Appendix E
Process for Establishing Performance Parameters

E-1. Introduction

a. General. Evaluating the performance of water resource structures is paramount to assuring their safety and continued operation. Thorough and timely judgment of engineers with the knowledge of case specific characteristics of the structure is necessary for an effective evaluation. That knowledge is available from individuals involved with the design, construction, and historical operation as well as from many technical documents developed throughout all phases of the project. The intention of the following guidance is to direct the use of that information to formulate an effective process that indicates the relative performance of the most critical aspects of the structure in a reliable and timely manner. The guidance begins with description of information and process and ends with a comprehensive example.

b. Performance criteria. Project requirements, loading conditions, unique project features, the initial geologic assessment, and site characterization, along with the design criteria for the dam and appurtenant structures, are the basis for the failure mode analysis and establishment of project performance criteria during the earliest phases of design. These performance criteria, generally expressed in terms of design limits and threshold performance limits, are refined as the project proceeds through more detailed levels of design, including design changes necessitated by site conditions more fully revealed during construction. Performance parameters continue to be refined and updated throughout operational life of the project as information acquired from instrumentation, visual observation, and surveillance is evaluated. A summary of the typical process for establishing and updating performance parameters is presented in Table E-1.

Table E-1
Development of Performance Parameters

Activity	Feasibility	Design	Construction	Operation
Initial Performance Parameters				
Project requirements	x			
Design criteria	x	x		
Geologic environment	x	x		
Failure mode analysis and final design		x		
Revised Performance Parameters				
Instrumentation plan		x	x	x
Observations during construction			x	
Documentation of construction			x	x
Initial reservoir filling plan		x		x
Observation and surveillance plan		x		x
Emergency Action Plan				x
Reservoir filling				x
Updated Performance Parameters				
Update with time and subsequent reservoir loading				x

c. Initial performance parameters. During the project formulation and feasibility studies, the initial performance parameters are established. These are based on the project functional requirements, unique project or site features, loading conditions, the initial geological and geotechnical characterization of the site, and the preliminary design criteria for the dam and appurtenant structures. At these early design stages, threshold limits and design limits are generally established based on the experience and judgment of the designers rather than on the basis of rigorous design analyses.

d. Revised performance parameters. As the design progresses, the project site is characterized in greater detail and the physical properties of embankment and foundation materials are defined on the basis of site-specific subsurface investigations and laboratory testing. Using this information, detailed design analyses are performed with appropriate factors of safety for the full range of potential loading conditions, providing a basis for revising the initial performance criteria. During the final design phase, those observations, measurements, and graphical representations required to evaluate the performance of the dam, foundation, or appurtenant feature are identified in the monitoring and surveillance plan. An instrumentation plan is developed to assure that appropriate measurements of seepage, pore pressure, strains, and movements are obtained during the construction and operational phases of the project.

e. Updated performance parameters. The instrumentation plan and the monitoring and surveillance plan are updated during construction based on observations of the exposed foundation, construction modifications, and record control tests. The new information also becomes the basis for further updating performance criteria that will be used to evaluate the response of the structure to loading during the initial reservoir filling, normal conservation pool conditions, and subsequent flood events. The updated plans will establish baseline threshold levels associated with satisfactory project performance and will identify appropriate emergency actions that might be initiated if the threshold levels are exceeded during operation. As performance data are acquired over a range of loading conditions, projections of response at greater loading levels can be compared to original design limits. If projected performance exceeds design limits, appropriate action, consisting of more refined analyses or remedial action, should be considered. Performance criteria should continue to be updated on a regular basis through annual evaluations of instrumentation data and the formal Periodic Inspection program.

f. Summary. In summary, this process is a comprehensive and simple summarization of the existing USACE philosophy for design, construction, and operation of civil works projects. It represents a systematic approach to the evaluation and assessment of project performance based on historical data and loading and the projected performance for the remaining range of loading. This process provides an insight to the designer, operator, and regulator into the actual behavior of the dam and appurtenant structures. When documented and updated in the periodic inspection report, it provides continuity over the project life for routine evaluations and proposed modifications to project purposes.

