CHAPTER 13
MONITORING PERFORMANCE OF SEEPAGE CONTROL MEASURES

13-1. General Considerations.

a. Before seepage control measures are implemented, site characterization by thorough exploration and testing is needed to determine if the seepage control measures will serve the intended purpose. Knowledge of the in situ site conditions along with the purpose of the seepage control measure and its physical dimensions will help determine' the overall number and the placement of monitoring devices. Several factors which can be monitored that can lead to a conclusion regarding the safety of a dam are: (1) progressive increase in the volume of seepage flow, (2) removal of solids by the seepage, (3) increased uplift pressures or locally depressed gradients, and (4) soft or wet areas on the downstream embankment.

b. Monitoring the performance of seepage control measures can lead to a collective conclusion drawn from several measurements. The most common and easiest monitoring is to rely on visual observations along with careful surface inspections at predetermined intervals. Another type of monitoring which should be completed before construction is the installation of piezometers, observation wells, and drainage collection systems to determine a site dependent pattern of behavior. Finally, the actual structure should be monitored by the installation of a site specific network of piezometers, observation wells, and drainage collection systems with flow measurements designed for the anticipated seepage problems. A regular review of the data collected will generally detect major changes between subsequent readings but equally as important are the long-range trends manifested by steady changes or intermittent surges.

c. If it is determined during the monitoring process that a possible problem exists, an expanded instrumentation program may be needed. This could include more piezometers, relief wells, etc., and a more extensive analysis of the seepage water; i.e., both a physical and chemical analysis of the sediment and water including temperature, salt content, and resistivity which could be compared with samples from the embankment and possible seepage sources. According to the complexity of the problem and/or the economics versus safety involved a group of other studies could be added including, but not limited to: resistivity and spontaneous potential of the embankment and foundation, dye tracing, infrared (aerial or portable ground based), and seepage acoustic emissions. In most cases, the scope of the monitoring program will be determined by the economics involved.

13-2. Piezometers for Seepage Pressures.

a. Foundation. To determine the performance of seepage control measures, a pattern of behavior should be established prior to and during construction where long-term trends can be related to design or seepage conditions. Piezometers should generally be installed in all compressible foundation soils, the number being dependent on the extent and thickness of the strata. If possible, foundation piezometers should be installed-in the sections selected for embankment piezometers and should extend beyond the upstream and downstream toes a distance equal to the expected migration of pore pressures. An effective piezometer installation plan should convert preconstruction piezometers into postconstruction seepage monitoring piezometers for an effective continuity of data. Shown in figure 13-1 is an example of a piezometer installation with the embankment resting on a compressibility foundation (Chapter 9) and an impervious core cutoff through a sand and gravel layer. Effectiveness of the cutoff and the presence of uplift pressures can be evaluated. Shown in figure 13-2 is an embankment with an impervious core that intercepts a pervious soil and rests on the top of rock (Chapter 11) and again the effectiveness of the cutoff and/or the integrity of the rock can be evaluated. Shown in figure 13-3 is an embankment founded on a thin impervious top stratum underlain by a deep zone of pervious material (Chapter 9). In this case a cutoff was impractical and seepage pressures are simply monitored beneath the dam to determine time effects on the control measures while the effectiveness of relief wells downstream is determined with foundation piezometers. An effective monitoring system should also include piezometers in the abutments to determine the effectiveness of drains and/or of the embankment-abutment interface which could include grout curtain cutoffs (Chapters 10 and 11). Also artesian flows may exist in the abutments and need to be monitored. Shown in figure 13-4 is a piezometer installation that is used to monitor a grout curtain cutoff and cut-slope drains. Remedial seepage control measures, discussed in Chapter 12, might require additional piezometers to monitor both the installation and the effect of the new measures.

b. Embankment. As discussed in Chapter 8 three methods for seepage control in embankments are: (1) flat slopes with or without drains, (2) embankment zonation, and (3) vertical (or inclined) and horizontal drains. An embankment with flat slopes (as defined in Chapter 8) constructed of impervious material, and which has infrequent high reservoir levels, should have only enough piezometers in the embankment to establish the phreatic surface. A typical example is shown in figure 13-5. To monitor seepage control measures in a zoned embankment (Chapter 8) the number and spacing of piezometers depend not only on the height of the dam but also on the material properties of the zones. The core must be monitored to determine the phreatic

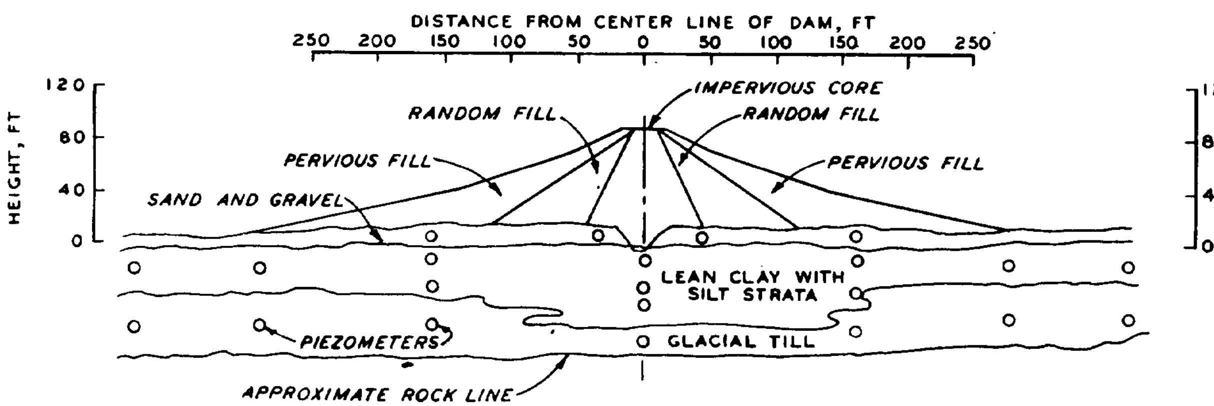

Figure 13-1. Example of foundation piezometer installation of Surry Mountain Dam (from EM 1110-2-1908)

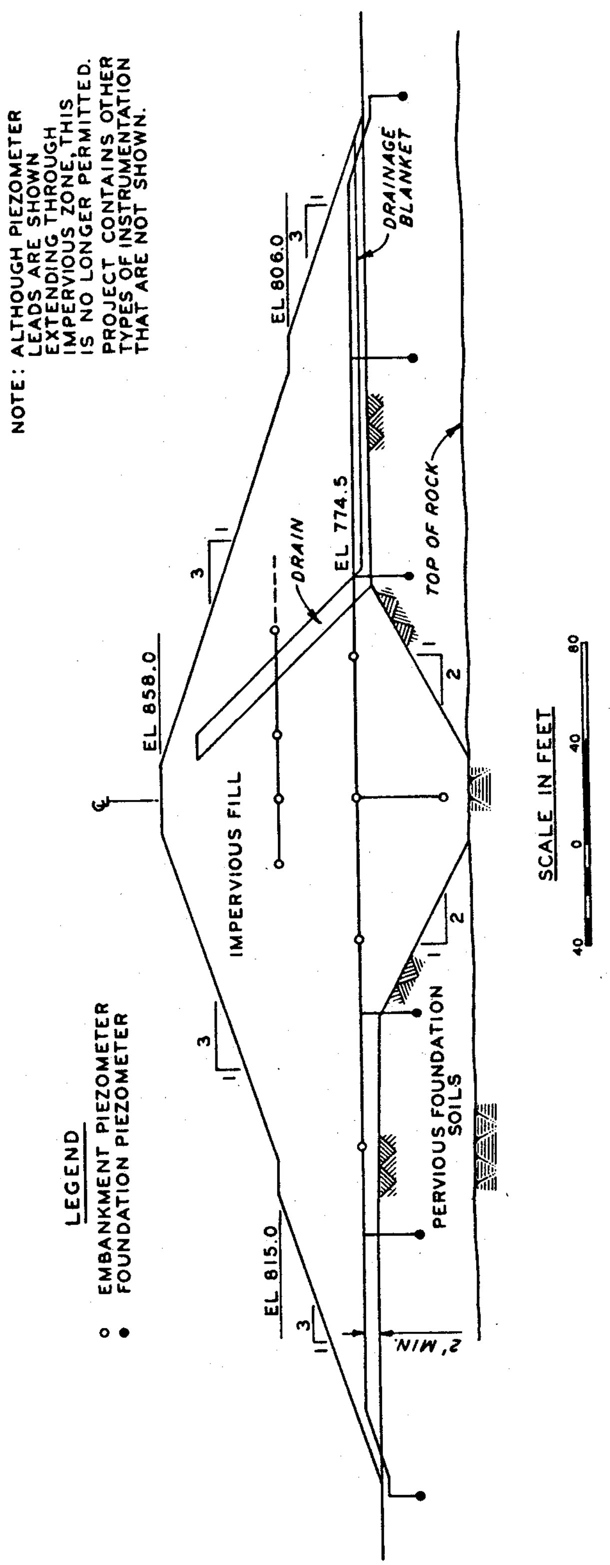

Figure 13-2. Piezometer installation for dams on pervious foundations, Deer Creek Dam (from EM 1110-2-1908)

