RELEARNING HOW TO LOOK AT PIEZOMETRIC DATA FOR SEEPAGE EVALUATION

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ABSTRACT

Examining field piezometric data from earth dams provides the direct link to understand seepage flow and potential seepage related problems. However, there are several issues that must be overcome to achieve optimum evaluation. The first issue is that field measured piezometric data are typically plotted in ways that can't illustrate seepage problems. A new method for plotting piezometer data versus reservoir level is introduced that can be used as a tool when evaluating piezometric data for situations ranging from foundation layer obstructions to formation of seepage piping.

INTRODUCTION

Pore pressure, seepage and their resulting effects are the number one issues influencing dam safety in terms of geotechnical engineering. Examining field piezometric data from earth dams provides the direct link to understand seepage flow and potential seepage related problems. Seepage problems can be high pore uplift pressures, soil piping (and pipe channel) generation, decreased strength for granular soils due to high pore pressure, etc.

There are several piezometric issues that must be overcome to achieve optimum evaluation. The first issue is that field measured piezometric data is typically plotted in ways that can't illustrate seepage problems. Another issue is that computer based seepage modeling today is too often the first (and also the only) step for evaluating observed piezometric data or to predict seepage behavior.

There are many requirements to lessen the potential for seepage issues at a dam, such as; to have (and follow) a technical dam safety program, require regular field inspections (with qualified inspectors) together with field personnel trained to recognize abnormal behavior, monitoring field installed instruments (such as piezometers, inclinometers, settlement markers, pressure cells, etc), evaluate field measured data, and finally to have an emergency action plan in case of problems. This paper will focus on issues related to evaluating piezometers, generally installed from the crest of an earthen dam and into a foundation sand layer.

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Unexpected seepage observed at the soil ground surface is the most direct indicator that seepage (and associated seepage velocities) may have generated underground cavities and/or piping holes. Regardless of the cause of seepage, it is a response to a problem that can escalate from a warning sign to a dangerous dam stability issue very quickly. Geotechnical engineers don't directly measure seepage flow in situ nor can we directly measure the generation of a water filled cavity (or seepage piping). Our best approach is to measure pore pressures inside critical soil layers and study the data using a wide range of evaluation tools.

BASICS OF SEEPAGE

Civil engineering departments at universities have taught seepage evaluation theory for over a hundred years. Teaching seepage concepts in the early 1900s started as over-generalized closed form equations (based only on Darcy's theory), then in the 1950s in terms of how-to make flow nets, and finally in the last 20+ years toward computer based seepage modeling. Civil engineering students today are taught basic seepage theory, then how to hand draw flow nets, and finally how to run computer seepage modeling software. Theory and hand drawn flow nets seem to be forgotten by the time the student becomes a mature practicing engineer.

Geotechnical engineers working with water control structures need to understand seepage concepts beyond what is taught at the graduate level. Many additional seepage concepts are important to understand, such as early/late pinching, leakage influence, flow/static differences, permeability independences, etc. This paper describes methods for basic data evaluation and plotting of piezometer data.

Seepage is defined as water flowing through soil generating a differential pore pressure condition. For this discussion, the driving pore pressure is the reservoir water level (head) and the lower pore pressure is potentially the tail water level. The tail water can also be a perched water level inside an earth dam or foundation inside the downstream embankment of an earth dam, or a ground water table in the natural soil abutment of a dam.

This paper describes a new procedure for pore pressure evaluation. Field measured piezometric data is today typically plotted in ways that can't illustrate seepage problems. The plotted slope (and intersection) of reservoir level versus piezometric level data provides important insight to infer seepage related performance.

We, as a profession, have no basic procedures for visualization of piezometric data. We understand that high pore pressures in the foundation along a downstream section of an embankment are bad, but assume that seepage computer modeling will provide the answers. We generally have little knowledge about how to set up acceptable piezometric trends – we therefore have difficulty selecting piezometric trends that would indicate a red flag condition.

SEEPAGE EVALUATION

Seepage (or water flow through soil) is simply caused by a water pore pressure drop between two points in the ground (called pore pressure differential) as shown in Figure 1. The pore pressure differential is caused by high reservoir pore pressure (also called the head level) on the left to the low water pressure on the right side (termed tailwater level). Therefore, differential head (i.e. decrease pore pressure along a seepage length) causes water flow. The soil path can be idealized as a simple pipe as shown representing a uniform thickness soil layer with an unchanging shape from left to right. Pore pressure at any point along the soil path will decrease as illustrated with the four measurement points: each measurement point has an equivalent water level in a water standpipe. Equivalent water level is also illustrated in the figure with a water well standpipe. The pore pressure can be defined either as a gauge pore pressure or as an elevation pore pressure. Gauge pore pressure is simply the pore pressure measured at a point. Elevation pore pressure is an important property in seepage evaluation and is the elevation level of the equivalent standpipe water level. In all cases the head, tail, and piezometers are reported as the elevation of the water level, and in the case of the piezometer as the elevation water level in a represented standpipe with the sensor tip inside a critical sand layer.

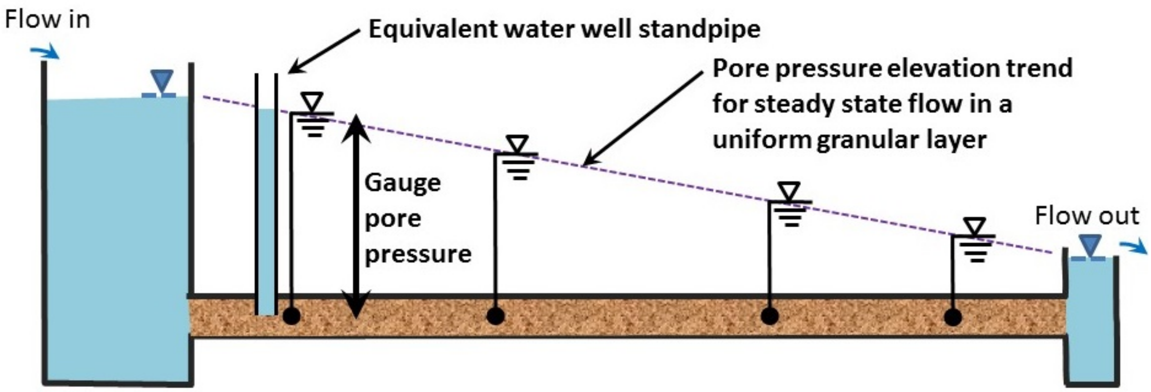


Figure 1. Pore pressure for an equivalent sand layer

Seepage velocity (or velocity of water in soil) is defined by Darcy's law using two parameters; soil permeability (which is related to soil type) and pore pressure differential. The only difference between sand and gravel in Figure 2 is water velocity. While the water flow velocity is much greater for gravel, compared to sand, the trend of elevation pore pressure from head to tail is identical. Therefore, sand/gravel type does not change the shape of the elevation pore pressure trend – This idealized soil pipe is soil type independent as long as the soil type remains constant. Also, pipe dimensions (vertical and width) are also independent as long as the vertical shape is constant from the head water level to tailwater (or equivalent) level.

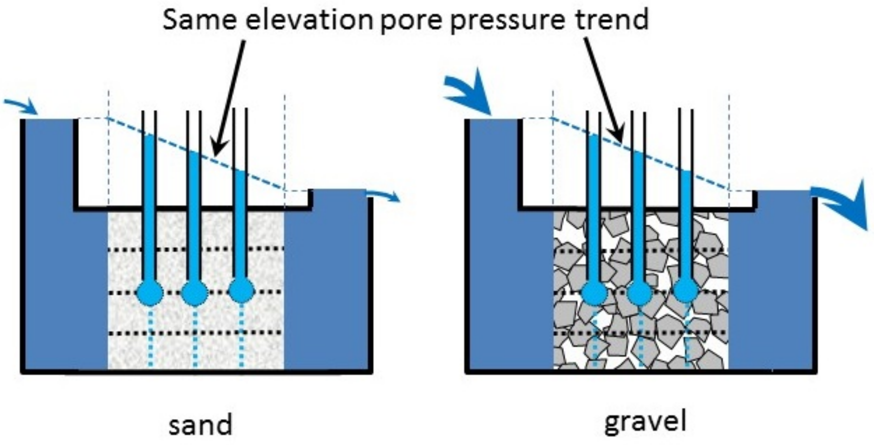


Figure 2. Comparison of pore pressure trend for sand and gravel layers

If the water flow path is blocked then seepage stops and there is no decrease in pore pressure due to seepage flow. No flow is because the pore pressure remains constant and equal to the head pressure. As shown in Figure 3, if there is no change in water pore pressure between two lateral points (i.e. no decrease in pore pressure) then there is no water flow – Seepage flow can only occur when there is differential pore pressure.

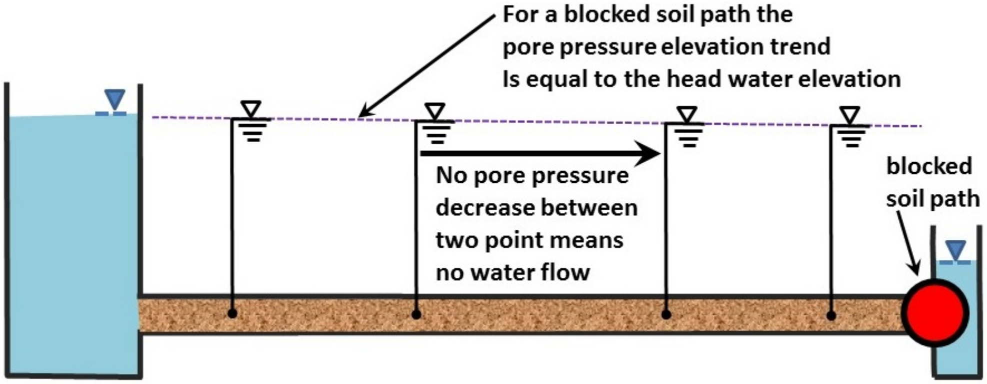


Figure 3. Pore pressure response for a blocked sand layer.

SEEPAGE NETS

Seepage flow nets have been a fundamental part of geotechnical engineering for at least 50 years. There are several basic behaviors for all seepage flow nets, no flow boundaries, water ingress face, water exit face, flow lines (contours), equal potential elevation pore pressure contours and finally material characteristics. Clay layers can easily be considered boundaries when the primary seepage soil layer is clean sand – generally because this assumption does not change the answer.

Seepage in geotechnical engineering is classically described using flow nets as shown in Figure 4. Differential pore pressure is defined as ΔH. Water flow is along seepage lines and equal potential lines define contours of equal elevation pore pressure. In this example there are 8.3 equal potential elevation contours and 4 flow lines defining this flow net (i.e. 4 flow zones). A pore pressure loss equal to ΔH/8.3 occurs as seepage along a flow lines pass each equal potential line. Figure 5 illustrates the elevation pore pressure level (shown as purple) for each equal potential contour as the water flows from the entry location to the exit – in this case it’s difficult to see any curvature of elevation pore pressure. Figure 6 includes a cutoff wall into the foundation – the curvature of the plotted elevation potential line (in red) along the seepage path is more obvious. Also plotted, for illustration is the elevation potential line for the interface between the embankment and foundation (in yellow).

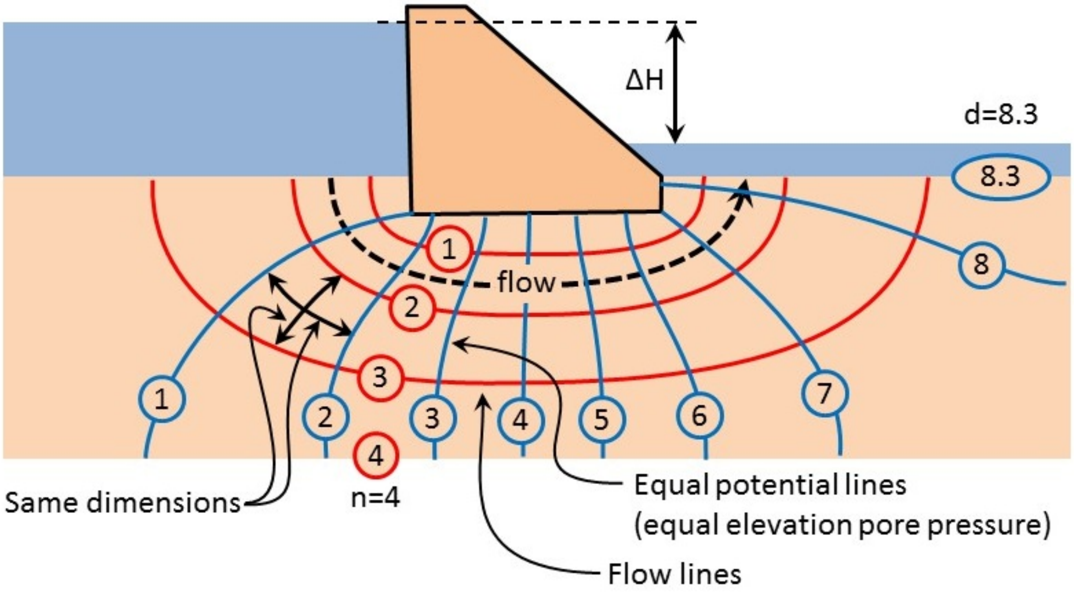


Figure 4. Simple flow net construction

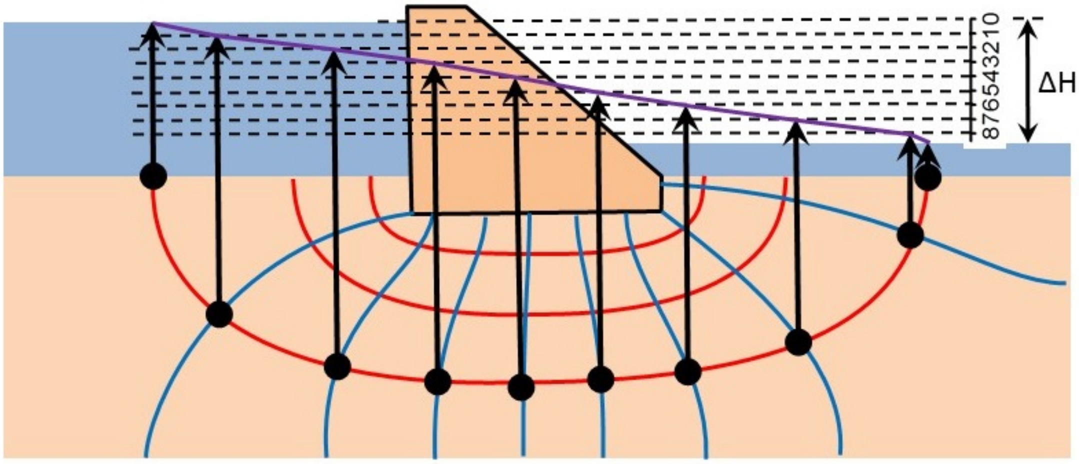


Figure 5. Determining elevation pore pressure along a flow line.

