Relearning How to Look at Piezometric Data for Seepage Evaluation

2019 May 14 - ASDSO webinar

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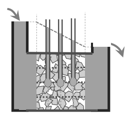
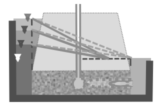
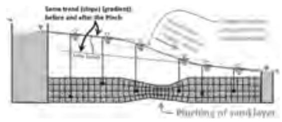






Previously
Technical Lead and Senior Policy Advisor
for Geotechnical Engineering
Headquarters - U.S. Army Corps of Engineers (USACE)

Section title

Each section title will be shown here

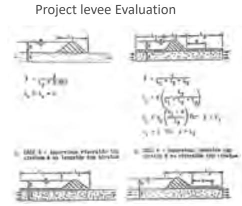
Lecture outline:
- historic seepage problems
- seepage in hillsides
- basics for seepage
- seepage in uniform foundation channels
- Flow nets in 5 minutes
- How to draw flow net introduction
- Sand boils, heave, and in situ gradient
- Backward erosion
- what it takes to have a critical in situ gradient
- Seep/w discussion
- Reservoir vs. piezometric (R-P) plot for a sand channels
- plotting field data examples on RP plots
- Using the CPT to measured in situ pore pressure
- How to depth plot support piezometer data for seepage evaluation
- How to plot field piezometric data

The material in this lecture was came from my published efforts & collaborations;

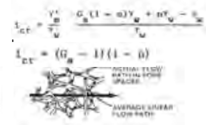
- 2016 USSD paper on seepage
- Two lectures on seepage at the USSD conferences
- Two USACE multiday seminars on seepage evaluation
- Numerous lectures at regional DOT workshops
- As part of my MSU graduate class entitled Advanced Geotechnical Site Characterization
- Part of my USACE two day intense class on Geotechnical Characterization
- My 40+ years working on Seepage
  - started with Dr. Bell at OSU in 1976
  - working with Drs. Seed and Duncan at UCB in 1977
  - 30 years of geotechnical research at ERDC
  - 6 years at USACE HQ performing oversight

Not in this lecture:

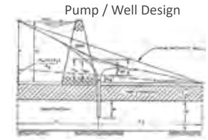
Project levee Evaluation



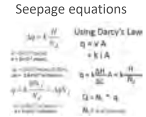
Seepage details



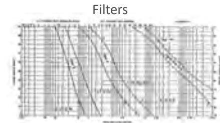
Pump / Well Design



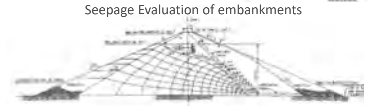
Seepage equations



Filters



Seepage Evaluation of embankments



We will:
Learn how to understand piezometer data from dams and levees

Failure of Embankment Dams

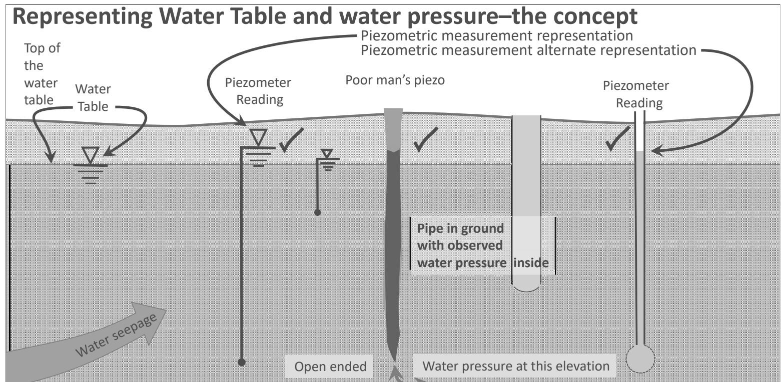
Geotechnical relative failures

Piping failures 54%

Slide failures 5%

Mode of Failure	% Total Failures (where mode of failure known)	% Failures pre 1950	% Failures post 1950
Overtopping	34.2 %	36.2 %	32.2 %
Spillway/gate (appurtenant works)	12.8 %	17.2 %	8.5 %
Piping through embankment	32.5 %	29.3 %	35.5 %
Piping from embankment into foundation	1.7 %	0 %	3.4 %
Piping through foundation	15.4 %	15.5 %	15.3 %
Downstream slide	3.4 %	6.9 %	0 %
Upstream slide	0.9 %	0 %	1.7 %
Earthquake	1.7 %	0 %	3.4 %
Totals (3)	102.6 %	105.1 %	100 %
Total overtopping and appurtenant works	48.4 %	53.4 %	40.7 %
Total piping	46.9 %	43.1 %	54.2 %
Total slides	5.5 %	6.9 %	1.6 %
Total no. of embankment dam failures (exc. During construction)	124	61	63
Total embankment dam years operation (up to 1986)	300,400	71,000	229,400
Annual probability of failure	4.1×10^{-4}	8.6×10^{-4}	2.7×10^{-4}

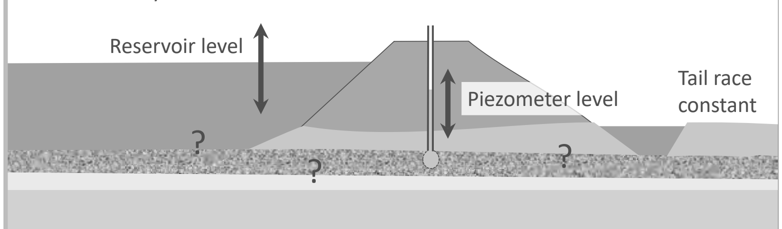
Representing Water Table and water pressure–the concept



The approach in this presentation is about **idealizing seepage issues** for direct comparison to project **field measured data** (for dams and levees).

This approach is especially for structures with a **single piezometer at the crest.**

But it's actually useful for **all water control structures.**



Our best example for seepage based failure

The 1976 Teton Dam Failure

(Teton dam failure occurred during my Senior year at Oregon State University while finishing my BSCE)

The Teton Dam Failure – it's our lesson to learn

Teton Dam (305 ft high) was completed 1976 and failed **during first filling** due to **internal erosion**

- **<u>no real filter</u> between core and shell**
- **poor rock <u>surface cleaning</u> and <u>poor dental grouting</u>**
- **<u>poor cutoff grouted curtain</u> (2 rather than 3)**
- **<u>poorly designed core trench</u> (too small and steep)**

Great initial thinking (and a GOOD design) **but daily compromises = failure**

GREAT project management ***But BAD geotechnical engineering management***

"we can compromise because dams don't fail in 1970s"

On June 3, two small spring areas developed on the left abutment approximately 600 and 900 feet downstream from the spillway stilling basin and just about river level. They were flowing clear water at approximately 40 and 60 gallons per minute.

On June 4, another small spring was found approximately 150 feet downstream from the toe of the dam on the left abutment, flowing clear water at approximately 20 gallons per minute. The abutments and downstream face of the dam were examined during the day until dark, and no seepage conditions were reported on any part of the embankment. A major leak was discovered on the morning of June 5. At the time, safety of the dam was not believed in jeopardy. A wet spot on the downstream face (left side) began eroding its way into the embankment.

Failure of Teton Dam in pictures

Two dozers began pushing rock material into the hole on the downstream face of the dam.
At 10:30 AM (**June 5th 1976**) the larger of the two dozers began to slide into the hole.

At 11:30 AM both dozers on the downstream edge of the embankment were lost in the eroded embankment hole. The embankment was now eroding rapidly.

Mrs. Olson left the site to get some coffee and met her photo Journalist son….Sure, right

Photos by Mrs. Eunice Olson on June 5 1976
(not related to me, Olson's are from Sweden and Olsen's are from Norway)

At 11 AM a whirlpool was observed in the reservoir 10 to 15 feet from the intersection of the reservoir surface with the embankment, and 100 to 150 feet from the left shoreline.

The whirlpool gradually increased in diameter and depth but stayed in a fixed location. Two dozers began to push riprap into the whirlpool

The Teton Dam site today

Downstream of Teton Dam

A few people died that were fishing just downstream of the dam

Outline of the Teton Dam before the failure

Cut section of Teton Dam to investigate the failure – Professor H. Bolton Seed (UC Berkeley) was the lead investigator

Ririe Dam

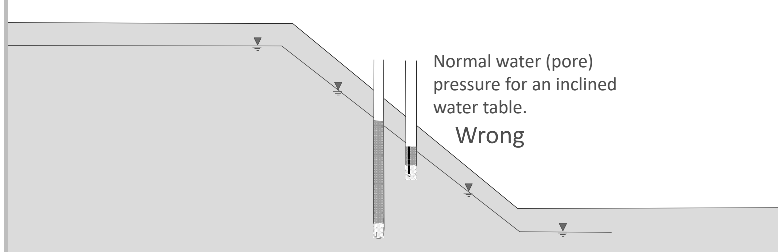
Ririe Dam was built by USACE few miles away from Teton Dam on an adjacent watershed. Ririe Dam was built during the same time and generally on the same type of rock foundation as Teton Dam.

Ririe Dam has performed great. The Corps used the Casagrande 3-line grout curtain beneath the dam plus used a better core cutoff trench and better defined core and sand filters.

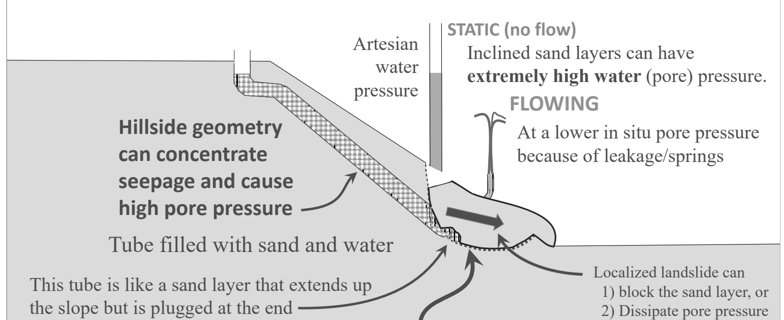
We must not forget the historical failures and successes

Professor Arthur Casagrande developed the 3-line grout curtain concept and presented it at the First ASCE Terzaghi Lecture in 1963.
The ERDC GSL building is named after Professor Arthur Casagrande.

Conventional thinking about pore pressure in slopes



How high can water (pore) pressure get ?




Example of water flow through a porous dam – showing flow lines
FLOW NETS
Let's start our efforts into flow nets slowly
A water drip will follow flow lines
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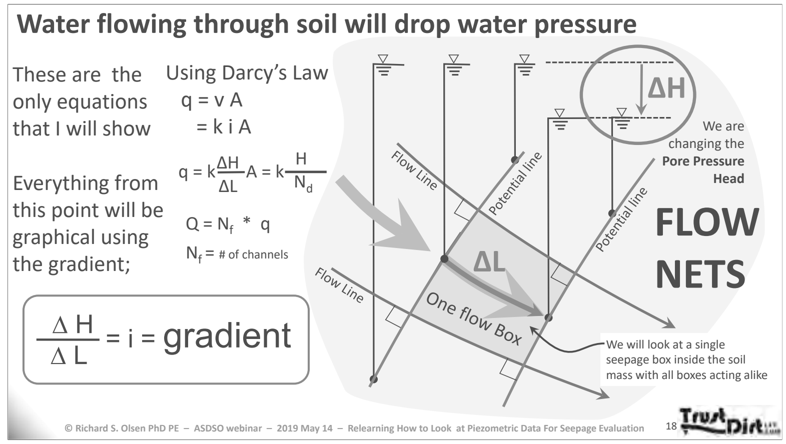
Water flowing through soil will drop water pressure
These are the only equations that I will show
Using Darcy's Law
q = v A
= k i A
q = k ΔH/ΔL A = k H/N_d
Everything from this point will be graphical using the gradient;
Q = N_f * q
N_f = # of channels
Δ H / Δ L = i = gradient
ΔH
We are changing the Pore Pressure Head
Flow Line
Potential line
Potential line
FLOW NETS
ΔL
Flow Line
One flow Box
We will look at a single seepage box inside the soil mass with all boxes acting alike
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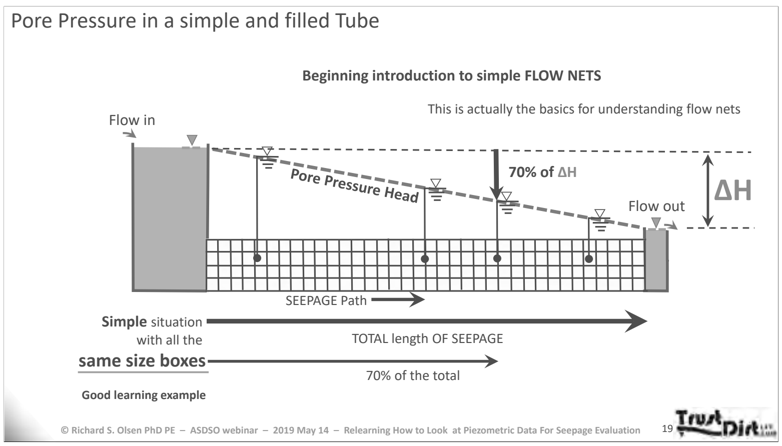
Pore Pressure in a simple and filled Tube
Beginning introduction to simple FLOW NETS
This is actually the basics for understanding flow nets
Flow in
Pore Pressure Head
70% of ΔH
ΔH
Flow out
SEEPAGE Path
Simple situation with all the same size boxes
TOTAL length OF SEEPAGE
70% of the total
Good learning example
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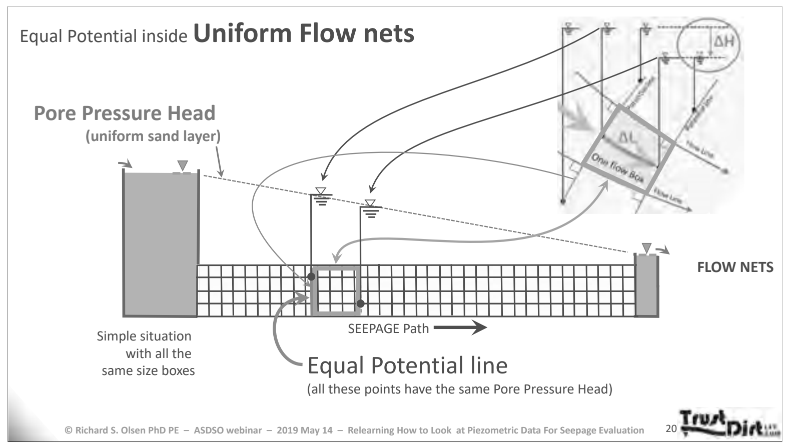
Equal Potential inside Uniform Flow nets
Pore Pressure Head
(uniform sand layer)
FLOW NETS
Simple situation with all the same size boxes
SEEPAGE Path
Equal Potential line
(all these points have the same Pore Pressure Head)
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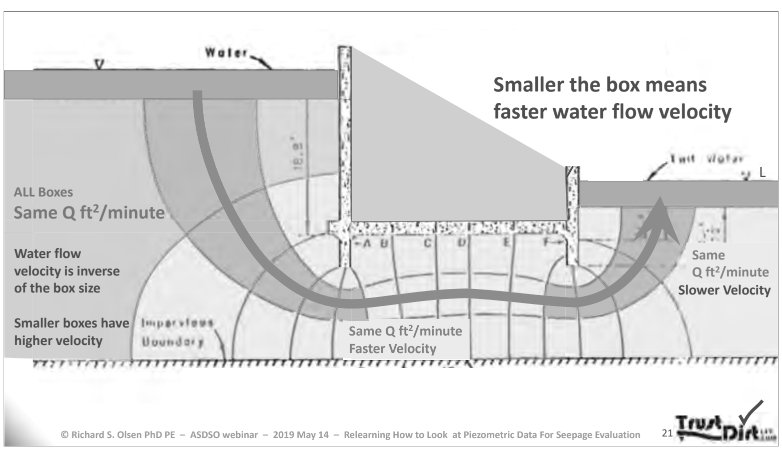
Water
Smaller the box means faster water flow velocity
Tail Water
ALL Boxes
Same Q ft²/minute
Water flow velocity is inverse of the box size
Smaller boxes have higher velocity
Impervious Boundary
Same Q ft²/minute
Faster Velocity
Same Q ft²/minute
Slower Velocity
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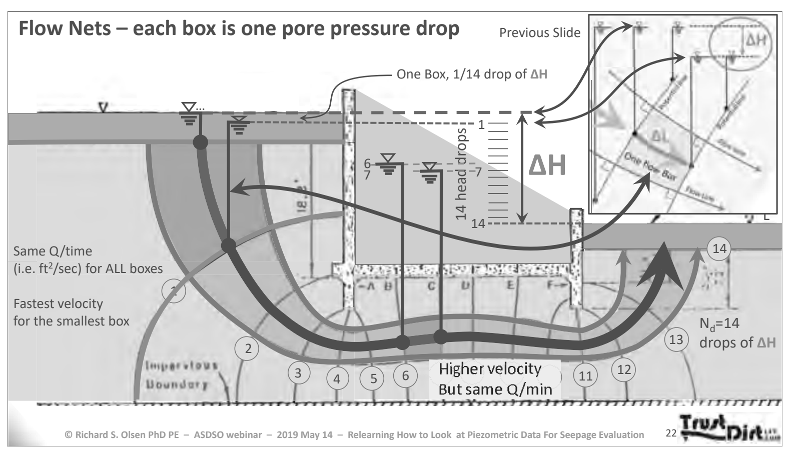
Flow Nets – each box is one pore pressure drop
Previous Slide
One Box, 1/14 drop of ΔH
14 head drops
ΔH
Same Q/time
(i.e. ft²/sec) for ALL boxes
Fastest velocity for the smallest box
Impervious Boundary
Higher velocity
But same Q/min
N_d=14 drops of ΔH
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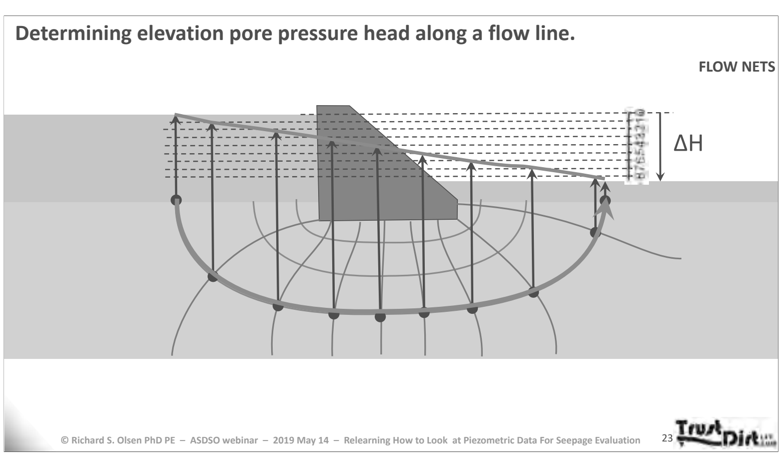
Determining elevation pore pressure head along a flow line.
FLOW NETS
ΔH
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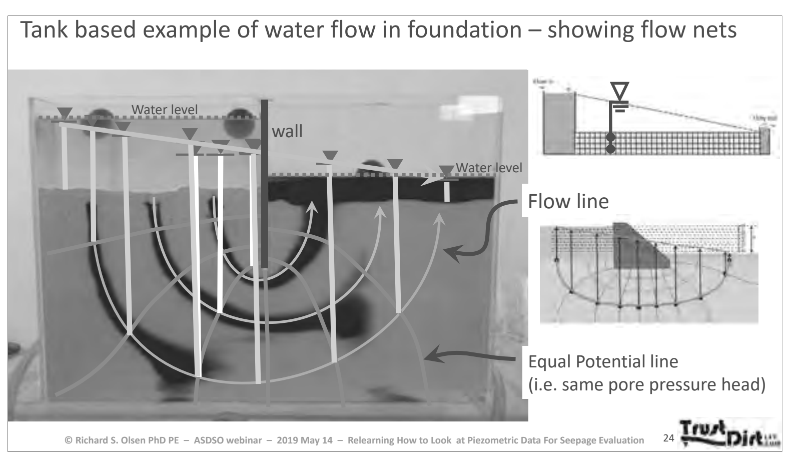
Tank based example of water flow in foundation – showing flow nets
Water level
wall
Water level
Flow line
Equal Potential line
(i.e. same pore pressure head)
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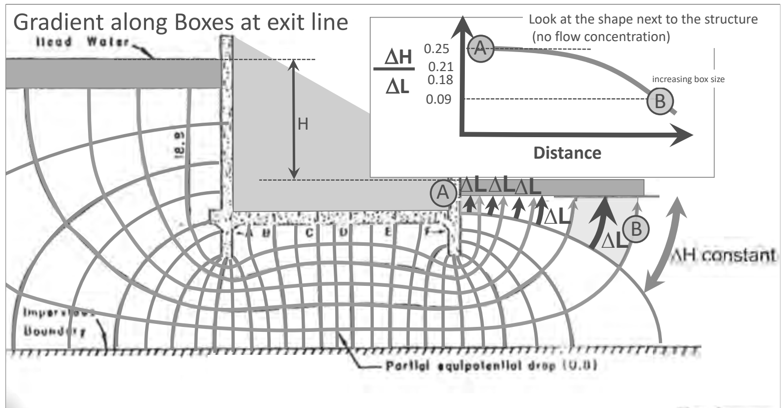
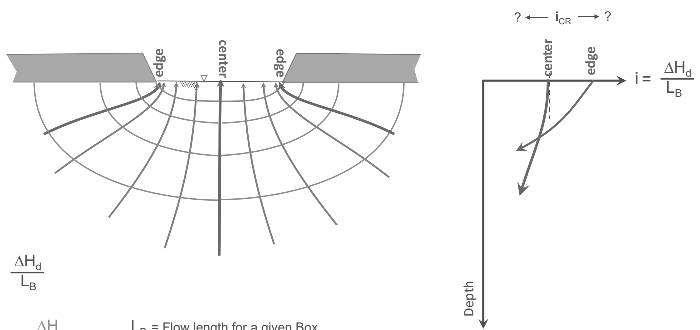
Flow Nets
and
seepage indexs