E-2. Development of Performance Parameters

a. Design intent. From the project purposes, establish the design intent of the dam. Typical project purposes may include flood control, water supply, hydropower, water quality, and recreation. The design intent would be the critical and essential requirements for operation. For example, at water supply and hydropower dams, seepage should be minimized.

b. Critical aspects or features. Determine what aspects or features of the project are considered to be critical or essential for satisfactory performance. Such aspects or features may include reservoir storage capacity; spillway discharge capacity; outlet discharge capacity; structural integrity of embankment dams, levees, and appurtenant structures; the mechanical capability to effect discharge; and integrity of foundations of embankment dams, levees, and appurtenant structures.

c. Behavior of critical features. The anticipated behavior of each feature is established initially during the design phase. Embankment dams, levees, appurtenant structures, and their foundations are designed to provide satisfactory performance with respect to static stability, seepage control, erosion protection for all potential hydraulic loading conditions, and stability during seismic events for normal hydraulic loading conditions. Spillway and outlet features, including consideration of mechanical and electrical features, are designed to accommodate design discharges for all potential hydraulic loadings.

d. Failure modes of unsatisfactory performance.

(1) Unsatisfactory performance is defined as *any response that would lead to unacceptable economic, environmental, health and safety, social, or operational consequences.* Modes of unsatisfactory performance for embankment dams might include overtopping, piping, instability of embankment or appurtenant structures, or erosion. Potential modes of unsatisfactory performance must be identified for each critical aspect or feature of the project. Information that should be considered in the development of potential unsatisfactory performance indicators may include the following:

- Site characterization data (foundation soil and rock geology, groundwater).

- Design analyses, design drawings.

- Construction records (as-built drawings, modification records).

- Instrumentation data and performance evaluations.

- Records of modifications to the project after completion of initial construction.

- Site-specific list of all potential failure modes considered possible at the project.

- Association of each potential failure mode with one or more aspects or features of the project.

Where possible, identify the specific location or locations where each particular failure mode might apply.

(2) Example. A loose sand deposit in the foundation of a dam near the downstream toe may be associated with concerns related to piping or stability. A significant seismic event could cause liquefaction of the deposit, resulting in slope instability. The development of high pore pressures within the deposit in response to a significant flood event could result in piping or slope instability. Site-specific investigations and analyses would be required to define the limits of the deposit in question.

e. Critical performance mechanisms.

(1) Mechanisms causing unsatisfactory performance must be identified. Mechanisms differ from modes of unsatisfactory performance in that each mode of unsatisfactory performance may be the result of several different causative mechanisms. Each mechanism, or combination of mechanisms, associated with each potential mode of unsatisfactory performance must be identified. Each mechanism must be specifically and precisely identified in sufficient detail to allow identification of potential triggers. The cause and effect relationship between a mechanism and a mode of unsatisfactory performance must be understood so that appropriate monitoring parameters can be identified.

(2) Example of piping, which could be caused by the following:

- The movement of the embankment core materials into coarse downstream embankment zones where filters are inadequate or not present.

- The movement of embankment core materials into open joints in inadequately treated abutment or foundation bedrock.

- The movement of groundwater from bedrock joints into adjacent embankment zones.

Each of these different mechanisms could be associated with a piping mode of unsatisfactory performance.

(3) Example of overtopping of the embankment, which could be caused by the following:

- Inadequate spillway capacity.

- Partial or complete blockage of the spillway due to debris accumulation.

- Large waves caused by reservoir slides.

- Mechanical or electrical failure of spillway gates.

f. Potential causes or triggers.

(1) Causes or triggers differ from mechanisms of unsatisfactory performance in that a cause may result in different or multiple mechanisms. For example, a flood event may initiate changes in internal seepage conditions that result in piping. The same event may initiate changes in pore pressures that result in slope instability. One or more potential triggers should be identified for each associated mechanism, and combinations of triggers, occurring concurrently or in sequence, should be considered. The cause and effect relationship between the initiating trigger and the mechanism should be understood. The magnitude and duration of load necessary to initiate unsatisfactory performance should be identified. It should be recognized that unsatisfactory performance may be triggered by unusual events (emergency spillway flow or significant earthquake), average events (freeze-thaw or wet-dry cycles over prolonged period), or extreme events (maximum credible earthquake or the probable maximum flood).

(2) Example. Seismic motion may trigger a number of unsatisfactory performance mechanisms such as liquefaction of foundation soils, liquefaction of pervious embankment zones, sliding of abutment soils or rock falls, transverse cracking of the embankment, or seiche waves overtopping the embankment.

E-3. Monitoring

a. Monitoring methods and devices. Monitoring programs typically include such methods and devices as surveys, piezometers, slope inclinometers, seepage weirs, extensometers, visual observations, and air photos or other remote sensing tools. The selection of monitoring devices and methods should be tailored to the characteristics of each project site and the key parameters that will enable identification of potential modes and mechanisms of unsatisfactory performance. A significant factor in the selection of monitoring devices and methods will be whether the site is manned or unmanned.

b. Key monitoring parameters. Those loads or triggers that can be directly measured and that are associated with a potential mechanism of unsatisfactory performance should be identified. The following typical parameters are subject to monitoring:

- Pore pressures in embankments or foundations (piezometer).

