The National Academies of
SCIENCES · ENGINEERING · MEDICINE

TRANSPORTATION RESEARCH BOARD

When to Use Fully Grouted Piezometer Installations

July 8, 2020
2:00-3:30 PM Eastern

@NASEMTRB
#TRBwebinar

PDH Certification Information:

- 1.5 Professional Development Hours (PDH) – see follow-up email for instructions
- You must attend the entire webinar to be eligible to receive PDH credits
- Questions? Contact Reggie Gillum at RGillum@nas.edu

The Transportation Research Board has met the standards and requirements of the Registered Continuing Education Providers Program. Credit earned on completion of this program will be reported to RCEP. A certificate of completion will be issued to participants that have registered and attended the entire session. As such, it does not include content that may be deemed or construed to be an approval or endorsement by RCEP.

#TRBwebinar

RCEP

REGISTERED CONTINUING EDUCATION PROGRAM

Learning Objectives

1. Identify the most effective way to properly install piezometers

2. Understand the consequences of inappropriate selection and installation

3. Analyze collected data

#TRBwebinar

When to Use Fully Grouted Piezometer Installations

Speakers

- Joel Swenson, PE, Barr Engineering
  - *Fully-Grouted (FG) Introduction, Implementation, Benefits and Drawbacks, Recent Research*
- Dr. Georgette Hlepas, PE, USACE
  - *Fully Grouted Vibrating Wire Piezometers Monitoring Dams, Levees, & their Foundations*
- Dr. Andrew Ridley, Geotechnical Observations Ltd
  - *Filters and measuring negative pore water pressures*

Moderators

- Dr. Scott Anderson, PE, BGC Engineering, Inc.
- Tony Simmonds, MSc, Geokon

A webinar hosted by TRB Committee AKG60 - Geotechnical Instrumentation & Modeling

Vibrating Wire Piezometer Installations

When to Use Fully Grouted Piezometer Installations

- TRB Committee AKG60 – Geotechnical Instrumentation & Modeling
  - Mission to promote research and technology transfer for emerging and state-of-the-art technology
- FHWA Guidance
  - National Highway Institute Course No. 132041 Geotechnical Instrumentation
    - No reference material, relies on instructor experience
- FHWA and State DOT experience
  - Seldom used
  - Opportunity for research and technology transfer

Vibrating Wire Piezometers

When to Use Fully Grouted Piezometer Installations

- Well suited for fully grouted installations
  - Diaphragm-type piezometer
  - Quick response time
- Failure modes
  - Lightning
  - Cut/severed cables
  - Over-ranged
- Factors affecting vibrating wire piezometers
  - Drift
  - Electrical interference (noise)
  - Operator error

When to Use Fully Grouted Piezometer Installations

Vibrating Wire Piezometers

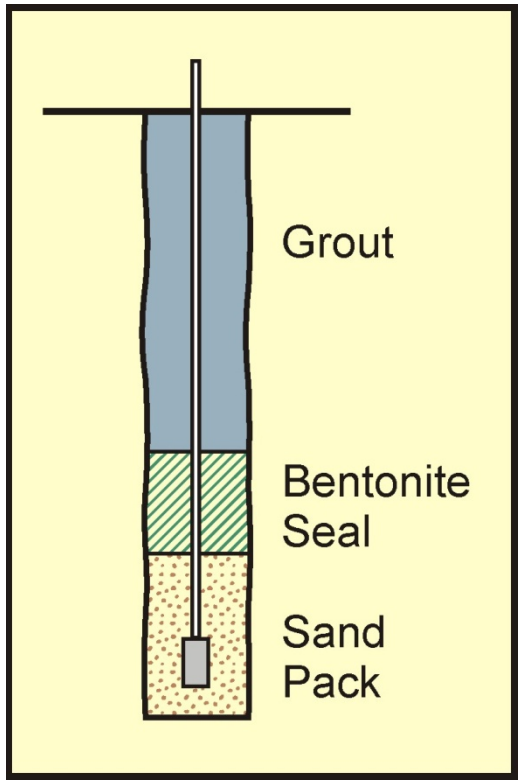
- The piezometer reading is wrong!
  - Why is the piezometer reading so high/so low?
- VW piezometers either work or they don’t!
  - They can only report the pressure they see
- Fully grouted installations
  - Not the correct method
  - Not fully understanding the method

outline

what is the fully-grouted method?

- what is it?
- how does it work?
- why do research?
- how is it constructed?
- what are some limitations?

introduction to the fully-grouted method



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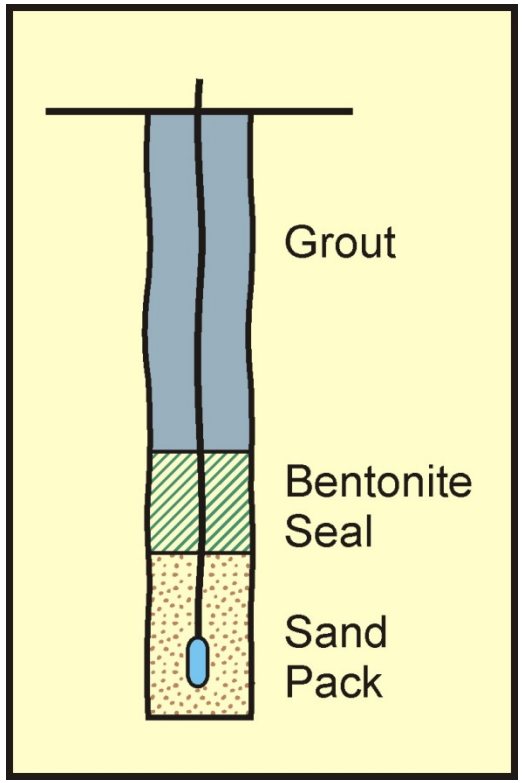
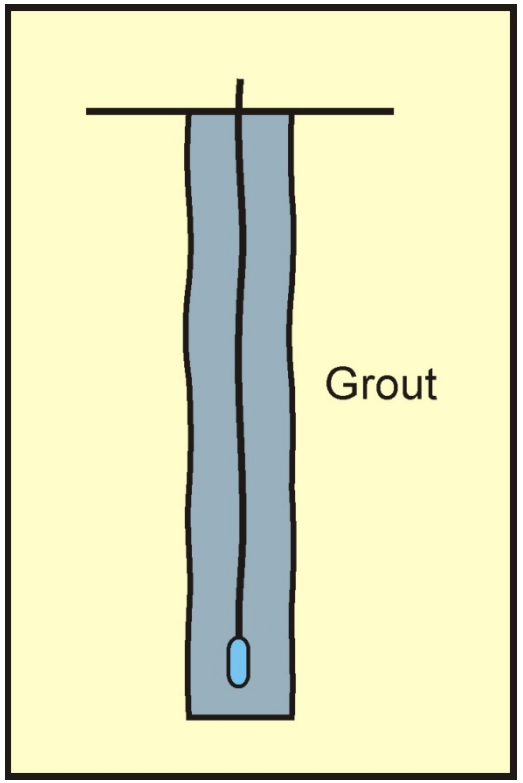
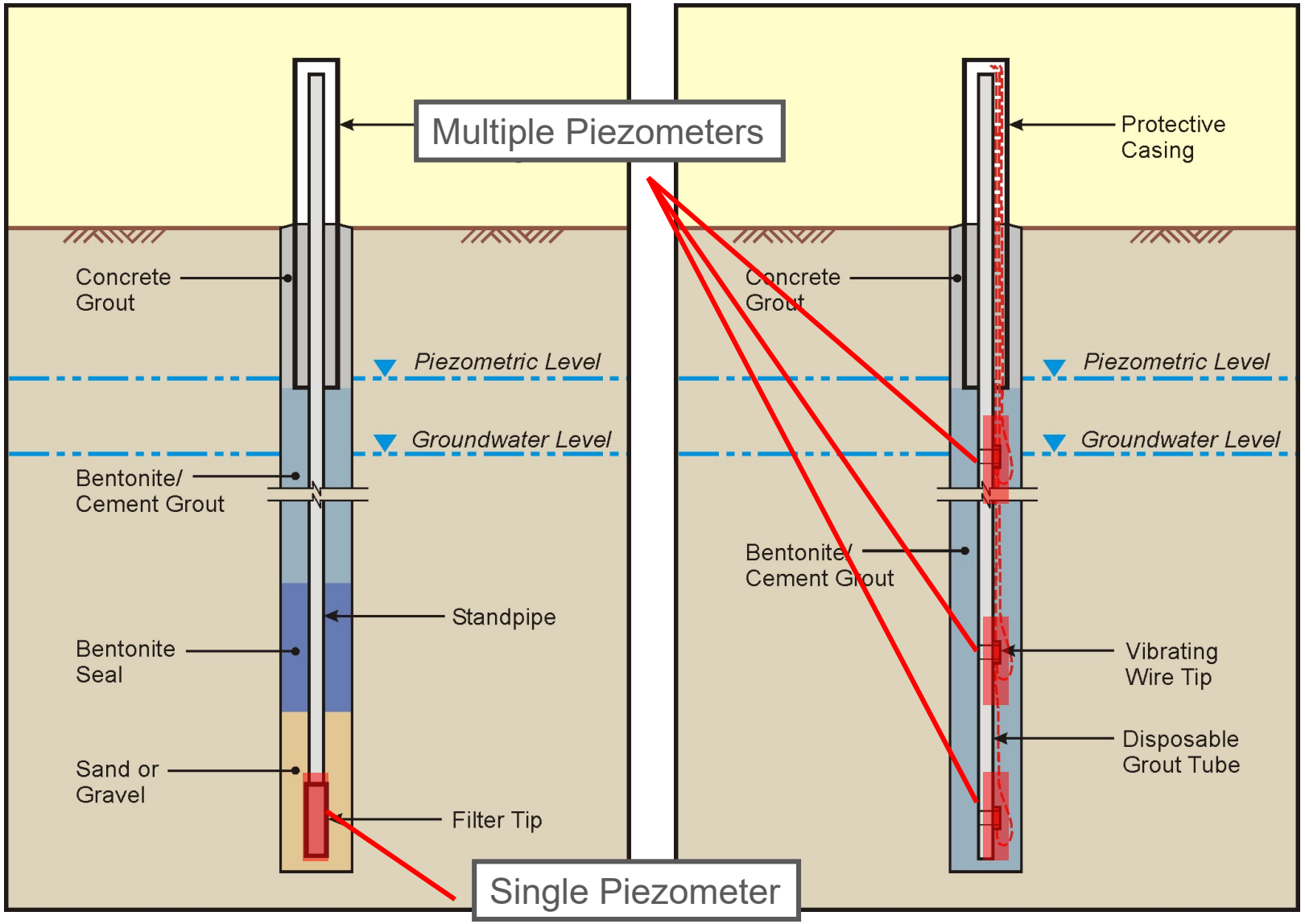


Common Practice

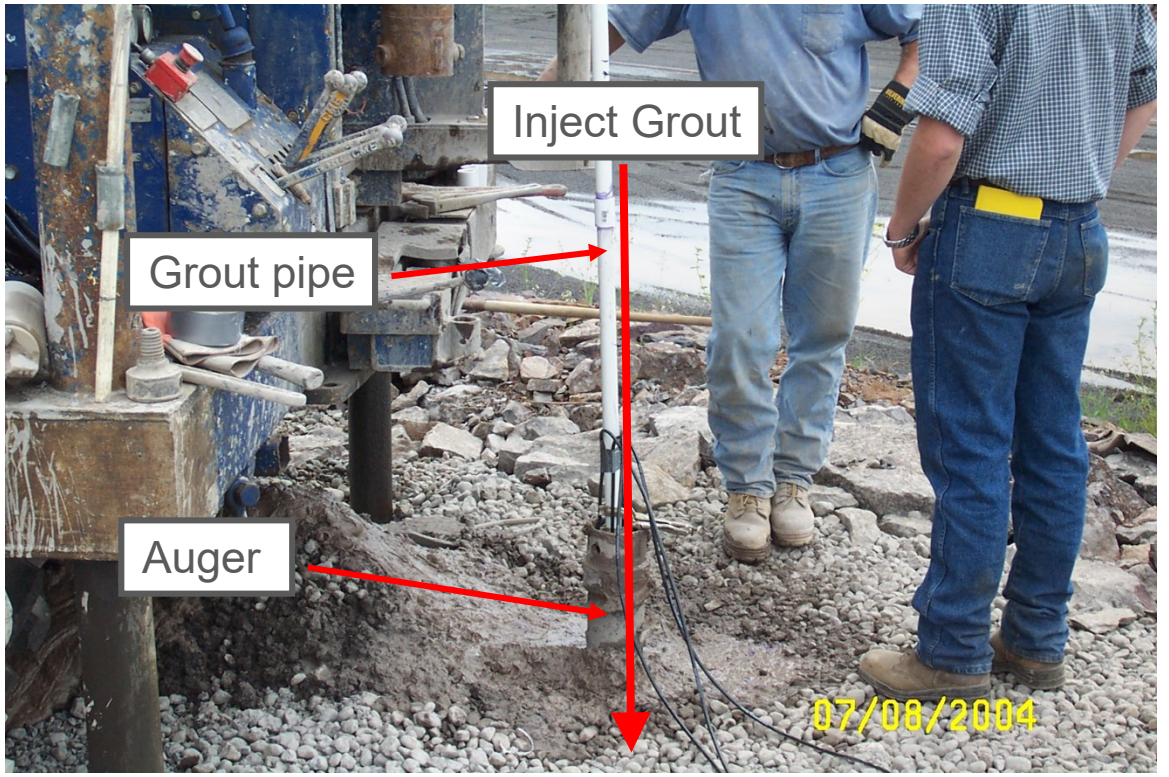


Fully-grouted

introduction to the fully-grouted method



introduction to the fully-grouted method



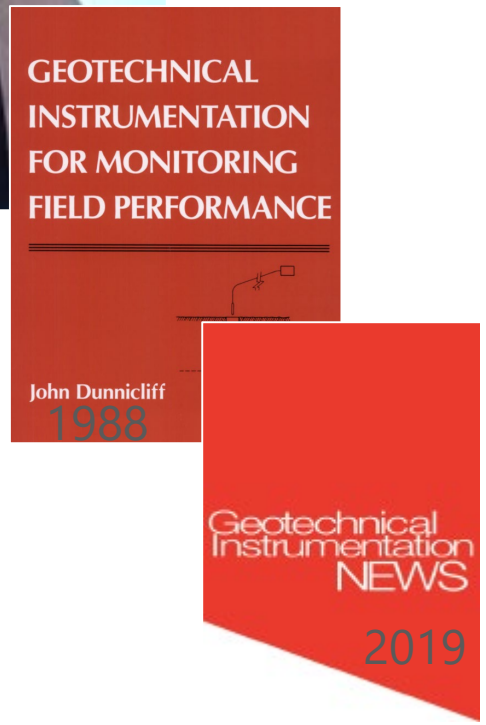
historical perspective

- Vaughn, 1969
  - early work
- Dunnicliff, 1993
  - geotechnical instrumentation and monitoring book
- Mikkelsen
  - initial research and implementation
  - 2003 instrumentation short course in Cocoa Beach, FL
- Barr, 2008, 2012, and ongoing
- Bayrd, 2011
- Slope Indicator, Geokon, and RST Instruments

why use it?

- better quality
- lower cost
- easier and faster installation than the "traditional" method of sand, bentonite chips/pellets, and grout.

"***Forget the sand and bentonite seal! This is no longer the way to go! Use the fully-grouted method!"*** *(John Dunnicliff, GIN, 2008)*

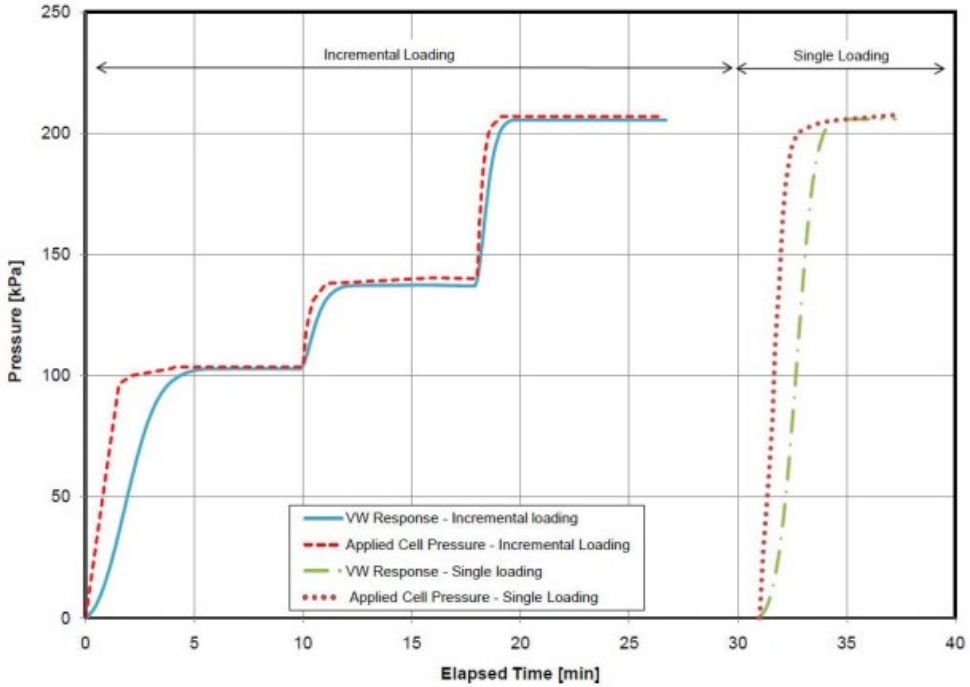


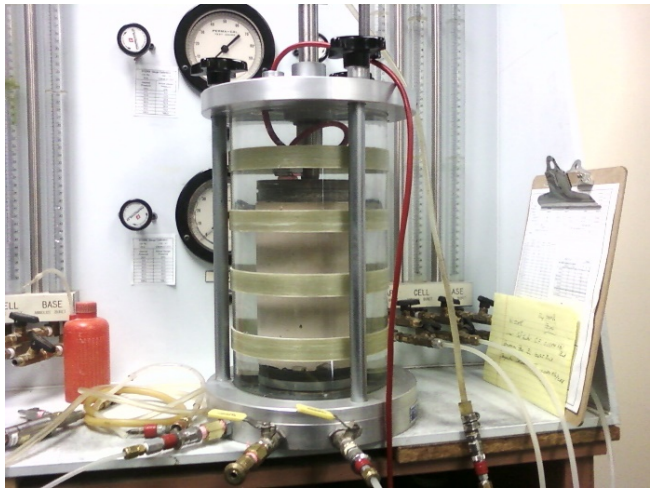
https://cgs.ca/instrumentation_news.html

93 issues with 190 articles spanning almost 20 years

it works because…

- requires very small volume change
- short hydrodynamic lag
- precision
- nested configuration





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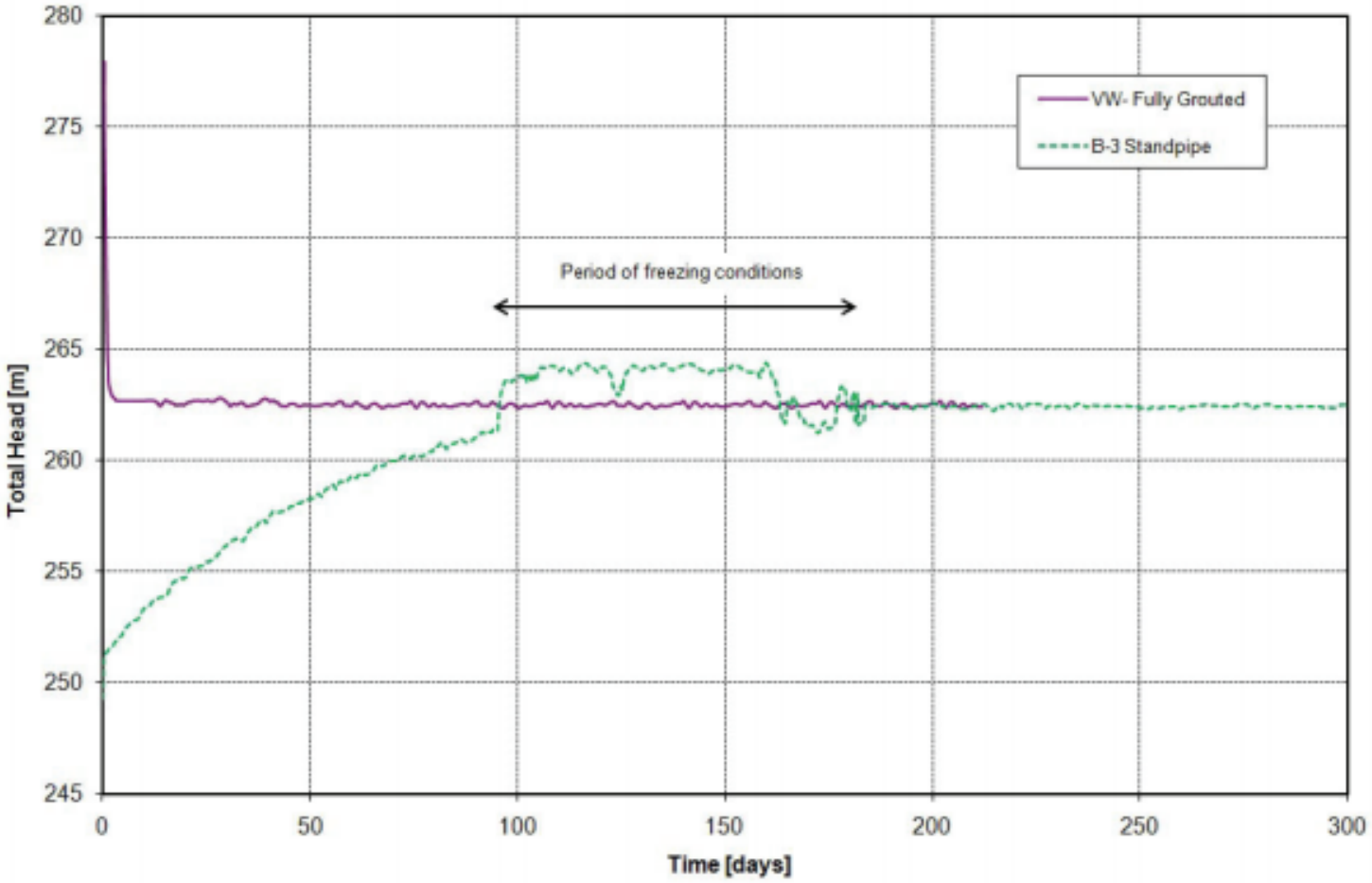