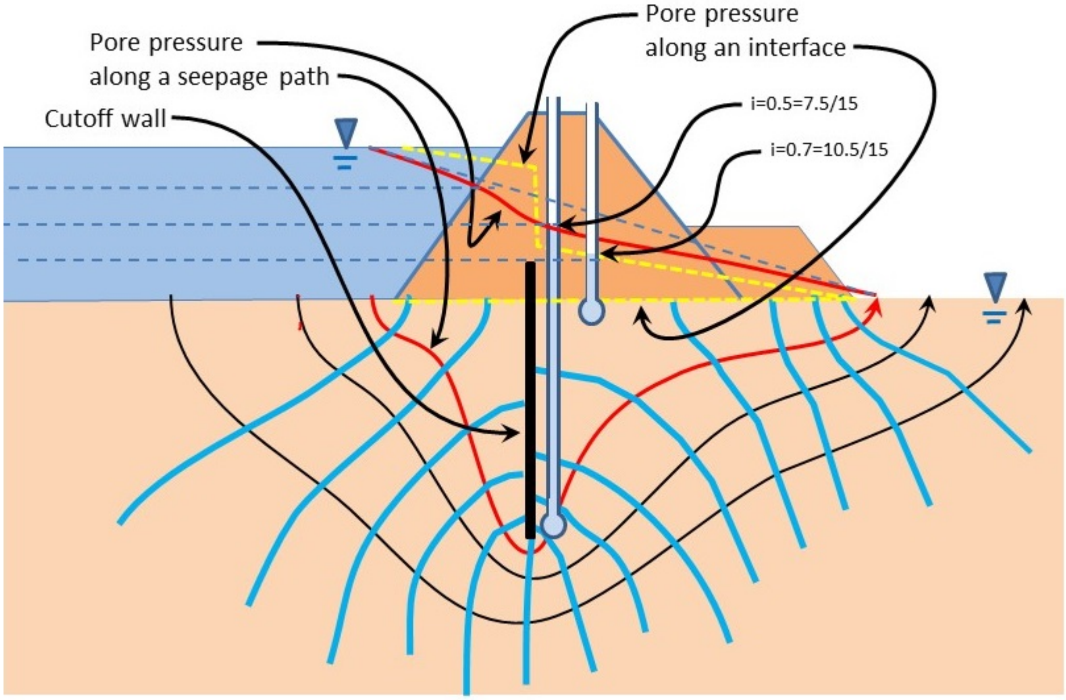
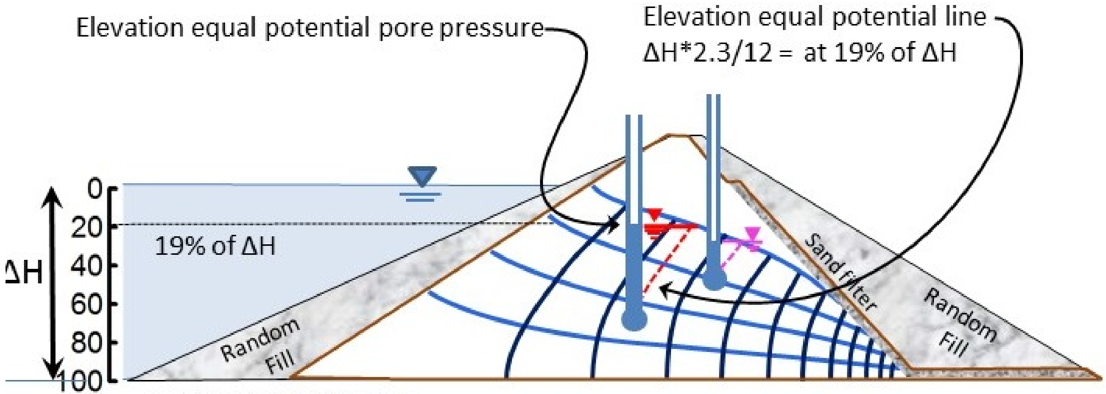


Figure 6. Elevation pore pressure for a complex flow net situation having a cutoff wall

Seepage through an earth dam core is shown in Figure 7 with flow lines, equal potential lines, and a free water table surface. The piezometer on the left has an equal elevation potential level equal to 19% loss of ΔH. The equal potential line for this piezometer intersects the free water table surface at an elevation pore pressure equal to 19% loss of the reservoir ΔH.



From USACE EM 1110-2-1908

Figure 7. Elevation pore pressure for piezometers in an earth dam clay core.

An equivalent soil pipe can also be represented using flow nets as shown in Figure 8. The slope of elevation pore pressure level versus location along the pipe is constant for any flow line and at any equal potential line.

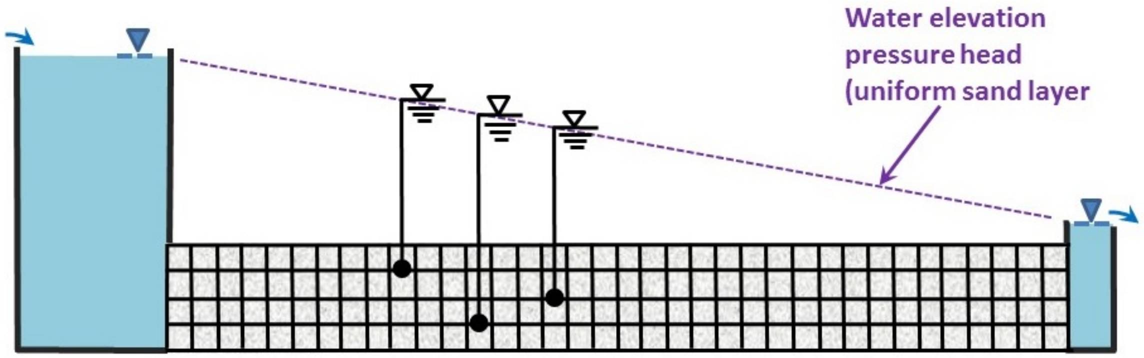


Figure 8. Flow nets representing an equivalent uniform sand layer

EARLY TO LATE PINCHING

Pinching is just as it sounds, there is some form of constriction of a uniform sand layer causing a change in pore pressure and velocity distribution along the seepage path. Pinching of the uniform sand layer in Figure 9 causes a change in the elevation pore pressure (red line) distribution. Specifically, pinching will cause higher pore pressures before the pinch and lower pore pressures after the pinch. The trend of elevation pore pressure with length for the initial zone (points H to P) is equal to the trend for the final zone (points B and T) because the equivalent pipe conditions are equal. In this case the "pinch" is at the middle of the equivalent pipe. Within the area of the pinch there is an increased trend of pore pressure loss with incremental length (ΔP/ΔL), between point P and B. The pinch is also causing a higher velocity flow rate (at point S) compared to initial and final zones (points H to P and points B to T). It should be noted that the volume flow (i.e. cm^3/sec) will decrease due to pinching compared to a uniform non-pinched condition. Figure 10 illustrates the individual calculations and elevation pore pressure values for a pinch at the midpoint. Note that the highest ΔP/ΔL trend is at the middle of the pinch having the smallest equivalent pipe size and largest seepage velocity.

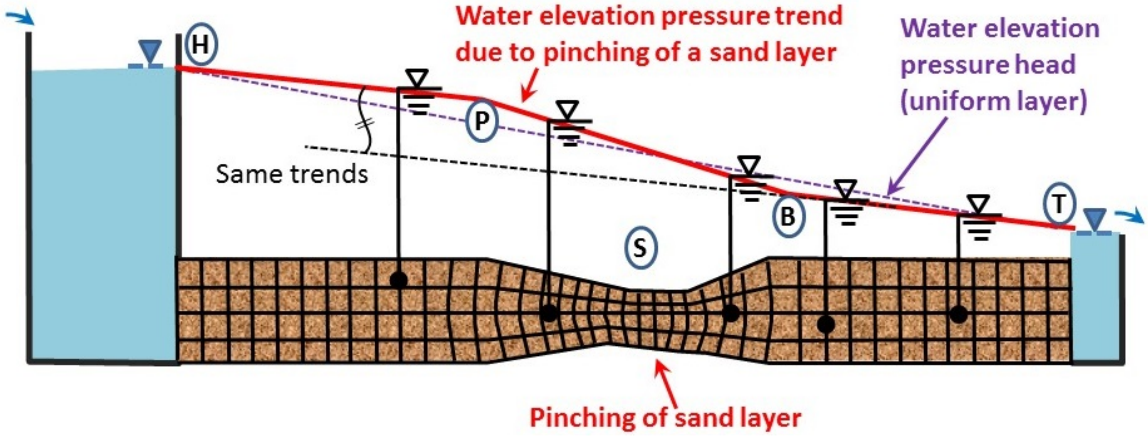


Figure 9. Defining a pinch condition in a uniform sand layer

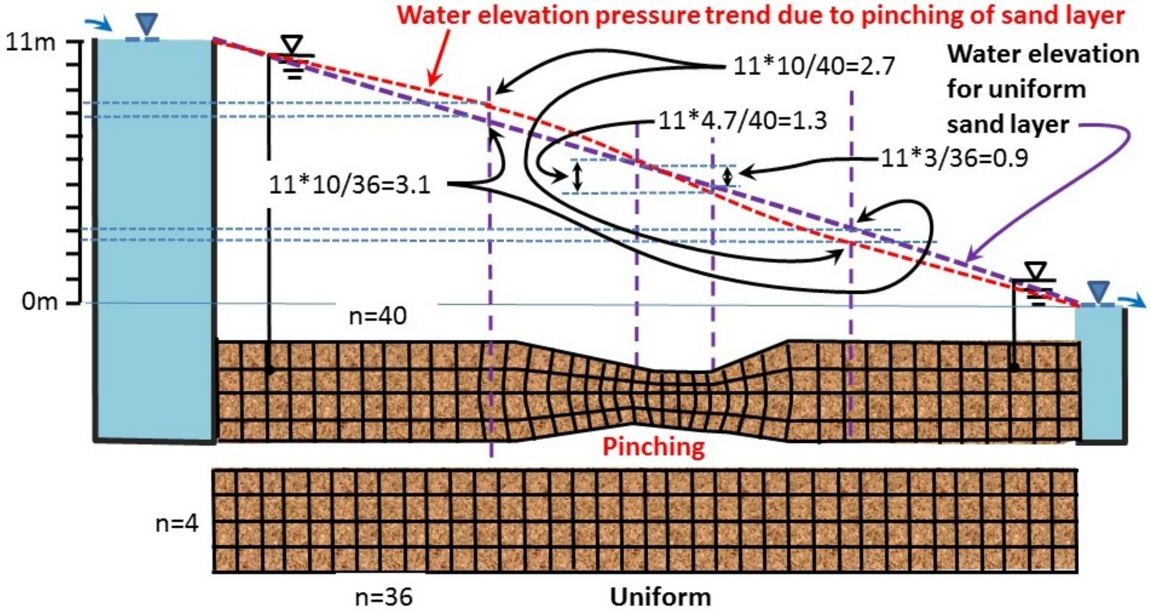


Figure 10. Details for pinching in a uniform sand layer.

