CHAPTER 12

INSTRUMENTATION

12-1. Introduction. There are several reasons to incorporate instrumentation into any dam. One reason is so that the design and construction engineers can follow the behavior of the dam during its construction. Another reason is to compare the performance of the dam under operating conditions with that predicted by the designers. There is also the need to evaluate the overall condition and safety of the dam on a regular basis. A good instrumentation program can also increase the knowledge of the designer, and that knowledge can be applied to future projects. This chapter will discuss the instrumentation requirements that are needed to accomplish several of these points as they relate to arch dams. EM 1110-2-4300 and the Concrete Dam Instrumentation Manual (USBR 1987) give a more detailed description of the various types of instruments discussed in this chapter, as well as several other types of instruments that may be of interest in a project-specific case. EM 1110-2-4300 also discusses some general requirements in establishing and executing an instrumentation program including the proper method of installation, calibration, and maintenance of the instrumentations as well as the collection and reduction of data.

12-2. General Considerations. In establishing any instrumentation program, it is important to understand the objectives of the program, the need for each type of instrument, the environment in which the instrument will be, the difficulty in gathering the data, and the time and effort in reducing and understanding the data generated. The wrong type of instrument may not measure the desired behavior. And while insufficient instrumentation may ignore important structural behavior, excessive instrumentation may bury the design engineer in a mound of paper that hides a serious condition. It is also important that some consideration be given to the initial and long-term cost of the program and the availability of trained personnel to collect the data. The cost of purchasing and installing the instruments will be up to 3 percent of the general construction cost (Fifteenth Congress on Large Dams 1985). A large instrumentation program will require a long-term commitment by management to maintain the program.

a. Instrument Selection. Instruments and associated equipment should be rugged and capable of long-term operation in an adverse environment. It is preferable to incorporate instruments of similar types (such as electric resistance versus vibrating wire types) in order to reduce the need for several types of readout equipment and training in numerous different types of equipment. The final decision of which type of instruments to use will be site specific. For example, most electric resistance instruments are restricted by the total length of the lead wires, while vibrating wire instruments are not. Therefore, if it is desirable to reduce the number of readout stations, then the length of the lead wires may dictate the use of vibrating wire instruments.

b. Redundancy. Every instrumentation program should include some redundancy, especially with embedded instruments since it is usually not possible to repair damaged embedded instruments. The cost to retrofit replacement instruments will far exceed the cost of providing adequate redundancy.

Redundancy, in this case, is more than only the furnishing of additional instruments to account for those that are defective or are damaged during installation. Redundancy includes providing different instruments which can measure similar behavior with different methods. For example, for measuring movement, a good instrumentation program should have both plumblines and a good trilateration system. Redundancy of instruments is especially critical in key areas and around special features (Moore and Kebler 1985).

c. Automatic Data Collection and Remote Monitoring. The use of automatic data collection and remote monitoring is becoming more popular in recent years because electronic instruments lend themselves to this type of operation. Automatic data collection and remote monitoring will reduce the labor involved in gathering data and will reduce the time required to process and evaluate the data. However, automatic data collection and remote monitoring should not preclude the design engineer obtaining knowledge of onsite conditions existing when the data was obtained (Jansen 1988). It is important to remember that instruments do not ensure dam safety, they only document performance. Remote monitoring is not a substitute for a thorough inspection program. Regular visits to the dam by experienced design engineers are essential.

d. Readings During Construction. Some of the most valuable information obtained in any instrumentation program is the information gathered prior to and during the construction of the dam and during initial reservoir filling. Because of the importance of gathering good data due to the effects of construction, efforts should be made to obtain readings as early and as frequently as possible during the construction. Special provisions should be made in the contract documents to allow access to the instrument readout points and/or stations at the regular intervals outlined in paragraph 12-9.

e. Fabrication and Installation. As noted in EM 1110-2-4300, fabrication and installation of the instruments should be done by trained Government personnel, not by contractor-furnished unskilled laborers. The initial readout schedule for the various types of instruments described in this chapter is presented in paragraph 12-9.

f. Instrument Types. The basic types of instruments can be described by the items that they measure. The types discussed in this chapter include movement, stresses or strains, seepage, pressure, and temperature. Each of these types is discussed in the next few paragraphs, with recommendations for each. Other types such as seismic, water elevation gauges, etc. are not discussed herein.

12-3. Monitoring Movement. Because of the monolithic behavior of arch dams, displacement is probably the most meaningful parameter that can be readily monitored. Although displacements occur in all directions, the most significant displacements are usually the ones that take place in a horizontal plane. All concrete arch dams should have provisions for measuring these displacements, including relative movements between points within the dam and movement of the dam relative to a remote fixed point. In new construction, plumblines are still the preferred instrument to monitor the relative horizontal movements within an arch dam. In existing structures, it may be easier to install inclinometers or a series of tiltmeters or electrolevels. All arch dams (new or existing) should include trilateration or triangulation surveys.

a. Plumblines. Plumblines and optical plummets measure bending, tilting, and deflections of concrete structures. Conventional plumblines are suspended from the top of the structure and extend down to the lowest readout gallery. If the curvature of the dam will not permit this type of installation, then a series of conventional plumblines can be installed as shown in Figure 12-1. Inverted plumblines are commonly used in conjunction with conventional plumblines to extend the total length of measurable deflections well into the foundation. The primary disadvantages to conventional plumblines are that they require trained personnel to obtain readings, the metal components are subject to corrosion, and no readings can be obtained until the structure is complete. An optical plummet can be used as a substitute for a conventional plumbline. The optical plummet is line-of-sight instrumentation that uses bubble levels or mercury reflectors to keep the reading line precisely vertical. Since it is an optical instrument, it is not susceptible to the corrosion problems of the conventional plumbline. However, as with the conventional plumbline, the optical plummet requires trained personnel to obtain readings, and no readings can be obtained until the structure is complete. Also, the optical plummet is susceptible to errors caused by refraction of light waves, as well as distortions due to atmospheric conditions.

