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Aspects of Safety in Engineering Structures: Need for Investigation– Special Emphasis to Dams

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Abstract: Hydraulic structure(s) viz. dams, canals, hydro-power stations etc. are engineering structures that need safety measures to be considered post commissioning. Although it's an inherent function in the planning, designing, construction, maintenance and operation of hydraulic structure(s), many of these structures show signs of distress and failures in spite of taking utmost care in planning, design and different stages of execution. Distresses might lead to seepage or leakage causing extreme conditions like failure of the structure. Suitable remedial measures need to be taken after comprehensive understanding of the cause and extent of seepage. There are several methods of which the non-destructive testing (NDT) is widely adopted to ascertain the exact path and source of seepage. Borehole logging and Tracer studies are aptly integrated to decipher the source and extent of seepage. Comprehensive information on non-conventional techniques i.e. borehole logging and tracer investigations with two case studies is highlighted in this manuscript. An integrated approach of these two investigation methods can depict the in-situ engineering properties, potential seepage pathways, lithological variations, solution activity and interconnectivity of seepage path. Consequently, a most suitable remedial measure can be adopted to rehabilitate the same.

Index Terms*:* Dam, (Nx)-borehole, Seepage, Tracer, Well Logging.

I. INTRODUCTION

Engineering structures like dams are constructed to facilitate and cater the needs of mankind in storing water for irrigation, drinking, flood control, power generation, etc. Since an enormous amount of financial investment is involved in planning, designing, construction, operation and maintenance of these structures, hence, safety is an important aspect to be considered for safeguarding these national investments and its benefits. In this paper, the safety aspect with a special emphasis to dams and canal is described, wherein the safety of a dam is primarily important as it can pose a threat to human life and property in its downstream reaches. Proper investigation and subsequent analysis of dam distresses and their corresponding causes can ensure its safety and also help in opting for the most appropriate remedial measures to ehabilitate the same. Majority of the dams in India were constructed during the period when knowledge about dam Construction and technology was not well established. In the recent past although several guidelines have been developed based on state of art technology, in terms of design, construction and maintenance of dams; the need arises to rehabilitate dams following a check of their compliance with current standards and also due to distresses resulting from various factors like ageing, foundation failure, seepage, heavy floods, earthquakes, etc. In addition, for augmentation of storage capacity, due to the growing demands in irrigation, drinking water and other sectors, it is sometimes necessary to increase height of the dam, which necessitates rehabilitation of the structure. A thorough background understanding and appropriate analysis of the proposed problem like seepage or leakage in dams, occurrence of distress, its location and quantum is therefore necessary in the study of dam safety and rehabilitation. There are numerous conventional and non conventional investigation methods that are widely adapted to study and analyze the actual cause of distress in dams.

The cost of these investigations may be a fraction of total cost of repairs of the structure. Multidisciplinary techniques such as geological and geotechnical methods, dam instrumentation, geophysical methods, tracer techniques, nuclear logging and mathematical modeling for monitoring, detecting, analyzing distresses in dams should be used effectively to arrive at an optimum solution for dam rehabilitation problems (Tech.Memo.II, 2015). The possible causes of deterioration (weakening) of any engineering structure should be understood before taking up the repair / restoration work failing which either the repairs will become ineffective resulting in wastage of money and or may lead to further damage necessitating additional expenditure. In case of dams, generally deficiency in design and quality of construction are the two prime factors responsible for distress. In this manuscript an attempt has been made to highlight the effective application of two non-conventional techniques namely borehole logging and tracer studies in deciphering the probable cause of seepage. It is also made evident Based on case studies that effective application of these two investigation techniques not only help in identifying the source and cause of the problem but also

Guide in selecting suitable remedial measures for attaining stability of dams.

II. METHODOLOGY

In this manuscript mainly two types of non-conventional investigation methods are elaborated, which aid in deciphering the actual cause of distress in dams. Two distinct case studies are described, where these two methods were used in integration. A brief understanding of these two methods of investigations is as follows:

2.1 Borehole logging techniques

Uncontrolled seepage is one of the prime causes for majority of dam failures. Seepage in dams is generally seen through the body of the dam; the geological formations in the foundation and vicinity of the reservoir; or through the structure-foundation interface. Borehole logging technique is increasingly used in seepage investigations of dams for identifying cracks / voids and permeable zones. The techniques are also applied for detecting engineering parameters of dam like bulk density, sonic velocities and mechanical properties of the rock and body of the dam. It is basically a study that involves lowering of a sensing device in a borehole and obtaining a continuous record of depth measurement (vs) variation in certain physical properties of rocks/lithology in the bore hole. The subsurface geological conditions and engineering characteristics can be determined directly or indirectly from the properties measured by these techniques. Borehole logs can be interpreted to determine the lithology, geometry of the formation, resistivity, bulk density, porosity, compressional and shear wave velocities (V_p & V_s), moisture content, water bearing strata and movement of water (Scott Key, 1971). Based on the parameter to be measured, borehole logging is classified into various types as tabulated below (Table-1).

