International Journal of Engineering and Technical Research (IJETR)
ISSN: 2321-0869, Volume-3, Issue-5, May 2015

Dam Instrumentation in Gravity Dams: A Case Study on Koyna Dam

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Abstract **- Number of aspects, parameters is assumed while designing the dams. The materials are tested in laboratories and designs are based on assumptions that the same results will be met with, during actual construction in most of the cases. The actual product defers from the original assumptions as there are always large deviations in materials, their properties, construction methods and their control. How the actual constructed dam acts against the expectations made that must be known by engineer. In this paper, the requirement, use and operation of the instruments required to check the behaviour and stability of dams are discussed. These instruments show their effectiveness in proper maintenance of dam, and hence they should be installed at appropriate places in the dam under the guidance of experts. It has been concluded from present study that there should be close co-operation between the designers, instrumentation specialist, expert analysis and site authorities to achieve the goal of instrumentation.**

Index Terms—Dam; Instruments; Dam Safety; Précautions; Failure; Remedies; Assumptions etc.

I. Introduction

It is essential for Engineers to design the dam to withstand alongside any damage because it is said that, "Dam instrumentation means number of instruments embedded in the body of dam to accumulate basic factors & to check behaviour of dam".

Number of factors, parameters is assumed while designing dams. The materials are tested in laboratories and designs are based on expectations that the same results will be met with, during actual construction in most of the cases. The actual product defers from the unusual assumptions as there are always large deviations in materials, their properties, construction methods and their control. This could be found out by many techniques. How the actual constructed dam behaves against the assumptions made that must be known by engineer. For filling structural behaviour, essential help from various instruments implanted in a dam body is taken. The operational of a structure or a system or the operation of a process depends on these instruments are devices to measure and / or control the variables.

Generally the major objectives of a geotechnical instrumentation plan may divide into four categories: first, analytical assessment; second, prediction of future performance; third, legal evaluation; and fourth, development and verification of future designs. These objectives of instrumentation can be achieved by providing measureable data to assess groundwater pressure, deformation, total stress, temperature, seismic events, leakage, and water levels. Relative movements as well as total movements between zones of an embankment and its foundation may also need to be monitored. For a given project to ensure all critical conditions, a wide variety of instruments may be applied in a comprehensive monitoring program are covered sufficiently.

For verification of design assumptions, construction technique & modification design, Instrumentation in dam is necessary. In determination of specific cause of failure, data collected from instrument could be tremendously valuable. A constant watch over the performance of the structure during service is taken care by instrumentation and obtains timely notices in respect of distress spots. Safety in dam can be assist by instrumentation. Recent dam failures in various part of world inspire important interest in monitoring various parameters as a means for ensuring adequate margin of safety. Basic parameters like pore pressure, displacement, seepage, strains, stresses, dynamic load, uplift pressure, temperature can study as per IS specification with the help of instrumentation.

In India there are about 4291 large dams. Out of these 1529 dams are in Maharashtra from which near about 40 Dams are instrumented. The approximate cost of these instruments is near about to 1% of total construction cost of dams.

II. Planning of Instrumentation

A. Importance of the instrumentation

Instruments play an vital role in checking the safety of the dams as instruments embedded in or installed at the surface of the dam keep a constant watch over their service and indicate the distress spot which call for remedial measures. A cumulative record for structural behaviour of dams is formed from the observations of the instruments. In modifying theoretical assumptions and includes the effect of field observations, the study of structural behaviour provides an important aid.

TABLE I. Instruments used to obtain parameters

Parameters	Instruments
Surface Displacement	1. Tilt meter 2. Surface extensometer
Uplift Pressure	1. For Structures on permeable foundation instruments. 2. Instruments for structures on rock foundations
Dynamic Loads	1. Seismometer
Stress	1. Total Pressure Cells *2.* Jack-Out Total Pressure
Seepage	1."v"notch weir large Discharge
Pore Water Pressure	1.Open stand pipe piezometer 2.Pneumatic piezometer 3.Vibrating wire piezometer

To provide for unknowns in the designs, most hydraulic structures are built on rather conservative assumptions.