Gradient along Boxes at exit line



Flow out of a hole at the ground surface (from 1 inch to 1+ foot)

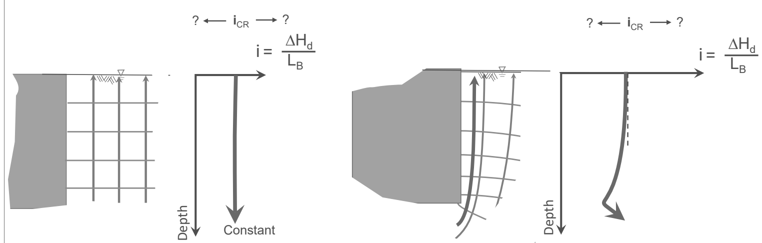


$i = \frac{\Delta H_d}{L_B}$

$i = \frac{\Delta H_d}{L_B}$

$\Delta H_d = \frac{\Delta H}{N_d}$ L_B = Flow length for a given Box

Flow next to a concrete structure and
Flow around a deep corner and up next to a concrete will

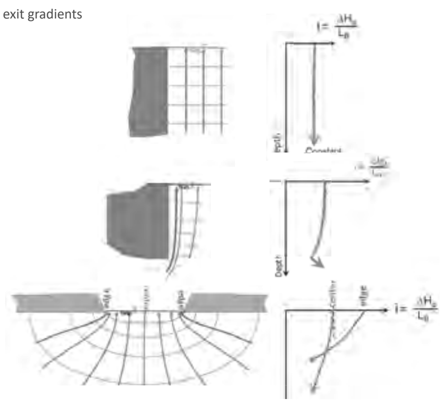


$i = \frac{\Delta H_d}{L_B}$ $i = \frac{\Delta H_d}{L_B}$

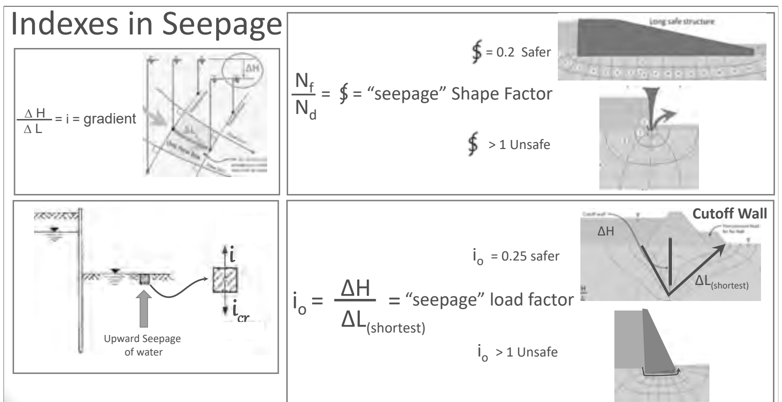
$i = \frac{\Delta H_d}{L_B}$

$\Delta H_d = \frac{\Delta H}{N_d}$ L_B = Flow length for a given Box

Comparison of the exit gradients



Indexes in Seepage



$\frac{N_f}{N_d}$ = ∱ = "seepage" Shape Factor

∱ = 0.2 Safer

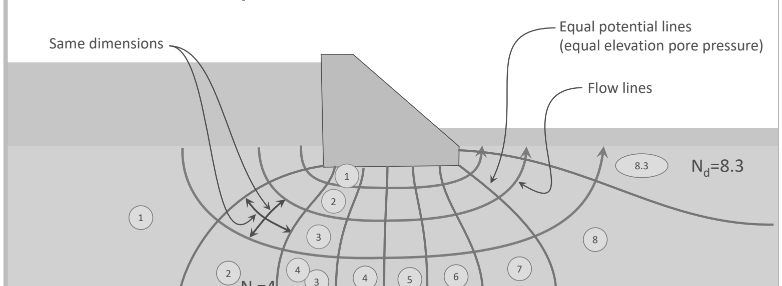
∱ > 1 Unsafe

$i_o = \frac{\Delta H}{\Delta L_{(shortest)}}$ = "seepage" load factor

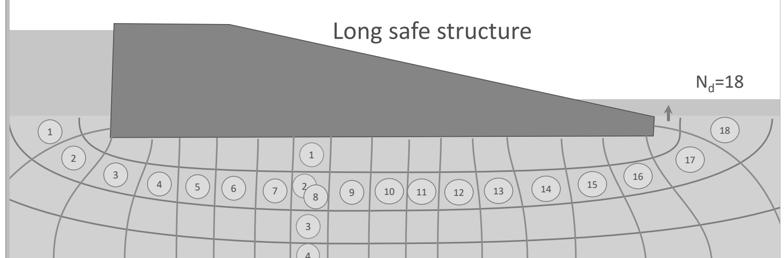
i_o = 0.25 safer

i_o > 1 Unsafe

flow nets - for a simple dam foundation



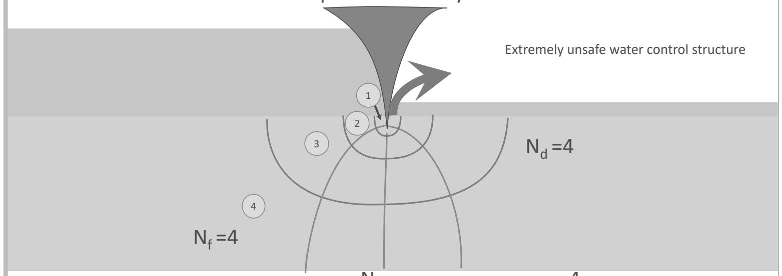
$i = \frac{\Delta H}{\Delta L}$ $\frac{N_f}{N_d}$ = ∱ = Shape Factor = $\frac{4}{8.3}$ = **0.48**



$i = \frac{\Delta H}{\Delta L}$ N_f=4 $\frac{N_f}{N_d}$ = ∱ = Shape Factor = $\frac{4}{18}$ = **0.22**

I_o = 0.08

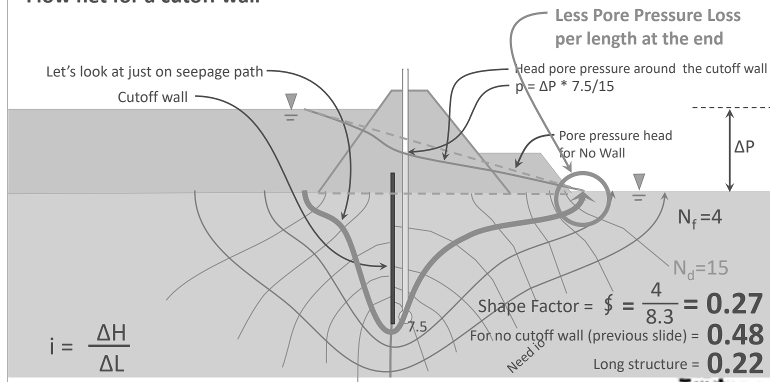
Short flow path



$$\frac{N_f}{N_d} = \$ = \text{Shape Factor} = \frac{4}{4} = 1$$

$l_o = 3$

Flow net for a cutoff wall



$$i = \frac{\Delta H}{\Delta L}$$

Shape Factor = $\$ = \frac{4}{8.3} = 0.27$

For no cutoff wall (previous slide) = **0.48**

Long structure = **0.22**

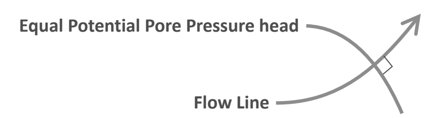
Hand Drawing Flow Nets

Guidelines for Drawing Flow Nets

It is best to **draw a crude flow net first** and then adjust it to improve the quality

- **Adjust** flow and equipotential lines to meet at 90º
- **Shift** lines to form squares
- If equipotential drops result in a fraction, place the fraction in an area of uniform squares
- Use only enough flow and equipotential lines to define the flow net
- If more precision is desired in an area subdivide the squares into smaller squares

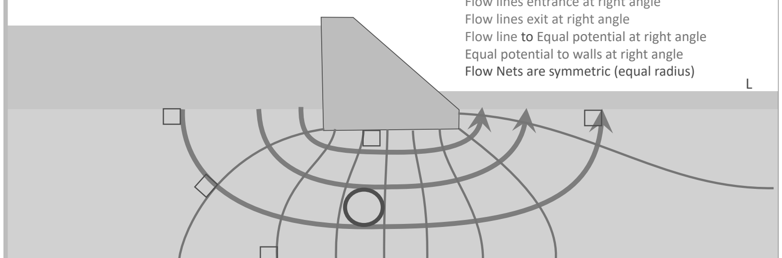
The big required: flow lines CROSS equal potential lines AT RIGHT ANGLE



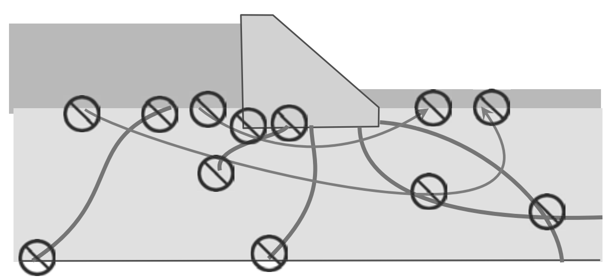
flow net rules

The basics RULES – flow lines and equal potential lines

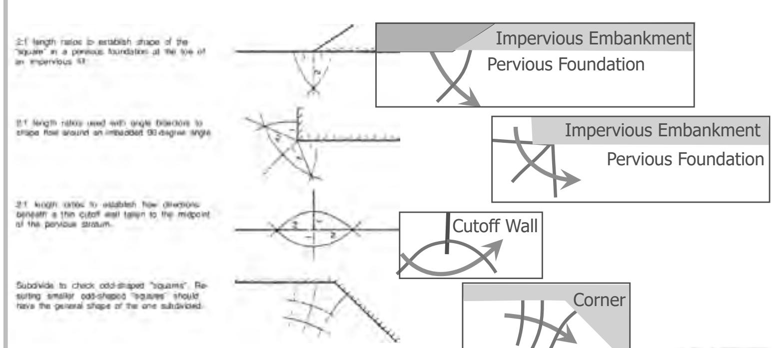
- Flow lines entrance at right angle
- Flow lines exit at right angle
- Flow line to Equal potential at right angle
- Equal potential to walls at right angle
- Flow Nets are symmetric (equal radius)