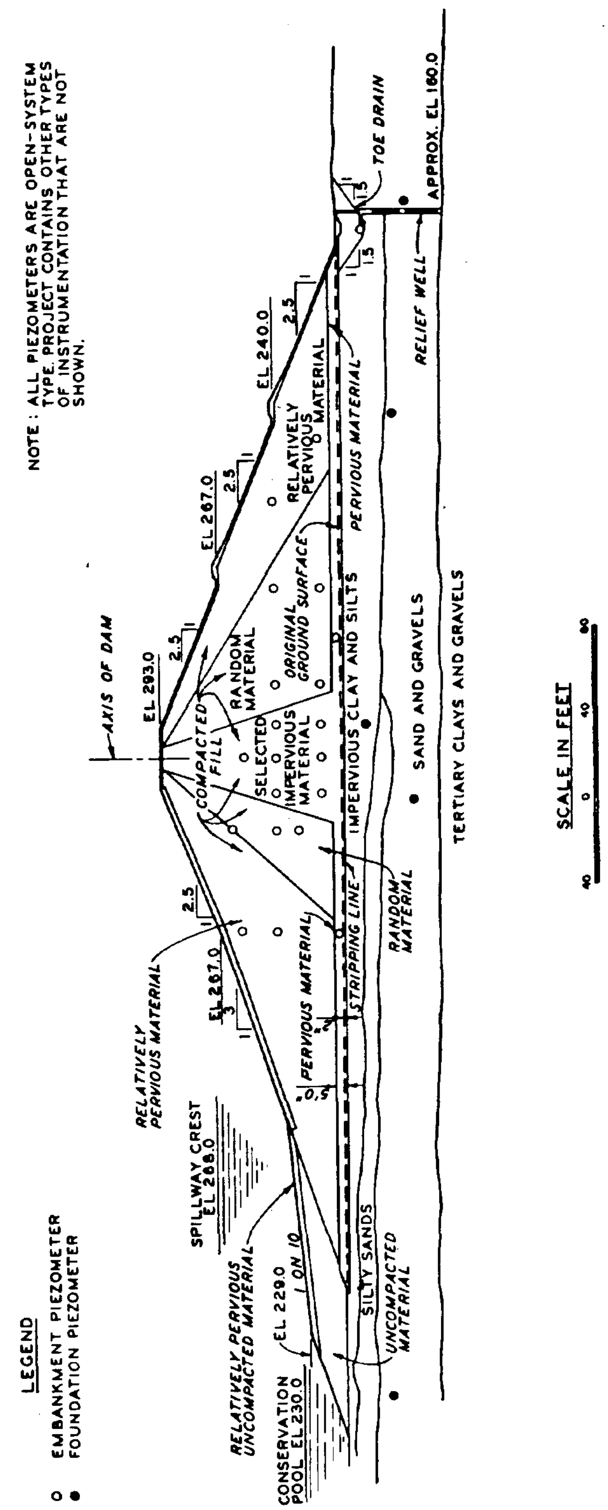

Figure 13-3. Piezometer installation with a thin impervious topstratum and relief well systems, Enid Dam (from EM 1110-2-1908)

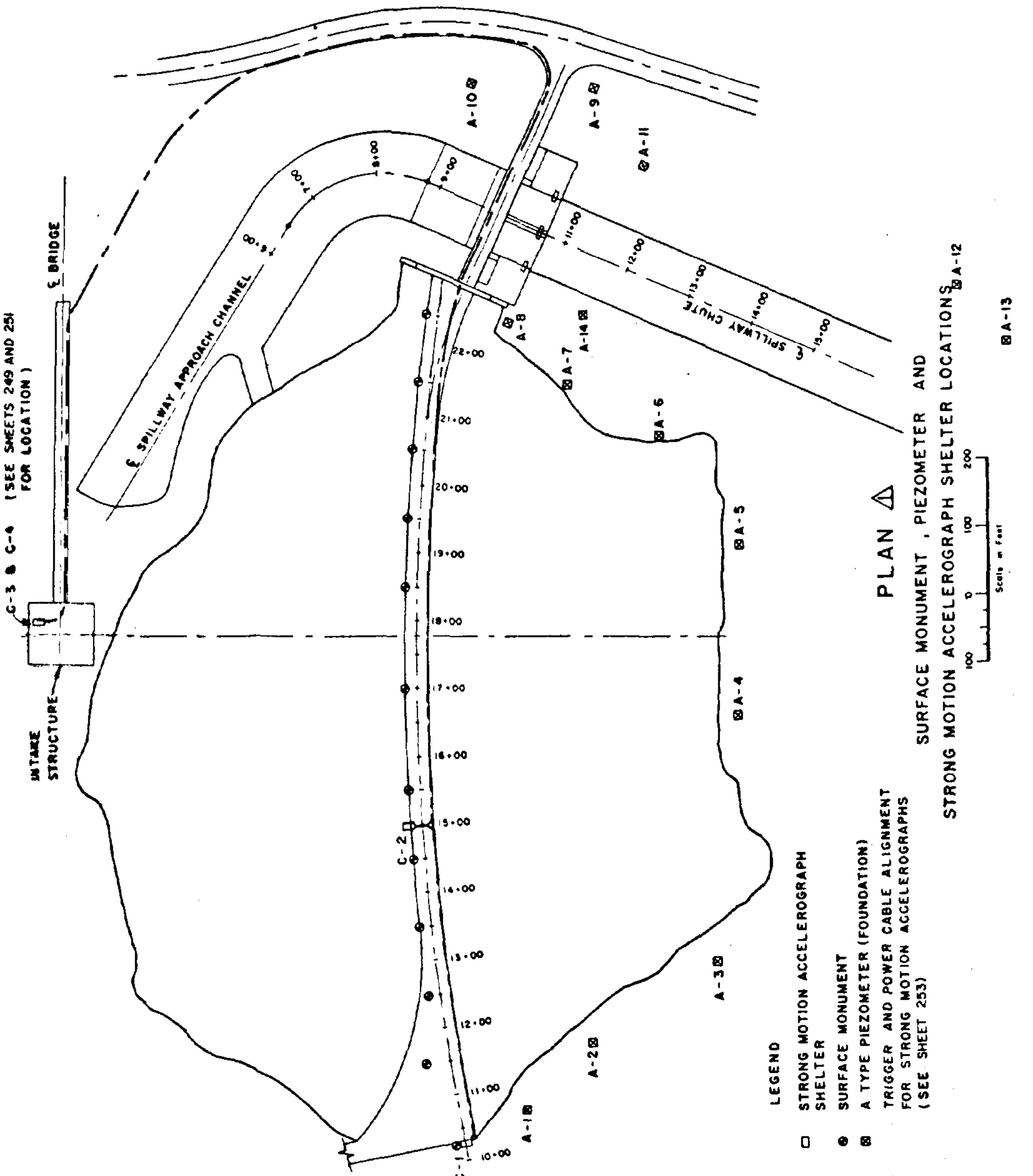

Figure 13-4. Piezometer installation for dam abutments having grout curtains or cut-slope drains, Applegate Lake Dam (from U. S. Army Engineer District, Portland[104])