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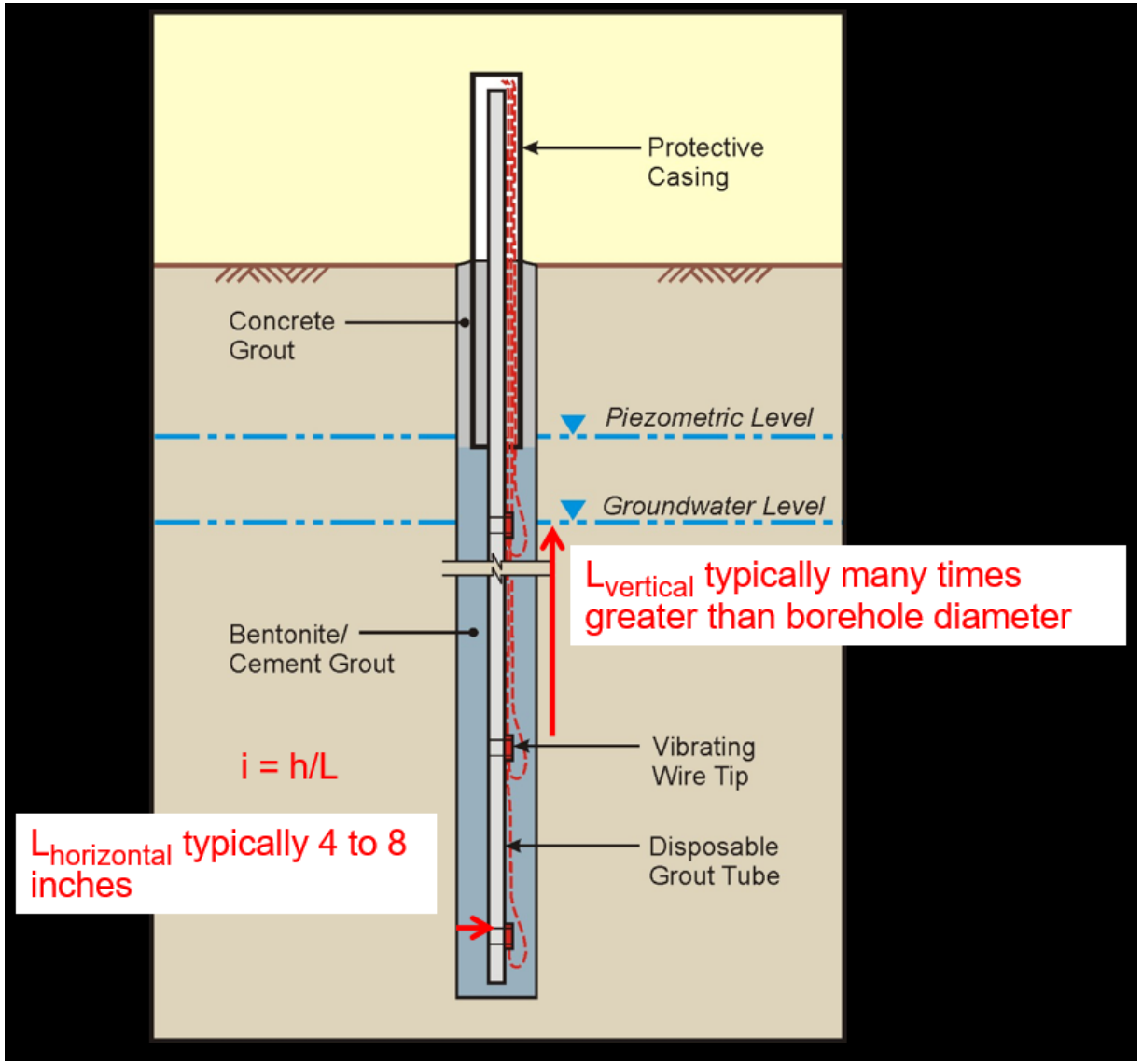


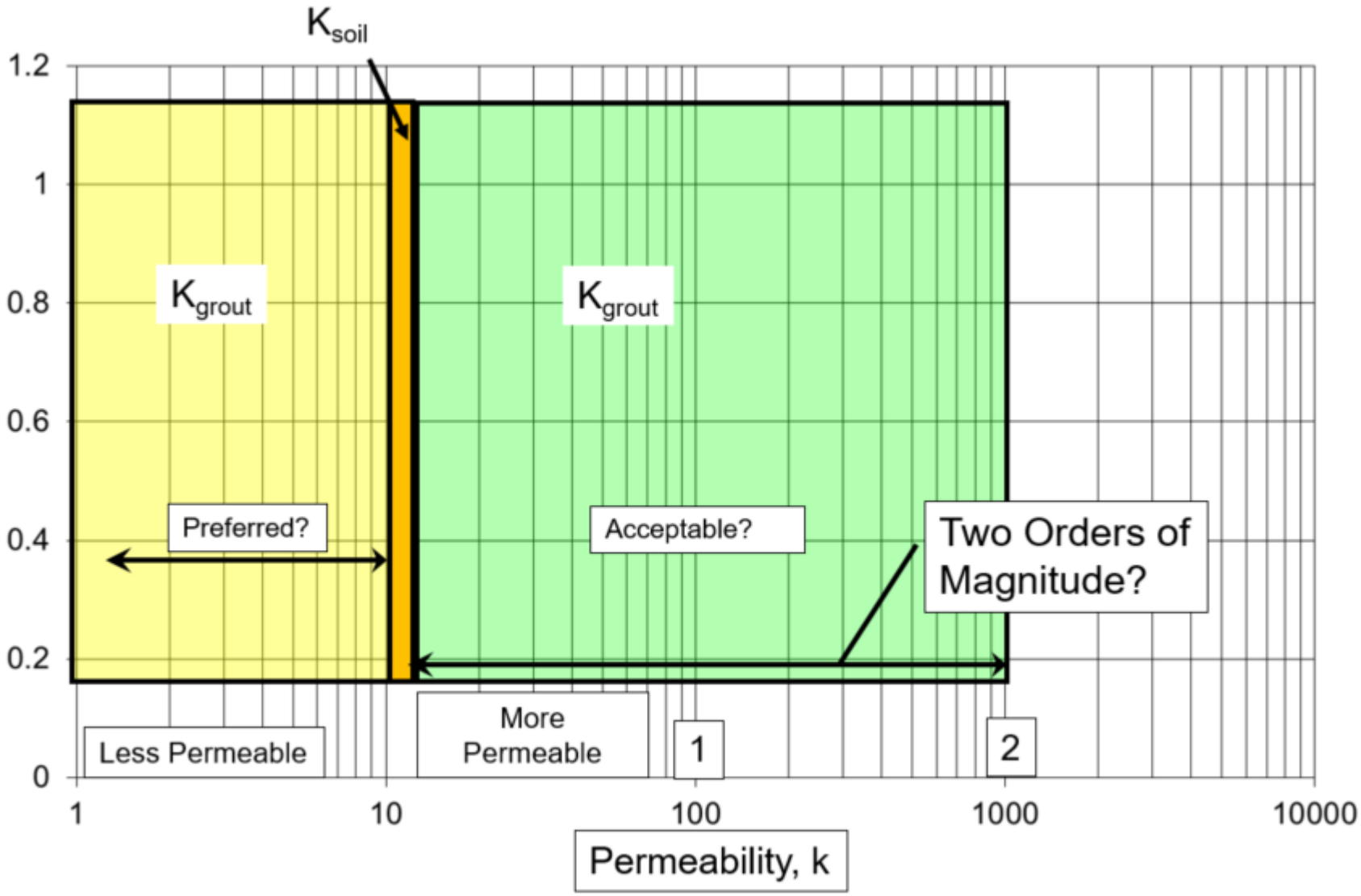
previous research

Grout Type	Characteristics	k (cm/sec)	Source
Neat cement	w/c = 0.53, γ = 112 pcf	10^{-7}	Baroid
Bentonite chips	hydrated	10^{-8}	Baroid
Bentonite slurry	6 % solids	10^{-5}	Baroid
Bentonite slurry	20 % solids	10^{-8}	Baroid
Cement-bentonite	water/solids = 4 to 1	10^{-6}	Vaughan, 1969
Cement-bentonite	w : c : b = 4 : 1 : 1	5×10^{-8}	Vaughan, 1973

Table 2. Permeability of some grouts

Mikkelsen, 2004

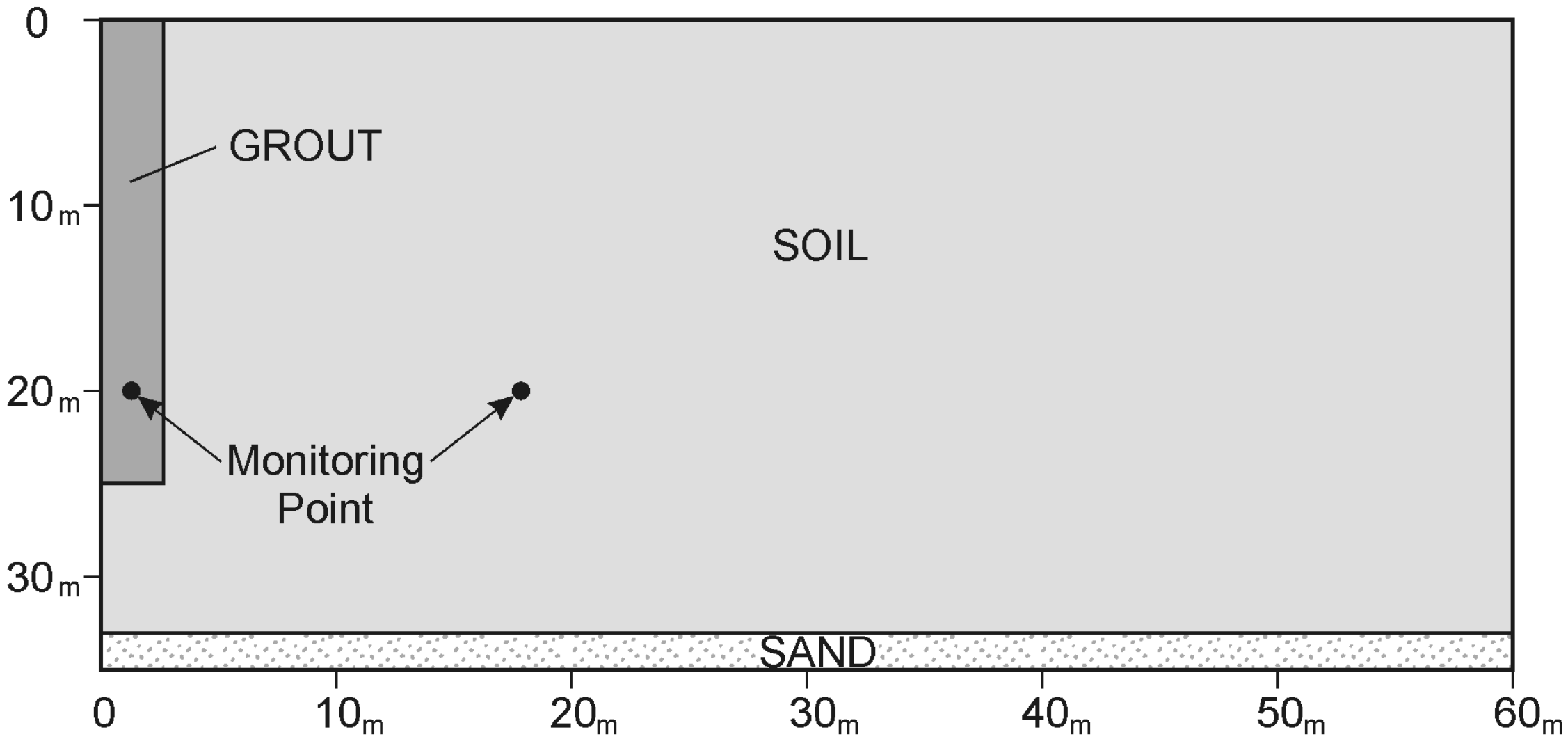
previous research



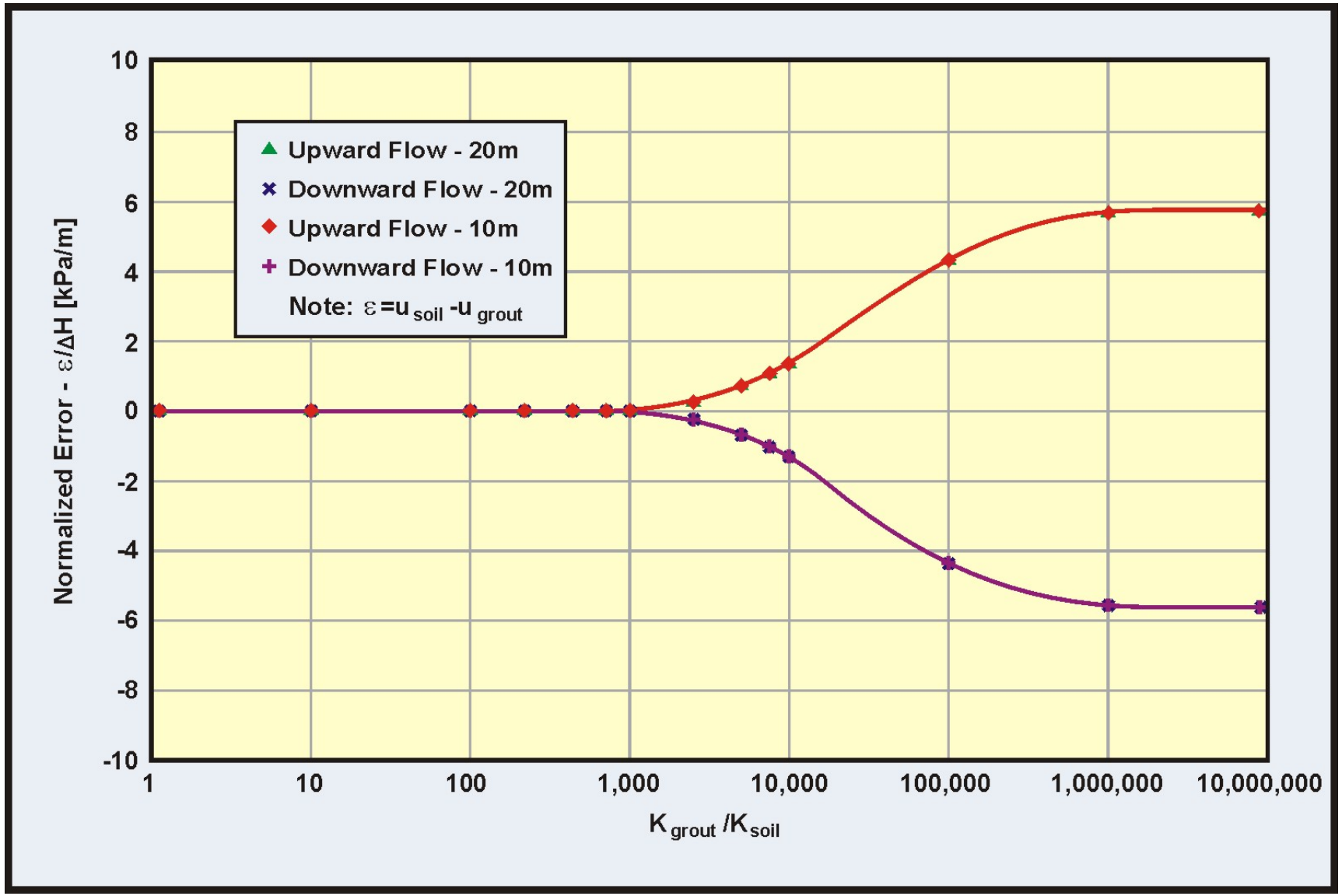
laboratory testing

- permeability
  - applicable to fully-grouted method
- strength
  - applicable to inclinometer installation
- stability of mix
  - separation and bleeding should be a minimum
  - shrinkage a minimum