No No's
for seepage flow next construction

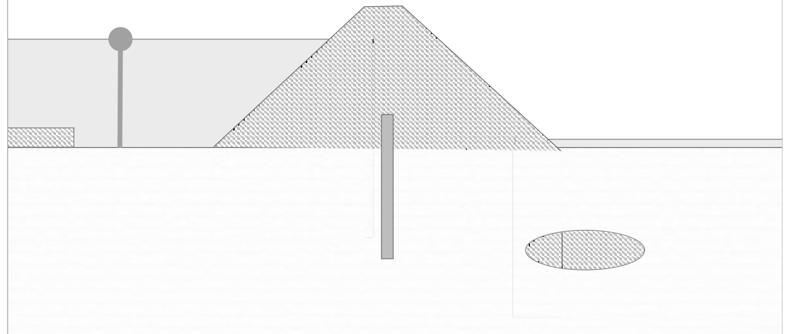


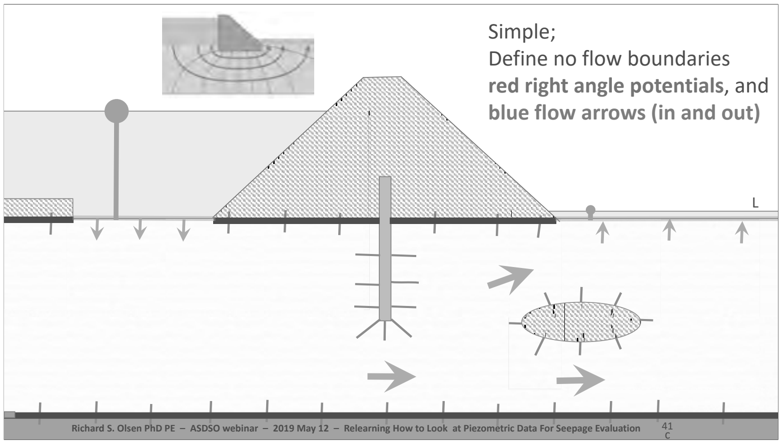
Guidelines for Flow Net Construction



Hand Flow Net Construction

First
- Defined input and outflow
- Define non flow boundaries




Simple;
Define no flow boundaries
red right angle potentials, and
blue flow arrows (in and out)
L
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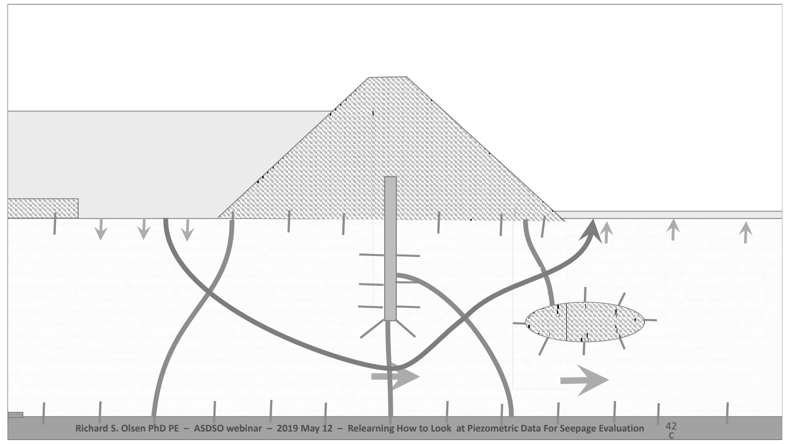
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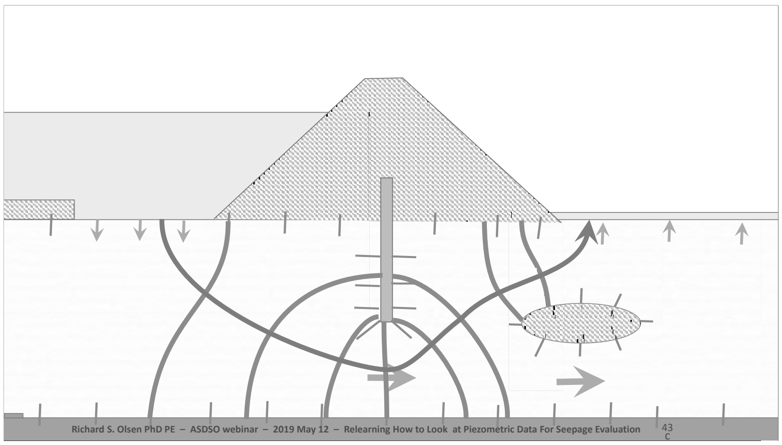
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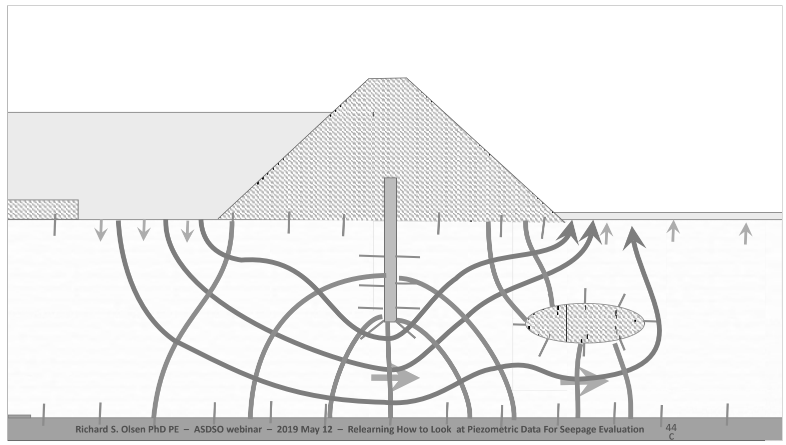
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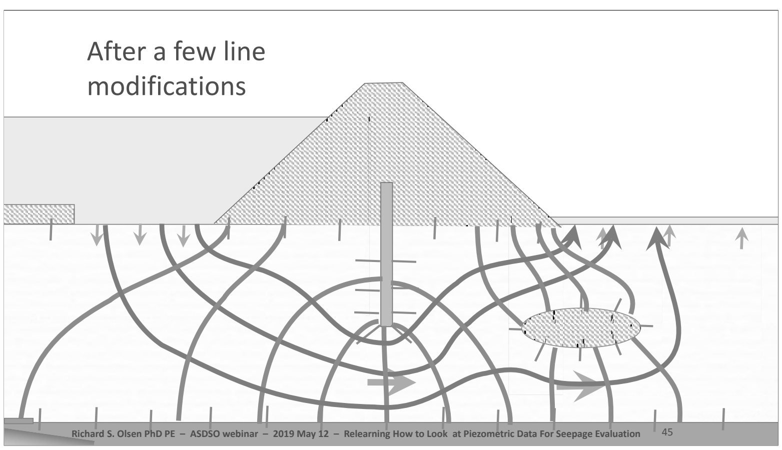
After a few line
modifications
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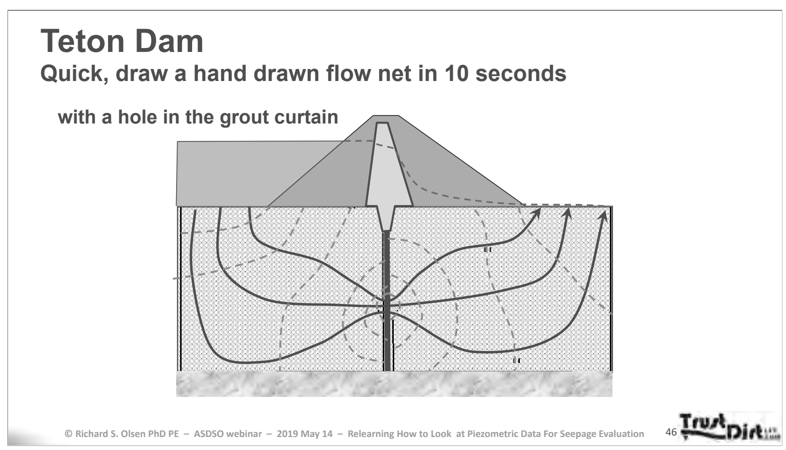
Teton Dam
Quick, draw a hand drawn flow net in 10 seconds
with a hole in the grout curtain
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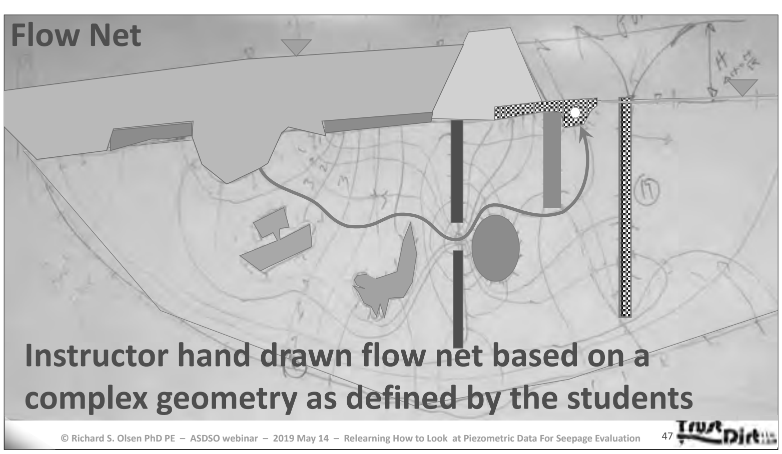
Flow Net
Instructor hand drawn flow net based on a
complex geometry as defined by the students
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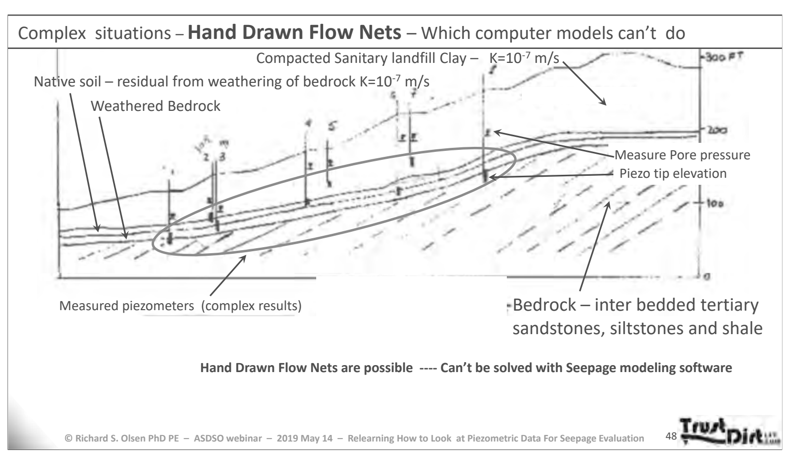
47


Complex situations – Hand Drawn Flow Nets – Which computer models can't do
Compacted Sanitary landfill Clay – K=10-7 m/s
Native soil – residual from weathering of bedrock K=10-7 m/s
Weathered Bedrock
Measure Pore pressure
Piezo tip elevation
Measured piezometers (complex results)
Bedrock – inter bedded tertiary sandstones, siltstones and shale
Hand Drawn Flow Nets are possible ---- Can't be solved with Seepage modeling software
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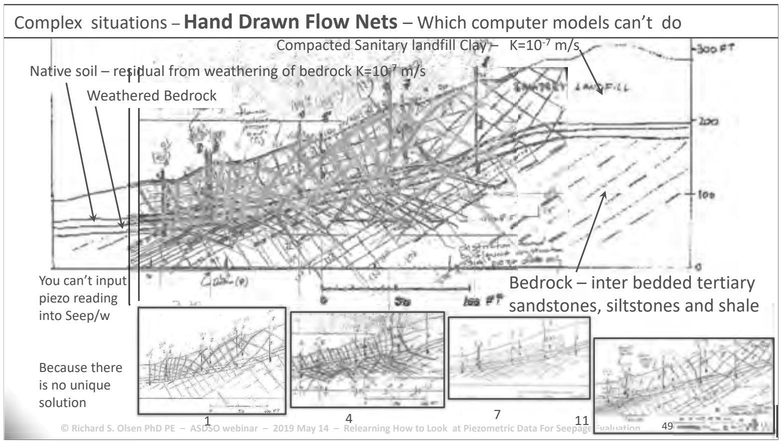

Complex situations – **Hand Drawn Flow Nets** – Which computer models can't do
Compacted Sanitary landfill Clay – K=10⁻⁷ m/s
Native soil – residual from weathering of bedrock K=10⁻⁷ m/s
Weathered Bedrock
You can't input piezo reading into Seep/w
Because there is no unique solution
Bedrock – inter bedded tertiary sandstones, siltstones and shale
1
4
7
11
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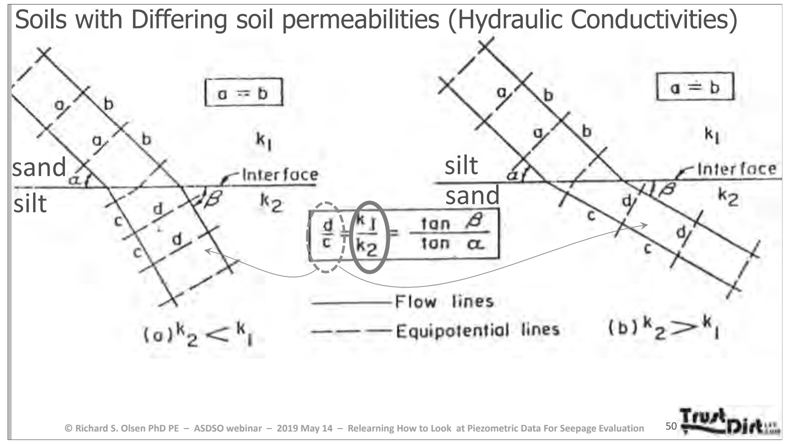

Soils with Differing soil permeabilities (Hydraulic Conductivities)
a = b
sand
silt
Interface
k_1
k_2
$\frac{d}{c} = \frac{k_1}{k_2} = \frac{\tan \beta}{\tan \alpha}$
Flow lines
Equipotential lines
(a) $k_2 < k_1$
(b) $k_2 > k_1$
silt
sand
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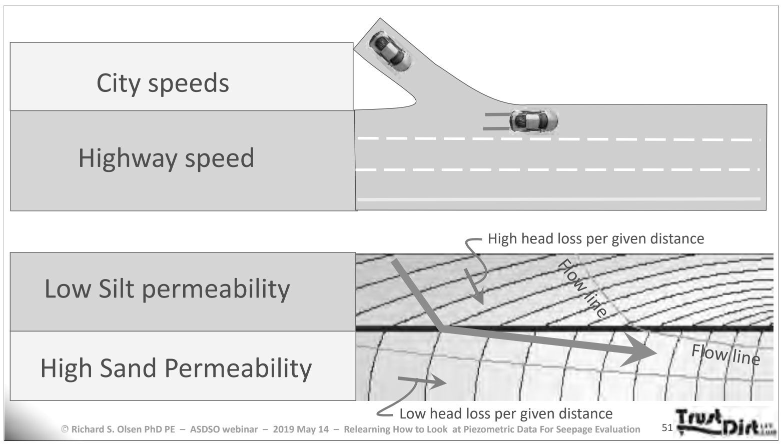

City speeds
Highway speed
Low Silt permeability
High Sand Permeability
High head loss per given distance
Flow line
Flow line
Low head loss per given distance
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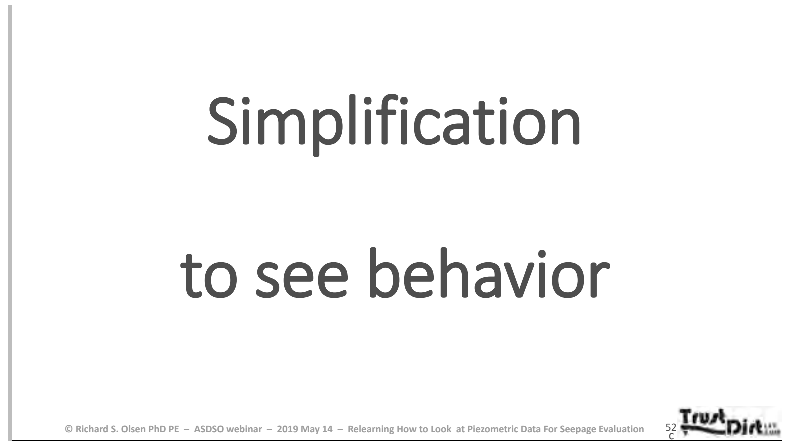

Simplification
to see behavior
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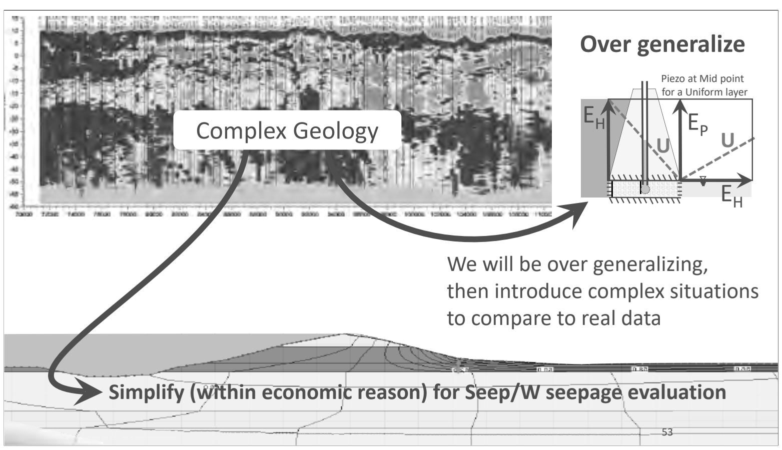
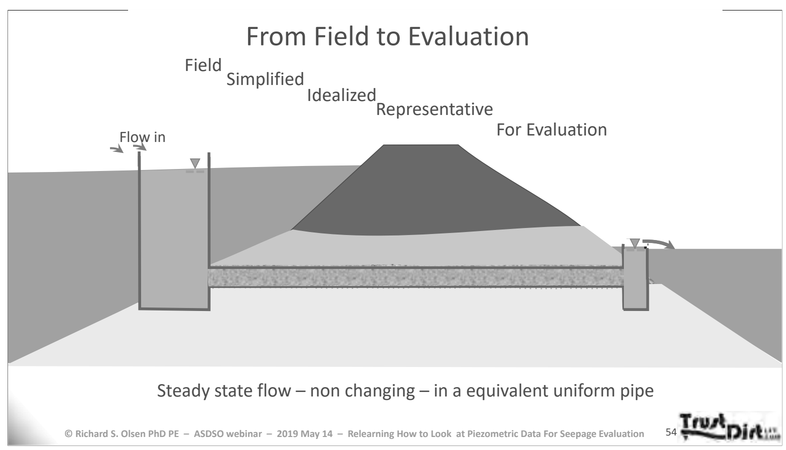


Over generalize
Piezo at Mid point for a Uniform layer
Complex Geology
We will be over generalizing, then introduce complex situations to compare to real data
Simplify (within economic reason) for Seep/W seepage evaluation
53



From Field to Evaluation
Field
Simplified
Idealized
Representative
For Evaluation
Flow in
Steady state flow – non changing – in a equivalent uniform pipe
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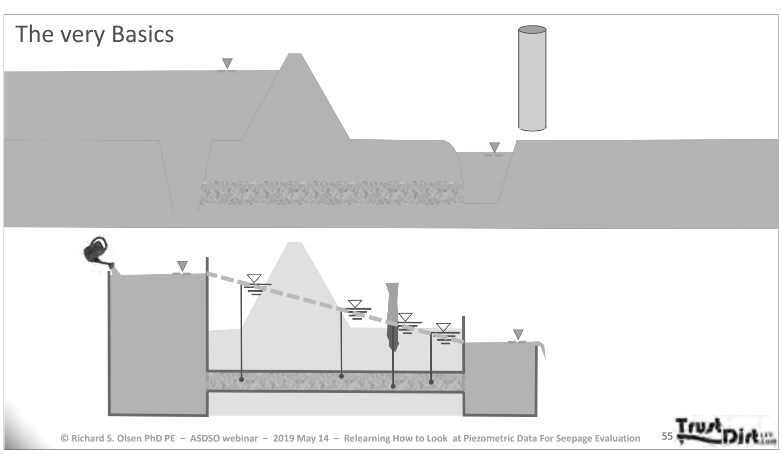

The very Basics
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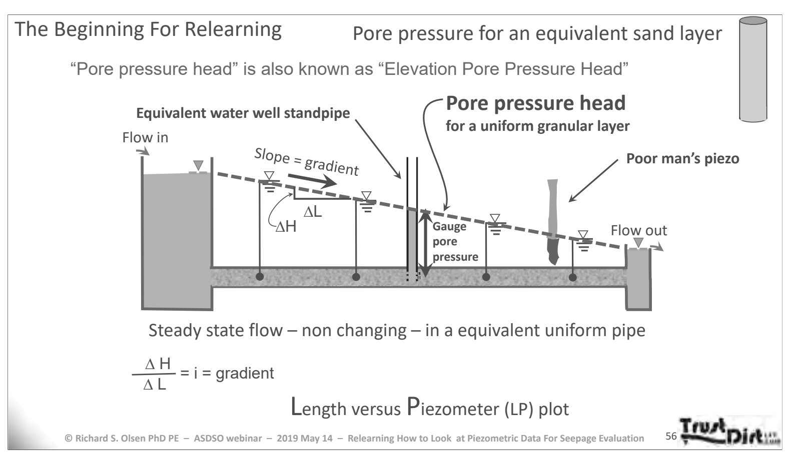

The Beginning For Relearning
Pore pressure for an equivalent sand layer
"Pore pressure head" is also known as "Elevation Pore Pressure Head"
Equivalent water well standpipe
Pore pressure head
for a uniform granular layer
Flow in
Slope = gradient
ΔL
ΔH
Poor man's piezo
Gauge pore pressure
Flow out
Steady state flow – non changing – in a equivalent uniform pipe
$\frac{\Delta H}{\Delta L}$ = i = gradient
Length versus Piezometer (LP) plot
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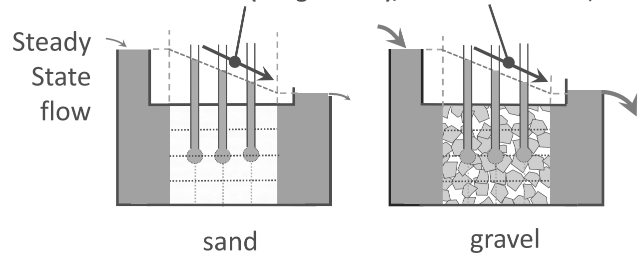
Comparison of pore pressure trend for sand and gravel layers

$$i = \frac{\Delta H}{\Delta L}$$

Same trend (i.e. gradient), but different velocity

if both are homogenous and have the same geometry

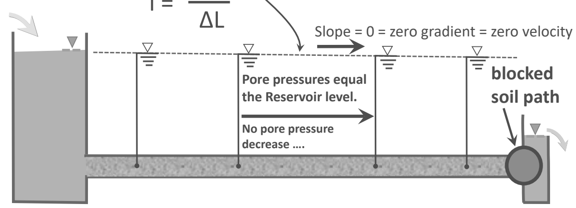


Pore pressure response for a blocked sand layer.