b. Inclinometer. Inclinometers are used to measure angles from vertical. They can be used both in the concrete mass or extended into the foundation. Extending the inclinometer into the foundation can provide information on a potential sliding plane being investigated. Inclinometers consist of a metal or plastic casing embedded into the concrete, a probe, and a readout unit. The casing is grouted into a core hole, which makes it especially attractive for installation in existing structures. If an aluminum casing is used, the casing should be coated with epoxy to prevent corrosion. The casing has four grooves on the inside walls at 90 degrees from one another. The casing should be installed so that one set of groves are in the radial direction and one set in the tangential direction. As with the plumblines, inclinometers require trained personnel to obtain readings. More information on inclinometers can be found in the Concrete Dam Instrumentation Manual (USBR 1987).

c. Extensometer. Extensometers are used to measure small (2- to 4-inch) deflections along the length of the instrument. Extensometers can be supplied with several (5 to 10) anchor heads. When inserted into a dam foundation, the heads can be positioned on either side of a zone of interest so that the deflection of that zone under load can be obtained. However, limitation on the amplitude of deflections that an extensometer can measure may require periodically resetting the reading heads. Extensometers can be installed at almost any angle. It is preferable to install some extensometers early in the concrete placement to determine deformations in the foundation during construction.

d. Joint Meter. Joint meters are used to measure the opening of monolith joints. Depending on the meter being used, the maximum opening that can be measured may range from 0.08 to 0.4 inches. Joint meters provide information about when the joints have begun to open and if there is adequate opening for grouting. They also give an indication of the effectiveness of the grouting and show whether any movement occurs in the joint during and after grouting.

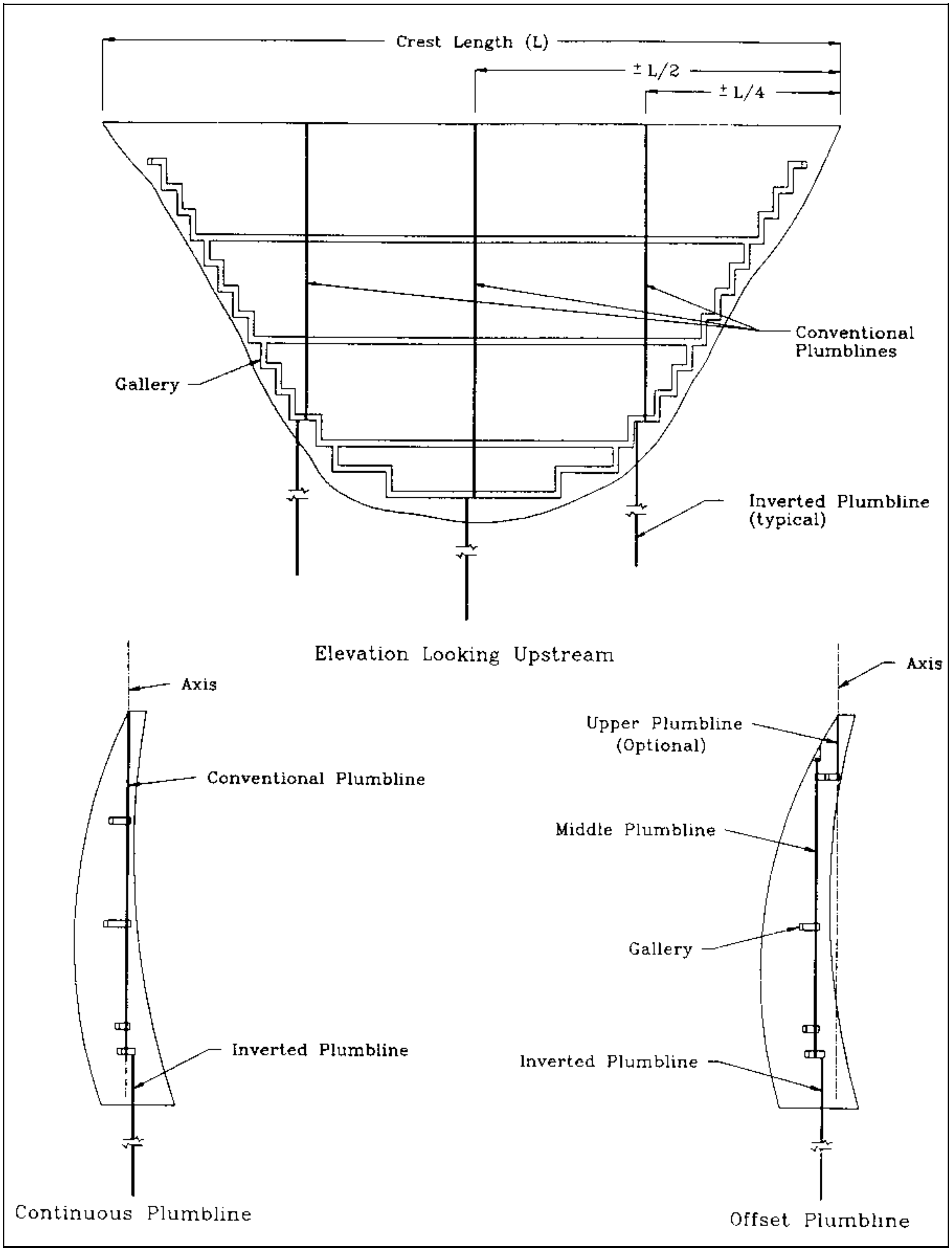

Figure 12-1. Typical layout for plumblines

e. Trilateration and Triangulation Surveys. These two methods of precise measurements utilize theories and equations of geometry to transform linear and angular measurements into deflections of alignment points. Triangulation is based on a single known side length (baseline) and three measured angles of a triangle to determine lengths of the remaining two sides. Trilateration uses electronic distance measurement (EDM) instruments to measure the lengths of the sides of the triangle and uses these lengths to calculate the angles. The accuracy of each of these methods is very dependent on the skill of the crew and equipment being used. It can also be costly and time consuming to gather and reduce the data. The required accuracy and precision of the two methods is outlined in the Concrete Dam Instrumentation Manual (USBR 1987).