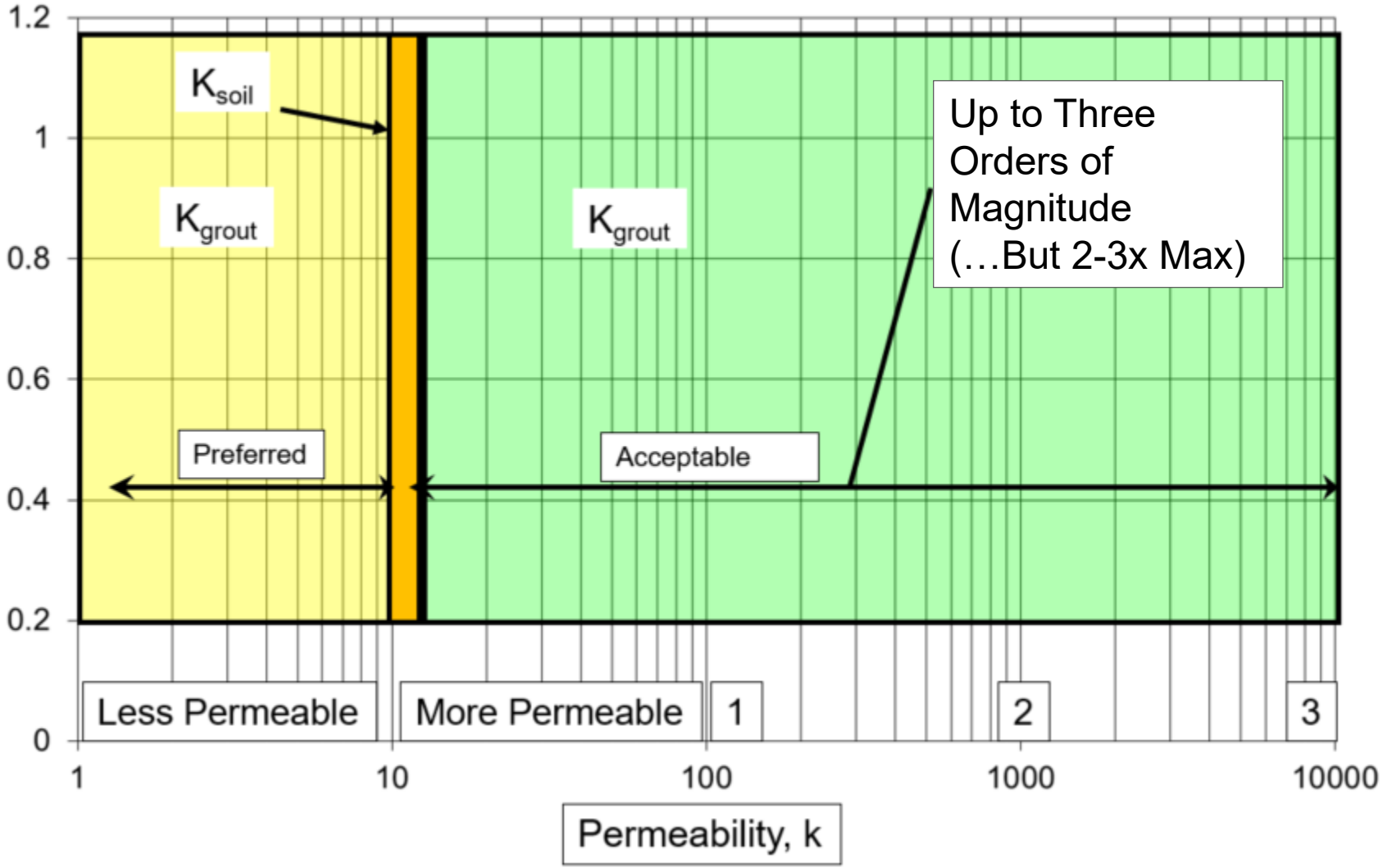
computer model



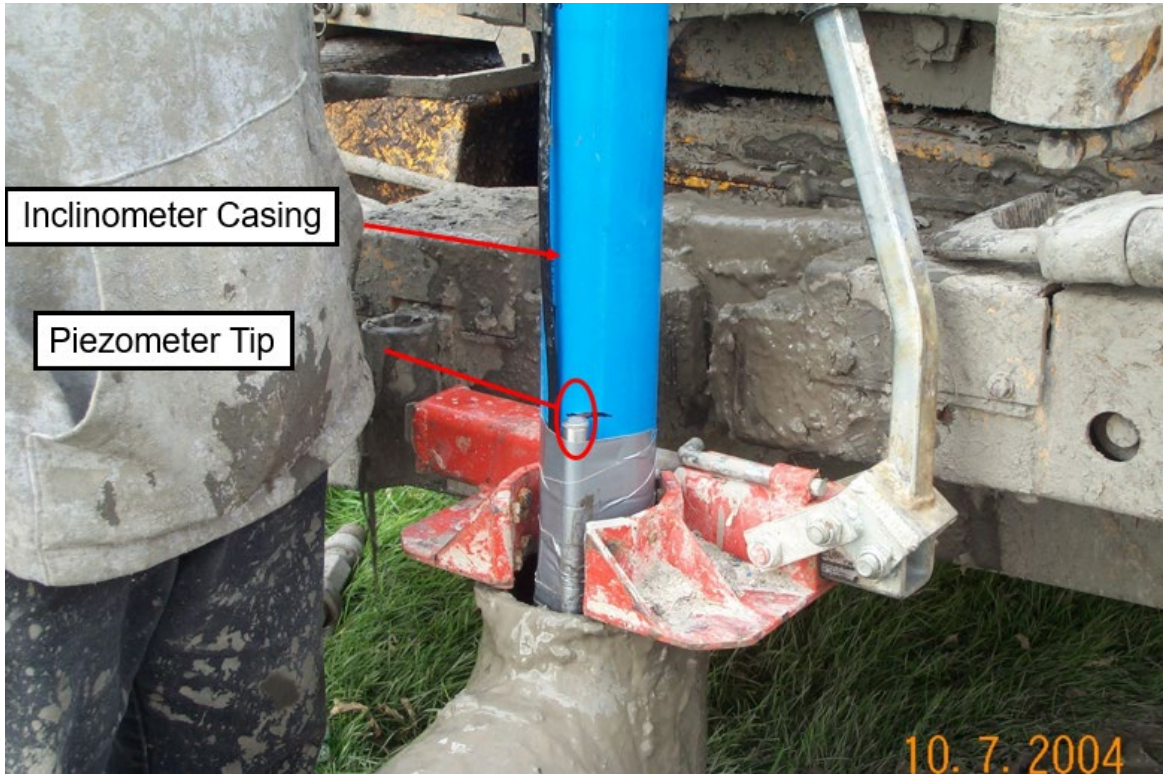
modeling results, normalized



summary, theoretical study

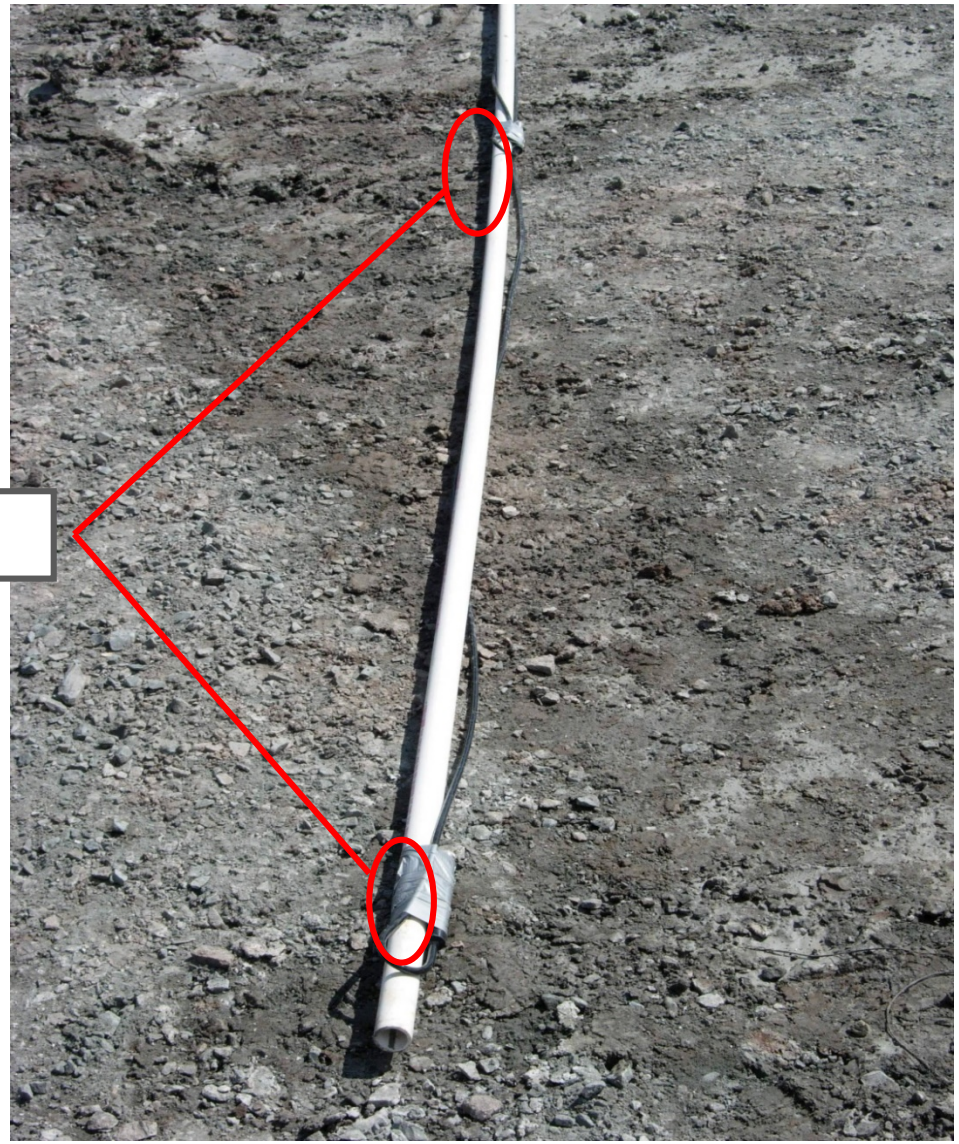


field examples

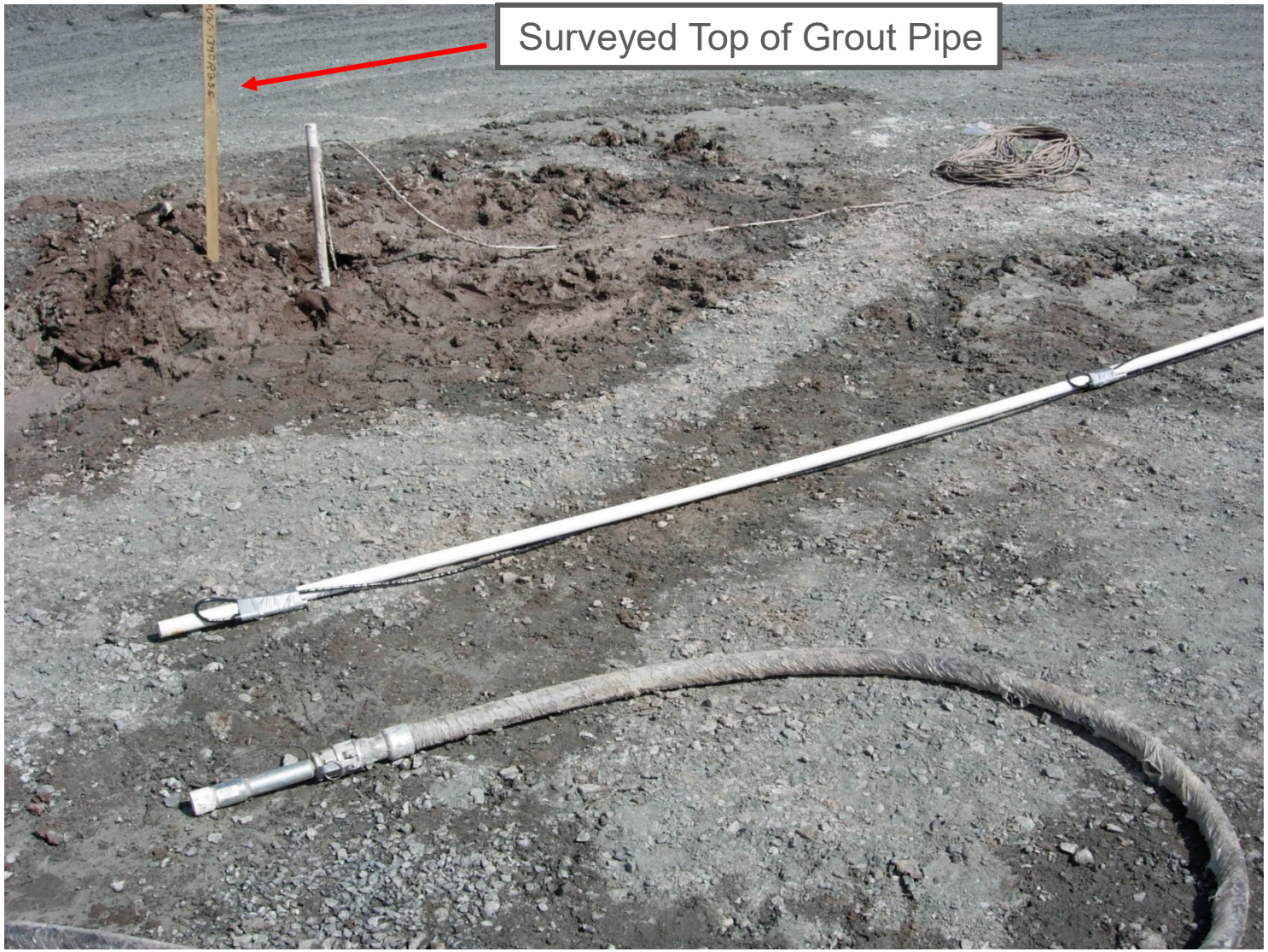


field examples

Multiple Piezometers



field examples, piezometers



when to use fully-grouted with caution

- State or locality may have particular grouting requirements to prevent transmission of water between aquifers. In these cases, variances may be required.

- Neat cement grout, due to its stiffness, doesn't necessarily facilitate porewater pressure transmission – and the sensor may not register a pore water pressure change.

installation in soft ground

- nested installations in soft ground (with sacrificial grout pipe) may be compromised due to down draw
- pipe compression may impact piezometer installation performance
- limit in vertical strain from compression

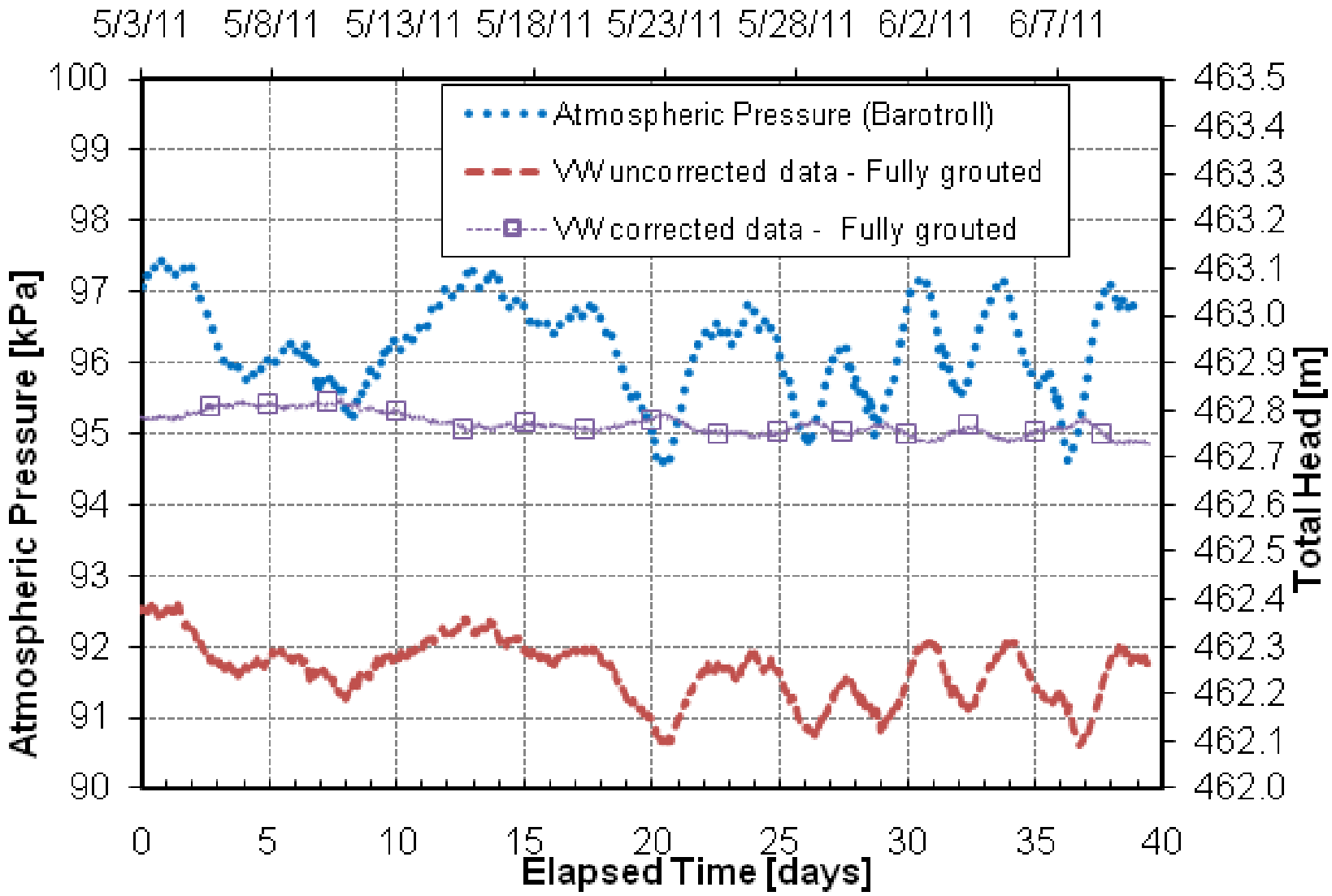
installation in soft ground

- nested piezometer installations with sacrificial grout pipe can be used in soft ground if vertical strain from compression is expected to be less than 15%
- in cases where the expected vertical strain from compression exceeds 15%, a different approach is required
- one option may be “multi-point” piezometer string cable

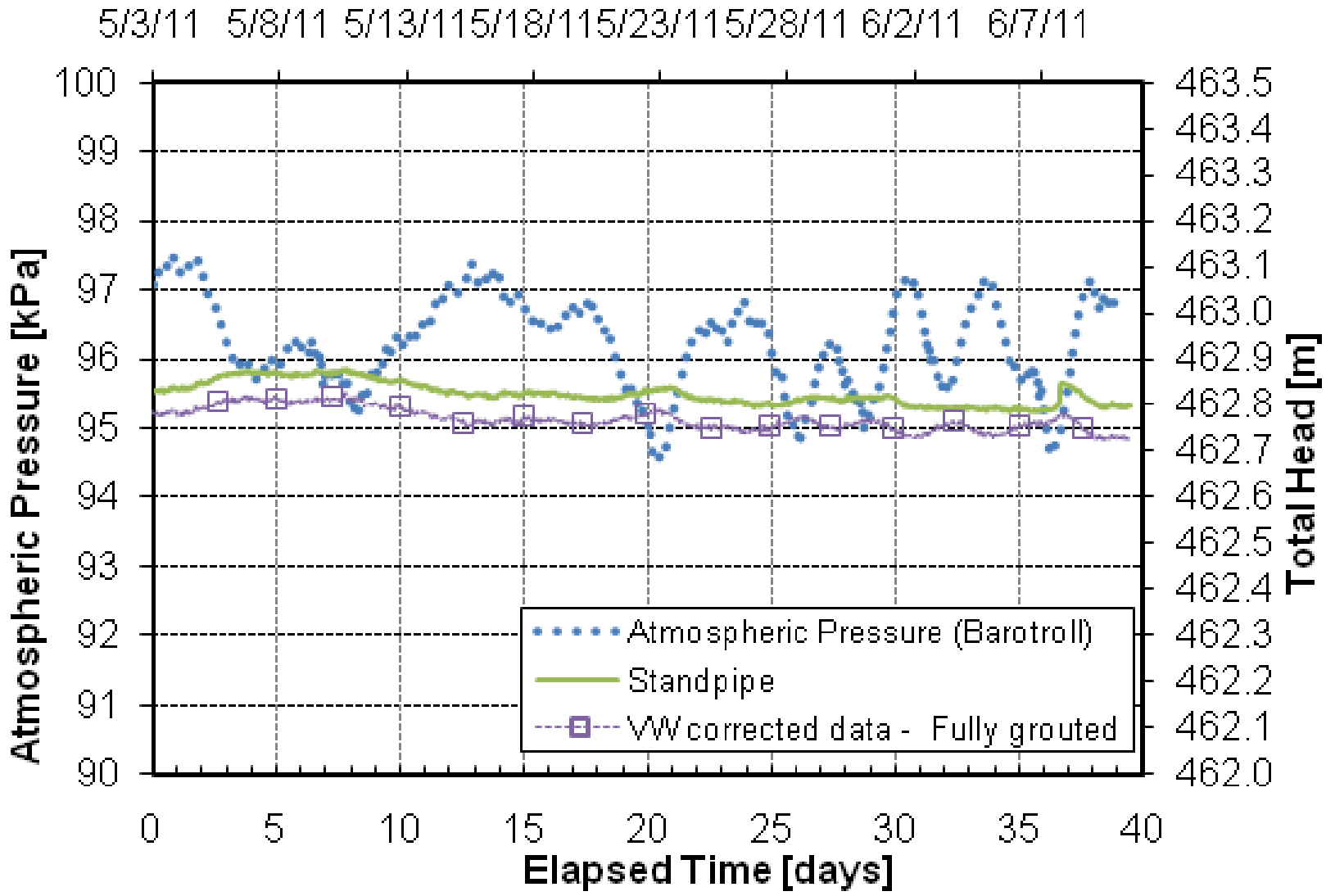
barometric pressure correction

- installed a vibrating wire piezometer (fully grouted) and a standpipe piezometer side by side
- monitored the atmospheric pressure independently
- data on vibrating wire with and without barometric correction

barometric pressure correction



barometric pressure correction



summary and conclusions

- fully-grouted method
  - simple, economical, and accurate
  - proper installation and appropriate permeability
- grout permeability requirements
  - Kgrout/ksoil can be up to three orders of magnitude
  - verified in computer model and field
- response time
  - short hydrodynamic time lag
  - field and laboratory

summary and conclusions

- installation in soft ground
  - adequate with sacrificial grout pipe (up to 15%)
  - string cable in softer ground
- barometric pressure correction (vw)
  - fully-grouted installations require correction
  - VW tips are not sealed
- inclinometers require good sealing!