- Seepage quantities (seepage weir or relief well discharge).

- Soil particles carried in seepage flows (turbidity measurement).

- Deformation of embankments or natural slopes (slope inclinometer and surface survey monument).

- Deterioration of slope protection (systematic visual observation and photographs).

- Erosion (systematic visual observation, photographs, and surveys).

- Seismic motions (accelerograph).

- Earth pressures on concrete structures (earth pressure cell).

c. Performance limits.

(1) Identification. The anticipated range of each monitored parameter associated with satisfactory performance should be identified so that unsatisfactory performance can be identified. Threshold levels associated with the onset of unsatisfactory performance must be identified for each monitoring device. It is generally prudent to establish an alarm setting at a level between the range of satisfactory normal performance and the threshold level that will call attention to performance data that exceed historical data trends.

(2) Example. A typical plot of piezometer data versus reservoir elevation may show a linear trend of increasing piezometer level with increasing pool. In flood control projects, the relationship is limited to data between the conservation pool and occasional flood storage events. Projections of the data to levels above historic maximum pool levels can be compared with design assumptions used in seepage or stability analysis to determine if performance with respect to piezometric levels will be acceptable at higher reservoir stages.

d. Load-response relationships. Where monitoring data indicate performance outside historical limits or in excess of established thresholds, a load-response relationship should be developed for each monitored parameter and each loading condition according to the following guidelines:

(1) Review historic data to develop adequate baseline information relating the magnitude and duration of each identified trigger/load to one or more critical performance mechanisms.

(2) Recognize that the relationship can be linear or nonlinear, or linear with a break point at a particular level of loading.

(3) Identify the magnitude and duration of triggers for which:

- The parameter was not measured/monitored or was not quantifiable.

- No response occurred in measured or observed parameters.

- A response occurred with no change in the loading condition.

(4) Develop quantitative relationships where possible and qualitative relationships where data are insufficient.

E-4. Predicting Future Performance

In the prediction of future performance, a performance indicator is developed in the form of a load-response relationship that can be graphically represented. The graph displays the historical data and the predicted future trend of the load versus the response. To develop the performance indicator, a design limit, threshold limit, and evaluation of historical performance are required.

a. Design limits. Design limits are values that represent the limit for acceptable settlement, stability, seepage, etc. that together constitute the performance criteria for a dam. The set of individual design limits constitutes the performance criteria for a dam, established originally during design, and later modified as a result of observations during construction and performance under hydraulic loading.

b. Threshold limits. Threshold limits are warning values, set before the design limits are reached, to allow for modification of the dam or its operation, prior to the onset of unsatisfactory performance. Threshold limits may be revised upward or downward as the performance history is more precisely defined by data collected under various loading conditions.

c. Performance indicators.

(1) Performance indicators are the tools to measure and chart the historical data and predicted future trends against the threshold limits and the design limits. A performance indicator can be graphically represented as a load-response relationship. Visual observations and physical measurements are made to obtain the data necessary to develop the performance indicator.

(2) The following are examples of the load-response relationships for performance parameters:

- Piezometric pressure versus reservoir elevation.
- Seepage flow rate versus reservoir elevation or precipitation.
- Chemical concentration versus reservoir elevation.
- Turbidity versus seepage flow.
- Peak ground acceleration versus vertical or horizontal displacement.
- Movement versus reservoir elevation or rate of reservoir drawdown.
- Erosion versus discharge.

The relationship of these parameters with time should also be summarized and used in the evaluation and decision process.

d. Development and presentation of results. To establish a performance indicator and predict future performance under different loading conditions, the following steps are necessary:

(1) Analyze available information including design criteria and assumptions, construction testing and as-built reports, instrumentation data and analyses, and studies and condition assessments. The historical information will reveal patterns or trends of behavior for the indicator developed. All available information should be included. Note the type, location, and source of the construction testing information and the instrumentation.

(2) Establish the design limit and threshold limit values for the indicator under development. Use of engineering judgment in conjunction with knowledge of the specific design and past performance is necessary and should be thoroughly documented.

(3) Predict the direction and magnitude of change of the load-response relationship for future or greater loading conditions than the dam has experienced. Subsequent observations and measurements will confirm the expected behavior shown in a load-response graph, or influence a change of the predicted behavior.