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Observations from the instruments help to reduce these unknowns and place future designs on sounder footing.

The instrumentation data also helps in the process of research and developments and also advancing the state of art. The present age instrumentation has become necessity to insure proper functioning, safety as well as the optimum utilization of resources.

Following table shows the instruments used to obtain parameter:

B. Failure of Dam

The incidents of failures demonstrate that failure of dams depends on the type of the dam. Various types of dam failure are listed below:

1. Sliding of dam
2. Overturning of dam
3. Tension failure of dam
4. Crushing of dam

TABLE II. Causes of dam failure in percentage

Sr.No	Cause	Percentage failure
1	Foundation failure	40%
2	Inadequate spillway	23%
3	Poor construction	12%
4	Uneven settlement	10%
5	High pore pressure	05%
6	Acts of war	03%
7	Embankment slips	02%
8	Defective materials	02%
9	Incorrect operation	02%
10	Earthquakes	01%

III. SYSTEM DEVELOPMENT

The following parameters need to be measured as per IS specifications:

1) Pore pressure
2) Displacement
3) Seepage
4) Strains
5) Stresses
6) Dynamic loads
7) Uplift pressure
8) Temperature

A. Characteristics of Good Instruments

The state of instrumentation design is far ahead of the art in user technology. The various instruments commonly available for measuring various parameters have been discussed in chapter 2 of this dissertation. Less than 2 decades ago the instruments deployed were simple and it was possible for the Civil Engineer to have a good knowledge of the operating principles and characteristics of such instruments. Since that time there have been major advances in the development of new instruments. The design of new generation instruments has gone into the domain of the instrument, engineer rather than the Civil Engineer. It is the responsibility of the user to develop an adequate level of understanding of the instruments before they select a particular instrument. Some general fundamental characteristics that are to be considered while making a selection of instruments for earth dam are discussed in the following paragraphs.

1. Conformance

Ideally, the presence of a measuring instrument should not alter the value of the parameter being measured. If in fact the instrument alters the value, it is said to have poor conformance. For example, Earth pressure cells should ideally have the same deformability characteristics as the material in which they are placed. In addition the act of compacting fills around an instrument should not result in a significantly different condition within the soil mass. Similarly piezometers should not create drainage paths that would reduce the measured pore water pressure below the value elsewhere. Conformance is a desirable ingredient of high accuracy.

2. Accuracy

Accuracy is the closeness of approach of a measurement to the time value of Quantity measured. Absolute accuracy is not only difficult to attain but also difficult to define and demonstrate. Accuracy of an instrument is evaluated during calibration. The true value is the value indicated by an instrument whose accuracy is verified and traceable to an accepted standard. Wherever possible traceable value should be with respect to the Indian Bureau of Standard. The accuracy of instrument depends on accuracy of each component of that instrument. The degree of instrument accuracy need only be as high as the ability to define the anisotropy of the parameters.

3. Repeatability

Repeatability (Precision or Reliability) is the measures of the smallest reading which can be consistently reproduced provided that the parameter being measured has not changed. The difference between accuracy and precision is illustrated in fig. 3.1. The bull's eye in the figure represents the true value. In the first case, the measurements are precise but not accurate, as would occur when using a survey tape with a bad kink. Such errors are systematic. In the second case the measurements lack precision but if sufficient readings are taken, the average will be accurate. Such errors are random. In third, the measurements are both precise and accurate.

4. Range

The need of adequate measuring range is sometimes overlooked because stress or shape change magnitudes of parameters, particularly in geological masses are difficult to predict. Range should be adequate, but not excessive, as range can generally be obtained only at the expense of some other desirable characteristics usually resolution.

5. Survivability

Instruments must be capable of surviving for the duration of the prospective measurement. Cables, tubes or pipes' that connect the, transducer to its readout unit must be able to survive imposed pressure changes, deformation, water, sunlight and chemical effects such as corrosion and electrolytic breakdown. This is not always a simple requirement as surrounding conditions of instruments are frequently more severe than anticipated.