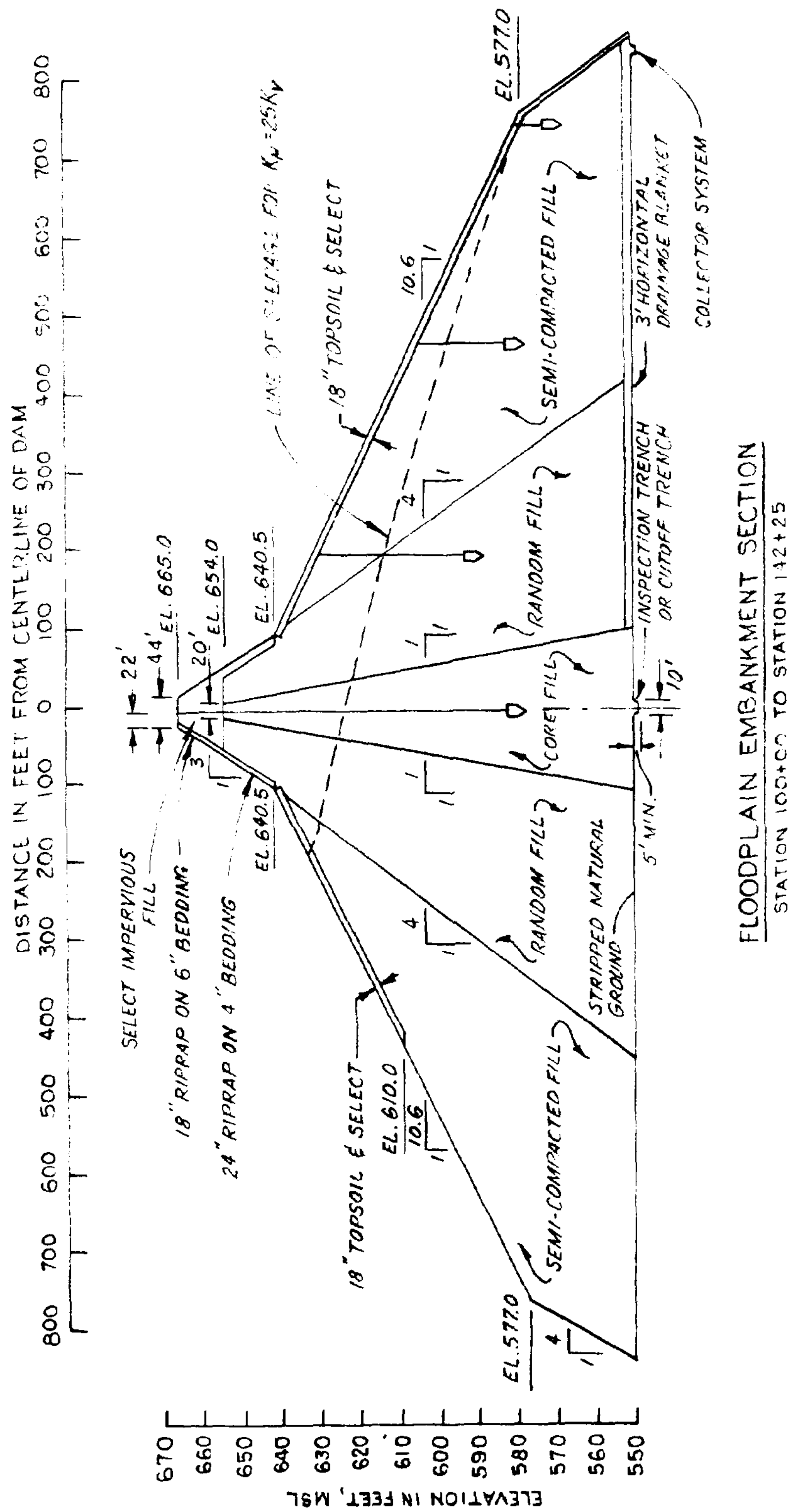

Figure 13-5. Estimated seepage for Aubrey Dam, Texas (from U. S. Army Engineer District, Fort Worth[81])

surface and in situ permeability. Using this information, cracking potential can be estimated. On either side of the core there can be filters, transition zones, random zones, outer shells, and blankets (Chapter 8). In general, the different zones should increase in permeability outward and should have piezometers in each zone. During rapid reservoir drawdown, the upstream piezometers would detect excess pore pressure buildup while during conservation and high pools, all the piezometers would indicate the effectiveness of the zones and check design values. A typical installation in a zoned embankment is shown in figure 13-3. In a zoned embankment the piezometers located near the upstream core face can be instrumental in determining the development of cracking in the core (Vaughan et al. 1970). Depression of the piezometric elevation in a localized area (cone of depression) can indicate velocity head loss which would indicate leakage through the core. Remedial work for Baldershead Dam (Vaughn et al 1970 and Lovenburg 1974) included placement of a large number of piezometers near the upstream face of the core (figure 13-6) which were successful in indicating piezometric depressions.

c. Drains. The purpose of vertical (or inclined) and horizontal drains is to control seepage either through the embankment or beneath the dam (underseepage). A vertical (inclined or horizontal) drain in the embankment may be used as a filter to prevent material from eroding from the core and/or as a method of collecting seepage exiting from horizontally stratified soil layers. Enough piezometers should be installed in the drain to determine if the seepage is coming through the embankment material or if it is underseepage, figure 13-7. If the horizontal drains intercept underseepage which in turn is drained by lateral drains, piezometers should be placed on either side of the laterals to determine their effectiveness, figure 13-8. Long-term trends (pressure buildup or depression) detected in the drains not directly related to the reservoir level could indicate either clogged drains (pressure buildup) due to embankment or foundation material moving into the drains or piping and erosion (pressure depression) due to material moving into pipe drains, high permeability zones, or into fractured rock. Toe drains are effective in collecting seepage and preventing saturated areas along the downstream toe. Piezometers in or near toe drains would only be effective when a downstream blanket has been added and uplift pressures need to be measured. Drainage galleries and tunnels are used mostly in abutments in the United States to intercept and control seepage in fractured rock. Drainage tunnels along extensions of the dam's axis or in downstream abutment areas serve to collect seepage. Piezometers located near the drainage tunnels would indicate the effectiveness of the tunnel. Cut-slope drains can be used to intercept seepage and collect drainage along abutment slopes while piezometers placed both upstream and downstream of the drains can determine effectiveness of the collection system, figure 13-9.

d. Downstream Areas. Seepage can migrate beyond the embankment toe particularly in clay shale or fissured formations. Geologic site characterization in most cases will determine the need for piezometers downstream of the toe but if there is any doubt they should be installed in the questionable formations 50 to 150 ft beyond the toe, figure 13-1. Piezometers should also be installed downstream of the outlet works, spillway, and stilling basin if they extend well beyond the toe and are not close to other piezometers.

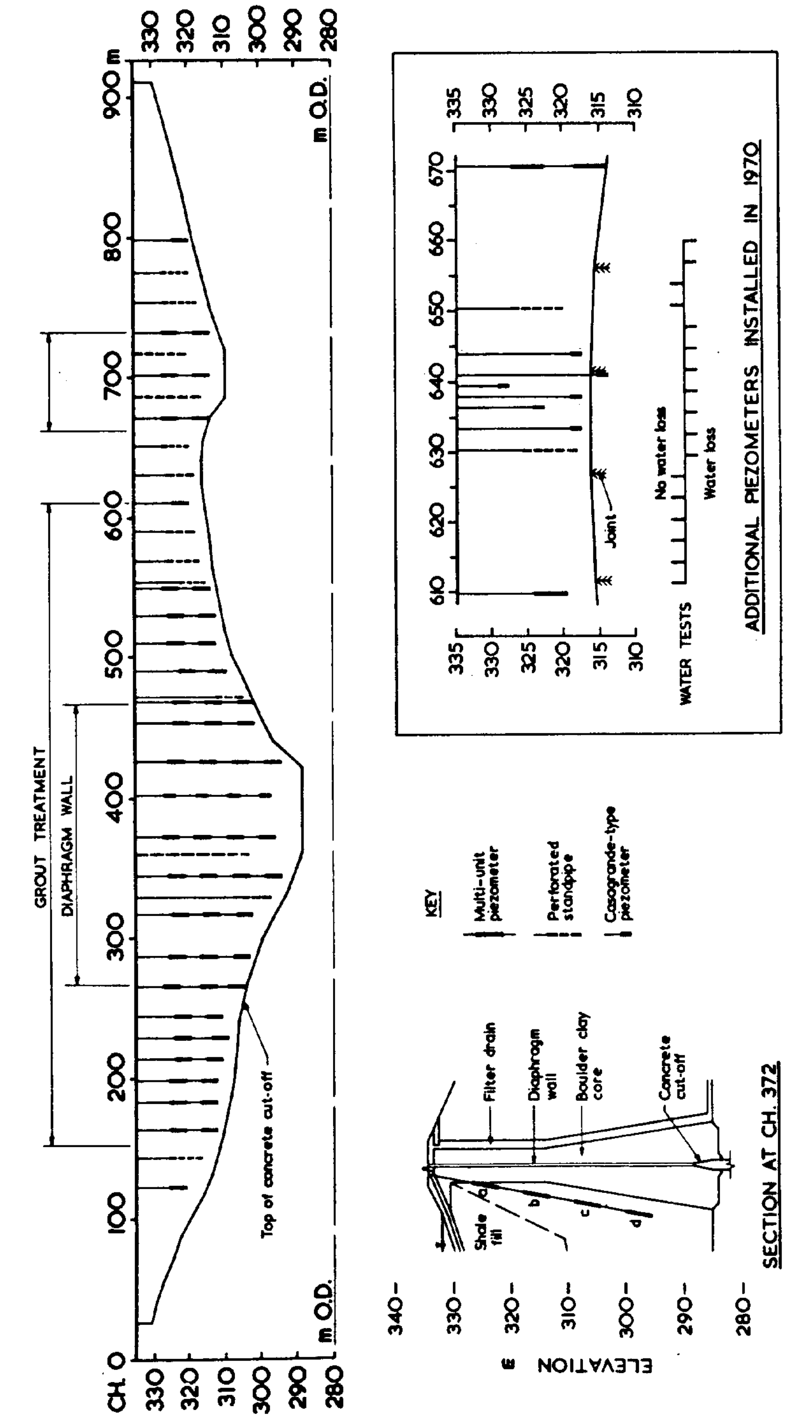

Figure 13-6. Layout of Baldershead Dam piezometer installation in upstream shale fill (courtesy of British Geotechnical Society[212])

