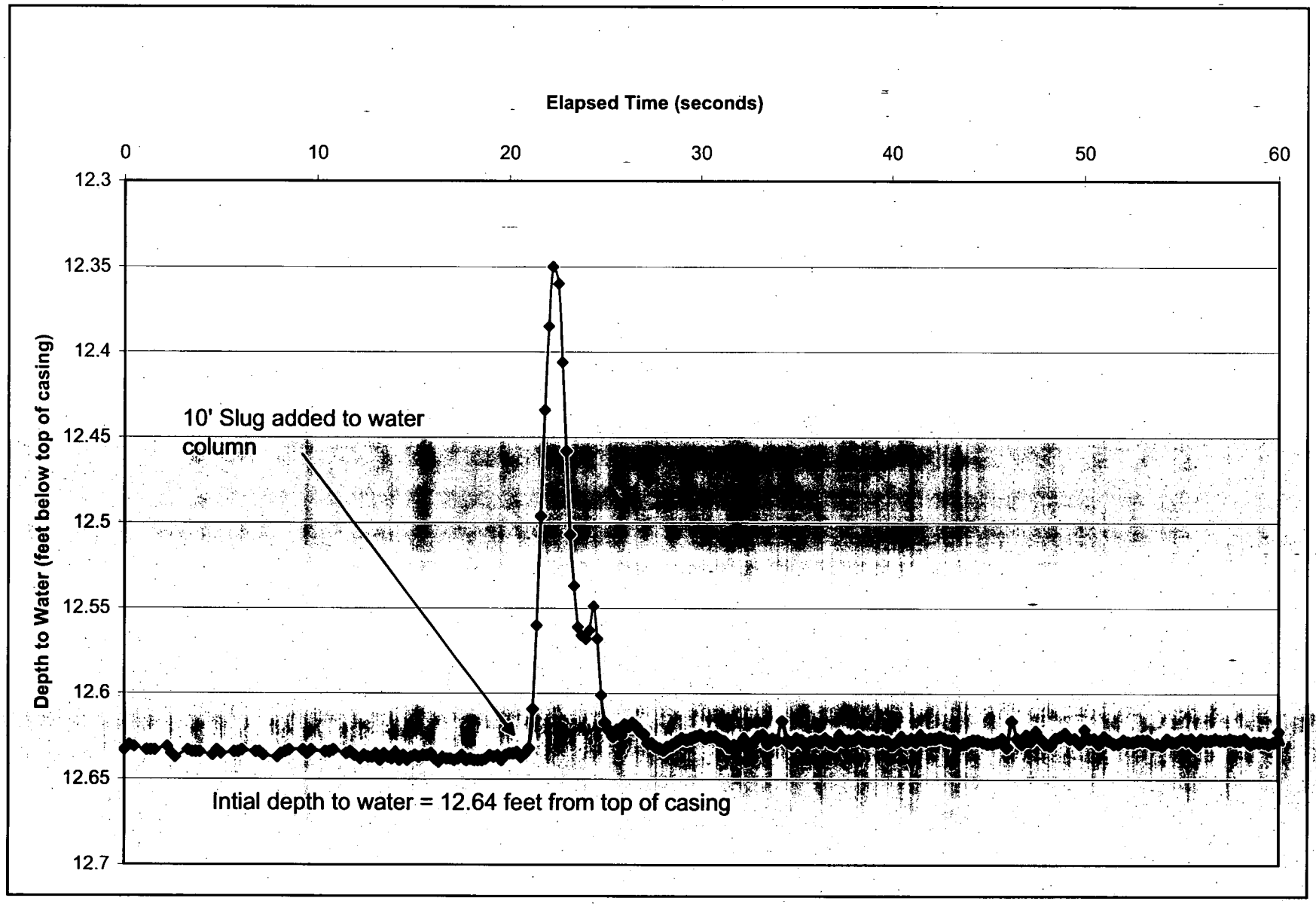

P:_ES06-121\PRB-Eval.9-06\Appx A\Appendix A-slug test plots.xls SW-D2 RH2 Chart

## PRB SW-D2 Rising Head Test #3



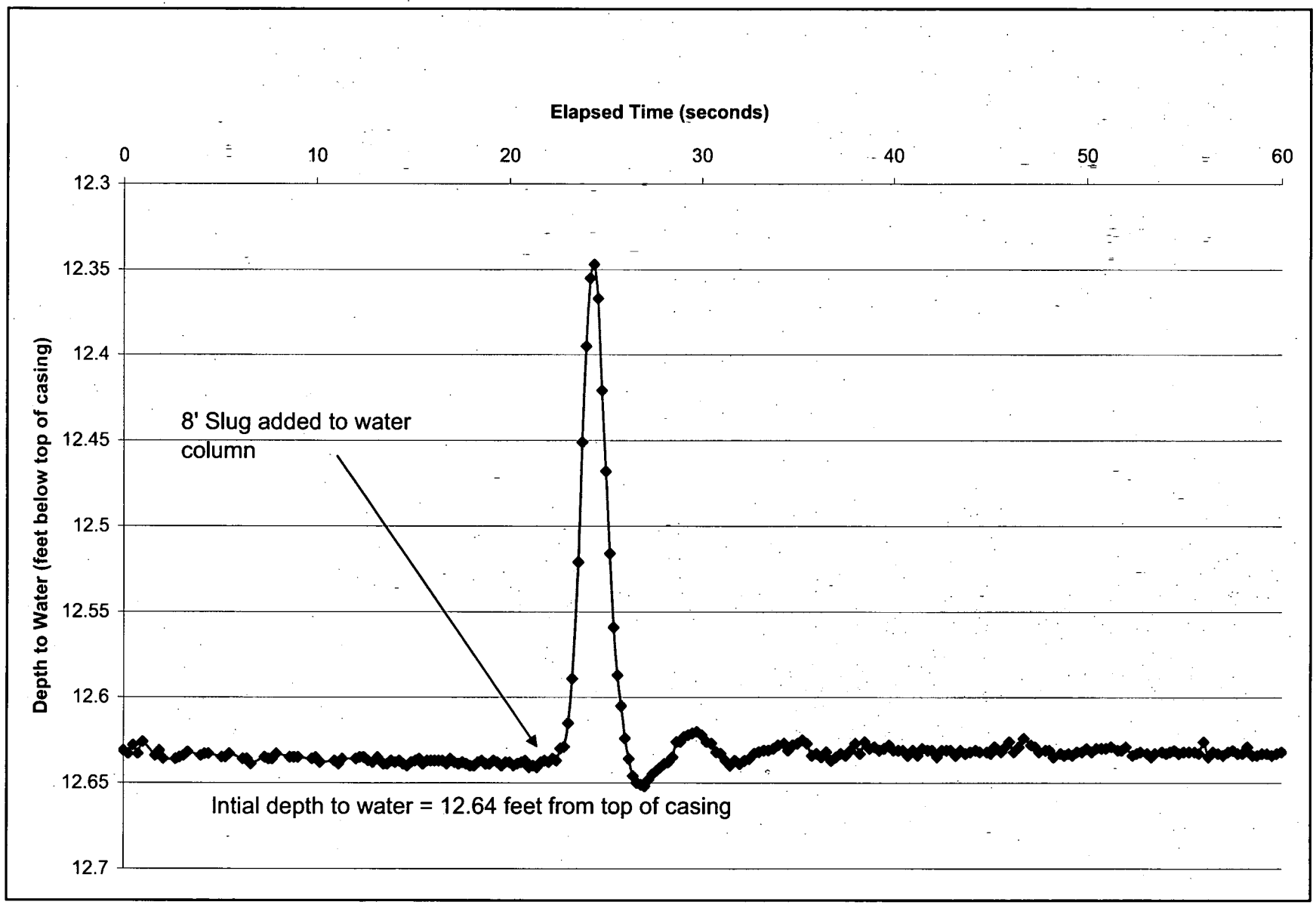

P:_ES06-121\PRB-Eval.9-06\Appx A\Appendix A-slug test plots.xls SW-D2 RH3 Chart

## PRB SW-D3 Falling Head Test #1



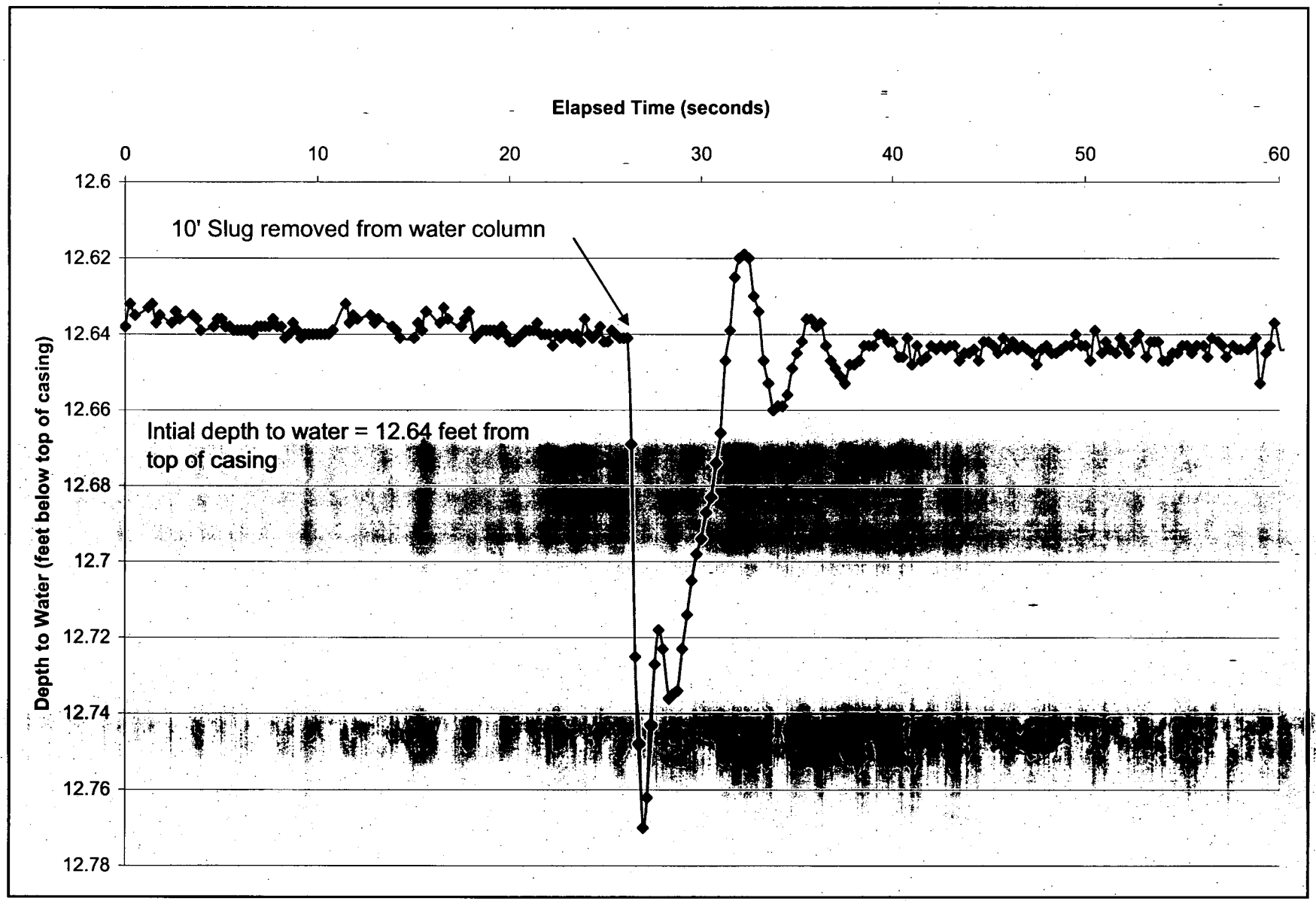

P:_ES06-121\PRB-Eval.9-06\Appx A\Appendix A-slug test plots.xls SW-D3 FH1 Chart

