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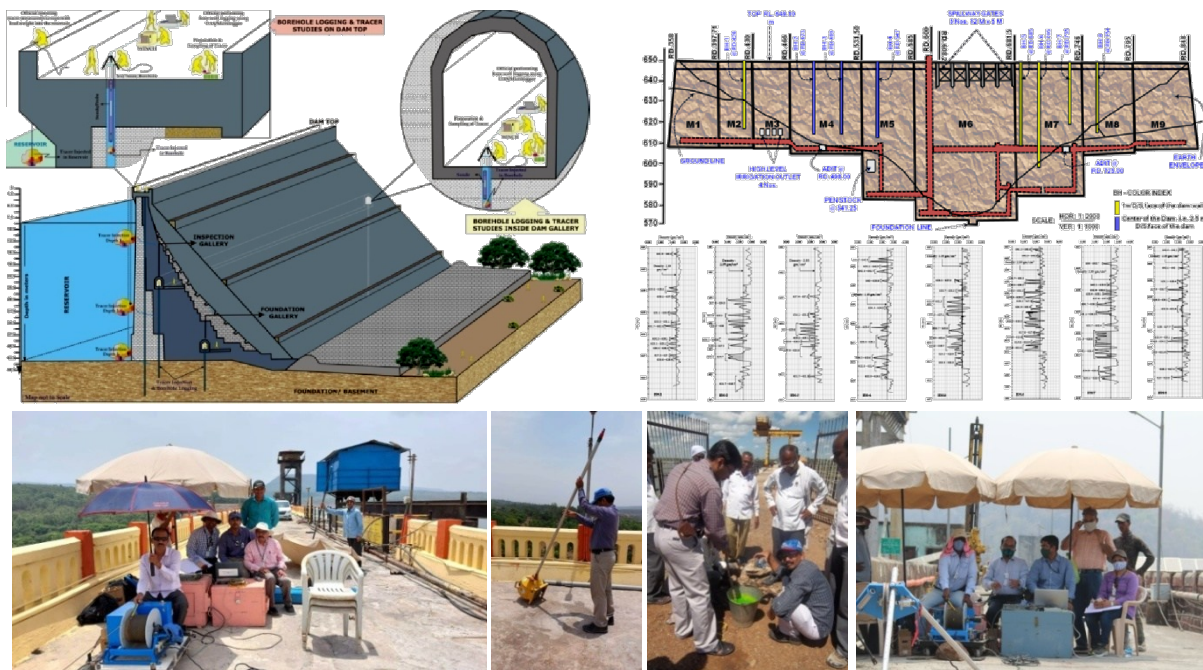
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Department of Water Resources River Development & Ganga Rejuvenation

TECHNICAL MEMORANDUM

ON

MITIGATING SEEPAGE RISKS: THE ROLE OF BOREHOLE GEOPHYSICAL LOGGING AND DYE TRACER STUDIES IN SEEPAGE DETECTION



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PREFACE

Dams are constructed by making huge investment for development of water resources for socio-economical development. Excessive seepage in Dams may intimidate their safety and stability, in addition to massive loss in water resources. In spite of taking proper care in planning, design and execution stages, there are incidences of distress in dams. As such, it becomes essential to diagnose dam distress and causes to ensure dam safety by using several possible techniques to arrive at the most suitable controlling measures to rehabilitate the dam. There are reported incidences of catastrophic dam failures all over the globe. To reduce the risk of failure regular monitoring and analyzing defects / distresses by applying advanced methods helps in deciding appropriate and economical remedial measures can be decided pertaining to the type of structures.

Central Water & Power Research Station, Pune, is a premier hydraulic research institute offering wide range of R&D services in problems related to dam safety and rehabilitation. For the past few decades, CW&PRS has developed expertise in providing cost effective and viable solutions for dam safety and rehabilitation by conducting field and laboratory investigations. Mathematical modeling is being also used for the purpose in some situations. This document provides comprehensive information on various aspects of safety and rehabilitation of gravity and embankment dams. Several case studies are also provided for the purpose of illustration.

This document portrays a general introduction about the various aspects of dam safety and rehabilitation, the basics of distress and its causes, consequences of distress in concrete, masonry and embankment dams with various causes of seepage through monitoring dams (i.e. Earthen, masonry and concrete). It also elaborates the site selection criteria to carryout Borehole Logging and Tracer investigation determine various engineering properties and path of seepage through body and foundation of Dam.

The various Borehole logging techniques, its objective and purpose with which it is adopted in dam seepage studies and also its importance in determining various physical and engineering properties is also elaborated. This document also distinguishes the Geophysical borehole logging tools and Nuclear logging tools. The application of Dye tracer techniques, its objective and scope in dam rehabilitation studies is also elaborated. The important aspects of borehole logging and tracer studies like detecting seepage using different methods and then employing suitable remedial measures to mitigate the seepage, highlighting importance in seepage investigation and suitable remedial measures in dams through success stories from CW&PRS catalogue is summarized.

The document is expected to be of great help to practicing engineers, researchers, scientists, consultants and other authorities of Water Resources Projects planning and execution to identify and mitigate seepage problems related to dam safety and rehabilitation.

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CHAPTER – I

INTRODUCTION

Dr. Rolland Andrade, Scientist 'D'

Hydraulic structure(s) viz. dams, canals, hydro-power & nuclear power stations etc. are basically 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. Seepage can be defined as interstitial movement of water through a structure, its foundation, or abutments; whereas leakage is the flow of water through holes or cracks. 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 and also to decipher mechanical properties towards strengthening of the dams. 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(s) can be adopted to rehabilitate the same.

An ideal site for construction of the hydraulic structure should be geologically and structurally undisturbed area with unfissured, unweathered rock totally exempts from joints, fractures, primary or secondary permeability, weak planes, devoid of any pockets or lenses of organic material or a clay subsoil etc. (Tančev. L, 2005, Milanovic, P.T. 2000). The upstream channel should have gentle slope and in general the water table in the surrounding area should preferably have more or less above the top water level of the ideal channel or reservoir. But getting such an ideal site in the nature is very rare and as a result an uncontrolled seepage is quite obvious (Agarwal K. B., 1979, Gadgil. M, 1979).

These hydraulic structures which store or carry water for irrigation and for other purposes are generally designed not to seep or leak. Seepage through such structures is a potential threat to public welfare and wastage of water (Nilsson, Å.; et. al, 2004).

The development of seepage through body and subsoil of a dam provides basic information on the state of a hydraulic structure and on the possibilities of its safe operation.



Therefore, seepage through or under a hydraulic structure can be considered as one of the most important objects in structural safety. To arrive at an optimum solution, every problem, involving occurrence of seepage or leakage, needs specific attention owing to its uniqueness. Very often costly repair works for addressing seepage problems are undertaken using conventional methods which are deficient in mitigating the problem. Hence, it is imperative to study the complex problem of seepage through hydraulic structures, systematically by knowing causes and symptoms of seepage, analyzing seepage with detail investigations and applying conventional and non-conventional techniques. Estimation of seepage and evaluation of seepage parameters will serve as inputs to repair or remedial measures applied for reducing seepage through hydraulic structures.

All dams have some seepage as the impounded water seeks paths of least resistance through the dam and its foundation. Seepage must, however, be controlled to prevent erosion of the embankment or foundation or damage to structures. If the majority of the seepage water is confined to only a few discrete seepage paths and the velocity of the seepage is sufficiently high, then progressive erosion of particles of soil may occur resulting in a piping type failure of the dam (Hani Al-Omash, et. al, 2008).

The seepage causes for different types of structures are discussed below:

- A. Mostly “**Earthen Dams**” are subject to seepage through the embankment, foundation, and abutments. In earth dams the principal failure modes are internal erosion/seepage/piping, overtopping, structural issues and slides on either upstream or downstream face. Seepage through earthen dams mainly occurs due to lack of filter protection and improper filter design, washing away or particles or clogging of drains, poor compaction, open seams, cracks caused by earth movement, etc. Transition between masonry/concrete dams and earth dams constitutes an area of discontinuity in the material properties and may lead to failure mode.
- B. In “**Masonry Dams**”, the failure is due to the seepage path through the body mass as concrete blocks when exposed to water are permeable and start seeping water by the lower pressure inside the body of the dam or through heterogeneous, pervious zone where seepage pressure in pervious layers exerts an excessive force on an overlying confining layer. The seepage occurs due to the moisture absorption by the weak zone, temperature effects, leaching, excessive uplift pressure, construction defects causing decrease in the relative density of the material, mechanical strength as well as water-tightness, earthquakes or floods, construction joints etc. Foundation

seepage pressure in pervious layers can exert significant uplift force on a confining layer of lower permeability soil downstream from a dam. This pressure occurs when there is a more permeable layer underneath that transmits a large percentage of the reservoir head downstream. Failure begins when the pore pressure on the bottom of the confining layer exceeds the overburden pressure created by the weight of the overlying soils. Evidence of any seepage, subsidence or undercutting of masonry walls is best observed with the impoundment at spillway crest elevation.

- C. In, “**Concrete Dams**”, construction deficiencies, disintegration and scaling, efflorescence, erosion, spalling and popouts and cracks etc are the major causes for seepage. Failures occur due to overtopping, piping and foundation failure because of the occurrence of uplift pressure or water pressure beneath the dam and in the rock mass. Overtopping failures result from the erosive action of the uncontrolled flow of water over, around or adjacent to the dam. Seepage can also develop behind or beneath concrete structures such as chute spillways or headwalls. If the concrete structure does not have a means such as weep holes or relief drains to relieve the water pressure, the concrete structure may heave, rotate, or crack. The effects of the freezing and thawing can amplify these problems. It should be noted that the water pressure behind or beneath structures may also be due to infiltration of surface water or spillway discharge (Pavlenko. V. V, 1974).

Transition between the masonry/concrete dam and earth dam requires special attention and detailing during design and construction phase, as it constitutes an area of discontinuity in the material properties, through which excessive seepage water may pass from upstream to downstream through the contact surface of masonry/concrete and earth dam at their junction and may lead to piping (Kanarskii. V. F, 1987, Panthulu. T. V, 2001).

Seepage in “Reservoirs” is mainly due to unfavorable geologic conditions occurring in the foundation. Few of these conditions are listed below.

- Loose, saturated, non-plastic soil deposits liquefying under earthquake
- Weak and sensitive clay
- Dispersive, organic, expansive, collapsible soils or clay
- Shales, limestone or calcareous deposits with solution channels
- Gypsiferous rocks
- Clay seams and shear zones
- Rock formations with low RQD (< 50%)
- Certain evaporites like gypsum etc.
- Buried palaeochannels
- Unconformities or discontinuities in the rock formation

The seepage loss from irrigation canals constitutes a substantial percentage of the usable water for irrigation. Seepage is most likely to cause water quality problems in areas adjacent to or near agricultural drains or canals. Canal seepage varies with the nature of the canal lining; hydraulic conductivity; the hydraulic gradient between the canal and the surrounding land; resistance layer at the canal perimeter; water depth; flow velocity; and sediment load etc (Zechner. E, 2004). Seepage in “Canals” refers to the water that percolates into the soil strata through wetted perimeter of a canal. Seepage losses affect the operation and maintenance of the canals by piping and eroding of the bank of canals. Canals, whether lined or not, produce excessive saturation and uplift pressure, which might produce failures of the canal and other structures (Rushton and Redshaw 1979). Even concrete lined canals also have seepage if the lined areas consist of cracks (Merkley 2007). Generally earthen canals are mostly constructed using local materials, often with high permeable characteristics. Despite attempts to reduce permeability, construction methods have often failed to achieve a watertight barrier, particularly in older canals. Importing of better-quality soils is often limited by availability or cost. Seepage from open canals especially with high embankment is therefore a gigantic concern. The common solution to stop the canal seepage is either lining canal i.e. stabilizing of bank or replacing them with pipes or through soil compaction. The seepage from a canal running through a stratified strata of highly permeable layers of sand and gravel underlie the top low permeable layer of finite depth is much more than that in homogeneous medium of very large depth. The difference in quantity of seepage becomes appreciable when the drainage layer lies at a depth less than twice the depth of water in the canal. Further, the quantity of seepage becomes very large as the drainage layer approaches the bed of the canal.

1.0 NEED FOR ANALYSIS AND CONTROL

It is important that an early detection of occurrence of seepage in hydraulic structures is carried out. This can be achieved by regular inspection and monitoring. Monitoring by visual inspection or instrumentation is essential to detect seepage and prevent failure of the structure due to seepage. It is important to keep written records of points of seepage exit, quantity and content of flow, size of wet area, and type of vegetation. Photographs provide invaluable records of seepage. Instrumentation can also be used to monitor seepage. V-notch weirs can be used to measure flow rates easily and inexpensively, and piezometers may be used to determine the saturation level (phreatic surface) within the embankment.

Regular observation and maintenance of the internal embankment and foundation drainage outlets is also required. The rate and content of flow from each pipe outlet for toe drains, relief wells, weep holes, and relief drains should be monitored and documented regularly. Normal maintenance consists of removing all obstructions from the pipe to allow for free drainage of water from the pipe. Typical obstructions include debris, gravel, sediment, mineral deposits, calcification of concrete, rodent nests, etc. Water should not be permitted to submerge the pipe outlets for extended periods of time. This will inhibit inspection and maintenance of the drains and may cause them to clog.

Measurements of seepage are indicators of the functioning and safety of a hydraulic structure which can be compared with the permissible seepage values. Inferences on the safe magnitude of seepage for the structure as a whole cannot be worked out based on the permeability values of the constituent materials. As such, in-situ measurements are required to be carried out. Permissible seepage values can be derived based on mathematical calculations.

If occurrence of seepage is noticed measures should be taken to identify the source of leakage. The detection and analysis of seepage in hydraulic structures can be done by adopting one or more techniques from the following:

- 1) conventional hydrological technique, based on geology and hydrogeology, water balance of the reservoir, relationship between water level in the reservoir and seepage rates, piezometric studies
- 2) Geophysical methods
- 3) Nuclear borehole logging
- 4) Tracer techniques

The major aspect of **geological studies** are regional and site geology, including engineering characteristics of foundation rock and soil, geologic features of the dam foundation, abutments and reservoir rim, Investigations of geological formations, soil deposits and rock in and around the construction site is very important for assessing their behavior during earthquake shaking, and how they might affect the ability of a structure to resist earthquake including evaluation of liquefaction potential etc (Fagerlund, F., et. al, 2003).

The **hydrological** (nuclear) technique comprises of C-14/H-3 dating of ground water, discharge of rivers, ground water velocity measurement, leakage/ seepage detection from dam/reservoir, etc. The analytical mathematical models are developed to simulate water

table fluctuations in the presence of transient recharge, pumping and seepage from any number of recharge basins, wells and leakage site of different dimensions using hydrological technique (Yurtsever. Y et. al, 1993).

Water balance studies are used to identify sources and quantify volumes of water inflows and losses. Surface water inflow and outflow, groundwater discharge, direct precipitation on the lake surface, discharge through outlet works, evaporation and lake bed seepage can be incorporated into a computer model to calculate predicted lake level fluctuations under a variety of conditions (Van Haveren, B.P. 1991). Estimates of seepage rates are developed from the updated **water balance** or water balance optimization (input/output, seepage, evaporation, precipitation), but are considered generally less accurate due to higher levels of uncertainty with some water balance components. A water balance equation can be used to describe the flow of water in and out of a system, i.e., several hydrological domains, such as a column of soil or a drainage basin. Removing effects from rainfall and other possible water sources drained to the downstream part of the dam may give a quantification of seepage or water-loss for a specified period of time using water balance equations. A combination of various methods including base flow method, soil moisture balance (numerical approach), lysimetric studies, storage and flow rate concept, ground water flow (numerical) modeling techniques etc. can be applied in the water balance projects.