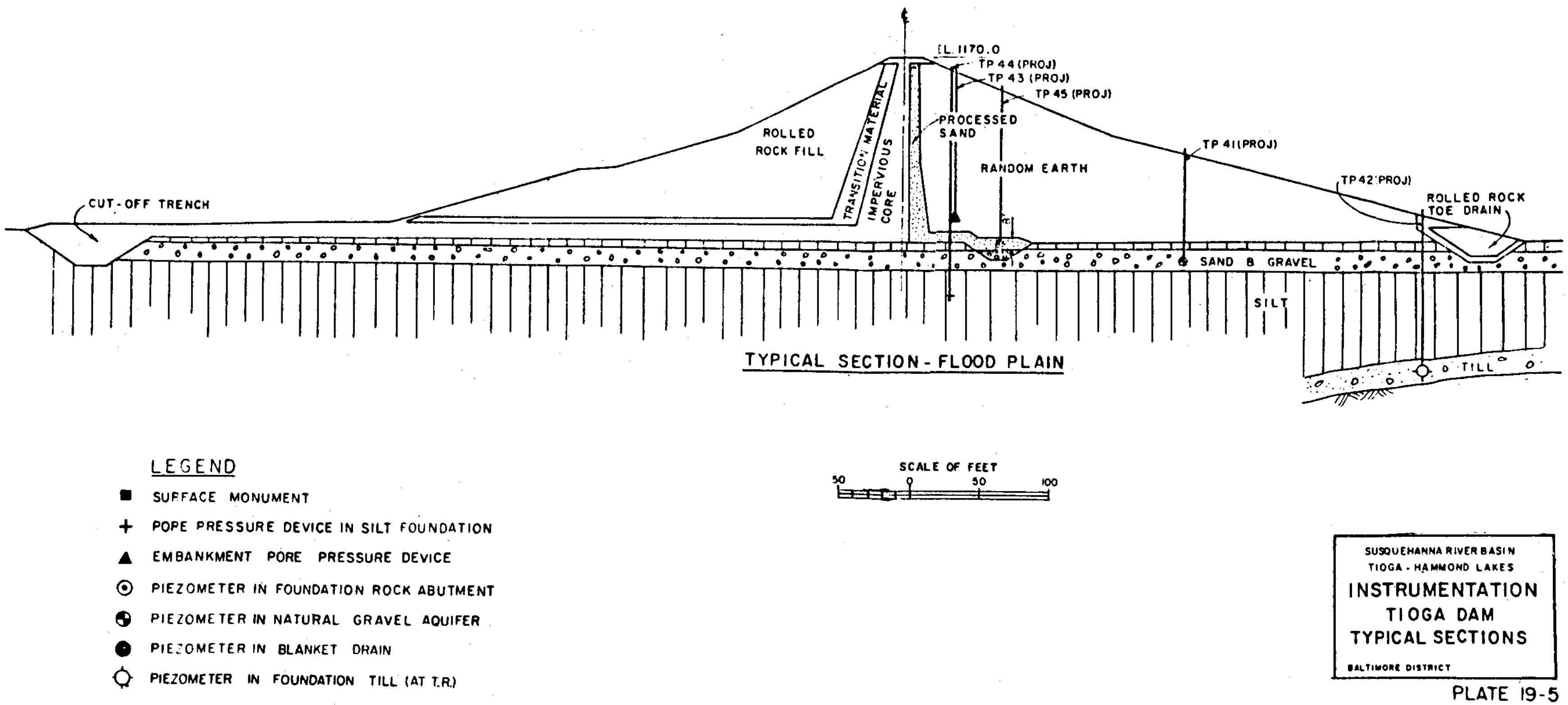

Figure 13-7. Piezometer installation for dams with through seepage and underseepage (from U. S. Army Engineer District, Baltimore[79])

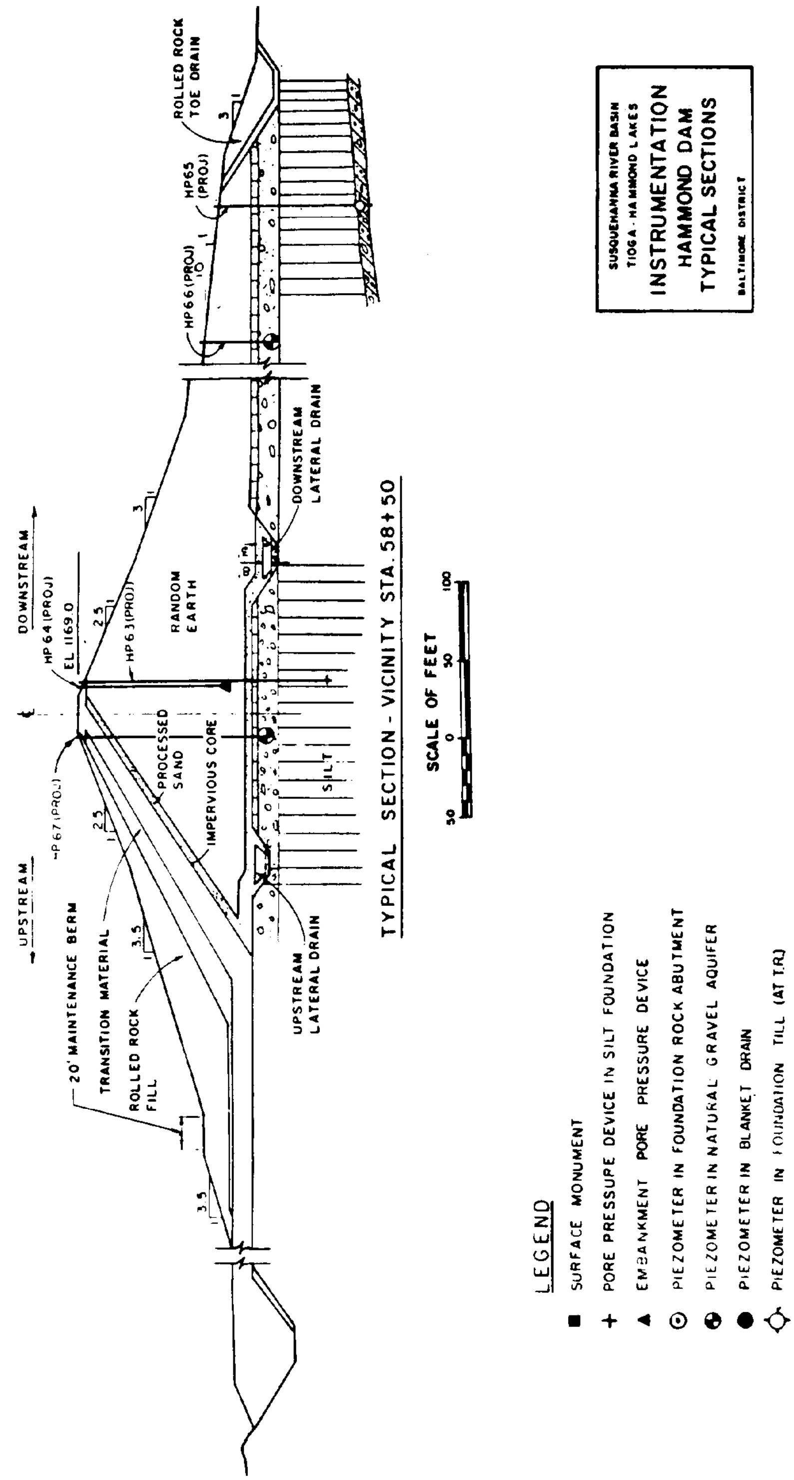

Figure 13-8. Piezometer installation for dams with lateral drains (from U. S. Army Engineer District, Baltimore[79])