12-4. Monitoring Stresses and Strains.

a. Strain Meters. Strain meters measure strain and temperature. Since they measure strain at one location and in one direction only, it is usually necessary to install strain meters in groups of up to 12 instruments with the help of a "spider" frame (Figure C-3 in EM 1110-2-4300). Since strain meters do not directly measure stress, it is usually necessary to convert strains to stresses. This will require a knowledge of the concrete materials which are changing with time, such as creep, shrinkage, and modulus of elasticity. These material properties, as well as the coefficient of thermal expansion and Poisson's ratio, are usually determined by laboratory testing prior to construction. However, if the mix design is revised due to field conditions, then the testing may need to be repeated to accurately determine stresses from the strain measurements.

b. "No-stress" Strain Meters. These meters are identical to the strain meters discussed in the previous paragraph, except the method of installation isolates the meters within the mass concrete so that the volume changes in the concrete can be measured in the absence of external loading. This arrangement usually consists of one vertical and one horizontal meter.

c. Stress Meters. Stress meters measure compressive stress independently of shrinkage, expansion, creep, or changes in modulus of elasticity. They are used for special applications such as determining vertical stress at the base of a section for comparison and checks of results from strain meters. They are also used in the arches for determining horizontal stress normal to the direction of thrust in the thinner arch elements near the top of the dam.

12-5. Seepage Monitoring. Seepage through a dam or its foundation is visible evidence that the dam is not a perfect water barrier. Continued measurement of this seepage can provide an indication of progressive dissolution or erosion in a dam foundation or abutment. The types of instruments used to monitor seepage include weirs, flowmeters, and calibrated catch containers.

12-6. Pressure Monitoring. Although uplift pressure is not a critical issue in the stress analysis of arch dams, it is extremely important in the foundation stability analysis and should be included as part of the overall instrumentation program. However, measuring water pressures in a rock foundation is always a difficult problem since it can change over short distances because of jointing and fissuration.

a. Open Piezometers. Open piezometers are used to measure the average water level elevations in different zones of materials. Open piezometers include observation wells and slotted-pipe or porous-tube piezometers. Foundation drains can be considered a type of observation well. However, the use of drains or other open piezometers with long influence zones is not recommended for measuring uplift pressures in concrete dams. They are accessible to water over most, if not all, of their length and, as such, they tap water from different layers. The result is often a water level that is an average between the smallest and largest pressure heads crossed with no indications of what it truly represents.

b. Closed Piezometers. Closed piezometers measure pressure over a small influence zone (usually 3 feet). Typical closed piezometers are the electric resistance or vibrating wire piezometers. These piezometers are applicable for measuring pore pressures at the concrete/foundation contact as well as at several zones within the foundation rock.

c. Standpipe with Bourdon-type Gauge. A standpipe with a Bourdon-type gauge is the one of the simplest, and perhaps the cheapest, ways to measure uplift pressures at the dam/foundation contact. There are various ways of installing this uplift pressure system, but the two most common are as shown in Figure 12-2. This type of uplift pressure measuring system is an example of an open-system piezometer discussed in paragraph 12-6a, but with a small influence zone, usually only about 3 feet into the foundation. Closed piezometers can also be added at a few locations as verification of this uplift pressure measurement system. In dams without a foundation gallery, closed piezometers should be used to measure uplift pressures at the dam/foundation contact.

12-7. Temperature Monitoring. Temperature sensing devices are very important in arch dams since volume change caused by temperature fluctuation is a significant contributor to the loading on a arch dam. Thermometers are used to determine the temperature gradients and history of the concrete mass for use in evaluating thermal stresses which contribute to thermal cracking. They are also used to control the cooling process during the grouting operations and are used to determine the mean concrete temperatures due to reservoir and seasonal fluctuation. Thermometers are preferred over thermocouples because they have been more dependable, have greater precision, and are less complicated in their operation. Standpipes filled with water have also been used as a substitute for permanent thermometers. In using a standpipe, a thermometer is lowered into the standpipe to the desired elevation and held there until the reading stabilizes. Standpipes can be an effective way to obtain vertical temperature gradients but are not practical for measuring temperature variation between the upstream and downstream faces of the dam. The addition of several standpipes through the thickness of the dam will add extra complications to the overall construction process. Standpipes also tend to indicate higher temperatures than thermometers (Sixteenth Congress on Large Dams 1986).

12-8. General Layout Requirements. The general instrument layout recommended for arch dams is shown in Figures 12-3 and 12-4. Instruments, other than those needed specifically for construction, should be positioned at points that correspond to those used in the design and analysis. This is done for ease of comparison of the predicted and measured performance of the dam.

