TECHNICAL NOTE 10

Analysis of Dam Instrumentation as part of a Five-Year Dam Evaluation

Montana Department of Natural Resources and Conservation

Working Draft Version 1.1 (revised January 2023)

These guidelines are consistent with Administrative Rule 36.14. This document was initially prepared by Gannett Fleming, Inc. (Version 1.0, October 2022) under contract with the Montana Department of Natural Resources & Conservation. Periodic updates to the guidelines and corresponding templates will be made by Montana Department of Natural Resources & Conservation as needed.

TECHNICAL NOTE 10

Analysis of Dam Instrumentation as part of a Five-Year Dam Evaluation

Montana Department of Natural Resources and Conservation

Working Draft Version 1.1 (revised January 2023)

TABLE OF CONTENTS

1.0 INTRODUCTION

Dams require surveillance and monitoring to detect potential problems when they arise. Performance of a dam cannot always be easily observed by the naked eye, requiring specialized equipment and regularly scheduled inspections of less-accessible parts of the dam to ensure the safety of the dam. Instrumentation is commonly used at dams to track seepage patterns, monitor the movement of structures (earth and concrete), assess the condition of outlet works and spillways, and monitor hydrologic data. Instrumentation data can be useful to evaluate the likelihood and/or initiation of potential failure modes. Potential failure modes specific to an individual dam should be considered when evaluating instrumentation data.

1.1 Regulatory Framework

Instrumentation is often the most important tool available to monitor the health of a dam. As such, Chapter 36.14 of the Administrative Rules of Montana (ARM) requires that dams be properly instrumented and regularly monitored. This includes means to measure the reservoir water level and storage capacity as well as an adequate seepage monitoring and collection system. Additionally, any dam that exceeds 50 feet in height must have a sufficient number of piezometers to monitor the piezometric surface within the dam and facilitate identification of unusual changes in seepage characteristics at the dam. As part of the dam permitting process, Montana Dam Safety can also require that other instrumentation be installed specific to an individual dam's design and condition.

During the Five-Year Dam Evaluation, the Engineer must review all available instrumentation or monitoring data for the dam. This includes review and analysis of piezometric levels, the rate and volume of seepage, and other pertinent data. The Engineer should also assess the condition and adequacy of existing instrumentation as well as the adequacy of current threshold and action levels. If available data is limited and the dam's condition warrants investigation and surveillance, recommendations should be made to design and implement a monitoring program including the installation of additional instrumentation if needed. If data is limited and the dam's condition does not warrant additional instrumentation, then this section of the evaluation will be relatively simple.

In documenting a Five-Year Dam Evaluation, a summary of available data and additional monitoring needs should be included as part of the Five-Year Dam Evaluation Report for all dams. This summary may provide adequate documentation of the evaluation for dams with little or no instrumentation. For dams that are instrumented, however, it is recommended that a separate Instrumentation Summary Report be prepared and included as an attachment to the Five-Year Dam Evaluation Report. The purpose of Technical Note 10 is to summarize Montana Dam Safety expectations regarding the Instrumentation Summary Report, including a description of how an evaluation of instrumentation data should be documented by dam owners and/or their engineers.

1.2 Dam Instrumentation Summary Report

Regardless of the complexity of the surveillance and monitoring instrumentation at a dam, the Dam Evaluation Report should include an overview of the instrumentation, summary of available historical instrumentation data, and the Engineer's findings from the review. For dams with piezometers or other instrumentation requiring analysis, it is recommended that detailed descriptions of instrumentation and supporting data analyses be documented in a Dam Instrumentation Summary Report and included as an attachment to the Evaluation Report. Other prior analyses can also be included as attachments if they are thought to be of significance. While not required to be submitted with a Dam Evaluation Report, all available instrumentation data should be available to Montana Dam Safety upon request.

The Dam Instrumentation Summary Report should include the following:

1. Detailed description of all instrumentation
2. Compilation and presentation of available instrumentation data
3. Data analyses
4. Summary of findings and recommendations

These four components of the Dam Instrumentation Summary Report are discussed in more detail in Section 2.0 – *Evaluation and Documentation Guidance*.

2.0 EVALUATION AND DOCUMENTATION GUIDANCE

This section outlines the recommended approach to reviewing and documenting an evaluation of dam instrumentation. In general, a Dam Instrumentation Summary Report should include the following subsections.

2.1 Detailed Description of Instrumentation (Step 1)

2.1.1 General Requirements for Instrumentation Descriptions

The initial step is to summarize all instrumentation at the dam including piezometers, toe drains, weirs, flumes, monitoring wells, staff gages, crack gages, settlement/alignment monuments, etc. A plan view drawing of the dam should be developed with the name and location of all instrumentation. An example plan map is provided in Figure 2.1.

Figure 2.1 – An example plan drawing showing the location and name of all instruments at a dam.