## PRB SW-D3 Falling Head Test #2



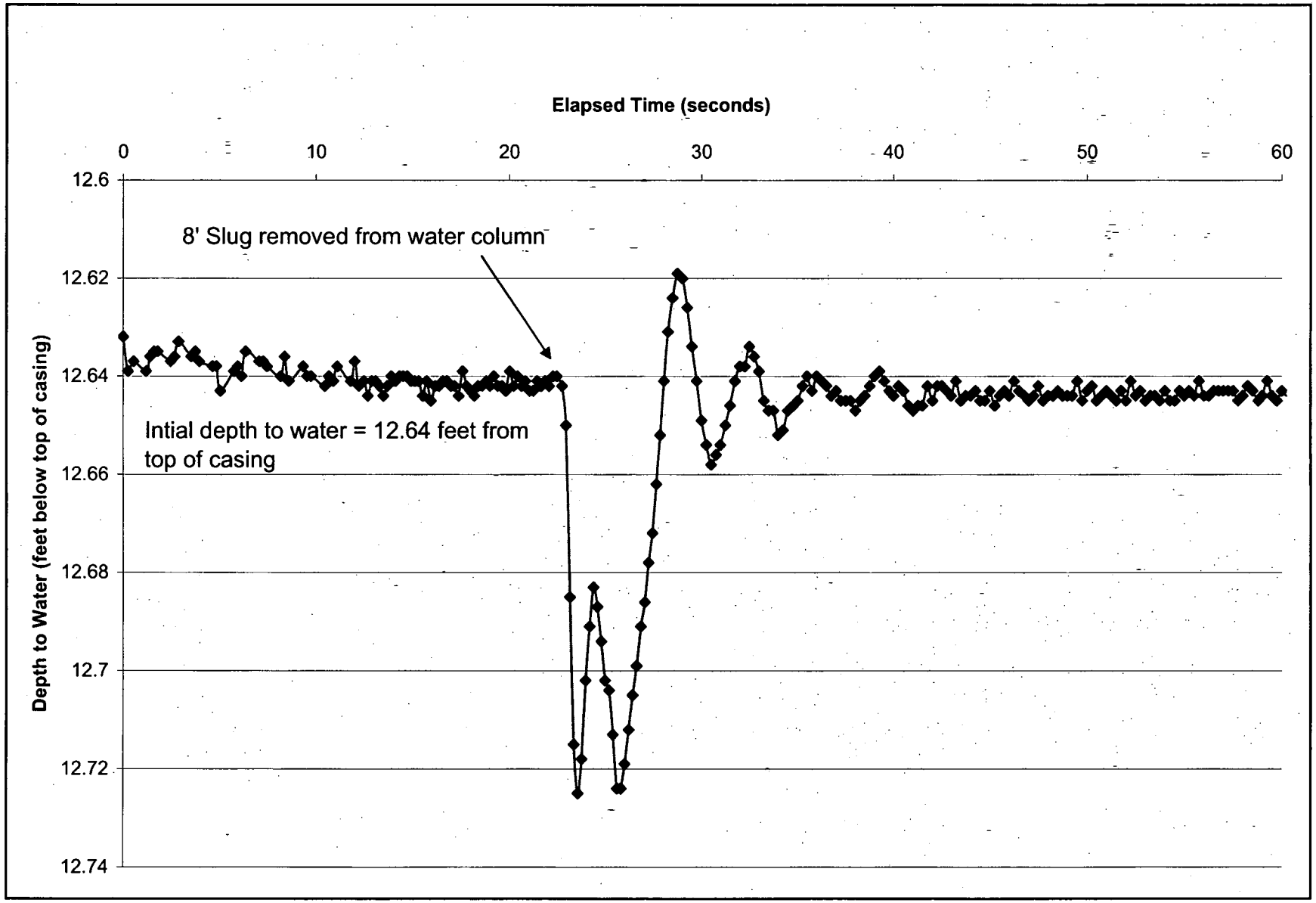

P:_ES06-121\PRB-Eval.9-06\Appx A\Appendix A-slug test plots.xls SW-D3 FH2 Chart

## PRB SW-D3 Rising Head Test #1



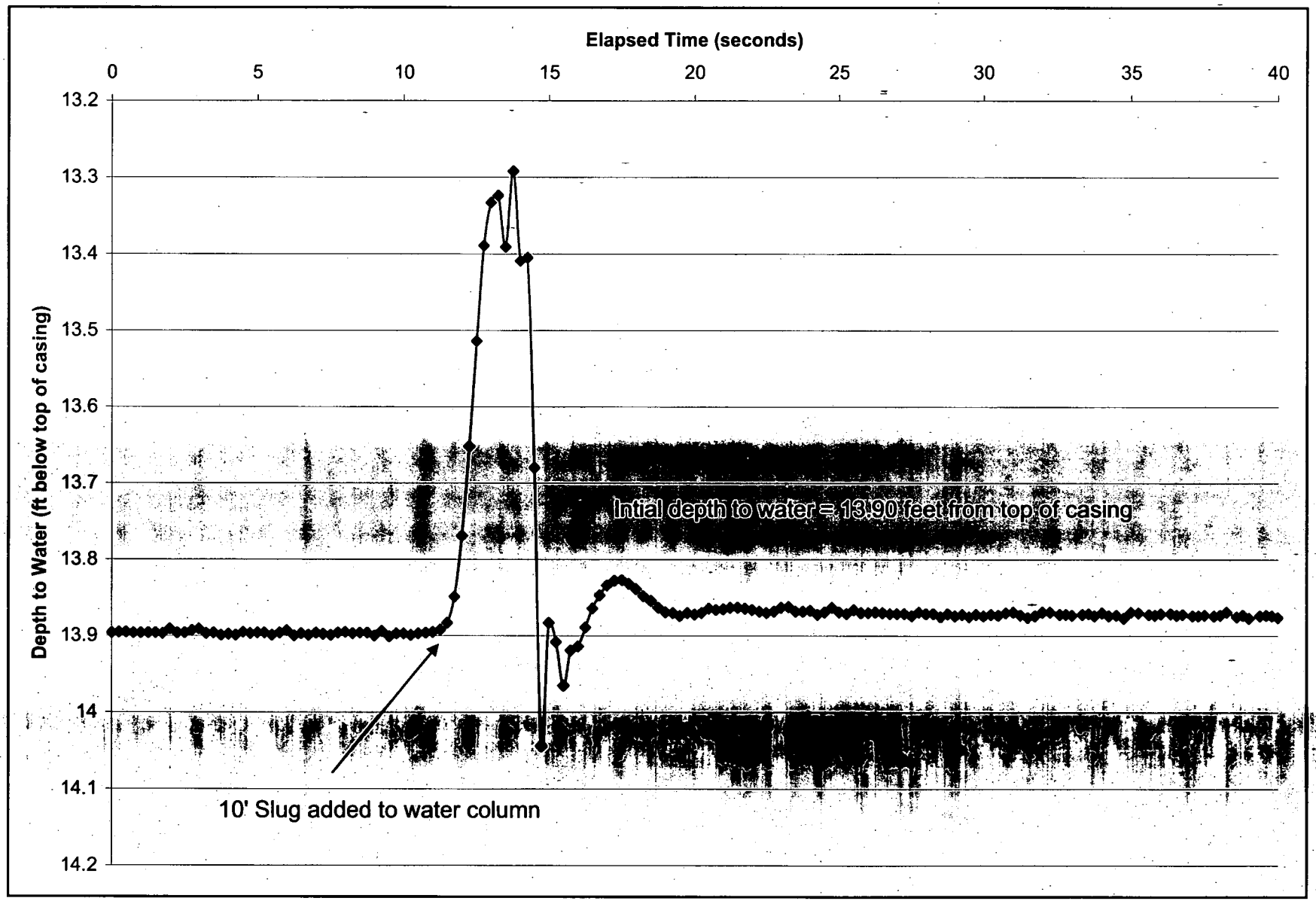

P:_ES06-121\PRB-Eval.9-06\Appx A\Appendix A-slug test plots.xls SW-D3 RH1 Chart

## PRB SW-D3 Rising Head Test #2



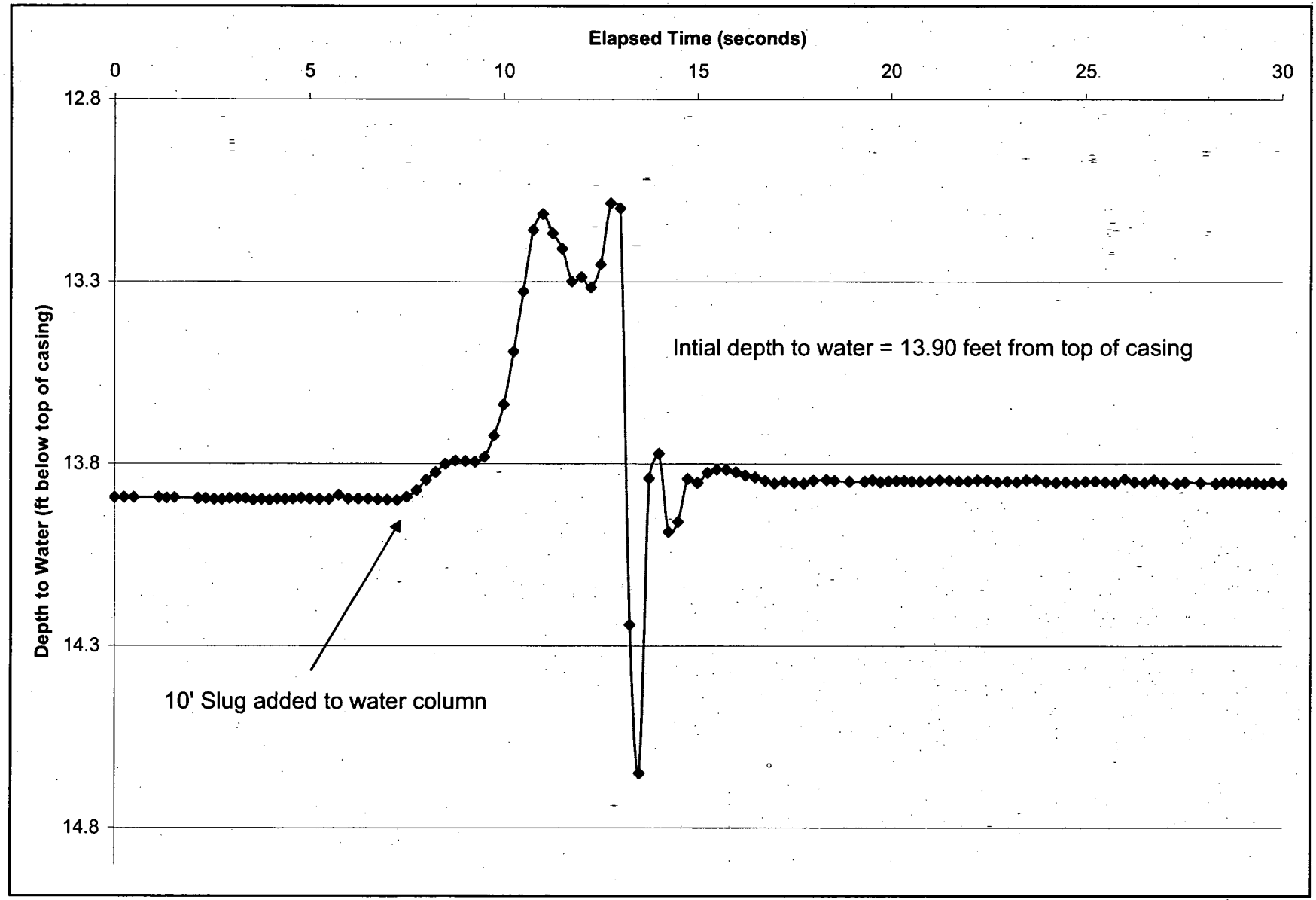

P:_ES06-121\PRB-Eval.9-06\Appx A\Appendix A-slug test plots.xls SW-D3 RH2 Chart