6. Hysteresis

When the quantity being measured is subjected to cyclic change, the indicated measured value sometimes depends on whether the measurement is increasing or decreasing. If the two relationships are plotted the separation between the two curves is a measure of hysteresis. Instruments with large hysteresis are not suitable for measurement of rapidly changing parameters.

7. Noise

Noise is a term used to cover random measurement variation caused by external factors, creating lack of precision and accuracy. Excessive noise in a system may mask small real changes. Groundwater interference in leakage were due to rain is an example of external factor that creates noise and affect the measurement of the seepage through embankment.

8. Cost

Comparison of cost should only be undertaken amongst those instruments which meet all the specifications discussed above. Any attempt to save expenditure by relaxing specifications often result in waste of funds since such relaxation results in instrument not performing the task it is chosen for practically it is impossible to select the instrument which conforms all above capabilities. Therefore, engineer has to make some compromise for selection of particular instruments. In order to satisfy one factor he may have to sacrifice the other. This leads to the errors in measurements.

IV. CASE STUDY- KOYNA DAM

To get more detailed knowledge about dam instruments and its components, a case study was conducted at KOYNA DAM. This section discusses the various aspects of the case study considering the perspective of dam instrumentation and its applications.

A. General

Salient features of Koyna Dam:

1. Name of Dam: Koyna Dam
2. Name of River: KOYNA RIVER
3. Location: Village: Deshmukhwadi, Tal. Patan Dist. Satara
4. Catchments Area: A. Main Dam : 891.78 Sq.km.
   B. Avg. Rainfall : 5350 mm
5. Dam & Reservoir:
   A. Gross Storage: 2980.68 M CUM / 105.26 TMC
   B. Live Storage: 2684.51 M CUM / 94.80 TMC
   C. Dead Storage: 296.17M CUM / 10.46 TMC
   D. From Spillway crest to top of the gate: 908.18 M CUM / 32.07 TMC
6. Height of Dam:
   Above River bed: 85.35 m
   Above foundation: 103.02 m
7. Length of Dam:
   Main Dam: 807.72 m
   Top of Dam: 654.97 m
8. Spillway gates 6 Nos. Tainer type: 12.50 m X 7.62 m
9. Design Purpose: Hydro Electric Project and Irrigation Project.
10. Hydro Electric Power Generation:
   A. Main Dam : 1960 MW.

B. Introduction

Koyna Dam is a rubble concrete dam 103.02 m high above the deepest foundation level, and 85.35 m high above River Bed. It has a total length of 807.22 m. It is constructed across river Koyna, which is a major a tributary of River Krishna. The dam is located near village Deshmukhwadi in Patan Tahasil in Satara district of Maharashtra State of India. The Dam is founded on basalt rock. Koyna is one of the major Hydro Electric Projects in the Country. The dam impounds 2980.34 MCum water to generate 1960 MW power.

The dam is built in 53 monoliths of which six end monoliths are constructed in masonry and the rest in rubble concrete. The spillway is centrally located and extends from monolith number 18 to 24 over a length of 88.70 m. six radial gates of size 41 ft X 25 ft are installed in the spillway (manufacturers M/s Conrad Czoke). In year 2003, these gates are fixed with 5 ft high flaps which are independently operated hydraulically. The height of gates can thus now be considered as 30 ft. Catchment area of the Dam is 891.78 SqKm and submerged area is 115.35 SqKm. 98 villages were affected by the submergence and 9069 families were displaced. These families are rehabilitated in 6 districts viz Satara, Sangali, Solapur, Kolhapur, Raigad and Ratnagiri.