In addition to the plan drawing, the following detailed information should be provided for all instruments:

1. Description
    a. Type of instrument (e.g., pneumatic/vibrating wire piezometer, Parshall flume, weir type, gap gage, inclinometer)
    b. Location
    c. Key dimensions and elevations

   d. Type of material
   e. Probable source of water, if applicable (e.g., chimney filter, left abutment blanket drain, toe drain, seepage, unknown)
2. Condition
   a. Functionality of the instrument
   b. Age, deterioration, or damage
   c. Note any deficiencies (e.g., iron-oxidizing bacteria clogging or impacting measurements, corrosion of v-notch weir, partially submerged toe drain)
3. Record-keeping
   a. Frequency of reading and recording
   b. Typical value and historic range of readings
   c. Problems with reading instrument
   d. Procedures for resolving spurious readings
   e. Reference to conversion tables if applicable
4. Threshold and Action Levels

There are various formats that can be used to acceptably provide this information. Both tabular and graphical summaries are acceptable if all pertinent information is provided. Template instrumentation description tables that were developed by Montana Dam Safety to facilitate this process are available from the MT DNRC website. Note that if an instrument has been abandoned or replaced, but the historic data is still being used for safety evaluations, appropriate information should be included for the record.

2.1.2 Additional Requirements for Piezometers

For dams with piezometers, additional description and information is required to be included in the Dam Instrumentation Summary Report. This includes both borehole logs that list the construction of piezometers and associated borehole lithology as well as cross sections of the dam showing piezometer location and typical phreatic conditions.

Borehole logs can be provided in either tabular or graphical format. In addition to the general information summarized in Section 2.1.1, the following information should be provided in tabular format or annotated on borehole logs for all piezometers:

1. Borehole depth
2. Ground surface elevation
3. Top of casing elevation
4. Measuring point elevation
5. Influence zones (e.g., gravel pack top and bottom elevations, screen top and bottom elevations)
6. Known problems (e.g., improper grouting, isolation of layers, influence zones spanning more than one soil layer, etc.)

Template piezometer description tables that were developed by Montana Dam Safety to facilitate this process are available from the MT DNRC website.

Cross sections of the dam that indicate locations of representative piezometers and measured pore water pressures (i.e., phreatic surfaces) through the dam for normal reservoir level should be provided. Developing cross sections of the dam can be helpful in interpreting piezometer readings, informing the need for additional analysis, and identifying appropriate threshold and action levels. The following cross sections are recommended to be included in the Dam Instrumentation Summary Report:

1. At least one cross section that is perpendicular to the dam crest centerline (more may be required for longer embankments where changes in tailwater may exist throughout the length of the structure). This allows for evaluation of piezometric and potentiometric surfaces as well as uplift pressures. An example cross section is provided in Figure 2.2.
2. At least one cross section that is parallel to the dam centerline near the dam crest or along the toe for evaluation of gradients from the left or right abutment (see example in Figure 2.3). It is common for a dam to have a gradient from an abutment, and cross sections in these locations can improve understanding of this gradient. Furthermore, these cross sections can provide valuable insight if additional seepage analysis is being considered since these types of gradients often make it impossible to calibrate a two-dimensional seepage model.

Each cross section drawing should include the following information:

1. Approximate location of representative piezometers including piezometer name, borehole depth, and influence zone (gravel pack). Vertical exaggeration of cross sections is acceptable to demonstrate piezometer construction. Projecting nearby piezometers is acceptable but should be noted. Nested piezometers should be carefully differentiated.
2. Generalized lithology of the dam embankment and foundation.
3. Maximum observed reservoir level at the time of piezometer reading from the last five years with corresponding tailwater elevation (if available) and piezometer readings.
4. Estimated phreatic surface (use question marks to note uncertainty).
5. Recent piezometer measurements and, if applicable, drain flows associated with reservoir level.

In some cases, plotting the phreatic surface for lower reservoir elevations may have value if there is reason to believe that gradients would reverse. This is common in high foundation pressure situations. In cases where there is significant lag, there may also be value in plotting the phreatic surface for the rising and falling limbs of reservoir filling/drawdown cycle.