## PRB MW-01 Falling Head Test #1



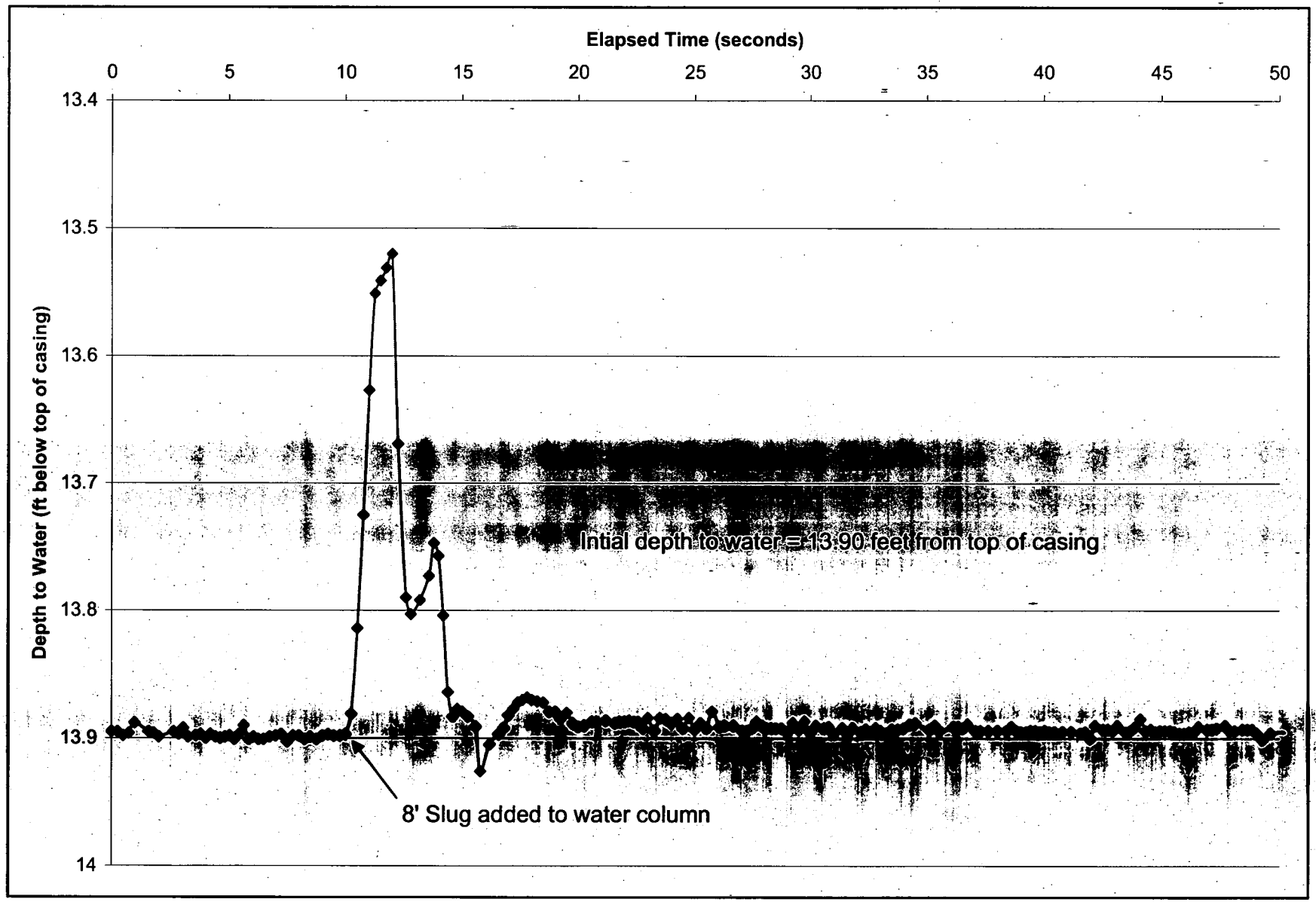

P:_ES06-121\PRB-Eval.9-06\Appx A\Appendix A-slug test plots.xls MW-1 FH1 Chart

## PRB MW-01 Falling Head Test #2



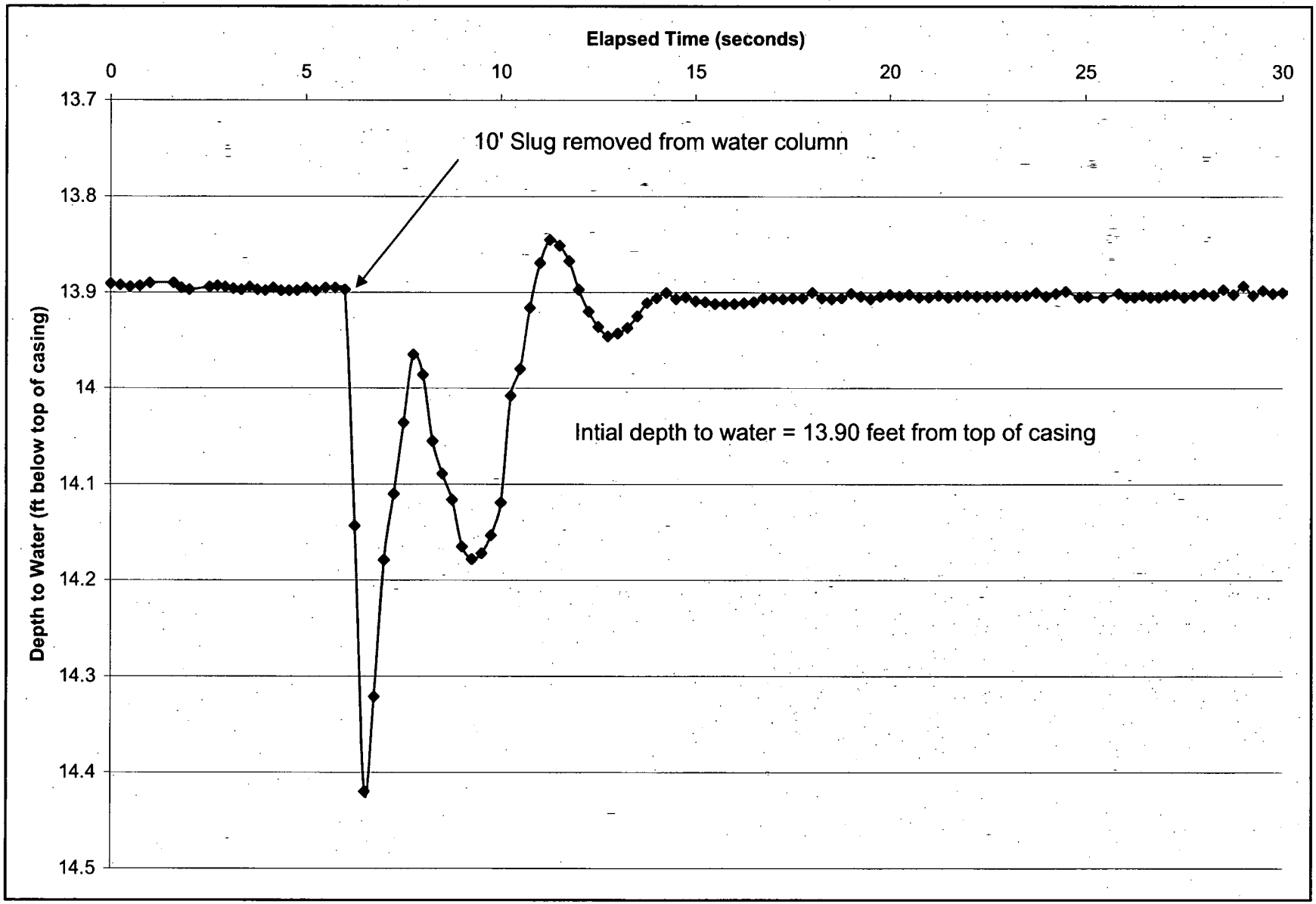

P:_ES06-121\PRB-Eval.9-06\Appx A\Appendix A-slug test plots.xls MW-1 FH2 Chart

## PRB MW-01 Falling Head Test #3



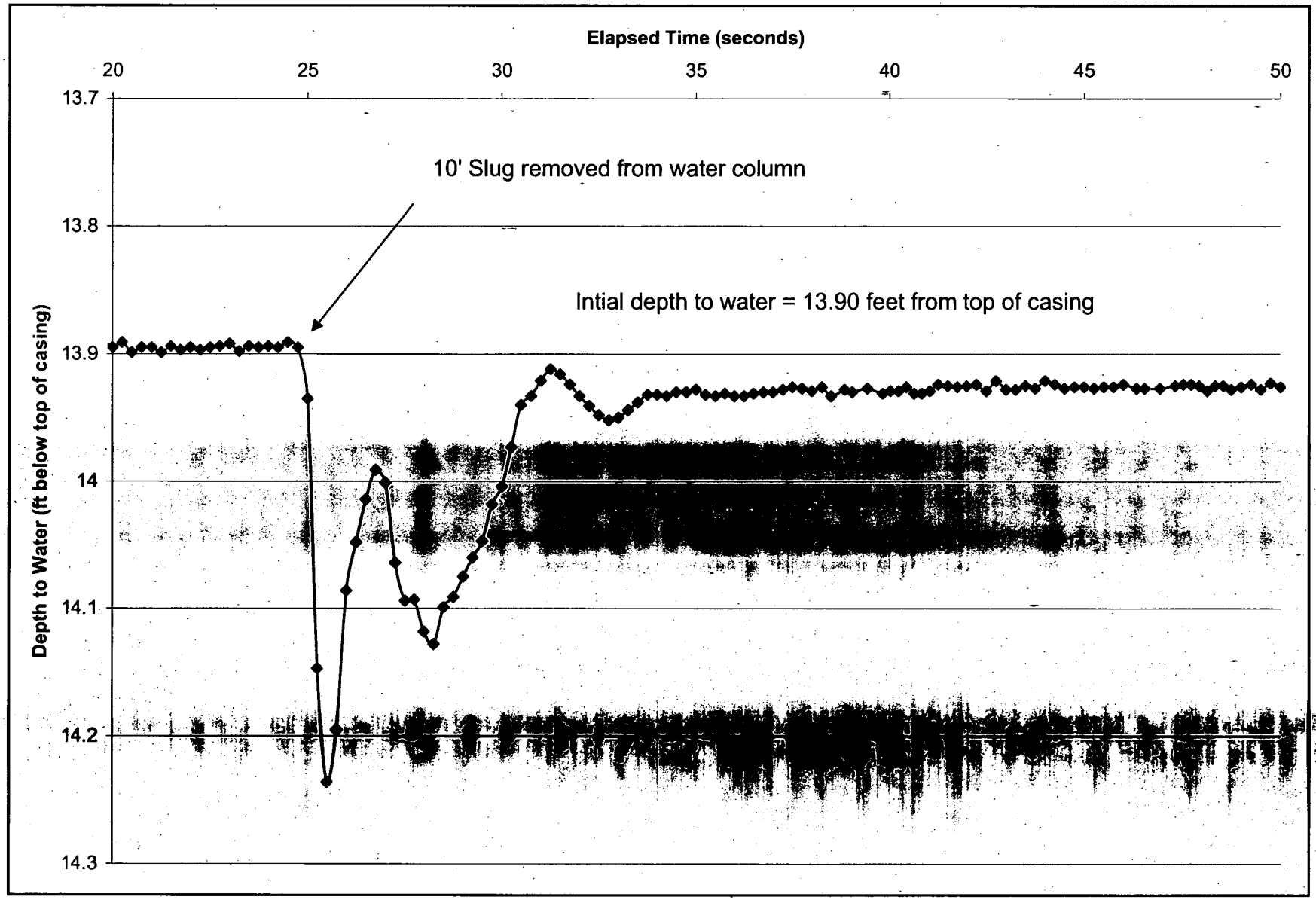

P:_ES06-121\PRB-Eval.9-06\Appx A\Appendix A-slug test plots.xls MW-1 FH3 Chart