The topography near the initial regime of Koyna River is very favorable for the location of Hydro Electric Project. There is a sheer vertical drop of 487.68 meters (1600 feet) on west side of the reservoir. The continental divide is only 56 Km. (35miles) from the Arabian Sea, and separates the land between the 579 meter (1900 feet) high ground of Koyna on the Eastern Side of the Sahyadri Range and the 152 m (500 feet) high base on an escarpment on its Western Side. This has rendered a high head Hydro Electric Scheme feasible at economical cost. Since the rock through which the tunnels pass is excellent basalt rock, it was possible to take advantage of this rock by transmitting part pressure of water to rock and part to steel plates which led to economy. Straight excavation of pressure shafts resulted in reduction in the length and saving in cost of Steel plates and annular concrete & thus enabled adoption of underground Power House. Thus Koyna Stage I&II Power Station went underground for the purpose of economy and safety. The Project subsequently developed in four stages to reach power production capacity today totaling to 1960 MW. Stage I & II accommodates 4 generators of 65 MW capacity and 4 generators of 75 MW capacity, totaling to 560 MW as a base station with 60% load factor The tail water of stage I & II power house was initially released in Vashishthi River at KRL 133.20 m (433.00 feet). To utilize this unused residual head before the water goes to the Arabian Sea, the water was then diverted in adjoining Vaitarni Valley through a 4.5 Km long tunnel and was stored behind a dam, called Kolkewadi Dam, 497 m long and 56.80 m high, to generate 320 MW with four machines of 80 MW each in the Dam Foot Power House. This is called as Stage III, which was designed as a peaking station with 24% load factor. Water for Irrigation was being released eastwards through a River Sluice in the main dam till 1980. To use the static head of height of reservoir, a dam foot Power House was constructed on right flank of the Dam during 1975 to 1980. 2 generators of 20 MW capacities are installed in this Power House, thereby generating 40 MW in Irrigation Rotation Period. Around 1985 it was realized that there is a vast diurnal hourly fluctuation in the power demand. Maximum power demand in morning peak (7 to 11 am) period and in evening peak (7 to 11 pm) period was as much as 15000 MW, while in between period it slowly reduces to 9000 MW. It was concluded that hydro power stations need not be run at 60% power factor. They can be run only in peak hours with 25% (or even less) Power factor. Then I&II stage PH was generating at 60% PF and utilizing 67.5 TMC of water. If the PF is reduced, westward water quota cannot be fully utilized. If a parallel Power House is built, and both the Power Houses are run with 25% PF, then the quota can be utilized fully. This concept gave rise to the IV stage Power House of Koyna Project. Accordingly a new Powerhouse comprising of 4 generators of 250 MW each was constructed and commissioned in 1999/2000.

C. Necessity of Instrumentation

The behaviour of this dam will have to be monitored carefully particularly with reference to the following points:

1. Instruments embedded in or installed at the surface of the dam keep a constant watch over their service and indicate the distress spot which call for remedial measures. Thus instruments play an important role in checking the safety of the dams.

2. The Instrumentation data also helps in the process of research and developments and also advancing the state of art.

3. The dam is located in highly seismic zone, with this point of view and even otherwise, the vertical settlement of dam as well as its horizontal spread on u /s and d /s needs to be monitored.

4. The behaviour of dam for comparison with design assumptions is to be observed.

5. The Koyna dam lies in heavy rainfall zone both in quantum and intensity. It would be interesting to a certain as to how far does the heavy rainfall affect the saturation of d /s slope even after provision of pitching.

D. Types of Instruments Installed

In order to monitor the safety, the dam was well instrumented since early construction stage. Following instruments have fixed in the dam for observation.

Instruments	Nos.	Location/s
1. Uplift pressure cells	66	M.No.1-C-1-G 21 24 25 and stilling basin
2.Co-Ordimeters	2	M.No.22 and 25
3. Thermometers	52	M.No 22
4. Stress Meters	17	M.No 22
5. Strain meter	38	M.No 22
6. Dial Gauges	6	Cross gallery in M.No 21
7. Piezometers	4	Lift Bank Out off
8.Spillway Thermometers	9	M.No 22 Spill Way.

Instrumentation in Koyna Dam Concrete Backing to study the Structural behaviour of Concrete Backing consists of following instrument;

1. Thermometer
2. Stress meter
3. Strain meter
4. Joint meter
5. Uplift pressure cells.

All these instruments are embedded in M.No 17 it being the deepest monolith. All these instruments are embedded during construction period 1969 to 1972.