E-5. Example of Performance Parameters for an Embankment Dam

Following is a hypothetical example illustrating the development of performance parameters for typical seepage and movement conditions. A plan of the dam is shown in Figure E-1.

a. Site conditions. A 100-ft-high, zoned earth embankment is founded on a soil foundation consisting of glacial and alluvial deposits extending as much as 100 ft below the base of the dam. The embankment section consists of an upstream impervious blanket and a central impervious core flanked by upstream and downstream pervious zones composed of well-graded sand and gravel. The inspection trench along the axis of the dam does not provide a seepage cutoff, but the dam has an extensive downstream drainage system designed to collect and safely discharge foundation and embankment seepage. The dam was designed in the 1930s prior to the establishment of modern filter criteria.

b. Reservoir history and instrumentation data.

(1) The reservoir is normally maintained at a low conservation pool (elevation 966 winter and 972 summer) as illustrated on the piezometer plots. (Elevations cited herein are in feet referred to the National Geodetic Vertical Datum (NGVD).) The record pool, spillway crest, and maximum pool elevations are 991.0, 1010.0, and 1030.8, respectively. Therefore, the dam has been subject to approximately 57 percent of the hydraulic loading that it will experience at spillway crest, and 39 percent of the hydraulic loading that it will experience at maximum pool.

(2) Piezometer levels are plotted versus time (Figure E-2) and reservoir level (Figure E-3) for all instruments and reported in the annual evaluation of instrumentation data. Plots of slope indicator deflection versus depth are also presented in the annual instrumentation evaluation report (see Figure E-4). Performance parameters, in the form of load-response plots, are developed only for instrument data, or groups of instrument data, in an area of concern for a performance condition.

c. Evaluation of seepage condition. In this example, high piezometric levels in piezometer P-13B at the toe of the main portion of the dam at the base of the left abutment (Figure E-1) cause concern for piping of erodible silt foundation soils from the foundation of the dam into a coarse gravel drainage layer that does not meet filter criteria. A performance parameter has been developed for piezometric levels at the toe of the dam versus reservoir stage (Figure E-3). Historic data have been projected to estimate piezometric levels in response to a reservoir stage at spillway crest. Threshold levels have been identified based on factors of safety against piping for critical piezometric levels in the area of concern. The lower limit of the threshold zone establishes an *alarm level* above the range of historic data and below the design factor of safety. The example performance parameter shows that the factor of safety for the data representing this particular location will reach unity at a reservoir level of approximately 1020, which is below the maximum potential pool elevation of 1030.8. The plot also shows that the factor of safety relative to piping is approximately 1.25 for a reservoir at the spillway crest elevation.

d. Evaluation of movement condition. High piezometric levels in piezometer P-11B and movements in slope inclinometers SI-1, SI-2, and SI-3 as shown in Figure E-1, cause concern for slope stability within the right portion of the embankment, which overlies a weak foundation clay layer. Slope inclinometer data for hypothetical instrument SI-3 (Figure E-5) shows the development of a distinct zone of movement approximately 52 ft below the ground surface. A plot relating the gradually increasing magnitude of movement at this depth versus time is shown in Figure E-4. A corresponding plot of reservoir elevation versus time, also shown in Figure E-4, establishes a relationship between movement and reservoir changes. A threshold level for maximum tolerable total movement provides a basis for estimating the amount of time required to reach the threshold in the absence of flood events, or the magnitude of flood event required to accelerate movements to the threshold level. The developed performance parameter shows that, based on the rate of movement over the past 5 years (i.e., 0.010 in./month), the threshold limit (an additional allowable movement of 0.66 in.) will be reached in approximately 66 months. Data from the highly active 1996 calendar year show that the time to reach the threshold could be reduced to 36 months. The data from the 1998 flood event also show that the threshold could be reached as a result of as little as two individual major flood events.