No pore pressure change means NO VELOCITY

Remember, Flow generates pore pressure head loss

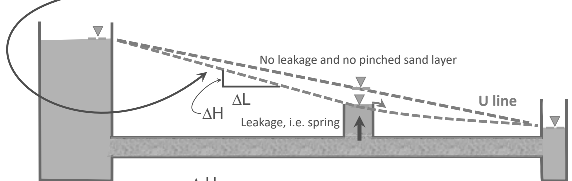
$$i = \frac{\Delta H}{\Delta L}$$



Leakage in middle of a uniform layer

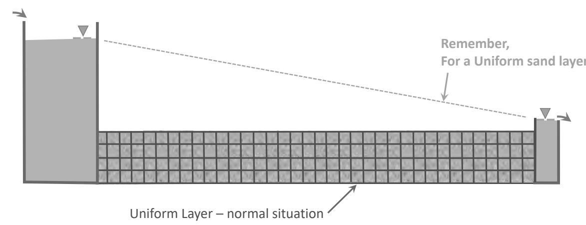
Water spring (leakage) in a slope

1) Decreases trapped water pressures (good),
2) Indicates trapped pore pressures (bad), and
3) The gradient before the leak is now higher…with consequences

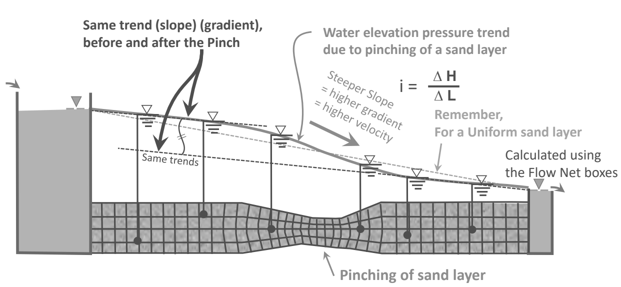


$$\frac{\Delta H}{\Delta L} = i = \text{gradient}$$

Defining a pinched condition in a uniform sand layer



Defining a pinched condition in a uniform sand layer

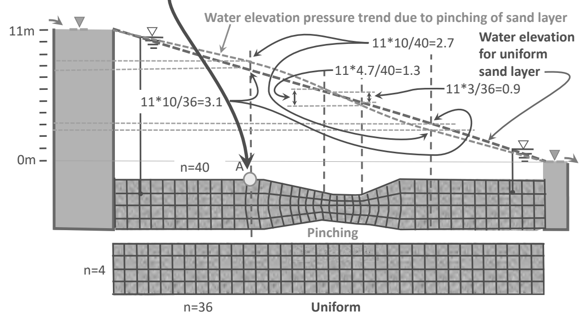


Q/sec decreases because of the pinch but Q/sec is always same for ALL boxes

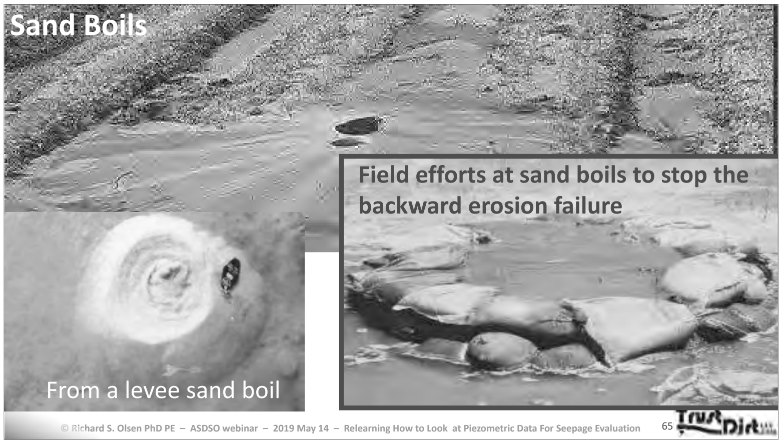
V (distance/sec) at the pinch (small boxes) will be higher than for either side

Details for calculating pore pressure head due to pinching in a uniform sand layer.

Point A: 11 equal potential lines
40 total equal potential lines



Sand boils, Backward erosion, High seepage gradients, and Heave


Sand Boils
Field efforts at sand boils to stop the backward erosion failure
From a levee sand boil
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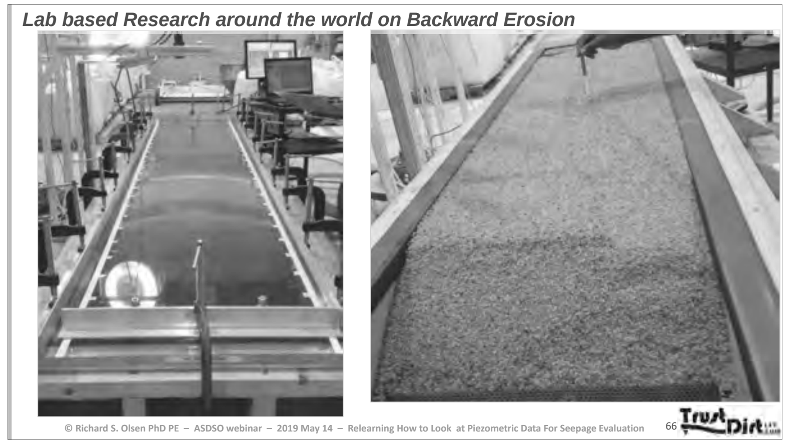
Lab based Research around the world on Backward Erosion
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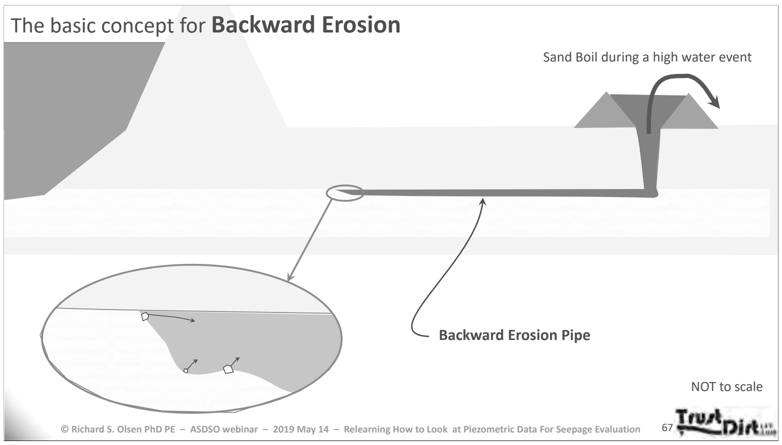
The basic concept for Backward Erosion
Sand Boil during a high water event
Backward Erosion Pipe
NOT to scale
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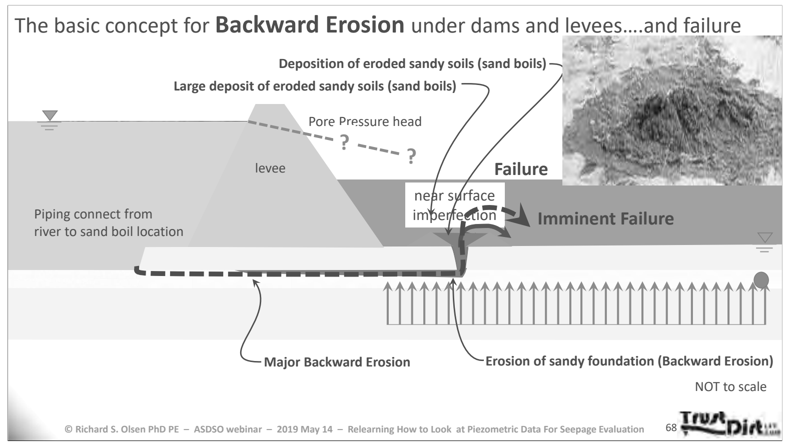
The basic concept for Backward Erosion under dams and levees….and failure
Deposition of eroded sandy soils (sand boils)
Large deposit of eroded sandy soils (sand boils)
Pore Pressure head
?
?
levee
Failure
Piping connect from
river to sand boil location
near surface
imperfection
Imminent Failure
Major Backward Erosion
Erosion of sandy foundation (Backward Erosion)
NOT to scale
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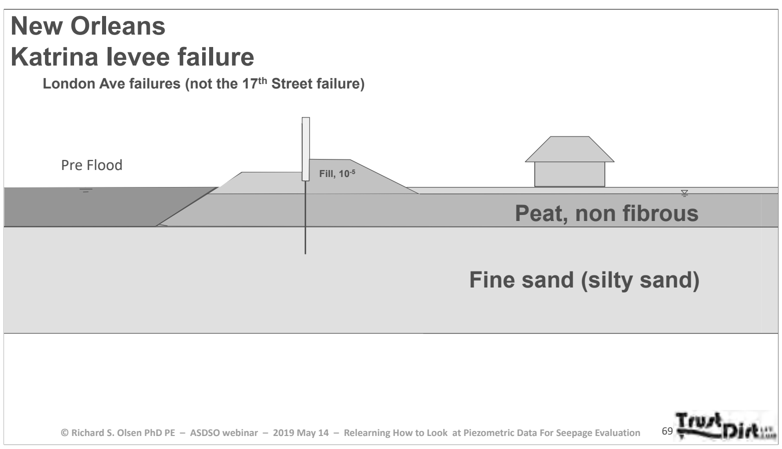
New Orleans
Katrina levee failure
London Ave failures (not the 17th Street failure)
Pre Flood
Fill, 10-5
Peat, non fibrous
Fine sand (silty sand)
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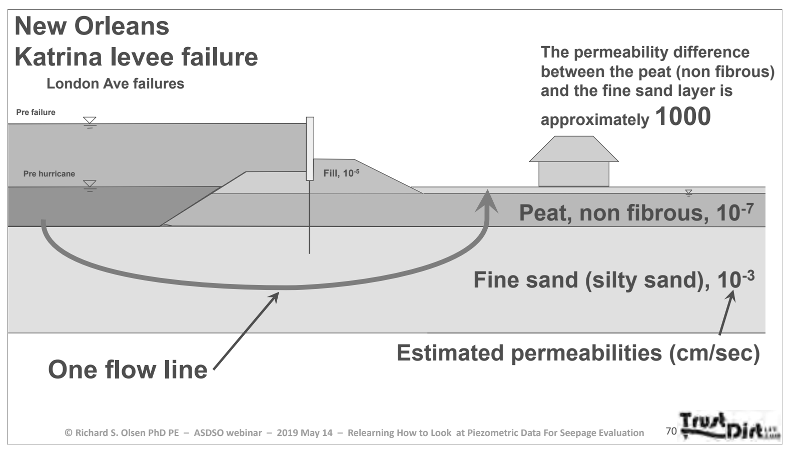
New Orleans
Katrina levee failure
London Ave failures
The permeability difference between the peat (non fibrous) and the fine sand layer is approximately 1000
Pre failure
Pre hurricane
Fill, 10-5
Peat, non fibrous, 10-7
Fine sand (silty sand), 10-3
One flow line
Estimated permeabilities (cm/sec)
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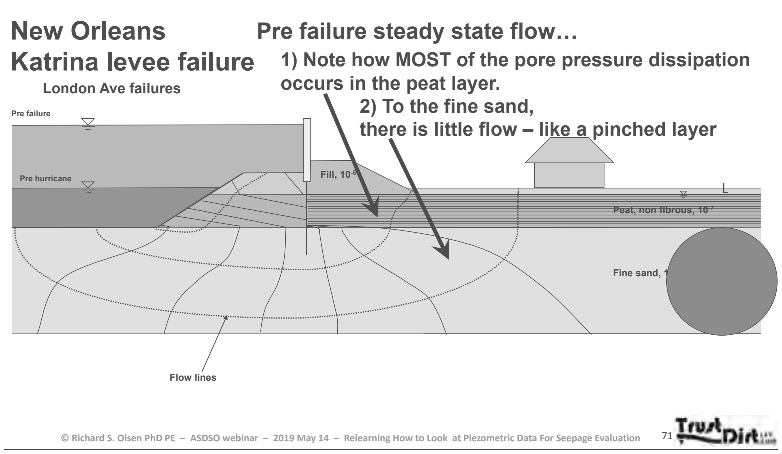
New Orleans
Katrina levee failure
London Ave failures
Pre failure steady state flow…
1) Note how MOST of the pore pressure dissipation occurs in the peat layer.
2) To the fine sand, there is little flow – like a pinched layer
Pre failure
Pre hurricane
Fill, 10-5
Peat, non fibrous, 10-7
Fine sand, 1
Flow lines
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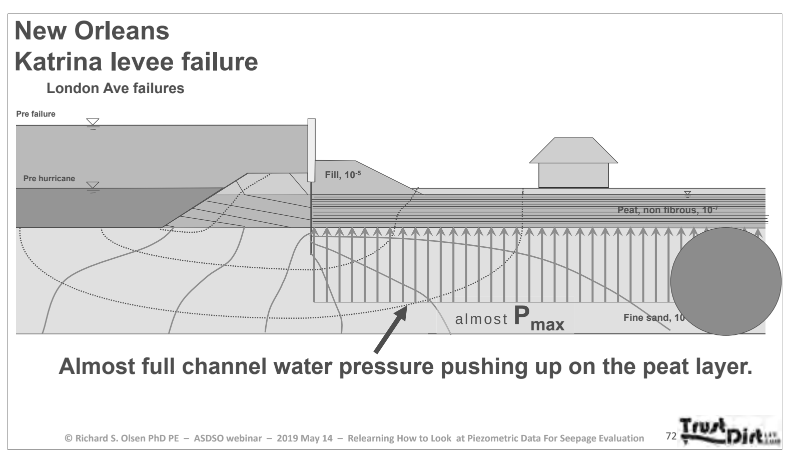
New Orleans
Katrina levee failure
London Ave failures
Pre failure
Pre hurricane
Fill, 10-5
Peat, non fibrous, 10-7
almost Pmax
Fine sand, 10
Almost full channel water pressure pushing up on the peat layer.
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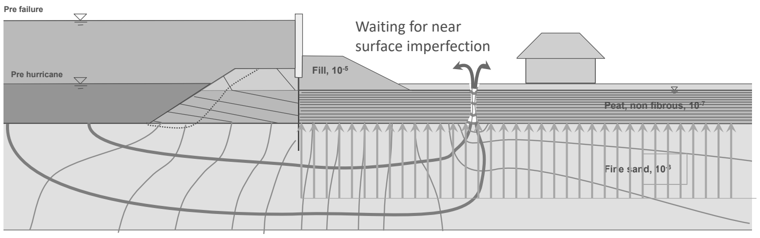
New Orleans Katrina levee failure

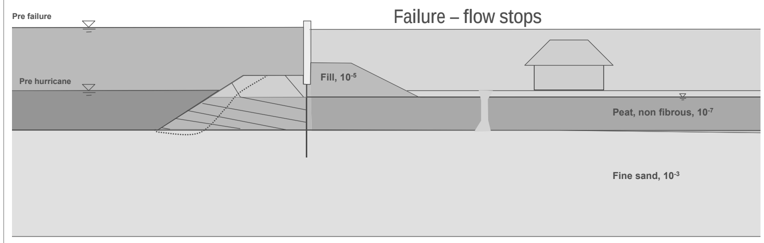
London Ave failures

1) A weak near surface point fails (a point of imperfection)
2) Upward flow starts because of high pore pressure
3) Foundation pore pressure decreases due to flowing