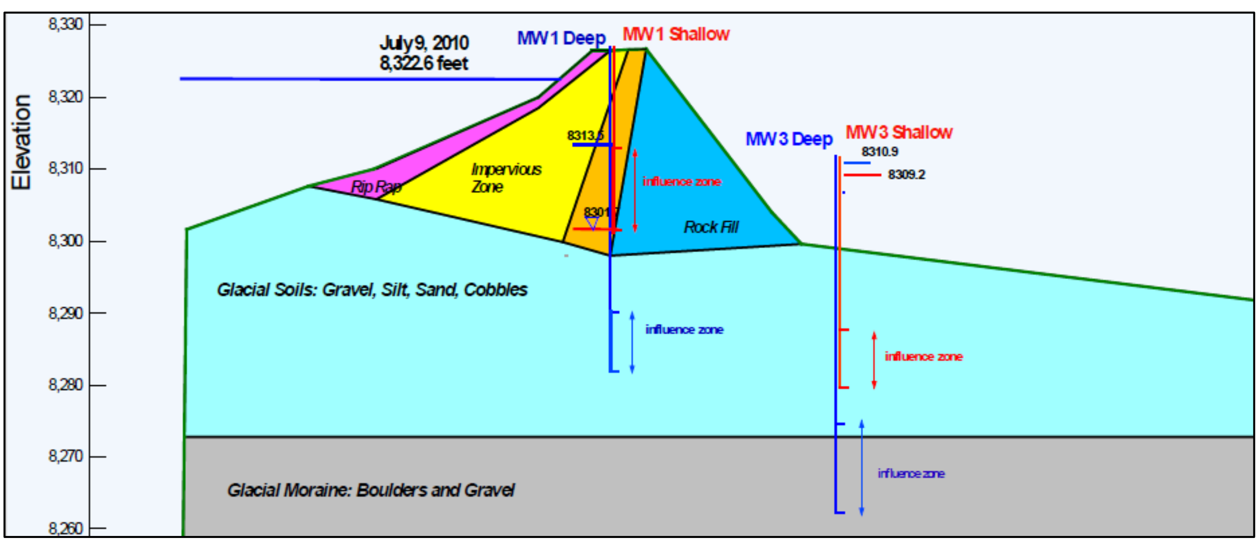

Figure 2.2 – Example of a cross section that is perpendicular to the dam crest centerline.

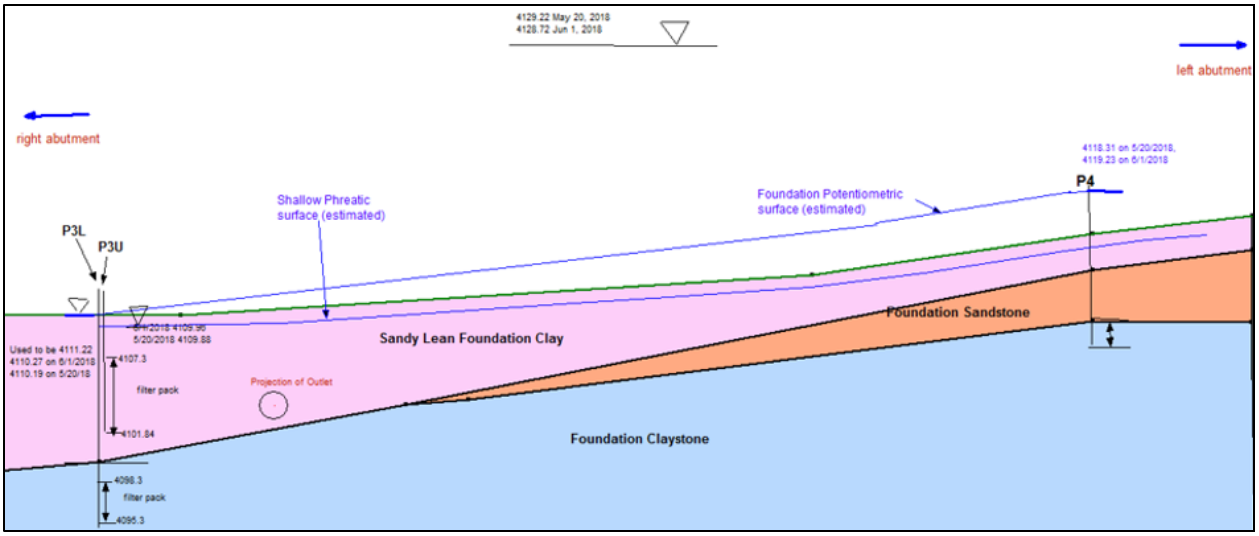

Figure 2.3 – Example of a cross section that is parallel to the dam crest centerline along the toe.

Groundwater flow analysis software such as GeoStudio SEEP/W can be helpful in creating these cross sections. CAD software, Excel or other spreadsheet applications, and even hand drawings can also be used to develop cross sections. Cross section locations should be noted on a plan view drawing (see example in Figure 2.4). Additionally, adding photos and annotations can be helpful in communicating the situation that the cross section is representing (see example in Figure 2.5).