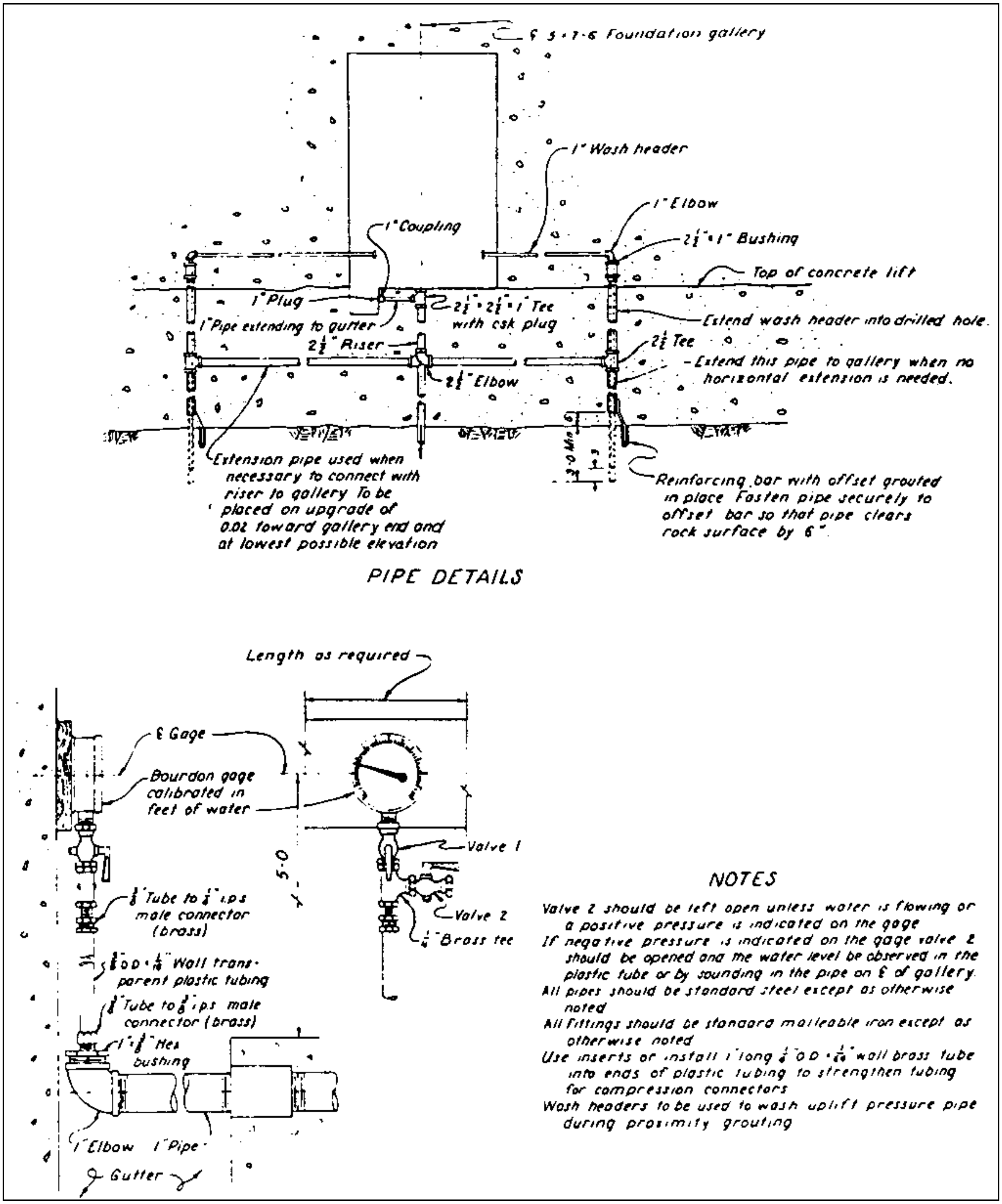

Figure 12-2. Typical Bourdon gauge installation (USBR 1987)