E. Frequency of Observation

- Once in a week in fair weather season.
- Twice in a week in rainy season.
- After every sizable earthquake.

2. Earth pressure cells for observation of stresses in dam.
3. Surface settlement plugs for measuring embankment movements.
4. Peak recording accelerographs to measure the ground acceleration duration earthquake.
5. Seismoscope to determine displacement relative velocity and acceleration response of dam to earthquake.

F. Seismic Instruments

The following types of instruments are installed in various observatories:

1. Wood Anderson Seismometer
2. Electromagnetic Seismometer
3. High Frequency Seismometer
4. Kirnos Seismometer
5. MEQ Seismographs
6. Accelerograph
   a. A.R. 240
   b. RFT 250
   c. Roorkee
   d. Peak Recording

Koyna region lies in Zone IV of earthquake hazard zoning. Below is a list of earthquakes having epicenter in or near the Koynanagar region in last few decades.

TABLE III. EARTHQUAKES RECORDED AT KOYNA DAM

Decades	Richter scale	Occurrences	Depth (Km)
Pre 67	5.4	2	4.9
1967	6	3	11.6
1980s	4.3	3	22.3
1990s	4.9	2	5.5
2000s	4.7	8	10.7
2010s	4.9	1	11

G. Feedback to Central Water and Power Research Station

The data collected from the seismological observatories of the Koyna network is regularly analyzed by Central Water and Power Research Station, Pune. The data from all other instruments is sent to MERI for further analysis.

FIGURE 1 ANALYSIS OF EARTH QUAKES ATKOYNA DAM

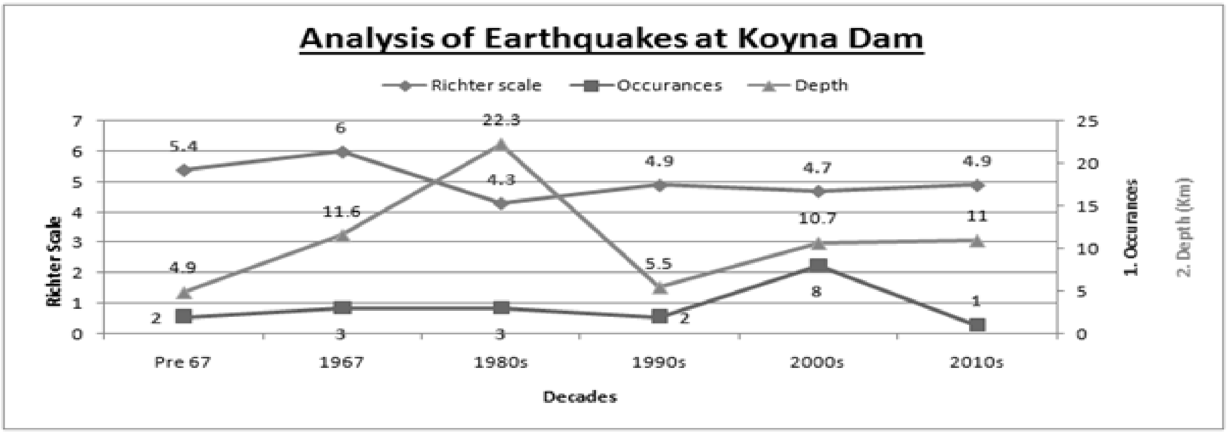
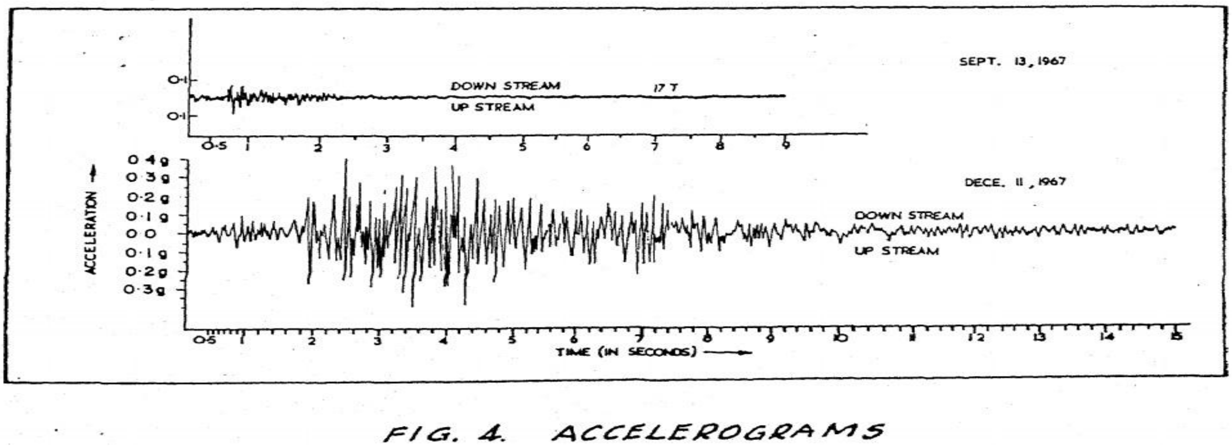
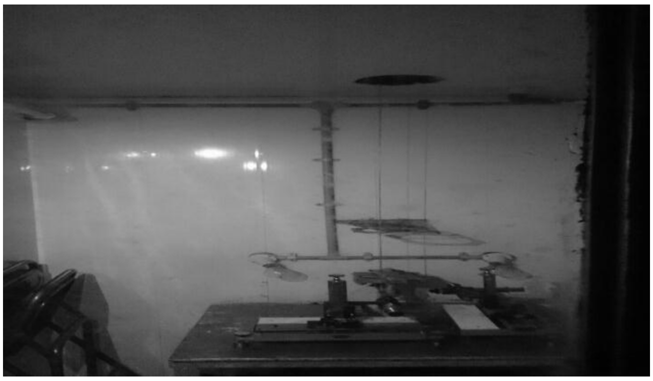