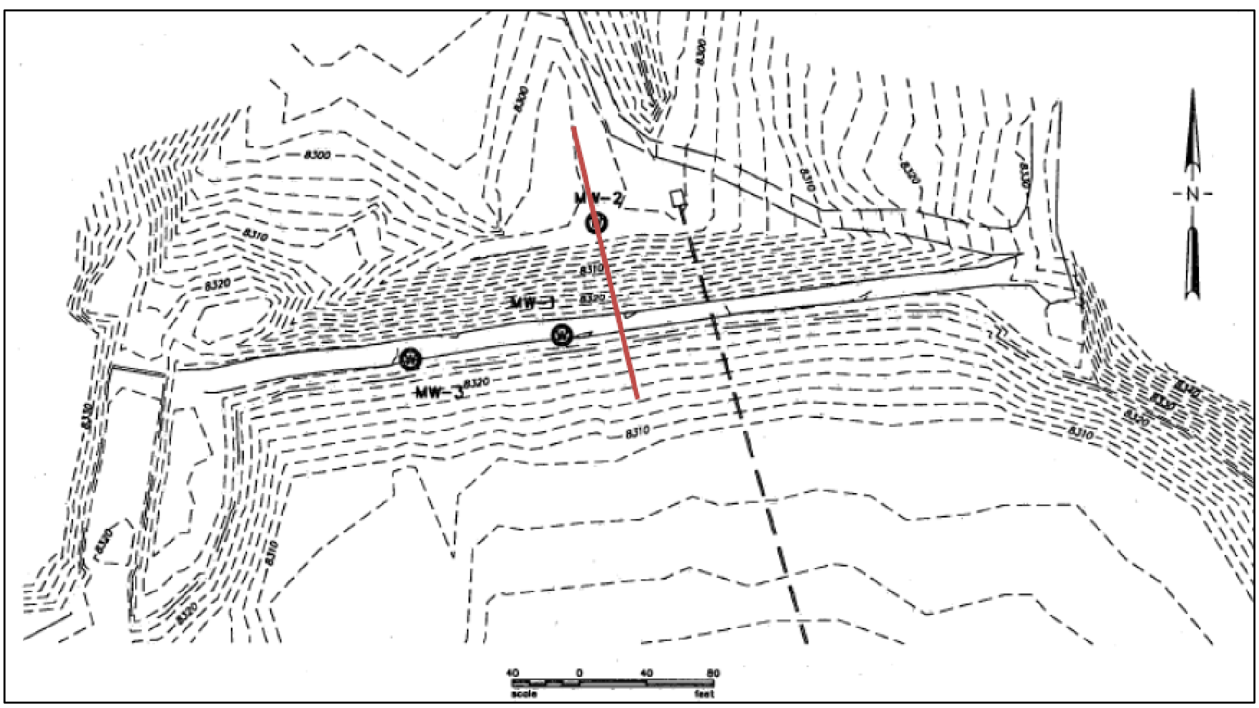

Figure 2.4 – Example of cross section location map in plan view. Note the approximate offset on the map if piezometers do not line up with the cross section.

