LONG TERM STRUCTURAL PERFORMANCE MONITORING OF GRAVITY DAMS THROUGH ANALYSIS AND INTERPRETATION OF INSTRUMENTATION DATA –A CASE STUDY

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ABSTRACT

Many dams have shown sudden distresses in the form of cracking, deformations, seepage and sometimes failures without any warning even after proper design. These sudden distresses in major structures gave a thought of having a proper warning system. The early warning system consisting of different type instruments installed in the dams at various locations, data acquisition & transfer mechanism, expert analysts and decision takers would help to avoid disasters in the event of sudden failures. Most of the countries are now making regulations to have a better early warning system, which should be efficient and reliable. India too not left behind in this engineering field and followed to remain at par with International Standards by installing instruments in most of the major dams constructed during last 4 decade. Recently Dam Safety Bill 2019 has been introduced by Government of India and it has been made mandatory to monitor the safety of the dams by installing instruments in all major dams. Proper analysis of the data obtained from these instruments is necessary to study the post construction structural behaviour of the dam and get early indication about the distresses likely to happen. This paper discusses about how a effective and sustainable data analysis and interpretation mechanism developed for Indira Sagar Dam is beneficial in getting early warning about the distresses likely to happen. It is a 92 m high Concrete Gravity and very well instrumented under the guidance of CWPRS during construction. From these instruments a large number raw data has been obtained which has been analysed to get useful information and enabled project authority to take timely remedial measures. Study indicated that the dam behaviour by and large is satisfactory except detection of high uplift pressure in toe region of non overflow block.

1. INTRODUCTION

Dam safety is considered an inherent function in the planning, design, construction, maintenance and operation of dams. In spite of taking due care in planning, design and execution stages; many of dams have shown signs of distresses in terms of cracking, settlement and seepage etc. Failures have not only occurred in dams built without proper application of engineering principles during design stage; but also in dams built to the accepted state of art of "dam engineering". Detailed investigations conducted on many dam failures occurred in various countries, have confirmed that a majority of these failures could have been avoided by proper design, construction, regulation and having a proper monitoring system. An early warning system through measurement of various parameters which may cause distress in the dam in future, gives very important timely information about the dam behaviour. This early warning system consists of set of instruments, regular data acquisition, analysis of acquired data and thereby monitoring dam behavior on long term basis. This paper describes the structural performance being monitored through analysis and interpretation of instrumentation data of Indira Sagar Dam in MP. Indira Sagar Dam is very well instrumented and dam structural behavior is continuously being monitored by analyzing the data obtained by the installed instruments under the guidance of CWPRS since 2003. The paper brings out the highlights of structural monitoring of the dam through analysis and interpretation of the data obtained by the various instruments since 2003.

2. INTRUMENTATION IN INDIRA SAGAR DAM

Indira Sagar dam, constructed across Narmada River in Madhya Pradesh is a concrete gravity dam of 653 m long and 92 m high (Fig. 1). The dam consists of 27 blocks (1 to 3 and 25 to 27 forming non-overflow portion and block Nos.4 to 24 forming overflow (Spillway) portion). The reservoir, one of the largest in India, with water storage of 12.22 Billion cubic meters is a multipurpose project, with an overall hydropower generation of 1000 MW (8 × 125 MW).

Figure 1 : A bird view of Indira Sagar Dam

The dam has been instrumented to study the structural behaviour by installing frequency based vibrating wire type instruments in block 13 and 25 during construction. Figures 2 and 3 show the location instruments installed in block no.13 and block no 25 respectively, The type and number of instruments are listed in Table 1.