## PRB MW-01 Rising Head Test #1



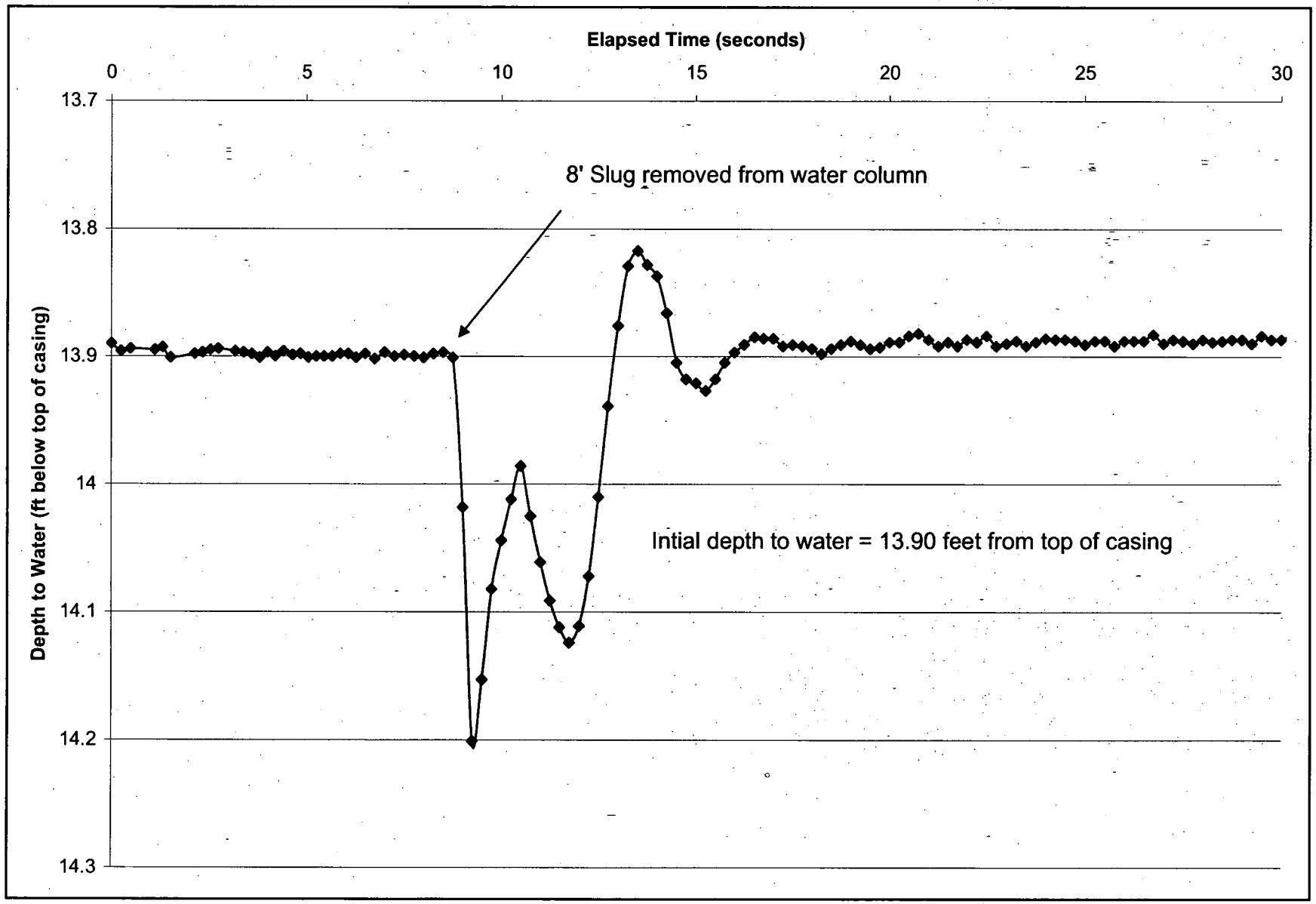

P:_ES06-121\PRB-Eval.9-06\Appx A\Appendix A-slug test plots.xls MW-1 RH1 Chart

## PRB MW-01 Rising Head Test #2



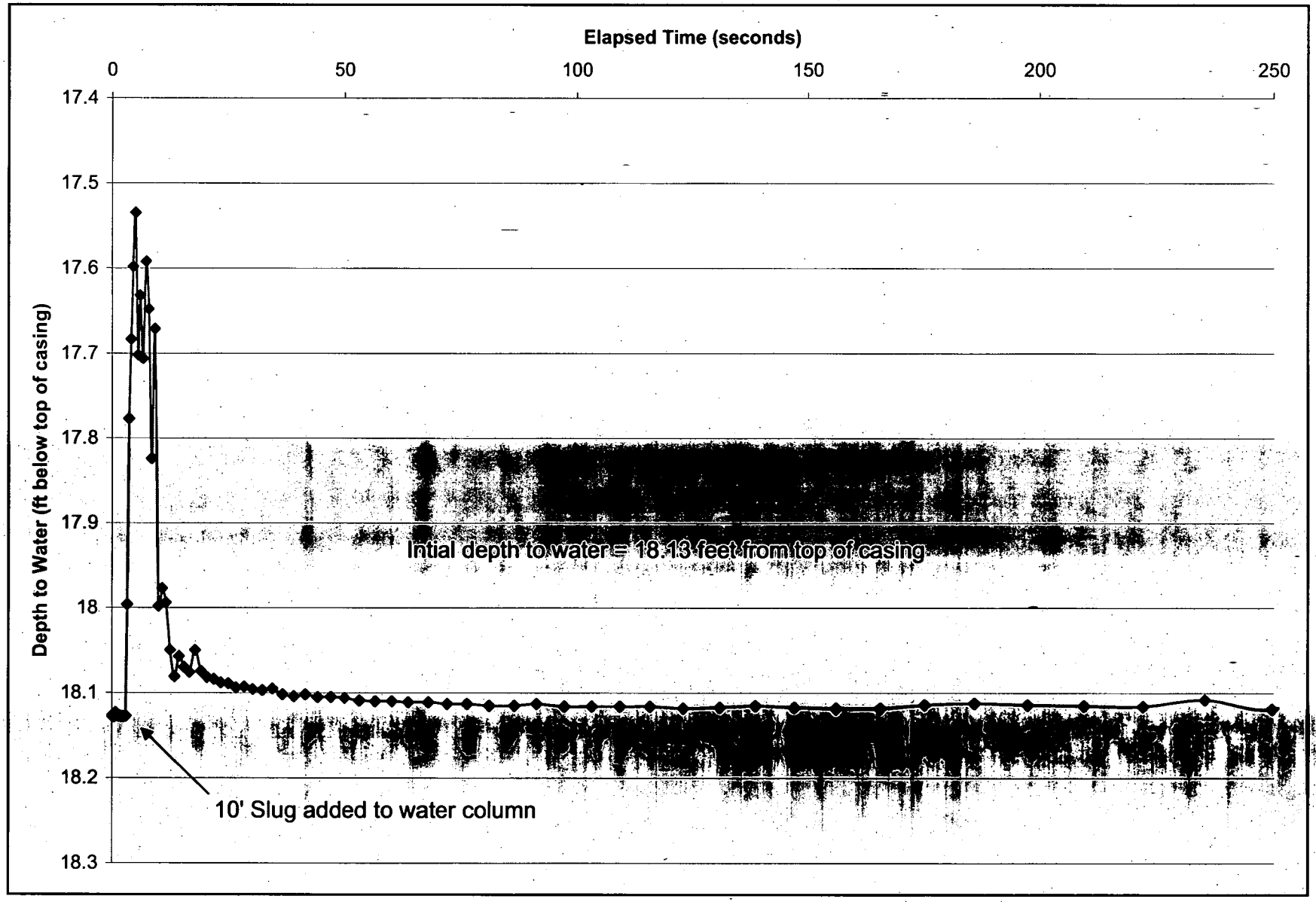

P:_ES06-121\PRB-Eval.9-06\Appx A\Appendix A-slug test plots.xls MW-1 RH2 Chart

## PRB MW-01 Rising Head Test #3



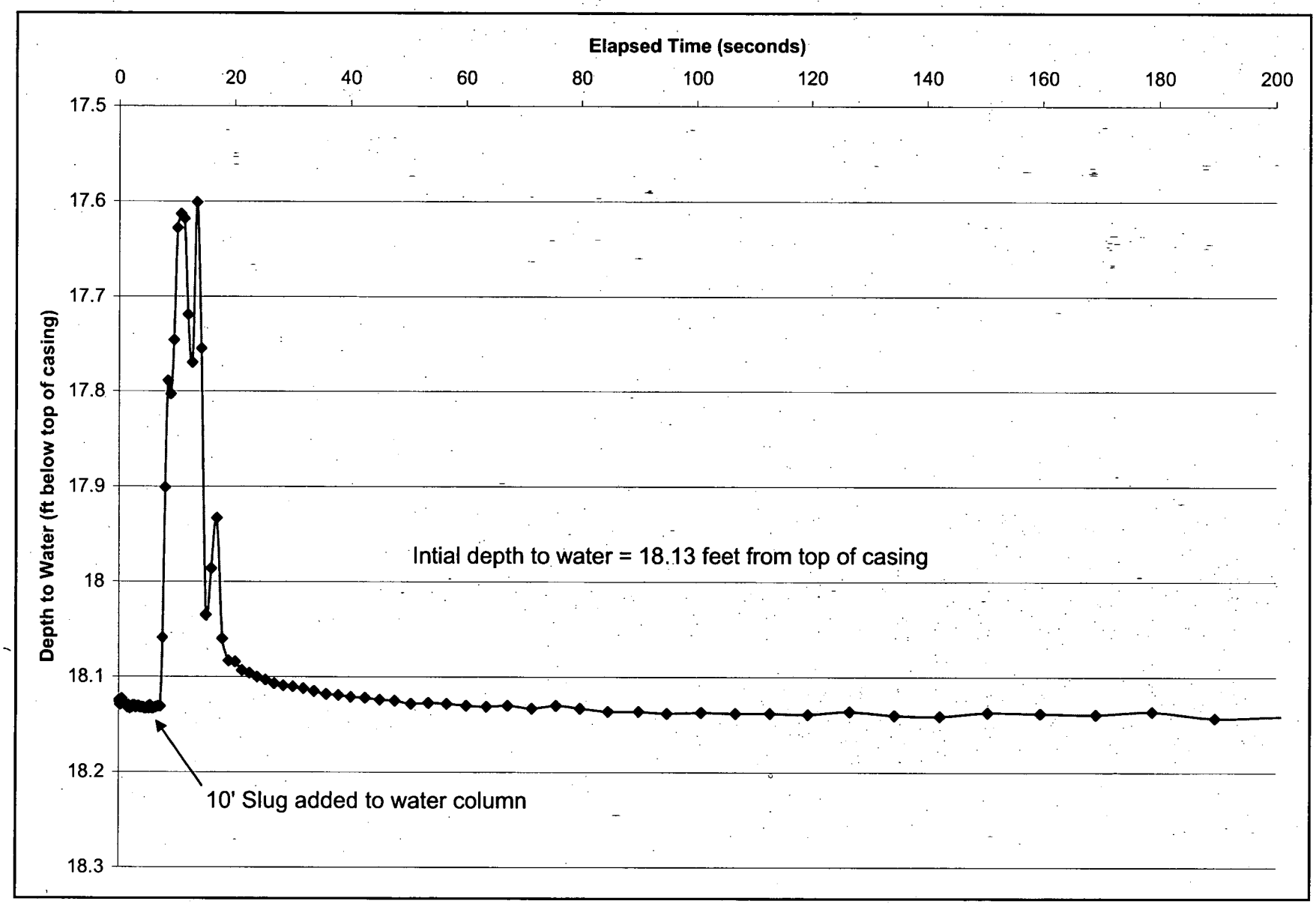

P:_ES06-121\PRB-Eval.9-06\Appx A\Appendix A-slug test plots.xls MW-1 RH3 Chart