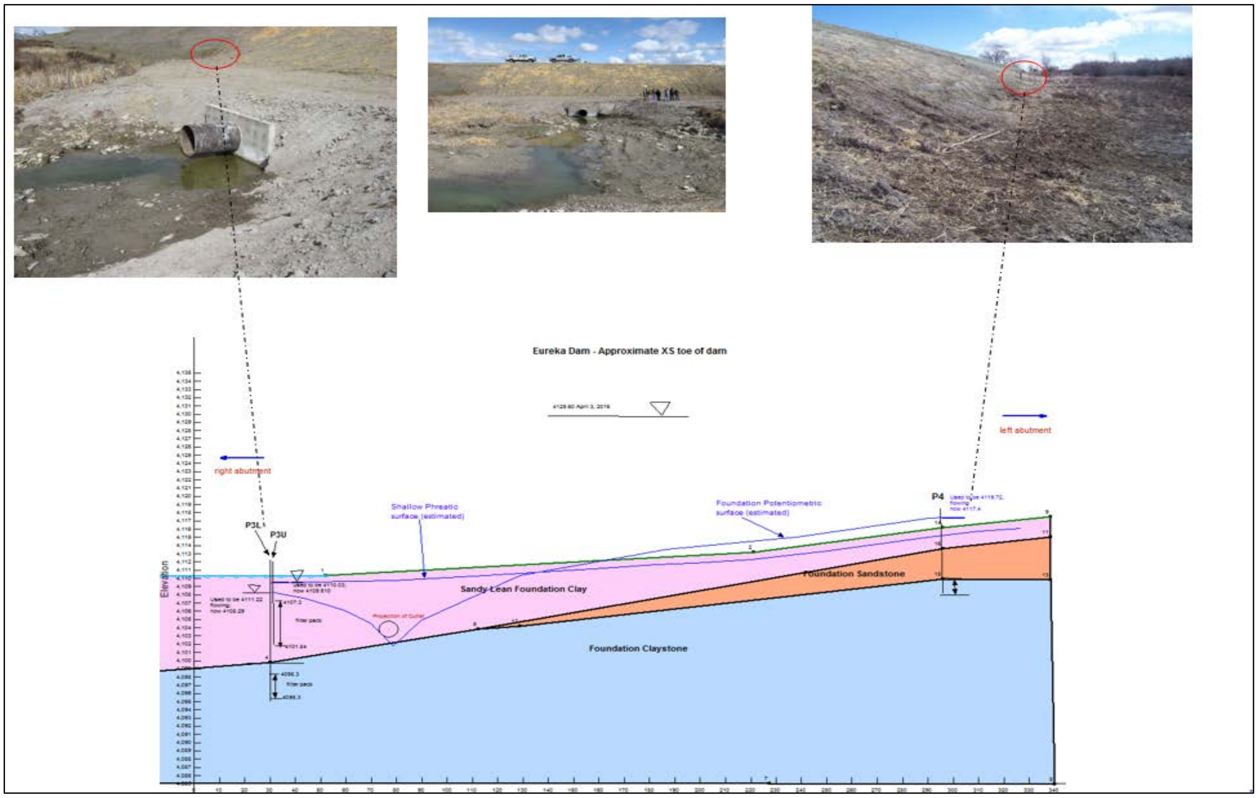

Figure 2.5 – Example of cross section annotated with photographs.

2.2 Compilation and Presentation of Available Instrumentation Data (Step 2)

Piezometric hydrographs, flow measurement hydrographs, and reservoir level correlation plots are commonly used to analyze instrumentation data. Only include plots in the Dam Instrumentation Summary Report if they have significance and support a conclusion. Otherwise, it is acceptable to simply mention these plots are available upon request. This section provides further guidance regarding the development and analysis of these plots.

Note that the raw data for all instrumentation identified in Step 1 should be available upon request. It is not necessary to include raw data in the Dam Instrumentation Summary Report. However, the location of the raw data should be referenced in the report. Other prior analyses can be included as attachments if they are thought to be of significance.

2.2.1 Piezometric Hydrographs

Piezometric hydrographs are plots which show the water surface elevation in the reservoir and pore water pressure as measured in the piezometers plotted on the Y-axis versus time plotted on the X-axis (see example in Figure 2.6). This type of plot illustrates how water levels in the embankment have changed over time with respect to the reservoir level. The following guidance pertains to piezometric hydrograph plots:

1. Horizontal gradients are best determined using piezometer measurements that are representative of the same soil or rock layer (i.e., piezometer influence zones are in the same layer).
2. Vertical gradients require the piezometers to be in the same borehole or very close together and isolated from each other.

3. To compare gradients in nested piezometers, data for both deep and shallow piezometers should be plotted. The potential for gradient reversal can be evaluated by comparing a nested piezometer with the reservoir level. The potential for lag can be evaluated by comparing max measurements between reservoir level and key piezometers (see example in Figure 2.7). It is important to understand if transient conditions exist and how they manifest in measurements; otherwise, incorrect conclusions can be made.
4. When comparing gradients from the abutments, the location of piezometers should be referenced.
5. If water levels are typically low, note the bottom of piezometer to avoid misinterpretation.
6. Plot all available data to date, not just the last five years. Depending on the number of piezometers and amount of available data, multiple graphs should be used if needed for clarity.
7. Note problems or lapses in data on the plot. Do not connect data points using continuous line plots if significant data gaps exist as this is misleading (see examples in Figures 2.6 and 2.8).