A **piezometer** nest of observation wells can be installed to determine the static level or piezometric surface of the water body. This is an imaginary surface that coincides with the static level of water. Piezometric readings can be used to establish isopiestic lines, which are contours of the piezometric surface of the water body. The piezometric network can be used to establish the general direction of seepage flow. Turbidity testing and hydro-chemical monitoring of the seepage water is the time-series of measurements on the composition of the water in the reservoir and the correlation to the same type of measurements on the seepage water. Temperature and conductivity measured inside the reservoir and in the region of the piezometer filters in the dam downstream slope, together with piezometric levels identify the preferential flow and identify the interconnection between piezometers and drains using dye tracers (Van Haveren, B.P. 1991).

Geophysical techniques applied to seepage measurement involve measuring a contrast in terrain conductivity (or its inverse, resistivity) in the subsurface profile around the seepage zone (Bogoslovsky V. A., et. al, 1979). This is done by either direct measurement

of conductivity of seepage water or identification of contrasts in soil properties and inference of the likelihood of greater seepage through more permeable materials in the zone above the water table. Among different geophysical methods, the self-potential method, the resistivity method and temperature measurements (viz. seasonal temperature variations) may have the best prospects (Reynolds, John M. 2000). The main objective of the resistivity method is to evaluate the potential of resistivity investigation and monitoring as tools for detection of internal erosion and anomalous seepage. The resistivity method is used in two ways: (1) detection of spatially anomalous zones by measuring resistivity along the dam and to investigate suspected structural weaknesses, (2) long-term resistivity monitoring for spatial information of the seepage-induced seasonal variation with time (Dahlin, T., P., 2008). It is non-intrusive, and collects information about the core where drillings normally are avoided. EM techniques can be used adjacent to the channel along with resistivity surveys for detection of channel seepage by **mapping** the distribution of relative seepage zones and quantification of seepage rates (Dwain K. B, 1990). Common application of tracer techniques and borehole nuclear techniques currently used in dam operation and safety during the site assessment phase and operational phase.

The major objectives of using **Tracers Techniques** are to determine (1) seepage studies in dam, reservoirs and canals, (2) location of seepage entry zones, delineating seepage path, assessing the efficiency of remedial measures, examination of soundness of bedrock etc. (3) hydraulic parameters of subsurface flow or seepage through hydraulic structures (4) aquifer characteristics (5) interconnection between solution cavities, (6) seepage losses through irrigation canals, (7) ground water recharge from river and other water bodies based on surface water studies (8) both unsaturated and saturated zones to estimate recharge, (9) demarcating the area benefited by artificial recharge, in assessing the extent of recharge and efficiency of recharge structures etc (Aulenbach, D. B., et. al, 1978).

The common tracer techniques are done by using conventional tracers, environmental stable isotopes and injected artificial tracers. Tracer techniques may be used as a definitive tool in helping to determine the needed remedial measures and best way of implementation, seepage monitoring and analysis of hydrostatic pressures at dam. This technique can be used as cost-effective means to focus on potential failure modes, seepage paths, piping, determination of the velocity and direction of leakage or seepage, vertical flow, detection of seepage zone, effective porosity etc., design, construction and monitoring phases (Dunnivant, F. M., et al., 1998).

The **Nuclear Borehole Technique** is done by using gamma logging, gamma gamma logging and neutron logging. Conventional and nuclear techniques can be used for collection of base-line geo hydrological data around the dam, studies of reservoir water tightness and slope stability, identification of major geological features e.g. faults, dykes, paleo river channels and foundation permeability studies, quantification of sedimentation and identification of changes in density material properties for dam/reservoir management (Cripps. A. C., et. al, 2000). Well logging techniques, based on the utilization of nuclear radiation (gamma, neutron, etc.) play an important role to determine physico-chemical properties of soils and rocks in situ, determine the soil's clay and carbonate content, and its permeability, bulk density of soils, water content in soil, porosity (in saturated soils); soil matrix density; and water velocity and diffusivity (in unsaturated soils), fractures in consolidated rocks, etc. Nuclear logging provides identification of weak zones prone for seepage and determination of its in-situ characteristics like density and porosity with depth. The determination of these physical properties provides information about the health of dam (Cripps. A. C., et. al, 2000). Therefore, it was suggested to identify seepage entry points and determine in situ density of masonry as parameters for the study of dam safety and stability.

The technical memorandum is aimed at giving concise information about various techniques utilized for investigation and analysis of seepage in hydraulic structures along with their causes, consequences and remedial measures for mitigation of seepage. Various causes of seepage, different methods for analysis and measures adopted for controlling seepage in different types of hydraulic structures, along with related case studies are discussed the Technical Memorandum.



CHAPTER – II

TYPES OF DAMS UNDER INVESTIGATION

Dr. Rolland Andrade, Scientist 'D'

Dams play a pivotal role in various agricultural and industrial activities through the construction of hydraulic structures like dams, canals, barrage, tanks etc. Mostly dams constructed in the past did not have adequate design methods, sophisticated techniques for ground investigation etc., hence their safety is a major concern. Efficient dam management practices demand incorporation of adequate seepage control measures in order to ascertain dam safety. This can be achieved by timely investigation of excessive and uncontrolled seepage and their flow paths. Several problems related to hydraulic structures across the globe have been reported and suitably dealt with in the recent past by adopting borehole logging and tracer study. In the recent past, across the globe, several problems related to hydraulic structures have been reported and suitably dealt with by adopting borehole logging and tracer studies. They form an integral part of Non-Destructive Technique(s) (NDT) towards delineation of weak zones through hydraulic structures, identifying source and path of seepage. In order to take up diagnostic studies, and to identify or determine the cause of seepage, site selection is an important criterion. Based on site suitability and feasibility, recommendation for drilling of borehole(s) is provided in order to perform logging and tracer studies to decipher weak zones prone to seepage through dams.

A. EARTHEN DAMS

The basic requirements for design of an earth dam are to ensure i) safety against overtopping, ii) stability and iii) safety against internal erosion due to seepage. These requirements are often interrelated in a complex manner. Generally, in embankment dams water passage is through body and foundation since all earth materials are porous. An uncontrolled and excessive seepage progressively erodes soil from the embankment or foundation, resulting in rapid piping, which may lead to failure of the dam. Slope failures are also caused by creating high water pressures in the soil pores or by saturating the slope. Assessment of seepage and early detection of piping is essential to avoid catastrophic incidences of dam failures.

The main causes of occurrence of seepage through earthen dams are i) piping/ erosion and ii) pore pressure developed.

Piping/ Erosion:

The flow of water through a pervious soil produces seepage forces as a result of the friction between the percolating water and the walls of the pores of the soil through which it



flows. Figure.1 shows the flow path of water through the pervious foundation of a dam. The water percolating downward at the upstream toe of the dam adds the initial seepage force, F_1 , to the submerged weight of the soil, W_s , to produce the resultant body force, R_1 . As the water percolates upward at the downstream toe of the dam, the seepage force tends to lift the soil, reducing the effective weight to R_4 . If exit seepage force, F_4 exceeds W_s , the resultant would be acting upward and the soil is carried out / eroded / "piped out." If the foundation materials are similar throughout, the erosion could progress backwards along the flow line until a "pipe" is formed to the reservoir, allowing rapid escape of reservoir storage and subsequent failure of the dam. This action can occur rapidly or can be slow.

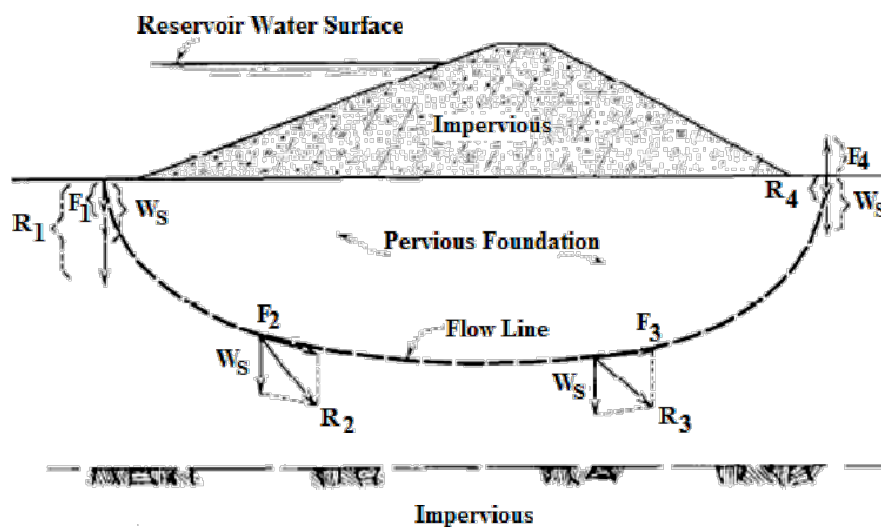


Fig.1. Seepage Forces in an embankment dam

If a more impervious layer at the surface overlies a pervious foundation, sudden upheaval of the foundation at the downstream toe of the dam can occur, called "blowout". Relatively impervious foundations are not usually susceptible to piping because impervious soil offers a greater resistance to seepage forces and, consequently, to displacement.

Pore Pressure

In the seepage flow region of the soil, the fluid pressure is developed which depends on the permeability of the soil, head difference on u/s and d/s ends, length of seepage path etc. In hydraulic structures, such as barrages, the **pore pressure** acting on the bottom of the floor of the structure exerts an upward pressure, called 'Uplift pressure' which is detrimental to the safety of the structure. In such cases, the uplift pressure at the bottom

floor of the structure is reduced by constructing cutoff piles on d/s and u/s ends. Regular monitoring is essential to detect seepage and prevent dam failure. Instrumentation should be used to monitor seepage. The two quantities that are essential to monitor and measure seepage are – i) Flow rate and ii) Pore pressure.

B. CONCRETE & MASONRY DAMS

Seepage not only results in loss of water, but if not attended in time, affects the structural integrity of the structure. The materials and the methodology for repairs of damages to this structure shall be suitable chosen as per site condition and amount and causes of seepage. Seepage is tolerable during early ages but it increases with age, sometimes exceeding limiting value. However, in some of the recent masonry dams, seepage starts prematurely which makes the structure unsuitable for its intended use and makes it structurally weak. The incidences are rare in case of concrete dams as compared to masonry dams, where seepage is mainly because of cracking due to thermal effects, alkali aggregate reaction or constructional deficiencies.

The main causes of seepage in concrete and masonry dams are (i) porosity of construction material (ii) construction joints (provided as part of structural requirement) and (iii) cracks induced due to various causes. The seepage in concrete dams is mainly due to improper mix design, inferior quality of construction material, and poor-quality control during construction. Development of cracks due to various reasons like shrinkage, thermal loading and other structural problems are also responsible for seepage in concrete dams. The seepage through masonry structures is mainly attributed to improper cement mortar ratio, type of cement, poor quality of stones, stiffness in the joints, in-expertise of mason in packing the rubble gaps and low degree of quality control exercised. Due to the technique used for construction, likelihood of seepages in masonry dams is more than that in concrete dams. The seepage due to thermal cracking in masonry dam can be ignored which is more evident in concrete dams and is detrimental to structure.

The construction quality of masonry dam solely depends upon the skillfulness of the mason doing the jointing work of stones. The ratio of mortar to stone depends upon and varies from mason to mason and sometimes may vary with location of work for an individual mason. Construction of masonry dam's rests entirely on a group of manual laborers engaged on it. The procedure of construction therefore, is liable to involve numerous human errors affecting quality. The art of placing of mortar in joints and packing joints is most

important factor governing quality of joints with respect to seepage. Since the quantity of stones (rubble) and the sand for making mortar is required in abundant, these materials have to be extracted from a number of quarries as such quality of these ingredients varies to large extent. Seals of rubber or copper are sometimes provided at joints to serve as water stops. Breakage of these seals is more likely during construction giving way to water. These and many other factors discussed herein make a masonry dam more susceptible to seepage.

C. SITE SELECTION CRITERIA FOR INVESTIGATION

Hydraulic structure(s) viz. dams and canals are national assets which demand safety measures and periodic maintenance pre and post commissioning of the structure. The implementation of the “Dam Safety Act 2021”, has emphasized the importance of maintenance and rehabilitation of as an essential component of dam safety. The Act provides for the surveillance, inspection, operation, and maintenance of all specified dams across the country. Accordingly, continuous efforts are now being made during design, construction and operation towards maintenance of dams and canals. Continuous and effective monitoring of dams and canals are necessary to foresee the inevitable changes in the characteristics of the material due to aging and other unfavorable situations.

Using materials that do not meet recommended specifications or implementing unsuitable construction techniques can create vulnerable areas in a dam, ultimately jeopardizing its structural integrity. Despite meticulous planning, precise design, and careful execution during construction, maintenance and operation, many dams still exhibit signs of distress and potential failure. These weaknesses manifest into seepage, leakage or structural cracks, which, if left unaddressed, can escalate into catastrophic failures posing significant risks to human lives and property leading to a long-term environmental and economic impact. Therefore, strict adherence to design specifications, quality control, and regular inspection throughout all phases of a dam's lifecycle is critical to ensure its safety and reliability. Subsequently, the efficiency and speed with which the seepage source can be located may be the difference between a timely remediation and a catastrophe.

The need to control water loss due to seepage underscores the importance of accurately diagnosing the root cause of the problem before initiating costly repair works. Seepage in dams typically occurs when water finds a path through a weak area, and it can



manifest in four different ways (i) through the body of the dam (ii) through the interface between the structure and the foundation (iii) through geological inhomogeneities near the abutments and (iv) through the foundation. Therefore, the identification of seepage entry points and areas of water loss is not merely a technical requirement but a crucial step in preventing structural distress from escalating into failure.

With an ever-increasing emphasis on dam safety, the need for continuous training, thorough examinations and proper evaluation cannot be overlooked. Investigation serves as a crucial phase, generating essential data for the safe, efficient and practical planning and design of hydraulic structures. Regular visual inspections, adequate monitoring and rapid analysis of data recorded from dam instrumentation provide field engineers with valuable insights into the structural behavior of dams. Dam inspections are normally entrusted to highly qualified and experienced professionals who possess the expertise to identify potential issues. Before initiating rehabilitation measures for a distressed dam, it is essential to first understand the underlying causes of distress. Physical inspections, supported by detailed investigations, are necessary to identify probable sources of distress such as cracks, fissures, voids, or cavities within the dam body, foundation, or abutments.

This manuscript emphasizes the significance of site conditions in decision-making processes related to “*site selection*” for conducting borehole logging and tracer studies in dams. These aspects are further substantiated through relevant case studies, highlighting their role in identifying and mitigating structural vulnerabilities to prevent dam failures.

Seepage Control and Analysis:

Early investigation into the occurrence of seepage in any dam is critical for ensuring its long-term stability and safety. Periodic monitoring helps maintain accurate records of seepage points, flow quantity and content, zones of wetness, and any periodic variations. In the recent years with the advent of technological development, instrumentation has been playing a significant role in monitoring seepage. V-notch weirs offer a simple, cost-effective method for measuring flow rates, while piezometers may be used to determine the saturation level (phreatic surface) within the embankment. Moreover, installing automated data acquisition systems can make available real-time monitoring and early warning alerts for abnormal seepage trends. It is also recommended to perform periodic dye tracing tests to identify seepage pathways and conduct geophysical surveys, to detect anomalies within the

dam structure. Proper training for field personnel in data interpretation and quick response protocols is crucial to address seepage issues swiftly and effectively.

Regular observation and maintenance of internal embankment and foundation drainage outlets are crucial. It is essential to monitor and systematically record the flow rate and content from outlets such as toe drains, relief wells, weep holes, and relief drains. Seepage measurements serve as key indicators of the performance and safety of a hydraulic structure and should be compared against permissible seepage values. However, the safe extent of seepage for the entire structure cannot be solely determined using the permeability values of its constituent materials. Therefore, in-situ measurements are necessary. If seepage is detected, immediate steps should be taken to identify the source of leakage. Diagnosing and pinpointing the source of seepage in hydraulic structures requires adopting appropriate techniques.