TABLE-1

TYPES OF LOGS AND PARAMETERS MEASURED

LOGGING METHOD	PARAMETER MEASURED
Resistivity	Electrical Resistivity
Spontaneous Polarization	Electrical Potential
Natural Gamma – Ray	Natural Gamma Radiation
Gamma-Gamma Ray	Bulk Density
Neutron	Porosity
Sonic	V_p & V_s Mechanical Properties of Rocks
Temperature	Fluid Temperature
Caliper	Borehole Diameter

2.2 Tracer techniques

Tracer technique is basically adopted by doping or injecting a predetermined quantity of tracer into the medium (soil/water) either through a Nx-size (78mm) borehole located in the near vicinity or on the banks of a canal or in the water logged area of the canal and the movement or dilution of tracer is observed in boreholes drilled either on the same side of the canal or in the same well. (Tanaka, 1999). Apart from the flow direction, other hydraulic parameters can be deduced using two well established methods i.e.

(a) Point Dilution Method:

The point dilution method is adopted to determine the Darcy velocity of the formation using a single borehole. Tracer is injected within the borehole in the medium (water) and its dilution is monitored at regular interval of time within the same borehole. This method is widely used to measure the filtration velocity of the lithology, seepage losses as well as permeability (Pitrak, 2007) using the following equations:

$$V_f = \pi d / 4\phi t \; \ln (C_0 / C) \qquad (1)$$

Where
V_f = filtration velocity
d = borehole diameter
ϕ = hydrodynamic distortion coefficient
And t = time taken for tracer conc. to fall from C_0 to C

The seepage losses from the canal can be calculated (Dhillon, 1980)

$$q = 2.V_f \, D. \, \theta. \, \mathrm{Cosec}\, \theta / P \qquad (2)$$

Where
V_f = filtration velocity
q = Seepage losses per unit length of the canal,
D = Half bed width of canal,
θ = Angle in radians which the phreatic line makes with the normal at the injection borehole.
P = fractional porosity.

The permeability of the formation is computed using the filtration velocity (V_f) and the hydraulic gradient (i):

$$k = V_f / i \qquad (3)$$

(b) Multi-well Method:

In this method a predetermined quantity of tracer is injected into an Nx-size injection borehole and monitoring its arrival in a number of boreholes drilled in the anticipated direction of flow. From the transit time or the peak concentration of the concentration versus time graph, the seepage velocity can be estimated (Huseby, 2009, Moser, 1989).

A number of samples from all possible sampling points or boreholes are usually collected before conducting the tracer study, which provides a background value of the water. The calibration of the measuring instrument

(Fluorometer) is also done using known water sample. The injected quantity of dye tracer lasts long enough to be detected in the monitoring boreholes. The seepage velocity through a hydraulic structure can be determined by knowing the arrival of the tracer peak in the concentration versus time plot.

The actual field setup and procedure for conducting tracer and borehole logging investigation studies in a dam site is conceptually shown in figure.1.