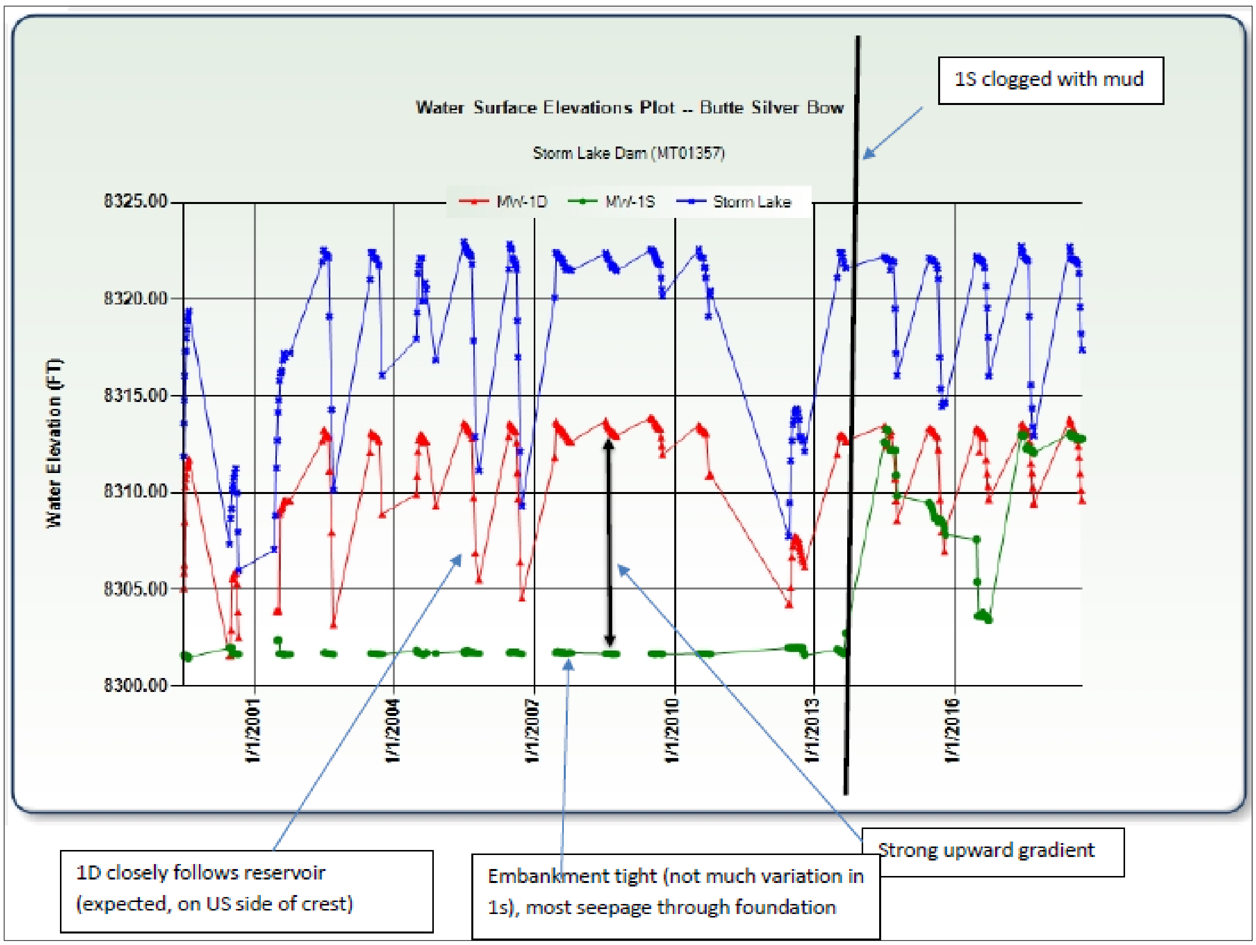

Figure 2.6 – Example of piezometric hydrograph with annotated observations and conclusions.

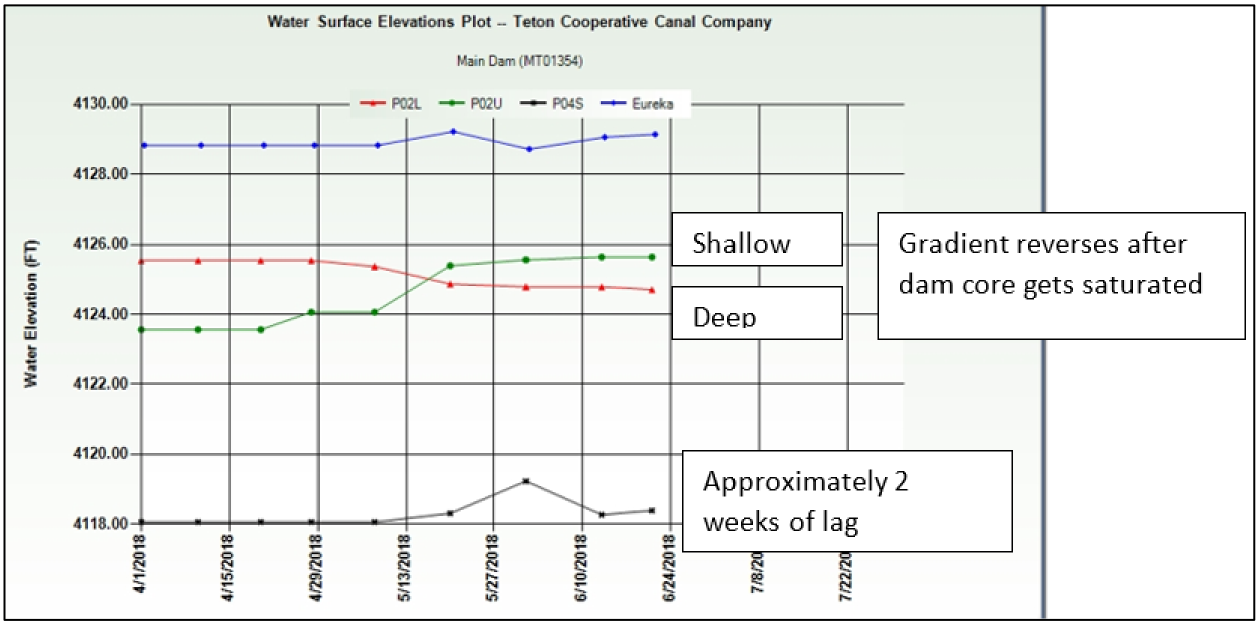

Figure 2.7 – Example of piezometric hydrograph with nested data indicating lag.