Fully Grouted Vibrating Wire Piezometers

Monitoring Dams, Levees, & their Foundations

Georgette Hlepas, PhD, PE

US Army Corps of Engineers (USACE)

TRB Webinar

When to use fully grouted VWPZ

8 July 2020

OVERVIEW OF TOPICS

- Current USACE Guidance related to FG VWPZ

- Case Studies and Lessons Learned
  - Mosul Dam
  - Center Hill Dam
  - Bolivar Dam

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USE OF PIEZOMETERS AT USACE DAMS & LEVEES

- Used at multiple projects and over several decades
- Evaluate Project Performance Over Time
    - Internal erosion potential
    - Uplift pressures
    - Seepage Barrier Efficacy
    - Drainage Feature Efficacy
- Provide Early Warning of an Issue
- Inform Risk Assessments of our project
    - Understand past performance and future expected performance
    - Reduces uncertainty in the risk estimate
- Inform Design

ADVANTAGES OF FULLY GROUTED METHOD OF INSTALLATION

USACE regulations for drilling in embankments require waiver

- Minimize risk induced from drilling methods
- Justification needs to be worth the risk

Fully Grouted Method

- Multiple sensors in fewer holes
  - Reduced risk associated with drilling
  - Reduced drilling costs
- Simpler Installation (one backfill) methods/more rapid
- Reduced concern of communication between monitored zones
- Reduced risk of infiltration/clogging of piezometer
- Can combine with Inclinometer Installations

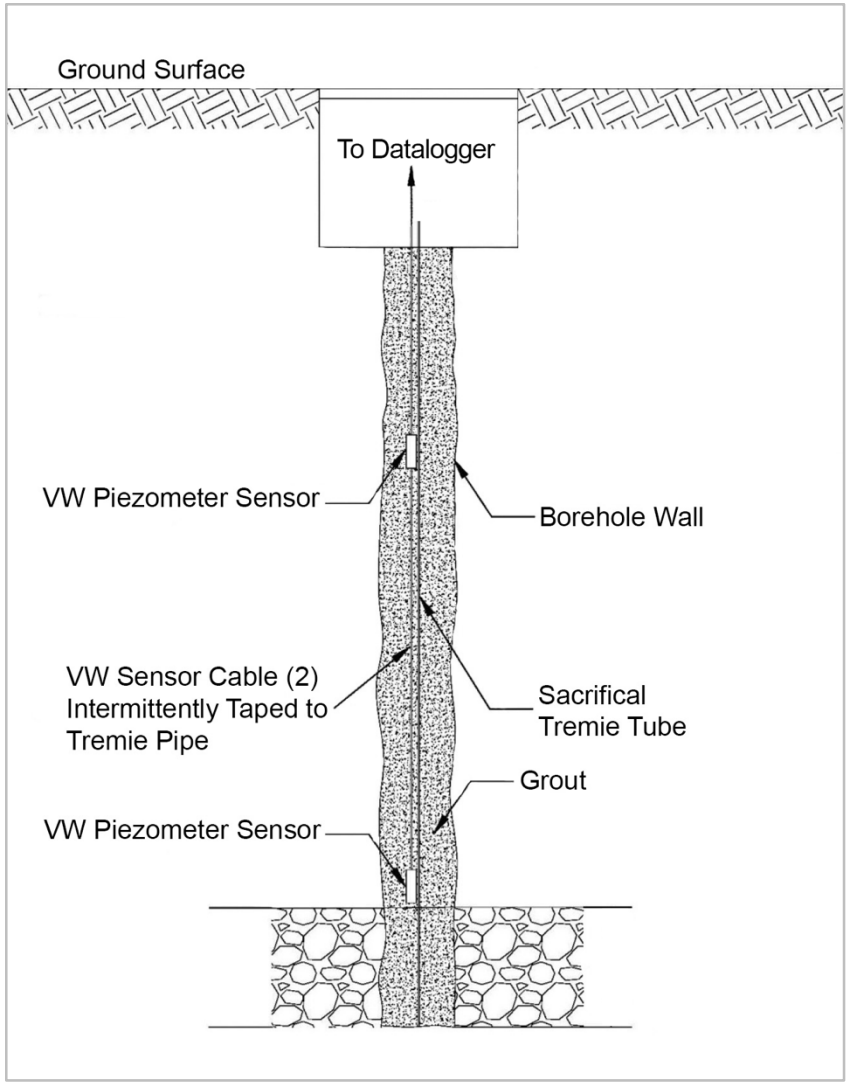
US ARMY CORPS OF ENGINEERS GUIDANCE

EM 1110-2-1908 Instrumentation of Embankment Dams and Levees

- 2020 version currently being formatted for publication
- Identifies FGVWPZ as a viable and cost effective option

Instrumentation Guide Specification

- Kick-off June 2020
- Based on lessons learned from previous projects, specifications, and SOW



EXPERIENCE WITH FG INSTALLS WITHIN THE USACE

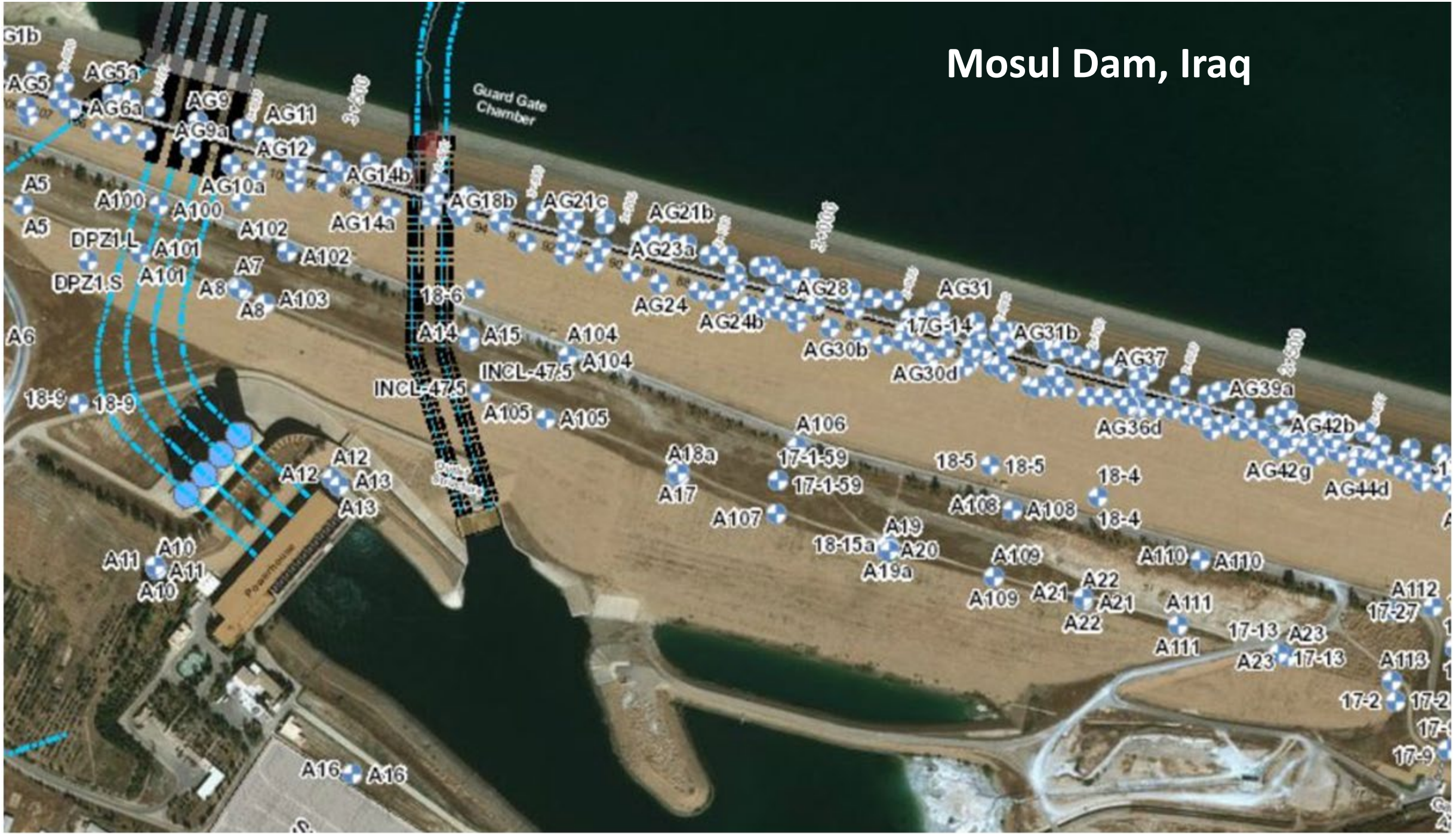
- Successful installs include oversight of installation by experienced staff
- Unsuccessful installation primarily due to inappropriate installation method or grout mix design
- Installations in materials that are not fully saturated have sometimes been unsuccessful

OVERVIEW OF TOPICS

- Current USACE Guidance related to FG VWPZ

- Case Studies and Lessons Learned
  - Mosul Dam
  - Center Hill Dam
  - Bolivar Dam

- Current USACE Research


Mosul Dam, Iraq
Guard Gate Chamber
Powerhouse
G1b
AG5
AG5a
AG6a
AG9
AG9a
AG11
AG12
AG14b
AG10a
AG14a
AG18b
AG21c
AG21b
AG23a
AG24
AG24b
AG28
AG31
17G-14
AG31b
AG30b
AG30d
AG37
AG39a
AG36d
AG42b
AG42g
AG44d
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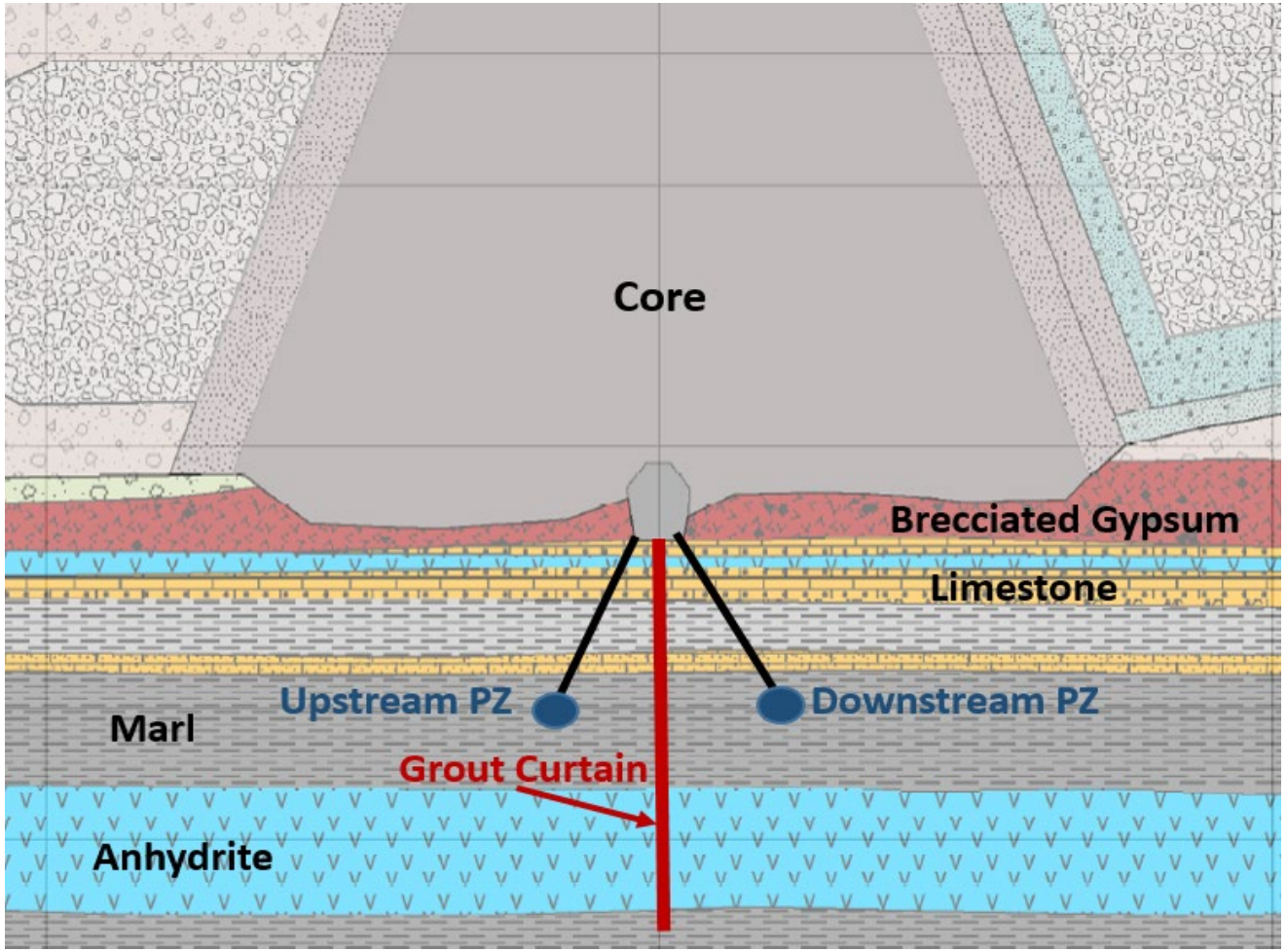
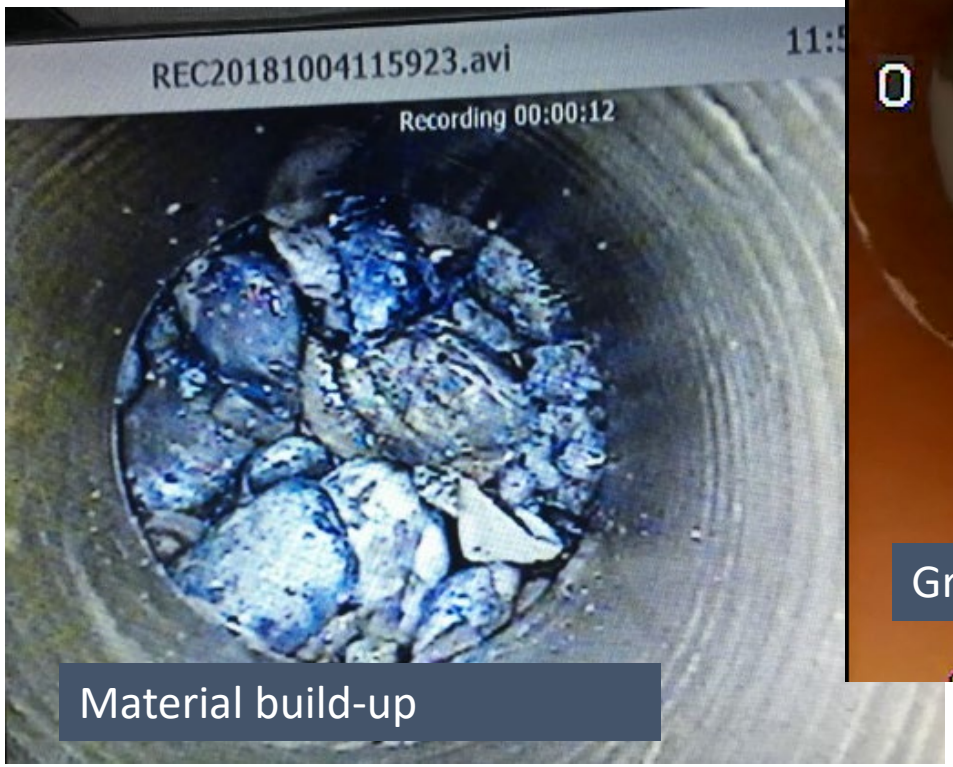
INSTRUMENT INSTALLATION ENVIRONMENT

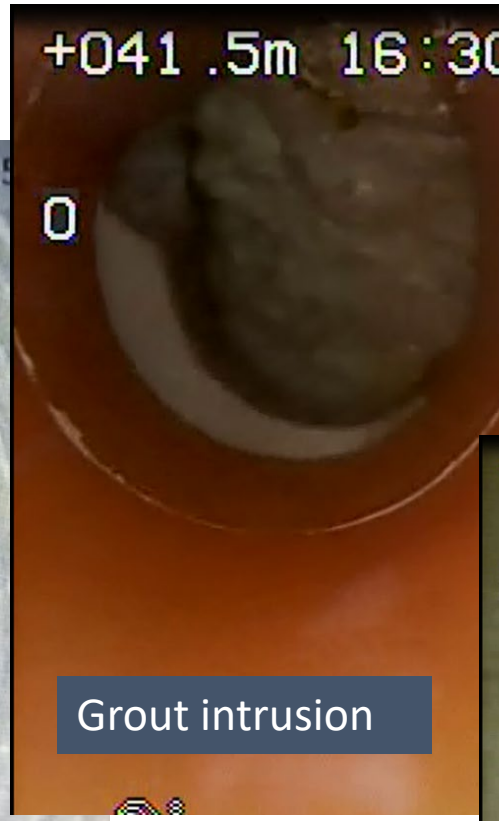


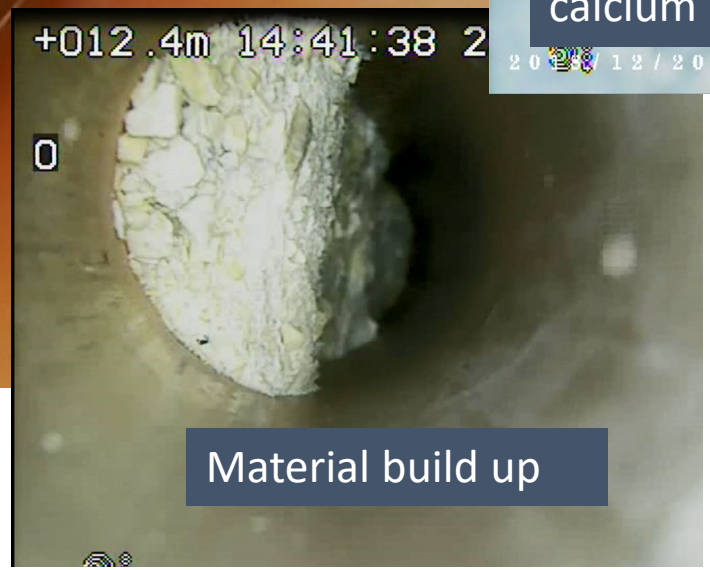
- ✓ 30+ years of maintenance grouting
- ✓ Complex geologic and artesian conditions across the project site

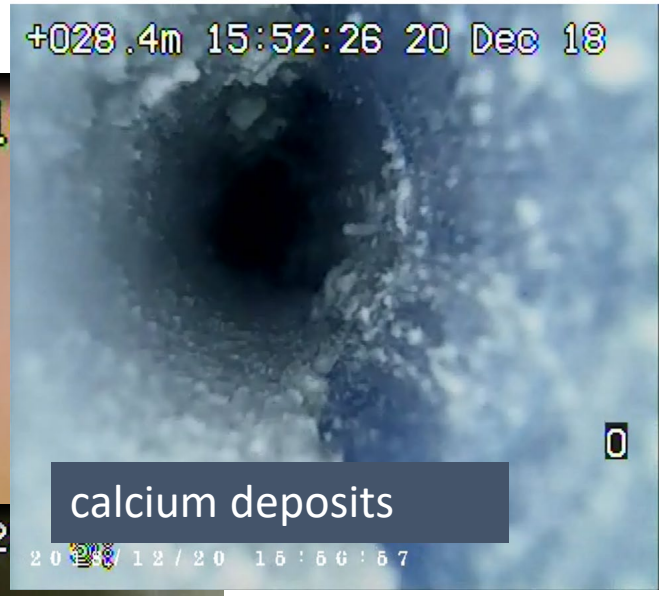
EXISTING CONVENTIONAL PIEZOMETER INSTALLATIONS

- Susceptible to infiltration/build-up of materials impacting readings

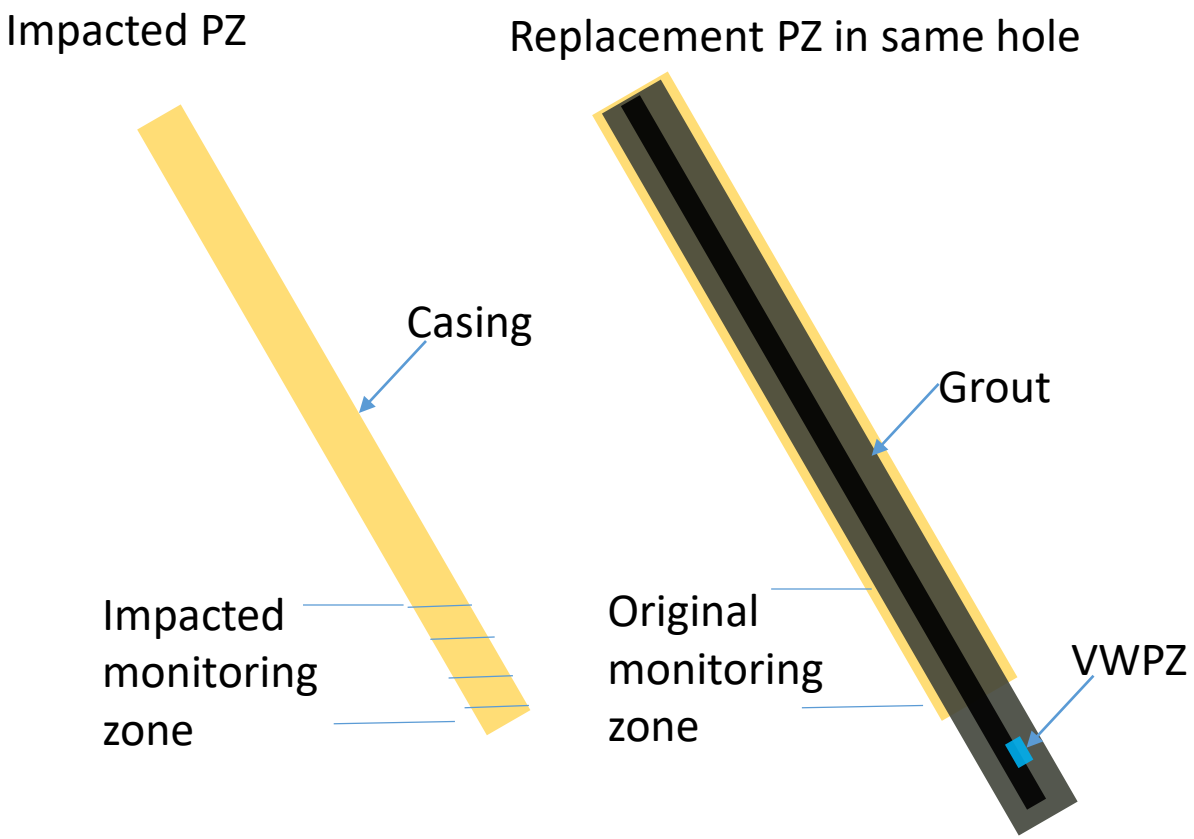








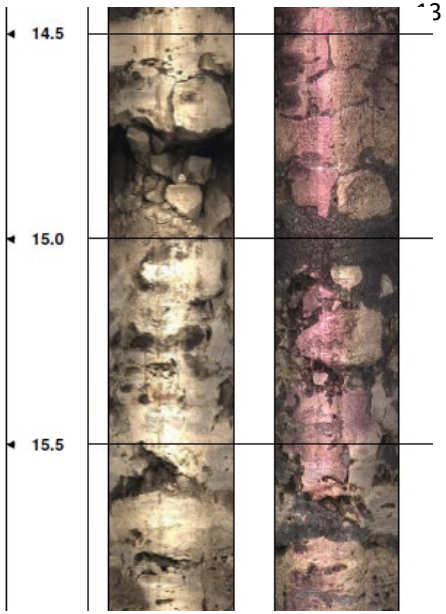
REPLACEMENT OF IMPACTED PIEZOMETERS W/ FG VWPZ

