Geotechnical Instrumentation in Earth and Rock-Fill Dams

Mauriya, Vinod Kumar  
Senior Engineer (FES) 
e-mail: vkmfes@gmail.com  
KOLDAM HEPP, NTPC Limited, Bilaspur

ABSTRACT

Earth and Rockfill dams impound large amount of water, and its failure may be catastrophic leading to large scale destruction of property and loss of human lives. In such case, instrumentation plays a vital role as any change in the structural behaviour can be established well in time based on the data observed by the instruments and remedial measures can be taken up so as to avoid failure of the structure. Adequate instrumentation in earth fills and their foundations provide significant quantitative data indicating the magnitude and distribution of pore pressures and their variations with time and other patterns of seepage, zones of potential piping, proper functioning of the filter media and effectiveness of under seepage control measures. Increase in the height of structures and varied geological/topographical conditions have focused attention to the study of the behaviour of dams in the construction as well as operation stage, both from the point of view of safety, stability and knowledge of behaviour pattern.

1. INTRODUCTION

The soil mass is composed of solid soil particles and voids filled with water and air. Pressures develop in the pore space due to the loading of the soil mass or due to other factors, such as, seepage and capillary action etc. The air is compressible while water is highly incompressible. Hence when embankment settles due to compaction by rolling, or due to self weight, the void space contracts. This causes pressure in the pore fluid comprising air and water. When such load is applied to an embankments, part of it is carried by the soil particle skeleton and remaining part by the air and water entrapped between the soil particle skeleton. The load is distributed in direct proportion to the relative stiffness of the individual phases.

Instrumentation helps in monitoring and evaluating performance of Dams during construction as well as during operation phase. It helps in following manner:

• In locating distress areas to provide remedial measures.
• In checking theory used in design and validating it.
• In measuring various parameters which helps in monitoring and evaluating the performance of dam during construction as well as during their operation.
• In ascertaining the performance in line with the expected behaviour in design.

2. GEOTECHNICAL ENGINEERING CONSIDERATIONS IN INSTRUMENTATION

Geotechnical engineering of Earth & Rockfill dams requires the exploration and analysis of a wide variety of earth and rock materials being used. These materials are considered for adequacy as foundations and for use in dam body. Since earth and rock are created by natural processes, unlike other engineering materials such as steel and concrete, they seldom exhibit uniform properties. There is risk in every project that unexpected conditions will be encountered. The inability of exploration programs to detect in advance all potential significant properties and conditions in natural deposits requires designers to make assumptions and generalizations that may be at variance with actual field conditions. However, even though geotechnical design and construction of earth & rockfill dams are subject to uncertainties, visual observations supported by quantitative measurements obtained from appropriate instrumentation can provide engineers the information for checking and verifying design assumptions. Visual observations combined with instrumentation data provide the basis for assessing dam body and foundation performance against safety and stability during actual operations.

3. INSTRUMENTATION PARAMETERS

Following are typical parameters that can be monitored in instrumentation.

(i) Seepage through the dam body and foundations (quality as well as quantity)
(ii) Pore pressures in the body, foundations and abutments
(iii) Internal Deformations of the slopes as well as foundations
(iv) Surface settlements along the dam length and berms.
(v) Reservoir and tail water levels
4. TYPES OF MEASUREMENTS

There are various types of measurements for determining the performance as per aforesaid parameters.

Pore Pressure

Under an externally applied stress, soil grains are forced into more intimate contact, and the soil mass volume decreases. Because soil grain volume cannot be changed appreciably, this volume change must take place primarily in the soil voids or pores. If these pores are completely filled with water, their volume cannot be changed unless some water is drained from the soil mass, because water is considered incompressible. If drainage is prevented or impeded, stress will develop in the pore water (i.e. pore water pressure) opposing the externally applied stress. Pore water pressures are a controlling factor on stability during construction.

Movements/ Deformation

Measurement of movements is as important as the measurement of pore pressures. Movements conforming to normal expectations are basic requirements of a stable dam. An accurate measurement of internal and external movements is of value in controlling construction stability. The measurement of the plastic deformation of the upstream and downstream slopes under the cycles of reservoir operation may indicate the likely development of shear failure at weak points.

Seepage

Continuous movement of water through the soil of a structure may result in removal of soluble solids or may result in internal erosion called piping. Piping must particularly be guarded against because it occurs gradually and is often not apparent until the structure’s failure is imminent. Seepage and erosion along the lines of poor compaction and through cracks in foundations and fills may specially be indicated by such measurements.

Strains and Stresses

Design analysis of earth and rockfill dams are based on radical simplifications of the stress pattern and the shape of the rupture planes. Stress measurements, therefore, require considerable judgment in interpretation. Accurate measurement of stress is difficult and distribution of stress in earth and rockfill dams is complex. Strains may be calculated from displacements or measured directly.