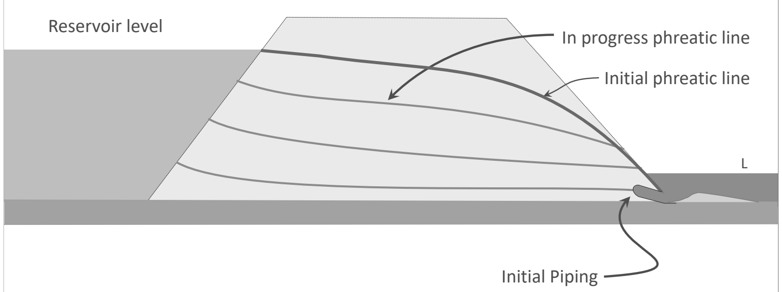


New Orleans Katrina levee failure

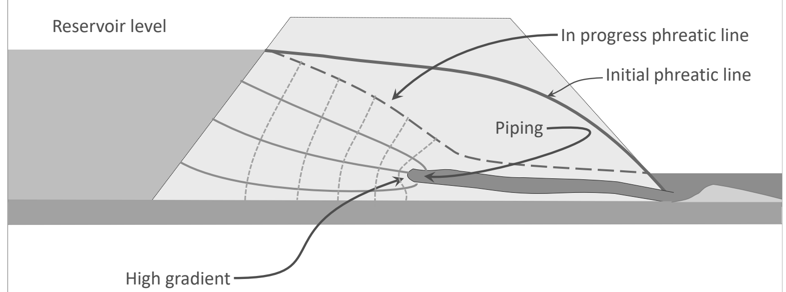
London Ave failures



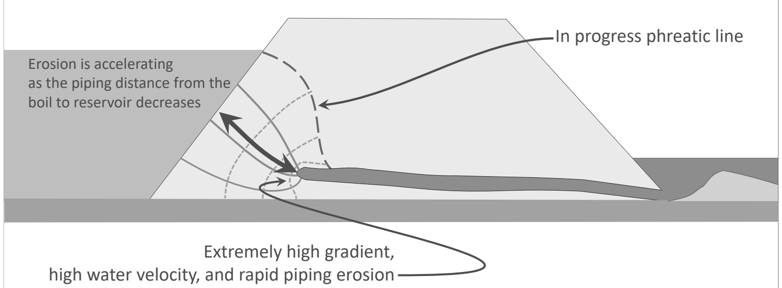
Starting of backward erosion piping through an embankment



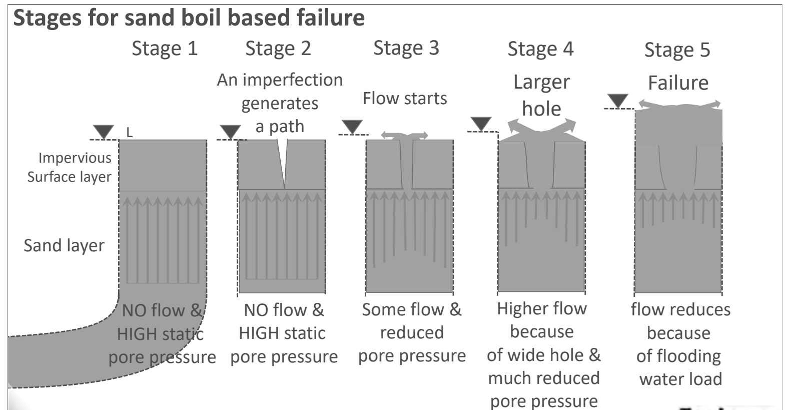
Backward erosion piping through an embankment



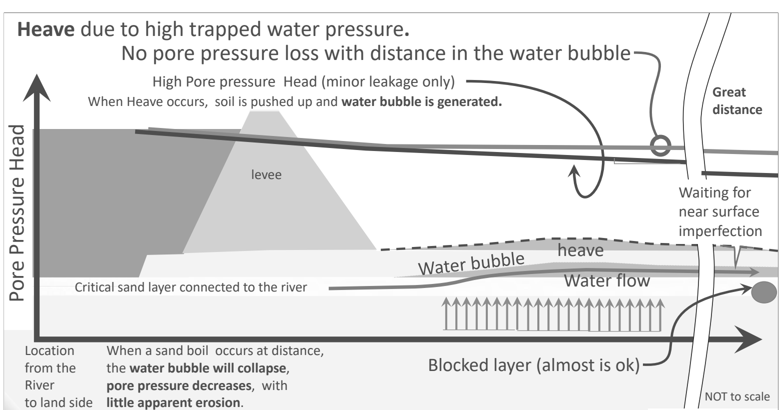
Backward erosion piping through an embankment is critical



Stages for sand boil based failure



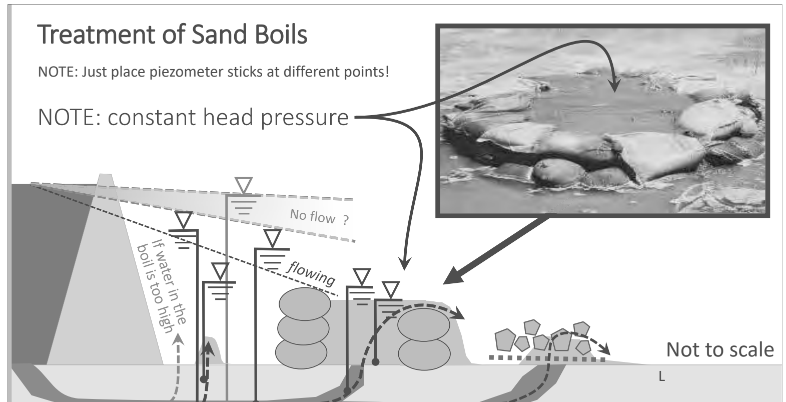
Heave due to high trapped water pressure.



Treatment of Sand Boils

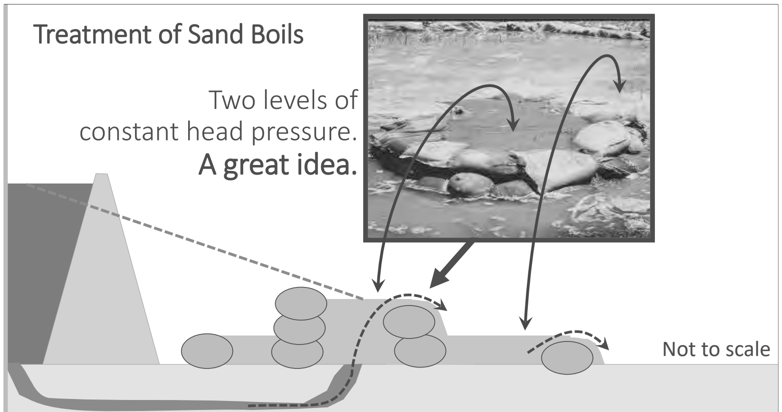
NOTE: Just place piezometer sticks at different points!

NOTE: constant head pressure



Treatment of Sand Boils

Two levels of
constant head pressure.
A great idea.

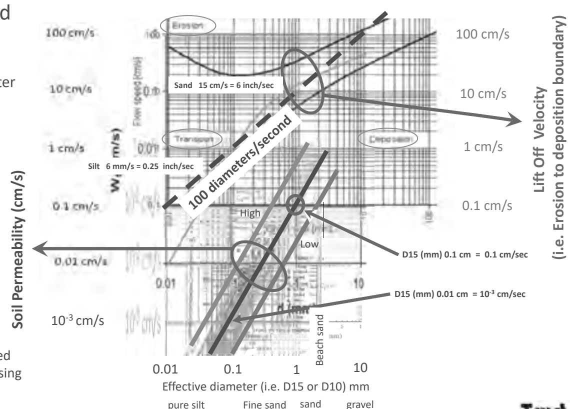


Interesting things to Know

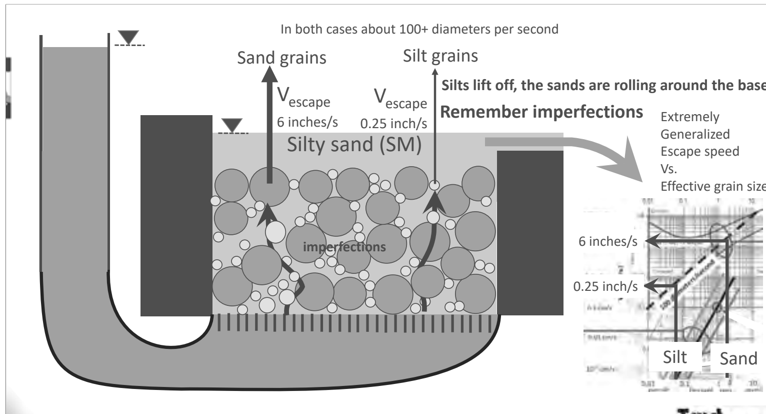
Permeability and Lift Off Velocity

in terms of
Effective Grain Diameter

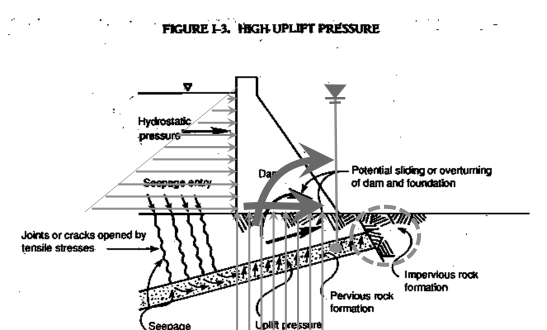
…interesting…



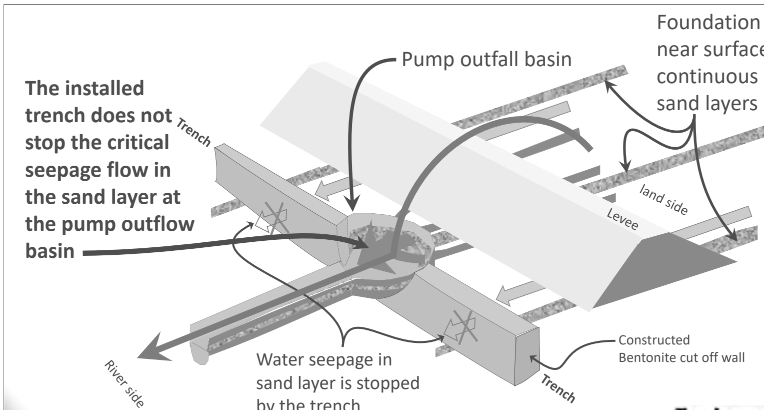
Using about 11 published relationships overlaid using PowerPoint techniques



Geotechnical Aspects of Concrete Dams-**Uplift Pressure**



The installed trench does not stop the critical seepage flow in the sand layer at the pump outflow basin



Question and Answers for a Few Minutes

Then on to:

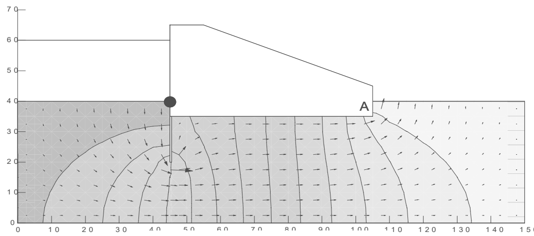
- Seep/W Modeling Issues
- R-P plot Construction
- Charting Field Piezometer data
- How to Intercept Time base data
- Field data examples
- Plotting standards for data

…

A look at Seep/W

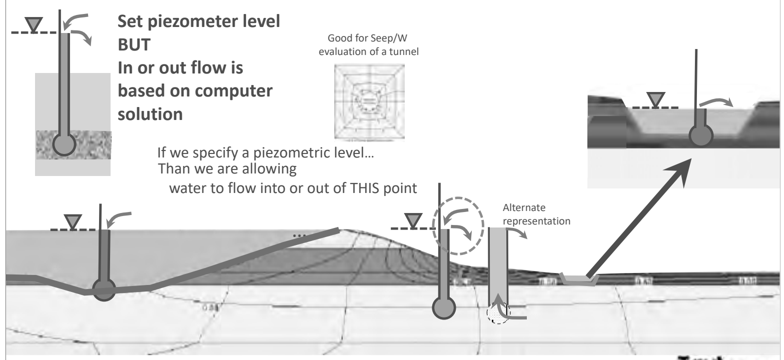
Seep/W Solution — Closed form solution for seepage evaluation

Best means to evaluate project based seepages;
for many soil types, soil layers (simple to complex), permeabilities, and anisometric ratios.

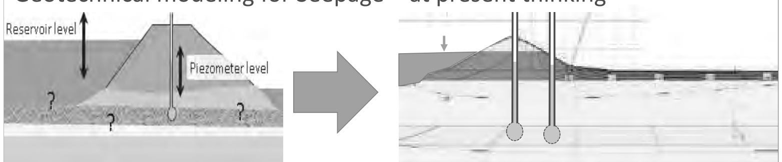


Results typically NOT a flow net
- Lines (and color contours) show equal total head
- Arrows usually show flow direction
- Can use results to construct flow net

When you specify a piezometric level in a seepage model (i.e. Seep/W), you are allowing water to flow into or out of that point (or line)



Geotechnical modeling for Seepage – at present thinking



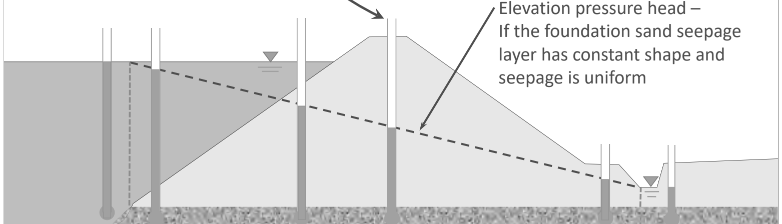
Generalize geology & geometry

Change a Seep/w computer model to "match field measured data":
1) With 1 piezometer "measurement" - it's possible to match field data.
2) Use 2 piezometer measurements - it's very hard to match field data.
3) Use several reservoir levels - a model can't be found.

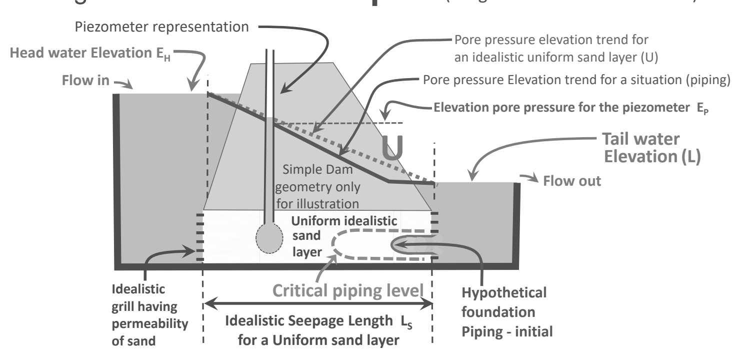
Generalizing seepage to see trends (for real projects)

Using Only One Piezometer for evaluation

We will concentrate on using only ONE piezometer from the crest

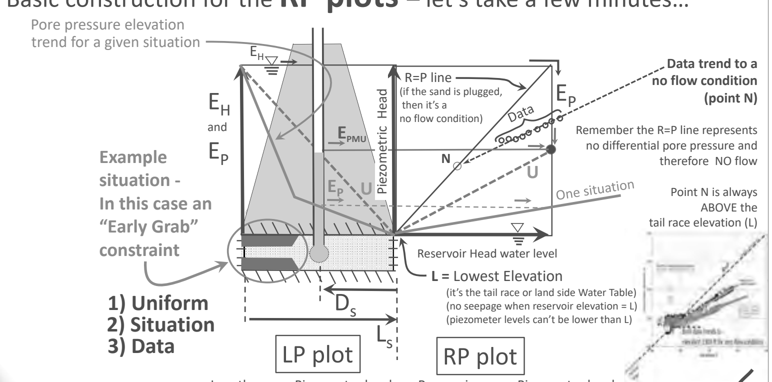


Defining Parameters for the **LP plot** (Length versus Piezometer level)

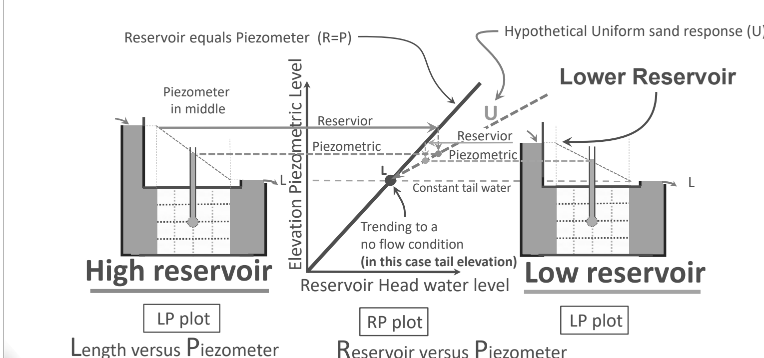


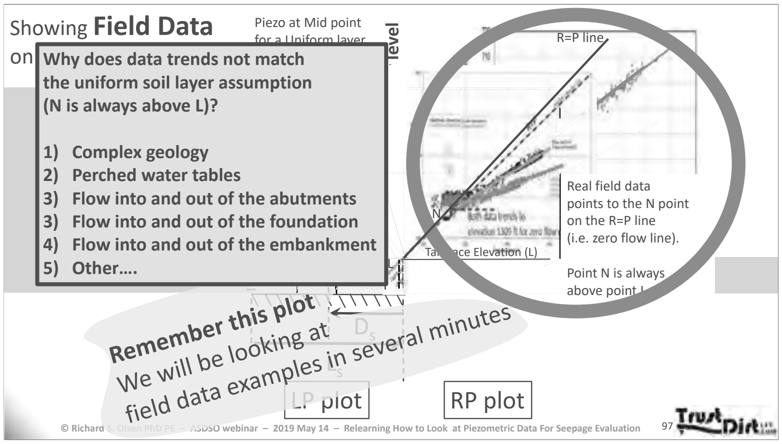
LP plot is **Length** of Seepage versus **Piezometer** level