## PRB MW-02 Falling Head Test #1



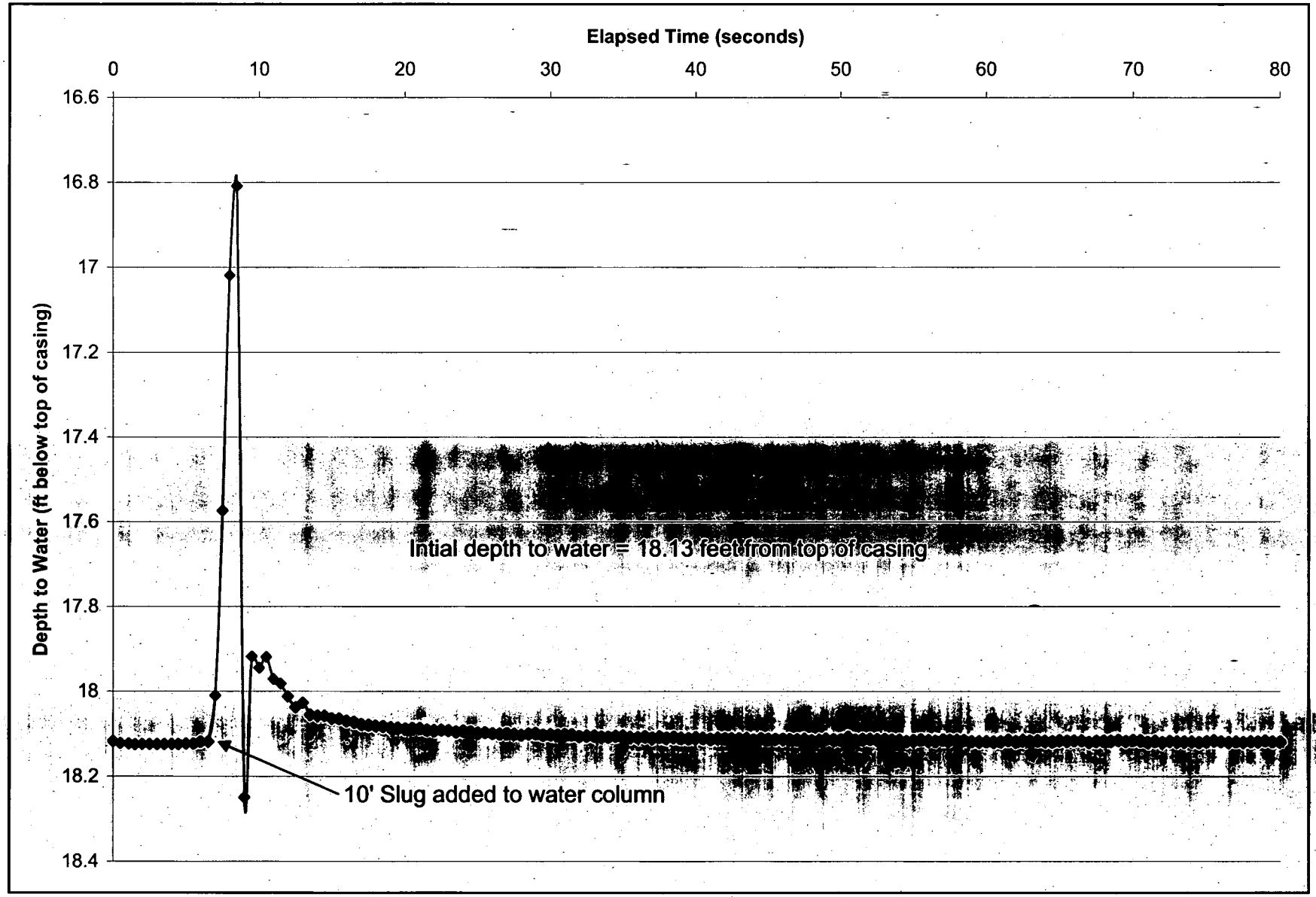

P:_ES06-121\PRB-Eval.9-06\Appx A\Appendix A-slug test plots.xls MW-2 FH1 Chart

## PRB MW-02 Falling Head Test #2



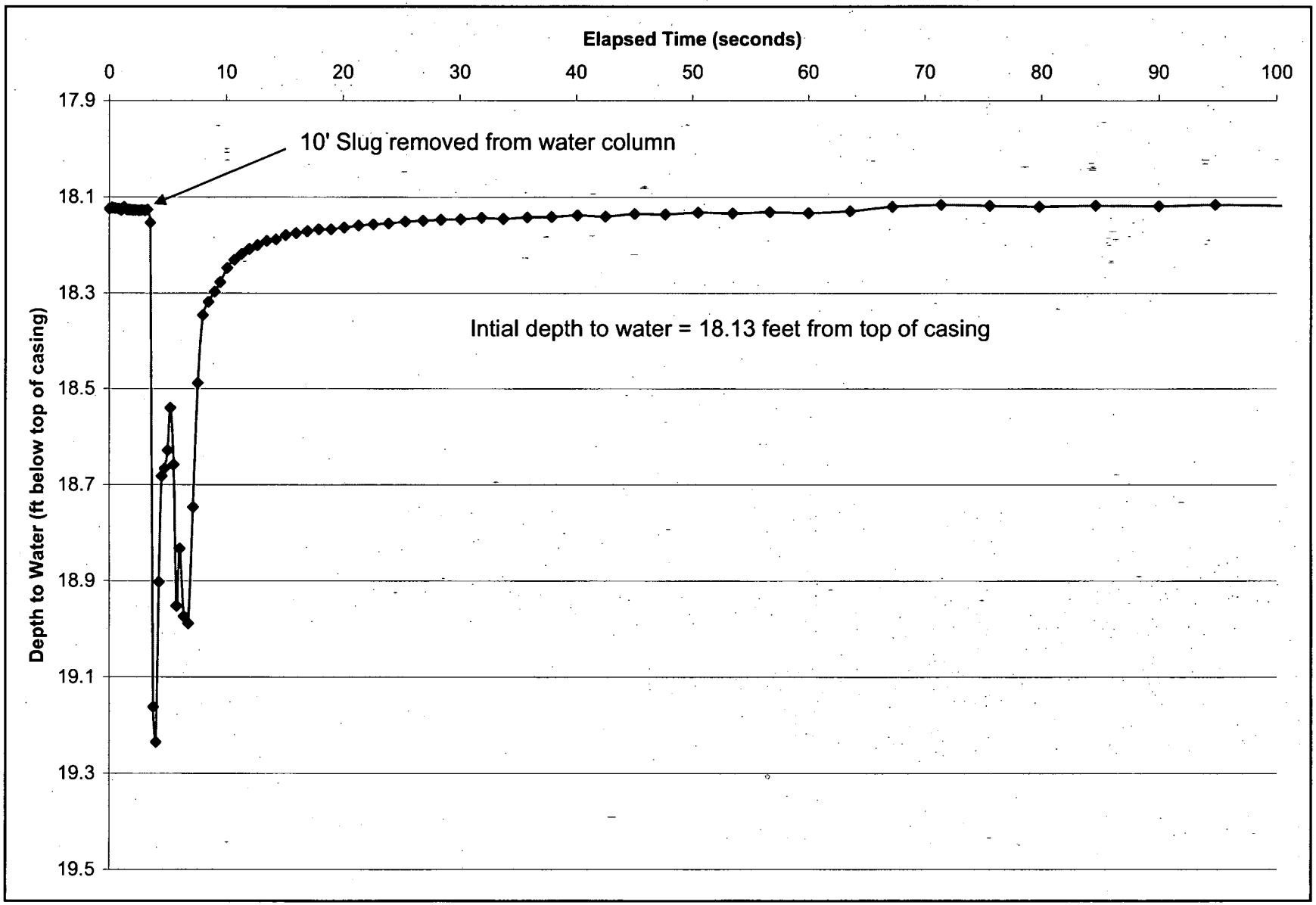

P:_ES06-121\PRB-Eval.9-06\Appx A\Appendix A-slug test plots.xls MW-2 FH2 Chart

## PRB MW-02 Falling Head Test #3

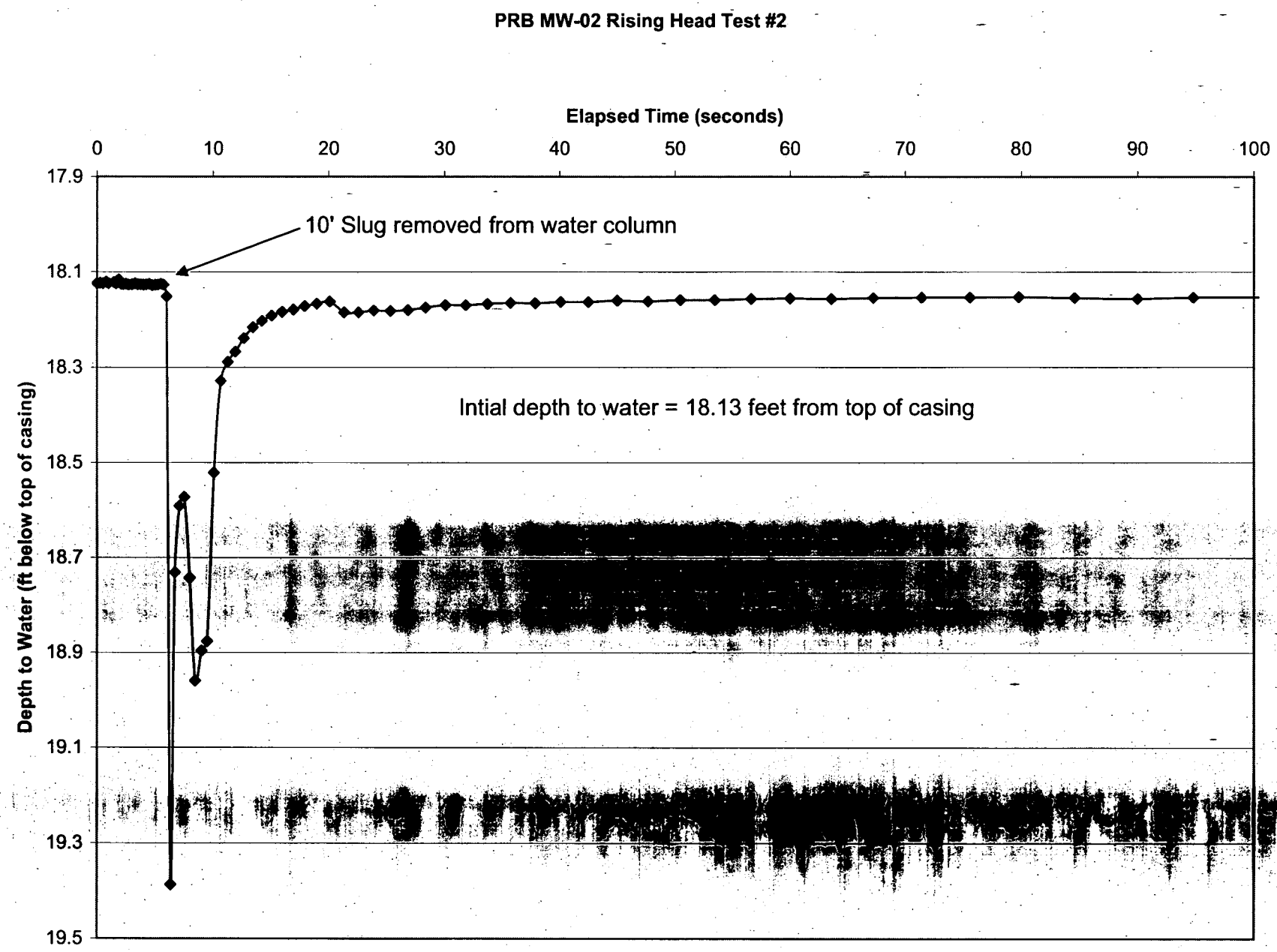



P:_ES06-121\PRB-Eval.9-06\Appx A\Appendix A-slug test plots.xls MW-2 FH3 Chart