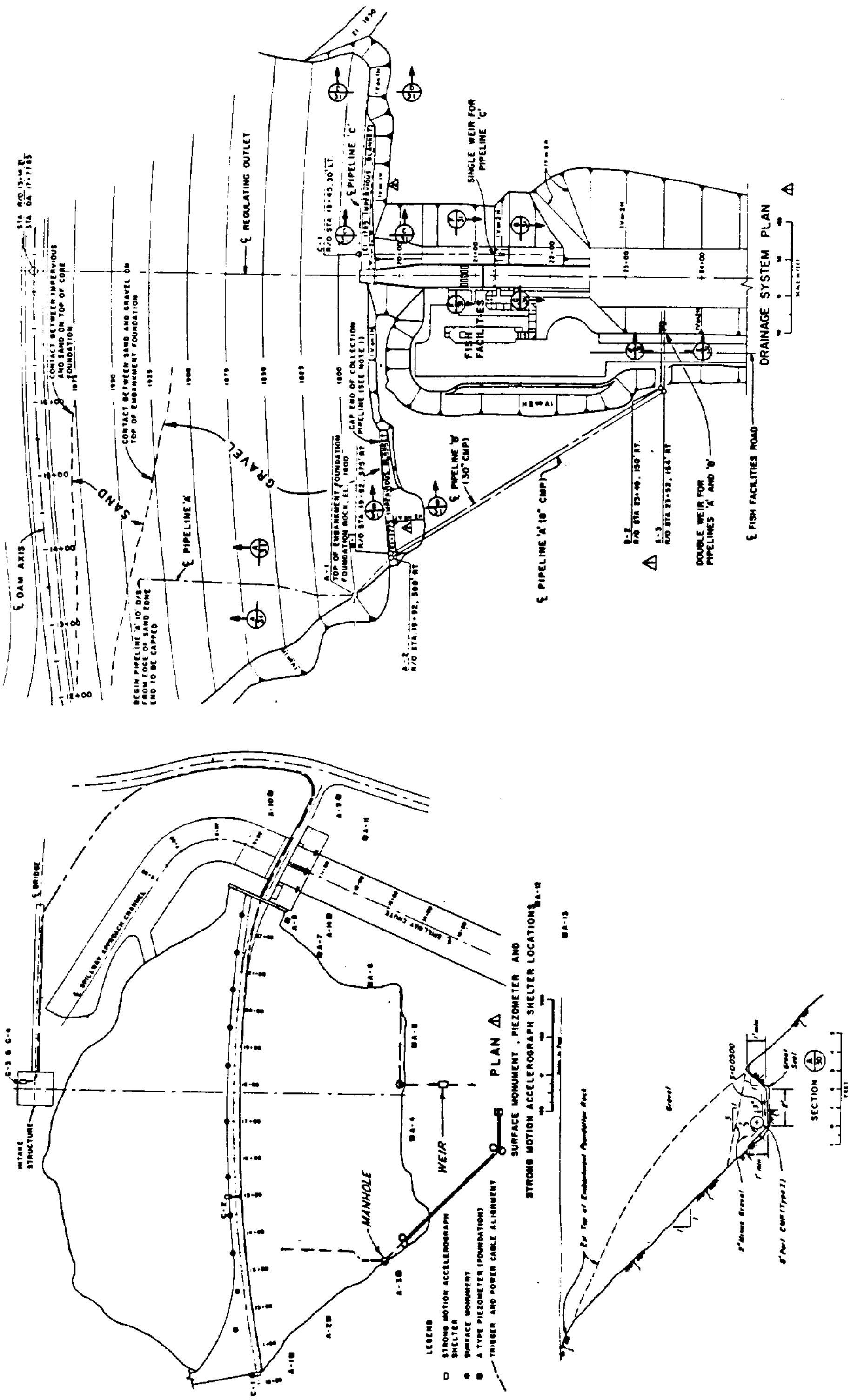

Figure 13-9. Drain and piezometer installation, Applegate Lake, Oregon (from U. S. Army Engineer District, Portland[104])

e. Near Relief Wells. If a relief well system has been installed, pore pressures should be checked in the vicinity to evaluate the efficiency of the system. Piezometers should be located both upstream and downstream of the relief wells and should intercept the stratum being drained, figure 13-3. If there is a line of wells, piezometers should also be installed generally at the midpoint between the wells or at the point expected to have the highest pore pressures.

f. Spillways, Stilling Basins, and Outlet Works. Underseepage control beneath the stilling basins of spillways and outlet structures founded on pervious foundations is generally provided by drainage blankets supplemented in the case of stratified foundations by deep well systems (figures 13-10 and 13-11). Drainage blankets extend beneath the chute slabs, if necessary. As shown in figure 13-10, piexometers should be installed to check the effectiveness of the drainage blanket and relief wells, and to check pore pressure beneath the outlet channel and against the stilling basin walls. Piezometers are used to check pore pressures occurring below the relief well system (figure 13-10). Generally, a sheet pile wall, with a minimum penetration of 15 ft, is installed along the downstream toe of the stilling basin to control piping and a piezometer installed downstream of the wall is needed to determine the effectiveness of the wall.

13-3. Flow Measurements.

a. Weirs. Seepage flow measurement is an important parameter of dam performance. Most installations have used a relatively simple weir, measuring the seepage over brass or stainless steel 90-deg V-notches like the collection system shown in figures 13-12 and 13-13. A number of weirs can be installed in drainage galleries to determine flows from different sources, i.e., left or right abutment, dam underseepage, and total seepage. A certain amount of sediments will settle out just upstream of the weir which is important if the sediment load is not continuous and occurs between visual inspections. If the seepage is exiting downstream of the dam and outside of a drainage collection system, a weir pond can be formed in conjunction with the V-notch weir for the specific purpose of determining long-term sediment content in the seepage.

b. Flumes. A flume is a short rigid-walled channel designed to constrict the flow and so give rise to critical velocity. A single measurement of water level is sufficient to measure discharge at critical velocity. The most commonly used flume for seepage measurements is the Parshall flume as shown in figure 13-14. Empirical charts for flow discharge have been developed for specified flume dimensions (Bureau of Reclamation 1967). The flume can be fabricated and placed in seepage flow that has been channelized. This method is a relatively rapid and simple way to obtain precise flow measurements.

c. Relief Wells. Relief wells, as the name implies, are widely used to relieve pressures and control seepage through pervious strata beneath earth dams, spillways, and outlet works. A thorough knowledge of the geologic conditions and characteristics of the soils at the dam must be available to design a system as part of initial construction or as remedial work. To be effective, the well must flow but must not allow the loss of foundation

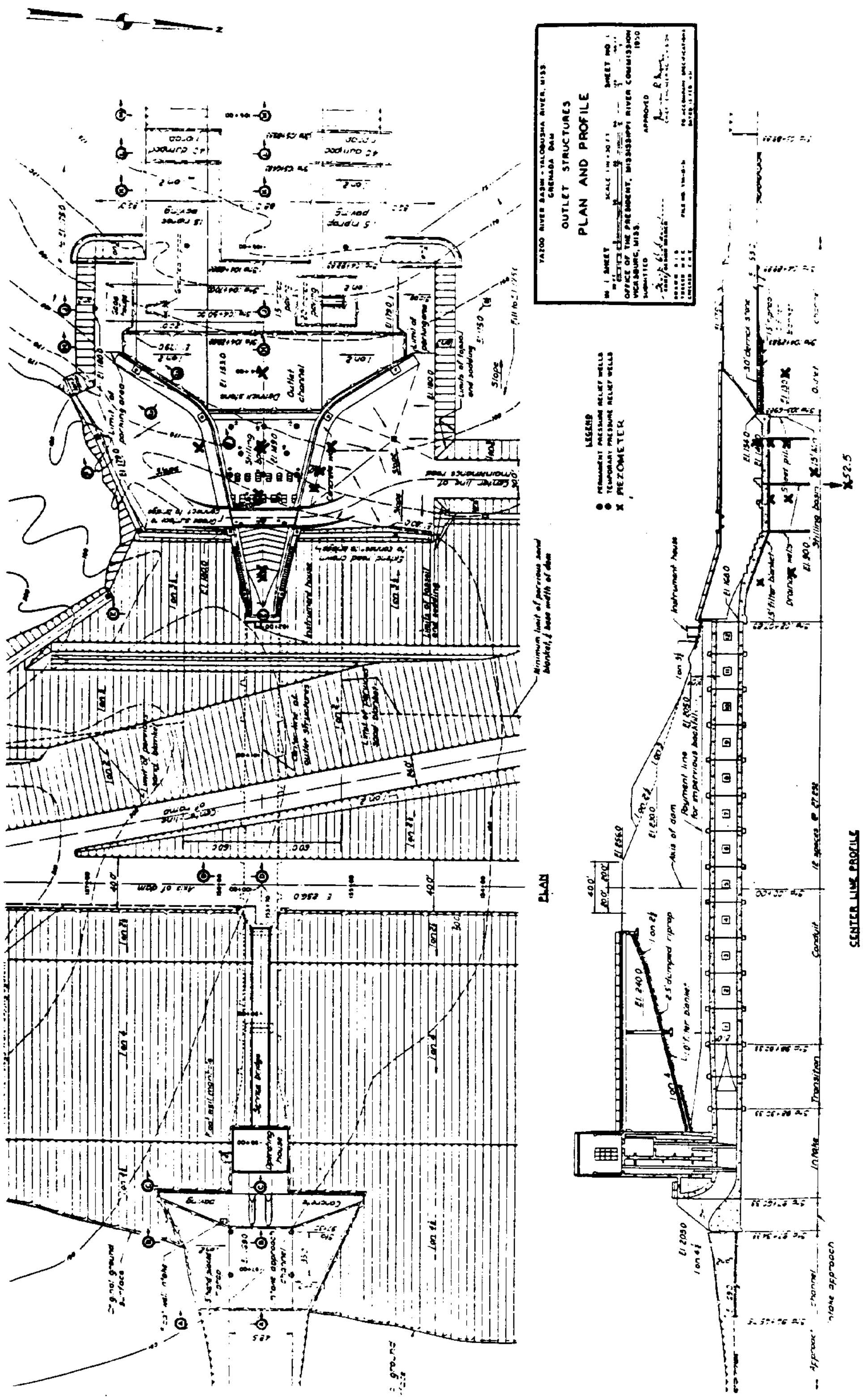

Figure 13-10. Piezometer installation for dams with outlet structures (adapted from U. S. Army Engineer District, Vicksburg[115])