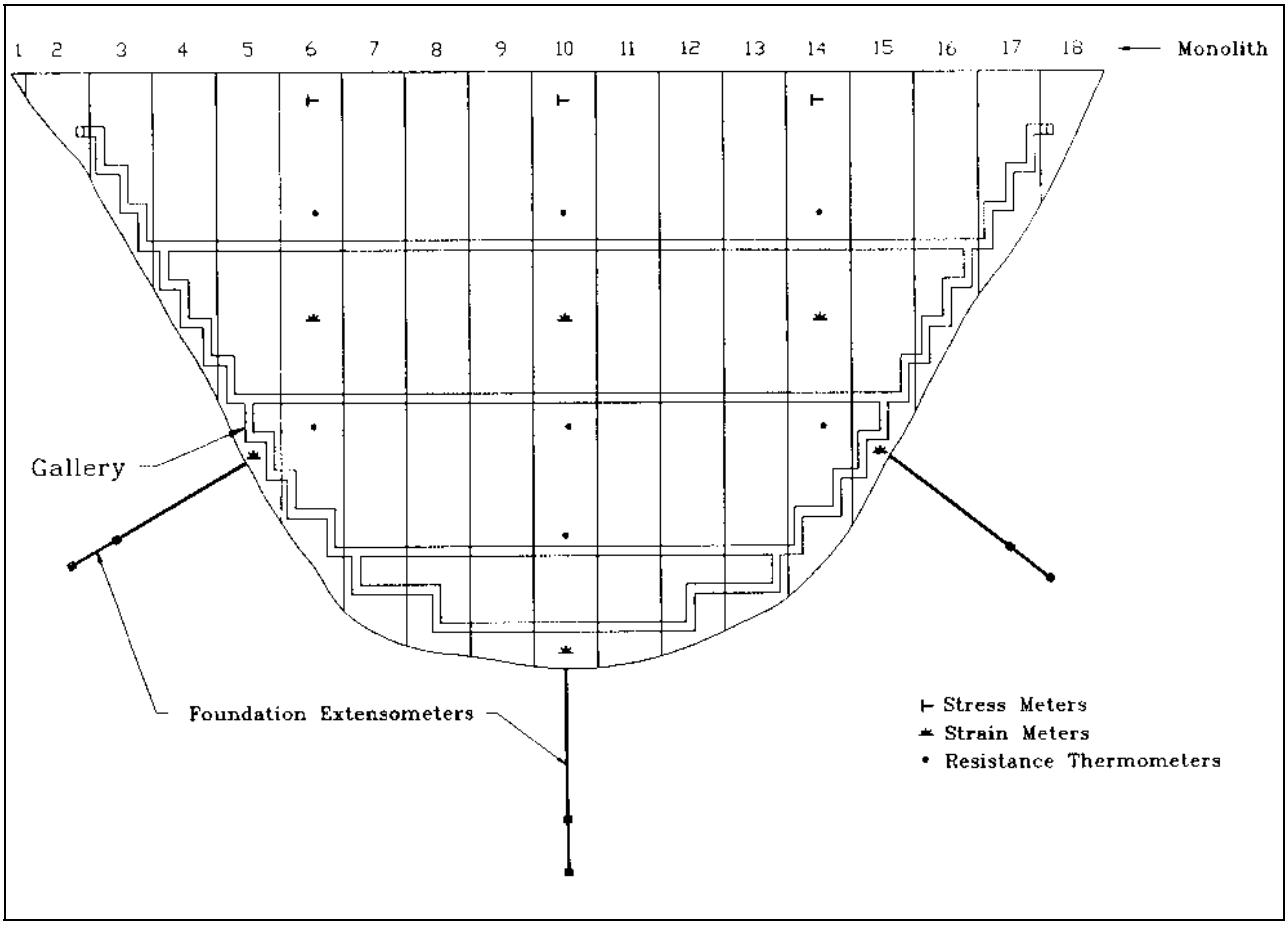

Figure 12-3. Recommended location of embedded instruments in arch dams (elevation looking upstream)

a. Movement Instruments.

(1) Plumblines. A minimum of three plumblines should be installed at locations that correspond to the maximum section of the dam (the crown cantilever) and to the midpoints to each abutment, as shown in Figure 12-1. If the curvature does not permit a continuous plumbline to be installed from the top of the dam, then a shortened plumbline can be installed. If an upper gallery is available, a staggered plumbline can be installed.

(2) Extensometers and Inclinometers. Extensometers and inclinometers should be installed into the foundation as early in the construction as practical, preferably before concrete placement, to determine deformations in the foundation due to construction activities. The location of the extensometers should correspond to the arch elevations for the other instrumentation groups. The total length of the extensometer should be between 25 and 50 percent of the height of the dam. Additional extensometers or inclinometers should be located wherever there is a change in foundation type or a potential slide plane. If inclinometers are to be used in lieu of plumblines, they should be installed at the general locations discussed in paragraph 12-8a(1).