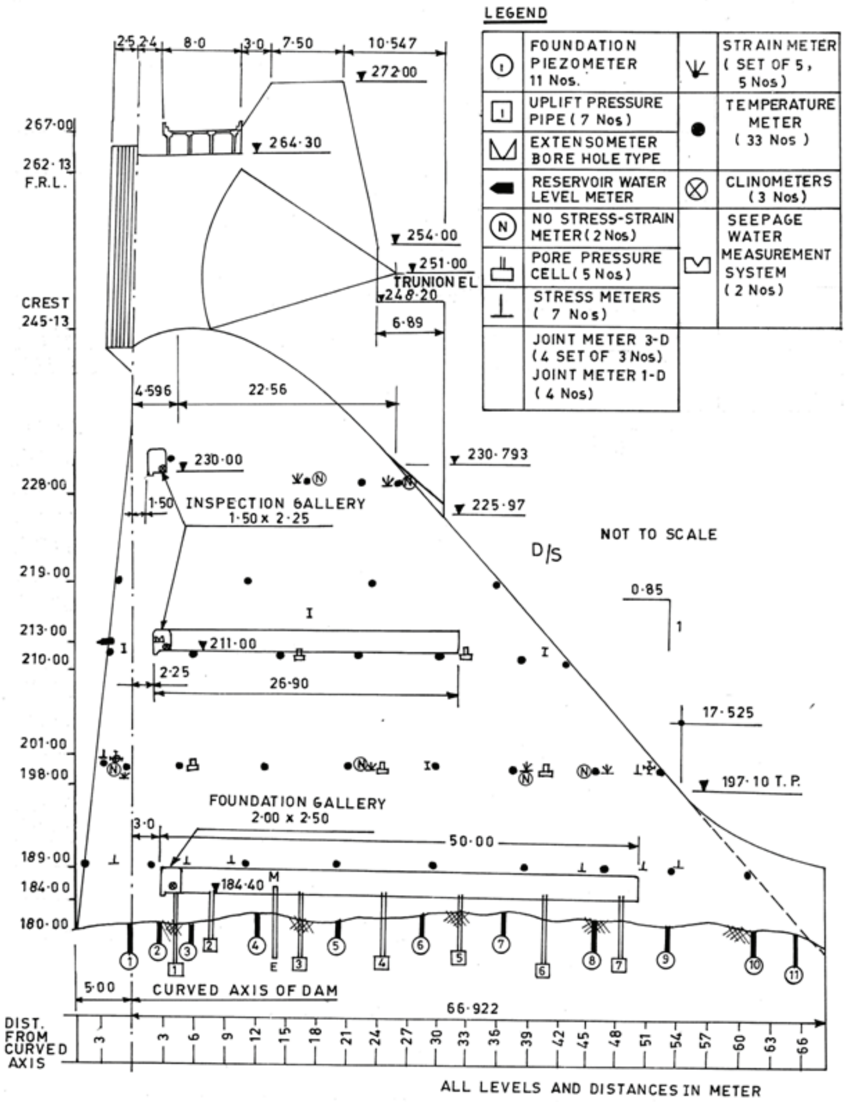

Figure 2 : Locations of Instruments installed in Block No.13

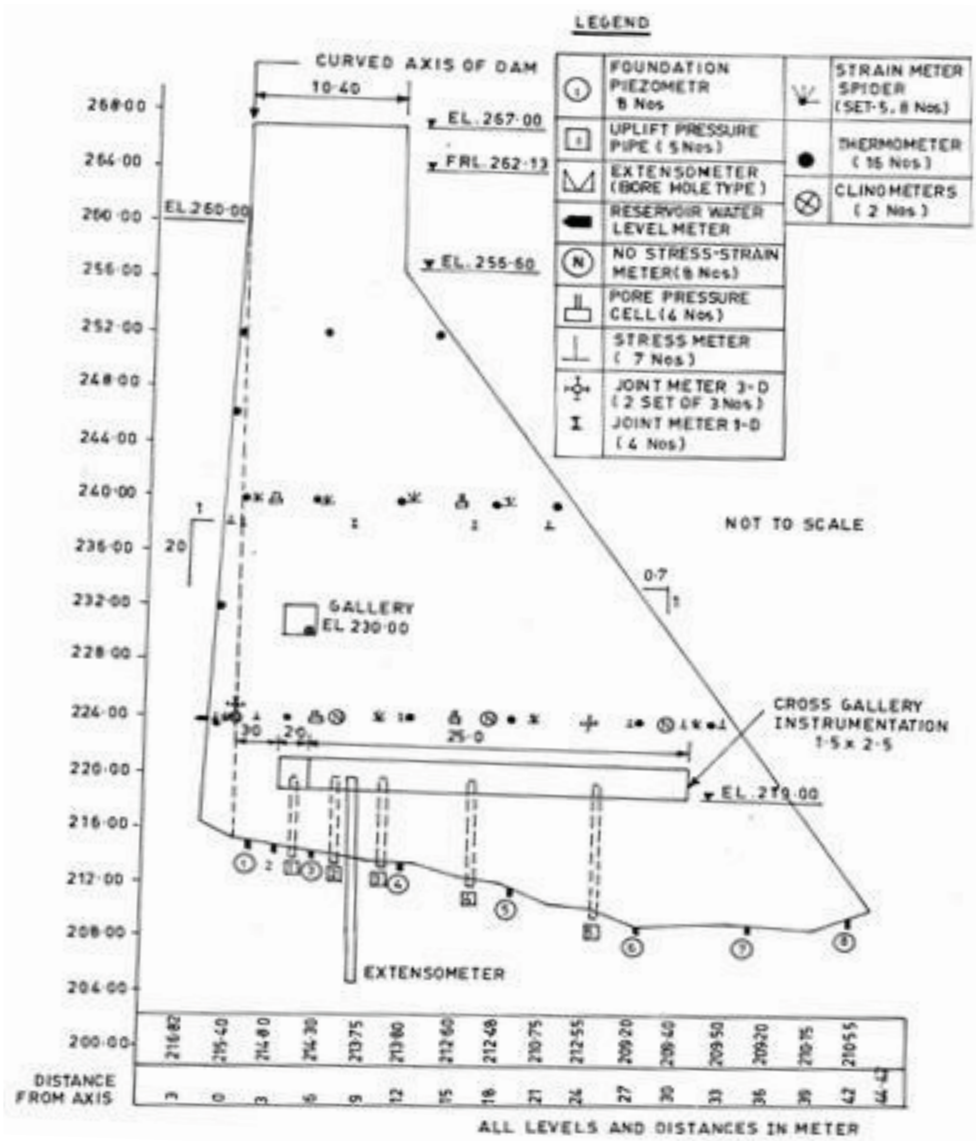

Figure 3 : Locations of Instruments installed in Block No.25

Table 1 : The type and number of instruments installed in Blocks 13 and 25

Sr. No.	Name of Instrument	Block No 25	Block No.13
1.	Foundation Piezometer	08	11
2.	Uplift Pressure Pipe	05	07
3.	Extensometer	01	01
4.	Reservoir Water Level Meter	01	01
5.	Pore Pressure Cell	04	07
6.	Joint Meter	10	13
7.	Temperature Meter	16	33
8.	Strain Meter	08	05
9.	No Stress Strain Meter	08	02
10.	Stress Meter	07	07
11.	Clinometers	02	07

3. ANALYSIS OF ACQUIRED DATA

The recorded/observed data supplied by the Project Authority, has been thoroughly examined and scrutinized. Data has been segregated, direction and location wise. Calibration coefficients of all the instruments, have been verified during the first site visit from calibration and installation records. Missing data has been obtained by interpolation and based on trend of graphs. The raw data, in terms of frequency square, has been converted into engineering units (wherever applicable) during analysis by incorporating calibration coefficients. Analysis of data from instruments has in general been made after applying necessary corrections, wherever applicable. The parameters have been plotted with time period and reservoir water level. Effect of reservoir water level on various parameters such as uplift pressure, pore pressure, temperature, strain, vertical stress etc., has been studied and presented. Even after incorporating correction to erroneous data wherever possible, some anomalies in the trend of a few graphs depicting as sudden spikes, have been observed, which can be attributed to either malfunctioning of instruments or error in data acquisition. The fluctuating trend of graphs in some cases has again stabilized and started showing normal trend over the years.

4. SETTING OF BASE LINE

Structural behavior of the dam has been studied by comparing expected values of each parameter based on baseline data. Parameters such as uplift and pore pressure are compared with computed values as per BIS code 6512-1984 criteria, Joint movement by BIS 456-2002, Temperature measurement by CWPRS predicted values and other parameters are compared with computation of various parameters by mathematical modelling using FEM.

5. PARAMETRS MONITORED

5.1 Reservoir Level

Water level measurement is vital as it is major destabilizing force and induces other destabilizing forces. Figure 3 shows the plot of observed reservoir water level for the period February 2004 to December 2018. The trend of the graph is cyclic in nature indicating normal behavior. The maximum water level reached during the year 2018 has been observed at El. 261.89 m