A few suitable diagnostic techniques adopted towards the delineation and identification of seepage zones are as follows:

- 1) Conventional hydrological technique, based on geology and hydrogeology, water balance of the reservoir, relationship between water level in the reservoir and seepage rates, piezometric studies.
- 2) Surface Geophysical methods
- 3) Geophysical wireline logging
- 4) Tracer techniques

Among the above-mentioned techniques, geophysical investigation, borehole logging and tracer studies are widely adopted to decipher the weak zones, seepage locations, interconnectivity and dimension of fracture/cracks/cavities, determination of density, porosity, shear strength etc.

Surface geophysical investigation methods are mainly adopted to assess seepage, which involves in measuring the contrast in terrain conductivity (or its inverse, resistivity) in the subsurface profile around the seepage zone. Among different geophysical methods, the self-potential method, the resistivity method and temperature measurements (viz. seasonal temperature variations) may have the best prospects. The resistivity method is used in two ways: (1) detection of spatially distributed anomalous zones by measuring resistivity along the dam and to investigate suspected structural weaknesses, (2) long-term resistivity monitoring for spatial information of the seepage-induced seasonal variation with time.

Application of tracer and borehole logging techniques are currently used in dam operation and safety audit studies during the site assessment phase and operational phase. The major objectives of using tracer technique is to determine (1) seepage studies in dams and canals, (2) location of seepage entry zones, delineating seepage path, assessing the efficiency of remedial measures, examination of soundness of bedrock etc. (3) hydraulic parameters of subsurface flow or seepage through hydraulic structures (4) seepage losses through irrigation canals.

1. METHODOLOGY EMPLOYED

In this paper the authors highlight two specialized techniques i.e. *Borehole logging* and *Tracer studies* which are aptly integrated to decipher the source and extent of seepage and also to decipher mechanical properties towards strengthening of the dams. An integrated methodology involving borehole logging and tracer studies can provide valuable insights into in-situ engineering properties, identify potential seepage pathways, reveal lithological variations, and assess solution activity and the interconnectivity of seepage routes. Based on the findings, the most appropriate remedial measure(s) can then be implemented to rehabilitate the affected hydraulic structure effectively.

1.1 Borehole Logging technique

Conventional and nuclear logging techniques are used for collection of base-line geo-hydrological data around a dam, studies of reservoir water tightness and slope stability, identification of major geological features e.g. faults, dykes, paleo river channels and foundation permeability studies, quantification of sedimentation and identification of changes in density material properties for dam/reservoir management. Well logging techniques, based on the utilization of nuclear radiation (gamma, neutron, etc.) play an important role to determine physico-chemical properties of soils and rocks in situ, determine the soil's clay and carbonate content, and its permeability, bulk density of soils, water content in soil, porosity (in saturated soils); soil matrix density; and water velocity and diffusivity (in unsaturated soils), fractures in consolidated rocks, etc. Nuclear and conventional geophysical logging provides an insight of weak zones prone for seepage and determination of its in-situ characteristics like density and porosity with depth. Typical borehole logging

techniques adopted in hydrological studies related to dam safety and rehabilitation are as described below:

a. Gamma-Gamma (Density) Logging →

Density logs are required in dam seepage investigations, as they provide continuous in-situ density along the entire depth of the borehole. Gamma-gamma logs record the intensity of gamma radiation from a gamma source in the probe after it is back scattered and attenuated within the borehole and surrounding rocks. Gamma radiation attenuation is assumed to be proportional to bulk density of material it passes through. Hence, a low value of count rate corresponds to a high value of density and vice-versa, enabling the identification of weak, low-density zones susceptible to seepage through the dam. The in-situ density also serves as an important input parameter for grout mix design.

b. Neutron-Neutron Logging

Neutron logs are principally used to delineate porous formations and their porosity. Here, the neutrons are introduced into the formation and the effect of the environment on the neutrons is measured. Fast neutrons are continuously emitted from a radioactive source such as AmBe^{241} . The neutrons collide with the nuclei of the formation material and the neutron loses some of its energy with each collision. The rate at which a neutron loses energy in elastic collisions varies inversely with mass of the target nucleus. Thus, the slowing down of neutrons depends on the amount of hydrogen in the formation. When the hydrogen concentration of the zone surrounding the borehole is large, most of the neutrons are slowed down and captured close to the borehole.

c. Caliper Logging

Caliper logs provide a continuous record of borehole diameter, which is essential in interpreting other logs that are affected by changes in borehole diameter. It basically comprises of an electromagnetic device having three arms, separated by 120° to each other. The caliper tool, can therefore detect the presence of weak zones and caving, if any, in the borehole.

d. Acoustic / Sonic Logging

The acoustic or sonic logging is used to determine the compressional and shear wave velocities of the formation adjacent to the borehole. Acoustic logging is undertaken in water filled borehole or below the water table in the borehole. The sonic probe uses dual-transmitter dual-receiver array to provide high quality data. The slowness, which is the reciprocal of the velocity, is actually reported by the

sonde, from which the velocity of propagation of the compressional waves of the body of the dam formation can be calculated.

e. PS logging

The PS Logger is a full waveform tool that would produce reliable P and S wave velocity measurements in unconsolidated materials and rock formations at depth. In recent years the PS Logger is being increasingly adopted for many civil and linear infrastructure projects, in preference to a conventional sonic probe. The PS Logger probe is a low-frequency acoustic probe that operates using indirect excitation rather than mode conversion as in a conventional sonic. The PS Logger probe contains a unique design of powerful hammer source and two receivers, separated by acoustic damping tubes. To acquire data, the probe is stopped at the required depth and the source is fired under surface command. It has varied applications in geotechnical engineering that include foundation studies, dam safety and determination of physical properties of soil/rock.

f. HiRAT logging

An acoustic Televiewer (ATV) can provide high-resolution information on the location and character of secondary porosity, such as fractures and solution openings. Acoustic image tools use a rotating acoustic beam to record the amplitude and the travel time of an acoustic impulse reflected at the borehole wall. The amplitude and travel time of the reflected acoustic signal are recorded simultaneously as separate image logs. The amplitude of the image log thus provides detailed structural information on bedding planes, fractures, faults, etc. Acoustic measurements are very sensitive to detect fractures in the rock.

The determination of these physical properties provides information about the health of dam. In order to perform borehole logging, Nx (3”dia) size borehole is to be drilled at selected site locations, which can be later on grouted after completion of the study. In comparison to surface geophysical investigation, conventional and nuclear logging techniques are more accurate and reliable. The only encumbrance in borehole logging is that for the operation and handling of nucleonic gauges we need to take prior approval from AERB.

1.2 Dye tracer technique

Tracers are basically substance added to a material in a chemical, biological, or physical system to mark that material for study, to observe its progress through the system, or to determine its final distribution. In most cases, the tracer is used to track the movement

of water [9], analysis of flow pathways, velocities and travel times, hydrodynamic dispersion, recharge, and discharge etc. This means that the nature and magnitude of seepage flux is inferred or calculated from the measurements of other parameters such as hydraulic head, hydraulic conductivity etc. The tracer is conservative in behavior. It moves in a manner similar to water without sorption to soils, sediments, or rocks, without degradation during the time frame of interest [9] & [12] and must be detectable at low concentrations to ensure high recovery rates, as well. Ideally tracers used in hydrogeological studies have properties such as no loss, no delay and having the same compound as traced fluid. And also they are nontoxic, inexpensive, moves with the fluid in contact, easily detectable in trace elements, does not alter the natural flow direction, is chemically stable for the desired length of time and for most purposes is neither filtered nor sorbed by the solid medium through which the fluid moves [10]. Tracer technique is very useful tool in identifying the path of seepage and also its interconnectivity. If the seepage point is at a greater distance from the source (source), then the quantity of tracer for doping and probability of dilution of dye tracer increases. Both these methods discussed are widely adopted in addressing problems related to seepage through dams. A conceptual view of these two techniques being executed in a dam is shown in Fig.2.

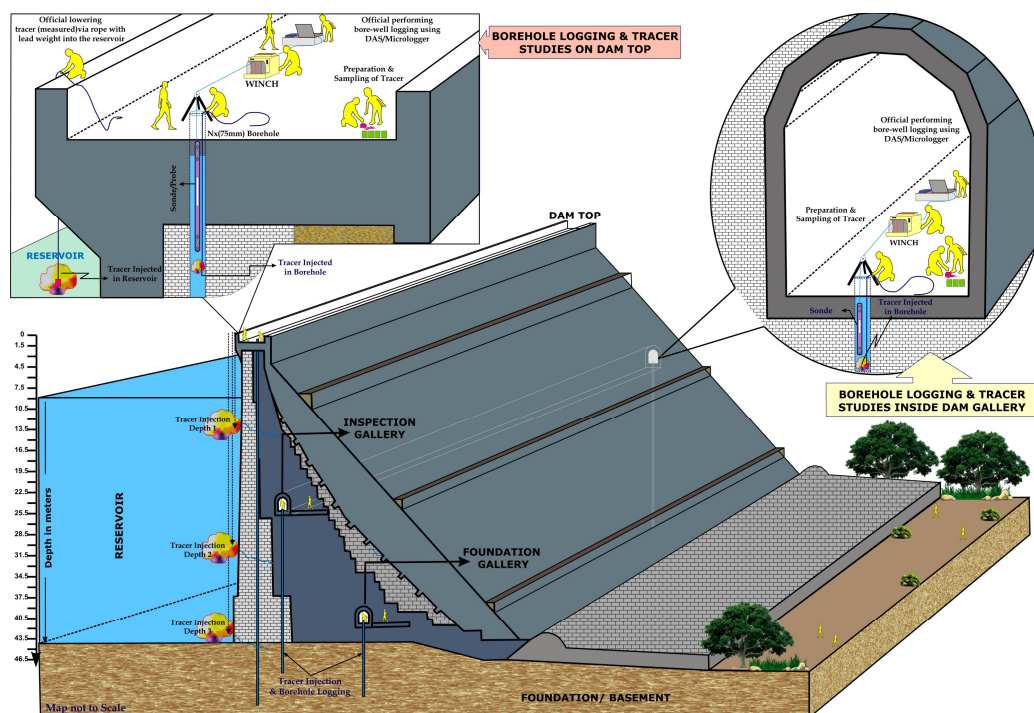


Fig.2 Conceptual model of a dam with logging & tracer study executed at different sites

2. Types of dams and causes of distress

There are numerous possible causes of deterioration of a structure, which needs to be investigated and understood before taking up the repair or restoration work. Otherwise, either the repairs will become ineffective resulting in wastage of money or sometimes lead to further damage necessitating additional expenditures. Usually, deficiency in design and improper management during construction are the two prime factors responsible for distresses in dams. The probable main causes of distresses are described with respect to different type of dams i.e. Concrete and Masonry dams

2.1 Concrete Dams: Concrete is a composite material that consists of an inorganic hydraulic binding medium (cement) embedded with fine aggregate (typically sand) and coarse aggregate (typically gravel), water and admixtures. The rate of strength development and the final strength depend on many factors including mix design, water/cement ratio, placement procedure, and aggregate and curing conditions. Cracking, spalling and disintegration are the three basic symptoms of distress in concrete structure. Due to low strength in the pre-hardened plastic state, concrete is susceptible to cracking. Even in its full hardness, the tensile strength of concrete is only about 10% of its compressive strength. Cracks are generally classified by direction, width, and depth. Before attempting to repair cracks, the cause and the source of the stress is to be identified through proper investigation.

2.2 Masonry Dams: In masonry dams the most commonly seen deterioration is in the form of seepage which is mainly attributed to improper cement mortar ratio, type of cement, poor quality of stones, stiffness in the joints, improper masonry in packing the rubble gaps, low degree of quality control etc. Due to the technique used for construction, likelihood of seepages in masonry dams is more compared to that of concrete dams. The art of placing of mortar in joints and packing joints is most important factor governing quality of joints with respect to seepage. Borehole logging and tracer investigation is widely adopted in addressing the cause of seepage and other structural flaws in concrete and masonry dams. A conceptual view of these two investigative techniques adopted in masonry & concrete dam are shown in Fig.3.

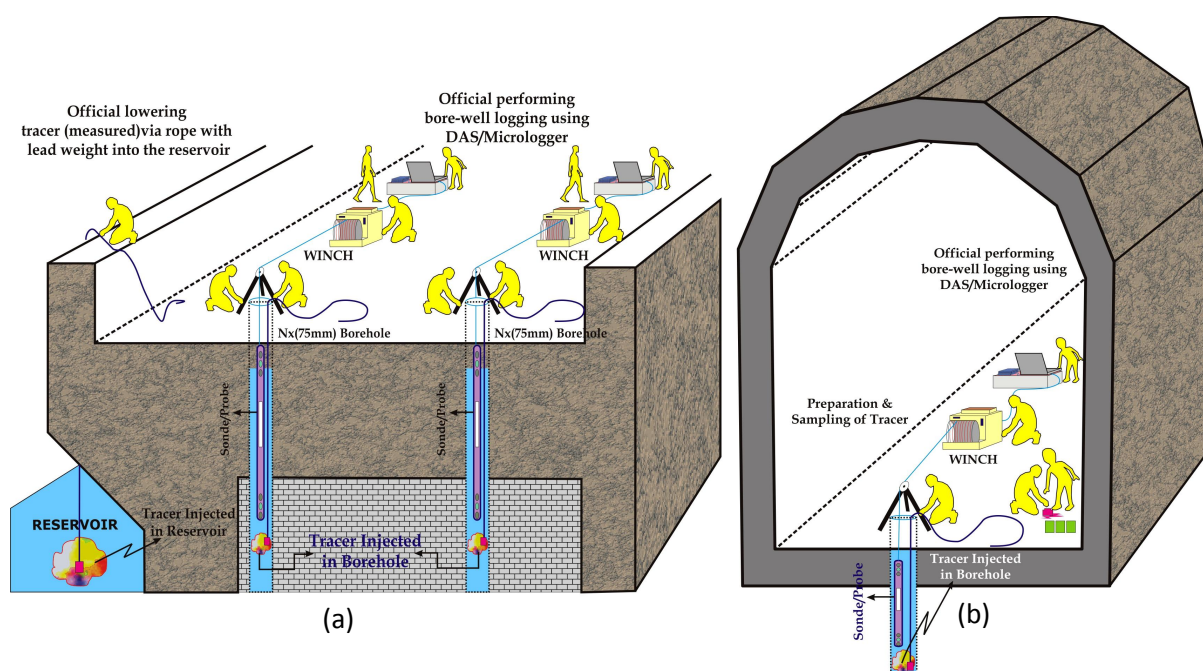


Fig.3 Well logging and tracer studies in a masonry/concrete dam (a) Dam top and (b) Gallery

3. Site Inspection (Reconnaissance Survey) / Selection Criteria

Usually at dam sites, excessive seepage is noticed on the downstream portion inside inspection / foundation galleries, abutments and key wall portion, Overflow & Non-Overflow joints etc. Also, the rate of seepage increases with the rise in reservoir water level. In view of the excessive seepage through the masonry or earthen portion of the dam, suitable investigative studies are recommended for suggesting remedial measures for controlling the seepage. Primarily before taking up the investigation a through site inspection (reconnaissance survey) is to be mandatorily conducted in order to access the actual severity of the site condition. Based on the site inspection, the selection criteria for borehole logging and tracer studies must consider the following site parameters:

3.1 Geological and hydrogeological considerations

The geology of the site and the properties of the underlying rock mass play an important role in dam design and construction. The strength, deformation, and permeability characteristics of the rock mass can affect the stability of the dam and the safety of the impounded water. Geological structures such as faults, joints, and bedding planes can affect the stability of the dam and the behavior of the foundation and abutments. These structures can provide pathways for seepage and can also affect the behavior of the rock mass under seismic loading. Hence, geological setting surrounding the dam site is an important parameter for

consideration, especially in case of seepage through foundation, abutment, key wall portion, diaphragm wall etc.