Dynamic Loads (Earthquakes)

The analysis of the behavior of dams hit by earthquakes in past, clearly shows that these structures have high intrinsic capability to resist the seismic forces, provided they are well designed and built. However there are evidences too that exceptionally strong earthquakes have produced remarkable damages, thus showing that the actual seismic behavior of these structures is not yet fully understood, and consequently some improvement as to their design is still possible. These considerations support and justify the concept that it is advisable to install on these structures seismic surveillance system. Earthquake causes sudden dynamic loading and measurement of vibrations in dams located in areas subjected to seismicity are important for evolving design criteria for such conditions.

Other Measurements Reservoir and Tail Water Level

Reservoir and tail water heads being one of the principal loading to which a dam is subjected, the measurement of reservoir and tail water levels is essential for interpretation and realistic assessment of the structural behaviour of the dam.

Wave Height

Records of wave height data along with wind velocity and other pertinent data help in deciding free board requirements more realistically.

Rainfall

This measurement is necessary for interpretation of pore water pressure and seepage development in earth dams.

4.6.4 Data about Material Properties

The knowledge of properties of materials which are relevant to the type of measurement is essential for interpretation of instrument observations.

5. GEOTECHNICAL INSTRUMENTATION

Planning

A correct determination of the number, type, and location of instruments required at a dam can only be addressed effectively by combining experience, common sense, and intuition. Dam/ hydro projects represent unique situations and require individual solutions to their instrumentation requirements. Therefore planning of an instrumentation system should be such that the required information can be obtained both during construction as well as during the life of the project.

Selection of Instruments

Reliability is the most desirable feature in the selection of monitoring instruments. This is to ensure that dependable data of adequate accuracy can be obtained throughout the period when the information is needed. Often there is a tendency to seek unnecessarily high accuracy and when accuracy and reliability are in conflict, high accuracy should be sacrificed for high reliability. High accuracy often requires excessive delicacy and fragility. Usually the most reliable instrumentation devices are the simplest devices. Where a choice exists, the simpler device is likely to have more success. The performance record of commercially available instruments should be considered.

The instruments required with respect to parameters are as follows.
Table 1: Instrumentation with Respect to Parameters

<table>
<thead>
<tr>
<th>SN</th>
<th>Parameters within the embankment</th>
<th>Instruments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Pore-water pressure within the embankment</td>
<td>Standpipe, Pneumatic and Vibrating Wire Piezometer</td>
</tr>
<tr>
<td>2</td>
<td>Total stress at contact points between embankment &amp; Strs.</td>
<td>Vibrating Wire Pressure Cells</td>
</tr>
<tr>
<td>3</td>
<td>Leakage downstream</td>
<td>V-Notch Weir Monitors</td>
</tr>
<tr>
<td>4</td>
<td>Vertical deformation within embankment</td>
<td>Double Fluid Settlement Gauges, Horizontal Inclinometers, Magnetic Probe Extensometers</td>
</tr>
<tr>
<td>5</td>
<td>Lateral deformation within the embankment</td>
<td>Magnetic Probe Extensometers, Vibrating Wire Soil Extensometers, Inclinometers</td>
</tr>
</tbody>
</table>

Location of Instruments

Locations for instruments should be determined based on predicted behavior of the site. The locations should be compatible with the geotechnical concerns and the method of analysis that will be used when interpreting the data. A practical approach to selecting instrument locations includes following:

(i) Identify zones of particular concern such as structurally weak areas that are most heavily loaded, and locate appropriate instrumentation,
(ii) Select zones that can be represented by typical cross sections where predicted behavior is considered representative of behavior as a whole,
(iii) Identify zones where there is discontinuity in the foundation or abutments,
(iv) Install some additional instruments at other potentially critical secondary locations to serve as indices of comparable behavior, and
(v) Locate rows of survey monuments at intervals in the longitudinal direction at appropriate elevations.

Instruments

Following are the variety of instruments used in instrumentation of Earth & Rockfill Dams.

(i) Vibrating wire Piezometer
(ii) Joint Meter(JM)
(iii) Thermometer(T)
(iv) Multipoint Borehole Extensometer (3 & 5 Point)
(v) Group of 5Strain meter and one Stress meter(SG)
(vi) Open Chamber Piezometer(OCP)/Porous Tube Piezometer(PTP)
(vii) Direct Plumbline
(viii) Inverted Plumbline
(ix) Fill Extensometer(FE)
(x) Strong Motion Acclerograph (SMA)
(xi) Seismometer

Some of the above instruments are described as below.