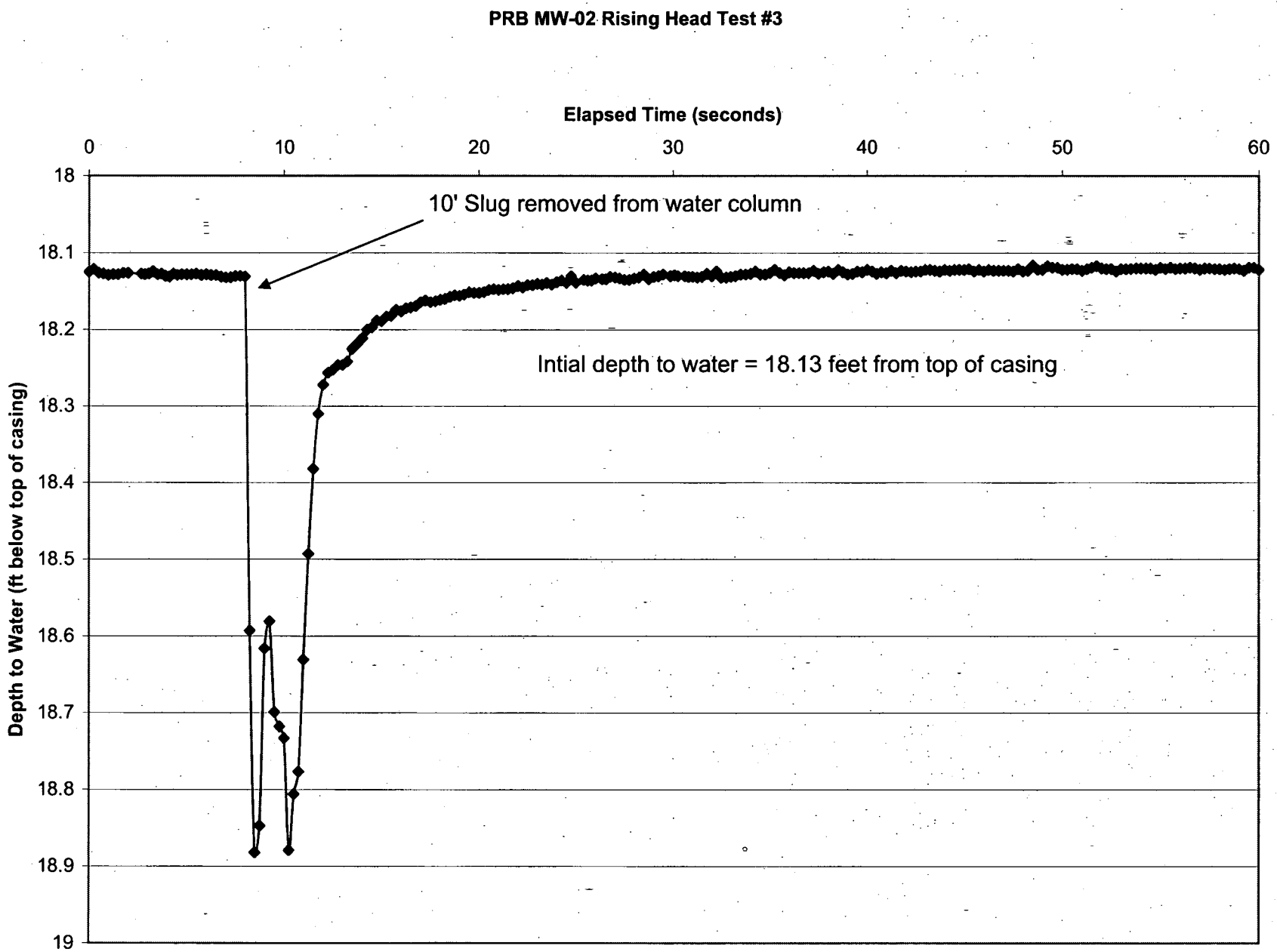
## PRB MW-02 Rising Head Test #1



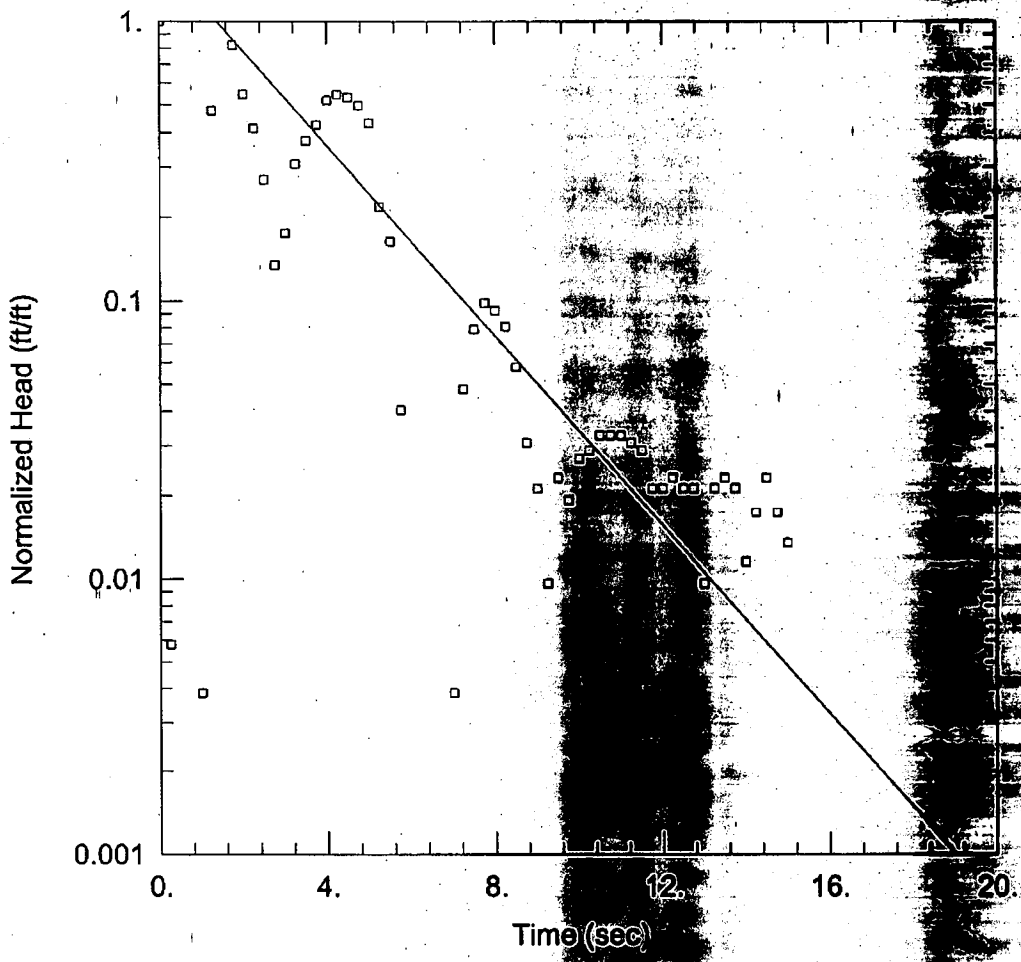

P:_ES06-121\PRB-Eval.9-06\Appx A\Appendix A-slug test plots.xls MW-2 RH1 Chart




P:_ES06-121\PRB-Eval.9-06\Appx A\Appendix A-slug test plots.xls MW-2 RH2 Chart




P:_ES06-121\PRB-Eval.9-06\Appx A\Appendix A-slug test plots.xls MW-2 RH3 Chart




**RH1**

Data Set: S:\Projects\ES06.0121_PRB_Evaluation\Modeling\MW-01 RH1.aqt
Date: 09/24/06 Time: 16:38:27