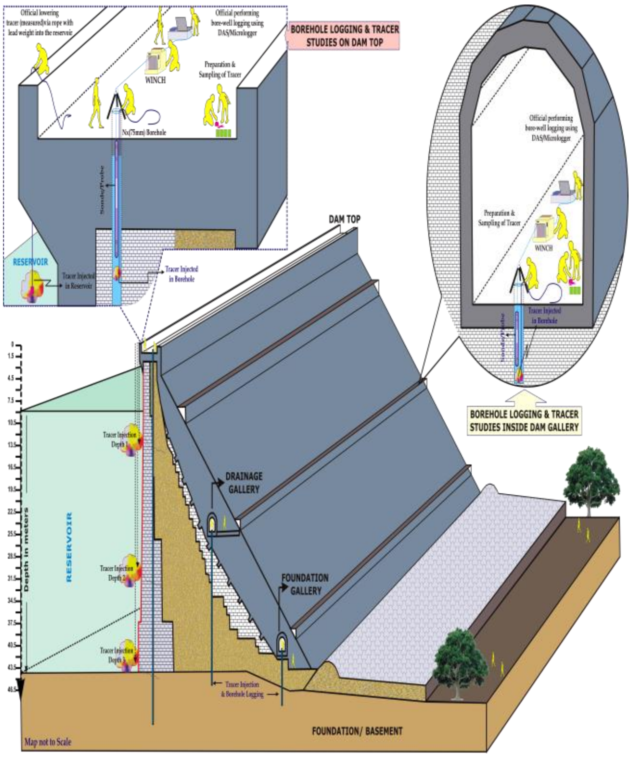

Fig.1. Conceptual Model depicting the execution of borehole logging and tracer studies in a DAM

There are several instances / problems pertaining to dam seepage reported by respective dam authorities, wherein, the application of borehole logging and tracer studies were carried out in conjunction with one another. Case studies pertaining to seepage through body of the dam (Nagarjunsagar dam, A.P) and drainage gallery (Pawana Dam, Maharashtra) are dealt in this manuscript to highlight the efficacy of borehole logging and tracer study in delineating the path/zone of seepage and recommendation of appropriate remedial measures based on investigation results.

Case-1. Determination of seepage path through the foundation at Nagarjunasagar Dam, Andhra Pradesh.

Nagarjunasagar dam was constructed in the post independence era across the river Krishna in the then A.P, which is one of the largest (4868 m) and highest (1246 m) rubble masonry dam in the world. The masonry dam (3418 m in length) in the centre of the gorge flanked by earth dams. The reservoir formed upstream of the dam is the largest man-made lake in the country and third largest in the world (Figure.2).

A settlement was observed at Ch. 142.5 upstream of the right earth dam resulting in the formation of a cavity at RL 182.88 m. Technical Experts Committee (TEC) was appointed by A.P Govt. to examine the cause of the formation of the cavity. As suggested by TEC tracer studies were conducted for determining the interconnection, if any and the seepage velocity through the earthen dam. The area under study lies in the sedimentary terrain of Cuddapah group with quartzite as a predominant rock type (Tech Rep.No.3030 & 3153).

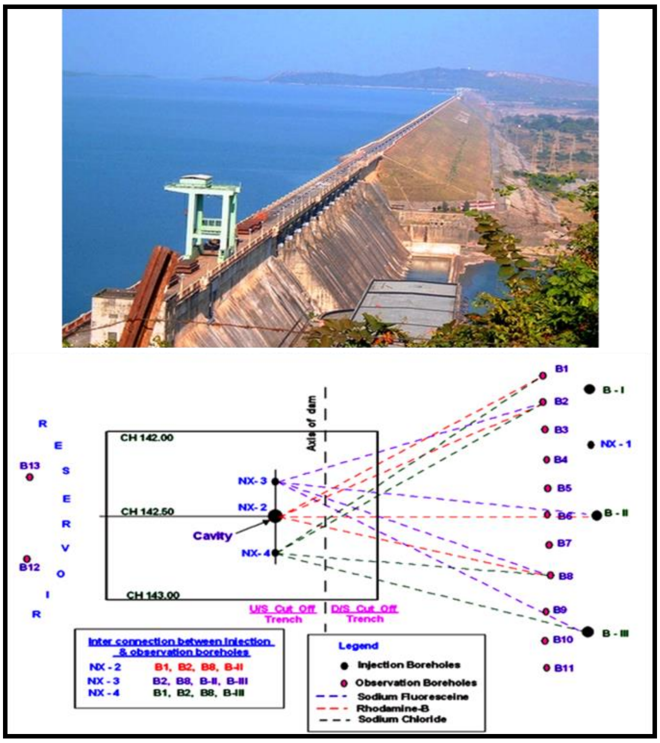

Fig.2 Plan of Location of Boreholes for Tracer Studies at Right Earth Dam, Nagarjunasagar Project, A.P.