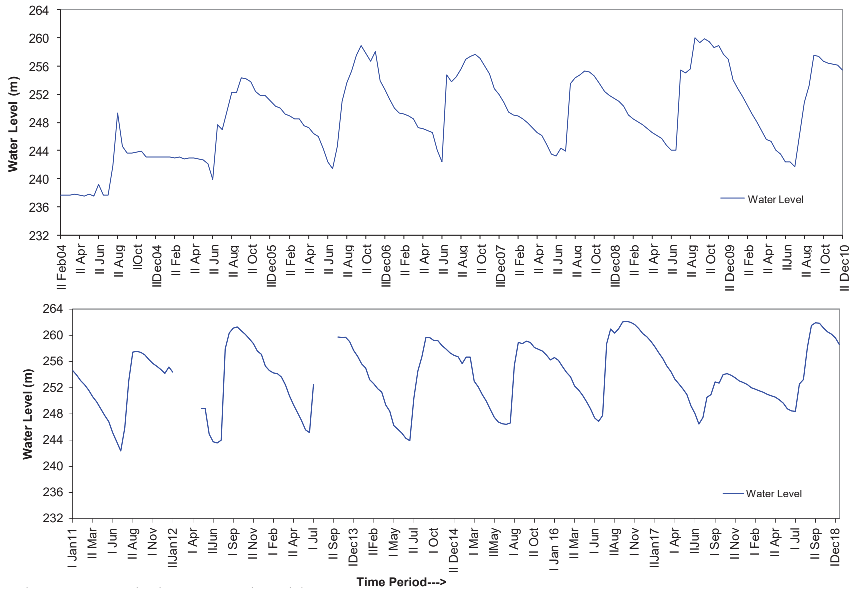

Figure 4 : Variation water level between 2003-2018

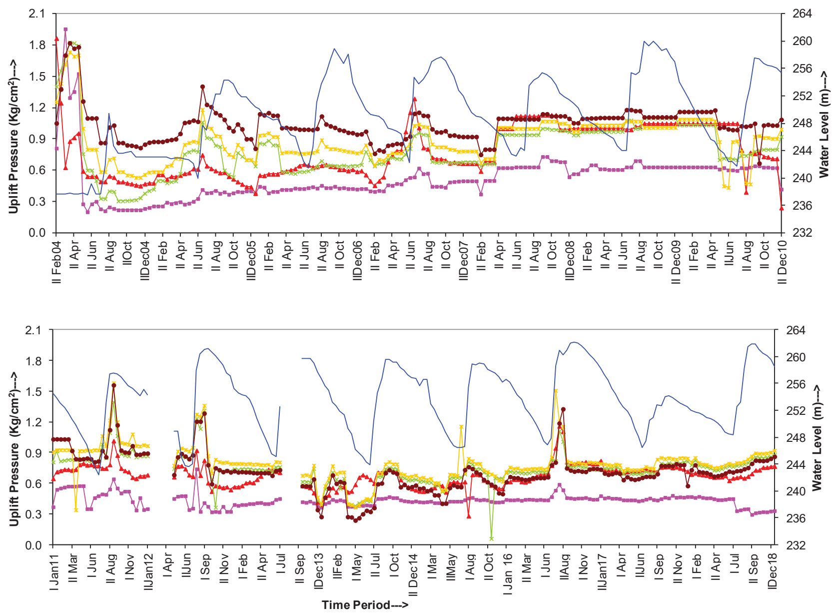

Figure 5 : Typical variation uplift pressure between 2003-2018 in Block No. 13

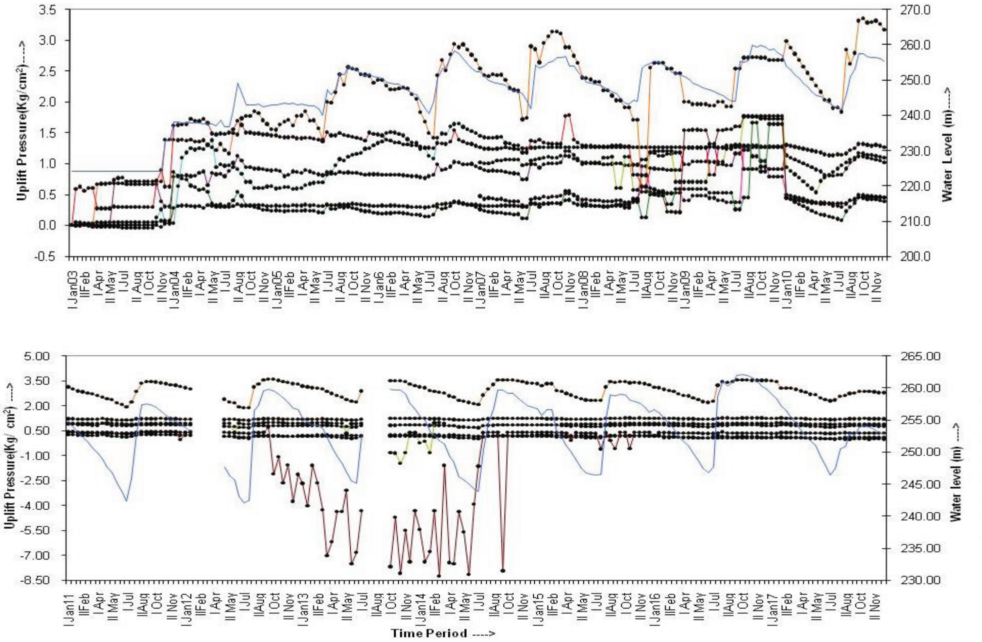

Figure 6 : Typical variation uplift pressure between 2003-2017 in Block No. 25

5.2 Uplift Pressure

The second most destabilizing force in gravity dams, is uplift. This can be measured by foundation piezometers. The Figures 5 & 6 show the variation of uplift pressure in block no 13 & 25 during the period 2013-2018/17. The maximum measured uplift pressure during the year 2018 in Spillway Block No.13 has been observed to vary from 3.72 kg/cm^2 at the dam axis to 0.02 kg/cm^2 at 12.4 m downstream from the dam axis. A comparison has been made between computed and measured uplift pressure at base of dam for maximum reservoir water level reached during the year 2018 (Fig. 8 & Fig. 9). From the figures, it can be seen that the uplift pressure development in block no. 13 is well within the limits whereas in block no. 25, it is exceeding towards downstream side. This phenomenon is being observed since very long based on the first year of data analysis. Tracer studies from CWPRS identified that, the leakage from intake HR tunnel through hillock was source of this leakage. CWPRS recommended Project authorities to take remedial measures to control the same.