FIGURE 2 ACCELLEROGRAM RECORDED IN 1967

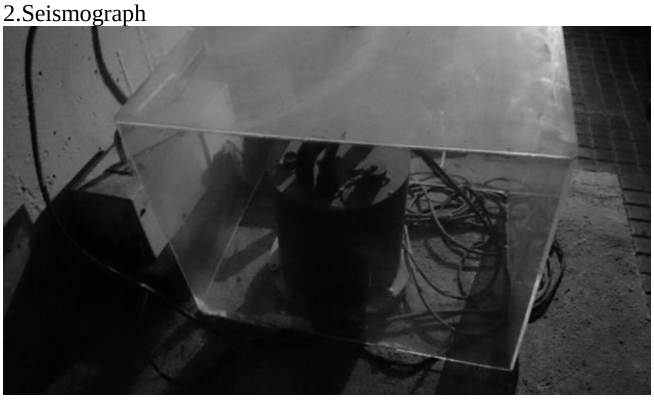


V. INSTRUMENTS INSTALLED AT KOYNA DAM

1.Tiltmeter



2.Seismograph



3.Analogue Seismograph

4.V-Notch Weir

5. Location of Thermometer, Stress meter, Strain Meter

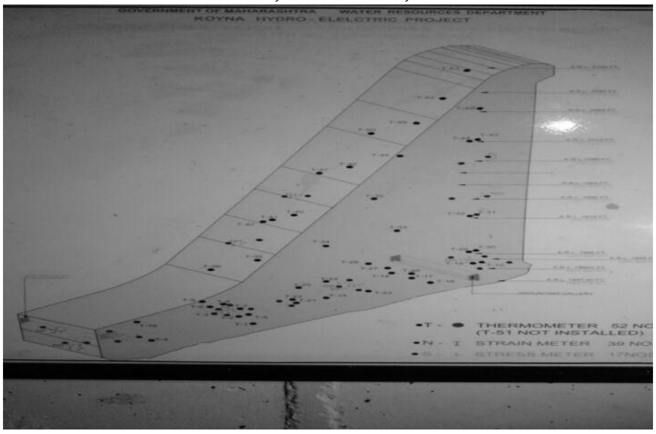


TABLE IV. DETAILS OF ACCELEROGRAPH STATIONS IN THE BODY

Accelerograph Stations	Foundation Type	Accelerograph Type	Date of Installation
1. Koyna Dam 1-A gallery, 644m above MSL, 17° 23.85'N, 73° 45'E	Concrete monolith founded on basalt	AR-240 RFT-250	03/29/1966 09/24/1971
2. Koyna Dam shear zone gallery, Monolith No. 13, 595m above MSL , 17° 23.85'N, 73° 45'E	Dam	AR-240 RFT-250	03/29/1966 09/24/1971
3. Koyna dam inspection gallery, Monolith No. 17, 585m above MSL, 17° 23.85'N, 73°45'E	Dam	RFT-250	1978
4. Koyna dam operation gallery, Monolith No. 17, 610m above MSL, 17° 23.85'N, 73° 45'E	Dam	RFT-250	1978
5. Koyna Dam top Monolith No. 17, 665m above MSL, 17° 23.85'N, 73° 45'E	Dam	RFT-250	09/24/1971
6. 100m downstream of the dam on right bank, 644 m above MSL, 17° 23.85'N, 73°45'E	Basalt	AR-240 RFT-250	09/10/1968 09/24/1971
7. Kirnos Observatory about 300 m from the right bank near the dam site, 675m above MSL	Basalt	RFT-250	1978
8. Pophali Power House 17° 26.00'N, 73° 41.00'E, and 168m above MSL	Basalt	RFT-250	09/17/1971
9. Pophali Interadit Point,17° 26.00'N, 73° 41.00'E, and 365m above MSL	Basalt	RFT-250	09/17/1971
10. Alore Observatory,17° 29.00'N, 73° 39.00'E, and 85m above MSL	Basalt	RFT-250	10/27/1971
11. Govalkot Observatory 17° 32.50'N, 73° 29.43'E, and 15m above MSL	Basalt	AR-240	06/27/1972
12. Satara Observatory,17° 40.87'N, 74° 00.00'E, and 650m above MSL	Basalt	AR-240	01/27/1972
13. Mahabaleshwar Observatory,17 55.36'N, 73 39.55'E and 1430m above MSL	Thick hard lateritic soil under lain by basalt	RFT-240	06/27/1972

VI. CONCLUSION

Different studies which have been done on dam instrumentation are discussed in this paper, conclusions obtained after studies are as follows:

1. There is different force which acts on body of dam. But major forces which affects the stability of dam are uplift pressure, dynamic loads etc. These kind of major forces cannot be handled with traditional approach of dam construction and hence it demand for dam instrumentation for better and ensured stability of dam.

2. While going through stress analysis of dam due to various forces, it has been observed that one set of instrument could not be used in every body of dam. It depends on various factors.

3. After selecting proper instrument, selecting the proper location of instrument is another vital part of dam instrumentation. But the location can be found out by many aspects need to be taken into account. Select the proper location of instrument in dam; this will lead to better performance of instrumentation in dam.

4. The data collected from Koyna dam, gives the idea about different forces acting, location of instrument to be used, type of instrument to be used etc. The major forces acting on the body of dam are observed as uplift force, seepage force, dynamic load etc.

5. For the stability and safety of dam, not only the part of instrumentation in dam is important but the part of construction of dam was also crucial part. If the dam is in proper condition it means that the seepage and erosion in the body are at minimum level. In such cases where the condition of a dam is not vulnerable to future attack of various forces like seepage, pore pressure etc. It does not require large scaled instrumentation in body of dam and it could be managed at some primary level of instrumentation by providing some small sized instruments like strain gauge, stress gauge etc. But in the case of dam where the seepage is considerable and the material used in the dam is of pure quality, in such case dam instrumentation should be adopted and instruments like piezometer, foundation piezometer, embankment piezometer, Casagrande type porous tube piezometer, and terminal well should be used in order to ensure the safety of dam.

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