Three Nx size boreholes viz. Nx-1, Nx-2 and Nx-3 were drilled on the upstream side of the cavity area to facilitate injection of tracer. For monitoring the arrival of the tracers, eleven shallow boreholes (B1…B11), three deep boreholes (B-I, B-II and B-III) and one Nx-1 borehole were used for borehole logging and also for sample collection at the toe of the right earth dam. In order to ascertain the direction of seepage towards the canal located 350 m downstream of the right earth dam, Nx-5 was drilled to monitor the flow of the injected tracer. B12 and B13 were drilled on the upstream side of the reservoir to monitor movement of the tracer towards upstream. Two different dye tracers namely sodium fluoresceine &

Rhodamine-B and common salt were used to establish the seepage path.

The tracer studies revealed that there was a hydraulic interconnection between the foundation rock and the toe viz. boreholes (a) Nx-2 and B1, B2, B8, B-II, (b) Nx-3 and B2, B8, B-II, B-III and (c) Nx-4 and B1, B2, B8, B-III. Also it was noted that there was no interconnection between cavity and B12 and B13. The permeability of the foundation rock varying from $4.93x10^{-4}$ cm/sec to $7.75x10^{-4}$ cm/sec indicated that the rock permeability for the rock in the cavity was higher than that for boreholes on either side of the cavity. High seepage velocity ranging between 3m/day to 7.8 m/day has also been observed as shown in figure.3. Borehole logging was employed using gamma-gamma, neutron-neutron and electrical resistivity in order delineate zone of seepage. The results revealed that the foundation rock below cavity (RL 547.5 – 539 ft.) was prone to excessive seepage, hence it was recommended that a suitable treatment should be given for the foundation at cavities zone to reduce the seepage through it.

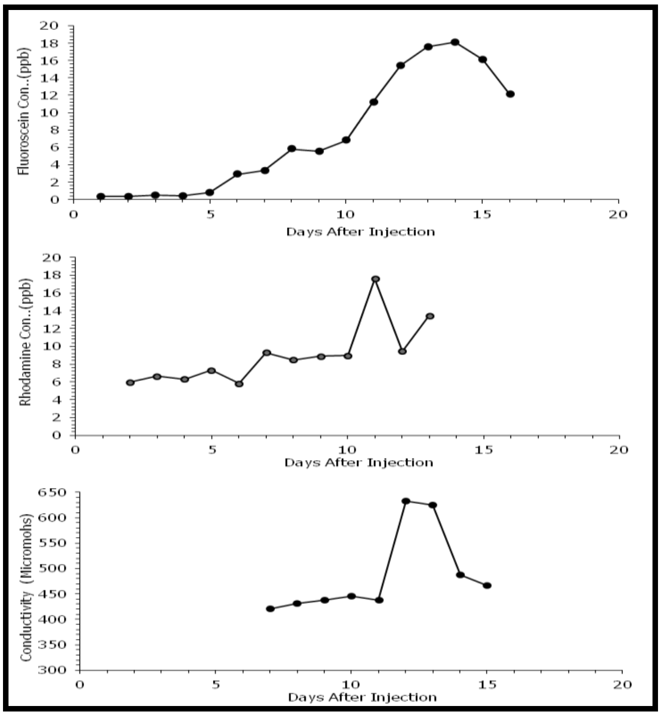

Fig.3 Arrival of Sodium Fluoroscein, Rhodomine and salt tracers in Nx Bore Hole B1 and B2 respectively

Case -2 Delineating path of seepage in the masonry at Pawana Dam, Maharashtra

The Pawana Dam of height 38.1 m was constructed across River Pawana, Maharashtra. It is a composite dam comprising 414 m long masonry dam with overflow and non-overflow portion and a 903 m long earthen dam. Excessive seepage which was related with the rise of the reservoir level was observed in the drainage gallery and body of dam. Hence grouting at a few places and guniting of the entire upstream face was done to reduce the seepage which was actually reduced by about 50%. Borehole logging was carried out to determine the insitu subsurface properties of the masonry for the purpose of strengthening the dam and raising the Full Reservoir Level by 0.5 m and tracer studies were conducted to delineate the path of seepage. Figure.4. shows the layout of dam and excessive seepage observed at drainage gallery and downstream of the dam (Tech Rep.No.4673).

The nuclear and caliper logging of boreholes revealed that in general, density of masonry varied from 2.3 gm/cm^3 to 2.58 gm/ cm^3 and presence of voids/ cracks were delineated in the boreholes (Kamble R.K, 2010).