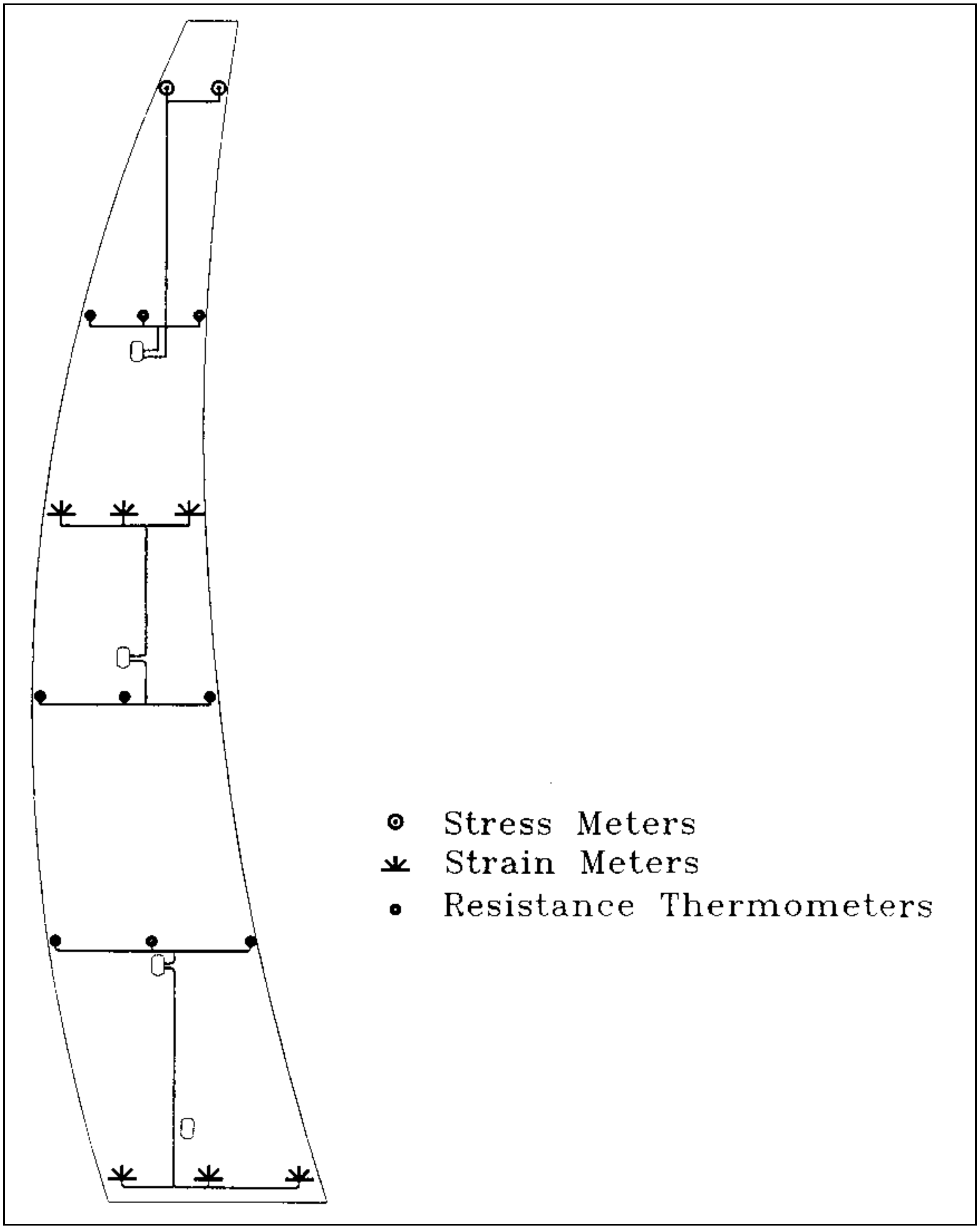

Figure 12-4. Recommended location of embedded instrumentation in arch dam (section at crown cantilever)

(3) Joint meters. One or two joint meters are required in every other monolith joint at the midheight elevation of alternate grout lifts (Figure 12-5).

(4) Triangulation and trilateration targets. Targets should be placed at the crest and at one or more points on the downstream face, as shown in Figure 12-6. The targets should correspond to the location of the plumblines.