A thorough site investigation is necessary to evaluate the geology, soil characteristics, and other factors that can affect the safety and stability of a dam. Areas with known or suspected faults, fractures, or other structural discontinuities should be prioritized as they can be major seepage pathways through the foundation. Also, the groundwater conditions near the dam site can affect the stability of the dam and the safety of the impounded water. Suitable site investigation should be carried out to assess the groundwater conditions, including the depth to groundwater, hydraulic conductivity etc. Typical geological features and site geology near a dam is shown in Fig.4 (a) & (b).



Fig.4 (a) Geology near dam abutment (b) Typical geology observed surrounding dam site

A thorough inspection of the entire dam must be undertaken to assess the probable anomalous seepage zones through the body of the dam, abutment, foundation, structure-foundation interface etc.

3.2 Hydraulic Consideration / Discharge measurements

The amount of seepage through, below, or around an embankment dam is a critical indicator of the health of the dam and is normally directly related to the water level in the reservoir. However, any sudden change in the amount of seepage without an apparent cause such as a change in reservoir level or rainfall could indicate a problem with the dam. Seepage measuring devices are mandatorily to be installed in order to measure the quantity of seepage through, around or under dams. Gallery drain outlets are commonly used as seepage measurements points. The most common type of seepage measurement devices are V-notch weirs, Parshall flume, calibrated containers etc. These devices provide accurate, repeatable flow measurement as shown in Fig.5 which emphasis the severity of the seepage problem in the dam.

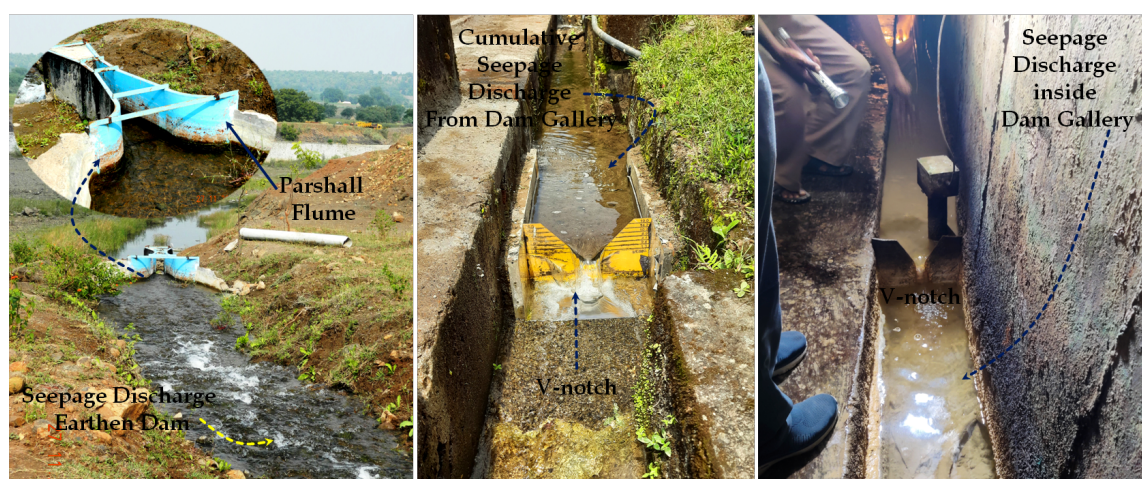


Fig.5 Dam seepage monitoring inside gallery and outside dam body

3.3 Dam Design and Construction (Cross Section and L Section)

The cross-section of a typical gravity dam is usually triangular with the upstream face being vertical to slightly inclined. Whereas in earthen dams the cross-section is almost or exactly trapezoidal. The study of Longitudinal section (L-Section) and cross section of the dam is important as they impart crucial information pertaining to dam i.e. location of gallery, rock line & ground line, depth to foundation, number and location of monolith w.r.t. chainage etc. it also imparts information regarding the dimension of gallery, Overflow and Non-Overflow section, key wall junction etc. These information's are extremely important while deciding the

location for drilling of Nx size boreholes on the dam top and also to ascertain the feasibility of drilling of borehole inside the gallery as shown in Fig.6. The material properties of the masonry and any construction materials used should also be considered, particularly in areas where different materials interface. Considerations must be given to identify seepage through the joints and cracks in the monoliths which is critical for finalizing the borehole drilling location for investigation. Historical data, visual inspections, and previous geotechnical studies should guide the placement of boreholes near areas where seepage is suspected or have been previously identified.

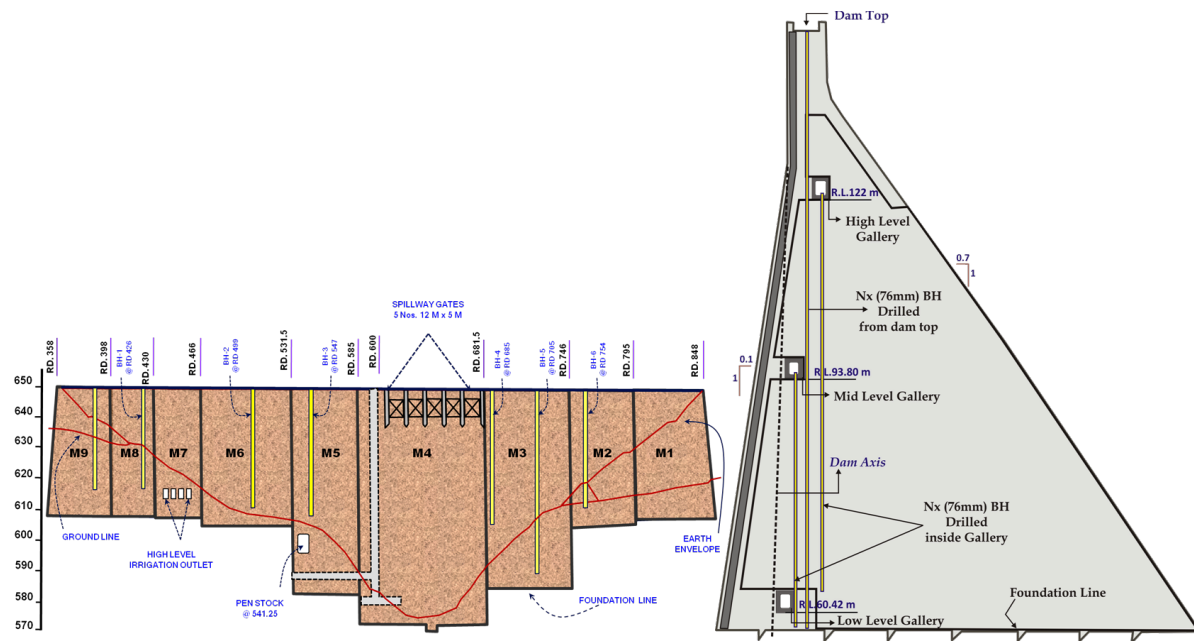


Fig.6 Typical 'L' section and dam cross section with Nx BH location for well logging and tracer studies in a masonry/concrete dam

3.4 Inspection of Gallery

Galleries in Gravity dams are mainly passages left in the body of the dam located at different elevations either parallel or normal to the dam's axis. The galleries are linked by steeply sloping passages or lift-equipped vertical shafts with variable shape and size. Mostly dam galleries have slope along their entire length with small channels on both edges. The channels run along the galleries gathering seepage water that leaks through the dam body. Moreover, the seepage through the dam body inside the gallery portion is noted with respect to Chainage and Monolith no. as shown in Fig.7. This facilitates in identifying the exact location for drilling of Nx size boreholes on the dam top and also inside the gallery.

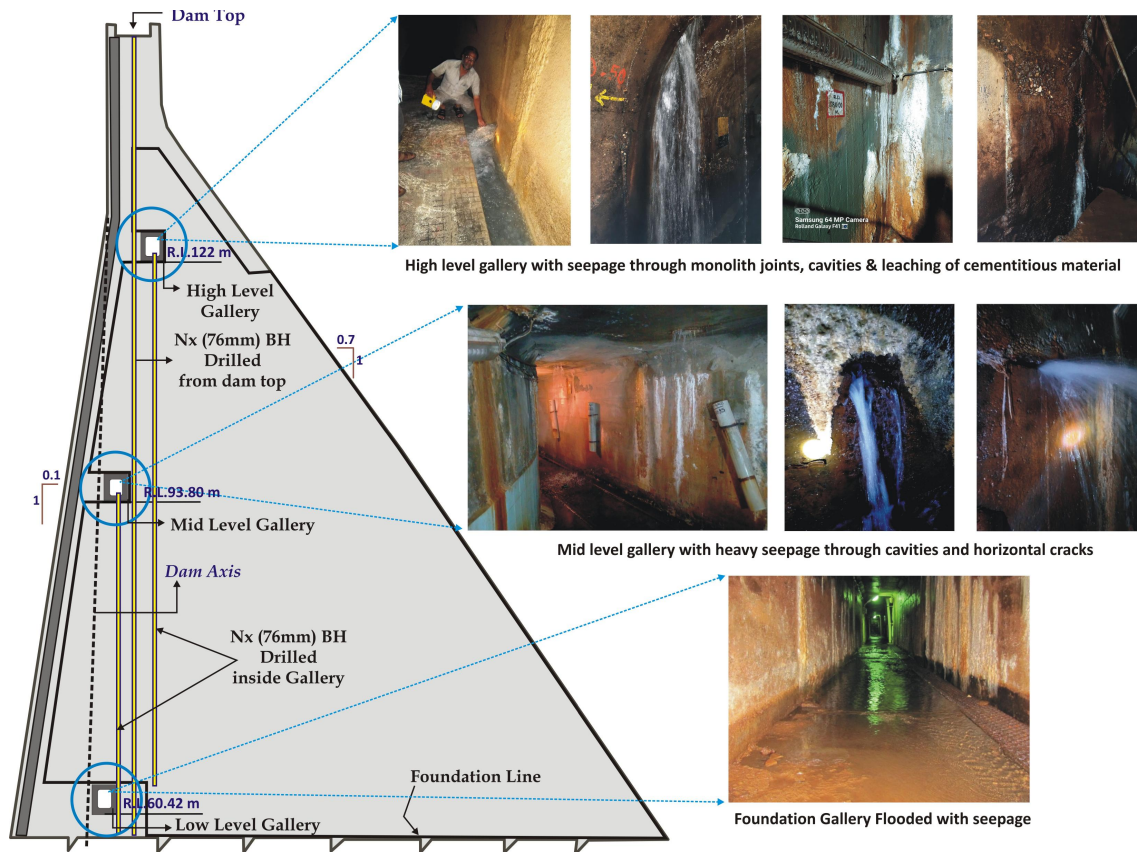


Fig.7 Typical Dam cross section with location of gallery at different levels with seepage

3.5 Monitoring and Instrumentation

Dam instrumentation is an integral part of safety assessment studies of dams. It is crucial for monitoring the structural health and stability of dams. Among various parameters, monitoring seepage is vital as it can indicate potential issues such as internal erosion, piping, or other forms of structural weakness. Instrumentation data often detect vital anomalies that serve as strong indicators for increased flow rates probably due to seepage issues. Cross-referencing data from multiple instruments provides a comprehensive understanding of seepage behavior. Regular monitoring and data collection help establishing baseline conditions which is crucial in defining normal operational parameters and identifying deviations. Long-term data analysis helps in identifying potential seepage issues. Sudden changes or persistent deviations from baseline conditions are suitable indicators for selection of borehole locations for further investigations.

CHAPTER –IV SUBSURFACE GEOPHYSICAL WELL LOGGING

Shri. G A Panvalkar, (Retd.) Sc. 'C'

1.0 OBJECTIVES OF GEOPHYSICAL WELL LOGGING

Subsurface geophysical well logging includes the science of recording and analyzing in-situ measurements in drilled boreholes or wells, to obtain a continuous profile of the physical and chemical properties of the surrounding soils and rocks. The measurements are recorded using specialized probes or “sondes” lowered into the borehole and the resulting logs are analyzed to interpret subsurface conditions. The main purpose is to provide essential information that enables the selection and use of the most appropriate geophysical well logs to solve problems related to groundwater, environmental studies and engineering projects.

Unlike surface-based geophysical methods (such as electrical resistivity imaging, seismic refraction, or ground-penetrating radar), which provide data averaged over large depths and areas, borehole logging delivers high-resolution, depth-specific information directly from the zone of interest. This makes it particularly valuable in critical engineering applications such as dam seepage investigations, where small-scale features like thin permeable layers, fractures or preferential seepage paths must be accurately located and characterized. The text discusses methodology of borehole logging techniques, equipment used and case studies on the applications of these techniques at some major projects.

1.1 Purpose and Benefits of Borehole Geophysical Logging

Subsurface geophysical well logging is an essential method for acquiring subsurface information that cannot be obtained through drilling, sampling, and in situ testing alone (USACE, 1995). In many site investigations, boreholes cannot be continuously cored and the use of advanced sampling techniques may be constrained by site conditions or budget limitations. As a result, recovered samples are often of variable quality and physical sampling may not be possible. Under these conditions, borehole logs provide a continuous, quantitative profile of the subsurface, offering a far more complete representation than discrete core samples, which are inherently subjective in interpretation.

The depth of investigation of most geophysical logging sondes far exceeds the limited volume represented by core samples. A wide range of physical and chemical properties can be measured, including formation resistivity, bulk density, porosity, primary and shear wave velocities (V_p and V_s), moisture content, and the nature and movement of

formation fluids. These parameters are vital for understanding engineering, hydrogeological, and geotechnical conditions.

Borehole logging is applicable in both newly drilled and existing boreholes. In older boreholes where geological records are missing or incomplete, logging offers an opportunity to reconstruct the subsurface profile without the need for re-drilling. Further, it can be conducted in uncased holes, as well as in boreholes cased with steel or PVC and is compatible in different borehole conditions including those filled with water, brine, drilling mud, or air.

Another significant advantage of geophysical logging is the ability to repeat measurements over time in the same borehole or across a network of boreholes. This repeatability makes it an effective tool for monitoring temporal changes, such as the response of the grout material to remedial works for seepage control in hydraulic structures. Data obtained from logs can also be used to calibrate empirical correlations and validate numerical models for geotechnical and hydrogeological analysis.

Interpretation of borehole logs facilitates determination of lithology, stratigraphic boundaries, formation geometry, and aquifer characteristics. The identification of water-bearing zones and assessment of groundwater movement are particularly important for dam safety evaluations, groundwater resource studies, and contaminant migration assessments (Scott Key, 1971). The graphical presentation of log data provides an immediate visual tool for field engineers, enabling rapid assessment of site conditions and more informed decision-making during ongoing investigations.

The determination of these properties offer a cost effective solution to various geotechnical civil engineering problems that include foundation investigations, detection of leakage, cracks, evaluation of mechanical properties for strengthening of structures, etc.

2.0 INSTRUMENTATION & SOFTWARE

The well logging unit consists of three parts: i) the down-hole probe or sonde, ii) cable and winch, and iii) surface system for signal processing and recording. Various sondes contain sensors to enable specific properties to be measured such as bulk density, porosity/moisture content, formation resistivity, natural gamma radiation, V_p & V_s , borehole diameter etc. The output, electronic signal of the sondes either in the analog or digital form is transmitted to the surface instruments via cable and winch. The cable serves the dual purpose of supporting the sonde and conveying power and signals to and from the sonde to

the surface unit. The surface unit consists of two sections to provide power and processing the signal from the sonde for recording. The data-recording units are either analog or digital such as laptop PC encoding the signal data from the sonde or surface modules formatting them and storing on magnetic media.

Central Water & Power Research Station is equipped with portable well logging unit manufactured by M/s Robertson Geologging Ltd., U.K. The Robertson Geologging (RG) equipment consists of a winch with a 200 m long multi-core cable, a Micro logger data acquisition system with high-speed data link to connect to a laptop and various probes VIZ. Electrical (consisting of Single Point Resistance, 16” Short Normal, 64” Long Normal, Self Potential), Focussed Electric, Temperature and Fluid Conductivity, Nuclear (consisting of Natural Gamma, Gamma-Gamma Density, Neutron), Caliper, Full waveform Sonic including the state of art PS-Suspension Logging and High Resolution Acoustic Televiewer, The general set up of RG well logging unit is shown in fig.1A.