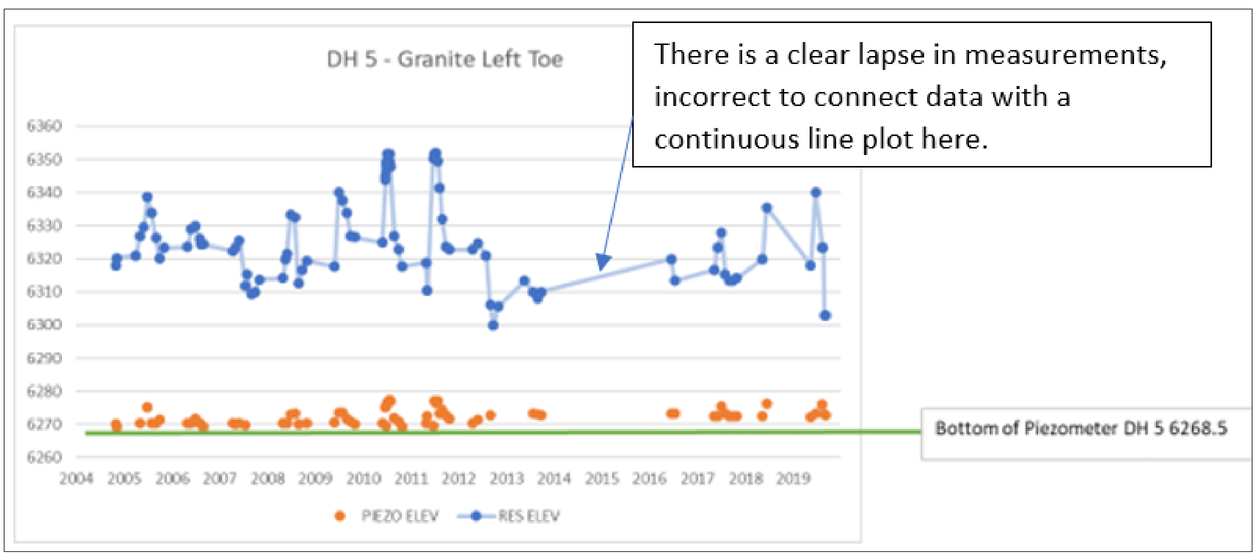

Figure 2.8 – Example of piezometric hydrograph with data gap incorrectly connected using a continuous line.

2.2.2 Flow Measurement Hydrographs

Similarly, flow measurement hydrographs are plots which show the water surface elevation in the reservoir plotted on the Y-axis and flow measurements plotted on a secondary Y-axis versus time plotted on the X-axis. This type of plot illustrates how seepage or other flows have changed over time with respect to the reservoir level. The following guidance pertains to flow measurement hydrograph plots:

1. Discharge gage readings should be converted to a corresponding flow rate in gallons per minute or cubic feet per second.
2. Note the name and location of the flow measurement device on the plot.
3. Groups of flow measuring devices should be included on the same plot as appropriate with a note in the caption indicating why they were grouped together (e.g., all left abutment drains)
4. Annotate the plot with findings and conclusions and develop explanations for inflection points (e.g., an increase in flow tapers off at a certain reservoir elevation when drains typically start to flow full).

2.2.3 Reservoir Level Correlation Plots

Reservoir level correlation plots are also commonly used to compare piezometric data and drain flow data with the reservoir elevation. An example of this type of plot is shown in Figure 2.9. Engineers should use caution in using these types of plots to evaluate overall performance of the dam. Piezometric hydrograph plots which show variation in performance over time are preferred and should be evaluated prior to developing reservoir level correlation plots.