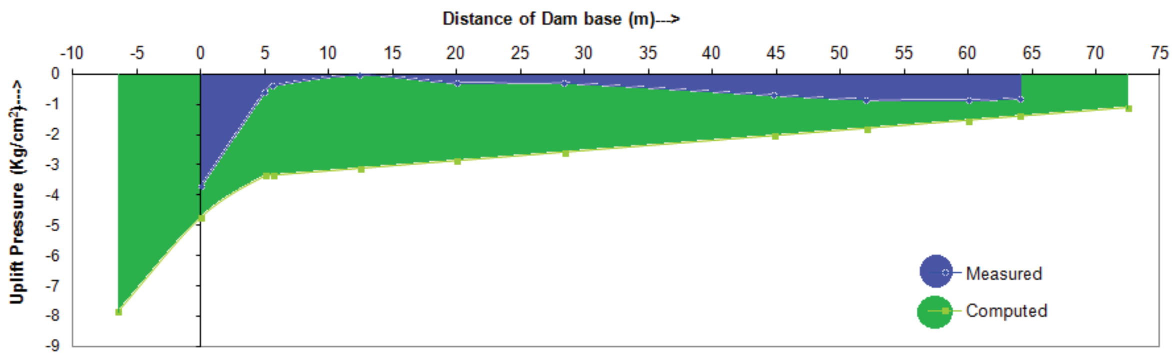

Figure 7 : Comparison of measured and calculated uplift pressure in Block No. 13

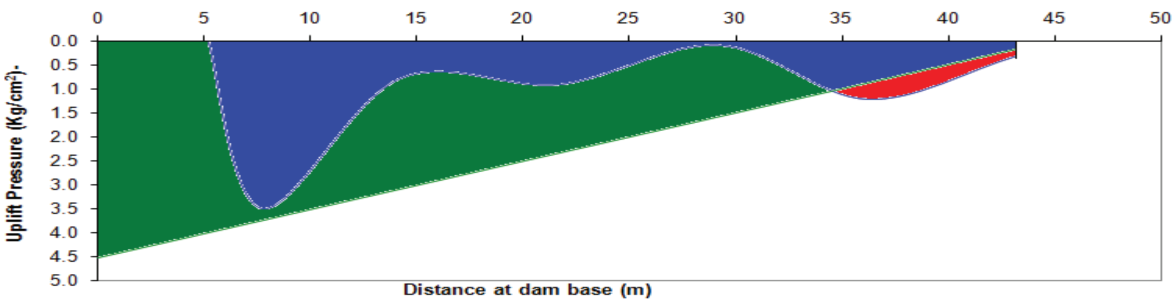

Figure 8 : Comparison of measured and calculated uplift pressure in Block No. 25

5.3 Pore Pressure

Pore pressure is developed in the body of the dam due to entry of water at different levels. Pore pressure cell measures the same. In general the main reason leading to development of pore pressure in concrete dams, is generally attributed to seeping of reservoir water through cracks, honeycombed concrete regions and block joints on upstream face. If no new cracks are developed on upstream face of the dam, pore pressure generally goes on diminishing with time due to deposition of silts and alkalis in cracks and honeycombed concrete as well as in block joints. Figure 9 shows the variation of pore pressure built up inside the dam body. The maximum pore pressure at El. 200 m developed during the year 2018, has been observed to be 0.96 kg/cm^2. The maximum pore pressure developed during the year 2018 is not excessive as compared to pressure computed corresponding to head of water above the pore pressure cell in the reservoir and does not pose any risk of crack propagation in mass concrete in spillway block. The trend exhibited by pore pressure variation continues to be cyclic. Cleaning of pore pressure relief drain holes at regular intervals may relieve pore pressure built up inside the dam body.