RESERVOIR LEVEL/PIEZOMETER DATA PLOTTING METHOD

The main portion of this paper deals with methods for evaluating piezometric data from earth dams, generally obtained from piezometers installed from the crest. Most earth dams have crest based piezometers (into the foundation), maybe a few piezometers on benches at mid slope on the downstream side, and only a few dams have piezometers at the downstream slope toe. In many cases the only piezometer is located at the crest and there is very little information in publications about how to evaluate this data. Generally, the most basic evaluation approach is comparing the measured pore pressure to the reservoir level. When the pore pressure measurements are relatively close to the reservoir level (and there is no definition for “relatively”) there are several potential problems:

1) A void exists in the foundation between the reservoir and piezometer location, or
2) Blockage of the foundation layer between the crest and downstream toe, which if unblocked due to high differential pore pressure, could lead to seepage piping.

On the other hand, a low measured pore pressure could infer:

1) A void exists in the foundation between the piezometer location and downstream toe,
2) There is transient or unstable blockage in the foundation layer between the reservoir and crest, that if unblocked could lead to high differential pore pressure, and could lead to seepage piping.

The issue is that there are no procedures for evaluating these types of piezometer measurements, and modeling point measured pore pressures with computer seepage software has no value because there are so many unknowns.

Evaluating measured pore pressures from foundation piezometers installed from the crest is a very complex issue. The key is to initially assume a uniform foundation sand layer and then add simplistic constraints such as; late/early "pinching," late/early "grabbing," initial/critical generated seepage piping, and finally seepage cutoff wall construction. This paper will provide tools to evaluate how measured pore pressure can be influenced by layer constriction, which can occur due to seepage piping, and what to expect after seepage wall construction.

There are two commonly utilized methods for plotting piezometric data;
1) time history of measured piezometric data plots, and
2) reservoir level versus measured piezometric plots.
This paper will focus on the latter method. In previous sections of this paper the discussion focused on how piezometric pore pressure varies from the dam upstream toe to the downstream toe. In many cases with earth dams there is only a single piezometer installed at the crest. For the purposes of this paper the assumption will generally be:
1) there is only one installed piezometer, and
2) that the water level at the toe is constant.
There will be some discussion about more than one piezometer location (in the upstream to downstream direction) and about how the tailwater level can vary.

Figure 11 shows the visualization progression from field realistic to the final representative format of plotting that will be used for most of the remainder of this paper. Note that the sand layer is bounded by impermeable upper and lower boundaries.

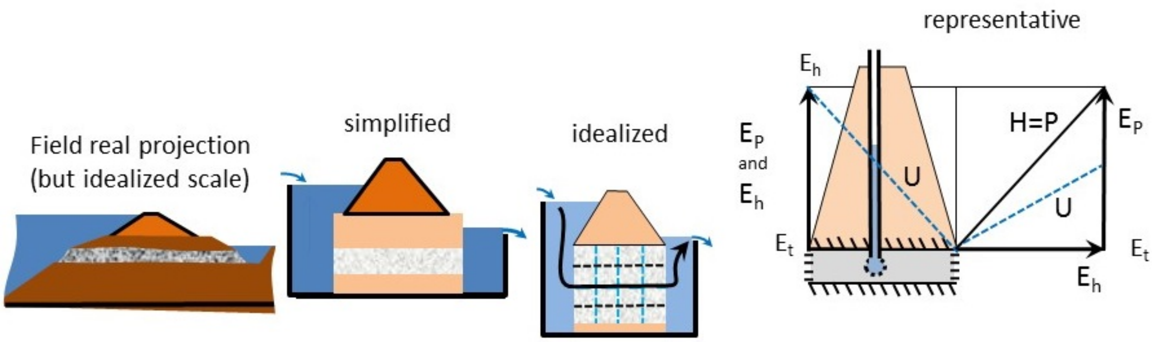


Figure 11. Visualization for changing from a field realistic to a representative section

Figure 12 illustrates the conventions that will be used in this paper. Specifically the different elevation values (E_H, E_T, E_S, and E_P) are standardized for all plots. Other parameters such as Seepage length (L_S), piezometer distance (or item of interest) offset from the tail end of the idealized sand seepage (D_s), and word description (i.e. Pore Pressure Elevation Trend) are defined. An over generalized piezometer is used throughout this paper to represent an elevation piezometer measurement (E_P) for a piezometer sensor elevation of E_P. Most plots will be over generalized representations of seepage flow through a sand layer. In most cases there will be at least two plotted lines (for an idealized uniform sand layer and a situational anticipated condition) from the left (head) to right (tail) sand layer boundary. A blue dashed line will always represent an equivalent uniform idealized sand layer, without pinching or other issues. An over generalized earth dam is shown only for illustration. It would be unstable at this shape. The sand layer is idealistically shown having vertical face surfaces together with a "grill" face: this grill (having a permeability of sand) allows the sand layer ends to have vertical faces.

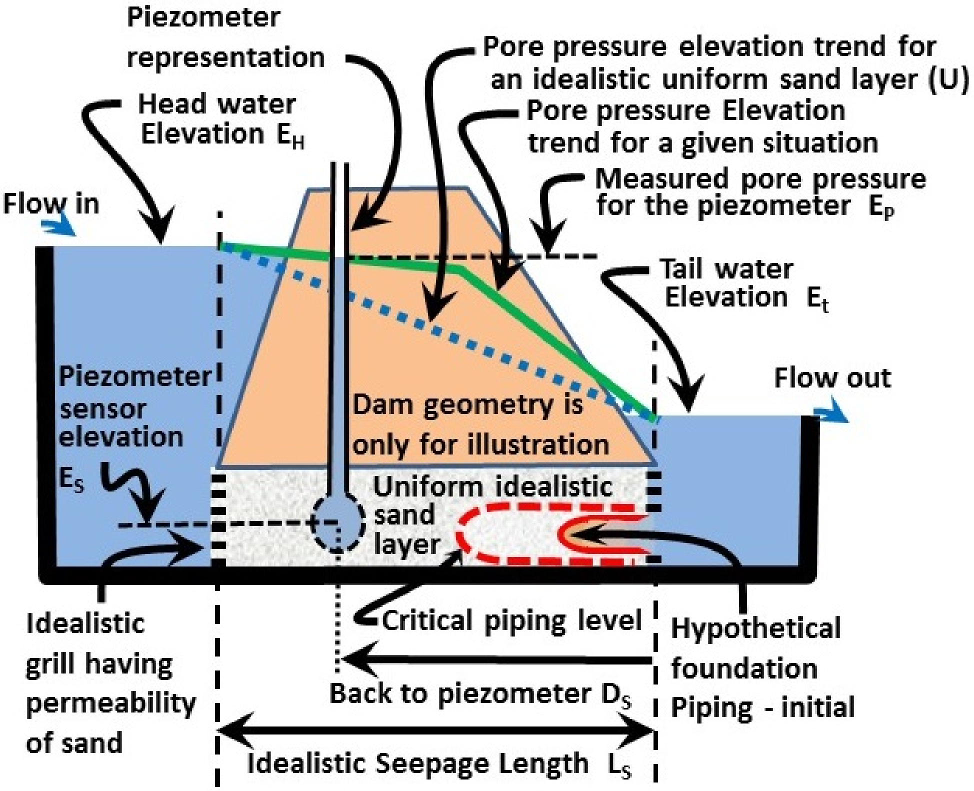


Figure 12. Defining parameters for the seepage evaluation technique.

This section introduces the concept of trending to a zero flow condition based on reservoir level versus piezometer level. Figure 13 shows two types of plots, namely the L-P plot (i.e. seepage length versus elevation piezometer plots) on both sides and the R-P plot (i.e. reservoir (head) elevation versus elevation piezometer plot) in the middle. This figure shows two L-P plots of different reservoir levels. The assumption is that the foundation sand is uniform. The plot in the middle is in terms of reservoir (head) level (on the X axis) versus measured elevation piezometer level (on the Y axis).

All R-P plots will have a line representing Head equal to Piezometer with annotation arrow added showing the following text "R=P (no soil or no flow)". The "no soil or no flow" statement infers that if the measured piezometer is equal to the reservoir then, a) either there is no soil between the reservoir and piezometer (i.e. no soil statement) or b) there is no water flow because the reservoir level is equal to the tail (downstream) level (or a perched water table) consequently there is no driving pore pressure differential to cause water flow. Both of these concepts will be fully described in this paper. Perched water tables (in or under the dam) and/or influence of water table from adjacent natural soil abutments can over shallow the influence of the tail (downstream) water level.

The middle R-P plot is constructed using both L-P plots (red for high water and green for low water). The high head water example on the left will be used to illustrate the construction of one data point for the trend to zero flow condition. The example starts with the reservoir level (point A) which is projected to the R-P line shown by point B. The procedure continues with a vertical line drawn downward from point B. The piezometer level (point C) is then projected laterally from the L-P plot to intersection (point D) using the vertical line from point B. The point D can also represent a typical field measured piezometer data point. This procedure is repeated for the low head water condition on the right (using green lines) to establish point E. A line (with an arrow) can now be generated through points D and E to intersect the R=P line at point G, which represents a condition of "no flow." having zero differential pore pressure. At point G the head water level is equal to the measured piezometer level representing no differential pore pressure and consequently no potential for seepage flow. The line defined by item F is generally termed the R-P trend line slope (and typically signified with a nearby "U" symbol) to a no flow condition point. This is for a uniform sand layer and this trend line will always be plotted with a blue dashed line. The piezometer for this example is in the middle of the section which should be approximately similar to installed piezometers from crests of earth dams.

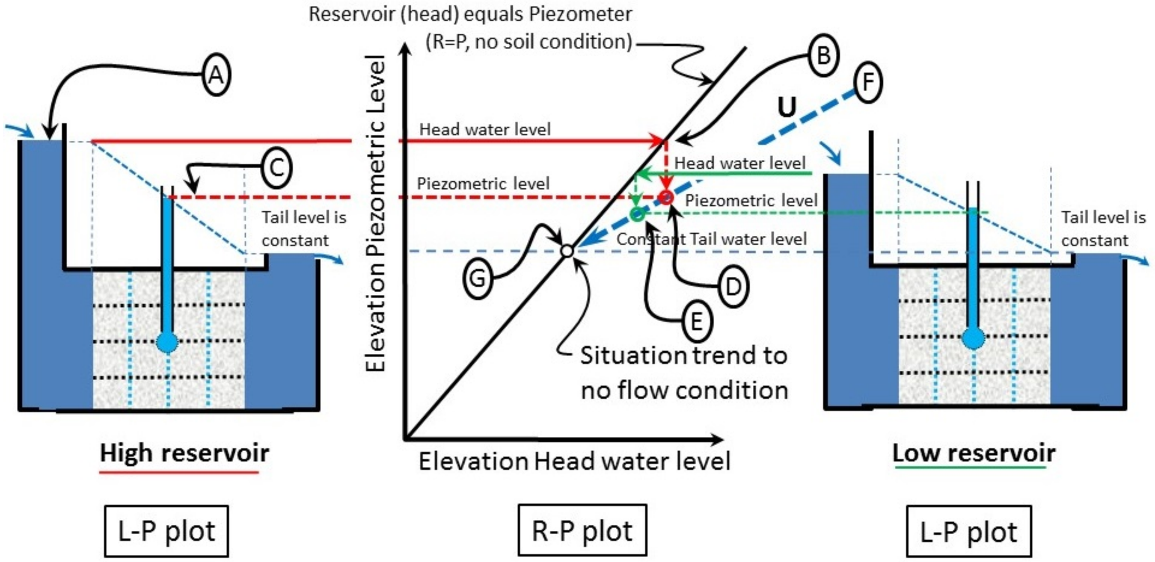


Figure 13. Construction of the R-P trend line to a no flow condition.

Figures 14 and 15 (derived from Figure 13) defines the standardized plotting format for combined L-P and R-P plots in this paper. The two plots are, 1) piezometric level versus location from the downstream toe to upstream toe on the left, and 2) reservoir (head) level versus measured elevation piezometric level on the right side.

Figure 14 illustrates piezometer data trend for a uniform sand layer condition. The L-P plot on the left side is in terms of the relative piezometer location (as D_S to L_S defined as R_S) on the X axis versus measured pore pressure (E_P) on the Y axis for a given reservoir (head) level (E_H). This figure is to explain how to represent the uniform "U" line on the standard L-P and R-P combined plots. For this (and many other) L-P plots the piezometer into the foundation sand is assumed to be in the middle of the dam and therefore R_S is equal to $R_{SM}=0.5$. The assumption for this uniform sand layer is that half the differential pore pressure between E_P and E_T has been dissipated (i.e. $\Delta H/2$) and the piezometer measurement is equal to E_{PMU}. This behavior for the L-P and R-P plots are shown using the standardized blue dashed lines. If the piezometer is not in the middle of a section then the trend slope for a uniform sand layer has the designation of a_{PU}.