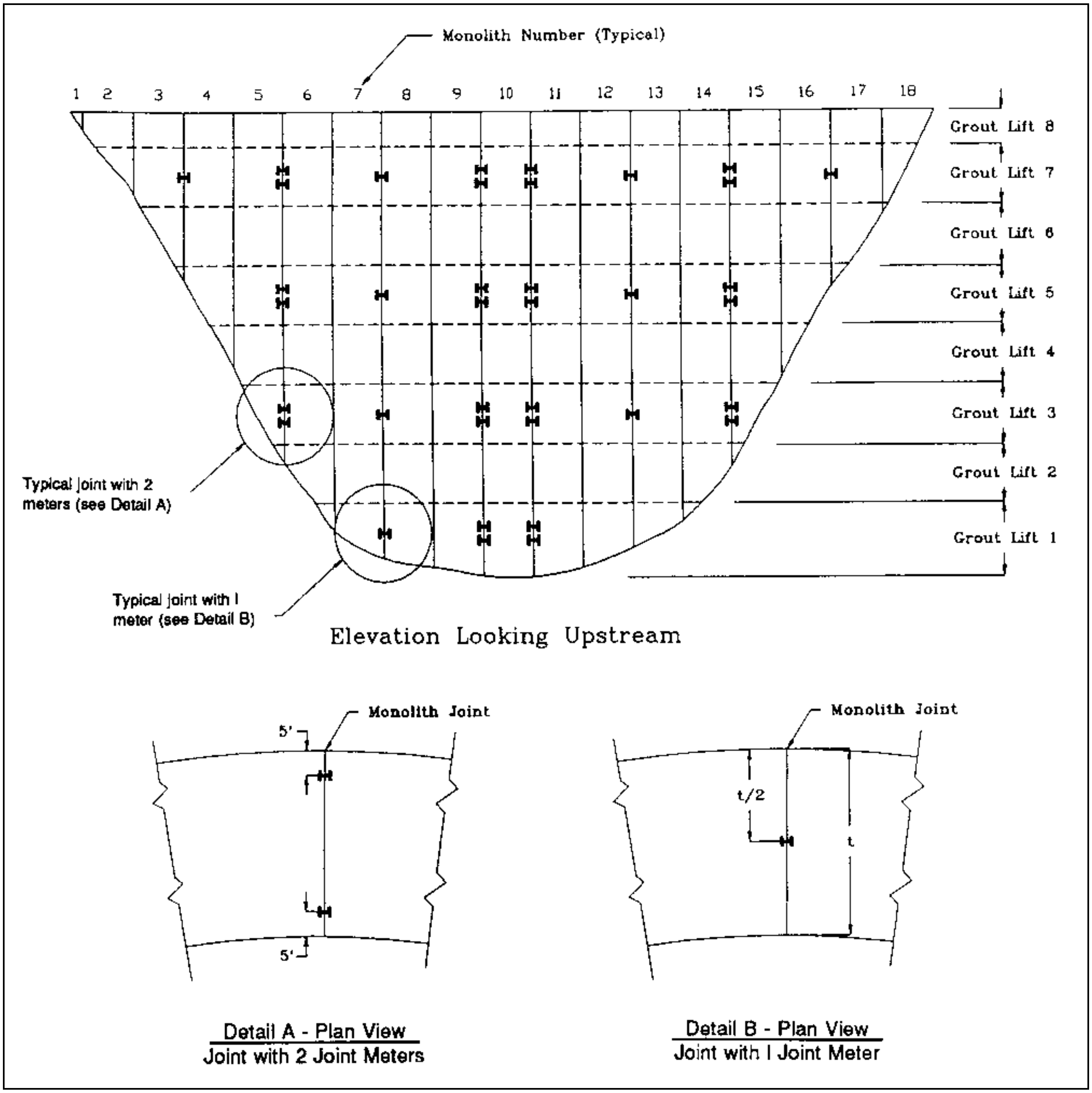

Figure 12-5. Layout for joint meters

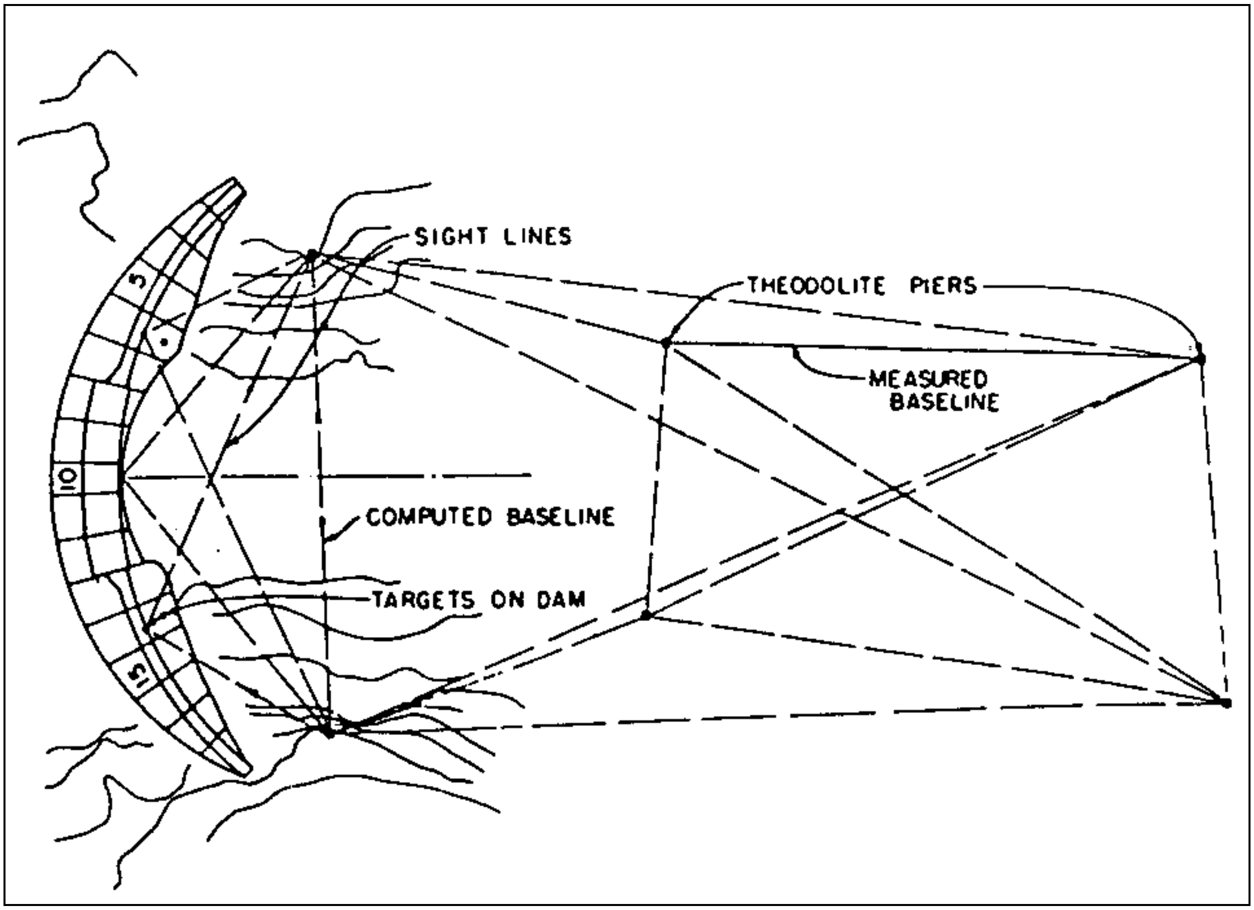

Figure 12-6. Layout for triangular or trilateration network

b. Stress/strain Clusters. Clusters of strain meters, "no-stress" strain meters, and stress meters should be positioned along four or five arch elevations that correspond to arch elevations used in the design and analysis (see Figures 12-3 and 12-4). An additional set of instruments should be positioned at the base of the crown cantilever. At each of the instrumentation points, two clusters of instruments should be placed near the upstream and downstream faces or at three locations between the faces. Where the thickness of the dam permits and where more detailed information is desired about the stress distribution through the dam, five or more instrument groups can be placed between the upstream and downstream faces of the dam.

c. Seepage. Initially, seepage through the joints and through the drains can be measured at two weirs, each located to collect seepage through the drains along each abutment. Measurements of individual drains should also be made on a regular basis. Additional seepage monitoring points can be added after the initial reservoir filling, if the need arises.

d. Pressure. Three uplift pressure groups (standpipe or closed piezometer groups) should be located in a similar manner as the plumblines. There should be at least four uplift pressure measuring points through the thickness of the dam in each group with a spacing between points of no more than 30 feet.

e. Temperature. Thermometers should be installed at locations shown in Figure 12-7 to verify the thermal gradient through the structure and to obtain the temperature history of the concrete. This information is used for comparison with the thermal studies discussed in Chapter 8. Thermometers are not typically located near the other instrument clusters when the instruments in these clusters also sense temperature. If the thermometer groups are not located at the center of the grout lifts, then additional thermometers may be required to monitor the temperature of the concrete from the time of placement through the time of joint grouting. These thermometers should be located at the center of each monolith at points that correspond to the midheight of each of the grout lifts and are used to assure that the concrete has reached the required grouting temperatures.

f. Other Instrument Groups. Instruments should also be positioned in various arrays near areas of special interest, such as around galleries or around any other openings through the dam. Conduits running through the dam should include strain meters on the metal conduits and on the reinforcing steel surrounding the conduits.

12-9. Readout Schedule. Each dam will have its own site-specific requirements for instrumentation and readout schedule. Table 12-1 shows some general guidelines that should be used in establishing the general readout schedule for each dam. EM 1110-2-4300 and the Concrete Dam Instrumentation Manual (USBR 1987) also provide general guidance on readout schedules for instruments not covered by this manual. Variations in the guidelines shown in Table 12-1 will occur when special conditions arise at the dam site, such as long periods of unusually high or low water levels, seismic activity, or unexplained behavior of the dam, such as cracking, increased seepage, etc.