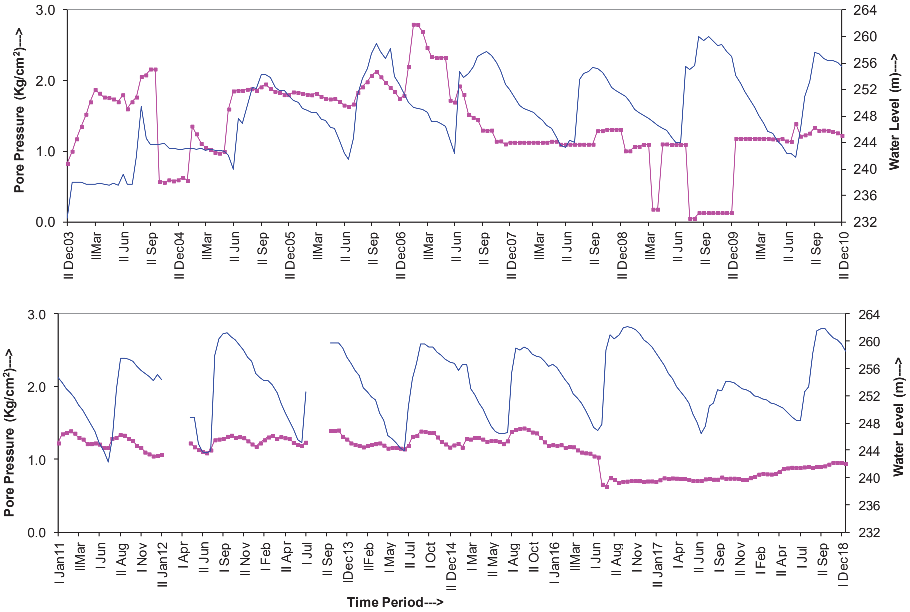

Figure 9 : Typical variation pore pressure between 2003-2018

5.4 Joint Movement

Joint meters are installed to measure relative displacement / movement between two lifts in vertical direction and dam block joints in three mutually perpendicular directions. Fig. 10 shows the variation of observed displacement/ movement with time along with reservoir water level in the Indira Sagar dam.