Basic construction for the **RP plots** – let's take a few minutes…



Construction of the R-P trend line **"to a no flow"** condition




Showing Field Data
on
Piezo at Mid point
for a Uniform layer
level
Why does data trends not match
the uniform soil layer assumption
(N is always above L)?
1) Complex geology
2) Perched water tables
3) Flow into and out of the abutments
3) Flow into and out of the foundation
4) Flow into and out of the embankment
5) Other….
R=P line
N
Tailrace Elevation (L)
Real field data
points to the N point
on the R=P line
(i.e. zero flow line).
Point N is always
above point L
Remember this plot
We will be looking at
field data examples in several minutes
LP plot
RP plot
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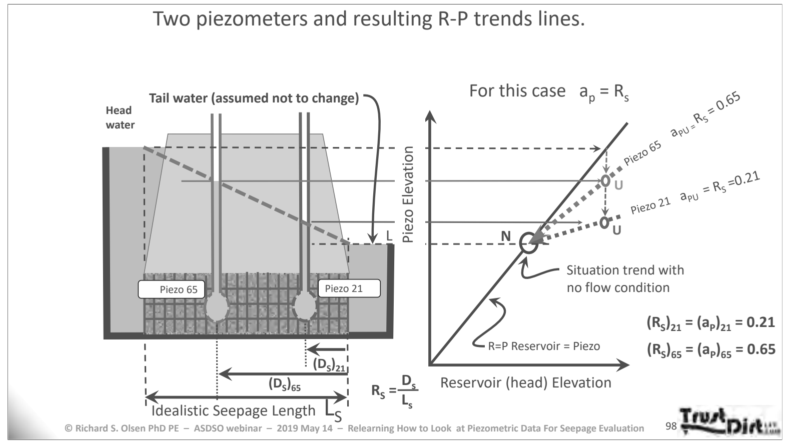
Two piezometers and resulting R-P trends lines.
Tail water (assumed not to change)
Head
water
For this case $a_p = R_s$
$a_{PU} = R_s = 0.65$
Piezo 65
Piezo 21
$a_{PU} = R_s = 0.21$
U
U
N
L
Piezo Elevation
Piezo 65
Piezo 21
Situation trend with
no flow condition
R=P Reservoir = Piezo
$(R_S)_{21} = (a_P)_{21} = 0.21$
$(R_S)_{65} = (a_P)_{65} = 0.65$
$(D_S)_{21}$
$(D_S)_{65}$
$R_S = \frac{D_s}{L_s}$
Idealistic Seepage Length L_S
Reservoir (head) Elevation
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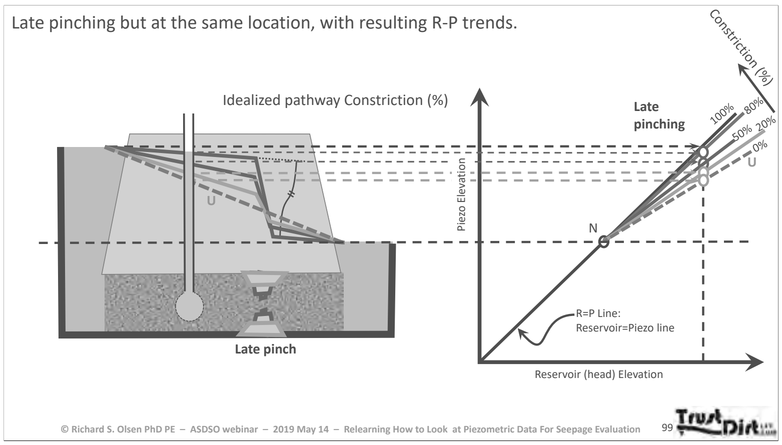
Late pinching but at the same location, with resulting R-P trends.
Constriction (%)
Idealized pathway Constriction (%)
Late
pinching
100%
80%
50%
20%
0%
U
U
Piezo Elevation
N
R=P Line:
Reservoir=Piezo line
Late pinch
Reservoir (head) Elevation
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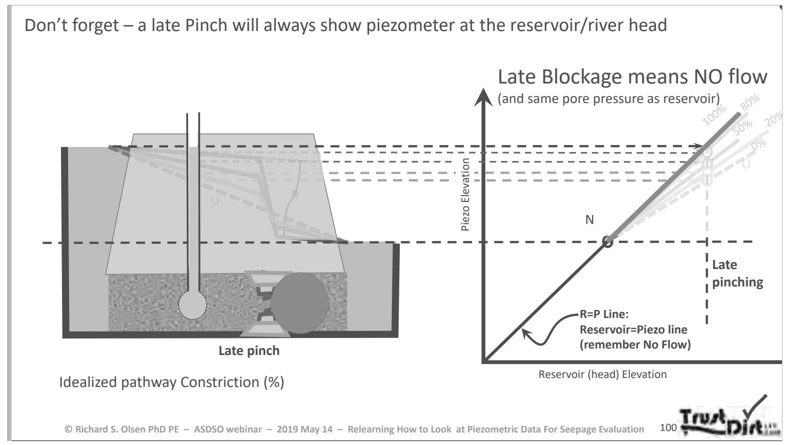
99


Don't forget – a late Pinch will always show piezometer at the reservoir/river head
Late Blockage means NO flow
(and same pore pressure as reservoir)
100%
80%
50%
20%
0%
U
Piezo Elevation
N
Late
pinching
R=P Line:
Reservoir=Piezo line
(remember No Flow)
Late pinch
Idealized pathway Constriction (%)
Reservoir (head) Elevation
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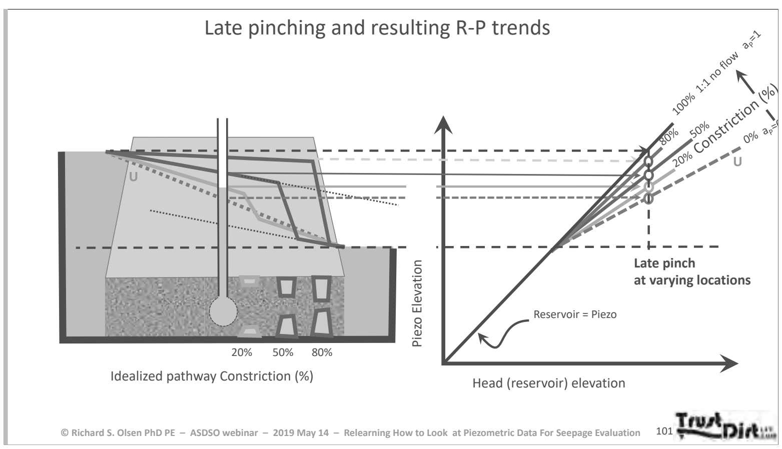
100


Late pinching and resulting R-P trends
100% 1:1 no flow a_p=1
80%
50%
20%
0%
Constriction (%)
U
U
Late pinch
at varying locations
Piezo Elevation
Reservoir = Piezo
20%
50%
80%
Idealized pathway Constriction (%)
Head (reservoir) elevation
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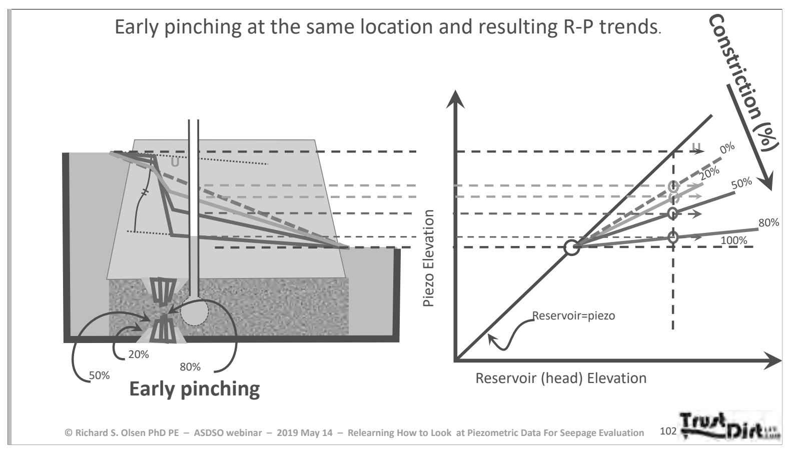
101


Early pinching at the same location and resulting R-P trends.
Constriction (%)
U
U
0%
20%
50%
80%
100%
Piezo Elevation
Reservoir=piezo
20%
50%
80%
Early pinching
Reservoir (head) Elevation
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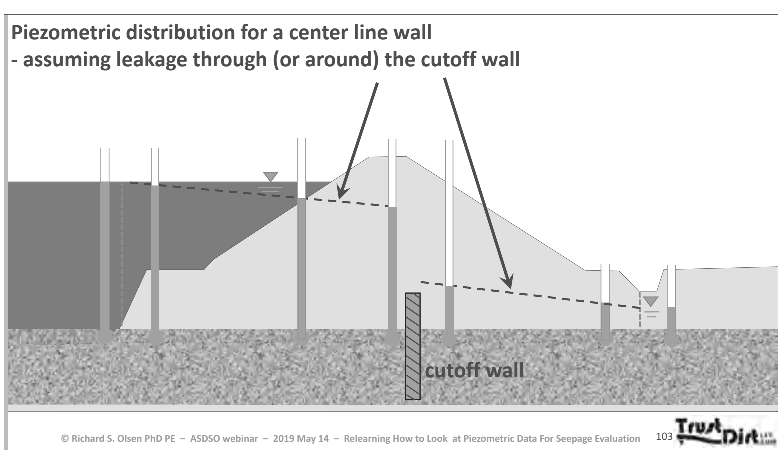
102


Piezometric distribution for a center line wall
- assuming leakage through (or around) the cutoff wall
cutoff wall
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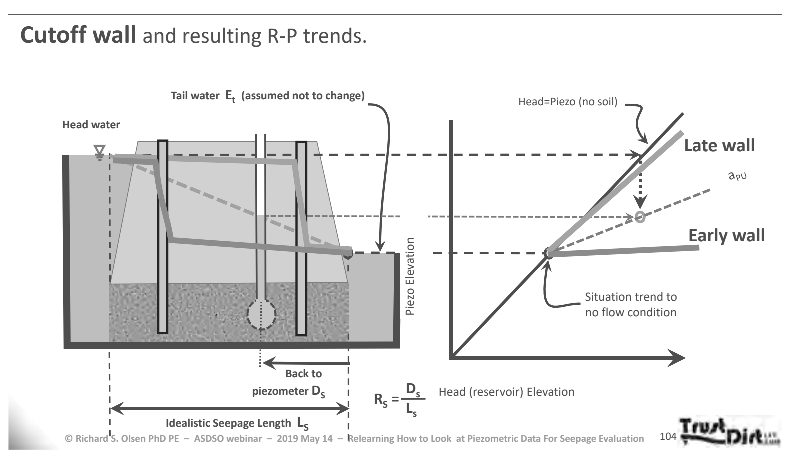
103


Cutoff wall and resulting R-P trends.
Tail water E_t (assumed not to change)
Head water
Head=Piezo (no soil)
Late wall
a_{PU}
Early wall
Piezo Elevation
Situation trend to
no flow condition
Back to
piezometer D_S
$R_S = \frac{D_s}{L_s}$
Head (reservoir) Elevation
Idealistic Seepage Length L_S
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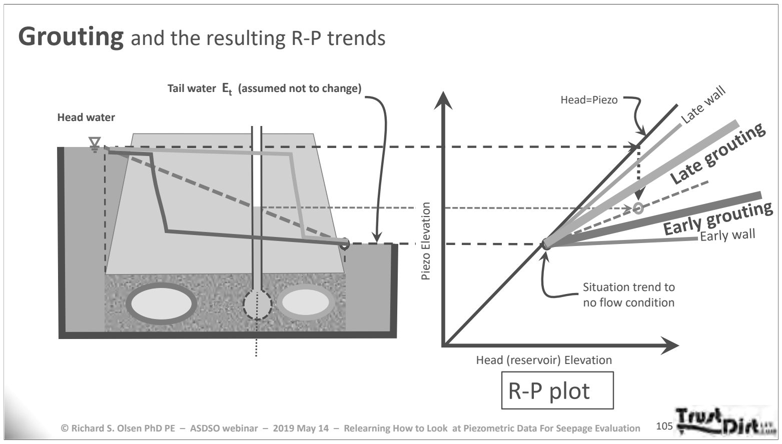
104


Grouting and the resulting R-P trends
Tail water E_t (assumed not to change)
Head water
Head=Piezo
Late wall
Late grouting
Early grouting
Early wall
Piezo Elevation
Situation trend to no flow condition
Head (reservoir) Elevation
R-P plot
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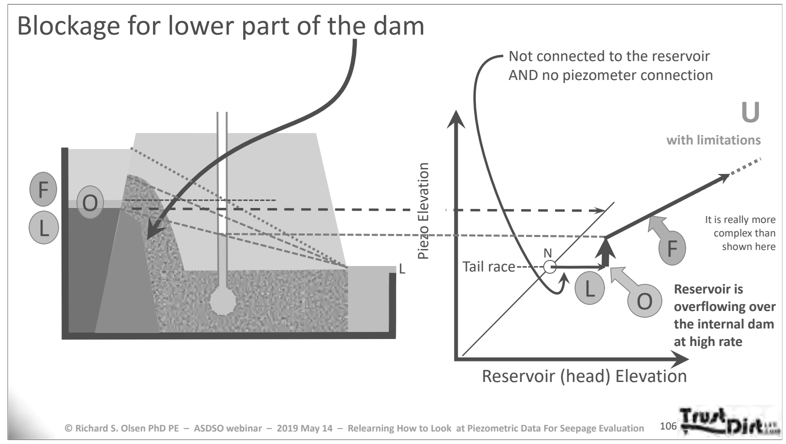
105


Blockage for lower part of the dam
Not connected to the reservoir
AND no piezometer connection
U
with limitations
F
O
L
Piezo Elevation
It is really more complex than shown here
N
Tail race
Reservoir is overflowing over the internal dam at high rate
Reservoir (head) Elevation
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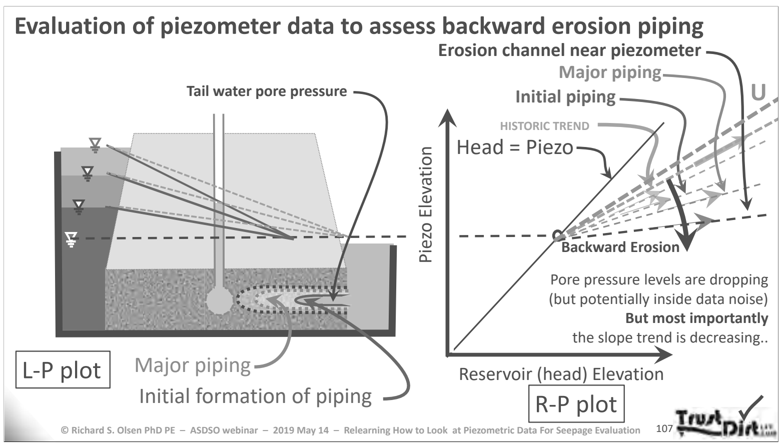
Evaluation of piezometer data to assess backward erosion piping
Erosion channel near piezometer
Major piping
Initial piping
U
Tail water pore pressure
HISTORIC TREND
Head = Piezo
Piezo Elevation
Backward Erosion
Pore pressure levels are dropping
(but potentially inside data noise)
But most importantly
the slope trend is decreasing..
L-P plot
Major piping
Initial formation of piping
Reservoir (head) Elevation
R-P plot
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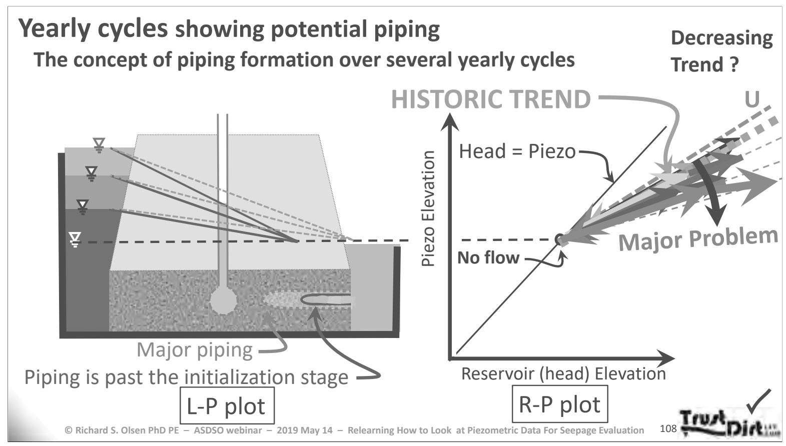
Yearly cycles showing potential piping
The concept of piping formation over several yearly cycles
Decreasing Trend ?
HISTORIC TREND
U
Head = Piezo
Piezo Elevation
No flow
Major Problem
Major piping
Piping is past the initialization stage
Reservoir (head) Elevation
L-P plot
R-P plot
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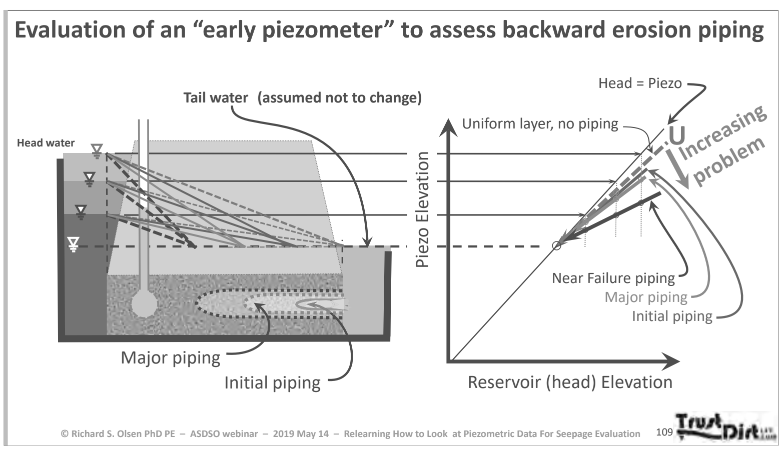
108