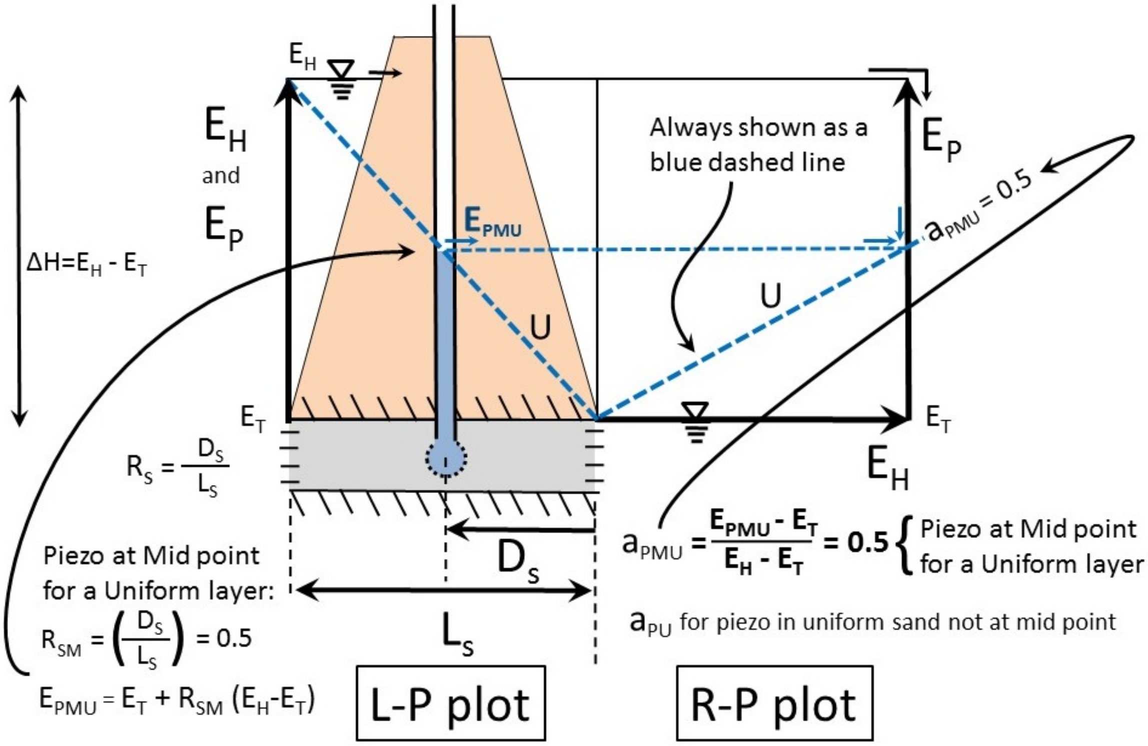


Figure 14. Description of a uniform sand condition in terms of L-P and R-P plots

Figure 15 differs from Figure 14 by showing other potential situations which are different than for a uniform sand layer. An example constrain situation (i.e. early grab) is shown (in red) together with the resulting plot on the L-P plot and trend line on the R-P plot. The trend line slope is defined as a_P. Also shown are example piezometer data points and the corresponding trend line (item T) to a zero flow point condition which infers that the tail level is not influencing the behavior.

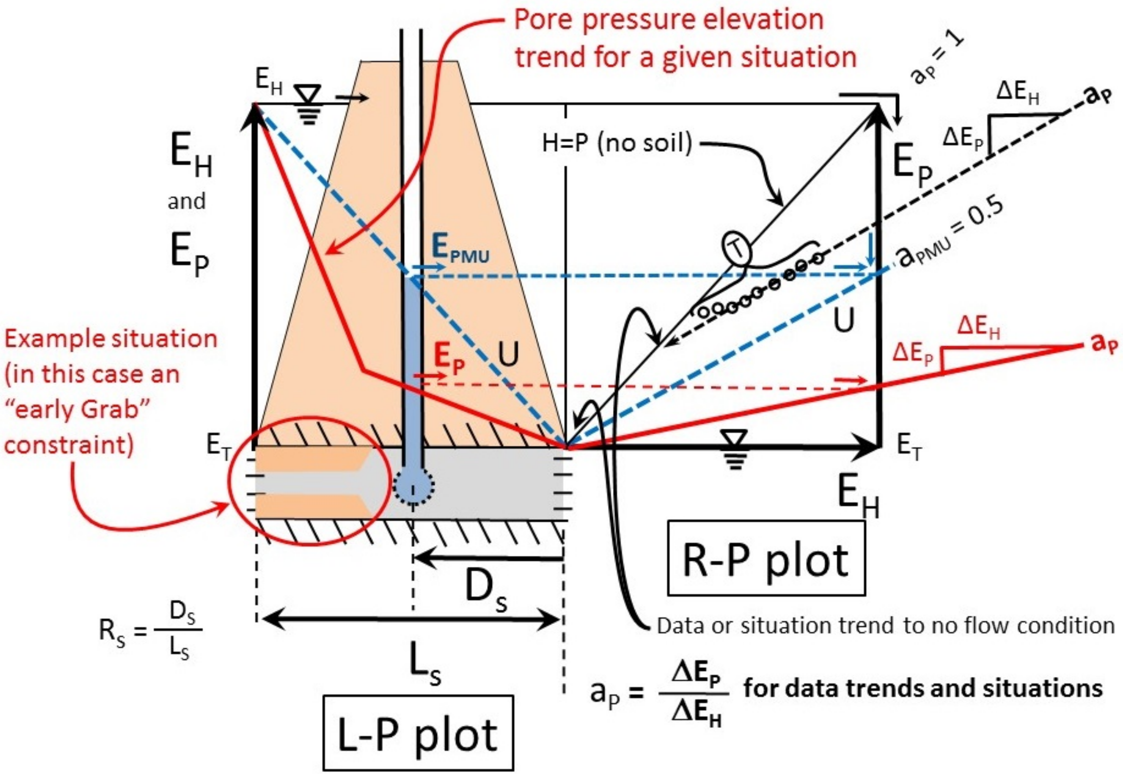


Figure 15. Description of other types of situations using the L-P and R-P plots

The first of a series of field example situations is shown in Figure 16 which simply represents two piezometers at different lateral locations, not at the standardized center location. R_S is defined as the ratio of D_S versus L_S. Both example piezometers have names representing the percent location from the right side (i.e. Piezo 65 and Piezo 21) with corresponding R_S values of $(R_S)_{65}=0.65$ and $(R_S)_{21}=0.21$. The a_{PU} trend line slopes on the R-P plot equal the corresponding R_S lines as shown. So, the a_{PU} trend slope angle equals the relative location of the piezometer in terms of the seepage length R_S – this can be important when evaluating piezometer data.

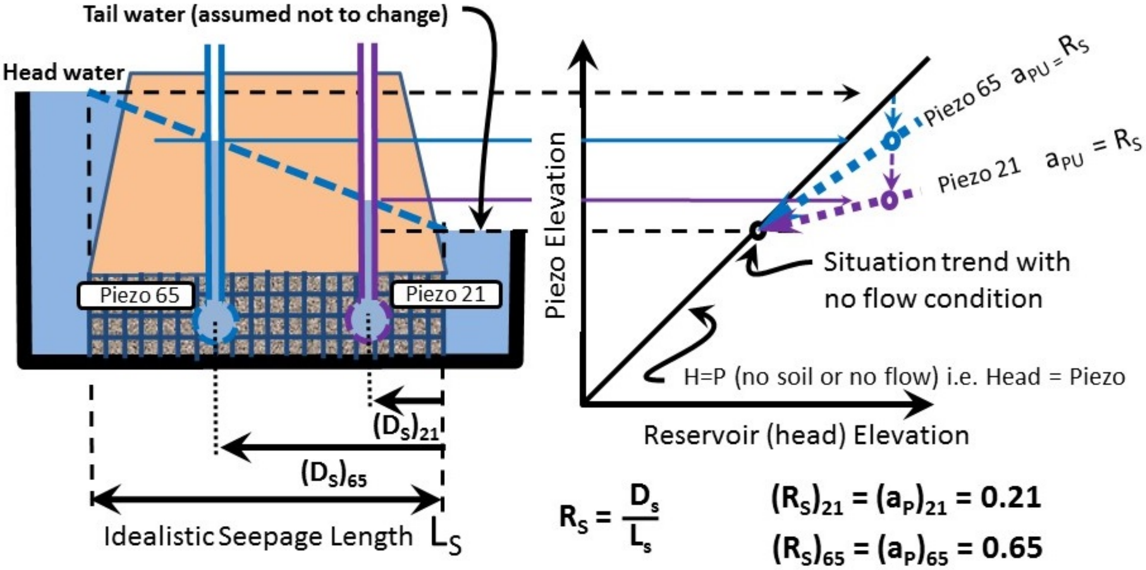


Figure 16. Two piezometers and resulting R-P trends lines.

The next example introduces how pinching of a uniform sand layer influences the trend line for R-P plots. Figure 17 shows three examples of late pinching at different locations and different degrees of constriction, approximating 20, 50, and 80 percent constriction. Late pinching is defined simply as pinching occurring on the downstream side of the foundation sand layer. Note in the L-P plot (left side) how the elevation pore pressure versus lateral distance line slope is the same before and after the constriction, this is because the sand type and path on both sides are identical. The resulting trends in the R-P plot are shown for the three examples plus for 0% and 100% constriction. The level of constriction for a late pinch increases the trend slope a_P level.

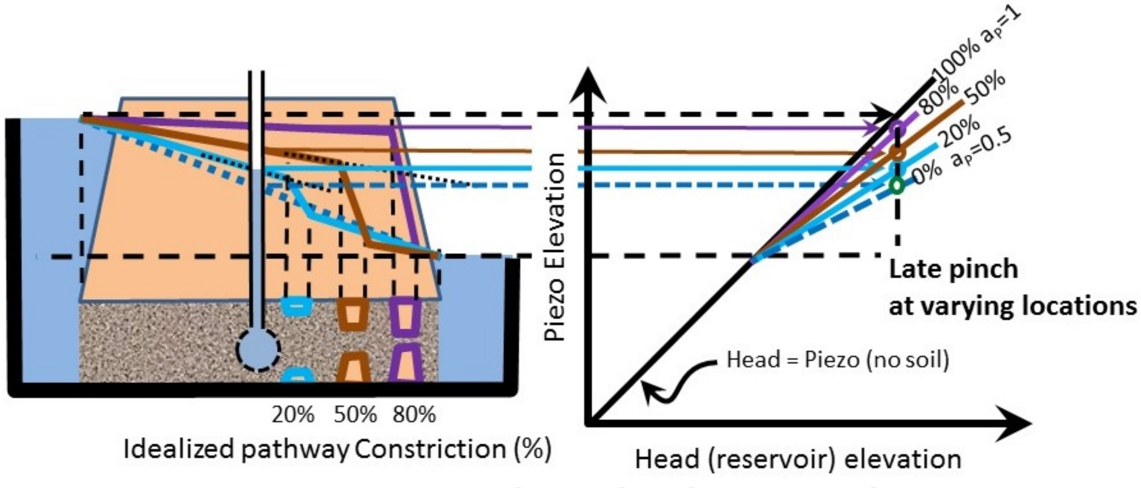


Figure 17. Late pinching and resulting R-P trends

Figure 18 shows early pinching all occurring at the same location and that pinching is upstream from the piezometer location. Note how increasing constriction for an early pinch situation decreases the R-P trend slope a_P which is opposite of the late pinching trend. This observation is because of the piezometer location in reference to the pinch location.

Figure 19 is for late pinch, similar to Figure 17) except that all pinching is occurring at the same location. The resulting R-P trends are also similar.

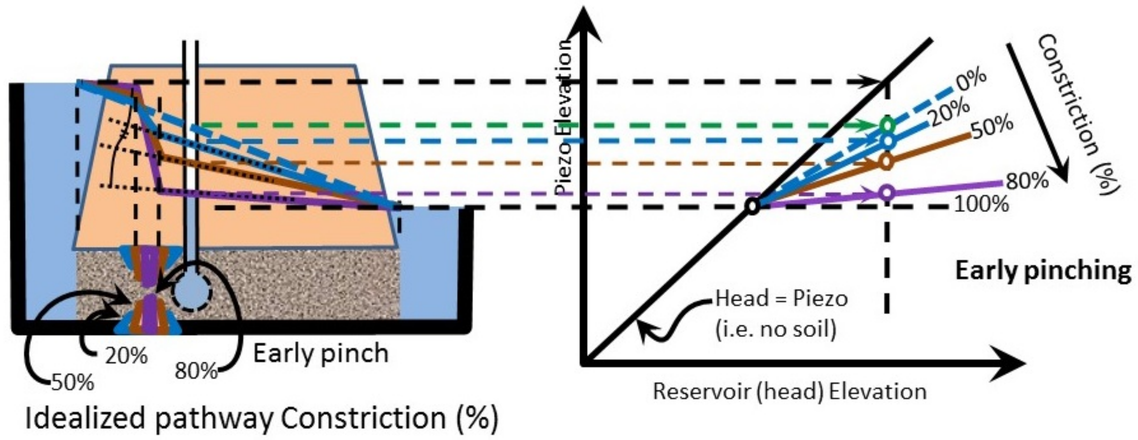


Figure 18. Early pinching and resulting R-P trends.