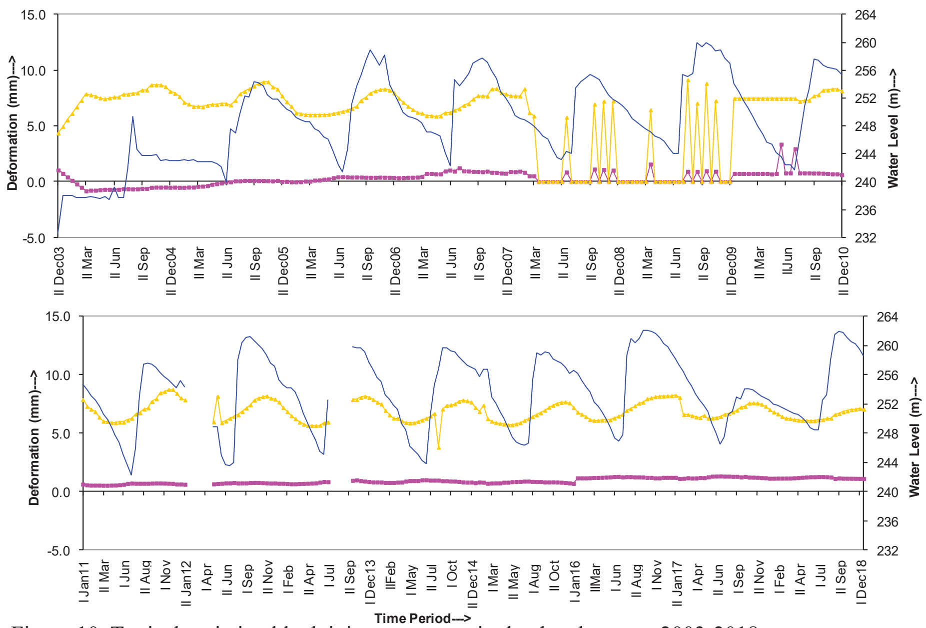

Figure 10 : Typical variation block joint movement in the dam between 2003-2018

5.5 Temperature

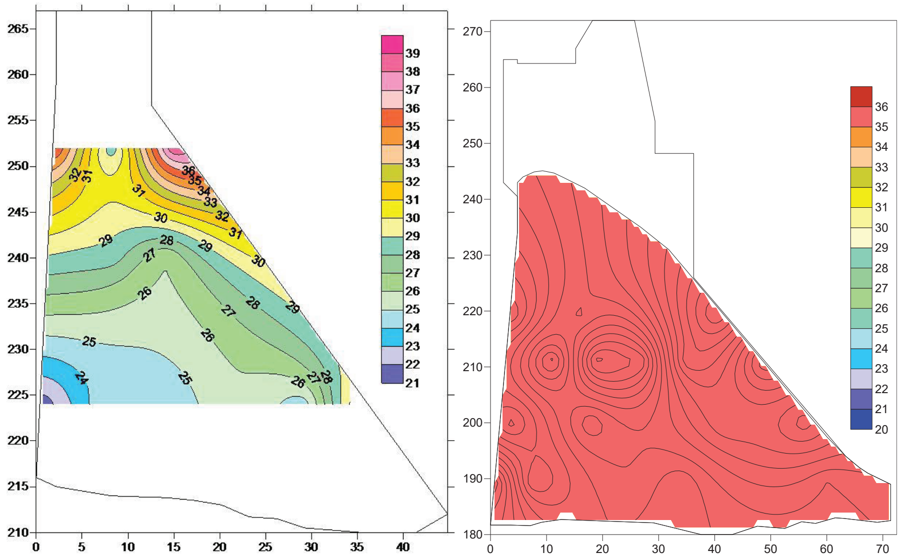

Figure 11 : Distribution of temperature inside the dam in NOF and OF blocks

Temperature measurement inside the mass concrete is very important for concrete dams as it leads cracks from the inside and water entry further propagates the cracks. Mass concrete temperature varies with respect to ambient temperature i.e. reduces during winter and increases in summer season. In addition, temperature of mass concrete is not much affected due to rise in reservoir water level. The pattern of isotherms fairly match with computed pattern obtained on the basis of laboratory studies undertaken earlier vide CWPRS Technical Report No. 3213 dated 01.01.1995. The temperatures recorded within the dam body at all locations are within allowable limits as predicted during laboratory studies conducted at CWPRS prior to construction of the dam and the ambient air temperature of the nearby area. The maximum temperature rise does not pose any danger towards cracking of the concrete on account of development of thermal stresses in the body of non overflow blocks as well as spillway blocks. There is not much change in temperature inside the dam body, which indicates concrete has attained equilibrium and no further hydration of cement is taking place causing any temperature rise. The cyclic pattern of temperature distribution in spillway blocks during summer and winter seasons indicates development of equilibrium condition and completion of hydration process of cement in mass concrete and eliminates any risk of thermal cracking of mass concrete.

5.6 Stress

Measurement of stress during first filling is very important as this parameter is cyclic and remains constant as per the water variation. However the analysis has begun after first filling hence measurement of stress is related to base data of 2003. Hence stress parameter is compared by compressive stress obtained with FEM model. Fig. 12 shows the comparison of observed vertical compressive stress at El. 189.4 m and dam base during the year 2018 with computed minimum principal stress from upstream to downstream end. The computed minimum principal stresses have been plotted for full width of the dam at El.189.4 m. The measured vertical compressive stresses are found to be less than the values computed by Finite Element Method and remain within permissible limit. The structural behaviour of the dam based on measured vertical compressive stresses indicates normal and comparable as per design assumptions.

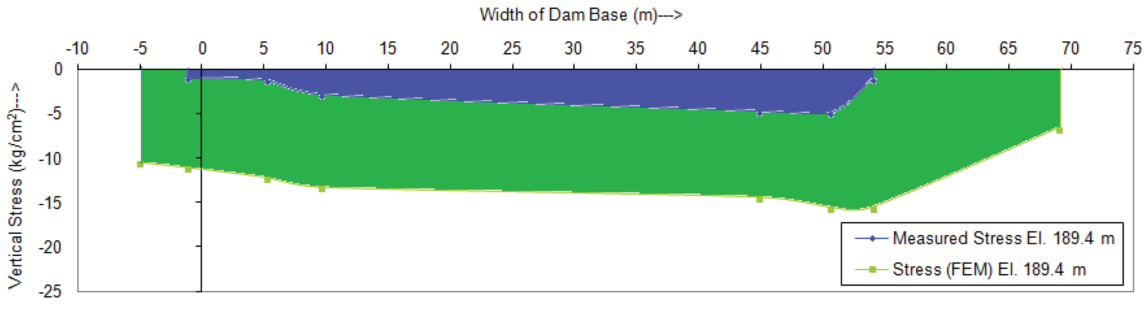

Figure 12 : Comparison of measured and computed stress using FEM at level 189.4

5.7 Strain

Measurement of strain is carried out by installing strain spiders which give strain in 0°, 45°, 90°, 135° and perpendicular to the dam axis direction. To account for the effect of temperature change on strain, five Nos. of No Stress Strain meters

(NSSM) have been installed in the vicinity of strain meters in closed container. The results of No Stress Strain meter have been deducted from strain meter results to obtain net strain. A typical variation of recorded net strain with time period is shown in Figure 13.