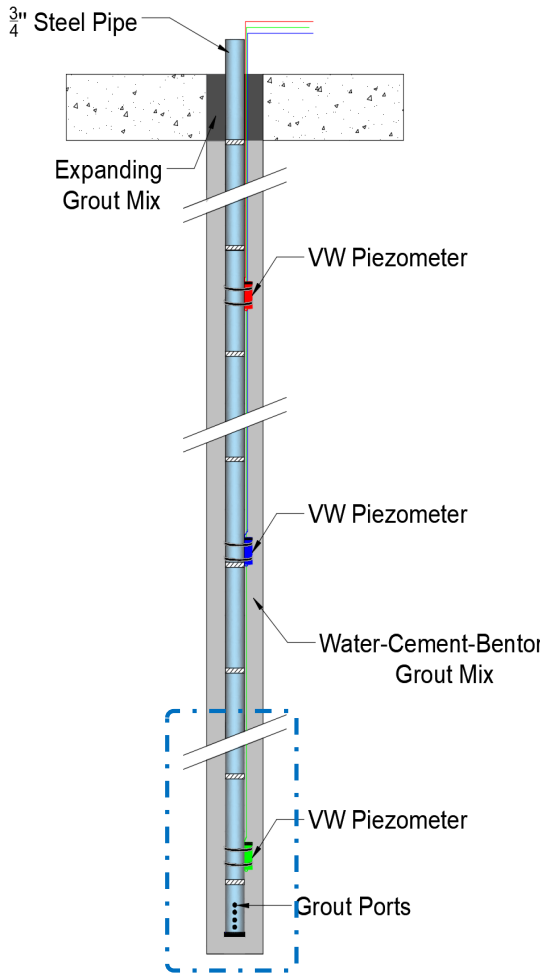


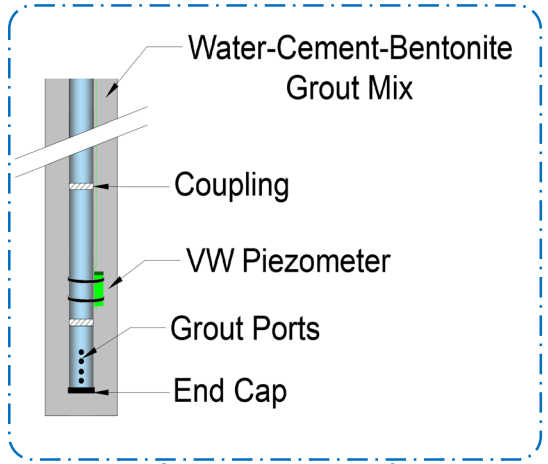
- Over-drill through existing PZ hole impacted zone
- Install FG sensor
  - Relocated monitored zone ~0.5m

INSTALLATIONS WITH NO TO LOW ARTESIAN PRESSURES (< 1 BAR)

- Multiple piezometers were installed at various designed depths
- Borehole collapses were experienced during installations.
  - Boreholes susceptible to collapses were grouted in stages.
  - Drill casing was recovered five sections at a time, followed by grouting through the ¾-inch sacrificial grout pipe.



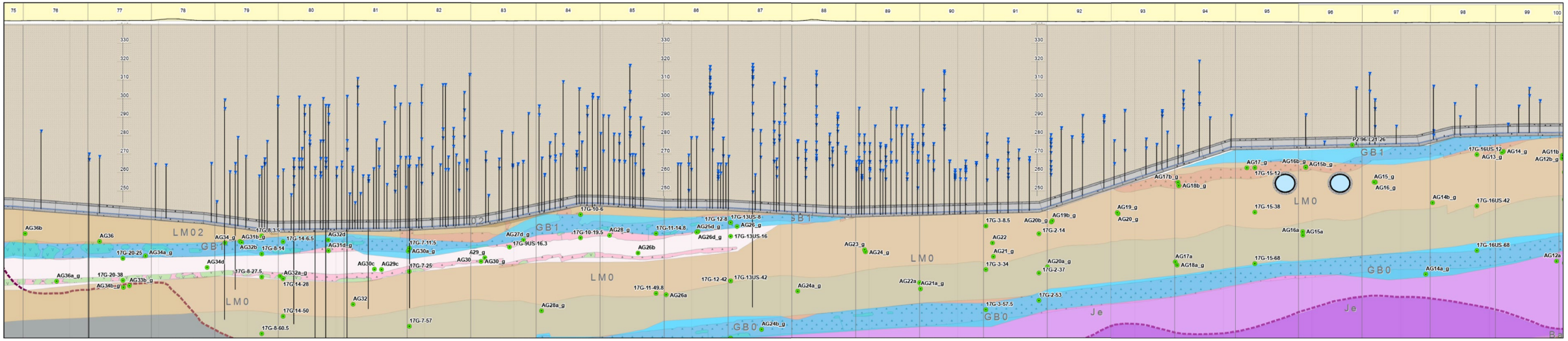




Close-up Detail

INSTALLATIONS WITH MODERATE ARTESIAN PRESSURES (> 1 BAR AND < 3 BAR)

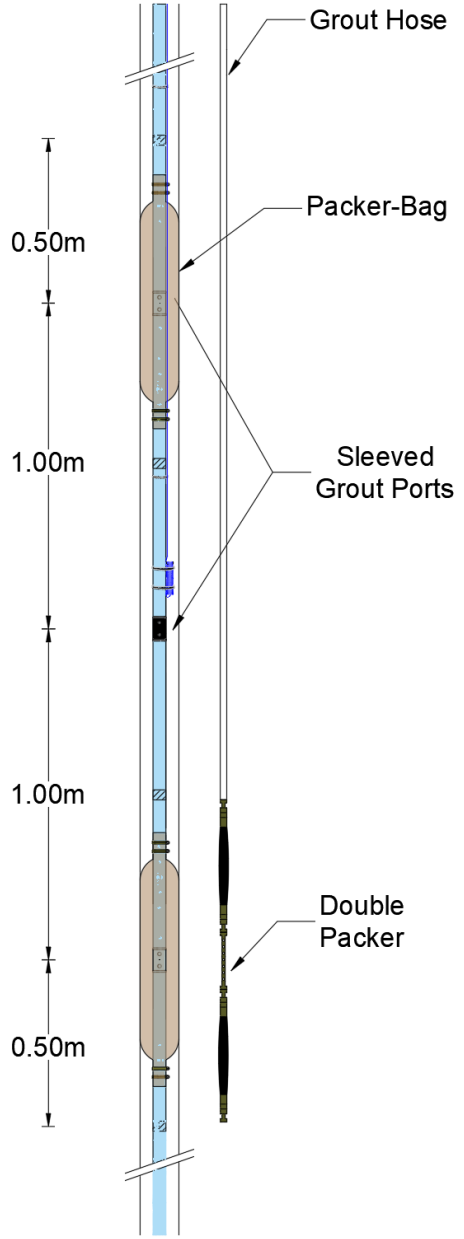
- Installation depths ranged between 15m to 100m.
- Varying pressures along borehole
- Concerns
  - Grout may not set properly and/or wash out
  - Communication between various zones through the borehole.



INSTALLATIONS WITH MODERATE ARTESIAN PRESSURES (> 1 BAR AND < 3 BAR)

Multi Packer Sleeved Pipes (MPSP)

- Inflatable packer-bags were used to isolate sensing zones.
  - Constructed of a permeable geotextile material (used zip ties at ends).
  - Fixed along a sacrificial MPSP (1 ½'' Sch. 80 PVC).
- Bags were inflated with a water-cement grout mix.
- A double-packer was lowered down the grout pipe to the lowest packer-bag for grout injecting (5 bar max).
  - Drill casing was retrieved stopping above the next couple of packer-bags for inflation.
- After isolating the sensing zones, the inter-space between the borehole and sensors were backfilled using the recommended grout mix.
- Borehole sections between sensing zones were backfilled with a less permeable water-cement grout mix.

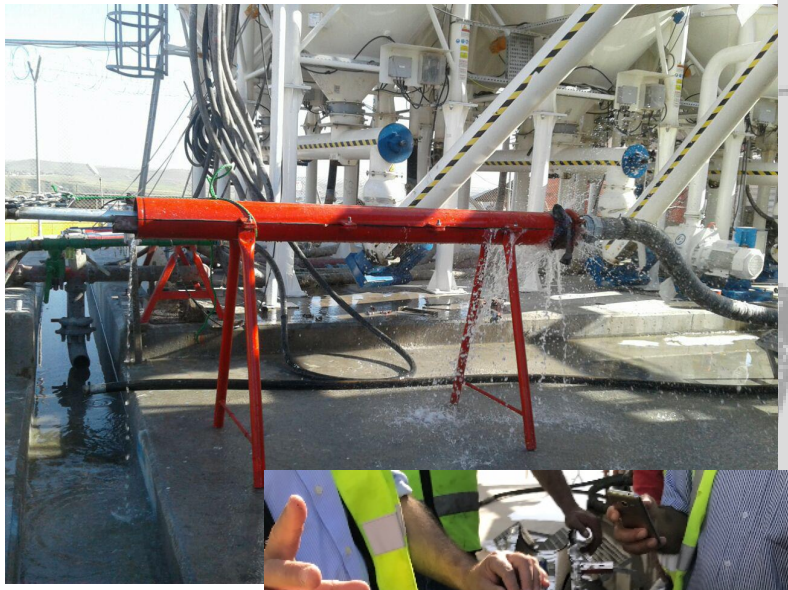


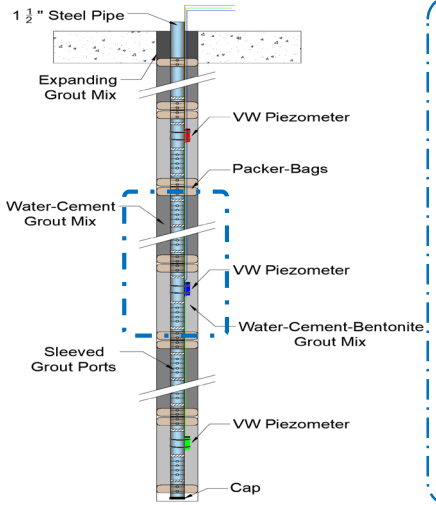
INSTALLATIONS WITH HIGH ARTESIAN PRESSURES (> 3 BAR)

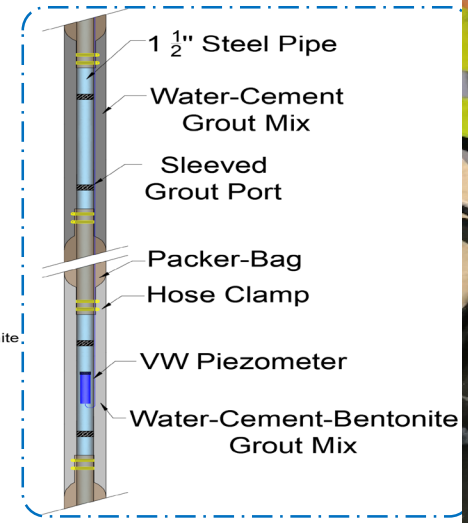
- Pressures up to 9 bar encountered
- Multiple installation failures at pressures greater than 4 bar.
  - Common failures: packer-bag ruptures (initial design rated for 5 bar max) and grout pipe assembly blowouts.
- Boreholes left open too long result in the foundation unravelling and material blow out.

FIELD TESTING NEW INSTALLATION METHOD

- New 1 m long canvas packer-bag with reinforced stitching (hose clamps at ends)
  - Pressure tested at 10 bar with no signs of distress.
- New mechanical anchoring attached to 1 ½'' steel MPSP pipe sections.
  - Steel sections helped weigh down the assembly.
- System custom fabricated in field by skilled craftsman
- Installation was complex and required close oversight







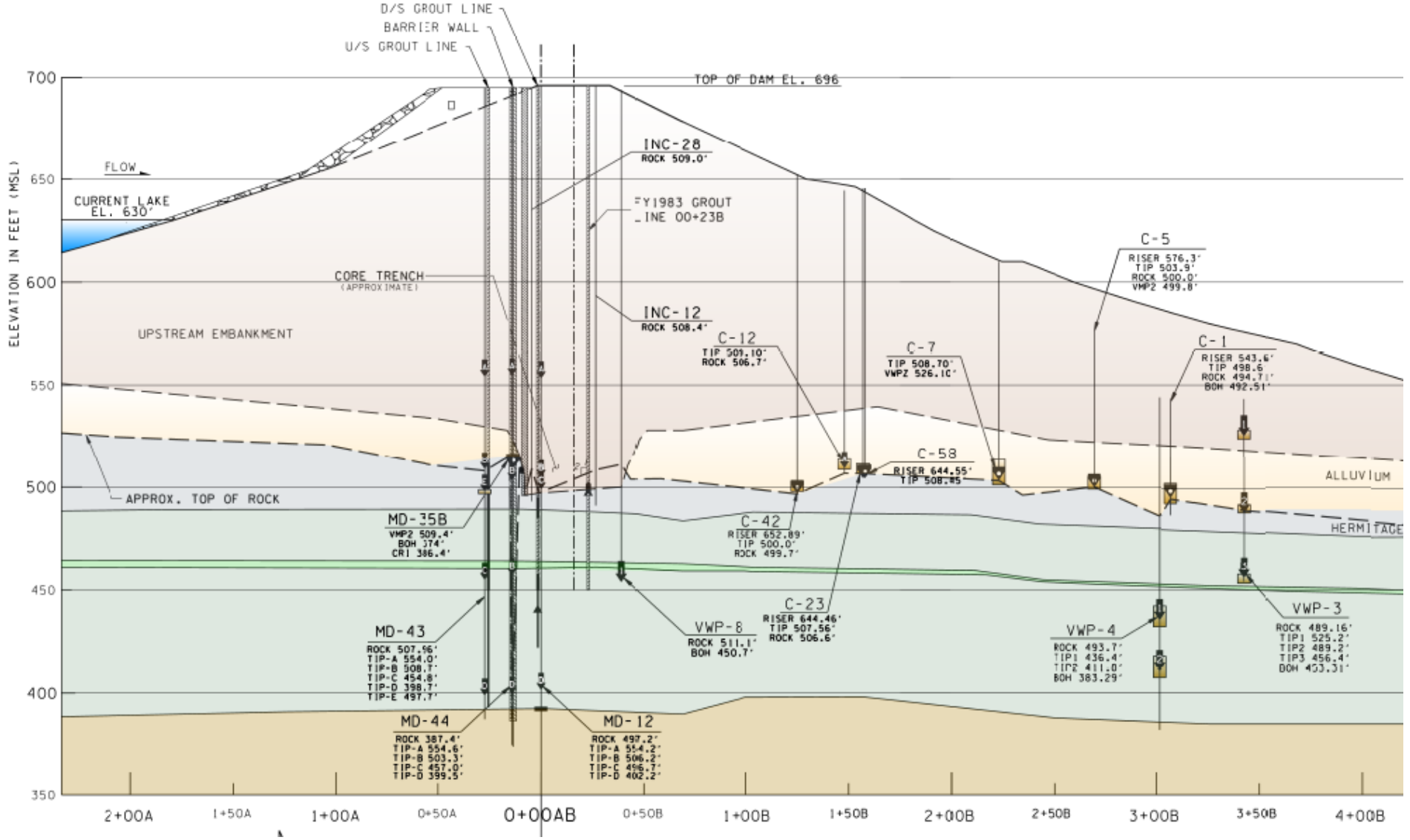
Close-up Detail

LESSONS LEARNED – MOSUL DAM

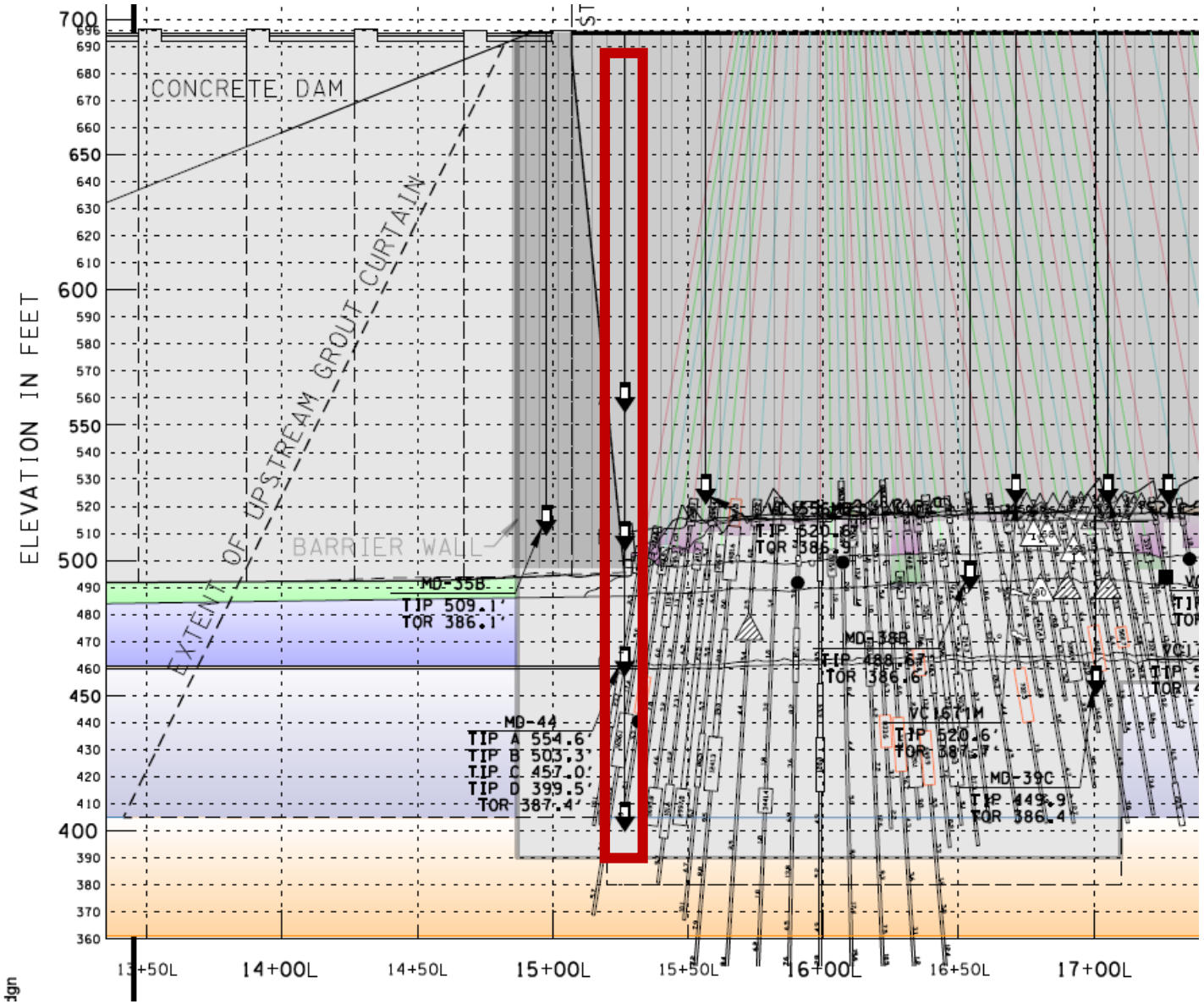
- FG installs generally considered successful based on instrument responses
  - Very few reliable historical instrument installs for which to make direct comparisons
- FG installs sensed grout pressure from foundation grouting activities and were able to track extents of foundation grouting events
- Packer bags were used successfully to isolate zones of interest in moderate to high artesian conditions
  - System was designed in the field as a custom application (not off the shelf)
  - Time/complexity of install led to use of single point installations late in the project
- Experienced staff/oversight required for successful installation in all cases