**PROJECT INFORMATION**

Company: Daniel B Stephens
Client: LANL
Project: ES06.0121
Location: PRB
Test Well: MW-01
Test Date: 9/13/2006

**AQUIFER DATA**

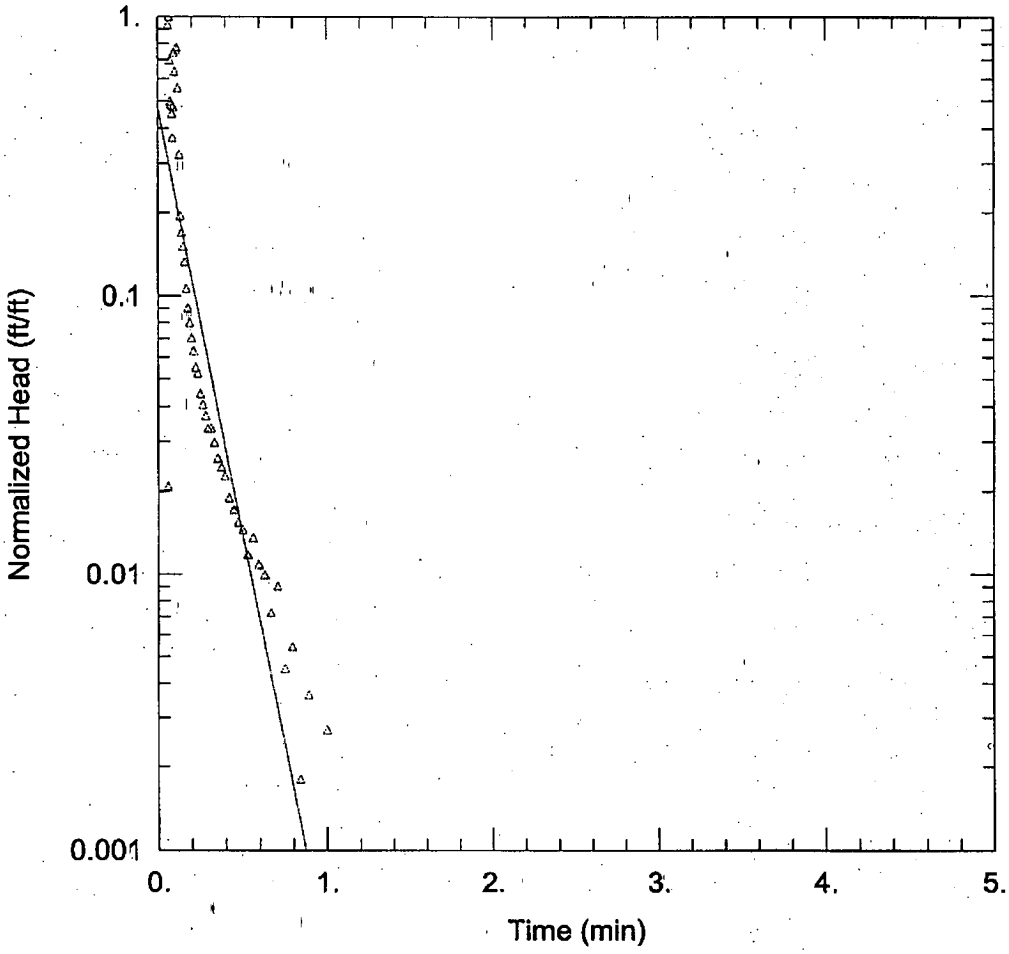
Saturated Thickness: 19.54 ft
Anisotropy Ratio (Kz/Kr): 1.

**WELL DATA (MW-01)**

Initial Displacement: 0.52 ft
Total Well Penetration Depth: 16.4 ft
Casing Radius: 0.0833 ft
Static Water Column Height: 19.54 ft
Screen Length: 16.2 ft
Wellbore Radius: 0.0833 ft

**SOLUTION**

Aquifer Model: Unconfined
Solution Method: Hvorslev
K = 0.01347 cm/sec
y0 = 0.8905 ft




MORTANDAD CANYON PRB EVALUATION

Data Set: S:\Projects\ES06.0121_PRB_Evaluation\Modeling\MW-02 RH1_min.aqt
Date: 09/24/06 Time: 16:26:22

PROJECT INFORMATION

Company: Daniel B. Stephens & Assoc
Client: LANL
Project: ES06.0121
Location: PRB, Mortendad Canyon
Test Well: MW-02
Test Date: 091306

AQUIFER DATA

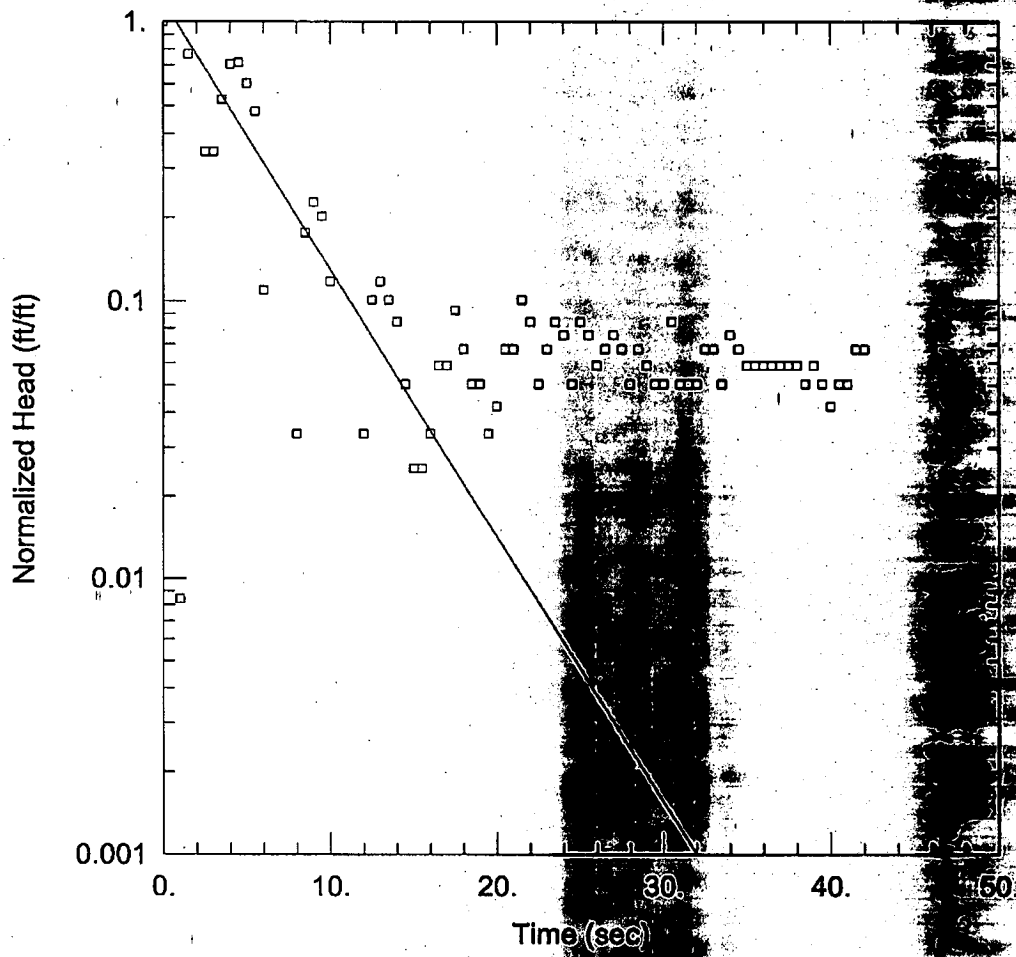
Saturated Thickness: 14.85 ft
Anisotropy Ratio (Kz/Kr): 1.

WELL DATA (MW-02)

Initial Displacement: -1.105 ft
Total Well Penetration Depth: 15.54 ft
Casing Radius: 0.17 ft
Static Water Column Height: 14.85 ft
Screen Length: 15.9 ft
Wellbore Radius: 0.17 ft
Gravel Pack Porosity: 0.459

SOLUTION

Aquifer Model: Unconfined
Solution Method: Hvorslev
K = 0.01478 cm/sec
y0 = -0.5226 ft




MORTANDAD CANYON PRB EVALUATION

Data Set: S:\Projects\ES06.0121_PRB_Evaluation\Modeling\SW-A2 RH2.aqt
Date: 09/24/06 Time: 16:28:06

PROJECT INFORMATION

Company: Daniel B. Stephens
Client: LANL
Project: ES06.0121
Location: PRB
Test Well: SW-A2
Test Date: 9/13/2006

AQUIFER DATA

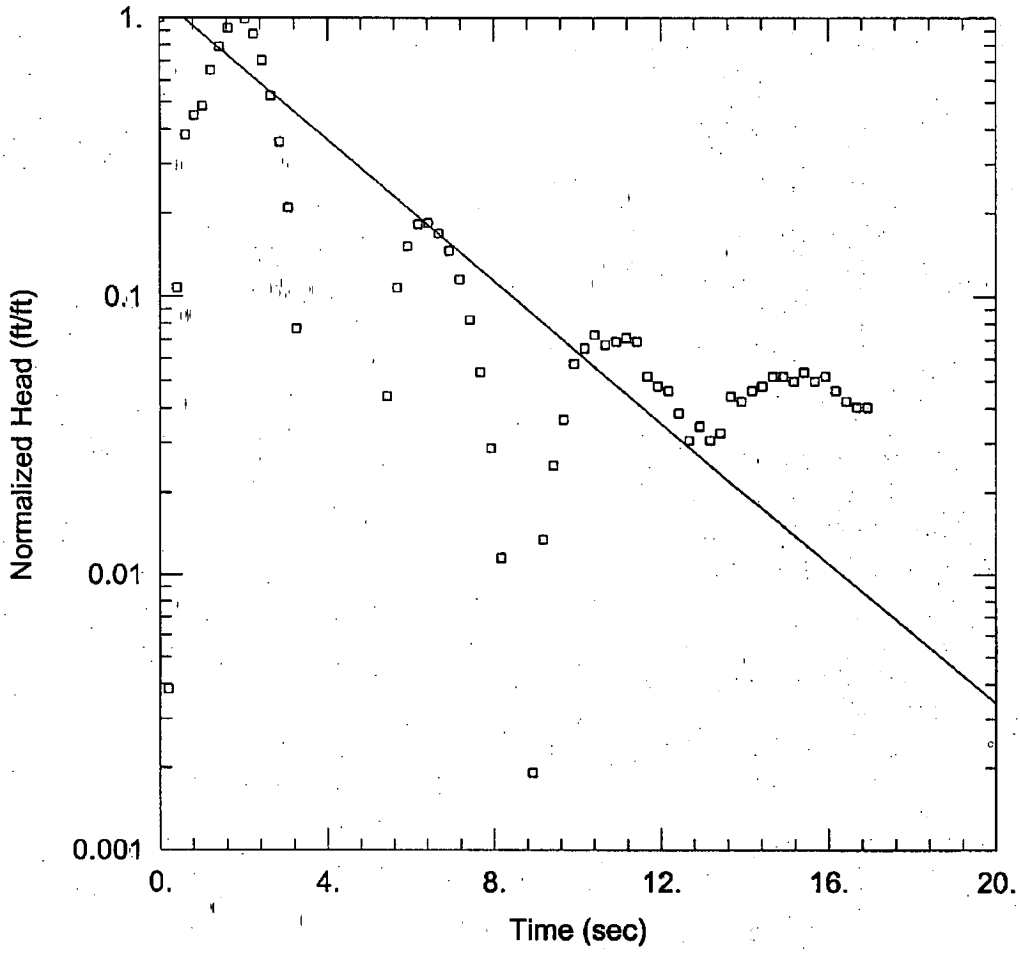
Saturated Thickness: 19.54 ft
Anisotropy Ratio (Kz/Kr): 1.