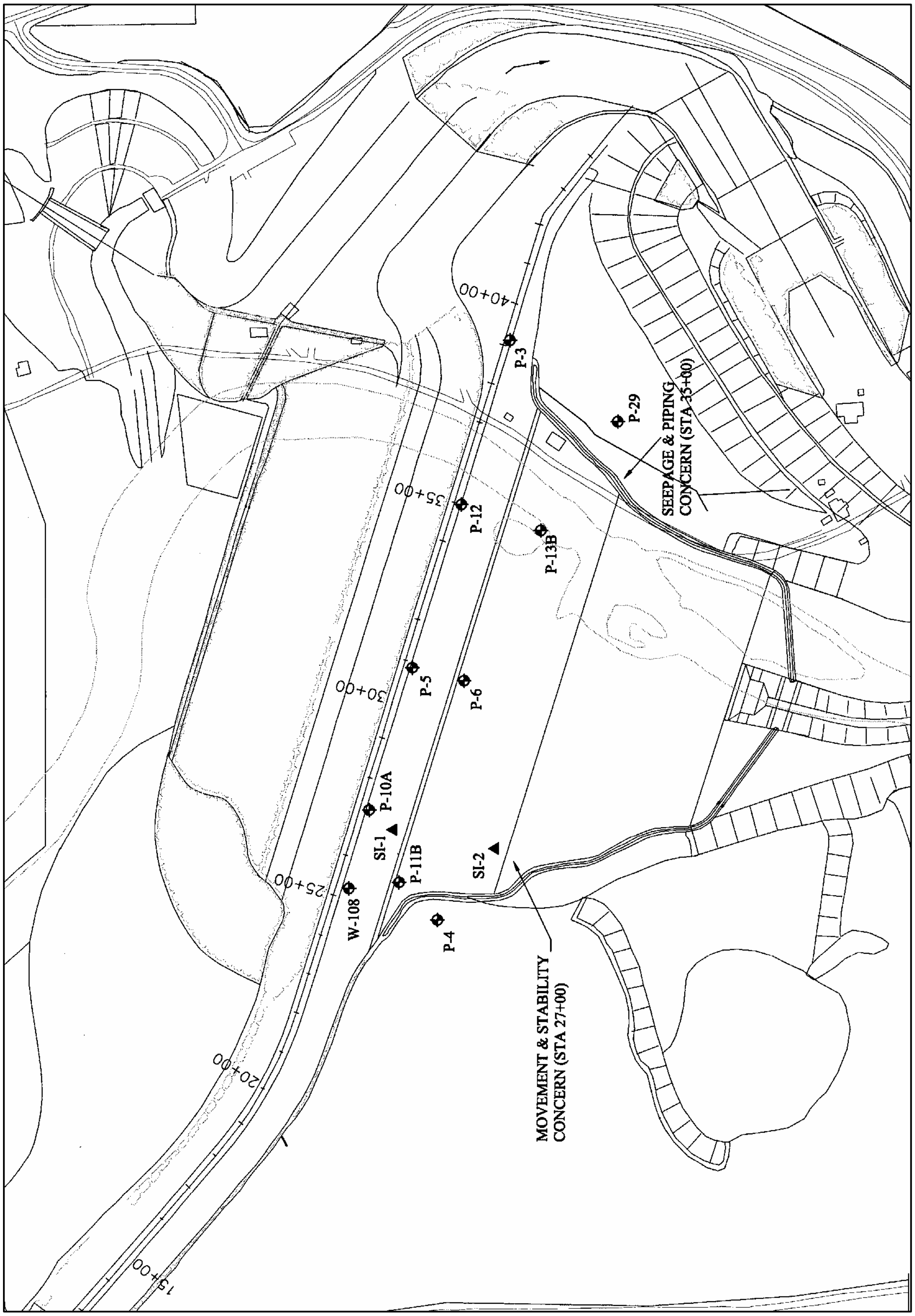


Figure E-1. Plan of instrumentation

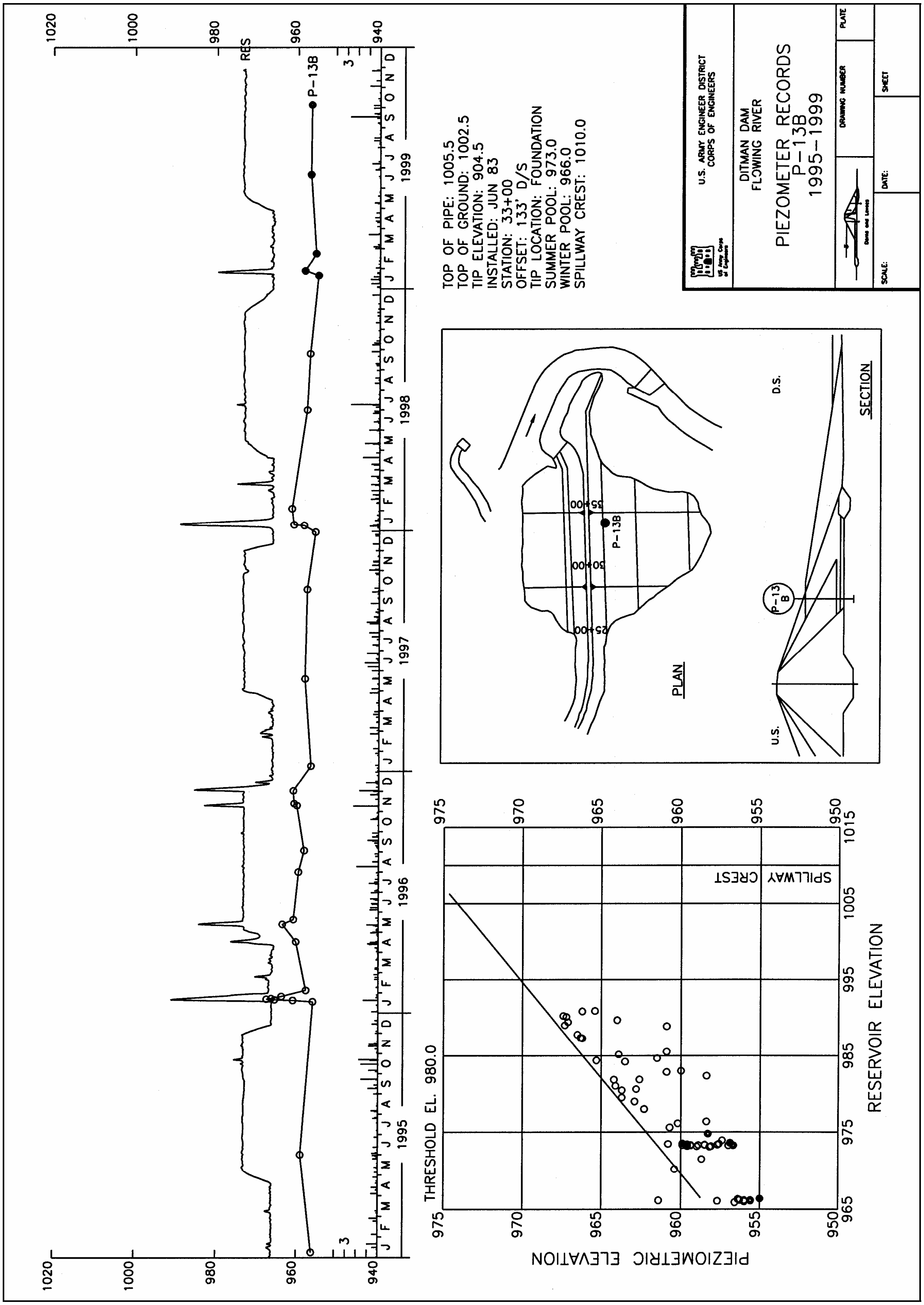


Figure E-2. Typical piezometer plot

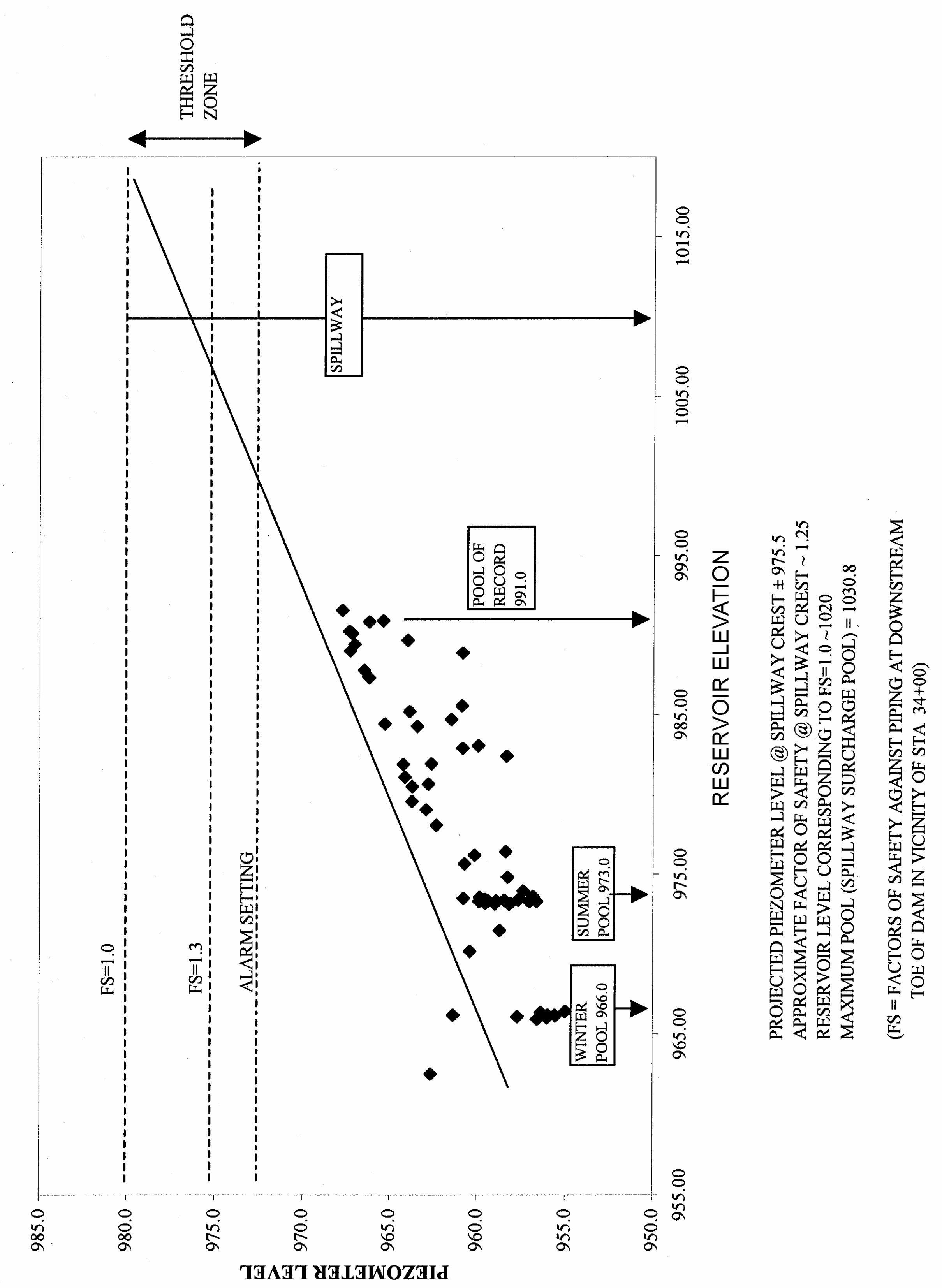
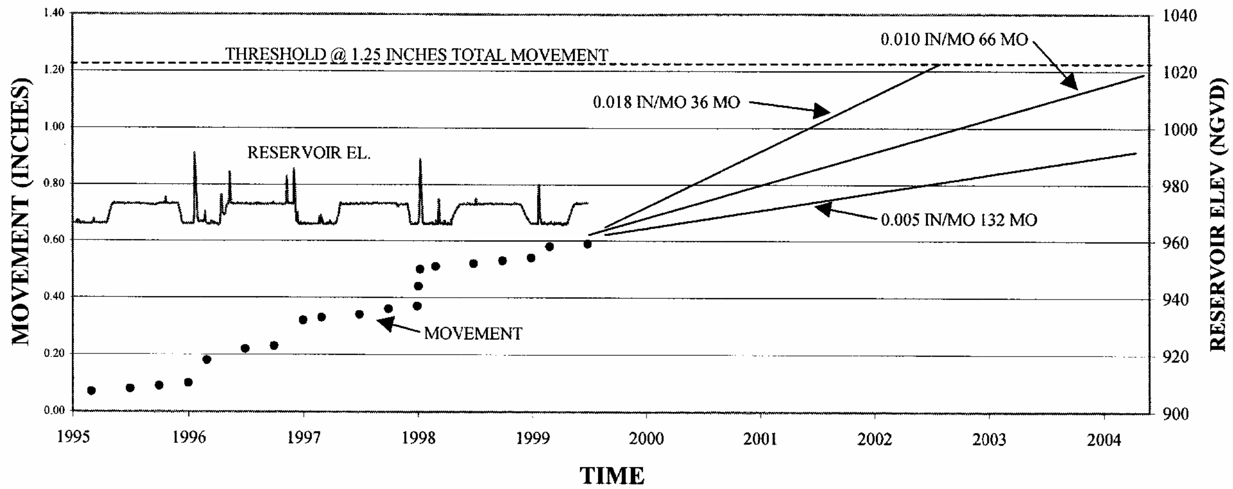


Figure E-3. Load – response (piezometer level versus reservoir elevation) at toe of dam at approximately sta 34+00



MOVEMENT @ 55 to 57'

ADDITIONAL MOVEMENT TO REACH THRESHOLD = 1.25 - 0.59 = 0.66 INCHES

DATE	TOTAL MOVEMENT
01-Mar-95	0.07
01-Jul-95	0.08
01-Oct-95	0.09
01-Jan-96	0.10
01-Mar-96	0.18
01-Jul-96	0.22
01-Oct-96	0.23
01-Jan-97	0.32
01-Mar-97	0.33
01-Jul-97	0.34
01-Oct-97	0.36
01-Jan-98	0.37
05-Jan-98	0.44
10-Jan-98	0.50
01-Mar-98	0.51
01-Jul-98	0.52
01-Oct-98	0.53
01-Jan-99	0.54
01-Mar-99	0.58
01-Jul-99	0.59

1) AVG RATE OF MOVEMENT MAR 95 TO JUL 99 $= \frac{0.59 - 0.07}{51 \text{ mo}} = \frac{0.520}{51} = 0.010$ IN/MO