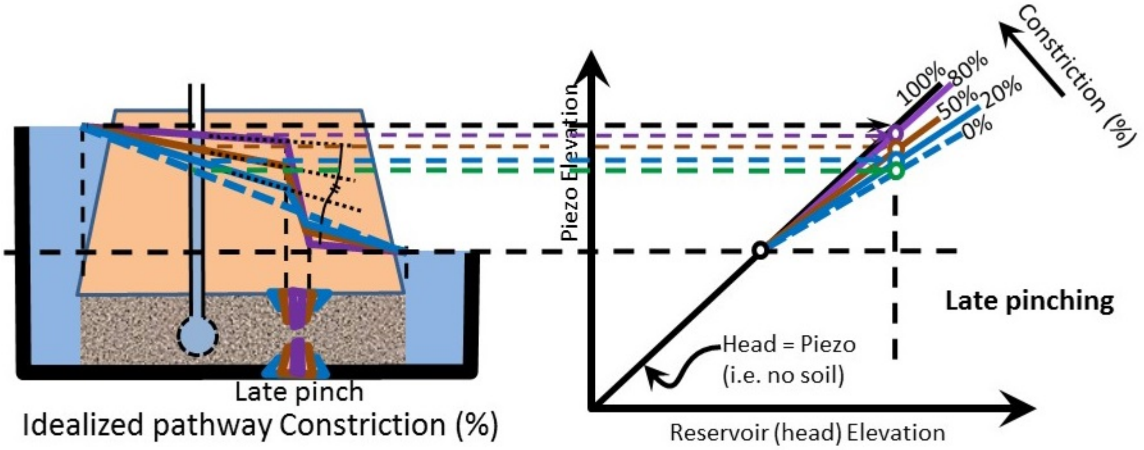


Figure 19. Late pinching but at the same location, with resulting R-P trends.

Figure 20 introduces a new concept, similar to pinching, called a grab as illustrated graphically in the figure. In this case grab constricts the layer for the entire length as shown. In this case the grab starts from the toe side (downstream side) and progresses toward the reservoir. The resulting R-P slope a_P is much more complicated than for the pinch situation. As the grab progresses (from item A, to item B and finally to item C) the R-P slope a_P initially increases then decreases. Actually, the a_P for a no grab situation (uniform sand) is $a_{PMU}=0$ (see R-P plot) then as the grab length increases (item A to B) the resulting a_P level increases. As the grab length goes past the location of the piezometer (item C) the result is that a_P slope will decrease. When the grab length extends the total length (i.e. back to a uniform sand layer situation) the resulting a_P is again equal to a_{PMU}. The R-P behavior is complex but can be explained by examining the pore pressure plotted shapes in the L-P plot.

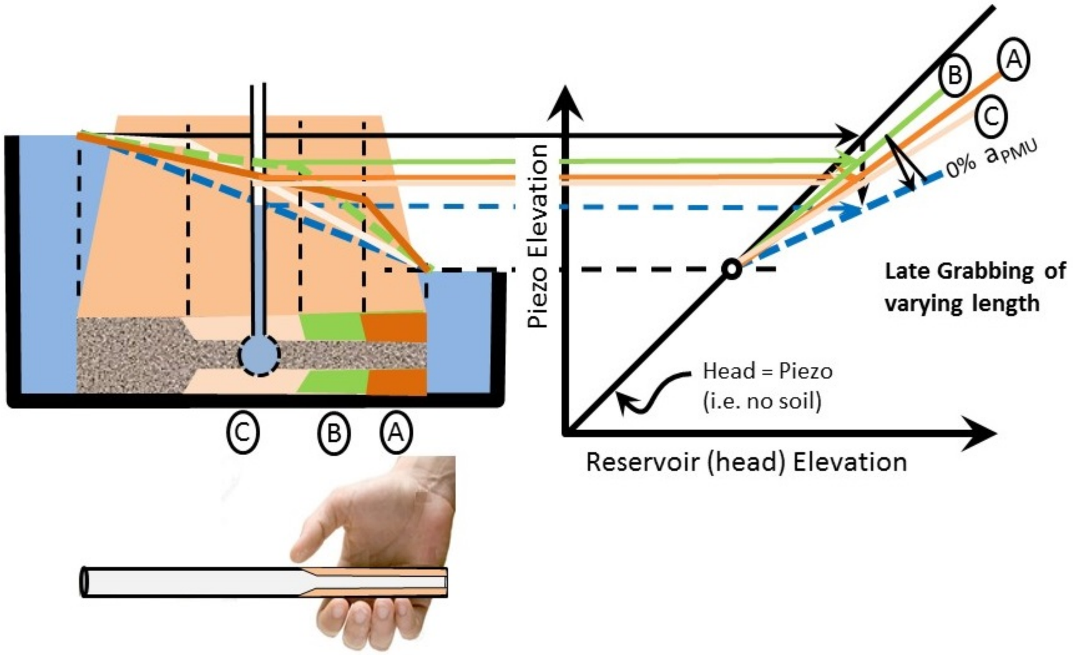


Figure 20. Defining Grab and resulting complex R-P trends.

Figure 21 illustrate two cutoff wall constructions, an early and late wall with the piezometer near the center of the sand layer. The resulting R-P trends slopes are shown at the right. Figure 22 is similar to Figure 21 but includes an early pinch. An early pinch and early cutoff wall have similar behavior which is to decrease the R-P trend slope a_G level. Figure 23 is again similar to the previous plots but for this case is for a late pinch.

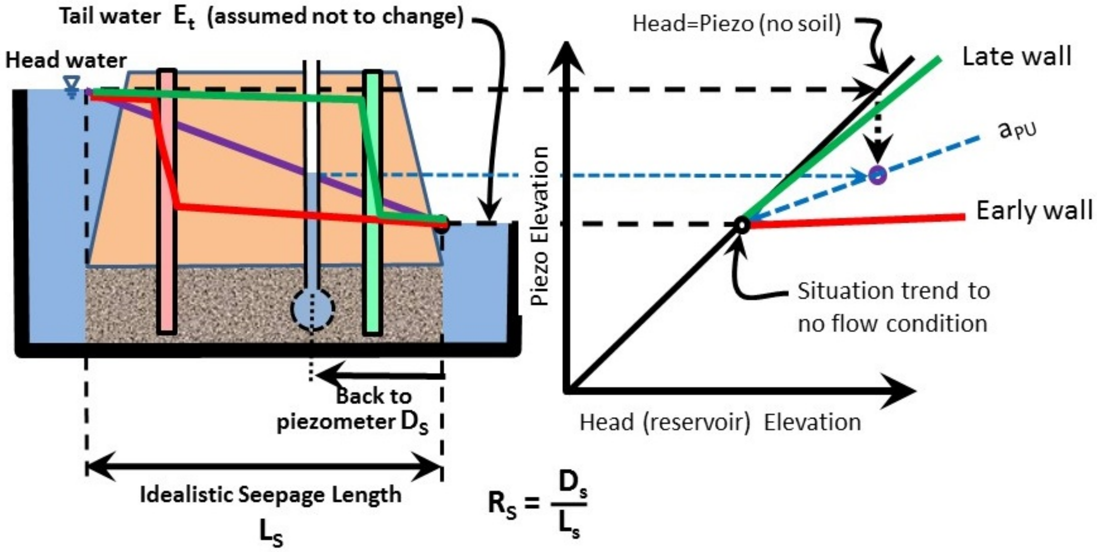


Figure 21. Cutoff wall construction and resulting R-P trends.

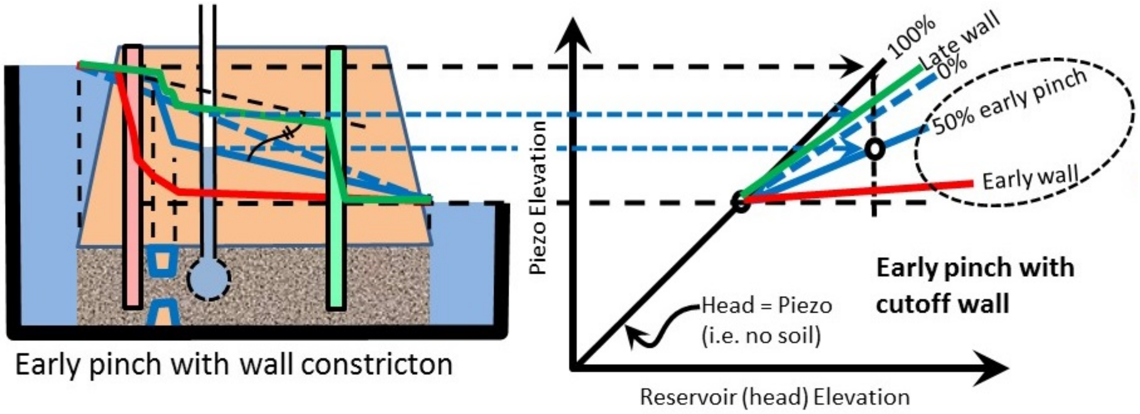


Figure 22. Cutoff wall construction with an early pinch and resulting R-P trend.

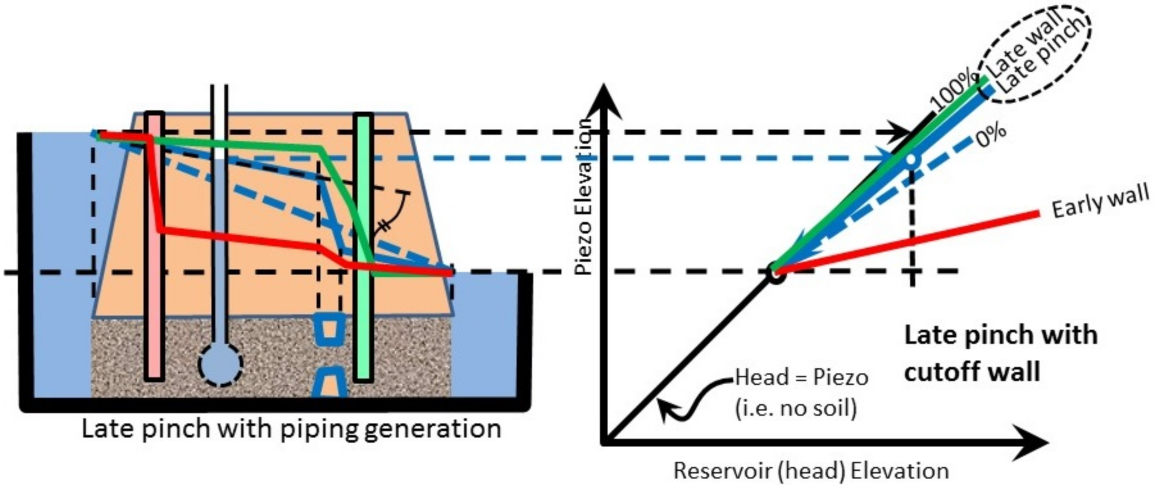


Figure 23. Cutoff wall construction with a late pinch, and resulting R-P trends.

Figure 24 introduces the concept of a seepage pipe progression from initial formation to a critical situation. Increasing seepage pipe formation (from initial to critical) results in the R-P slope trend a_P to decrease initially from a_{PMU} to lower values as shown. Seepage piping formation will always decrease a_P. When a_P is zero there is a seepage pipe extending from the upstream tail area to the piezometer sensor. Figure 25 is similar to Figure 24 except that the piezometer location is near the upstream reservoir. The R-P trend is similar but the shape is different. Figure 26 includes an early pinch together with increased seepage piping. The R-P trend slope in this case starts at the pinch trend slope (shown as 50%) and decreases with increased seepage piping criticalness. Finally, Figure 27 shows a late pinch with increased seepage piping. It is difficult to differentiate initial piping and late pinching for this condition. However, as seepage piping progresses past the late pinch the R-P trend slope a_P drops dramatically, as shown. Figure 28 shows a late grab together with seepage piping formation. The R-P trend slope a_P for this grab situation is very high. The decrease of a_P is dramatic as the seepage piping length approaches the grab length, as shown.

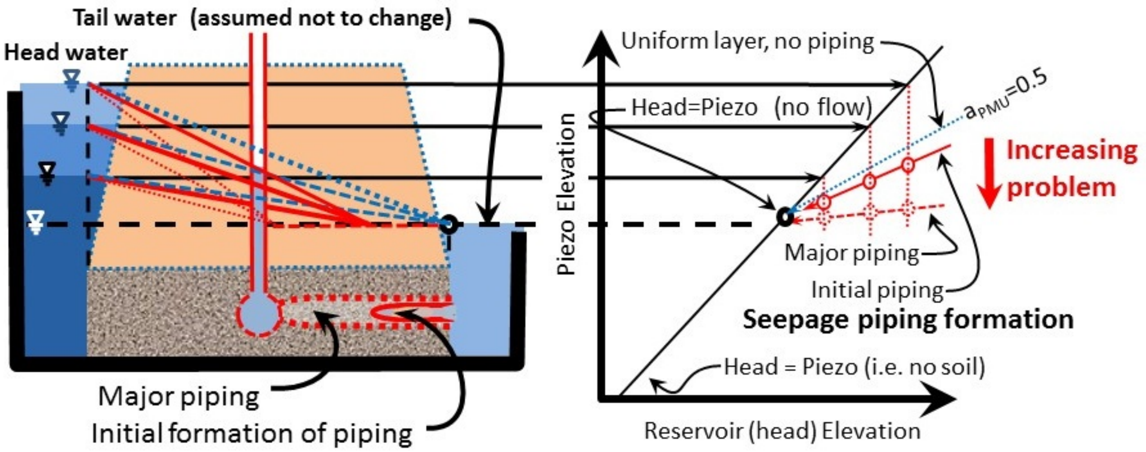


Figure 24. Seepage piping and resulting R-P trends.