Fig.1A Schematic Setup of Borehole Logging

Micro-logger

The Micrologger (fig.1B) is a small and highly portable single-unit logging-equipment interface. It includes an advanced sonde interface incorporating multiple functions into a single system. The Micrologger is powered at 12 Volts, in order to maximize its flexibility in use.

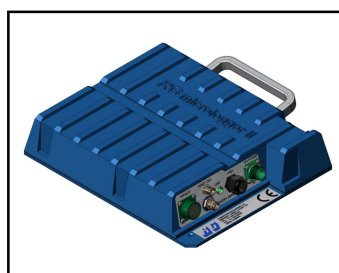


Fig.1BMicrologger

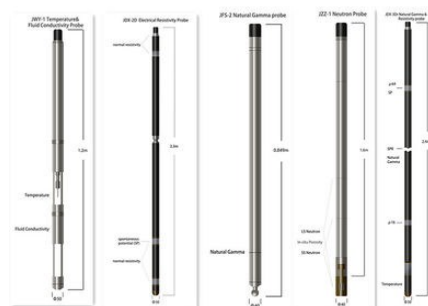


Fig. 1CTypes of Probes

Types of borehole logging

The different logging methods are tabulated below in Table-1.

- i) Caliper Log
- ii) E-Log/Focused electric log
- iii) Sonic Log
- iv) P-S Log
- v) HRAT Log

TABLE – 1

Borehole Logging Methods and Applications in Dam Engineering

Logging Method	Parameter Measured	Key Applications in Dam Seepage & Foundation Studies
Caliper	Borehole diameter	- Identifying cavities, fractures, or washed-out zones. - Assessing borehole stability. - Locating zones of possible grout take.
Electrical Resistivity	Spontaneous Potential, Single Point Resistance, Normal, Focused	- Detecting saturated/permeable zones in foundations and abutments. - Locating seepage paths and leakage zones. - Differentiating fresh water from saline/brackish water - Mapping changes after grouting.
Temperature & Fluid Conductivity	Fluid Temperature	- Fluid movement, identifying plumes - Identifying changes in water quality due to seepage. - Tracing saline intrusion or contamination sources.
Nuclear Logs	Natural Gamma, Bulk Density, Porosity, Moisture	- Assessing density changes due to fractures or voids.

	Natural gamma radiation	- Determining degree of compaction or weathering. - Checking improvement after grouting. - Estimating moisture content in dam foundations. - Detecting saturated zones indicating seepage
Sonic /Acoustic	Compressional & Shear wave Velocities, Mechanical Properties of rocks	- Assessing rock quality and elastic properties. - Detecting fractured or weak zones. - Estimating dynamic modulus for stability analysis.
P-S Suspension Log	Compressional & Shear wave Velocities,	P & S velocities in soft rock formations
High Resolution Acoustic Televiewer (HRAT)	High resolution image of borehole wall	- Mapping fractures, joints, and bedding planes. - Orienting seepage-related discontinuities. - Documenting foundation conditions for records.

2.1 Caliper Log

The caliper log provides a continuous record of borehole diameter variations using either mechanical arms or acoustic transducers. It is among the most fundamental and widely used geophysical borehole logs, owing to its simplicity and reliability (Keys, 1990). Since borehole diameter directly influences the interpretation of several other geophysical logs, a caliper log is considered essential in all boreholes where additional logging is planned. Fig. 2A & 2B depict a caliper sonde and a typical caliper log plot. Beyond recording the physical size of the drill hole, caliper logs provide valuable indirect information on subsurface lithology, fracture zones, and rock mass quality.

Mechanical calipers are available in one-, two-, three-, four-, or six-arm probe configurations. In multiple-arm designs, the displacement of feelers or bow springs is converted to electrical signals and transmitted to the surface through an armored cable. Depending on the system, the output may be limited to an averaged borehole diameter or may include both the average and the individual arm readings. Where individual arm data are available, the borehole cross-sectional geometry can be determined, enabling assessment of borehole shape irregularities.

Borehole caliper surveys have specific applications in dam safety and foundation investigations, including:

- Identification of washouts, swelling zones, fractures, and solution openings, particularly where core recovery is poor.
- Correlating with other geophysical log responses for correction of borehole diameter variations
- Estimation of grout take requirements in solution features or enlarged borehole sections.

In dam safety assessments, where precise characterization of foundation conditions is critical, caliper logs provide indispensable data for evaluating the integrity of the foundation rock mass and for planning grouting or remedial measures.

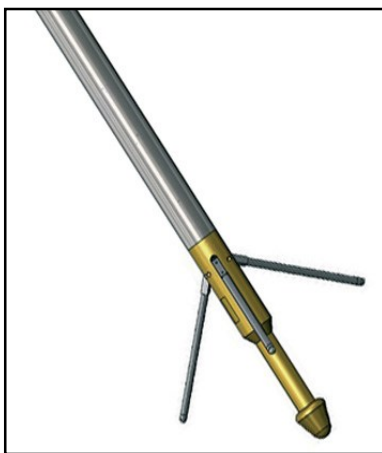


Fig. 2A Typical 3 arm caliper

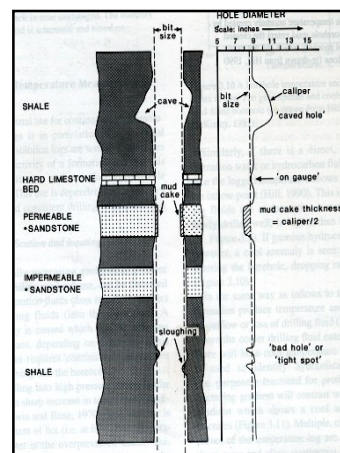


Fig.2B Plot of Caliper Log showing caving

2.2 Electrical Resistivity Logging

An electric log is a continuous record of the electrical properties of the material in and around a borehole. In dam safety and seepage investigations, electric logging is particularly valuable because changes in electrical resistivity often reflect the presence of water movement, zones of higher permeability and weak strata that may form seepage paths.

Electric logging is performed in the uncased fluid filled portion of the borehole by passing current through electrodes in the probe (sonde) and out into the surrounding ground and borehole fluid. Other electrodes located at the surface or within the borehole complete the circuit. Because modern sondes combine several electrode configurations, multiple measurements are recorded simultaneously, making the process efficient and cost effective.

A single probe can record:

- i) Self Potential (SP) Log
- ii) Single Point Resistance (SPR) Log
- iii) Multi Electrode -Normal Log - 16" and 64", Lateral Log , Focused E-log

These logs, when interpreted together, are powerful tools in evaluating seepage zones within and beneath earth and masonry dams.

2.2.1 Self Potential (SP) Log

The spontaneous potential (SP) log (fig. 3A & 3B) records the natural electrical potentials developed between borehole fluid and surrounding rock or soil. The potential difference (in millivolts) is measured between a fixed electrode at the surface and a down hole electrode. SP response depends on fluid chemistry, clay content, and temperature. In seepage investigations, the SP log is especially useful to:

- Detect movement of seepage water carrying dissolved salts, which produces measurable potential contrasts.
- Assist in correlating strata boundaries with resistivity logs.
- Estimate formation water resistivity, which helps in evaluating the quality of seepage water.

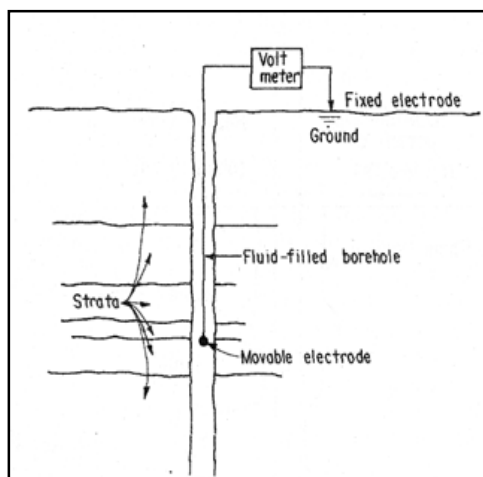


Fig. 3A - Set Up Of SP Log

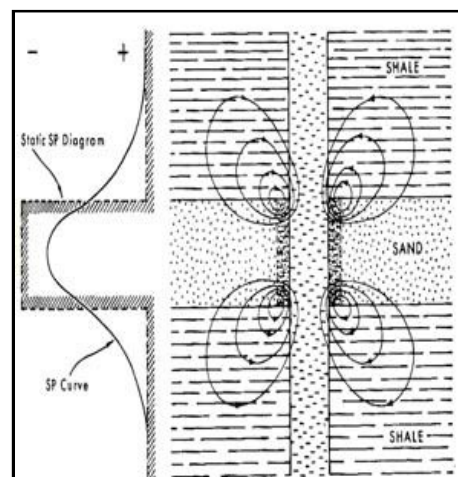


Fig. 3B A Typical SP Curve

2.2.2 Single-Point Resistance Log

Single-point resistance log measures resistance between a single electrode placed in a borehole and another electrode at the ground surface. The earth between the electrodes completes the circuit. The resistance, R , of the circuit (electrodes plus earth) can be

calculated from Ohm's Law, $R = V/I$, where V is the measured voltage drop and I is the current through the circuit. A single point resistance log, measures an apparent resistance of a section made up of borehole fluid and the different material between the borehole and the ground surface electrode. As the current and potential points are on the same electrode, the radius of investigation is small, about 5 to 10 times the electrode diameter. Figure 4A and 4B illustrates a typical SPR log. Resistance logs are used primarily for lithology determination, correlation and identification of fractures and washout zones (Benson, 1991). In dam foundations, abutments, and galleries, SPR logs are applied to:

- Identify zones of low resistance that may indicate fractures, weathered seams, or potential seepage pathways.
- Provide lithological information for correlating across multiple boreholes.

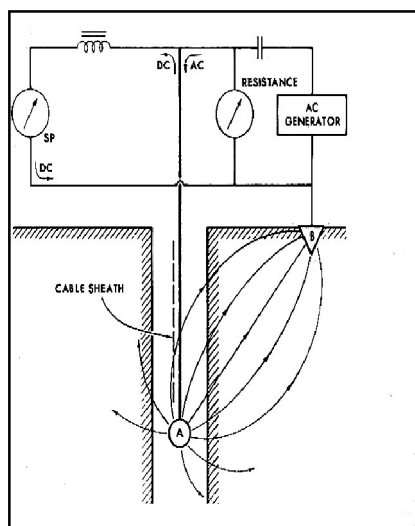


Fig. 4A - Set up for SPR log

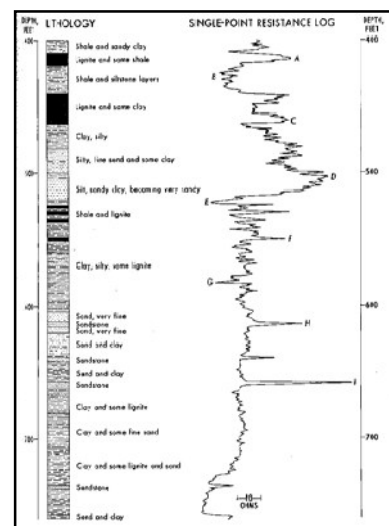


Fig. 4B - Typical SPR Curve

2.2.3 Multiple Electrode Array Logs- Short Normal (16"), Long Normal (64"), Lateral,

Multiple electrode arrays provide better resolution of resistivity and associated properties of individual strata in the subsurface than what can be achieved with the single-point array. Multiple electrode arrays include the short and long-normal array, lateral array, and focused-current or guard logging systems. The general nomenclature is to designate current electrodes as A and B, and potential electrodes are designated M and N. "Normal" arrays place the in-hole current electrode far away, considered as effective infinity. "Lateral" devices place the two potential electrodes close together with respect to the in-hole current electrode. Conventional modern logging system use a sonde made up of two normal devices

and one lateral device to produce three resistivity log along with SPR and SP log simultaneously. The normal resistivity arrays are called Short Normal (16") and Long Normal (64") depending on the spacing of the in-hole current (A and B) and potential (M and N) electrodes. The industry standard AM electrode spacing is 16 inches (in) for the short normal and 64 in for the long normal. The multiple resistivity array is shown in figure 5A. The influence of the geologic medium away from the borehole (the effective penetration of the system) is greatest for the lateral array with an 18-foot 9-in spacing and least for a 16-in short normal array. Typical normal and lateral curves are shown in fig. 5 B.

The focused-current, or guard, resistivity device is a modified single-electrode array in which "guard" current electrodes are placed above and below a central current electrode and two pairs of potential electrodes (figure 5c). Focusing the current into a band of predetermined thickness gives the focused array much greater thin bed and stratum boundary resolution than the other arrays. They applications include:

- Short Normal Logs investigate the near-borehole zone, useful for detecting local seepage and borehole effects.
- Long Normal Logs penetrate deeper, providing information about foundation strata and identifying zones of higher permeability at greater depths.
- Lateral logs are valuable for Identifying thin permeable zones, which may serve as preferential seepage paths.
- Integration of these logs enable evaluation of zones where seepage is concentrated, particularly beneath cutoff trenches or grout curtains

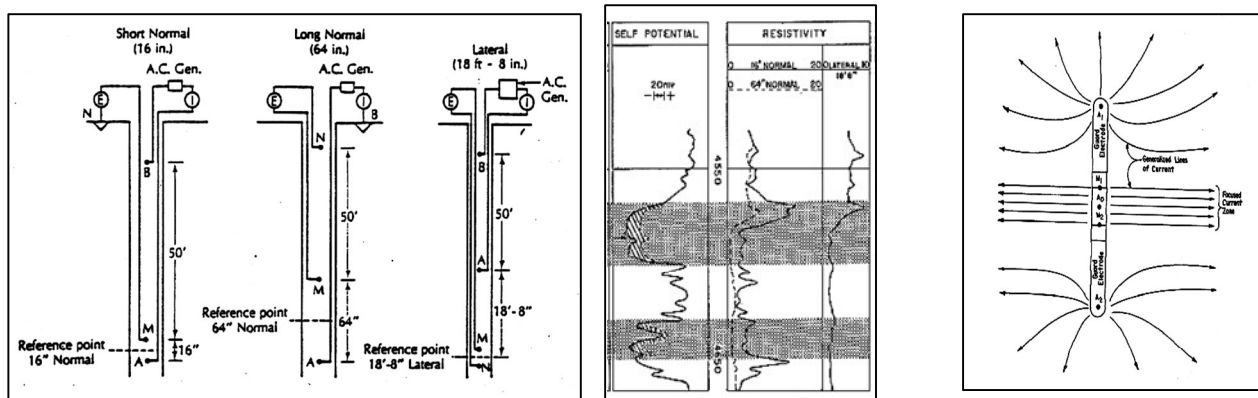


Fig. 5A Normal and Lateral Logs Fig. 5B Normal and Lateral curves Fig. 5C Focused Log

2.3 Acoustic (Sonic) Logging

Acoustic (sonic) logging systems employ medium to high-frequency acoustic energy, typically in the range of 5–30 kHz (Crain, 2004), to measure the seismic velocities of geologic materials surrounding a borehole. These systems operate by transmitting an acoustic pulse from down-hole sonde transmitter to receivers, with the recorded output being the transit time of the pulse. Sonic logging is particularly valuable in dam investigations, as it provides information on porosity, fracture conditions, and elastic properties of foundation and abutment materials—parameters directly influencing seepage behavior and overall dam safety.