2) MULTI-EVENT PERIOD JAN 96 TO JAN 97 $= \frac{0.32 - 0.10}{12 \text{ mo}} = \frac{0.220}{12} = 0.018$ IN/MO

3) MAJOR EVENT RESPONSE Jan-98 $= \frac{0.50 - 0.37}{0.35 \text{ mo}} = \frac{0.13}{0.35} = 0.371$ IN/MO

4) TYPICAL INACTIVE PERIOD JAN 98 TO JUL 99 $= \frac{0.59 - 0.50}{18 \text{ mo}} = \frac{0.09}{18} = 0.005$ IN/MO

Figure E-4. Deflection/threshold movement

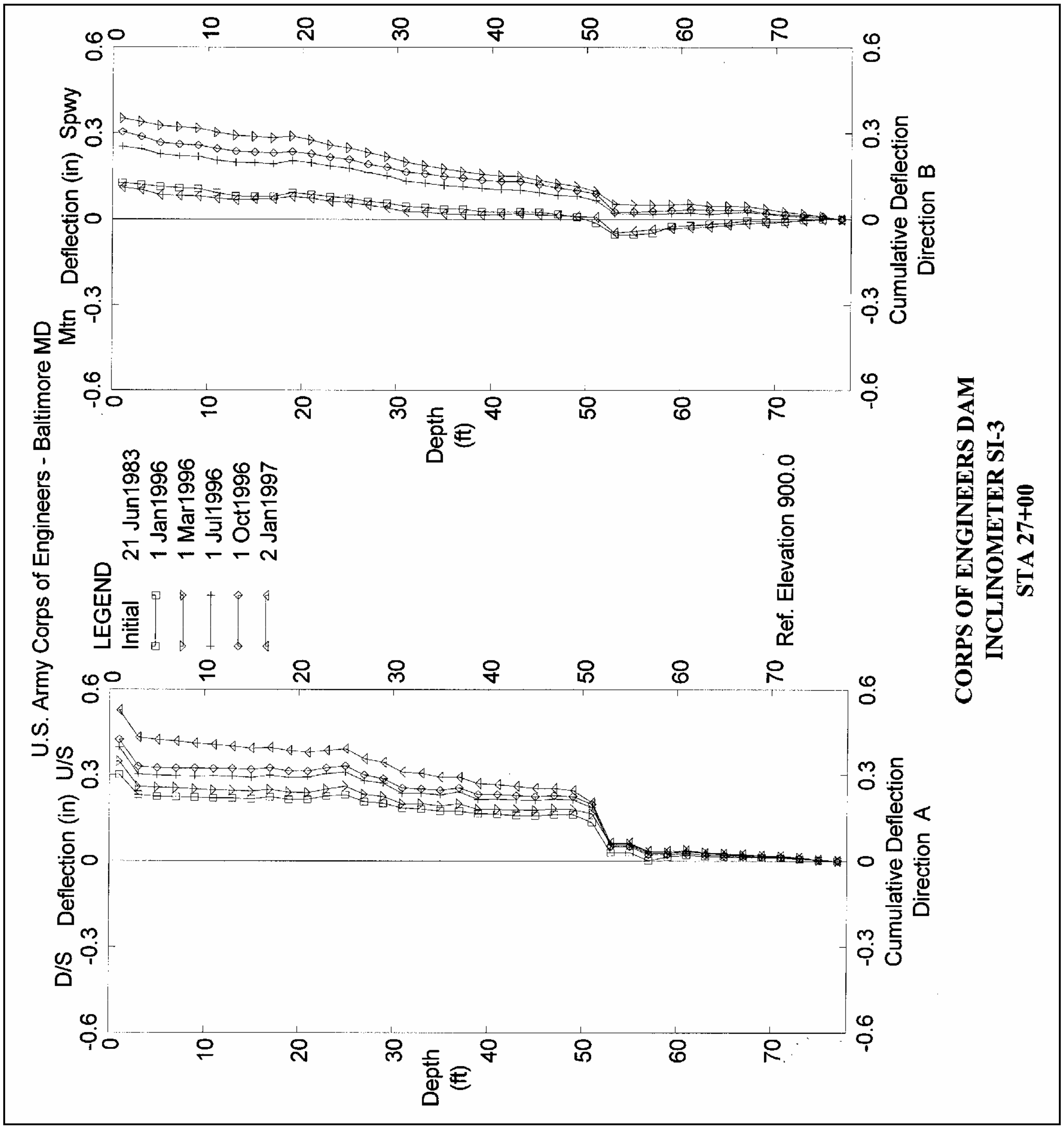


Figure E-5. Typical inclinometer plot