Evaluation of an "early piezometer" to assess backward erosion piping
Head = Piezo
Tail water (assumed not to change)
Uniform layer, no piping
U
Increasing problem
Head water
Piezo Elevation
Near Failure piping
Major piping
Initial piping
Major piping
Initial piping
Reservoir (head) Elevation
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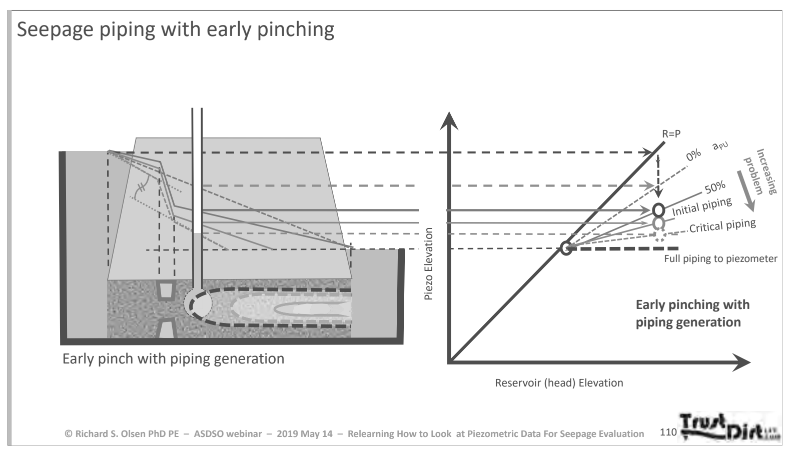
109


Seepage piping with early pinching
R=P
0%
50%
Increasing problem
Initial piping
Critical piping
Full piping to piezometer
Piezo Elevation
Early pinching with piping generation
Early pinch with piping generation
Reservoir (head) Elevation
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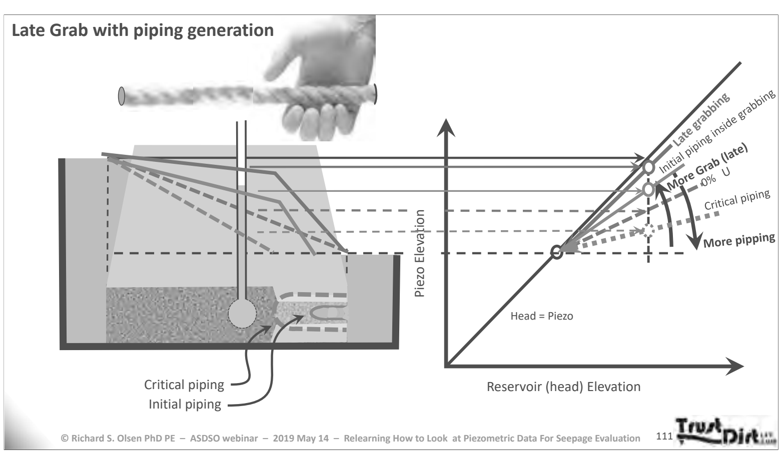
Late Grab with piping generation
Late grabbing
Initial piping inside grabbing
More Grab (late)
0% U
Critical piping
More pipping
Piezo Elevation
Head = Piezo
Critical piping
Initial piping
Reservoir (head) Elevation
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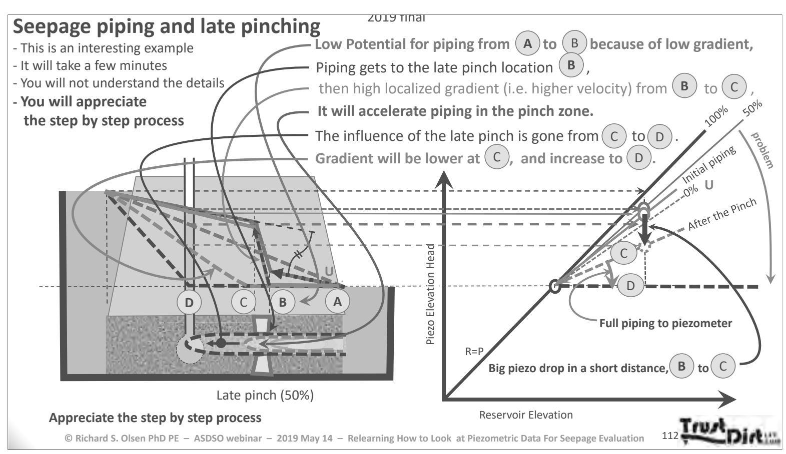
Seepage piping and late pinching
2019 final
- This is an interesting example
- It will take a few minutes
- You will not understand the details
- You will appreciate the step by step process
Low Potential for piping from A to B because of low gradient,
Piping gets to the late pinch location B,
then high localized gradient (i.e. higher velocity) from B to C,
It will accelerate piping in the pinch zone.
The influence of the late pinch is gone from C to D.
Gradient will be lower at C, and increase to D.
100%
50%
problem
Initial piping
0% U
After the Pinch
D C B A
U
C
D
Piezo Elevation Head
Full piping to piezometer
R=P
Big piezo drop in a short distance, B to C
Late pinch (50%)
Reservoir Elevation
Appreciate the step by step process
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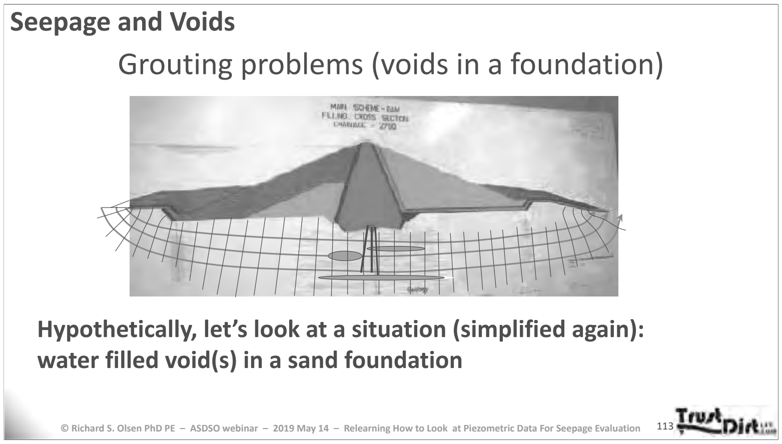
Seepage and Voids
Grouting problems (voids in a foundation)
Hypothetically, let's look at a situation (simplified again):
water filled void(s) in a sand foundation
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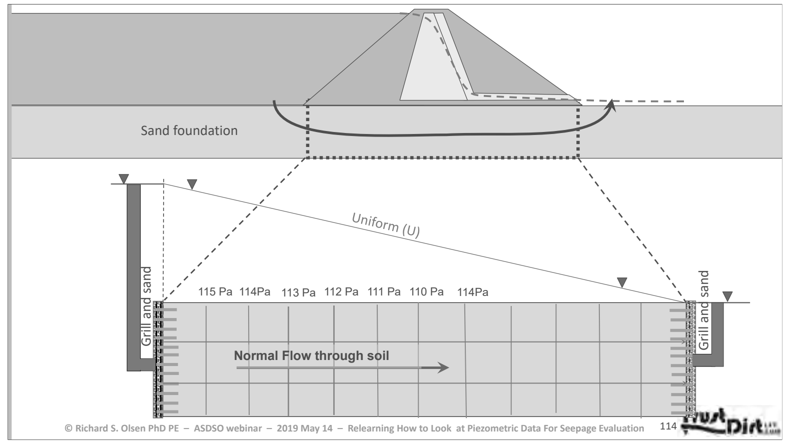
Sand foundation
Uniform (U)
Grill and sand
115 Pa
114Pa
113 Pa
112 Pa
111 Pa
110 Pa
114Pa
Normal Flow through soil
Grill and sand
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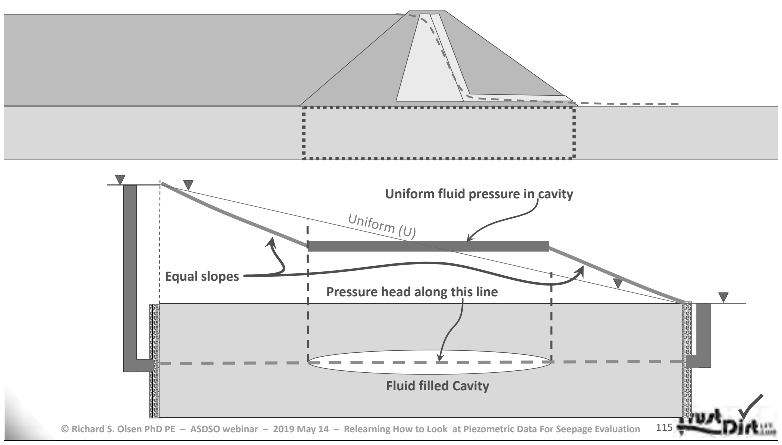
Uniform fluid pressure in cavity
Uniform (U)
Equal slopes
Pressure head along this line
Fluid filled Cavity
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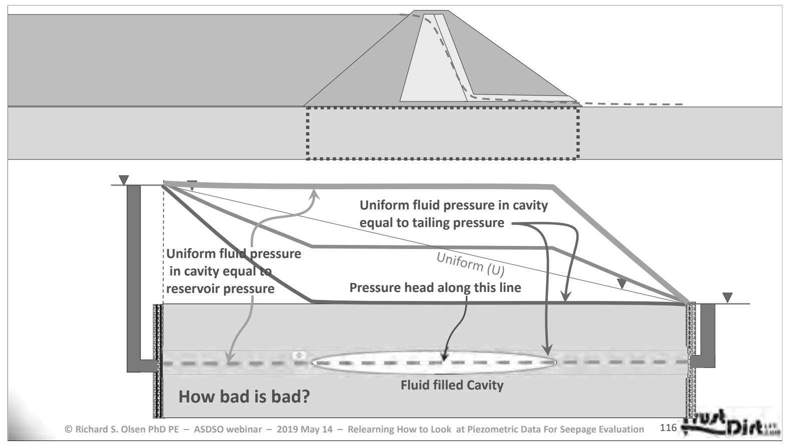
Uniform fluid pressure in cavity
equal to tailing pressure
Uniform fluid pressure
in cavity equal to
reservoir pressure
Uniform (U)
Pressure head along this line
How bad is bad?
Fluid filled Cavity
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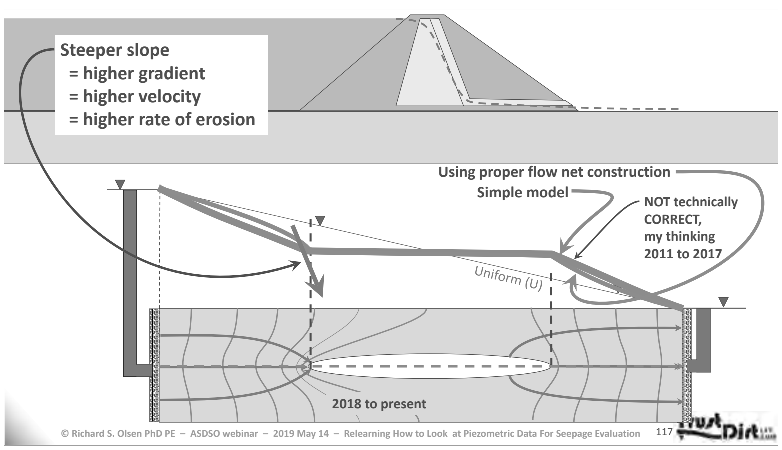
Steeper slope
= higher gradient
= higher velocity
= higher rate of erosion
Using proper flow net construction
Simple model
NOT technically
CORRECT,
my thinking
2011 to 2017
Uniform (U)
2018 to present
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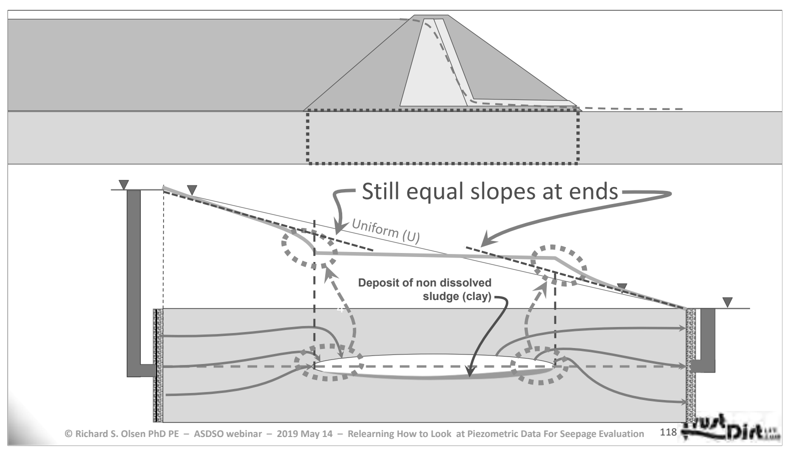
117


Still equal slopes at ends
Uniform (U)
Deposit of non dissolved
sludge (clay)
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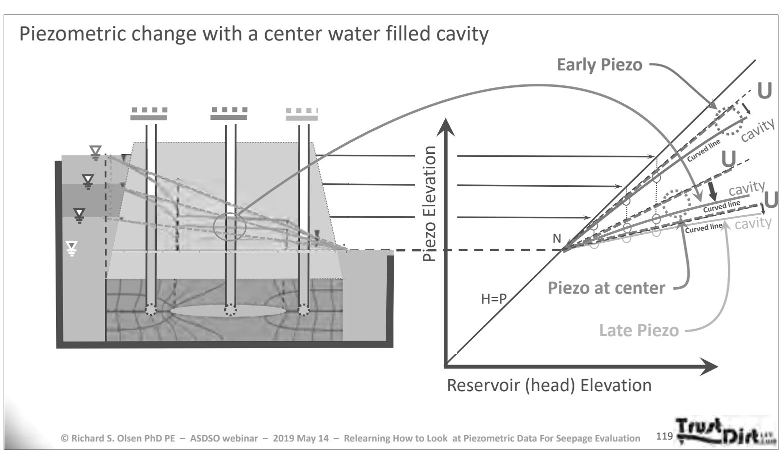
Piezometric change with a center water filled cavity
Early Piezo
U
cavity
U
cavity
U
cavity
Curved line
Curved line
Curved line
Piezo Elevation
N
H=P
Piezo at center
Late Piezo
Reservoir (head) Elevation
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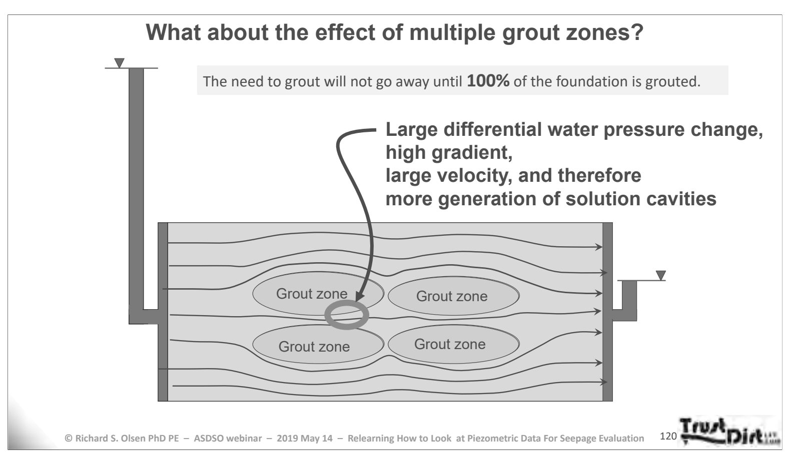
What about the effect of multiple grout zones?
The need to grout will not go away until 100% of the foundation is grouted.
Large differential water pressure change,
high gradient,
large velocity, and therefore
more generation of solution cavities
Grout zone
Grout zone
Grout zone
Grout zone
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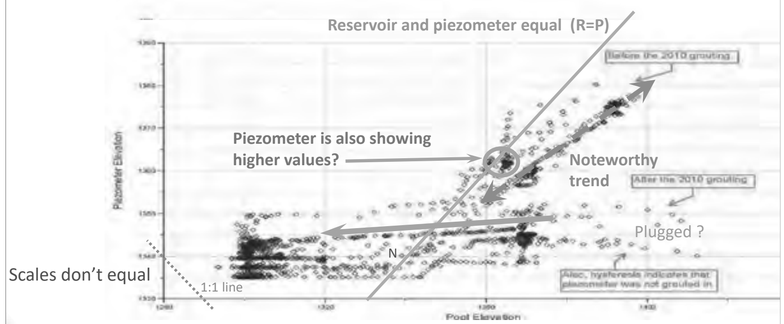
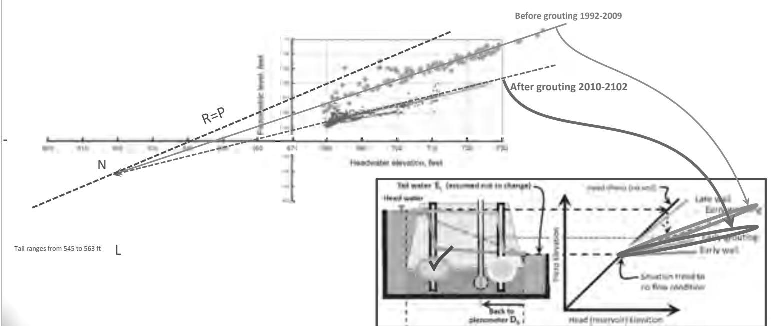
Examples of Field Measured Piezometer Data