Basically, all acoustic logging devices contain one or two transmitters that convert electrical energy to acoustic energy, which is transmitted through the environment as an acoustic wave. The receivers then convert the acoustic energy back into electrical energy for transmission up the cable (fig.6). The propagation velocities of the seismic waves can be calculated by travel times and distance travelled from transmitter to receiver. The devices must be operated in a fluid-filled borehole. The recorded acoustic signal typically includes several types of waves: Compressional (P) waves – highest velocity, arriving first; Shear (S) waves – slower than P-waves, sensitive to rock stiffness and Surface waves – lowest velocity, influenced by borehole boundary conditions. Devices with two receivers cancel the borehole fluid travel times so that only the refracted wave paths through the borehole wall are measured. The acoustic pulses generated at the transmitter are in the lower ultrasonic range around 23 kilohertz (kHz). The radius of investigation of the sonic tool varies with frequency and wavelength of the elastic wave as well as with the sonic velocity. It is reported to be 3 times the wavelength (Pirson, 1963). A sonic log is conventionally recorded in terms of “Transit Time”- the time in microseconds taken for the compressional wave to travel through 1 foot of the formation and is reciprocal of velocity. This measurement provides insights into the material's dynamic properties

When combined with nuclear density logs, both compressional (V_p) and shear (V_s) wave velocities can be derived, enabling the estimation of key geo-mechanical parameters critical for dam safety evaluations:

- Poisson's Ratio (σ):

$$\sigma = 1/2 * (V_p^2 - 2V_s^2) / (V_p^2 - V_s^2) \quad (1)$$

- Dynamic Young's Modulus (E_d):

$$E_d = \rho V_p^2 * ((1+\sigma) (1-2\sigma)) / (1-\sigma) \quad (2)$$

Shear Modulus (G):

$$G = \rho V_s^2 \quad (3) \quad \text{Where } \rho \text{ is the bulk density of the material.}$$

These parameters are indispensable for assessing the strength and deformability of foundation rock masses, identifying fractured or porous zones prone to seepage, and evaluating stress–strain response under reservoir loading.

In dam safety investigations, acoustic logs therefore play a dual role: (i) aiding in the detection of seepage-prone features, and (ii) providing the input data required for geo-mechanical stability analyses.

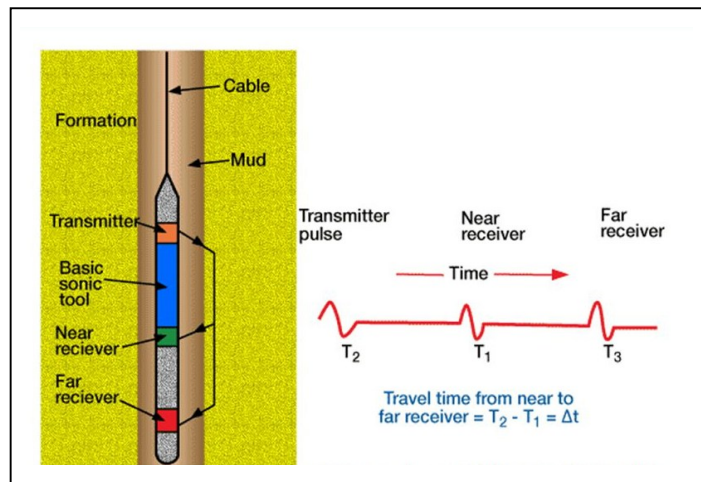


Fig. 6 Setup of Sonic Log

2.4 P-S Suspension Logs

The P-S Suspension Logger was developed in the 1970's by the OYO Corporation as a full-waveform tool capable of providing reliable measurements of both compressional (P-wave) and shear-wave (S-wave) velocities in unconsolidated materials and rock formations at depth. Its earliest applications included micro-zonation studies, aimed at characterizing earthquake-prone zones based on their geological and geophysical properties. From this beginning, the probe gained acceptance in civil engineering projects across Japan and Asia, and during the 1980s was introduced to the United States, where it quickly became part of research and infrastructure investigations. Since the 1990's, the PS Logger has also been increasingly used for determination of Vs30 at major projects involving bridges, dams, linear infrastructure, and power plants. In recent years, it has often been preferred over conventional sonic probes because of its ability to produce more reliable P- and S-wave velocity data in complex ground conditions. For dam engineering

and safety assessment, the method is particularly valuable as it provides insights into the seismic response, stiffness, and overall stability of dam foundations and abutments.

The PS Logger is a low-frequency acoustic probe designed specifically for measuring compressional and shear-wave velocities in soils and soft rock. Unlike conventional sonic tools, it operates through indirect excitation rather than mode conversion, thereby improving signal clarity in a variety of ground conditions. The probe incorporates a uniquely designed hammer source and two receivers separated by acoustic damping tubes (fig.7A).

During operation, the probe is stopped at the required depth within a fluid-filled borehole or a properly grouted PVC-cased borehole and the source is triggered by a surface command. A solenoid-operated shuttle strikes plates on opposite sides of the probe in turn, generating a pressure doublet in the surrounding fluid. This produces a tube wave at the borehole wall—closely matching the shear velocity of the formation—alongside a compressional wave. As these waves propagate along the borehole axis, they induce fluid motions that are detected by two neutral buoyancy 3D hydrophone receivers and geophones, enabling precise velocity determination.

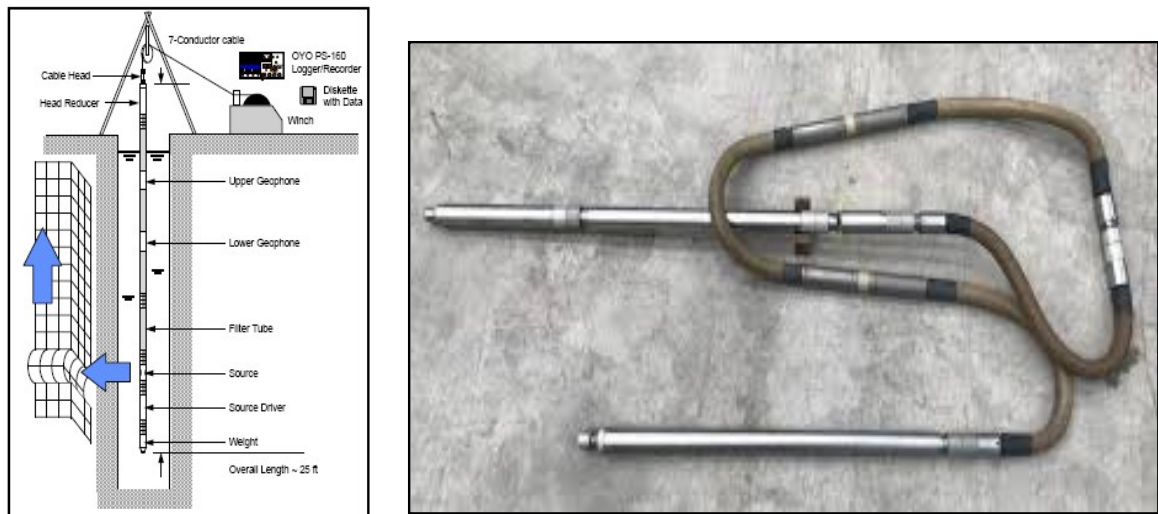


Fig. 7A P-S Suspension Log

The system also allows for stacking of multiple shots and filtering of data, similar to conventional seismic acquisition, thereby enhancing signal-to-noise ratio. Fig. 7B shows a typical waveform display. Such capabilities make the PS Logger a powerful tool in geotechnical engineering. In the context of dam safety, its applications include:

- Characterizing soil and rock stiffness beneath foundations and abutments.
- Evaluating dynamic properties of embankment and foundation materials relevant to seismic stability.
- Detecting zones of weak or weathered material that may influence seepage or deformation.
- Providing baseline geophysical data for long-term monitoring and safety assessments.

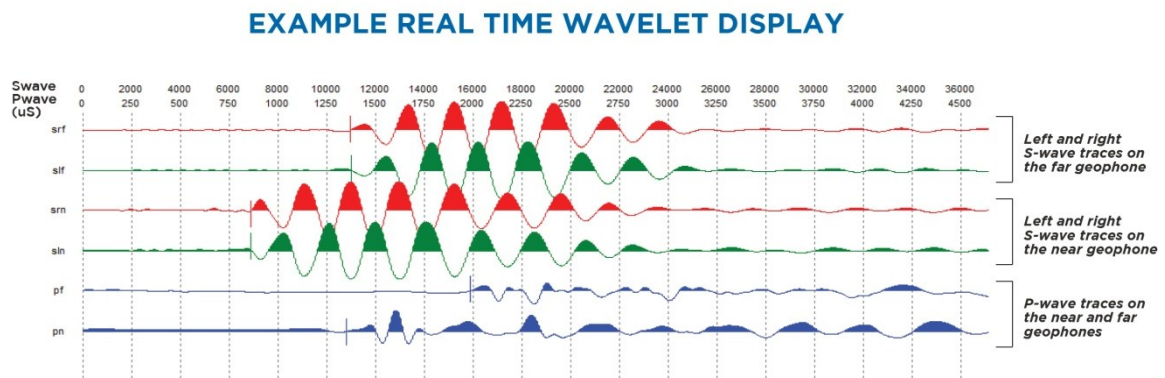


Fig.7B PS Logger Waveforms display

Thus, the PS Logger plays a critical role in modern dam safety investigations, supporting both design and long-term risk management by offering accurate subsurface velocity profiles essential for seismic hazard analysis and structural integrity evaluation.

2.5 High-Resolution Acoustic Televiewer (HRAT)

The High-Resolution Acoustic Televiewer (HRAT) is a borehole imaging tool that provides oriented, high-resolution images of the borehole wall in pseudo-colour (fig. 8A & 8B). It uses focused ultrasound beams, allowing operation even in murky or opaque borehole fluids where optical devices fail. This makes it particularly suitable for geotechnical and dam safety investigations. The system uses a fixed piezo-electric transducer and a rotating acoustic mirror to scan the borehole wall. Pulses of ultrasound (typically 1.5–5 MHz) are transmitted through the borehole fluid, reflected from the borehole wall, and recorded by the same transducer. Two key measurements are obtained simultaneously:

- Amplitude log – indicates the acoustic reflectivity of the borehole wall. Hard, intact rock reflects strong signals, while fractures, soft zones, or rough surfaces return weaker signals, appearing as dark sinusoids on the log.

- Travel-time log – measures the time taken for the signal to return, effectively serving as a 360-degree caliper to detect borehole diameter variations, breakouts, and open fractures.

The tool incorporates magnetometers and inclinometers, which orient the images in real time with respect to geographic north and borehole inclination. To ensure accurate data, proper centralization is essential, with non-magnetic centralizers required to avoid interference with internal magnetometers. HRAT images are collected in water-filled or lightly mudded boreholes. Because it uses acoustic rather than optical methods, the tool is more reliable across a wide range of borehole conditions and is highly sensitive to detecting fine fractures. The major advantages include:

- High-resolution, oriented borehole wall images
- Mean amplitude values can be related to lithology and apparent rock hardness.
- Produces a continuous 360° caliper log for detailed structural analysis.

From a dam engineering and safety assessment point, HiRAT logging is a powerful diagnostic tool. Its applications include:

- Fracture identification and orientation – critical for detecting weak zones and seepage pathways,
- Structurally controlled instabilities in dam foundations and abutments.
- Stratigraphic studies – for understanding bedding planes, lithological contacts, and weathered zones beneath dam foundations.
- Local stress assessment – by identifying borehole breakouts that reflect in situ stress directions, important for seismic safety and stability studies.
- Core orientation – providing reference orientation when core recovery is limited or incomplete.
- Characterization of secondary porosity – including solution openings and joint apertures, which may influence permeability and seepage through dam foundations.

By integrating acoustic televiewer data with other logs and core observations, engineers can distinguish between open versus closed fractures, assess rock mass quality, and evaluate long-term seepage and stability risks. This makes the HiRAT a key tool in the modern dam safety toolbox, providing essential data for design, monitoring, and risk management.

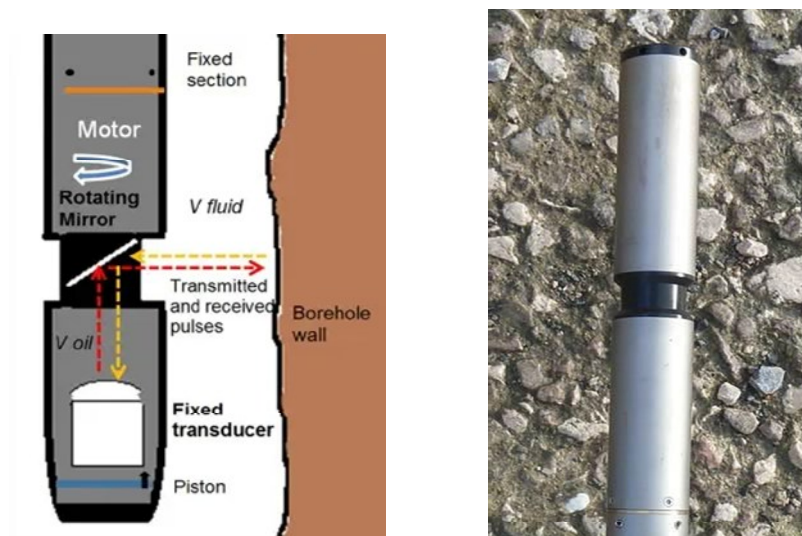


Fig 8A. Illustration of Acoustic Televiwer Tool

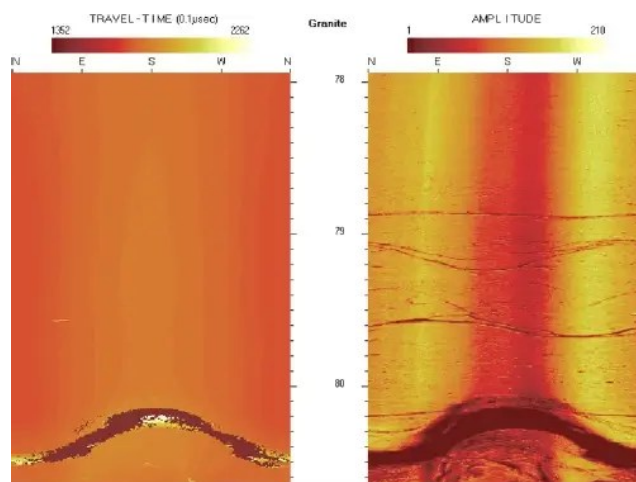


Fig. 8B Borehole Image from Acoustic Televiwer Log

Borehole logging techniques have emerged as powerful tools for addressing a wide spectrum of geotechnical and dam engineering problems. These methods provide reliable, repeatable, and non-destructive means of characterizing subsurface conditions, identifying weak zones, and assessing the in-situ properties of foundation strata. By characterizing subsurface conditions with precision, they enable effective seepage detection, guide rehabilitation strategies, and ensure the long-term stability and safety of dams.

Caliper logs reveal variations in borehole diameter, cavities, and voids, which are often associated with weak or weathered zones susceptible to leakage or instability.

Electrical logs help delineate geological formations and detect variations in fluid content and resistivity, thereby aiding in the identification of seepage-prone zones. Their continuous nature ensures reliable correlation across depth profiles.

Sonic and suspension PS logs provide accurate measurements of shear-wave and compressional-wave velocities. These parameters are fundamental for determining the dynamic and mechanical properties of foundation materials, seismic site response, and long-term dam stability.

Acoustic televiewer (HRAT/ATV) generates high-resolution, oriented images of borehole walls, enabling detailed identification of fractures, bedding planes, stress-induced breakouts, and secondary porosity—all of which directly influence seepage pathways and foundation strength.

By integrating the results from these complementary methods, engineers can build a comprehensive understanding of subsurface conditions. This integrated approach provides:

- Early detection of “potential seepage zones” through fracture characterization and fluid pathway mapping.
- Assessment of “foundation and abutment integrity” to identify weak or weathered strata.
- Input parameters for design, rehabilitation, and monitoring of hydraulic structures.
- A cost-effective and scientifically robust basis for **long-term dam safety management.

In conclusion, borehole logging techniques form a basis of modern dam safety investigations.