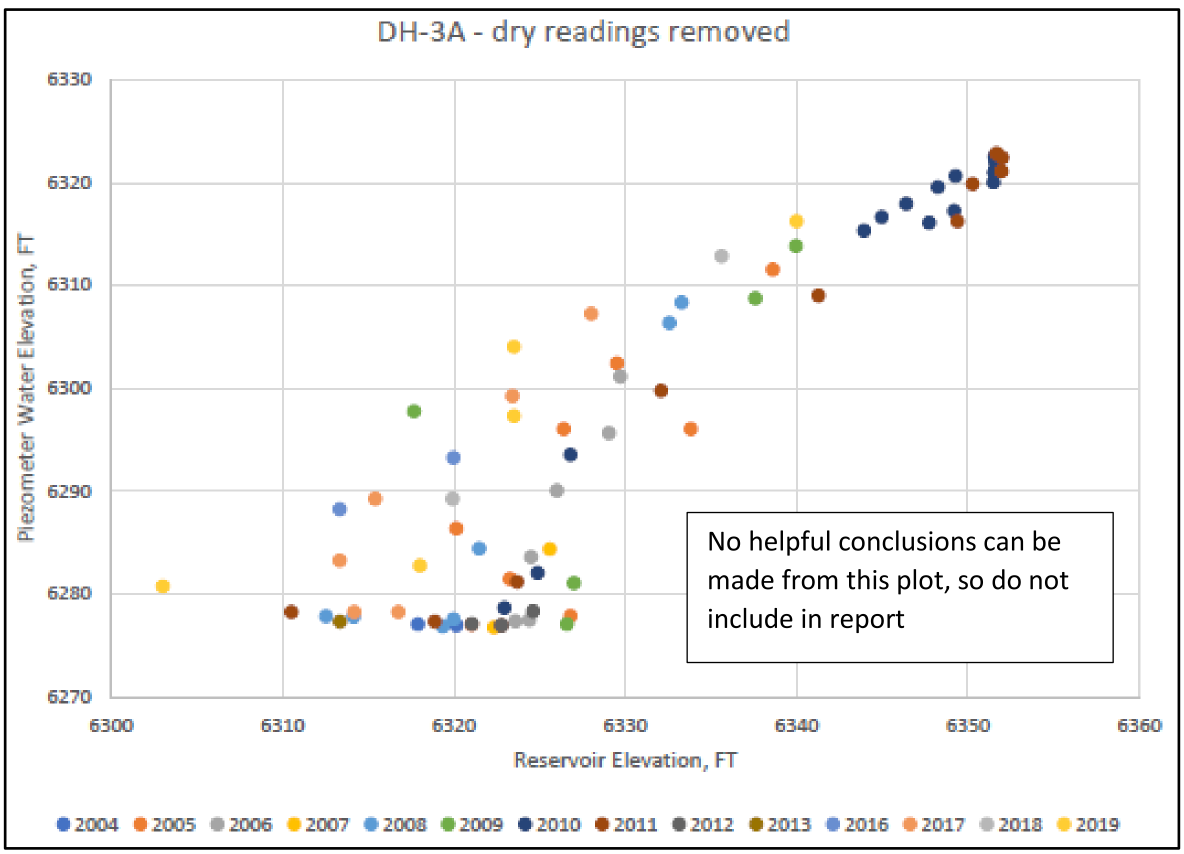

Figure 2.9 – Example of piezometric vs. reservoir elevation correlation plot. This type of plot should not be used unless the purpose of the plot can be clearly articulated.

If these types of plots are to be used, engineers should be able to clearly articulate the objective of the plot and confirm that:

1. There are no data problems (clogging, piezometers improperly constructed, lack of isolation within specific dam/foundation soil layers, data measurement issues).
2. The piezometer zone of influence is isolated in a single embankment/foundation layer. Only plot data that has meaning being plotted together (e.g., all piezometers perforated in a specific foundation layer).
3. The influence of gradients between nested piezometers is understood. If there is a gradient reversal below a certain reservoir elevation, these plots may have limited value without understanding this condition.
4. The influence of lag between reservoir levels and piezometer pore water pressures is understood, including whether there is a difference between filling and drawdown.
5. Explanations for any inflection points in the plotted data can be developed.
6. Significant conclusions drawn from these plots can be reinforced by referencing the cross section.

2.2.4 <u>Applicability</u>

In all cases, the purpose and conclusions of a specific instrumentation data plot should be clearly annotated on the plot. Arbitrary plots with no clear message should not be included. If there is no justification for or conclusions derived from a given plot, then do not include it in the report.

2.3 Data Analyses (Step 3)

In conjunction with developing instrumentation data plots, the Engineer should analyze the data to evaluate the dam's performance, identify any concerning trends or data points, and assess whether any data gaps exist that warrant the installation of additional instrumentation. Items that should be analyzed based on the instrumentation data include:

1. Gradients from left/right dam abutments,
2. Gradients within the dam and foundation,
3. Approximate gradient values (if sufficient information exists),
4. Approximate lag in measurements based on a comparison of filling/drawdown measurements with measurements taken at maximum reservoir levels (these are especially common in piezometers located in dam cores),
5. Approximate uplift pressure calculations (if warranted),
6. Stability assessment based on phreatic surface location/pressures,
7. The rate and volume of seepage and adequacy of existing seepage collection facilities,
8. Concerning trends in data (e.g., increasing or erratic phreatic surface or seepage over time), and
9. Data gaps and recommendations for additional monitoring or further analysis.

Based on these analyses, the threshold and action levels for each instrument, or group of instruments as appropriate, should be reviewed. A threshold level is the value used in the analysis or design or is established from the historic record. An action level is the instrument reading that triggers increased surveillance or an emergency action. Potential failure modes of the dam should be considered by the Engineer as part of the review and assessment of the monitoring program.

2.4 Summary of Findings and Recommendations (Step 4)

A summary section should clearly itemize conclusions and recommendations. The summary should note data collection problems and propose solutions. If completing the instrumentation analysis will take significant time and effort, the summary section can propose a reasonable schedule to complete the required analysis.