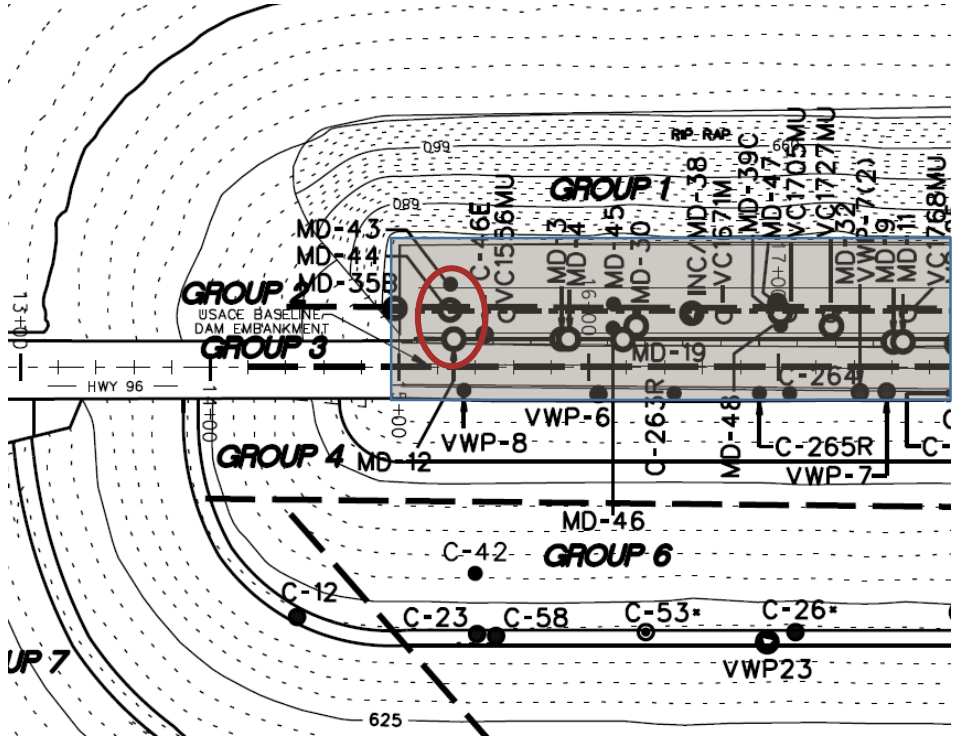
CENTER HILL DAM - FG PIEZOMETER INSTALLATION

- Multi-level fully grouted vibrating wire piezometers to monitor barrier wall efficacy



INSTRUMENTS INSTALLED WITHIN CONCRETE BARRIER WALL





- Installation w/in Concrete Panel
- Grout mix for “hard soil” was used

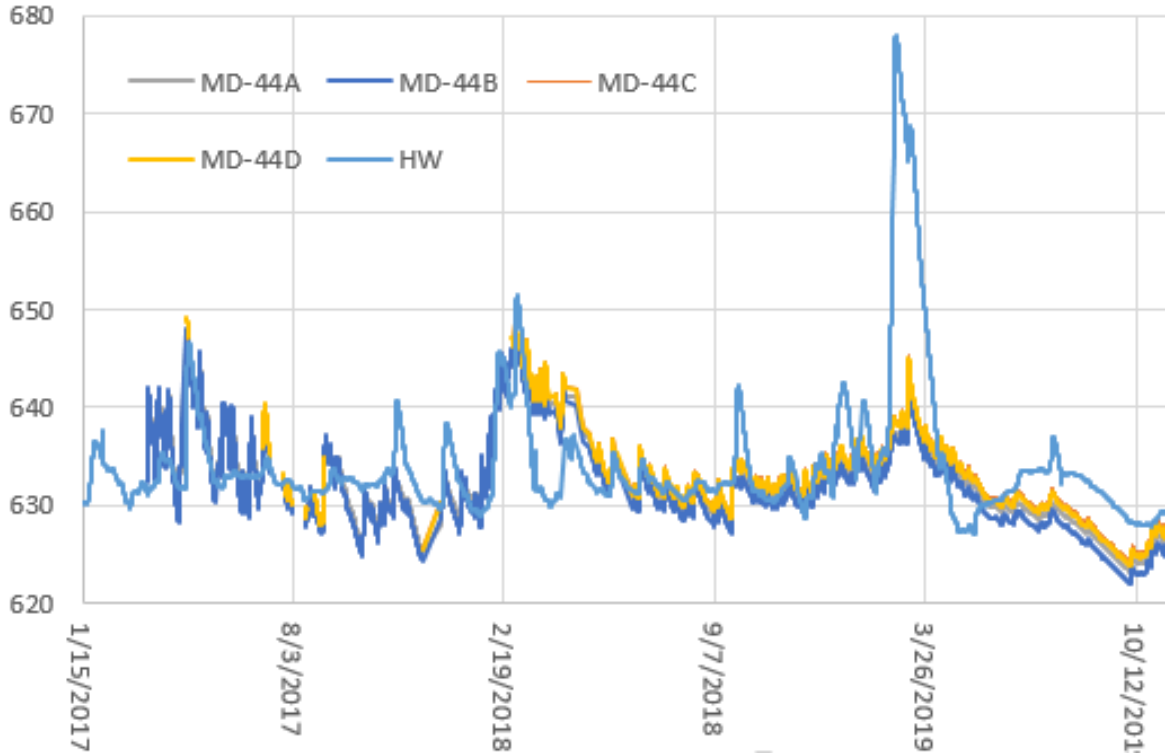
INSTRUMENTS INSTALLED WITHIN CONCRETE BARRIER WALL

- Kgrout = ~ 10^{-6} -10^{-5} cm/s
- Concrete K_{min} = 1x10^{-6} cm/s (specs)
- $K_{grout} > K_{concrete}$?
  - vertical communication w/in hole

Instrument	Elev	Adjacent Zone
MD-44A	554.6	Embankment
MD-44B	503.3	Alluvium
MD-44C	457.0	Rock
MD-44D	399.5	Rock

Lessons Learned

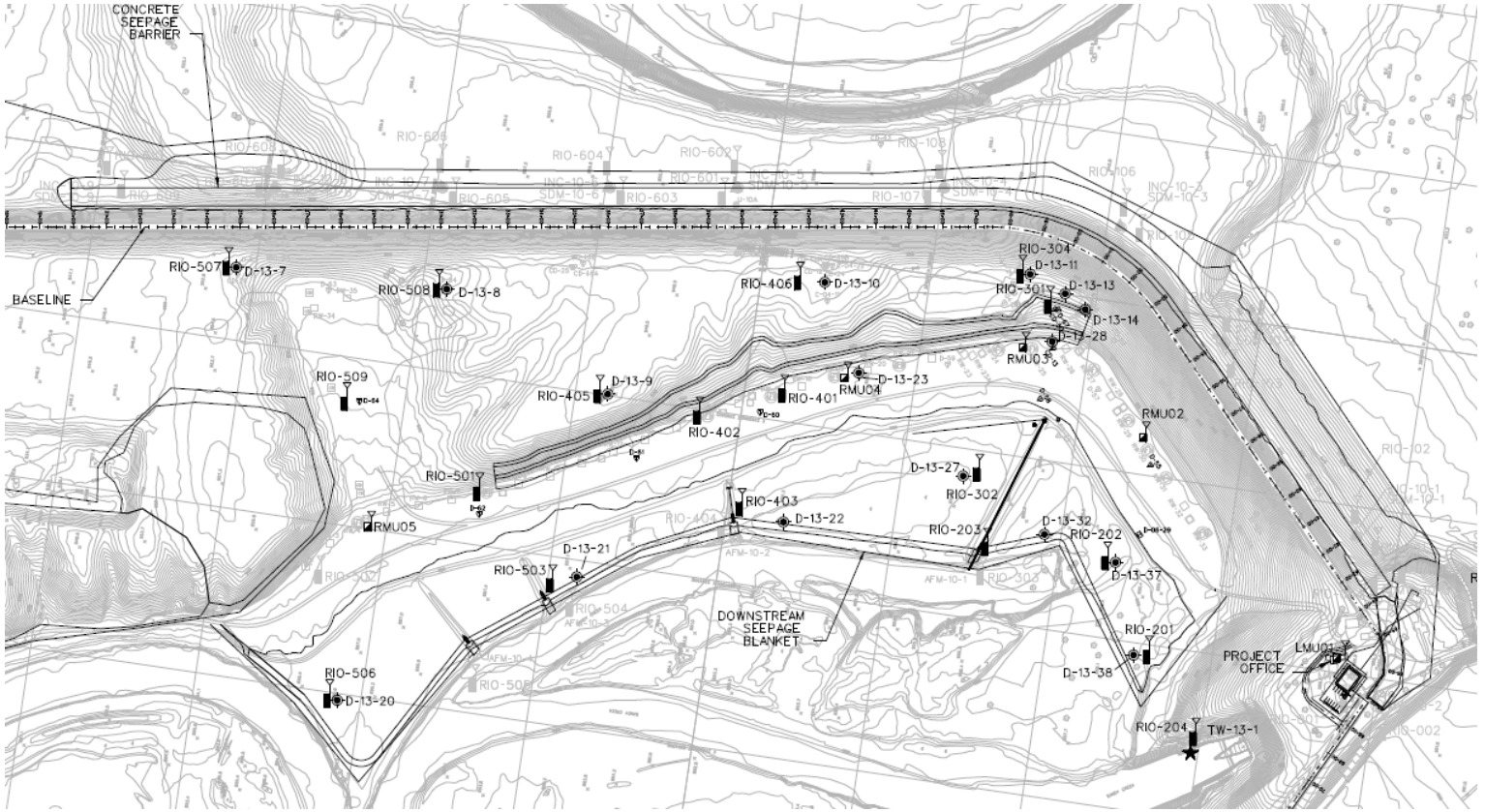
- Mod-Hard grout mix design may not appropriate for concrete installation
- Monitoring upstream and downstream of the Barrier wall may be more effective



BOLIVAR DAM - FG PIEZOMETER INSTALLATION

Installations of Multi-level fully grouted vibrating wire piezometers to monitor barrier wall efficacy

- Numerous installations showing abnormal readings
  - All in zones near above the phreatic surface
- Installation details have been rigorously reviewed
  - Behavior determined to be “abnormal”



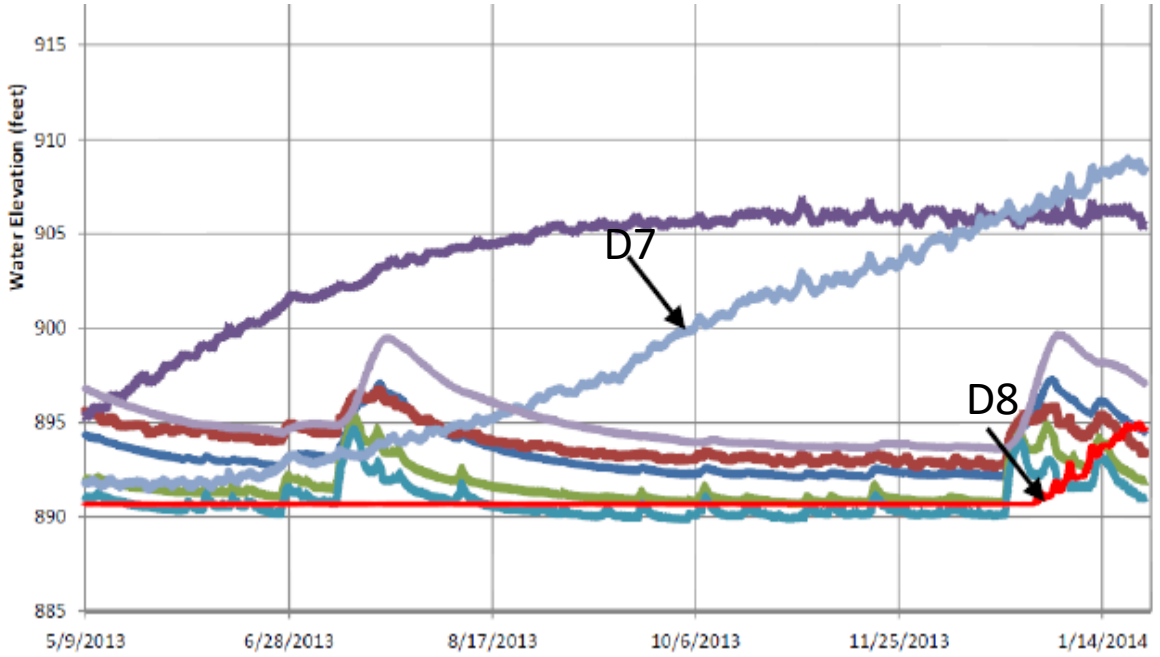
EXAMPLE ANOMALOUS READINGS

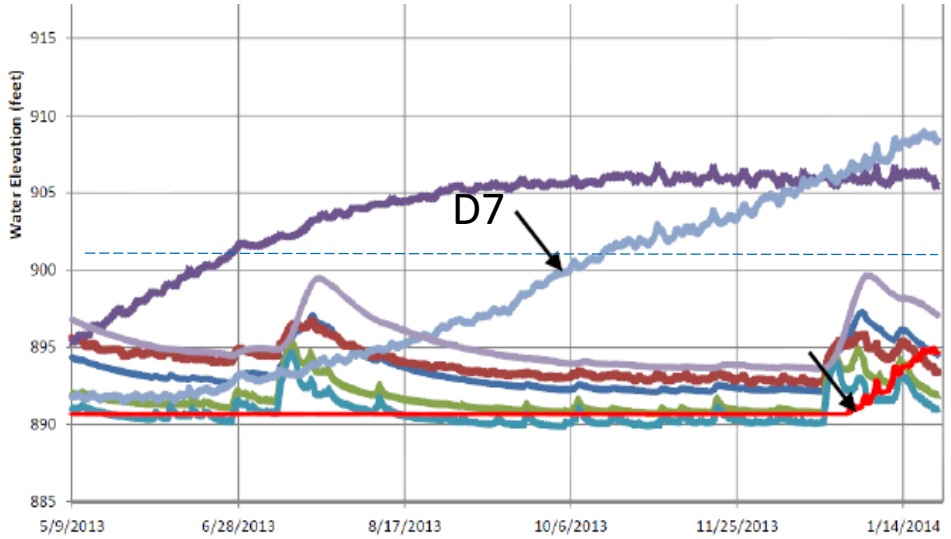
D7 has consistently risen from around El. 892 to 910 (18 ft. total) since installation

- Expected water elevation at EL 892-901
- No event/geologic unit explains increase
- No correlation to pool, tail, precip

D8 consistently reading “dry” from installation until the end of 2013 (over 6 months) and then started a gradual increase rising 7 ft.

- Expected water elevation at EL 892-901
- No event/geologic unit explains increase
- No correlation to pool, tail, precip

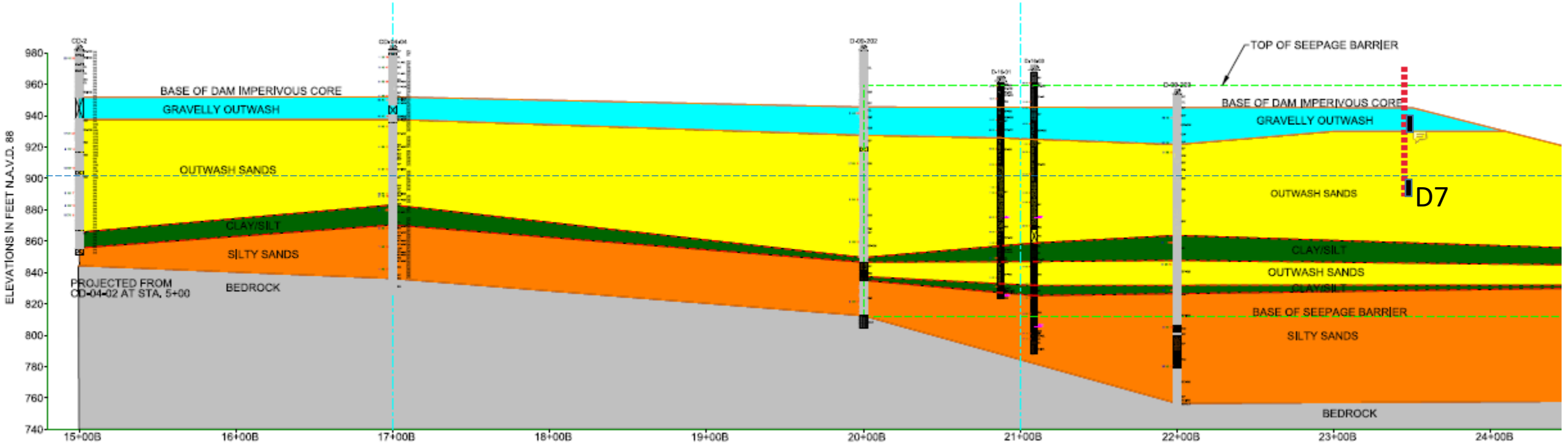




- Neighboring PZ (El 901) reads dry
- D7 has continued to increase beyond EL 901

Lesson Learned

- Installs near phreatic surface susceptible to wet/dry
- Potentially vulnerable to deposit build-up
- Lubricant under filter tip may help (TBD)???



TAKE-AWAYS FROM USACE EXPERIENCE

- Fully grouted installations can be a cost effective solution
- Appropriate Experience and Oversight required
  - Incorrect installation or application can result in loss of time/$$
- Proper verification and documentation
  - QA/QC grout mix properties
  - Recording of appropriate installation details
- Additional Research Recommended
  - Installation in large void conditions
  - Installation in zones subject to unsaturated conditions
  - Optimization of materials and mixes for use in various applications
  - Off the shelf design for use in artesian conditions

Coverage of fully grouted method in ISO 18674

Geotechnical Monitoring by Field Instrumentation

The development of ISO Standards for Geotechnical Monitoring started in 2010. The standards are developed under the Vienna Agreement between CEN and ISO.

To date the following standards have been developed:

- ISO 18674-1 General rules, 31 p.; 2015
- ISO 18674-2 Measurement of displacements along a line: Extensometers, 45 p., 2016
- ISO 18674-3 Measurement of displacements across a line: Inclinometers, 38 p., 2017
- ISO 18674-4 Measurement of pore water pressure: piezometers, 64 p., 2020
- ISO 18674-5 Stress Change measurements by total pressure cells. 32 p., 2019

Acknowledgements to all past and present members of ISO/TC182/WG2.

Andrew Ridley

EN ISO 18674-4

Geotechnical Monitoring by Field Instrumentation - Piezometers

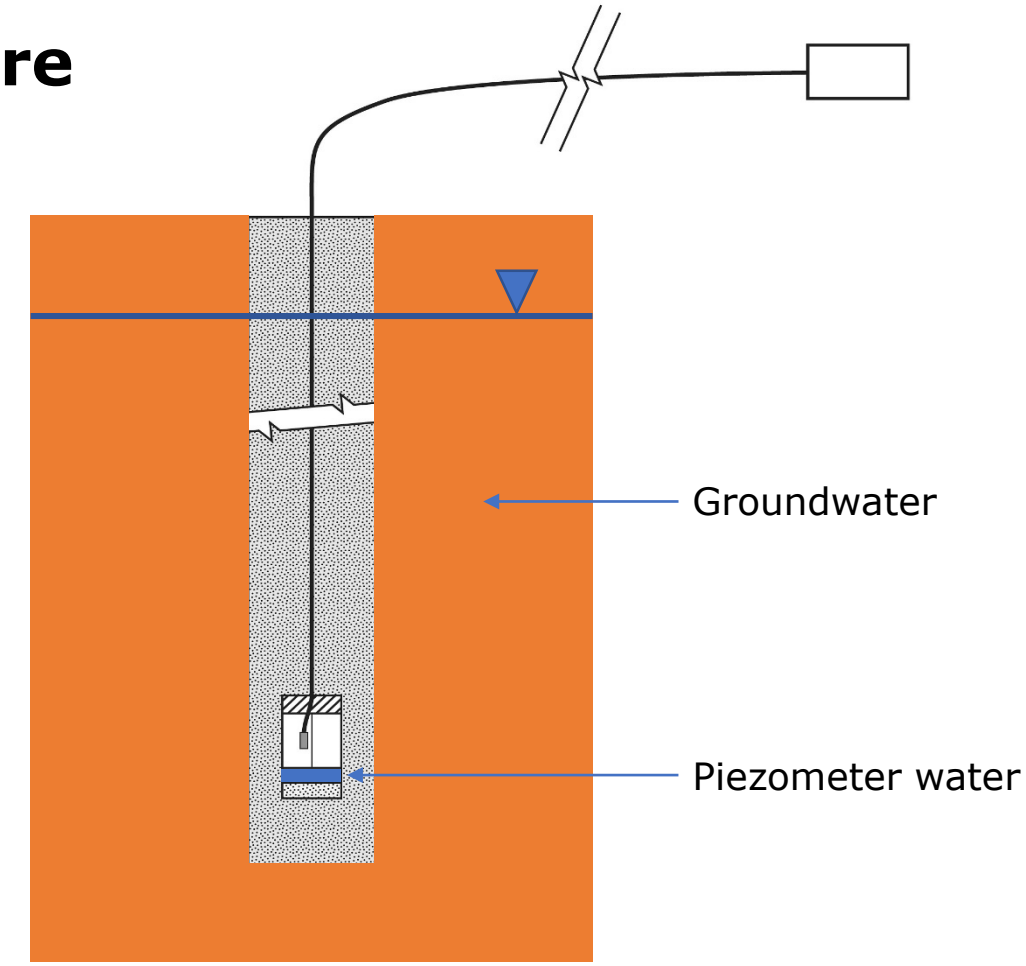
6. Installation and measuring procedure

6.1.3.3

When selecting the installation method, consideration shall be given to ensure a good contact between the measuring device and the ground.

This applies particularly to the water, which is the medium that carries the pressure in the groundwater to the water in the piezometer and hence to the force on the diaphragm that causes it to deflect.

It is therefore essential that all components of a piezometer (i.e. the reservoir, the filter tip and the filter pack) are saturated and remain saturated throughout the monitoring programme for a piezometer to record accurate measurements of pore **water** pressure.