CHAPTER IV

NUCLEAR BOREHOLE LOGGING

Shri Amol D. Chunade, ARO

Surface Geophysical well logging chapter discussed about the objective of geophysical logging, Instrumentation and softwares used in well logging technique. Borehole logging investigations represent an economic, noninvasive alternative and can provide in situ assessment of the engineering properties of the subsurface, potential seepage pathways, lithological variation and solution activity. Application of these methods has demonstrated cost saving through reduced design uncertainty and lower investigation costs. Nuclear well logging involves the use of radioactive sources and detectors to measure the properties of subsurface formations in a borehole. Along with other logging, nuclear logging plays an important role in borehole logging techniques.

1.0 NUCLEAR LOGS

Nuclear or radiation logs are related to the measurement of radiations from the nucleus of an atom. The radioactivity measured can be either due to the natural radioisotopes within the formation or from transient response of radioactive sources kept in a probe. These nuclear radiations are in the form of alpha, beta, gamma rays or neutrons. Both gamma radiation and neutrons possess appreciable penetrating power and are measured in nuclear/ radioactive logging. Further, nuclear borehole logs have a fundamental advantage over most other logs; they can be run in cased/uncased and fluid filled boreholes and can be repeated an number of times. The different logging tools are named either on the basis of the parameter measured or according to the principle by which the measurement is made. In the subsequent chapter the primary nuclear logging tools include gamma ray, density and neutron logs each providing unique insights into the geological environment are discussed.

1.1 Natural Gamma Logs

As magma cools and crystallizes, radioactive elements like uranium, thorium and potassium which are generally larger atoms, tend to concentrate in the residual melt. This means that lighter-colored igneous rocks like granite, which form from these later-stage melts, often have higher levels of radioactivity compared to darker, iron- and magnesium-rich rocks (mafic and ultramafic rocks).



All rocks exhibit some level of natural radioactivity due to the presence of naturally occurring radioactive elements within them. This radioactivity is a fundamental property stemming from the spontaneous decay of unstable atomic nuclei (radio nuclides) into more stable forms, a process that releases energy in the form of alpha particles, beta particles, and gamma rays. The vast majority of natural radioactivity in rocks comes from the decay of three primary radioelements such as Uranium (U), Thorium (Th) and Potassium (K) and their respective decay chains.

Natural gamma logs are records of the amount of natural gamma radiation that is emitted by all rocks. The gamma ray log is primarily used for identification of lithology, shale indicator, Volume of shale and stratigraphic correlation. The probe used for this logging consists of a detector and amplifier; the detector mostly is a scintillation counter which employs thallium activated sodium iodide crystals to detect gamma radiation.

1.2 Gamma-gamma (Density) Log

Gamma-gamma density logging (GGD) is a widely used active-nuclear method in borehole geophysics. It provides a continuous record of the bulk density of formations intersected by a borehole, which is crucial for various geological and engineering applications. The core principle behind GGD logging is the interaction of gamma rays with the electrons in the subsurface formation.

A logging tool, or sonde, is lowered into the borehole. This tool contains a radioactive gamma-ray source, typically Cesium-137 (^{137}Cs), which emits medium-energy gamma rays into the surrounding formation. These gamma rays collide with the electrons in the formation. As these gamma rays penetrate the formation, they primarily interact with electrons in the rock and pore fluids through a process called Compton scattering. Fig. 1 shows the scattering principle in Gamma probe. In Compton scattering, an incident gamma-ray photon collides with an electron, transferring some of its energy to the electron and being scattered at a different angle with reduced energy. Density probe is so designed that the tool response is predominantly due to this phenomenon. The amount of scattering is directly proportional to the electron density of the material.

The logging tool also contains one or more gamma-ray detectors (usually two: a short-spaced and a long-spaced detector) positioned at a fixed distance from the source.

These detectors measure the intensity of the scattered gamma rays that return from the borehole.

A formation with a higher bulk density will have more electrons per unit volume. This higher electron density leads to more Compton scattering and consequently, fewer scattered gamma rays returning to the detectors. Conversely, a lower bulk density means fewer electrons, less scattering and a higher count rate at the detectors. Therefore, the detected gamma-ray count rate is inversely related to the formation's electron density, which is directly proportional to its bulk density.

Early GGD tools used a single detector, making them susceptible to borehole irregularities (like variations in borehole size or the presence of drilling mud, often called "mudcake"). Modern GGD tools use a dual-detector system to compensate for these effects. The short-spaced detector is more influenced by the near-borehole environment, while the long-spaced detector provides a measurement more representative of the formation. By comparing the readings from both detectors, corrections can be applied to obtain a more accurate bulk density measurement.

The gamma-gamma or density logging device measures the response of the geologic medium to bombardment by gamma radiation from a source in the sonde. Electrons in the atoms of the geologic medium scatter and slow down the source gamma rays, impeding their paths to the detector. The main use of gamma logs is for the measurement of bulk density and porosity of rocks.

Probes used for density logging contains a concentrated source of mono-energetic gamma rays, a Caesium-137 (Cs-137) or Cobalt-60 (Co-60), the detector usually a scintillation counter.

1.3 Formation Density log

The Formation Density probe provides a calibrated, borehole-compensated density measurement using a detachable ^{137}Cs gamma source and dual shielded detectors. The far spaced detector (LSD) is calibrated, giving the best estimate of formation density as borehole wall effects are minimised. A shorter spaced detector (HRD) is also calibrated which provides improved vertical resolution.

The source and detectors are held in contact with the borehole wall by a spring-loaded caliper arm measuring diameter for borehole compensation. Gamma radiation from the source is back-scattered (Compton effect) in the formation, reaching the detectors where the relative counts are measured using sodium iodide scintillation detectors. It gives Compensated density output directly in engineering units (g/cc). Fig. 2 and Fig.3 shows density probe and formation density probe.

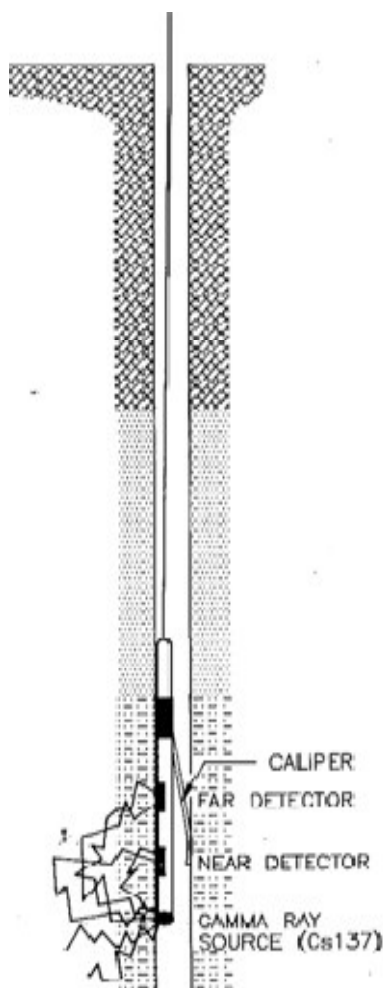


Fig. 1 Schematic diagram scattering principle



Fig. 2 Density Probe

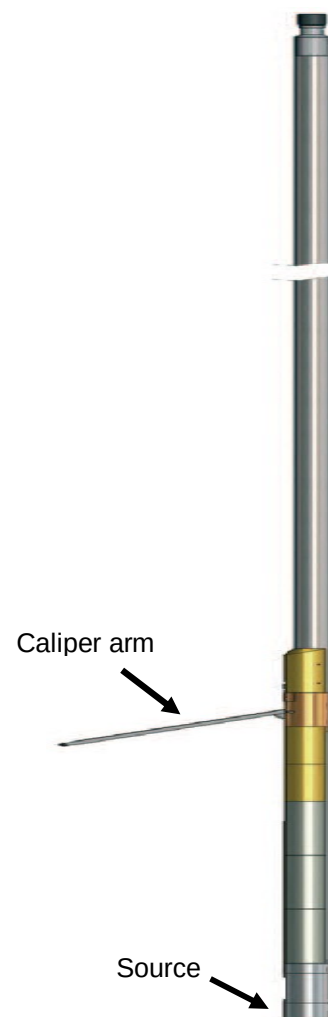


Fig. 3 Formation Density Probe

1.4 Neutron - Neutron (Porosity) Log

Neutron logs are used principally for delineation of porous formations and determination of their porosity. In neutron logging, neutrons are artificially introduced into the formation and the effect of the environment on the neutrons is measured. The neutron interaction with the subsurface material measures the amount of hydrogen present, which is a direct indication of water content.

The ratio of the volume of void space to the total volume is one of the principal used to determine porosity. The various types of neutron logs are potentially the most useful techniques in borehole geophysics, as applied to ground water investigation, because most of the probe response is due to hydrogen and therefore, also to water. Neutron logs also have advantages peculiar to other radiation logs; they can be used in liquid-filled or dry holes or in cased or open holes and they have a relatively large volumes of influence.

Americium-241-Beryllium is used as neutron source. Fast neutrons continuously emitted from a radioactive source collide with nuclei of the formation material and lose some of its energy. Within a few microseconds the neutrons are slowed down by successive collisions to thermal velocities, corresponding to energies of around 0.025 eV. Thus the slowing down of neutrons depends largely on the amount of hydrogen in the formation.

The neutron log thus measures porosity by determining the amount of hydrogen, hence the amount of fluid filling the pore spaces. When the hydrogen concentration of the zone surrounding the borehole is large, most of the neutrons are slowed down and captured close to the borehole. Fig. 4 shows the neutron thermalisation. This results in a low count rate and is interpreted as an indication of high porosity and vice versa. Modern neutron tools most commonly use Americium-241-Beryllium source and count thermal neutrons with a He-3 detector.

Depending upon the application two different probes 1) Neutron probe and 2) Dual neutron probe can be used. Both the probes work on same principle. The Neutron probe provides qualitative porosity logging under most borehole conditions including through steel or plastic casing and drill-pipe. The Dual Neutron probe provides a calibrated borehole-compensated neutron porosity measurement in mud-filled open holes. Fig 5 and Fig 6 shows the Neutron probe and Dual neutron probe.

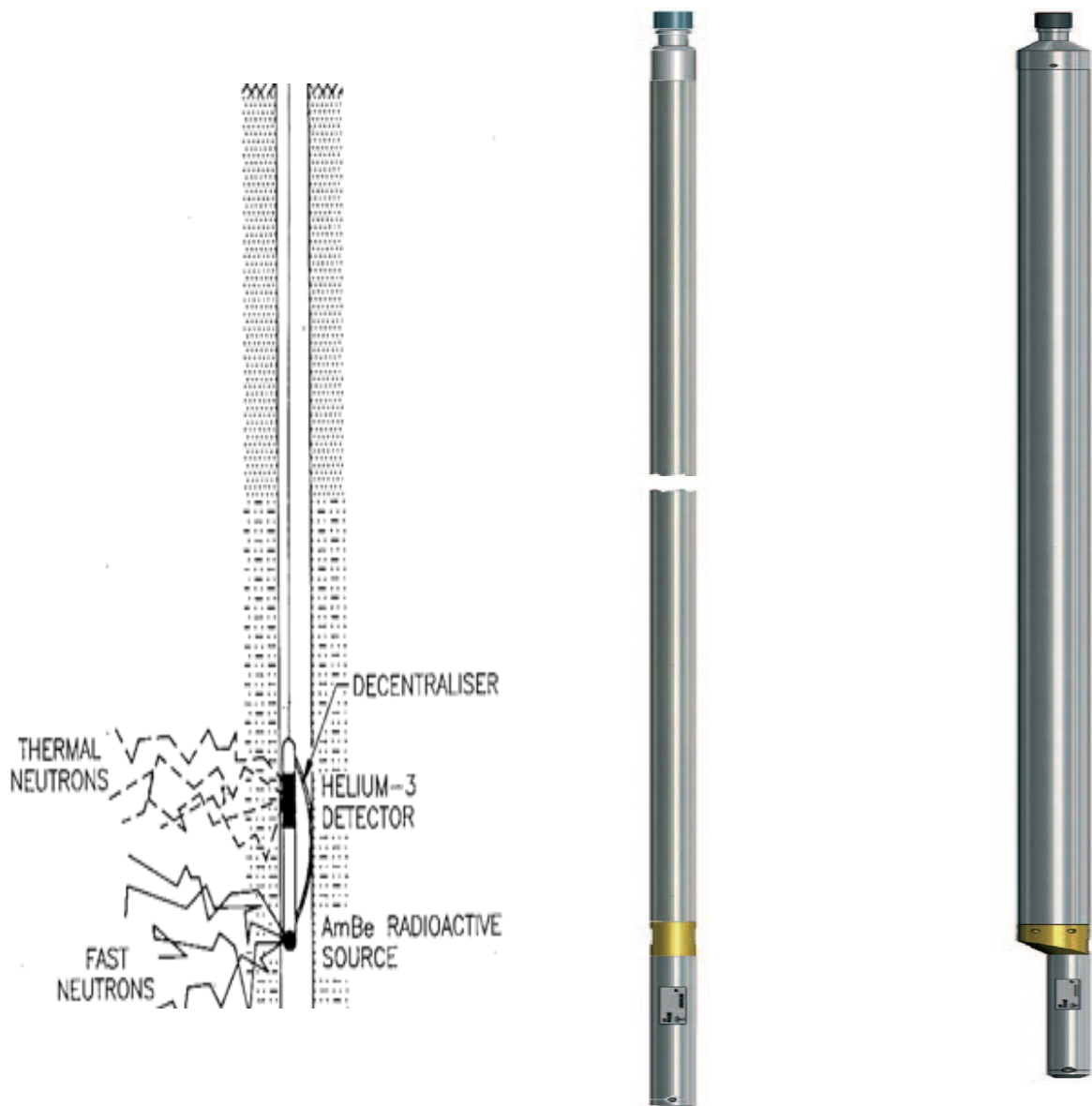


Fig. 4Neutron Thermalisation**Fig. 5**Neutron Probe **Fig.6** Dual Neutron Probe

2.0 RADIATION SAFETY ASPECTS OF NUCLEAR LOGGING

2.1 Effects of radiations

Although nuclear logs are highly reliable, accurate and valuable, some inherent precautions are required to be observed while handling radioactive sources like ¹³⁷ Cesium and ²⁴¹ Americium-Beryllium. The interaction of ionizing radiation with human body, arising

either from external radioactive sources, leads to biological effects which may later shows clinical symptoms. At very high doses, radiation can impair the functioning of tissues and organs and produce acute effects such as nausea and vomiting, skin redness, hair loss, acute radiation syndrome, local radiation injuries (also known as radiation burns), or even death.

2.2Operational Limits

People who work with sources of ionizing radiation are exposed to risk of ionizing radiation. It is not possible to eliminate these risks totally, but it is feasible to control them within acceptable limits by following the principles of radiation protection. Hence, it is necessary to develop safety standards to work with radiation so that the risks are kept minimum.

The International Congress of Radiology established the International Commission on the Radiological Protection (ICRP) in 1928. ICRP issued its recent basic recommendations on the radiation Protection in 1991. The Atomic Energy Act, 1962 (33 of 1962) articulates India's resolve to pursue the development, control and use of atomic energy for the welfare of the people of India and for other peaceful purposes and for matters connected therewith. The powers and responsibilities include those for (i) production, development, use and disposal of atomic energy / radioactive substances; (ii) control over radioactive substances or radiation generating plants in order to prevent radiation hazards, secure public safety and safety of persons handling radioactive substances or radiation generating plant and ensure safe disposal of radioactive wastes. The Act has also empowered the Central Government to delegate any power conferred or duty imposed on it under the Act to a subordinate authority or officer of the Central or the State Governments. Exercising this power, the Central Government established the Atomic Energy Regulatory Board (AERB) to carry out certain regulatory and safety functions. Hence, it is recommended that protective measures should be optimized that the radiation exposures are kept As Low As Reasonably Achievable (ALARA). By considering the total harm arising from somatic(fatal cancer, non fatal cancer and hereditary effects), the commission recommends a limit to the effective dose of 20 mSv per year averaged over 5 years (100mSv in 5 years), with further provision that the effective does should not exceed 50 mSv in single year.