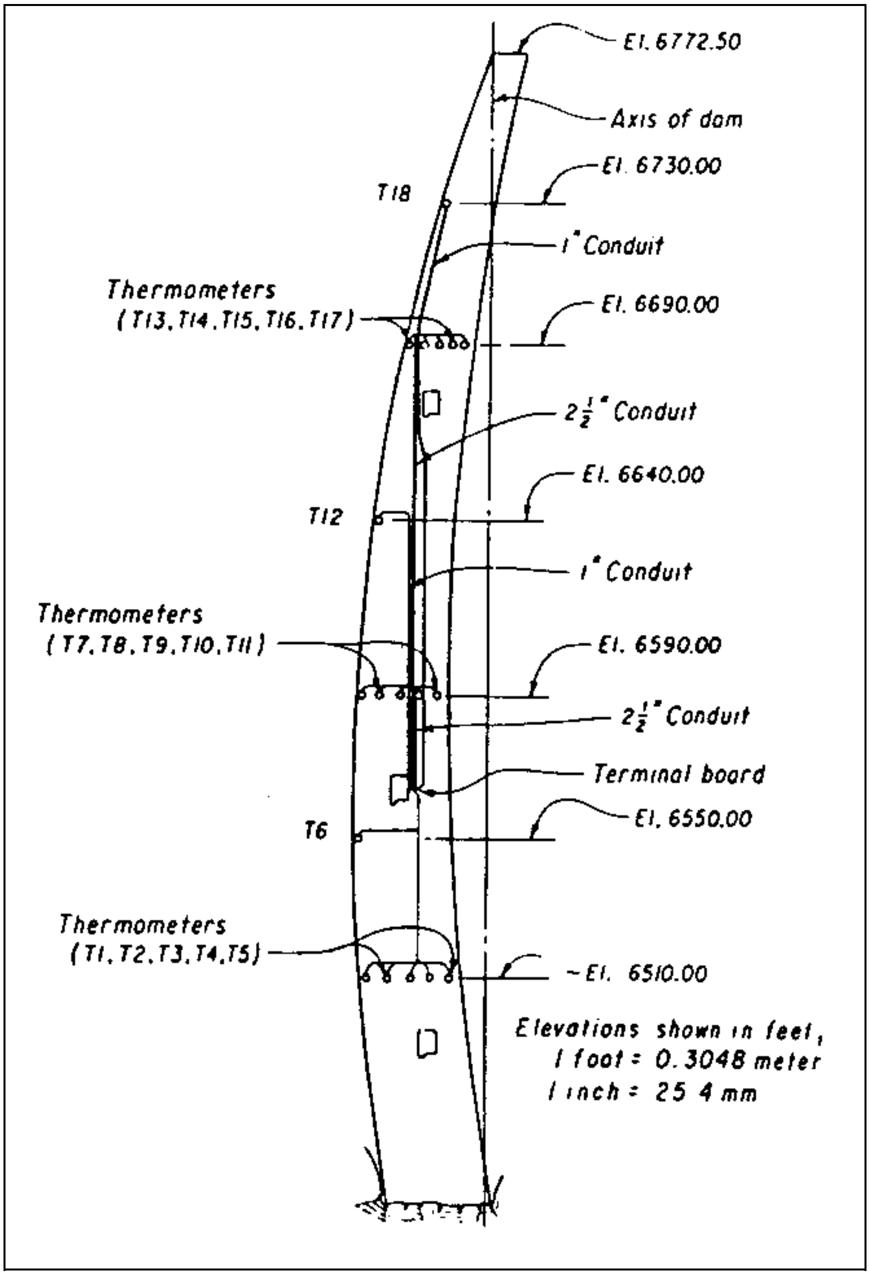

Figure 12-7. Layout for thermometer installation (USBR 1987)

TABLE 12-1

Recommended Readout Schedule

Type of Instrument	During Construction[1]	During Initial Filling	First 2 years of Operation	Next 5 years of Operation	After 7 years of Operation
Plumblines and optical plummets	N/A	weekly	monthly	quarterly	semi-annually
Inverted Plumblines	weekly	weekly	monthly	quarterly	semi-annually
Inclinometers	weekly	weekly	monthly	quarterly	semi-annually
Extensometers	weekly	weekly	monthly	quarterly	semi-annually
Joint meters	weekly	weekly	biweekly	quarterly	semi-annually
Triangulation	N/A	weekly	monthly	quarterly	semi-annually
Trilateration	N/A	weekly	monthly	quarterly	semi-annually
Strain meters	weekly[2]	weekly	monthly	quarterly	semi-annually
"No-Stress" strain meters	weekly[2]	weekly	monthly	quarterly	semi-annually
Stress meters	weekly[2]	weekly	monthly	quarterly	semi-annually
Weirs, etc.	N/A	weekly	weekly	monthly	quarterly
Open piezometers	monthly	monthly	quarterly	quarterly	semi-annually
Closed piezometers	weekly[3]	weekly	monthly	quarterly	semi-annually
Uplift pressure gauges	weekly	weekly	biweekly	monthly	quarterly
Thermometers	weekly[4]	weekly	monthly	monthly	quarterly

[1] Initial readings for all embedded instruments should be made within 3 hours after embedment.

[2] After initial readings are obtained, readings are continued every 12 hours for 15 days, daily for the next 12 days, twice weekly for 4 weeks, and weekly thereafter.

[3] Daily during curtain grouting.

[4] After initial readings are obtained, readings are continued every 6 hours for 3 days, every 12 hours for 12 days, daily for the next 12 days, twice weekly for 4 weeks, and weekly thereafter.