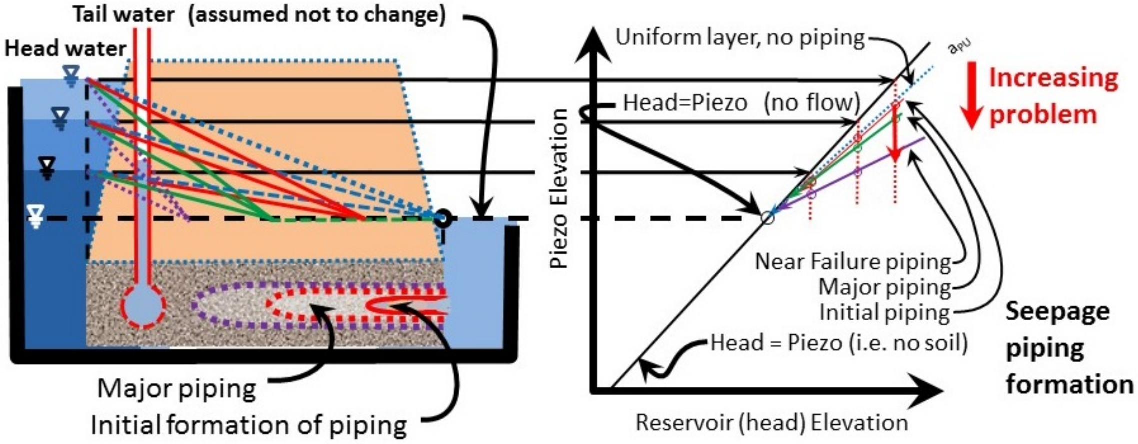


Figure 25. Seepage trends with piezometer located near reservoir side.

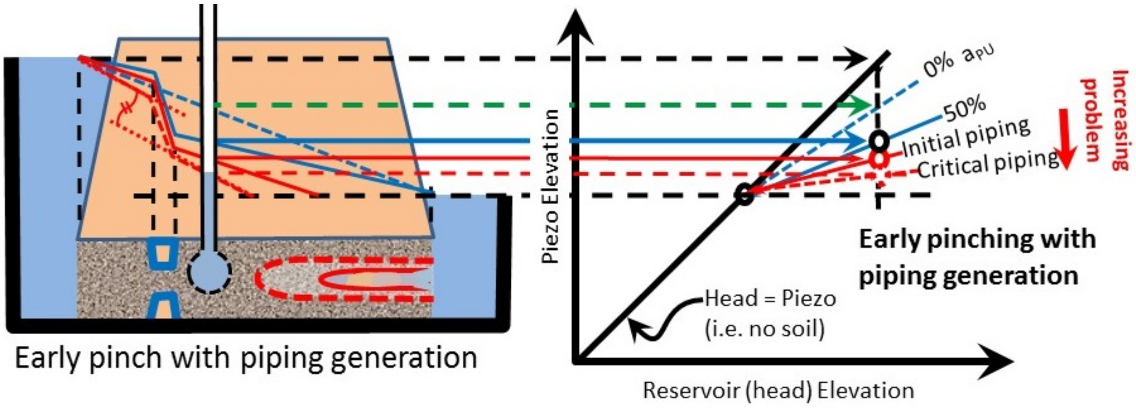


Figure 26. Seepage piping together with early pinching, and resulting R-P trends.

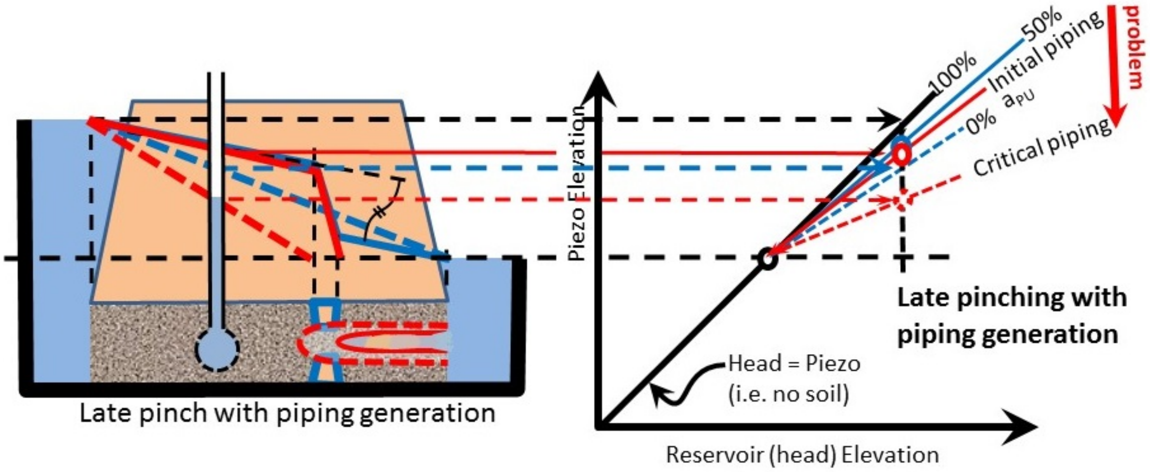


Figure 27. Seepage piping and late pinch, and resulting R-P trends.

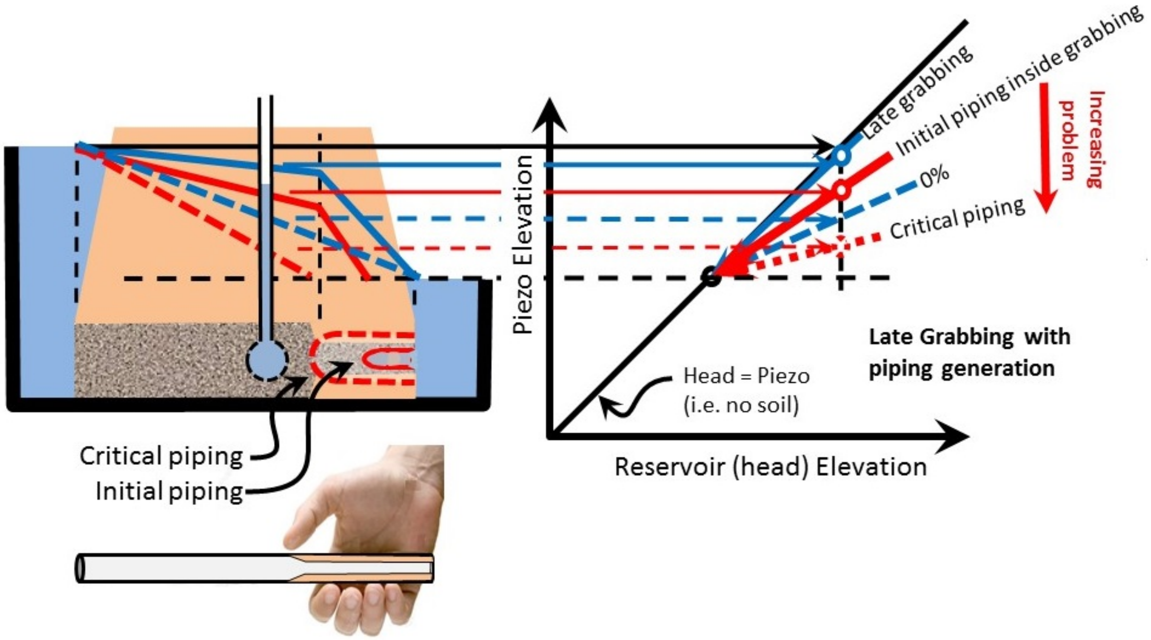


Figure 28. Defining late grab and seepage piping and resulting R-P trends.

Figure 29 is the accumulation of all the above situations. This plot is only for a piezometer at the midpoint of the foundation sand layer. The resulting plot, termed the L-AP plot, shows how a_P changes for given situations (i.e. pinching or grab) from the reservoir side to the toe side. An example is the best means for explaining this plot. The example is for a late pinch with approximately 80% constriction, shown by item A. The resulting measured piezometer (at the midpoint along the sand layer) is shown by item B. Item C on the R-P reflects item B level, resulting in $a_P = 0.7$ (item D). This a_P is placed on the L-AP plot on the Y axis at item E. Item F is the intersection of item E (i.e. item D) and the location of the late pinch (item A). As should be expected, the L-AP plot for a grab is more complex than for a pinch. In all cases, increased seepage piping will decrease the a_P as shown by the red arrow.

Evaluating reservoir piezometer data is always complex, especially when there is only a single piezometer located at the crest. Figure 29 as well as Figures 16 to 28 are only tools to aid in evaluating piezometer data.

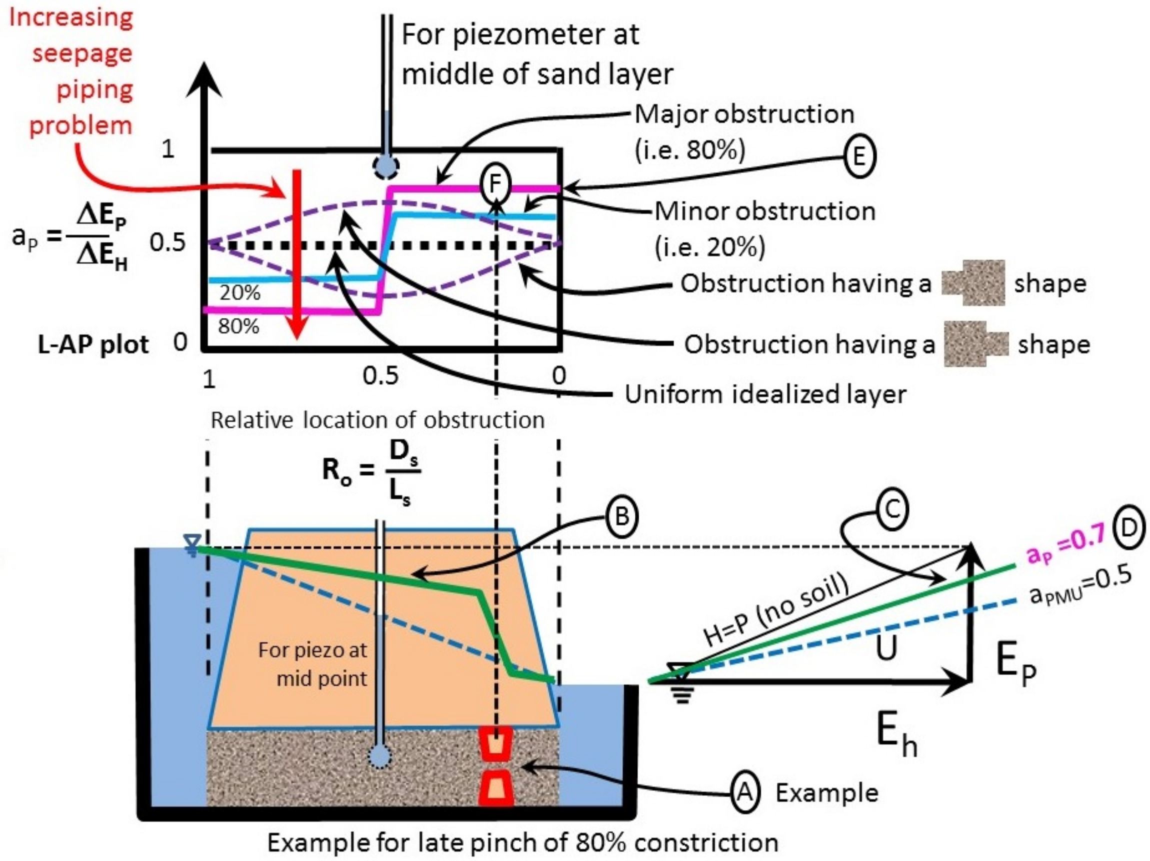


Figure 29. Defining the L-AP plot as a tool for evaluating piezometric data.

The next several plots (Figures 30 to 34) show R-P trending to a zero flow condition (at the H=P line) using data from USACE sources and others. Further evaluation for these examples was not performed because more information is required such as; tail level, location of piezometers, foundation type, geology, etc. In most cases the trend to a zero flow condition has an elevation much higher than the tail level, inferring a pinched water table in the dam or seepage from the adjacent dam abutment. These examples are only to illustrate how existing data can be used to construct the R-P plot using L-P data. Figure 35 is shown to illustrate that adding the H=P line shows that the dramatic observed changes (items A) have a slope equal to H=P. It is unknown if it's important but a good observation.