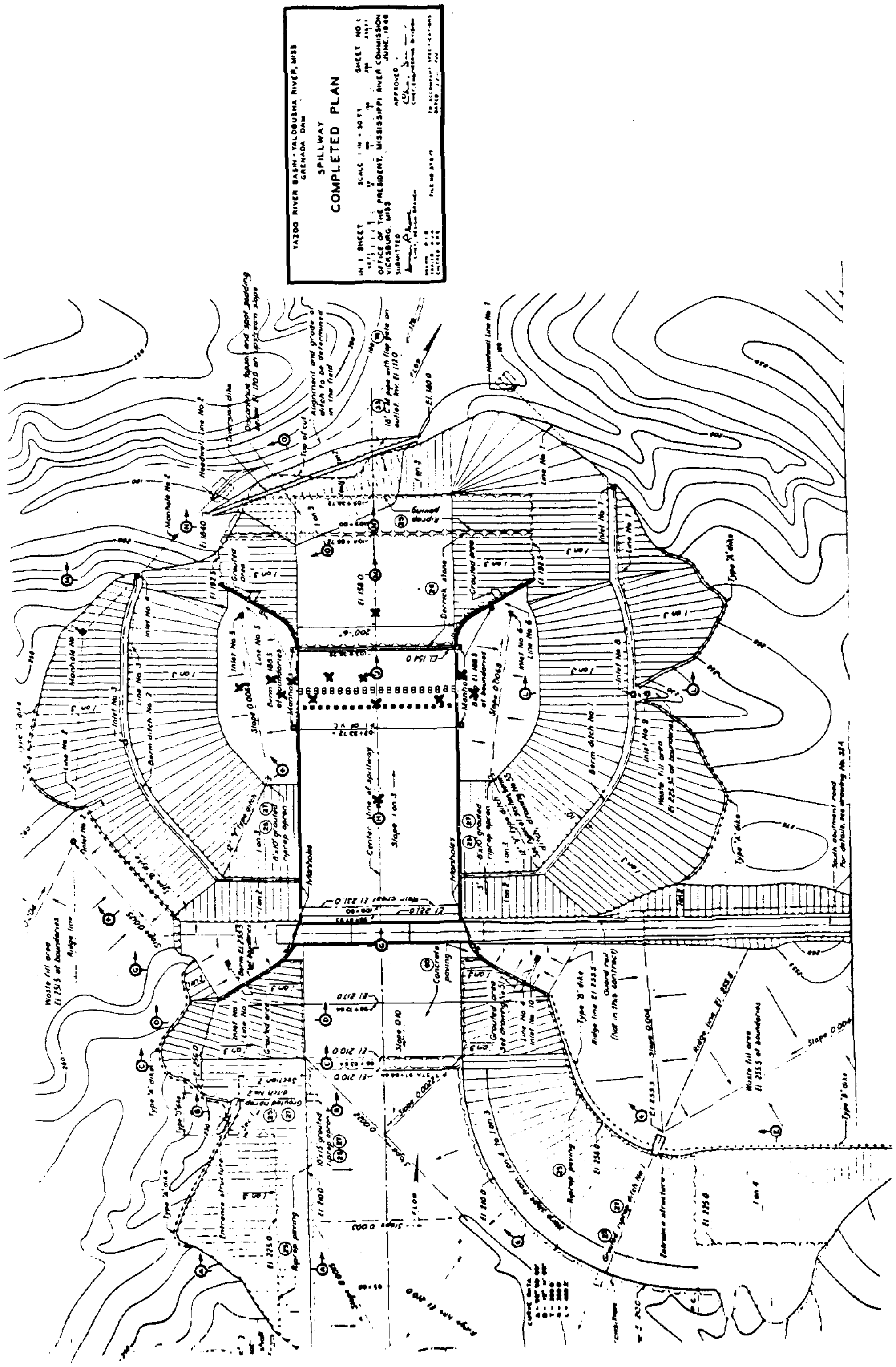

Figure 13-11. Piezometer installation for spillways (adapted from U. S. Army Engineer District, Vicksburg[115])

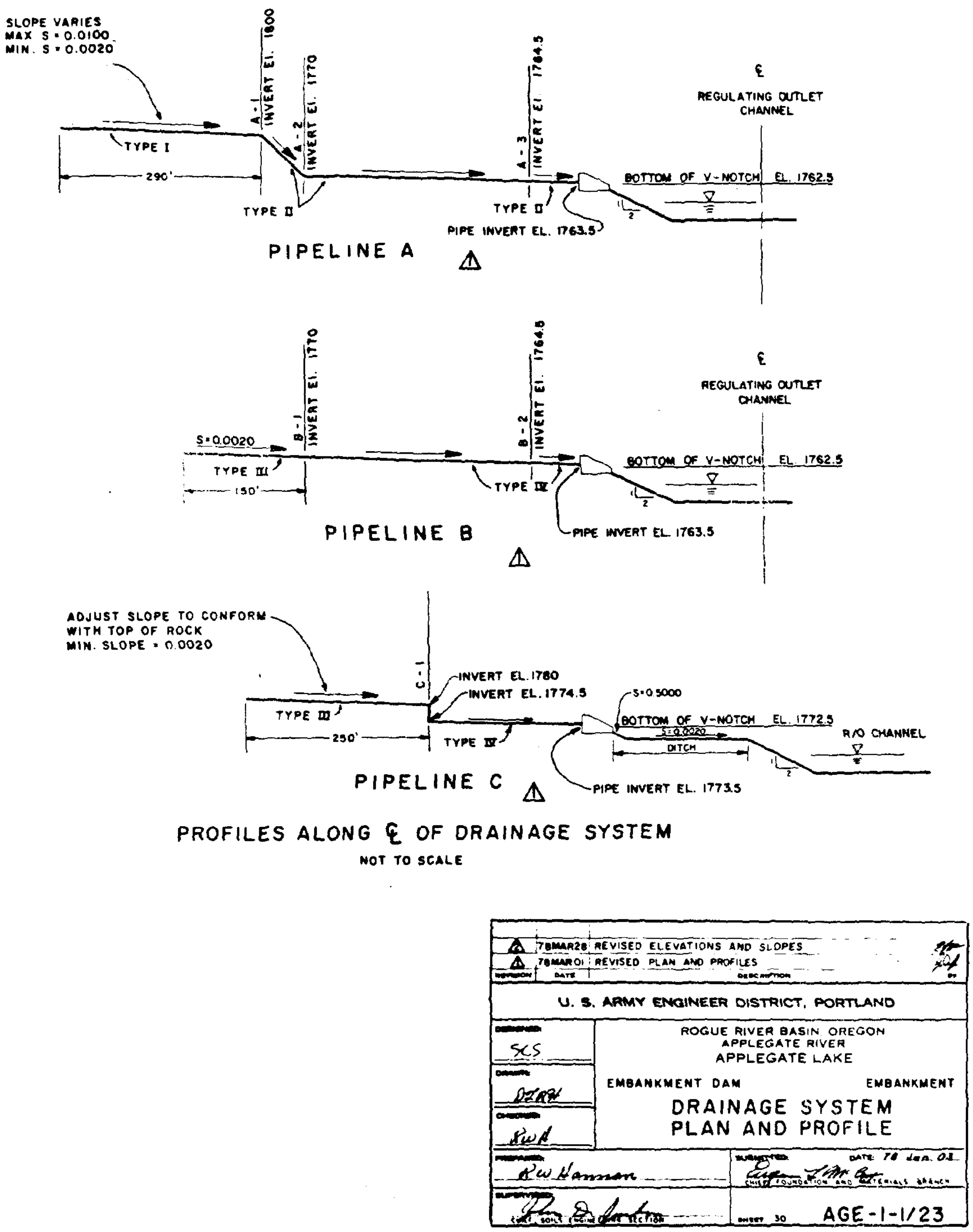

Figure 13-12. Installation of drainage system with weirs (from U. S. Army Engineer District, Portland[104])