Seepage was observed in the form of water jets on the downstream slope of Left Hand Side (LHS) of masonry between Ch.725 ft. and Ch. 849 ft. in monoliths 5, 6 & 7 and between RL 1935 ft and 2004 ft. The leakage was observed from a number of porous holes on the Right Hand Side (RHS) drainage gallery but no appreciable seepage was seen in the LHS drainage gallery. This is an example of seepage through structure. Tracer studies were carried out in two phases, pre-monsoon when the reservoir level was between 1975 ft. and 1976.30 ft. and post monsoon when lake level was around 2010 ft. The appearance of Potassium Permanganate dye tracer used for injection in the reservoir and boreholes, was monitored in the downstream observation points at every 10 minutes interval for about two hours after injection.

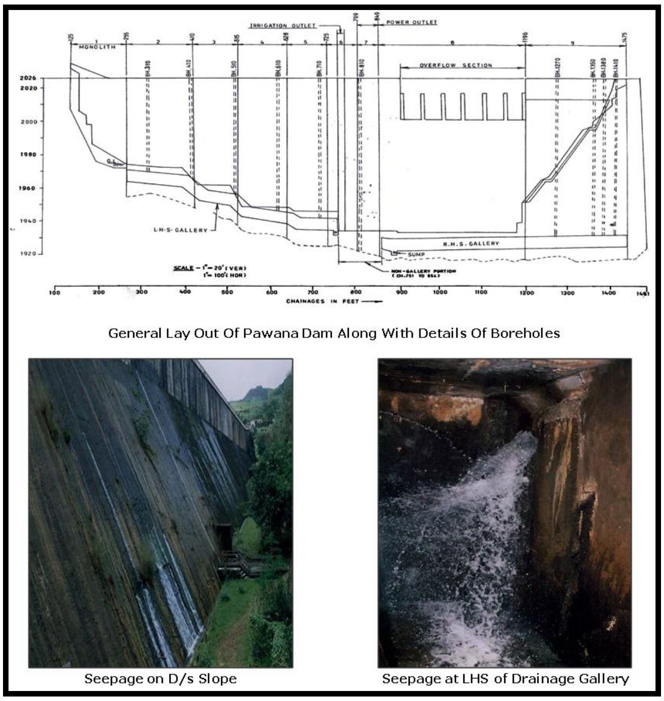

Fig.4. Dam layout with visible seepage sites along the downstream

The results indicated that the tracer injected at Ch.225 m (RL 590 m) had a direct connection with water jet in the LHS drainage gallery and small quantity of tracers were also observed at the downstream slope for the tracer injections at Ch.250 m (RL 598 m & 594 m), Ch.

259 m (RL 598 m). The tracer injected at other locations has not arrived at the downstream monitoring points, indicating that there is no direct interconnection between these points. The direct arrival of dye for injection in borehole at Ch.247 m (RL 592 m, 594 m and 598 m) may be due to the presence of gaps in masonry dam. The tracer also appeared distinctly for the injection points in a well at Ch. 226 m (RL 609 m). It was observed that except for injections on the upstream face of dam at Ch. 226 m and Ch. 230 m, dye appeared at the remaining injection points.

Tracer studies revealed that dye injected in the boreholes, where prominent cracks/ voids were detected by nuclear logging, arrived at leakage points in the downstream slope of dam. It was inferred from the studies that cracks / voids in masonry might have occurred due to process of leaching and seepage which was also was occurring through these portions. It was recommended to undertake controlled grouting in the body of dam where prominent cracks/ voids were located to reduce / stop seepage.

III. CONCLUSION

Detection of seepage through hydraulic structures, its timely and efficient control is a highly skilled task. This should be based on sound background of geology of the area, investigations followed by proper data analysis as regards to the occurrence of seepage, its location and quantity.

As such, it is necessary to identify and locate the zones of defects/flaws in dams, which are susceptible for seepage by applying advanced and integrated methods for assessment of seepage. Non conventional investigation techniques like borehole logging and tracer techniques may cost a fraction of total cost of repair of the structure.

In India many dams have been constructed and are increasingly facing several structural deficiencies thereby resulting in operation and monitoring short comings. To reduce the risk of failure, regular health inspection of dams is necessary in order to identify the defects and whenever severe deficiencies are observed, comprehensive remedial measures are required to be undertaken.

To summarize, it can be stated that a timely adoption of appropriate seepage monitoring, detection and analysis measures using non-conventional techniques and appropriate remedial measures based on investigation results will surely lead to safe functioning of dams throughout its design life.

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