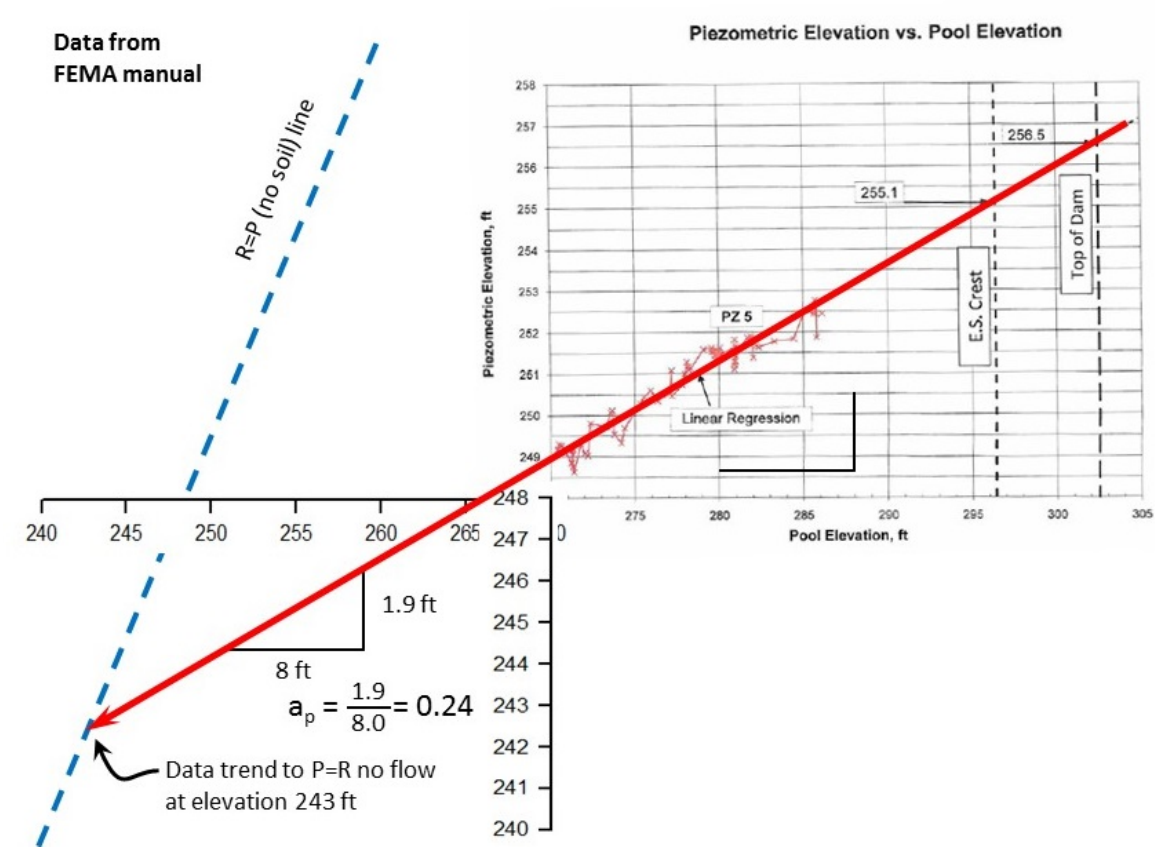


Figure 30. Data example from FEMA P-1032 (figure 8-8) to determine the zero flow condition.

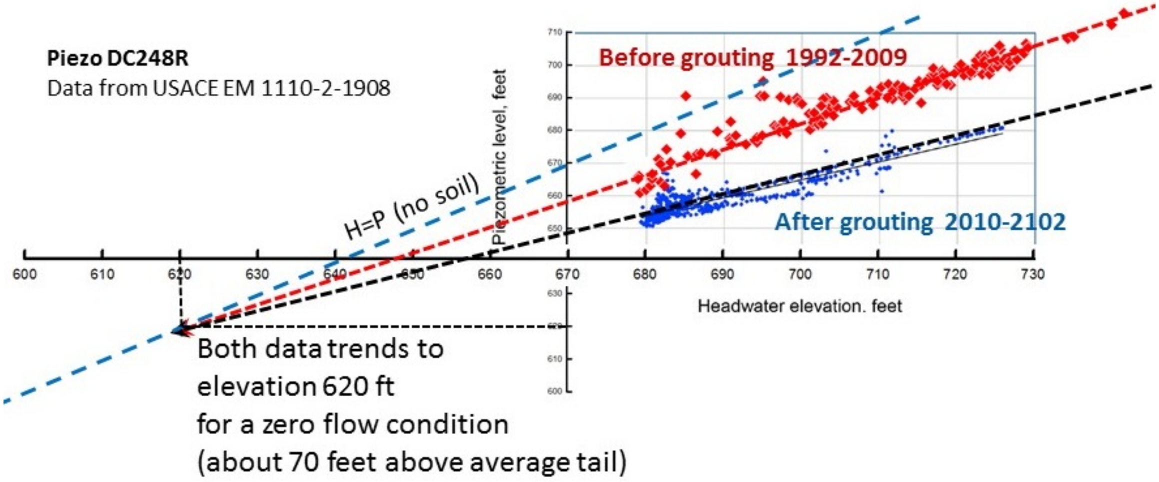


Figure 31. DC248R data example from USACE manual to determine the zero flow condition.

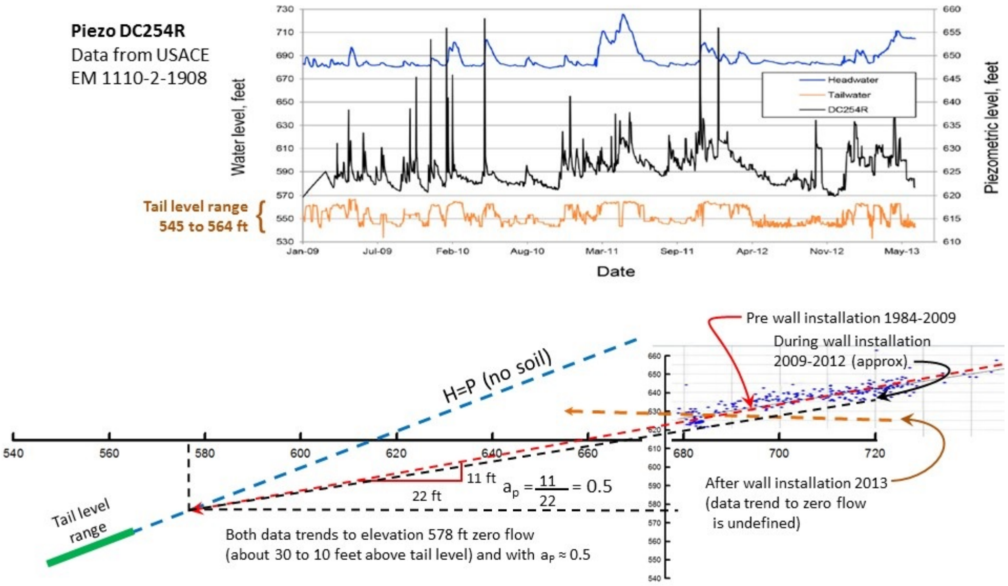


Figure 32. DC254R data example from USACE manual
to determine the zero flow condition.

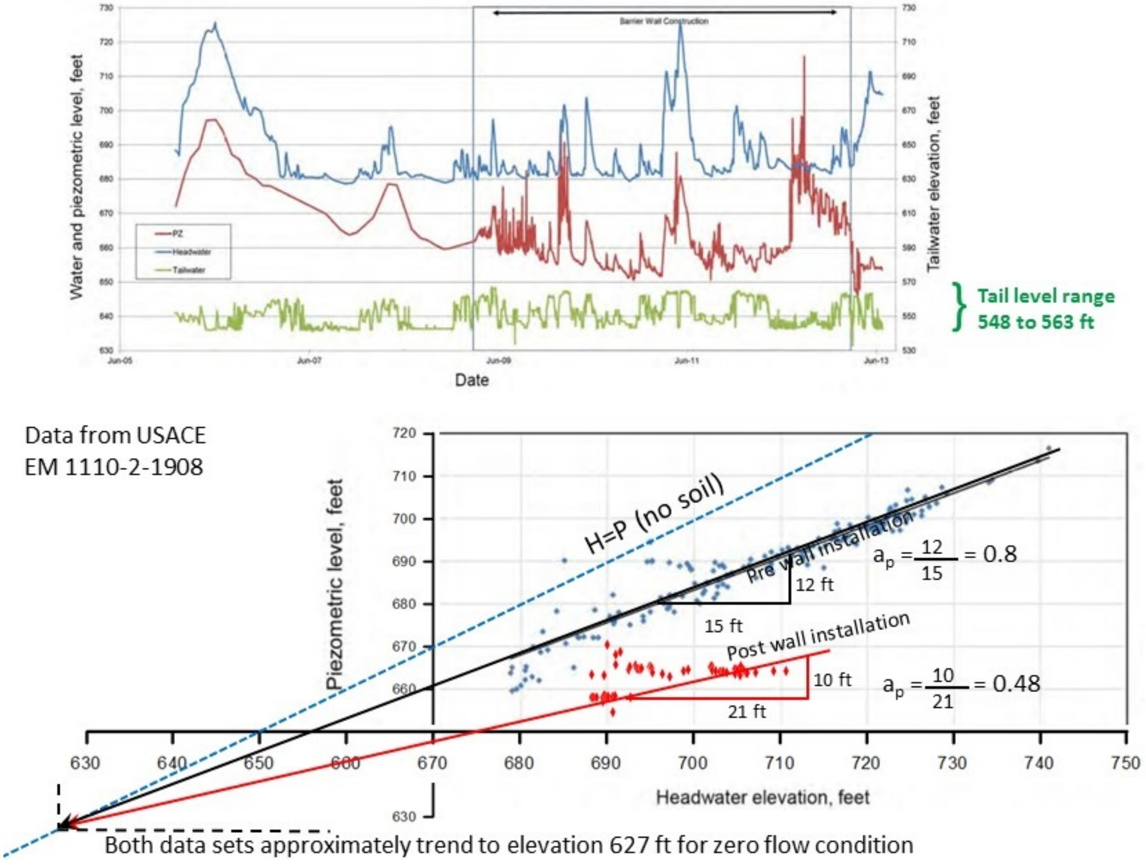


Figure 33. Data example from USACE manual to determine the zero flow condition.

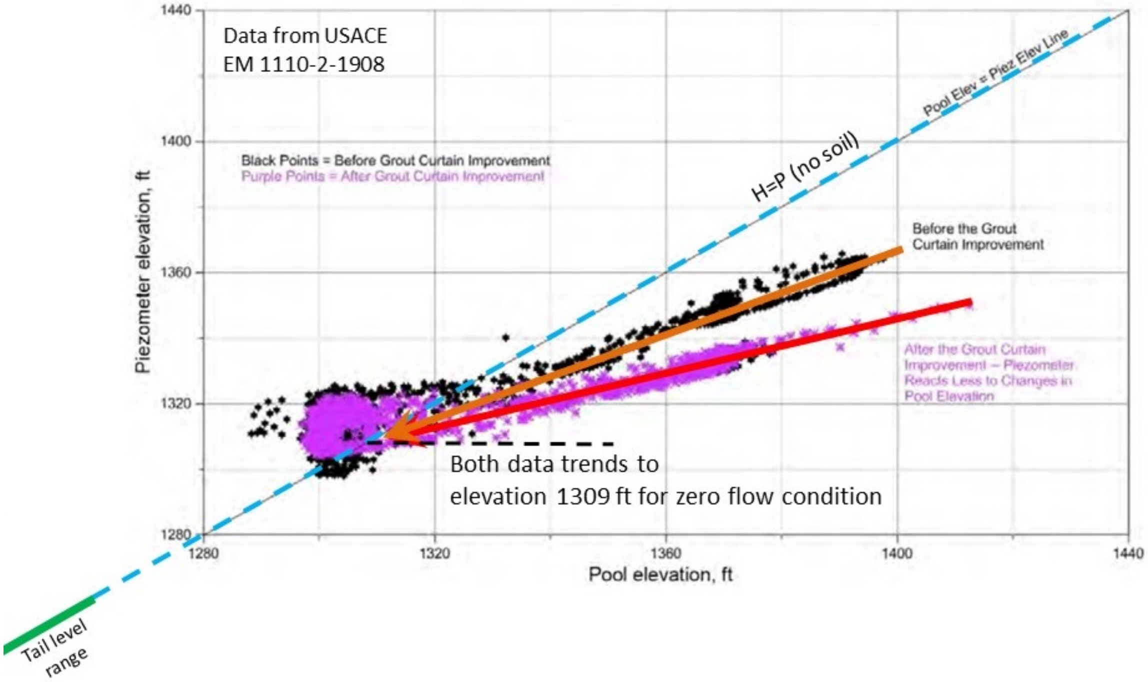


Figure 34. Data example from USACE manual to determine the zero flow condition.