Vibrating Wire Piezometer

Vibrating wire Piezometer is high precision instrument, which have been designed to measure pore water pressures. Its advantages are long lead lengths and very fast response time to changes in pore water pressure. It converts water pressure to frequency signal by VW technology. Its range is 2 to 100 Kg/cm$^2$.

Fig. 2: Vibrating Wire Piezometer Installation

The vibrating wire Piezometer contains a steel wire stretched between a fixed anchorage and a sensitive stainless steel diaphragm. The ends of the wire are anchored to ensure excellent long-term stability. An electromagnetic coil assembly, located close to the wire, is used to pluck the wire and also to sense and convert the subsequent wire vibrations into an electrical AC output whose frequency is related to the tension of the wire. Change in pore water pressure cause the diaphragm to deflect, thus altering the tension of the wire and consequently the frequency of the output (pore pressure is proportional to frequency). This frequency is measured using a Digital Readout Unit and readings can be displayed in units of pressure. Since only frequency is measured, changes in the length, resistance or temperature of the connecting cable have a minimal effect on the signal (as assumed). Transducers are fabricated entirely in stainless steel mounted in a rigid PVC housing.

Fill Extensometer

Fill Extensometer is an instrument for measuring deformation and measures longitudinal displacement between two points in fill and lateral strains in earth dams. It has an outer pipe fitted with two end flanges and an inner stainless steel rod. One end of the rod is attached to a flange, while the other end of the rod is attached to a displacement sensor, which is attached to the other flange.

The fill extensometer is designed for short term or long term monitoring of displacements between two points inside any type of manmade fill. The base length, the distance between the two end flanges, is variable and is generally from 1.5 to 50 meters. The fill extensometer is normally installed horizontally in trenches and can be assembled in series using threaded rods inserted in the holes on each end flange. However, in some applications such as for measuring settlement at the point of contact with the foundation, it is installed vertically. Reading are obtained with a portable FC Series readout or with a C.A.F. or SENS–LOG automated data acquisition system. Each instrument comes with a calibration curve to convert frequency into a displacement value.
Joint Meter
This is to measure relative movement across joints and consists of a displacement transducer, fixed between anchors on opposite side of the joints.

Open Chamber Piezometer (OCP)/ Porous Chamber Piezometer (PTP)
This is used to measure water pressure in Spillway / Dam body. The porous tube is set in a hole drilled into the foundation to a pre-defined depth to measure pore water pressure in the foundation. The pressure of the pore water surrounding the porous tube causes a flow through the piezometer until the pressure is equalized by the head of water in the standpipe (plastic tube). The elevation of water in the plastic tube is determined by Water Level Sounder. Its range may vary from 0 to 15 m.

5.4.6 Seepage Measurement
Seepage measuring devices are used in dams to measure amounts of seepage through, around, and under the dam body. Observations of seepage rate can be correlated with measurements of piezometric pressure, and be used to examine the effectiveness of drains, relief wells, and cutoffs. Relief wells, drainage outlets, channels, and ditches are common measuring points of seepage.

Seismic Instrumentation
The outdated concept that seismic instrumentation of earth and rockfill dams and reservoir sites are only a research tool has given way to the modern concept that seismic instrumentation is necessary for moderate-to-high hazard dams in seismic areas. Three types of recording devices are popular today. They are:

i) Acclerograph,
ii) Seismic acceleration alarm device (SAD), and
iii) Non-electronic peak Acclerograph recorder.

6. EMERGING TRENDS IN INSTRUMENTATION
An emerging trend in instrumentation is Distributed Fiber Optical Technology. This optical technology detects and measures seepage flow all along the entire dam. This is used in short and long term monitoring of seepage flow changes. In this temperature measurement is used to detect the seepage. This is being widely used in Sweden and Germany e.g. Hylte Dam, Sweden. This technology uses scattering characteristics of laser light where scattered light has strong relation to temperature and detector measures the change in power and frequency of scattered light against time at all positions of fiber. Seasonal temperature variations are also measured and correlated to seepage flow.

7. CONCLUSION
Instrumentation which is essentially a technology of measurements helps in monitoring and evaluating the performance of dams during their construction as well as during their operation. It facilitates in locating distress areas and providing remedial measures. Instrumentation greatly helps in checking the theories used in design and validating them. Such a comparison between prediction and performance become invaluable for indicating the directions in which design principles can be improved and erroneous concepts discarded. The behaviour of dam during construction and operation is being and shall be monitored through well planned scheme of instrumentation.

REFERENCES
ASCE (2002), “Guidelines for instrumentation and measurements for monitoring dam performance”, prepared by American Society of Civil Engineers (ASCE)-Task Committee on Instrumentation and Monitoring Dam Performance.