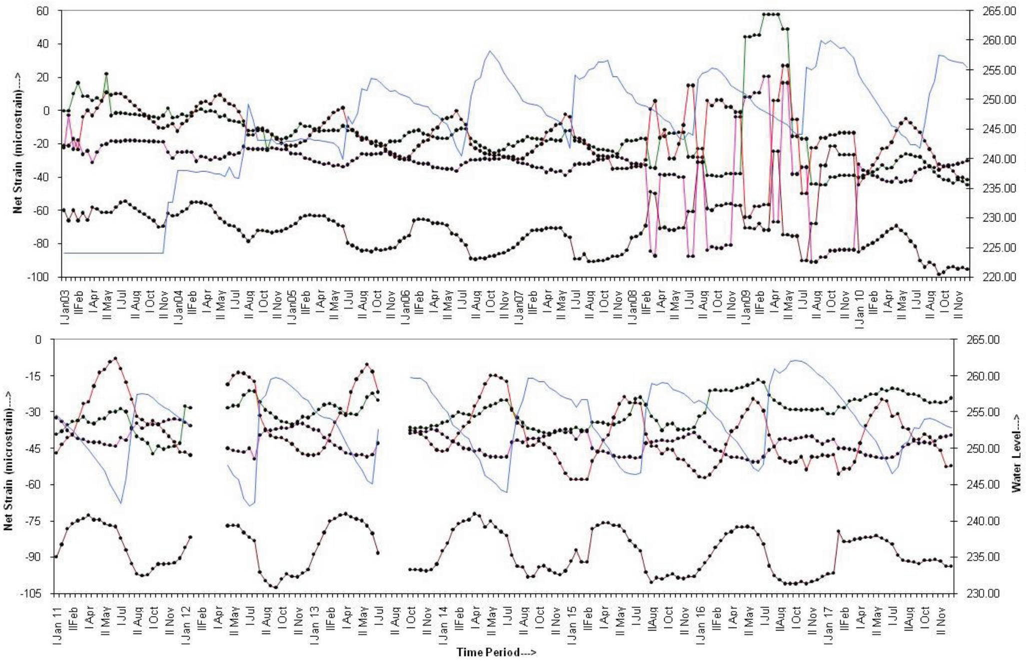

Figure 13 : Typical variation of strain in Indira Sagar dam

5.8 Foundation Settlement

Foundation settlement is being measured by borehole extensometer at depth elevation El. 199.0 m below dam base. The measured settlement is compared with vertical settlement of foundation calculated by 2D stress analysis of dam using FEM by incorporating certain portion of foundation in the mathematical model. It is found that the measured foundation settlement is within acceptable limits. A typical variation of recorded settlement with time period is shown in Figure 14.

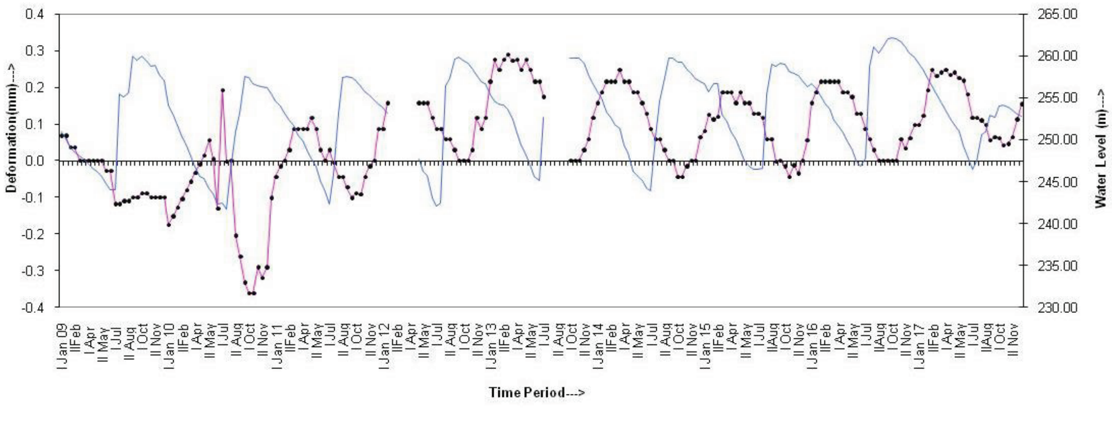

Figure 14 : Typical variation of settlement in Indira Sagar dam

6. CONCLUSIONS

Dams are designed to impound or pass floods of specific magnitudes without compromising the water retention integrity of the dam and foundation. Along with design and construction, monitoring of dam performance, is critical in maintaining safety of the dam. Use of instrumentation can improve the dam owner's ability to monitor the on-going performance of the dam by providing more comprehensive and timelier information (USSD). In this paper successful structural monitoring of Indira Sagar Dam concrete dam using dam instrumentation has been discussed. Parameters like uplift pressure pore pressure, joint movements, temperature inside dam, stress, strain and foundation settlement are being effectively monitored and found within baseline limits set as per BIS guidelines, Laboratory studies and based on theoretical computations using FEM. Detection of higher uplift accumulation at downstream side of block no 25 and subsequent identification of cause of leakage further justifies the use of dam instrumentation and analysis of recorded data. This monitoring programme also brought out the importance of cleaning of weep holes in case of controlling of pore pressure and drain holes in the foundation gallery in controlling uplift pressure.

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