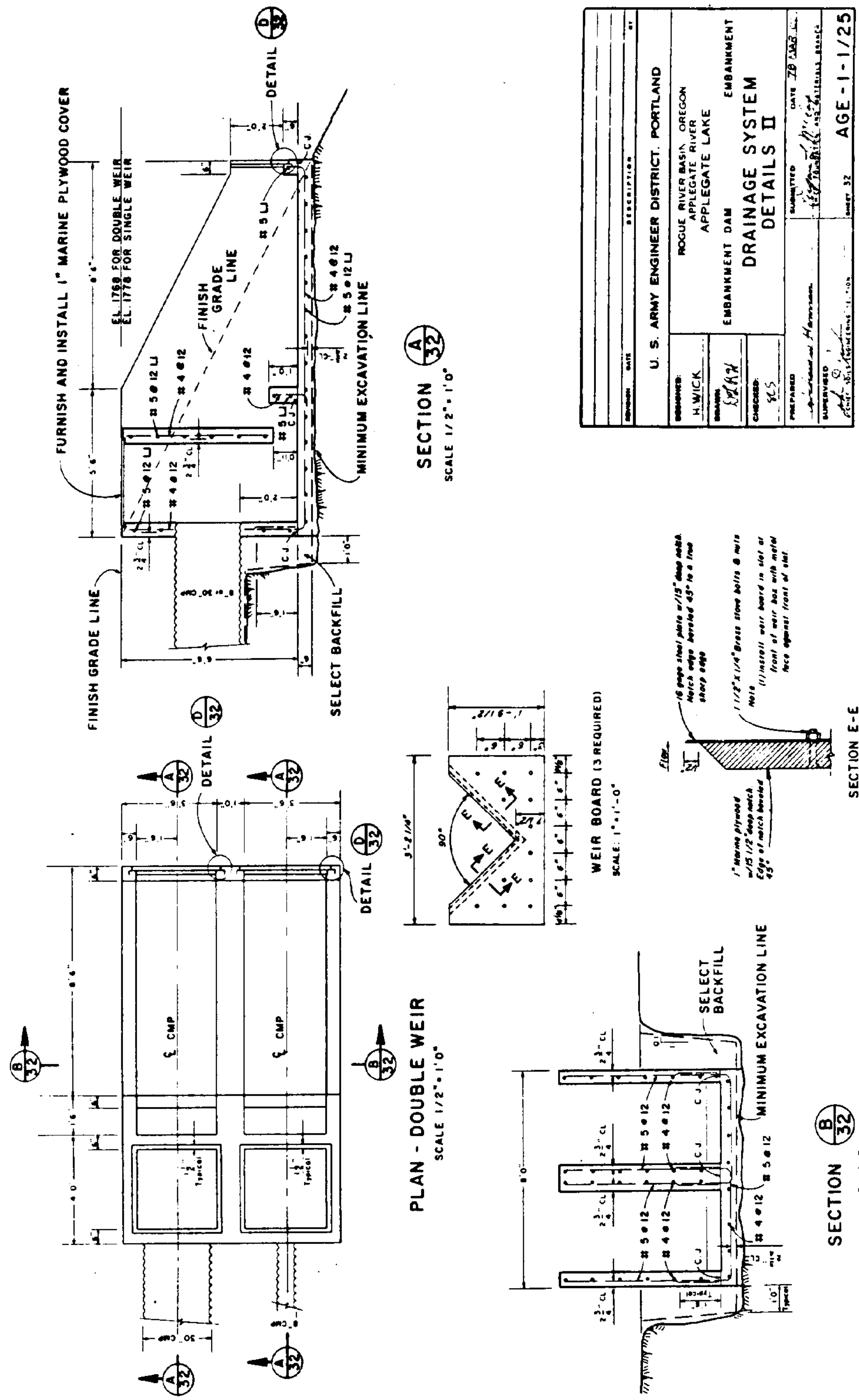

Figure 13-13. Typical weir installation (from U. S. Army Engineer District, Portland[104])

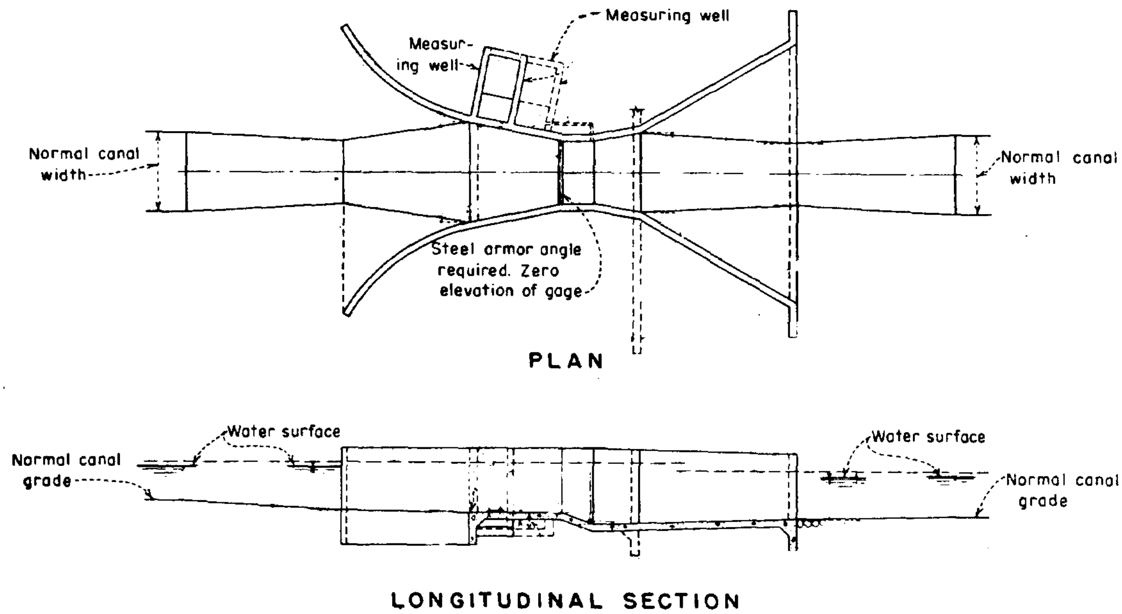

Figure 13-14. Modified Parshall flumes of 6- to 65-second-foot capacity (after Bureau of Reclamation[24])

material which could lead to piping or erosion failure. A frequent use of relief wells is near the downstream toe of a dam to control seepage through a pervious zone, figure 13-13. A toe drain is used to collect the flow while weirs in the drains or manometers on the wells can determine the quantity of flow. Relief wells can be pumped to determine the effect on surrounding ground water and the permeability of the soil near the well. In many cases where dams are built on jointed or fractured rock, grout curtains are used as seepage cutoffs. It has been found in some cases that grout curtains do not appreciably affect the uplift pressures downstream of the curtain and that a series of drainage wells is a more effective tool to reduce uplift pressures when the volume of seepage loss is not a problem and when the high cost of grouting is hard to justify (Casagrande 1961). Relief wells have been successfully used when the pervious strata is too deep and wide-ranging to effectively use any type of positive cutoff. Relief (drainage) wells are used beneath spillway and outlet works slabs to relieve excess pressure in the rock, the underslab drains, or a pervious strata. An example of a group of wells designed to relieve pressure under an outlet works stilling basin is shown in figure 13-10. Relief wells can be used in rock abutments to intercept seepage and to control artesian flow.

d. Seepage Outlets. Monitoring seepage outlets downstream of the dam is handled according to the present severity of the problem or to future associative problems if the seepage worsens. A small wet zone near the toe might require only routine visual examination as would a small trickle from a rock abutment. If there is sufficient seepage to measure, an effort should be made to estimate the volume with a container and a stopwatch and to note sediment content. Operation and maintenance personnel should be trained to observe the situation especially during high reservoir levels. All seepage outlets should be monitored to determine long-term trends. Sand boils developing downstream require immediate attention. An estimate of the pore pressure involved can be determined by sandbagging around the boil to measure the height of water rise. If the seepage exiting at the toe or abutment is severe and will require remedial work but the dam is not in imminent danger of failing, collection systems must be designed as a pattern develops. Temporary control measures such as toe drains and surcharge berms might be installed with weirs to establish the severity and the trends of the seepage for use in design of remedial work. Any changes noted during monitoring, i.e., volume change, sediment load change, etc., should be considered important. After the remedial work has been designed it may include any number of the monitoring systems discussed previously in this chapter. If the seepage is exiting from a drain system that is not being monitored internally, visual monitoring should continue at specified intervals and during heavy runoffs and high reservoir levels.

13-4. Seepage Water Analysis.

a. Physical Analysis. Physical analysis of the seepage could include information on suspended solids, temperature contours, and water resistivity values. This information may be obtained from physical testing of samples or by remote testing techniques.

(1) The amount of suspended solids in the seepage is an indication of material movement and piping. Although there are obvious problems with muddy or turbid flow, seepage which appears clear may often carry small amounts of suspended solids that would be detected by occasional samples and analysis. Sediment traps built in conjunction with manholes and weirs can be used to indicate the amount of suspended sediment and to obtain samples for chemical analysis.

(2) Several different methods of measuring temperature are designed to help locate seepage areas not yet visible and to trace seepage from its origin to its exit. One remote sensing method (U.S. Army Engineer District, Los Angeles 1981) is an aerial survey which includes any or all of the following: (a) color photography, (b) color infrared photography, (c) thermal infrared, and (d) color oblique imagery. The basis for the study is that different materials (wet or saturated versus dry) possess different heat absorption rates; therefore, heat radiation rates will differ. Since the specific heat of water is higher than soil or rock, a warm zone in a known seepage area is a suspected seepage outlet. This method is intended for large areas but smaller areas can be covered by thermal infrared using portable hand-held units (Leach 1982). A second method of thermal monitoring (U. S. Army District, Los Angeles 1981) is to physically place an array of gages in and adjacent to the embankment and measure the diurnal temperature (temperature below the reach of the surface but within the annual temperature zone). A temperature fluctuation is interpreted as seepage related and becomes the basis for further study in that zone. A vertical thermal contour can be made in present open system piezometers or in remedial planned piezometers, again with temperature fluctuations or inversions interpreted as seepage related (U. S. Army Engineer District, Los Angeles 1981 and Leach 1982). These data are interpreted or

expanded by determining the temperature stratification of the reservoir, the temperature of all known seepage sources, and the temperature at the seepage exits.