EN ISO 18674-4

Geotechnical Monitoring by Field Instrumentation - Piezometers

Annex E - Fully grouted installation

E2 **The grout mix shall be designed before installation. The important variables to consider are the permeability, viscosity and strength of the grout.**

Permeability of the grout / Permeability of the ground

Permeability of the ground might not be constant with depth.

EN ISO 18674-4

Geotechnical Monitoring by Field Instrumentation - Piezometers

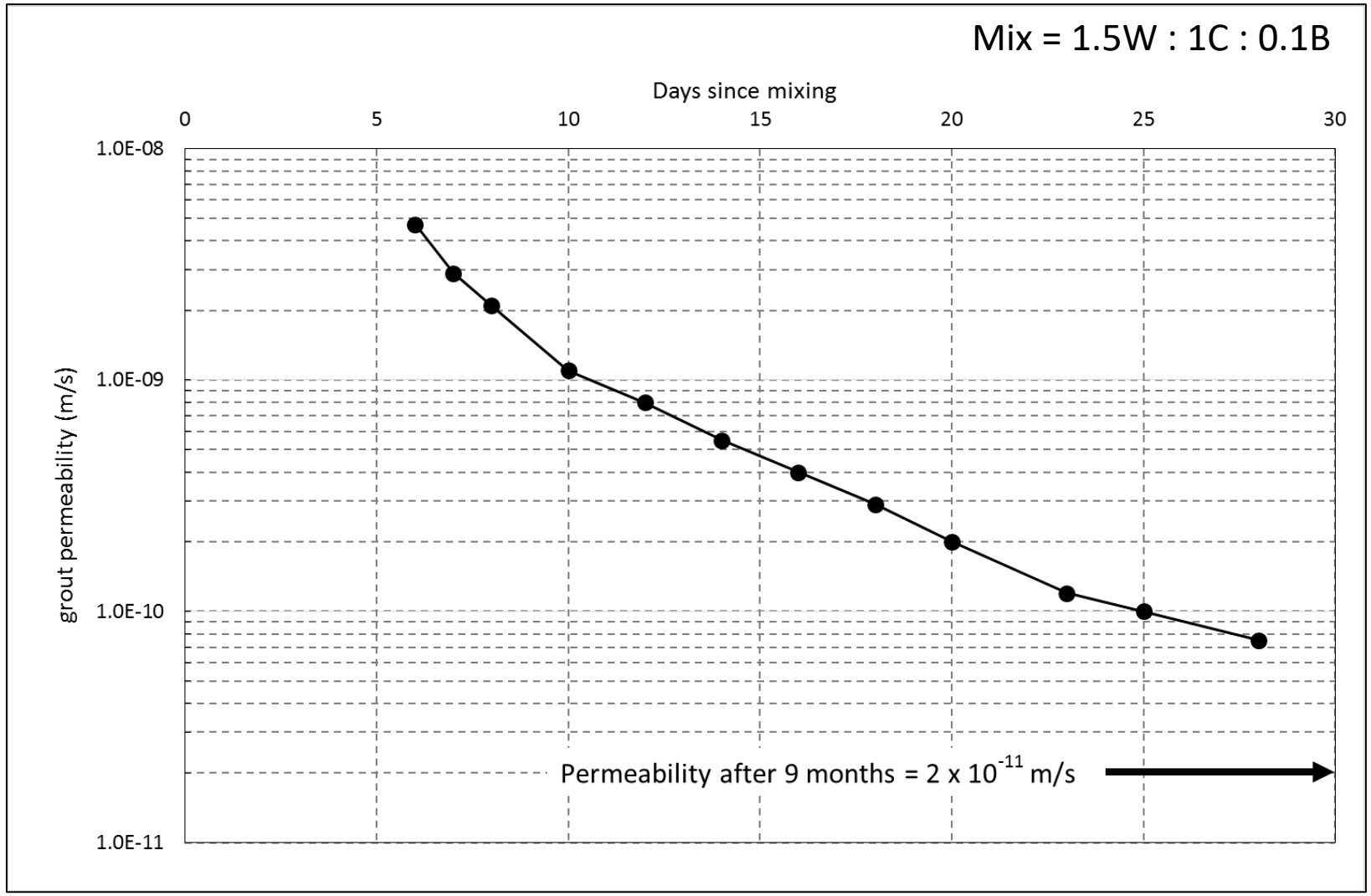
Annex E - Fully grouted installation

E3 The grout shall act as a filter so as not to adversely affect the horizontal flow of water to the piezometer and as a seal so as not to allow vertical flow along the borehole.

NOTE 1 This can be achieved if permeability of the grout is no more than 1000 times the permeability of the ground (this includes grouts that are less permeable than the ground).

NOTE 2 When the grout is less permeable than the ground, response time is increased.

NOTE 3 The permeability can decrease up to a factor of 1000 in the months after installation.



The permeability of the grout decreases over time and can become up to a factor of 1000 times smaller over a period of a year. This has to be taken into account when long-term monitoring is required.

EN ISO 18674-4

Geotechnical Monitoring by Field Instrumentation - Piezometers

Annex E - Fully grouted installation

E4 **The viscosity of the grout shall allow it to be pumped and avoid excessive penetration of the grout into the surrounding ground.**

NOTE **In soils with a high permeability the viscosity of the grout is more important than the permeability.**

EN ISO 18674-4

Geotechnical Monitoring by Field Instrumentation - Piezometers

Annex E - Fully grouted installation

E5 **The cement and the water should be mixed first as the water / cement ratio determines the permeability (as well as the strength and stiffness of the mix). Bentonite shall be used to control viscosity and to avoid excessive bleed.**

NOTE 1 **It is considered best if the strength and the stiffness of the grout are similar to the surrounding ground.**

NOTE 2 **There exist many types of bentonites. The viscosity of the grout will depend on the quantity and type of bentonite which is used.**

E6 **Cement without additives shall be used.**

EN ISO 18674-4

Geotechnical Monitoring by Field Instrumentation - Piezometers

Annex E - Fully grouted installation

Cement	Water	Bentonite	Hydraulic conductivity [m/s] at 28 days	$q_{u,grout}$ [kPa]
1	6	1	~5.10^{-8} to 1.10^{-7}	100
1	4	0.7	~2.10^{-8} to $5.\ 10^{-8}$	200
1	2,5	0.4	~10^{-8}	700
1	2	0.36	~10^{-9}	1500

Table E.1 — Typical grout mixes (ratios in weight) and order of magnitude of hydraulic conductivity and uniaxial compressive strength

The essential properties of the grout are:

1. It should not adversely affect the response of the piezometer (i.e. it should act like a filter).

2. It should prevent water pressures being transmitted along the borehole (i.e. it should act as a seal.

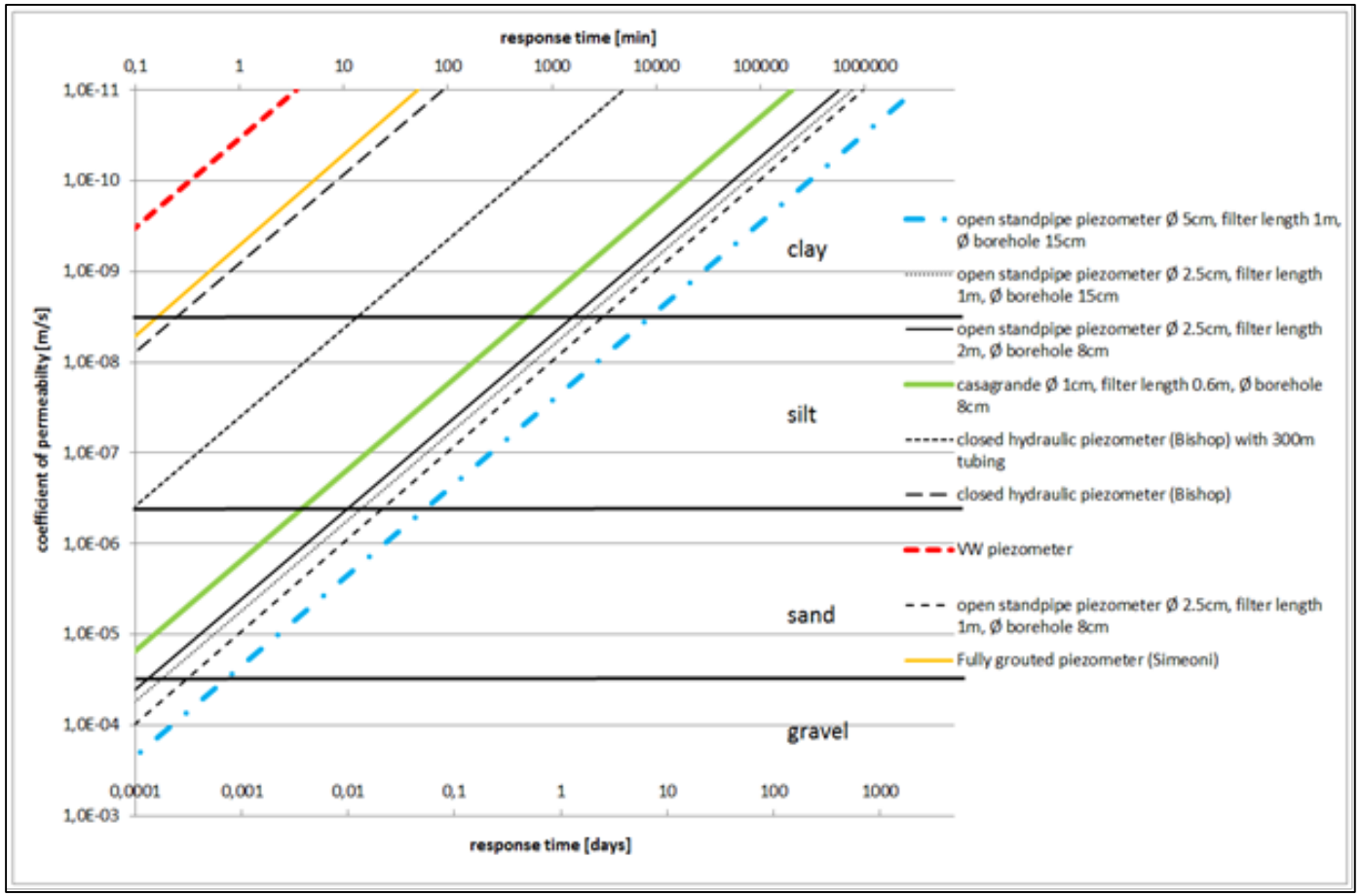
   Both of these properties depend on permeability (not strength or stiffness) and crucially they depend on the ratio between the permeability of the grout and the permeability of the ground at the point of measurement.

Why therefore are people concerned about using The Fully Grouted Method?

Most people associate low permeability with a slow response.

EN ISO 18674-4

Geotechnical Monitoring by Field Instrumentation - Piezometers



Graph adapted from Terzaghi and Peck.

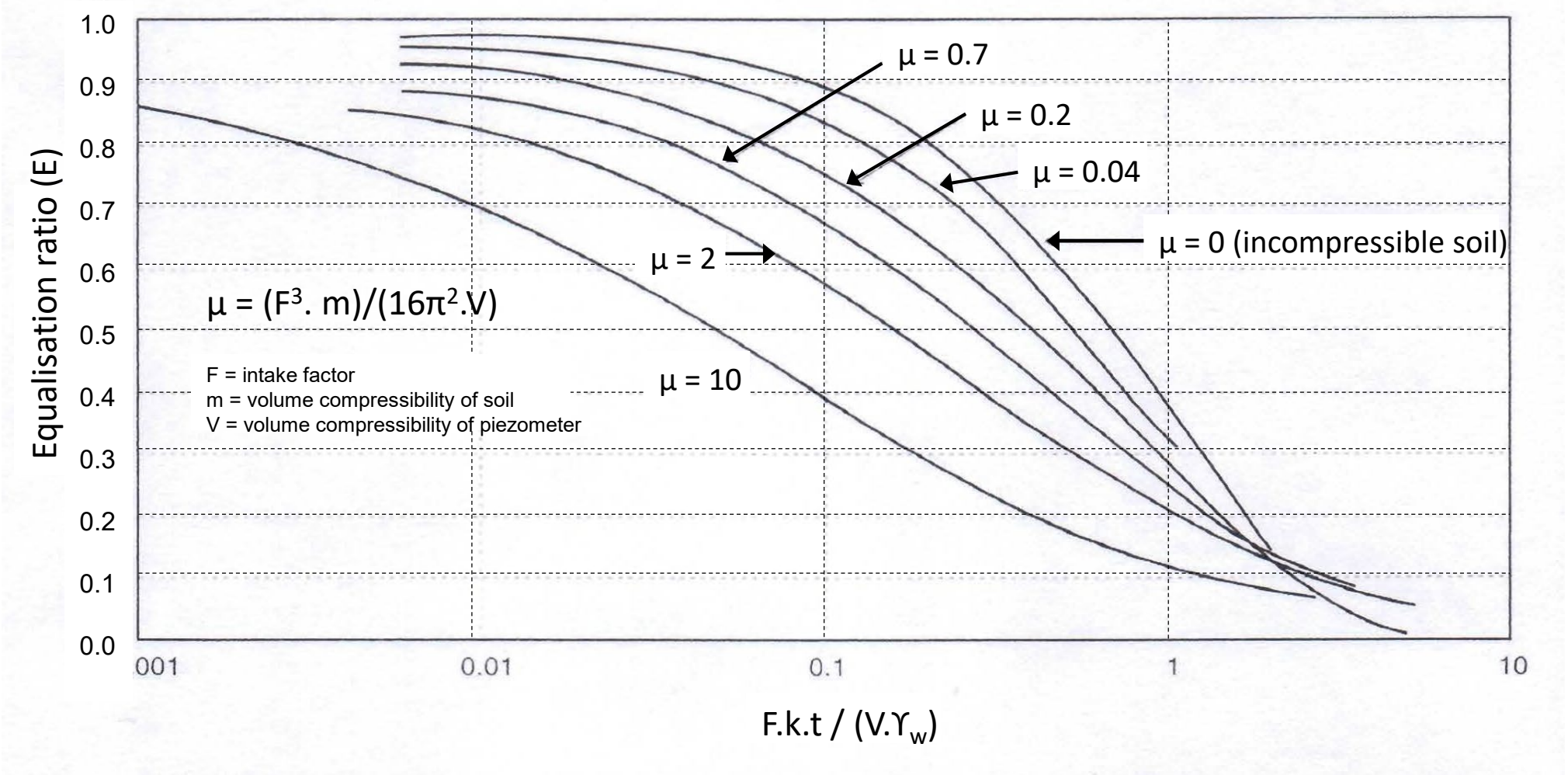
In fully grouted installation, the response time depends on:

- the permeability of the grout,
- the permeability of the soil,
- the dimensions of the borehole and
- the type of piezometer,

and varies between a few seconds and 10 minutes.

6.1.3.5 When applying the fully grouted method, the borehole diameter shall be as small as possible

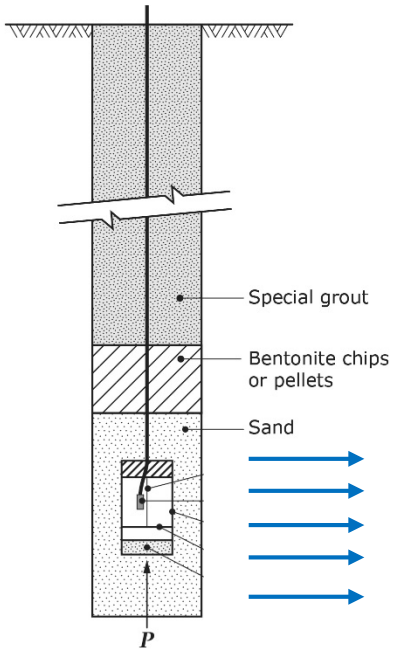
Vaughan (1969) showed that the fully grouted method can be used with open standpipes as well as diaphragm Piezometers.



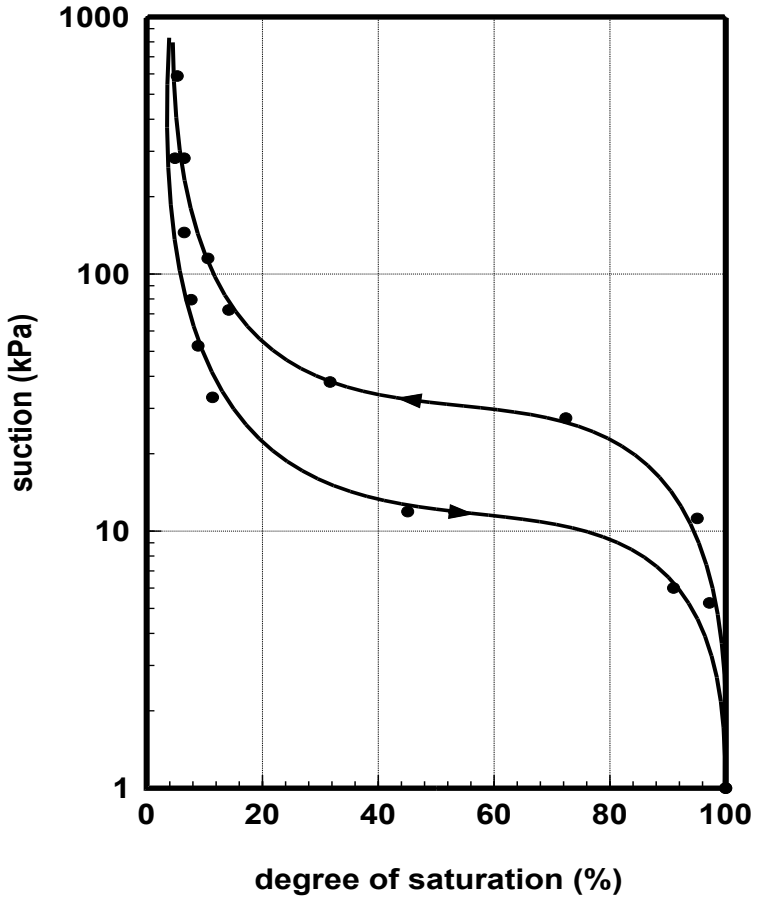
After Gibson 1963

It's very important to remember that the response time of a piezometer is as much about the ground as it is about the piezometer and the grout.

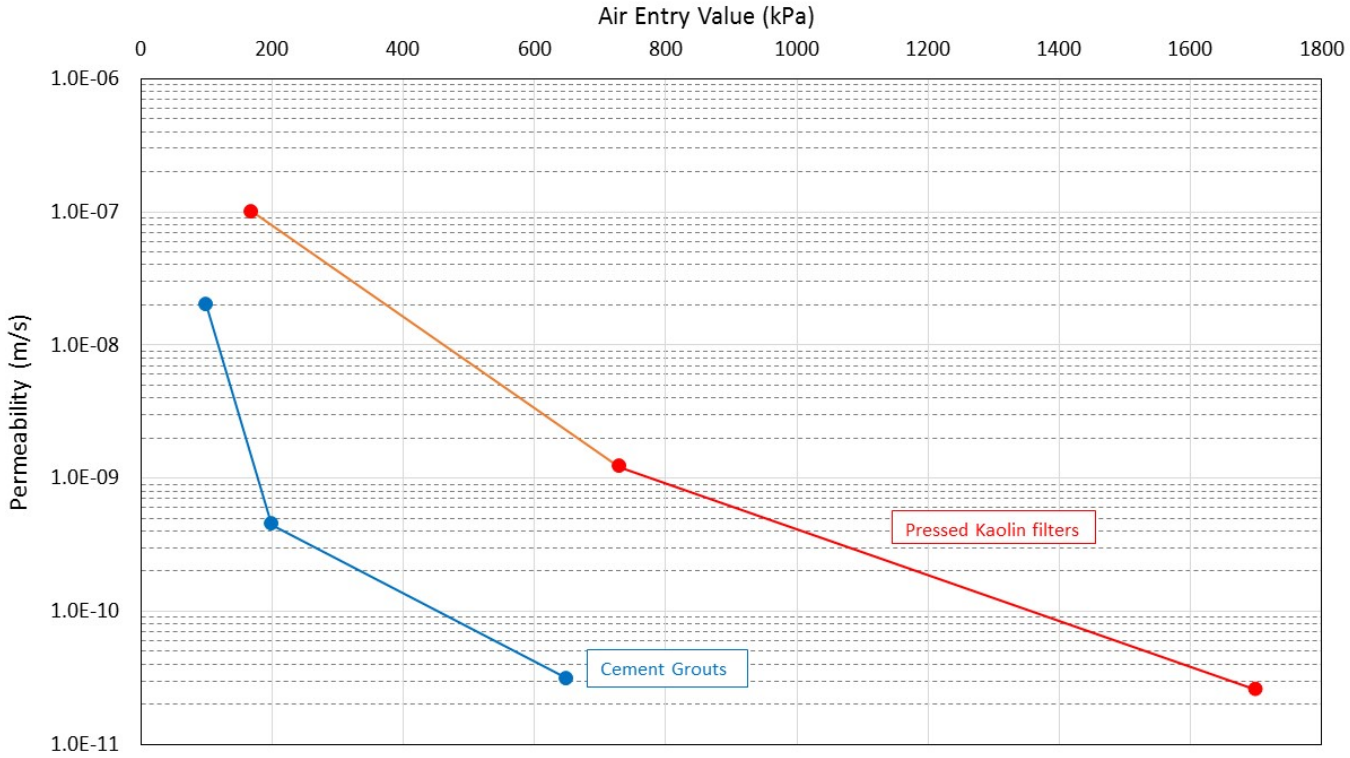
Another important property of cement bentonite grout is its ability to sustain hydraulic tensions without desaturating. This is particularly useful if negative pore water pressures are expected.