Field Piezometer Data 1

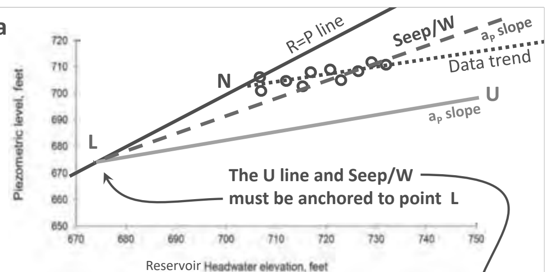


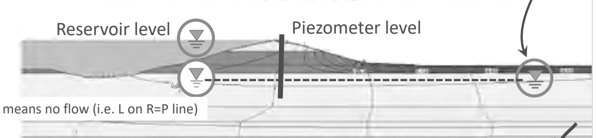
Field Piezometer Data 2



Seep/W to field data

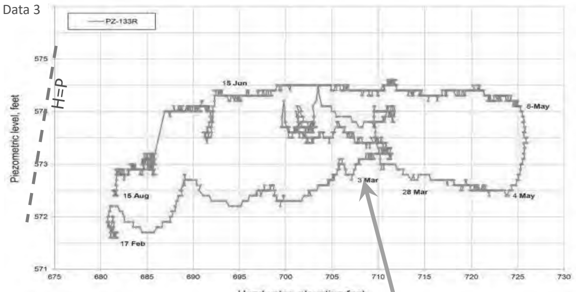
Seepage computer modeling can not match ALL reservoir levels



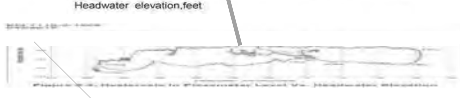


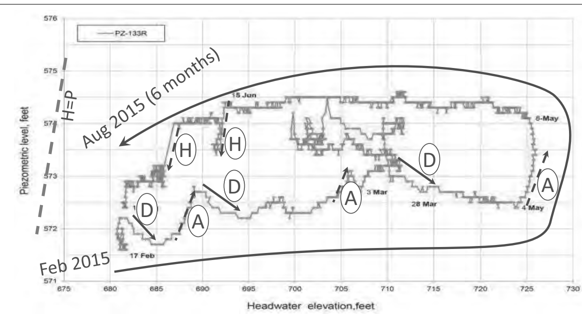
No differential pore pressure means no flow (i.e. L on R=P line)

Field Piezometer Data 3

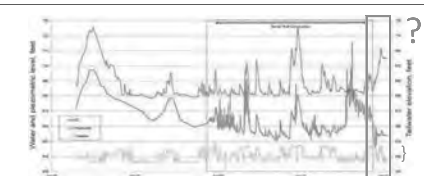


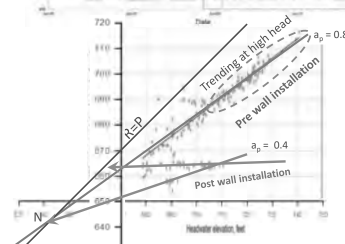
You can't see interesting detail at a 1:1 scale





Field Piezometer Data 4

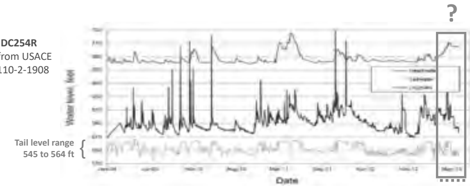


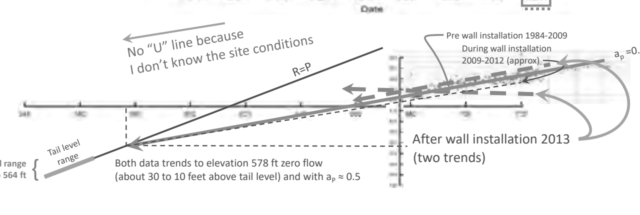


Data from USACE EM 1110-2-1908

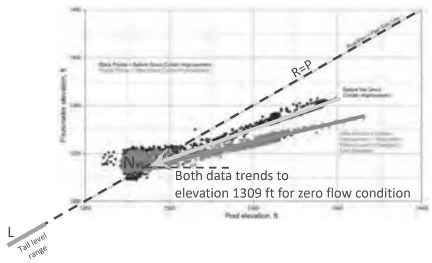
Field Piezometer Data 5

Piezo DC254R
Data from USACE
EM 1110-2-1908





Field Piezometer Data 6

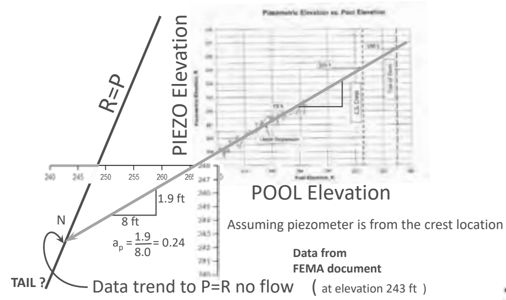


Field Piezometer Data 7

Data example from **FEMA** manual to determine the zero flow condition

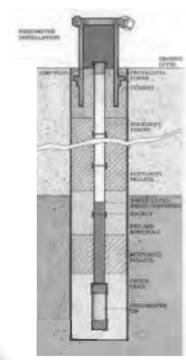
$$\text{Net head dissipated (NHD)} = \frac{\text{Reservoir elevation} - \text{Piezometric elevation}}{\text{Reservoir elevation} - \text{Tailwater elevation}}$$

FEMA manual (2013) use of a New Ratio – got me started looking at a graphical solution



Measuring Pore Pressure

Measuring pore pressure and Piezometers

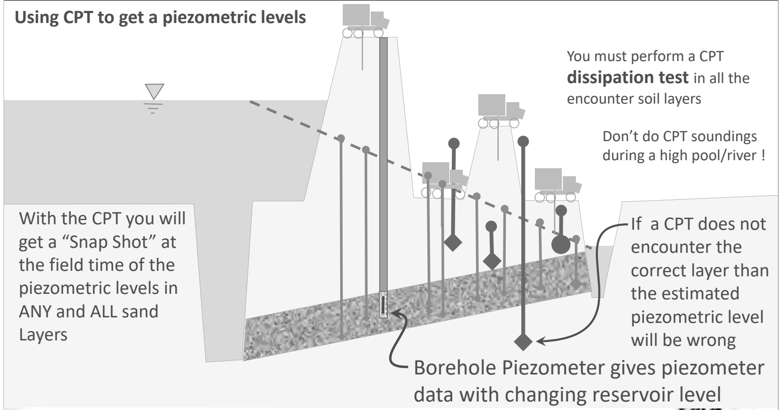


When we think about measuring pore pressure we think about bore hole based piezometers

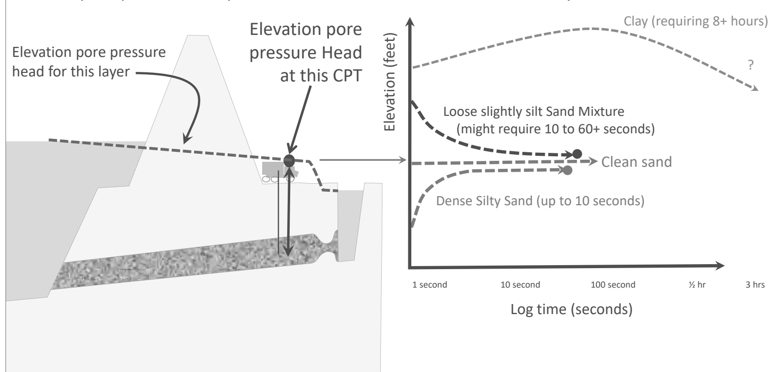
This is the best approach for long term monitoring of pore pressure.

But the CPT can provide stratigraphy and also piezometer measurements of MULTIPLE SAND LAYERS at the time of the field investigation

Using CPT to get a piezometric levels

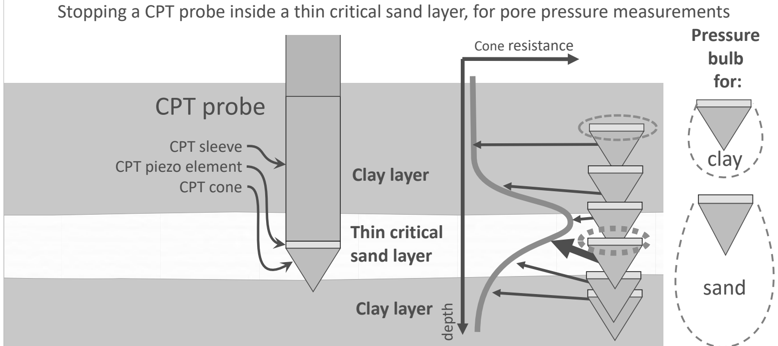


Use CPT pore pressure dissipation to ensure that the test is in a sand layer

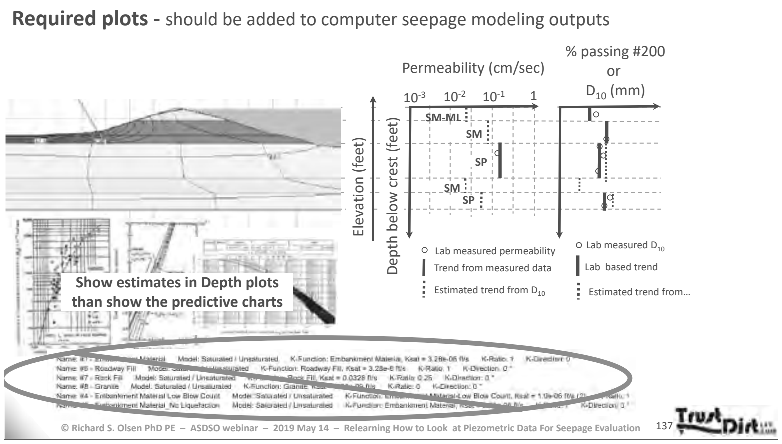


Measuring pore pressured in thin sand layers using the CPT

Stopping a CPT probe inside a thin critical sand layer, for pore pressure measurements



Data Plotting Standards


Required plots - should be added to computer seepage modeling outputs
Permeability (cm/sec)
% passing #200
or
D_{10} (mm)
10^{-3} 10^{-2} 10^{-1} 1
SM-ML
SM
SP
SM
SP
Elevation (feet)
Depth below crest (feet)
Lab measured permeability
Trend from measured data
Estimated trend from D_{10}
Lab measured D_{10}
Lab based trend
Estimated trend from…
Show estimates in Depth plots
than show the predictive charts
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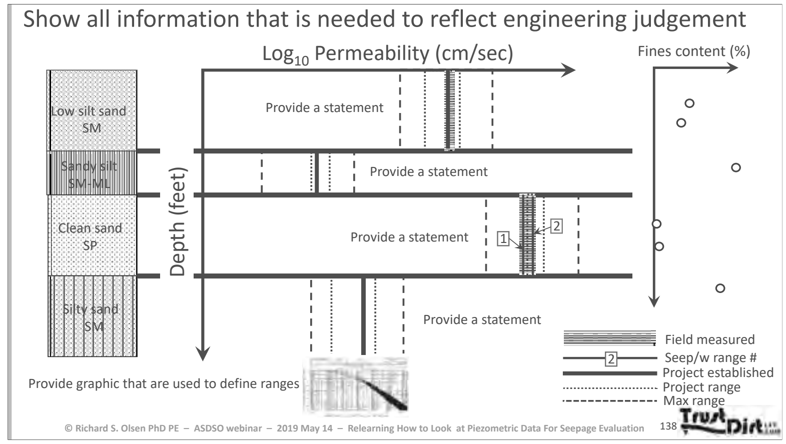
Show all information that is needed to reflect engineering judgement
Log_{10} Permeability (cm/sec)
Fines content (%)
Low silt sand
SM
Sandy silt
SM-ML
Clean sand
SP
Silty sand
SM
Depth (feet)
Provide a statement
Provide a statement
Provide a statement
Provide a statement
1
2
Provide graphic that are used to define ranges
Field measured
Seep/w range #
Project established
Project range
Max range
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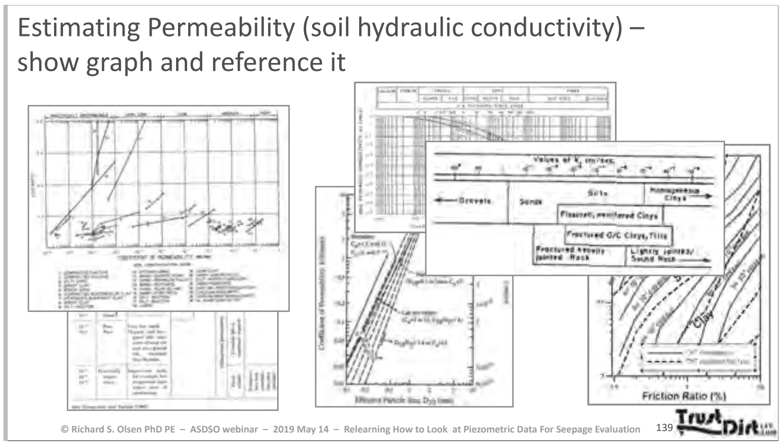
Estimating Permeability (soil hydraulic conductivity) –
show graph and reference it
Gravels
Sands
Silts
Fissured, weathered Clays
Fractured O/C Clays, Tills
Friction Ratio (%)
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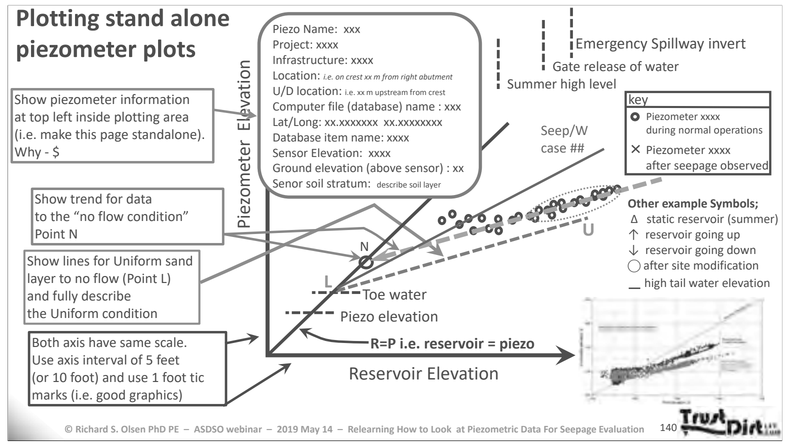
Plotting stand alone piezometer plots
Piezo Name: xxx
Project: xxxx
Infrastructure: xxxx
Location: i.e. on crest xx m from right abutment
U/D location: i.e. xx m upstream from crest
Computer file (database) name : xxx
Lat/Long: xx.xxxxxxx xx.xxxxxxxx
Database item name: xxxx
Sensor Elevation: xxxx
Ground elevation (above sensor) : xx
Senor soil stratum: describe soil layer
Emergency Spillway invert
Gate release of water
Summer high level
Show piezometer information at top left inside plotting area (i.e. make this page standalone). Why - $
Seep/W case ##
key
Piezometer xxxx during normal operations
Piezometer xxxx after seepage observed
Other example Symbols;
static reservoir (summer)
reservoir going up
reservoir going down
after site modification
high tail water elevation
Show trend for data to the "no flow condition" Point N
Show lines for Uniform sand layer to no flow (Point L) and fully describe the Uniform condition
Both axis have same scale. Use axis interval of 5 feet (or 10 foot) and use 1 foot tic marks (i.e. good graphics)
Piezometer Elevation
N
L
U
Toe water
Piezo elevation
R=P i.e. reservoir = piezo
Reservoir Elevation
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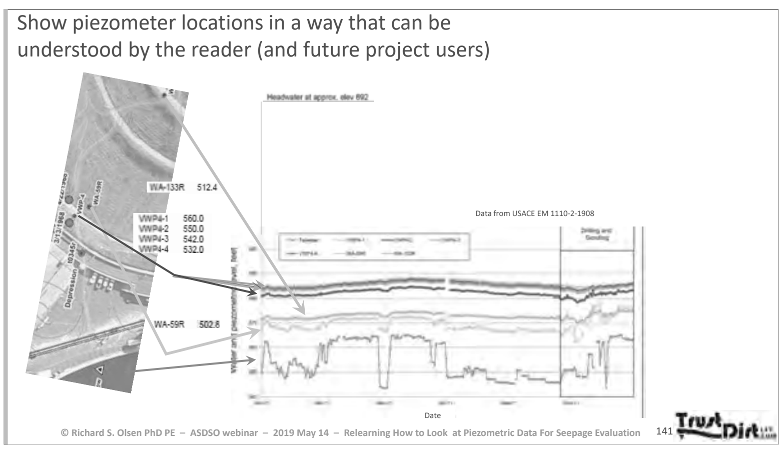
Show piezometer locations in a way that can be
understood by the reader (and future project users)
Headwater at approx. elev 692
WA-133R 512.4
VWP4-1 560.0
VWP4-2 550.0
VWP4-3 542.0
VWP4-4 532.0
WA-59R 502.8
Data from USACE EM 1110-2-1908
Date
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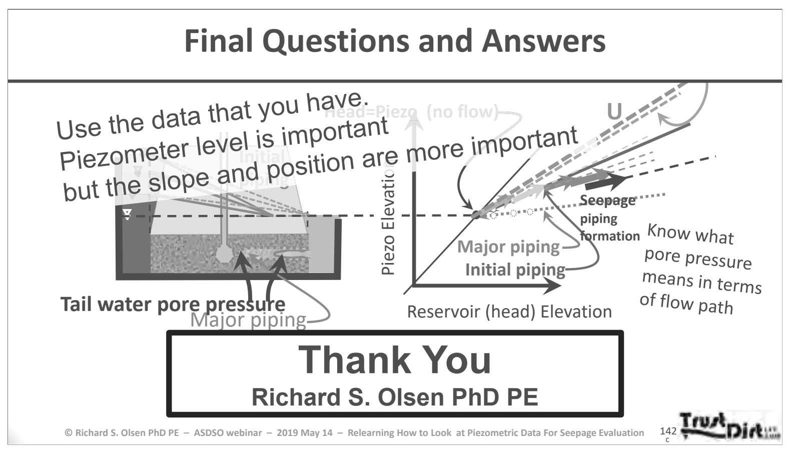
Final Questions and Answers
Use the data that you have.
Piezometer level is important
but the slope and position are more important
Head=Piezo (no flow)
U
Seepage piping formation
Major piping
Initial piping
Know what pore pressure means in terms of flow path
Piezo Elevation
Reservoir (head) Elevation
Tail water pore pressure
Major piping
Thank You
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