(3) Seepage can be monitored by the physical detection of tracer elements such as dye and isotopes that have been introduced upstream of the seepage exit either in the reservoir or a piezometer close to the suspected seepage path. The dye selected should have a favorable absorption and decay rate and should meet state water quality control requirements. Samples taken from piezometers, drains, and downstream exit points are monitored using an instrument capable of measuring parts per billion, e.g., a fluorometer for fluorescein dye. By recording time of arrival and concentrations, interpretations can be made as to the source of the seepage and the permeability of the strata along the path of seepage. Environmental isotopes are also traced by obtaining samples which can be measured by a mass spectrometer for oxygen -18 and deuterium and by the low level counting system for tritium.

(4) Another physical property of the seepage that can be measured is its conductance or resistance. Resistance which would be defined in the field by a resistivity survey is a measure of the ability to resist current flow through the seepage, a factor that is altered by the introduction of salt compounds, graphite, etc. A thorough sampling program from all possible sources of seepage, all seepage exits, and all available piezometers can produce a group of resistivity values that is an important tool in defining seepage sources and possible paths. Using the geologic profile for the site, and by comparing individual resistivity values or by comparison against a range of known values (Telford et al. 1976), an interpretation as to the source of the seepage and the strata through which it travels can be made.

b. Chemical Analysis. To monitor and interpret the chemical composition of seepage requires a thorough knowledge of the surrounding geology or chemical analysis of samples in the different strata. If possible, a preconstruction chemical analysis should be conducted on all water sources and on any formation that might contribute minerals or salts or that might affect acidity or alkalinity.

(1) One important chemical property would be the salt concentrations in the seepage. In this case to determine correlations, reservoir and groundwater concentrations are essential along with the mineral content of the area, e.g., water flowing through limestone would generally increase in chloride concentration. Minerals such as feldpoid sodalite and apatite (Turkish National Committee 1976) or caliche in volcanic regions (U. S. Army Engineer District, Los Angeles 1981) can release chloride ions into the water. Interpretation of chloride concentrations and its long-term trends can help determine the relative length of seepage paths (shallow or deep seated), the extent of the leaching of the formation (whether concentrations are constant, increasing, or decreasing), and the source of the seepage (comparable concentrations). Interpretation is sight-dependent and any of the above or possibly other conclusions may be reached.

(2) Another chemical property needed for interpretation is the mineral content of the seepage. Mineral concentrations of calcium and magnesium

bicarbonate containing dissolved carbon monoxide increase with length of flow through a limestone formation while flow through some clay minerals may increase concentrations of calcium and magnesium. Again, interpretation is site dependent and requires a thorough knowledge of the existing conditions.

(3) Stiff diagrams, as shown in figure 13-15, are a graphical method of presenting the anions and cations that are dissolved in the water (Hem 1970). The Stiff method uses ions plotted in the same sequence to give an irregular polygonal shape or pattern. In tracing the movement of seepage water, the Stiff patterns are plotted on a map of the site for various locations downstream of the dam and the reservoir. The Stiff patterns may yield information regarding the path(s) of seepage from the reservoir, prior land uses downstream of the dam (feedlot, septic field, etc.), and type of formation (gypsum, dolomite, etc.).

13-5. Remote Sensing Methods.

a. Resistivity and Spontaneous Potential. As part of a total seepage study, resistivity and spontaneous potential methods have been used successfully for seepage delineation in soil and rock (Cooper and Bieganousky 1978; Cooper, Koester, and Tranklin 1982; and Koester et al. 1984). Resistivity surveys used as part of a seepage study help identify possible zones of high moisture as a function of depth and location. After the surveys are correlated to previous borings or geologic information, new borings are placed in the seepage flows. Spontaneous potential surveys are used to detect negative D. C. voltage anomalies in the surface electrical field which have been found to indicate zones of seepage flow (Cooper, Koester, and Tranklin 1982; and Koester et al. 1984). Although flow is indicated, depth to flow can not be determined for a given anomaly.

b. Photography. Methods using color, color infrared, aerial and ground base thermal infrared, and color oblique photography were discussed previously in paragraph 13-4.a.

c. Refraction Seismic Surveys. Seismic surveys can be used indirectly in a seepage study by providing a bedrock profile that can be used as an aid in determining the location and depths of observation wells, piezometers, and relief wells. It is a quick and inexpensive method for obtaining subsurface profiles.

d. Seepage Acoustic Vibrations. Acoustic emissions are the noises generated whenever a material deforms or possibly by seepage whenever there is turbulent flow against and around a casing (Koerner, Lord, and McCabe 1977). The technique has been used to detect seepage by placing an accelerometer on a waveguide that extends to the bottom of a borehole and recording the vibrations present (Koerner, Lord, and McCabe 1977; and Leach 1982). Increases in emissions activity are interpreted as seepage flow. A similar technique that consists of lowering an acoustic microphone down into a reservoir has been used to detect leakage on the upstream asphalt-covered face and in the reservoir itself (Coxon and Crook 1976). One disadvantage would be high background noise levels.

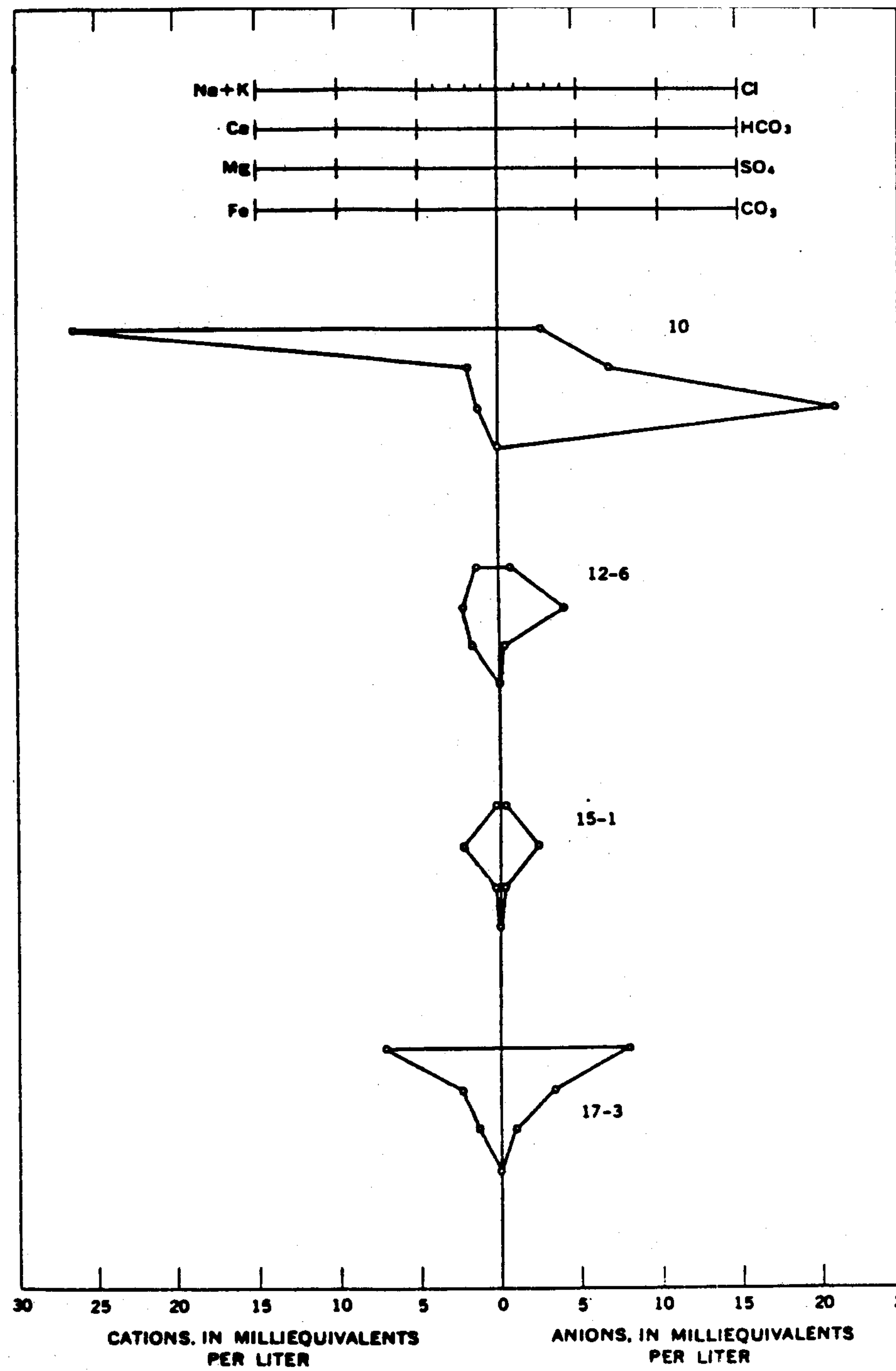

Figure 13-15. Stiff diagram used to graphically present anions and cations in seepage water (from Hem 1970)