Negative pore water pressure will try to draw water out of the piezometer and the sand filter



Another important property of cement bentonite grout is its ability to sustain hydraulic tensions without desaturating. This is particularly useful if negative pore water pressures are expected.



What type of porous filter should be used, HAE or LAE?

For piezometers with a sand filter pack it is generally accepted that LAE filters should used.

EN ISO 18674-4

Geotechnical Monitoring by Field Instrumentation - Piezometers

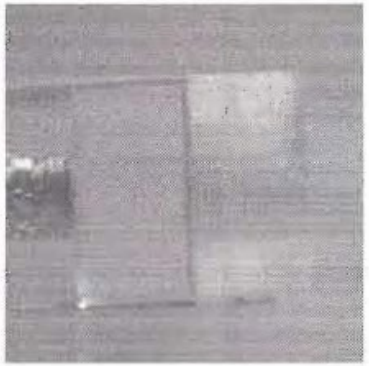
Application	Method of Installation	Saturated soil or rock	
		Type of Filter	Need for saturation
Positive pore water pressures	push-in	LAE	preferred
	in a borehole, within a sealed filter pack	LAE	preferred
	in a borehole, fully grouted	LAE	preferred
	placed in fill	HAE	required
negative pore water pressures	push in or in a fully grouted borehole	HAE	required

E7 High air entry porous filters **shall** not be used with the fully grouted method unless there is a means of removing air from the piezometer.

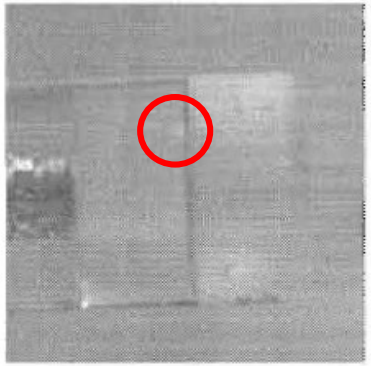
Problem:
If air forms in a piezometer and cannot escape or be removed, the piezometer will not respond correctly.

High Air Entry (HAE) filters by definition restrict the passage of air.

Mendes & Buzzi (2013)
Canadian Geo Journal

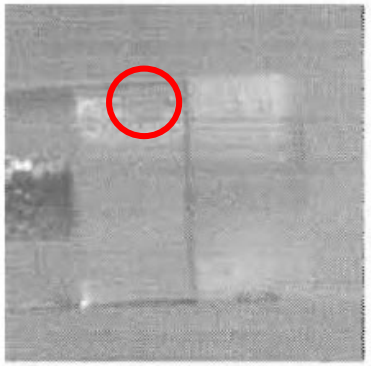


a) Initial state, t=0s



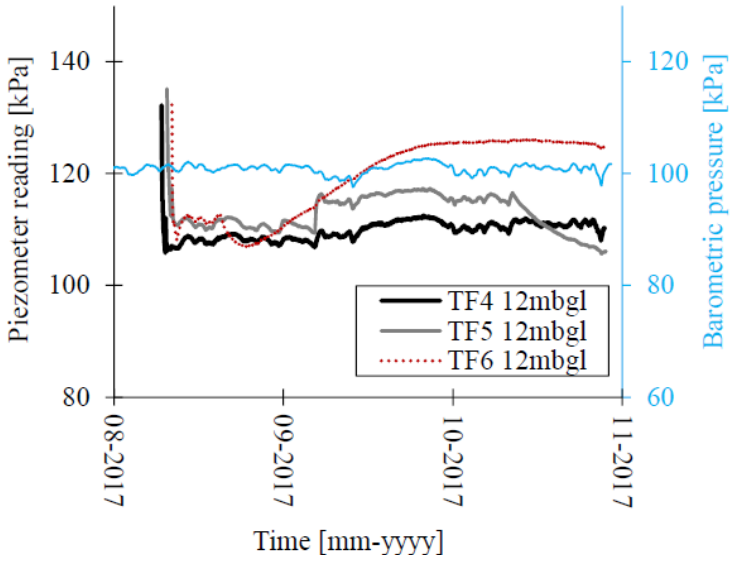
b) Small bubbles emerging from the ceramic, t=0.5 ms

c) Small bubbles have agglomerated into a large bubble, t=5.5 ms.

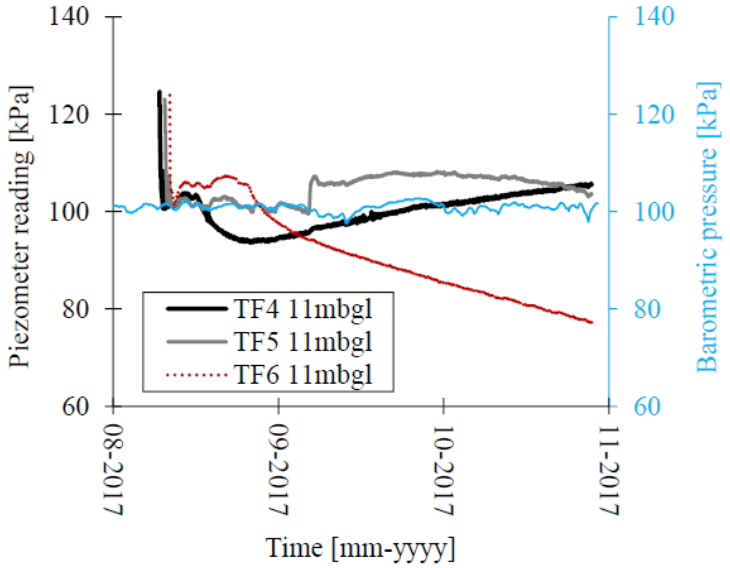


d) Final state after more bubbles have formed, t=4.4s

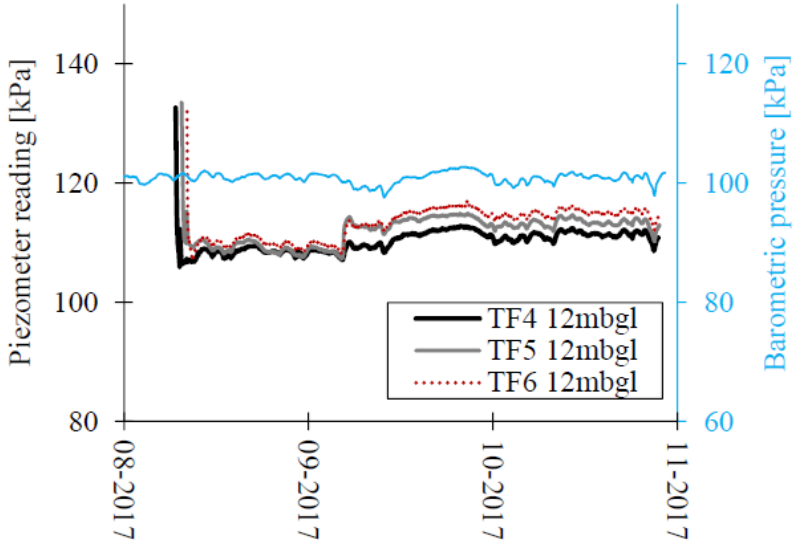
Performance Of Vibrating Wire Piezometers In Very Low Permeable Clay (Simonsen T.R. & Sorensen K.K. FMGM2018)



HAE filter (saturated by boiling)



HAE filter (saturated by vacuum)



LAE filter (saturated by immersion)

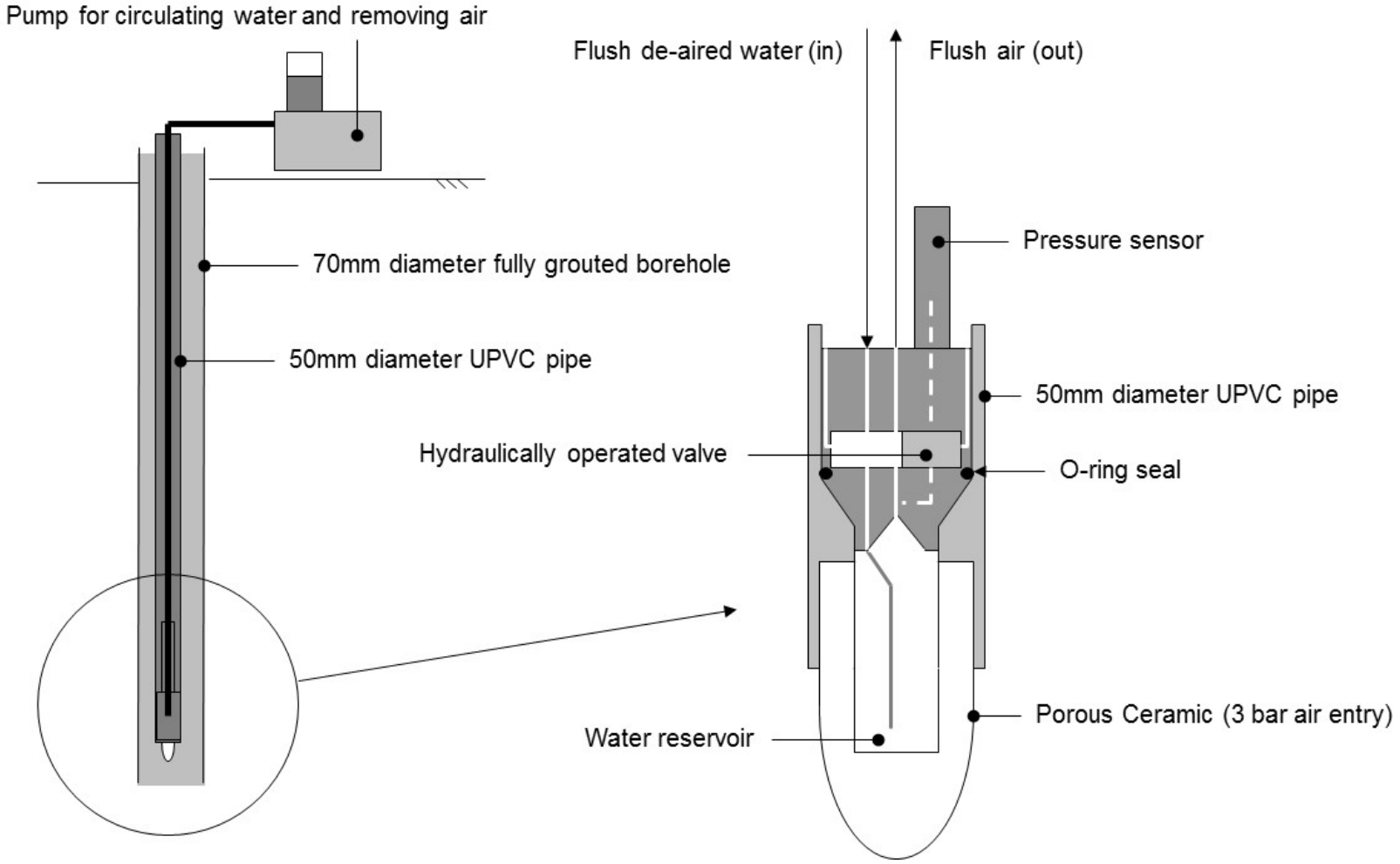
Variables:

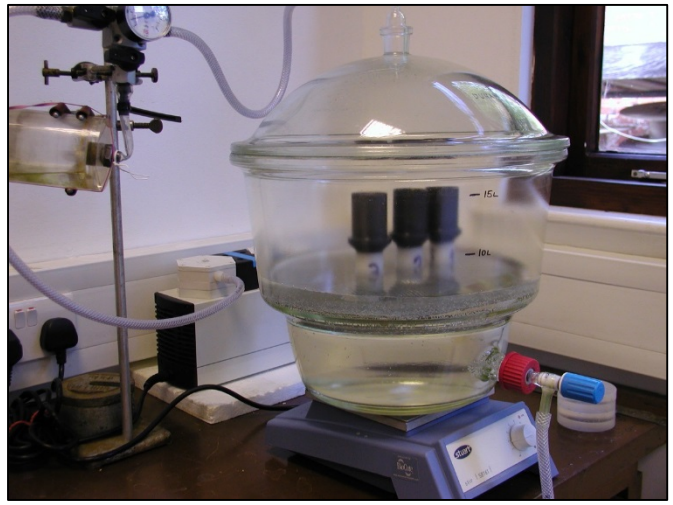
1. Grout mix (C / W / B).
2. Filter type (LAE / HAE).
3. Saturation procedure.

Constants:

1. Soil type.
2. Installation team.

If High Air Entry (HAE) filters are required because the excess pore water pressures are likely to be negative, it is essential that a means of removing the air is available (e.g. the piezometer must be flushable).

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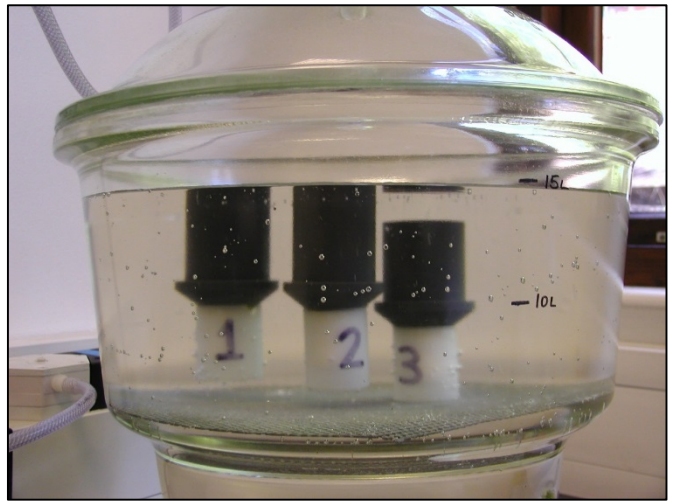
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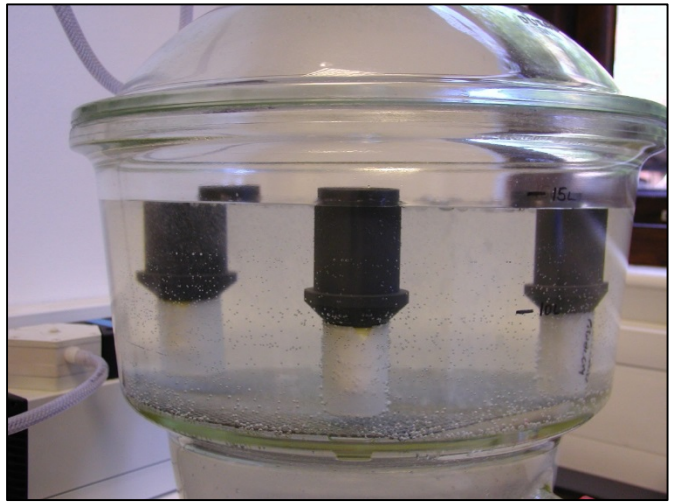
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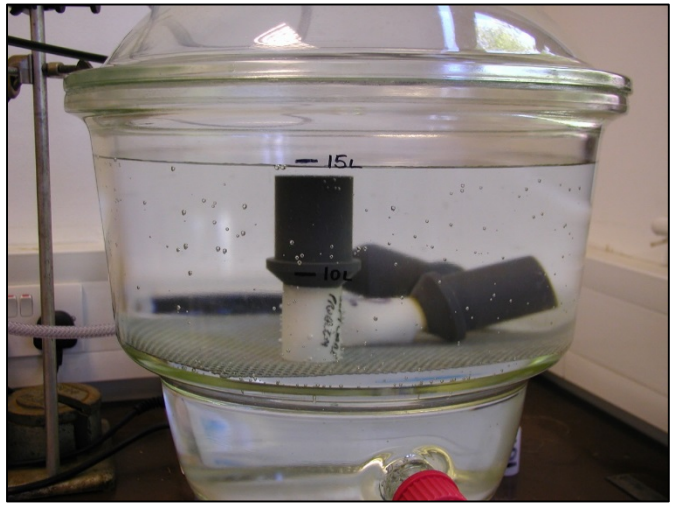
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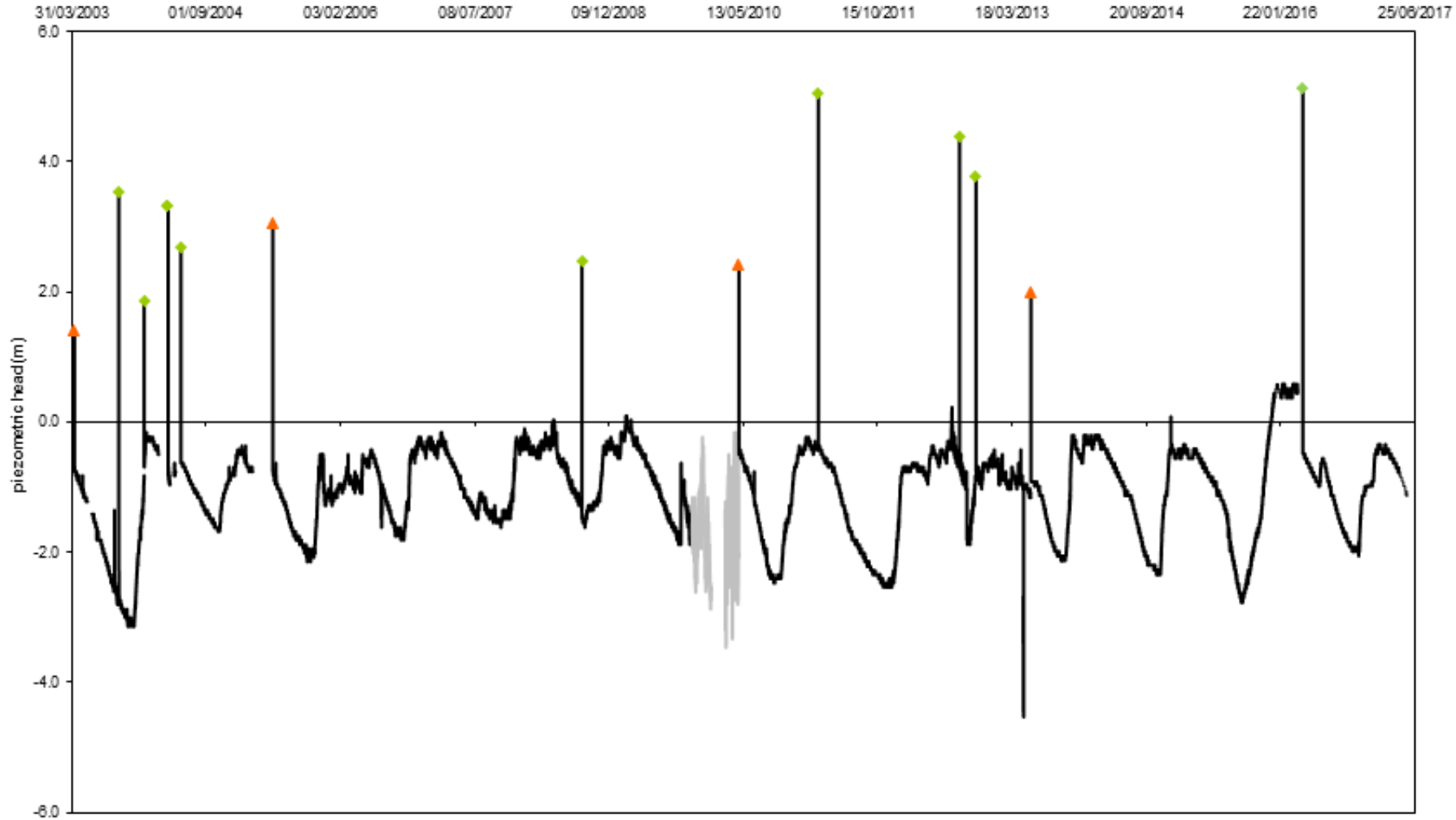
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01/09/2004
03/02/2006
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15/10/2011
18/03/2013
20/08/2014
22/01/2016
25/06/2017
6.0
4.0
2.0
0.0
-2.0
-4.0
-6.0
piezometric head (m)

Main points:

1. **Grout needs to act as a filter and a seal.**

2. **Grout permeability can reduce with time.**

3. **Viscosity of the grout is also important.**

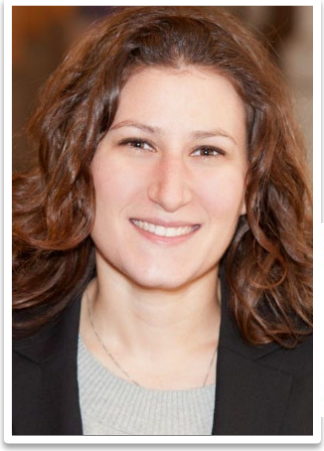
4. **High air entry porous filters shall not be used with the fully grouted method unless there is a means of removing air from the piezometer.**

Many people still require HAE filters for use with vibrating wire piezometers!

WHY?

Joel Swenson
JSwenson@barr.com

BARR



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