WELL DATA (SW-A2)

Initial Displacement: 0.119 ft
Total Well Penetration Depth: 15.59 ft
Casing Radius: 0.0833 ft
Static Water Column Height: 19.54 ft
Screen Length: 10. ft
Wellbore Radius: 0.0833 ft

SOLUTION

Aquifer Model: Unconfined
Solution Method: Hvorslev
K = 0.0112 cm/sec
y0 = 0.1411 ft




## MORTANDAD CANYON PRB EVALUATION

Data Set: S:\Projects\ES06.0121_PRB_Evaluation\Modeling\SW-B3 RH3.aqt
Date: 09/24/06 Time: 16:38:54

## PROJECT INFORMATION

Company: Daniel B Stephens
Client: LANL
Project: ES06.0121
Location: PRB
Test Well: SW-B3
Test Date: 9/13/2006

## AQUIFER DATA

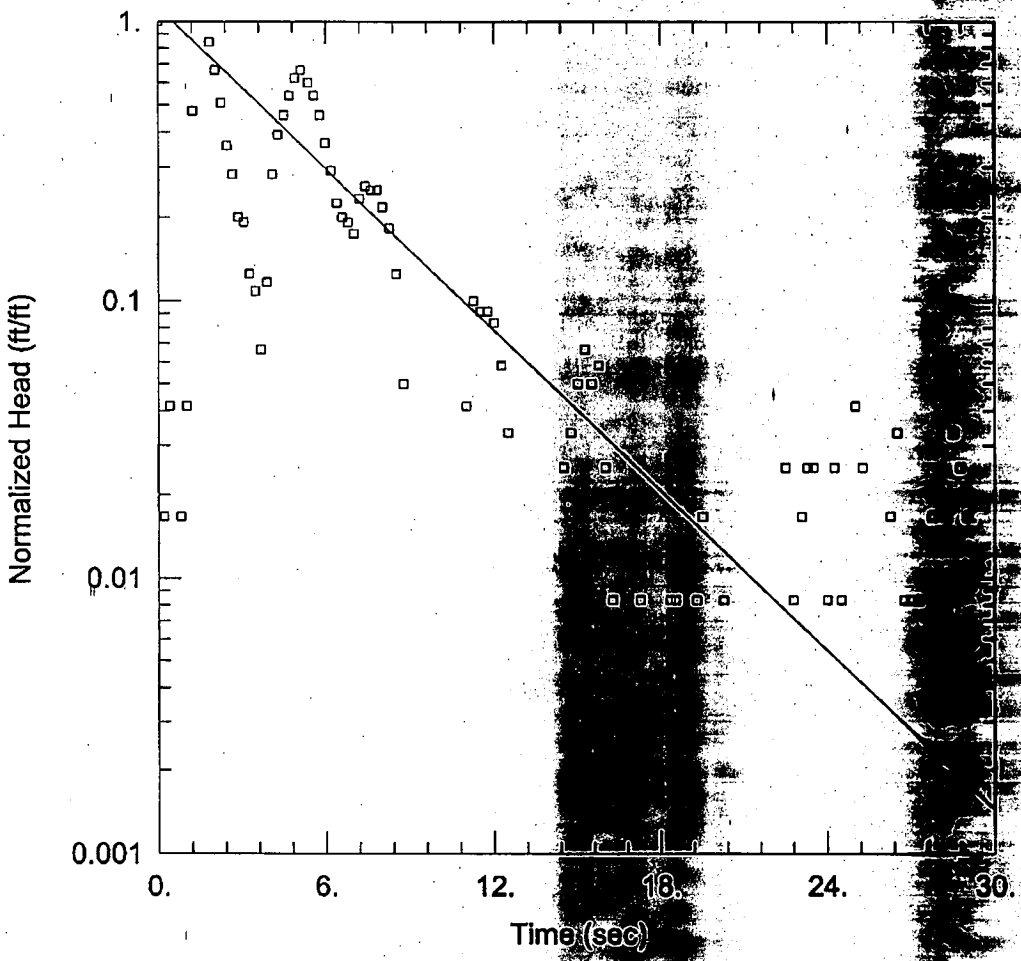
Saturated Thickness: 17.91 ft
Anisotropy Ratio (Kz/Kr): 1.

## WELL DATA (SW-B3)

Initial Displacement: 0.521 ft
Total Well Penetration Depth: 17.91 ft
Casing Radius: 0.0833 ft
Static Water Column Height: 17.91 ft
Screen Length: 10. ft
Wellbore Radius: 0.0833 ft

## SOLUTION

Aquifer Model: Unconfined
Solution Method: Hvorslev
K = 0.01695 cm/sec
y0 = 0.6161 ft




MORTANDAD CANYON PRB EVALUATION

Data Set: S:\Projects\ES06.0121_PRB_Evaluation\Modeling\SW-C1 RH2.aqt
Date: 09/24/06 Time: 16:39:14

PROJECT INFORMATION

Company: Daniel B Stephens
Client: LANL
Project: ES06.0121
Location: PRB
Test Well: SW-C1
Test Date: 9/18/2006

AQUIFER DATA

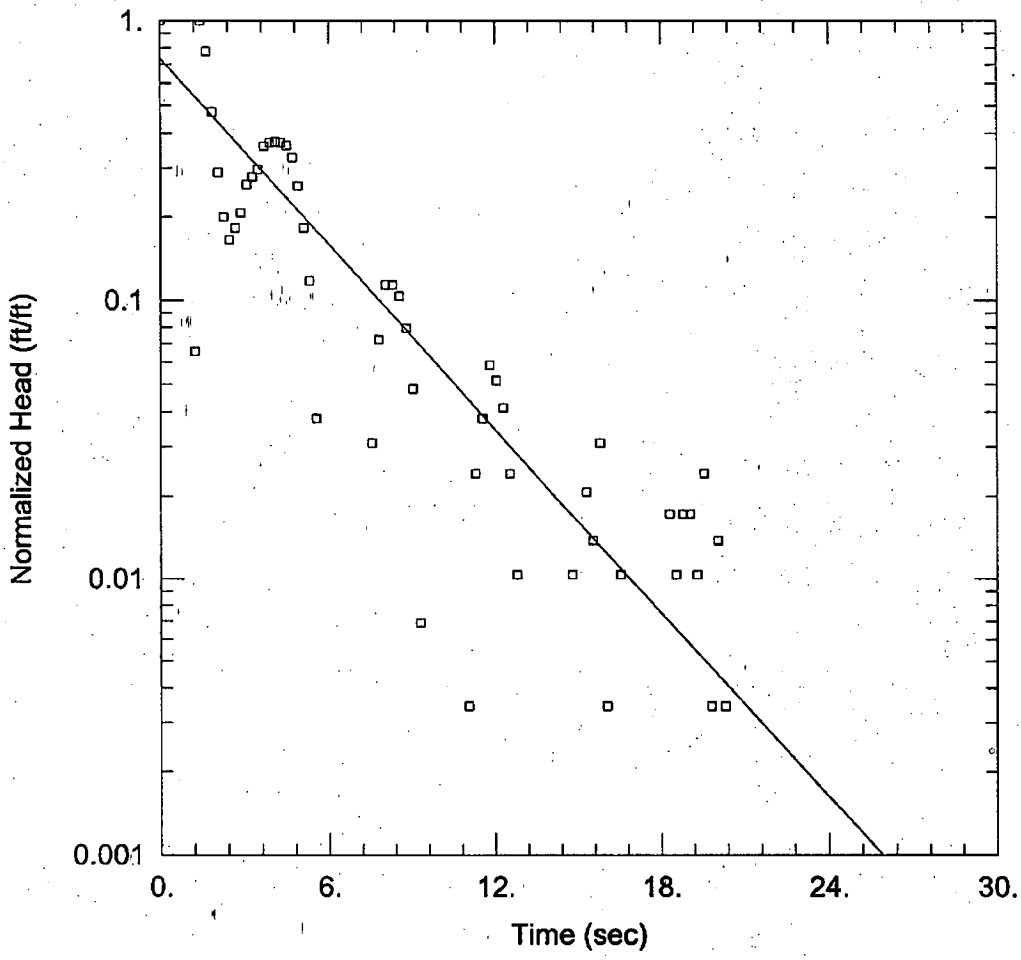
Saturated Thickness: 21.1 ft
Anisotropy Ratio (Kz/Kr): 1.

WELL DATA (SW-C1)

Initial Displacement: 0.12 ft
Total Well Penetration Depth: 21.1 ft
Casing Radius: 0.0833 ft
Static Water Column Height: 21.1 ft
Screen Length: 10. ft
Wellbore Radius: 0.0833 ft

SOLUTION

Aquifer Model: Unconfined
Solution Method: Hvorslev
K = 0.01286 cm/sec
y0 = 0.1348 ft




## MORTANDAD CANYON PRB EVALUATION

Data Set: S:\Projects\ES06.0121_PRB_Evaluation\Modeling\SW-D2 RH2.aqt
Date: 09/24/06 Time: 16:30:43

## PROJECT INFORMATION

Company: Daniel B Stephens
Client: LANL
Project: ES06.0121
Location: PRB
Test Well: SW-D2
Test Date: 9/18/2006

## AQUIFER DATA

Saturated Thickness: 20.44 ft
Anisotropy Ratio (Kz/Kr): 1.

## WELL DATA (SW-D2)

Initial Displacement: 0.29 ft
Total Well Penetration Depth: 20.44 ft
Casing Radius: 0.0833 ft
Static Water Column Height: 20.44 ft
Screen Length: 10. ft
Wellbore Radius: 0.0833 ft

## SOLUTION

Aquifer Model: Unconfined
Solution Method: Hvorslev
K = 0.01476 cm/sec
y0 = 0.2136 ft