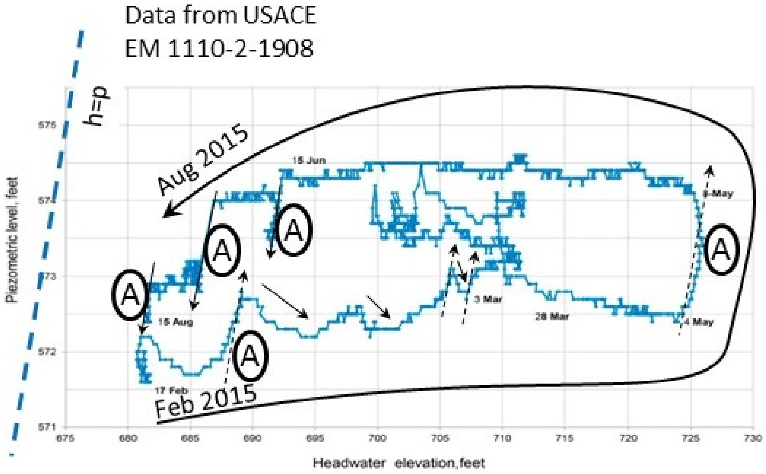


Figure 35. Data example from USACE manual
to show the potential usefulness of the H=P line.

MAKING PIEZOMETER VERSUS RESERVIOR PLOTS

Making plots of piezometer measurements versus reservoir level must be more than just computer software plotting the data and copying the plot into a report. Previous sections described how to critically examine the measured pore pressure data. Figure 36 specifically illustrates the minimum information required. Always include the piezometer information at the top left of the plot to allow the reader to quickly understand critical information: This block of text is required to allow a plot to be standalone. Use different plotting symbols for different situations, such as maybe pre construction of a cutoff wall, before (and after seepage), etc. Add the R=P line and the trend slope line pointing to the zero flow on the P=R line. For many situations a separate plot may be required to show the two additional lines (i.e. the R=P line and the trend slope line pointing to the zero flow).

Another suggestion is to plot time histories of piezometer data at the same scale as for the reservoir (head) and tail levels. Having the same scale is important when comparing how piezometer data is changing in reference to reservoir and tail levels. If required, the reservoir and tail levels can be plotted separately above and below the piezometer but all three having the same scale.

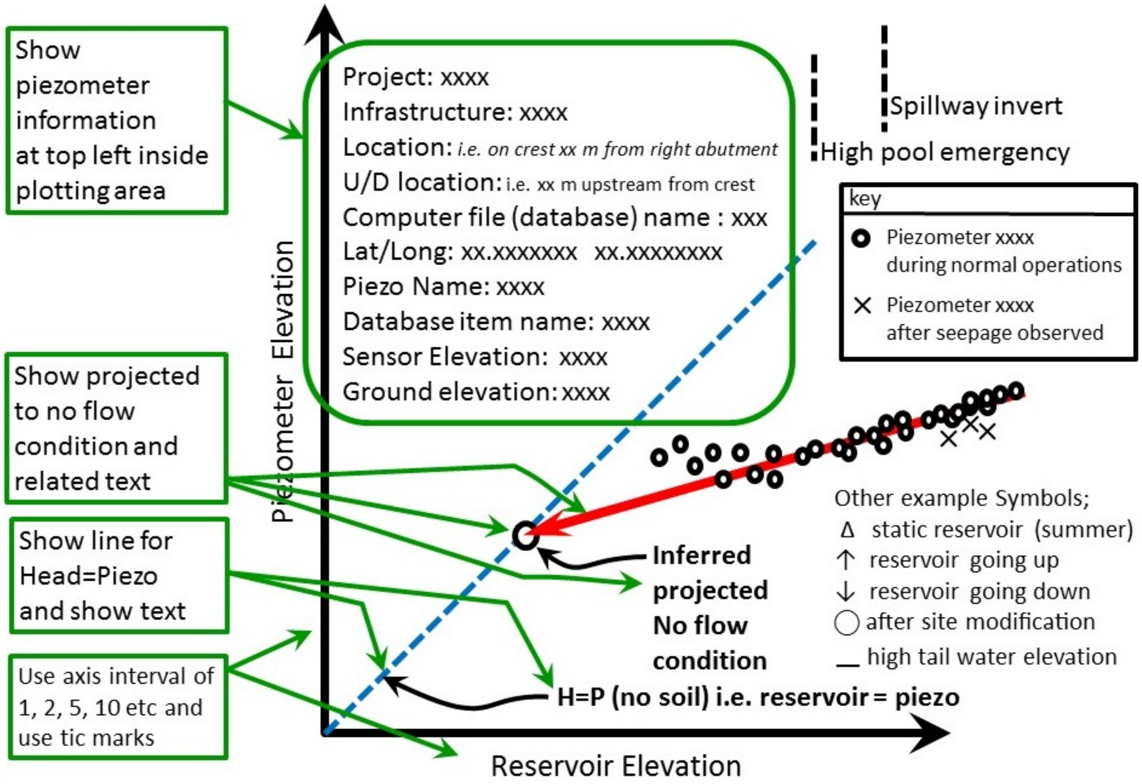


Figure 36. Required information for a R-P plot.

An important part of piezometer data evaluation is to provide clear site maps of piezometer locations and other site information. Figure 37 combines a modified site map together with the time histories of several piezometers. Figure 38 shows in concept how to include a photo of a dam together with a simplified cross section showing the piezometer locations.

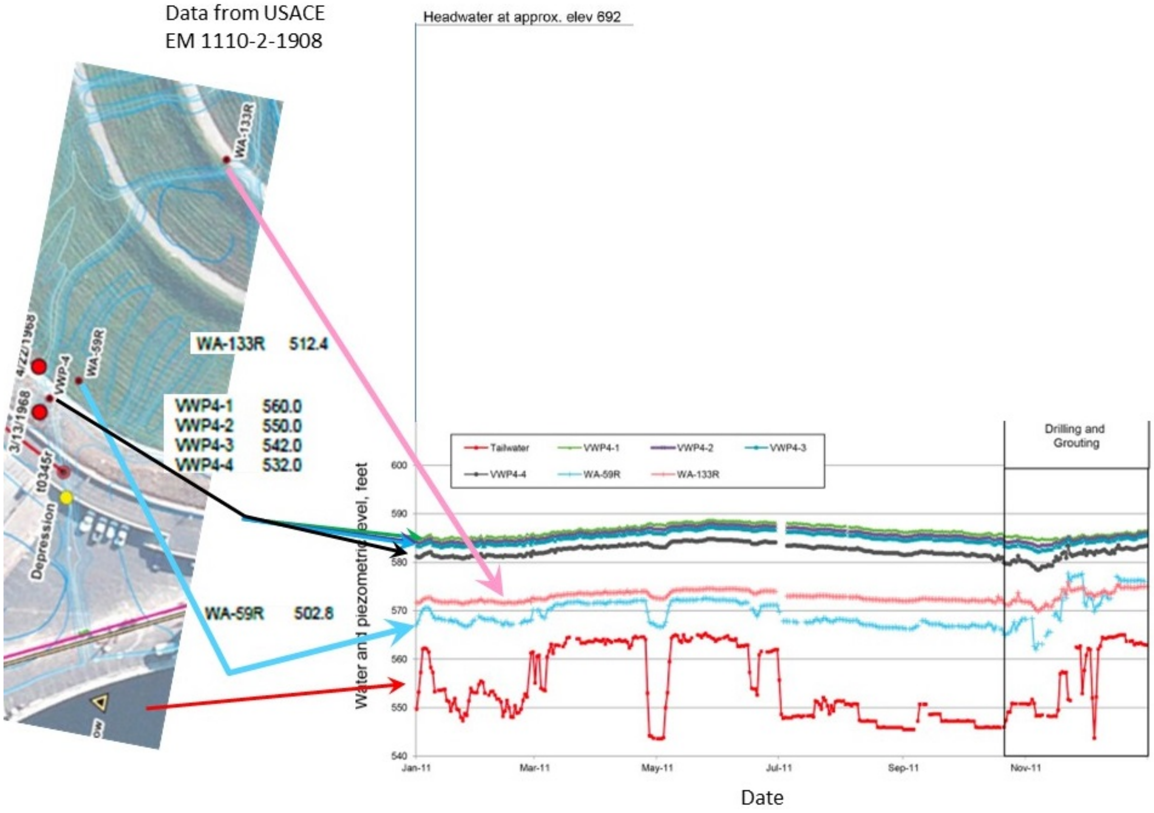


Figure 37. USACE information to show a site map and time histories of piezometer data

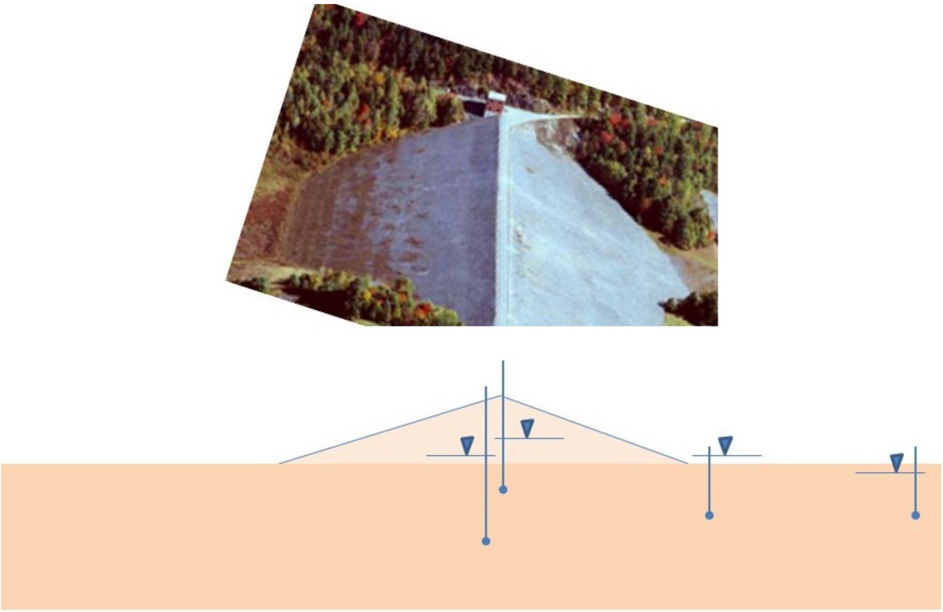


Figure 38. Illustration showing a photo of a dam and cross section with piezometer locations

When performing computer seepage modeling it's important to graphically show how permeability changes with different soil layers. Most commercial software provide an option to include a table showing soil layers and corresponding input values. Presenting critical data in tables does not allow the engineer to easily visualize how the soil layers differ. Figure 39 shows two depth/elevation plots next to a software generated embankment plot. For this example, the two plots are for permeability and D_{10}. For both plots there is a difference between measured values and engineering assigned values.

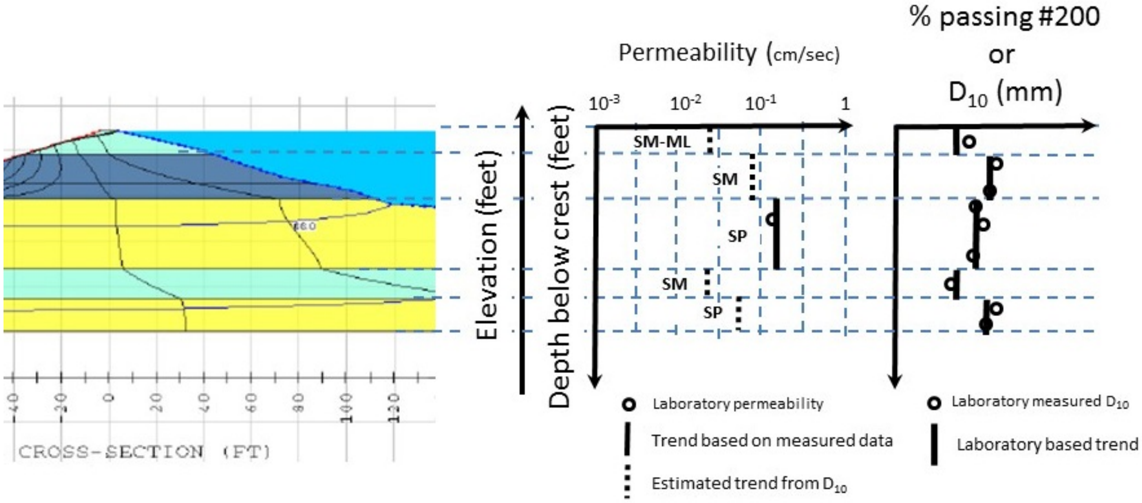


Figure 39. Plots that should be added to computer seepage modeling output

CONCLUSIONS

Piezometric data can be one of the best indicators of seepage in earthen embankments, but the evaluation for earth dams can often be difficult because of the many interrelated factors. Factors such as the character of permeable layers, micro geology in critical foundation materials, the location and character of seepage obstructions all have a role in piezometric response to seepage. A fundamental understanding of seepage forces and flow are essential to correctly interpret the significance of piezometric changes over time. This paper provides several new tools for interpreting piezometer data in terms of reservoir levels. A standard way of plotting piezometric data is proposed and trends that generally indicate seepage problems are identified. When established pore pressure trends drop it's likely an indicator of an increased seepage flow and/or an increased seepage condition severity. A procedure for defining trends to a zero flow condition is described.

ACKNOWLEDGEMENTS

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USACE, Engineering Manual EM-1110-2-1908, “Instrumentation and monitoring of Embankments Dams and Levees. Draft 2015 Sept 04.

FEMA, “Evaluation and Monitoring of Seepage and Internal Erosion” - Interagency Committee on Dam Safety (ICODS), FEMA P-1032 /May 2015