2.3 Requirements for radiation users

In India, only AERB authorized persons or institution are permitted to procure and handle radiation sources. Institute should have person trained in radiation safety aspect of nucleonic gauges also Radiological Safety Officer (RSO) should be appointed in the institute. Institute should have proper and calibrated radiation monitoring instrument. Fig. 7 shows gamma radiation survey meter to measure gamma radiation. Fig. 8 shows Neutron radiation survey meter to measure neutron radiation survey meter. The radiation sources should be kept in approved isolated source storage room away from working place to minimize the exposure.

Fast Neutron Monitoring (FNM) badges for Neutron source and Thermo luminescence Dosimeter (TLD) card for gamma source should be worn by the personnel to maintain a record of the radiation exposure. Institute needs to follow all the guidelines mention by the AERB.



Fig.7Gamma Radiation Survey meter**Fig. 8**Neutron Radiation Survey meter



Fig. 9 TLD card for Gamma monitoring



Fig. 10FNM badges for Neutron monitoring

3.0 ADVANTAGE & LIMITATIONS OF BOREHOLE LOGGING

Borehole logging techniques have the potential for addressing seepage related problems effectively. Borehole logs have a number of advantages over the conventional core logs. These techniques provide reliable and repeatable methodology for identification of weak zones, assessment of nature of foundation strata of dam and its insitu characteristics. Furthermore, a number of physical and chemical properties of surrounding rock and fluids contained therein can be investigated. Caliper logs, provides information on the borehole diameter, cavities and voids which are susceptible for seepage. The different physical properties measured by these techniques are useful for planning tracer studies for the seepage path and source.

Nuclear logs have significant advantage as they are non-destructive and provide continuous recording of bulk density and porosity. Nuclear logging is also useful for studying weak zones in the dam created by leaching of binding material and reaction with cement mortar. Nuclear logging can be used in cased or uncased boreholes (though responses differ). Nuclear log less affected by borehole fluids compared to electrical logs (especially in resistive muds). Nuclear log provides direct measurements related to rock density, porosity, and shale content. The graphical presentation of borehole logs also allows rapid visual interpretation at the site

Along with the advantage the borehole logging technique had some limitations. Borehole logging cannot completely replace sampling, because some information on the local geology is needed on each new area to aid log analysis. Laboratory analysis of core is also required either for direct calibration of logs or for checking calibration carried out by other means. Some log results can be influenced by borehole conditions (e.g., mud weight, borehole size, casing). Nuclear log requires careful handling of radioactive sources. Environmental regulations and safety protocols must be strictly followed. Calibration of logs carried out in one rock type may not be valid in other rock types because of the effect of chemical composition of the rock matrix. Although borehole logging is often an economic alternative to expensive core logging, cost of logging can be significantly reduced by running only those logs that offer the best possibility of providing the answer sought.



1.0 OBJECTIVE OF TRACER TECHNIQUES

Hydraulic structures store a huge quantity of water for large periods in reservoirs and ponds. However, a significant amount of water is generally lost due to evaporation, seepage and leakages. Seepage can be defined as interstitial movement of water through a structure, its foundation, or abutments; whereas leakage is the flow of water through holes or cracks. Both seepage and leakage are matters of concern for safety of the structures and pose a serious water management problem. In spite of taking due care in planning, design and execution stages, many of hydraulic structures have shown signs of distress due to occurrence of excessive seepage or leakage. These hydraulic structures which store or carry water for irrigation and for other purposes are generally designed not to seep or leak. Seepage through such structures is a potential threat to public welfare and wastage of water (Nilsson, Å.; et. al, 2004).

Although these hydraulic structures viz. dam, reservoir, canal etc. are designed not to seep or leak, still minimum seepage or leakage occurs through them. Generally, large quantity of seepage in dam occurs through (i) the abutments i.e. through geological inhomogeneities occurring in the vicinity of the structure, (ii) the structure - foundation interface and (iii) the body of the dam itself. The excessive seepage causes softening or weakening of rock or soil mass and leading of excessive hydrostatic uplift pressure. As such, excessive seepage is a potential threat to safety of the structure (Nilsson, et. al, 2004). Similarly, seepage losses from irrigation canals also hampered the efficiency of canal and irrigation system, in terms of water logging, salinization, natural groundwater balance etc. (Singh, 2013).

All dams have some seepage as the impounded water seeks paths of least resistance through the dam and its foundation. Seepage must, however, be controlled to prevent erosion of the embankment or foundation or damage to structures. In India there are many large and small dams that are widely distributed in different provinces, it is thus apparent that the affected populations and sectors are many, and that the effects of dam-related hazards can be very serious. Accordingly, allocations for dam operation & maintenance (O&M) need to be more in line with need-based assessments. In view of above and the largely ageing

profile of Indian dams – about 76% of them over 20 years old—immediate action is required to:

- Ensure rehabilitation and modernization of dams to bring them back to full standard of safety and operation;
- Develop and implement adequate O&M programs;
- Ensure regular review of the status of the dams, both by the operator and by independent review panels, to examine problems relating to sustainable O&M of dams; and
- Formulate standards and guidelines and asset management systems to minimize future risks of dam failures.

There are several causes of seepage for different types of hydraulic structures, a very few are enlisted below:

- a. *Earthen Dams*: Seepage generally occurs through the embankment, foundation, and abutments. In earth dams the principal failure modes are internal erosion/seepage/piping, overtopping, structural issues and slides on either upstream or downstream face. Seepage through earthen dams mainly occurs due to lack of filter protection and improper filter design, washing away of particles or clogging of drains, poor compaction, open seams, cracks caused by earth movement, etc.
- b. *Masonry Dams*: Seepage occurs due to the moisture absorption by the weak zone, temperature effects, leaching, excessive uplift pressure, construction defects causing decrease in the relative density of the material, mechanical strength as well as water-tightness, earthquakes or floods, construction joints etc. Foundation seepage pressure in pervious layers can exert significant uplift force on a confining layer of lower permeability soil downstream from a dam. This pressure occurs when there is a more permeable layer underneath that transmits a large percentage of the reservoir head downstream.
- c. *Concrete Dams*: Construction deficiencies, disintegration and scaling, efflorescence, erosion, spalling and popouts and cracks etc are the major causes for seepage. Failures occur due to overtopping, piping and foundation failure because of the occurrence of uplift pressure or water pressure beneath the dam and in the rock mass.
- d. *Canals*: Seepage varies with the nature of the canal lining; hydraulic conductivity; the hydraulic gradient between the canal and the surrounding land; resistance layer at the canal perimeter; water depth; flow velocity; and sediment load etc (Zechner. E, 2004). Canals, whether lined or not, produce excessive saturation and uplift

pressure, which might produce failures of the canal and other structures. Even concrete lined canals also have seepage if the lined areas consist of cracks.

1.1 Need for Monitoring and Control

It is important that an early detection of seepage occurrence of seepage through hydraulic structure is carried out. This can be achieved by regular inspection and monitoring. Monitoring by visual inspection or instrumentation is essential to detect seepage and prevent failure of the structure. It is important to maintain written records of points of seepage exit, quantity and content of flow, size of wet area and type of vegetation. Photographs provide invaluable records of seepage. Instrumentation can also be used to monitor seepage. V-notch weirs can be used to measure flow rates easily and inexpensively and piezometers may be used to determine the saturation level (phreatic surface) within the embankment.

If occurrence of seepage is noticed, measures should be taken to identify the source of leakage. The detection and analysis of seepage in hydraulic structures can be done by adopting one or more techniques from the following:

- 1) Conventional hydrological technique, based on geology and hydrogeology, water balance of the reservoir, relationship between water level in the reservoir and seepage rates, piezometric studies
- 2) Geophysical methods
- 3) Nuclear borehole logging
- 4) Tracer techniques

2.0 TRACER TECHNIQUES

Tracers have become a primary tool for process investigation, qualitative and quantitative system analysis and integrated resource management in the field of hydrology. Tracer tests are one of the most reliable and efficient means of gathering subsurface information. A Tracer is thus defined as a certain substance added to a material in a chemical, biological or physical system to mark that material for study, to observe its progress through the system, or to determine its final distribution. Human-applied tracers are mainly used to investigate certain aspects of the hydrological system. The multi parameter detecting technology which synthesizes the advantage of the nature tracer, manpower tracer and isotope has gained great effect on detecting the leakage passage of dam (Lin. T, et. al, 2008), canal or any hydrological system. In most cases, the tracer is used to track the

movement of water (Flury. M, et. al, 2003), analysis of flow pathways, velocities and travel times, hydrodynamic dispersion, recharge and discharge etc (Moser. H, 1995).

Tracers are innocuous (nonhazardous and nontoxic) chemical compounds, salts and dyes, having unique passive-type nature, which behave exactly similar to the materials to be traced but differ from them by a particular property, which may be physical or chemical including radiochemical (Moser, 1995). The properties of the tracers are that they are stable and sensitive in nature, easily soluble in cold water, easily detectable at low concentrations, water like movement and without degradation during the time frame of interest. The major objectives of using tracers techniques in geotechnical studies are to determine (1) seepage in dams, reservoirs and canals, (2) location of seepage entry zones, delineating seepage path, assessing the efficiency of remedial measures, examination of soundness of bedrock etc., (3) hydraulic parameters of subsurface flow or seepage through hydraulic structures, (4) interconnection between solution cavities, (5) seepage losses through irrigation canals etc (IAEA, 1983). Tracers are broadly classified into two groups: (i) Conventional tracers and (ii) isotope tracers including stable isotopes viz ^{13}C , ^2H , ^{18}O , environmental isotopes viz. tritium, chlorine etc. and unstable isotopes like ^3H , ^{51}Cr , ^{60}Co etc. (Gaspar et. al, 1972).

2.1 Objective

The general applications or objectives of Tracers are:

- Determination of sediment transport rates, hydraulic connection, direction, velocity and subsurface flow etc.
- Determination of aquifer characteristics like filtration velocity, porous velocity, porosity, permeability, transmissivity etc., linking sediment transport to hydrodynamic mechanisms.
- Stratification of aquifers
- Interconnection between solution cavities in karst areas (Turkmen S, et. al. 2002)
- Seepage through hydraulic structures
- Assessment of seepage losses through irrigation canals
- Selection of waste disposal sites, monitoring of sediment plume behavior, assessment of the influence of man-made structure on sediment movement, wastewater treatment process studies etc.
- Estimation of infiltration for recharge studies.

2.2 Types of tracers

Depending on application, tracer can be used to characterize properties of large subsurface volumes or investigate small-scale transport phenomena. A tracer can be entirely natural like the heat carried by a plume of geothermal water or intentionally introduced like dyes placed to determine leakage source and establish interconnection.

Tracers can be broadly divided into two groups:

- i) Conventional tracers and
- ii) Isotope tracers

2.3 Conventional Tracers

Conventional tracers including strong electrolytes like Sodium Chloride (NaCl) and organic dyes like Sodium Fluorescein, Rhodamine-B, etc. (figure.1). They move with the same velocity as the groundwater or the medium through which they flow and its concentration is affected only by hydrodynamic dispersion. Major ions such as chloride and bromide are used as they behave conservatively and rarely sorbs onto geological material. Although a wide variety of tracers are available, dyes remain, among the most prominent subsurface water tracers. Dyes or organic dyes are low toxic, detectable at low concentrations and over long distances, relatively low sorption tendencies, good solubility in cold water and low cost, as well. Sodium Fluorescein is orange in color, low toxicity, sensitive to Ultra-violet light and characteristic bright yellowish green colour in dilute concentrations (Divine, et. al, 2005). Congo red is a red dye that may turn blue in acid waters and Rhodamine-B is a red dye similar to Fluorescein.

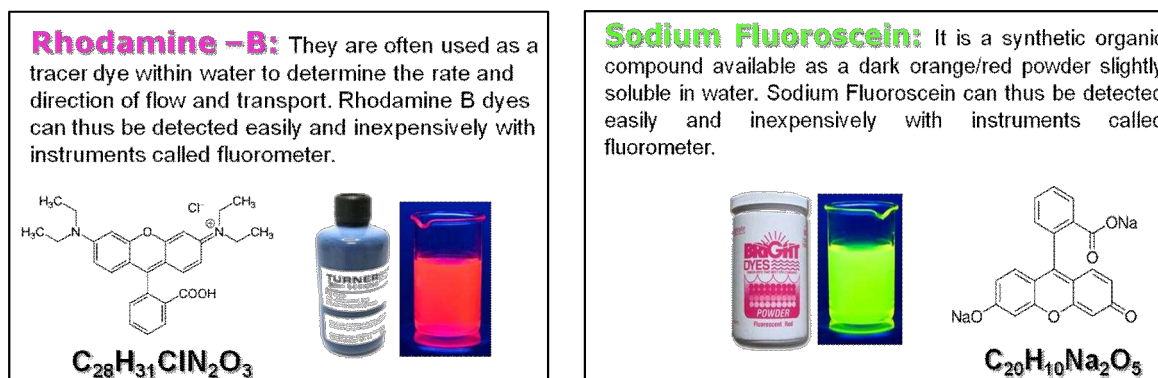


Fig.1: Conventional dye tracer(s) and their chemical formula

2.3.1 Limitations of Conventional Tracers

Chemical and dye tracers are generally affected by absorption and adsorption processes. While detecting these tracers diffusion, dispersion is predominant and therefore many times exact detection is not possible (Rao, 1984). The sampling intervals need to be carefully and accurately planned. Further, these tracers cannot be detected over long distances. Also, their detection with leached material is difficult many times.

2.4 Isotope Tracers

Isotope tracers can be subdivided into stable and unstable isotopes. Stable isotopes are those isotopes that do not undergo radioactive decay with time (Ahmad, et. al, 2007); so their nuclei are stable and their masses remain the same. Stable isotopes include environmental isotopes while unstable isotopes are radioactive (e.g. ^3H , ^{51}Cr , ^{60}Co , ^{82}Br , and ^{131}I) (Gaspar et. al, 1972).

2.4.1 Environment Isotopes Tracers

Environmental Isotopes means naturally produced and incorporated into the hydrological cycle or are released inadvertently to the environment through human activities. The application of environmental isotopes in seepage studies comprises the use of stable and radioactive isotopes of the water molecule and its solutes (Gasper et al. 1972). They have same physico-chemical behavior as normal water molecules and are ideal geochemical tracers of water because their concentrations are usually not subjected to change by interaction with the aquifer material. So, by comparing the isotopic composition of seepage water and its suspected sources, it is possible to confirm or rule out the possibility of interconnections (IAEA, 1983).

2.4.2 Radioactive (Unstable) Isotope Tracers

Radioactive tracers should have an optimum half-life period; i.e. long enough duration for the experiment to be conducted and short enough so that the radioactive contamination is minimum for the period of the experiment and later should be negligible. The examples of radioactive tracers are Bromine- 82, Iodine-131, Cobalt-60, Rubidium, Hydrogen-3 (Tritium) etc. Injected radioactive tracers like Tritium, K^{131}I , NH^{82}Br and $\text{K} [^{60}\text{Co} (\text{CN})]$ satisfy the physico-chemical behavior requirements of a good water tracer. Ease and speed of measurement are the most significant advantages of the radioactive tracer technique (Lichner, 2001). Radon gas can be used as a natural tracer of ground water seepage as the groundwater has a higher concentration of ^{222}Rn than surface water (Kraemer et.al, 1998).

The potential contribution of isotope methods are: (1) determination of physical parameters related to flow dynamics and system structure, (2) delineation of processes involved (process tracing) during flow and circulation of water, (3) study of origin (genesis) of water, mixing ratios of component flows (component tracing) and (4) study of "Time-scale" of events.

3.0 INSTRUMENTATION FOR DETECTION OF TRACERS

The advancement in electronics has led to use of large number of devices for detection of injected tracers. The type of instruments required depends on type of tracer used. The ionized substances like sodium chloride are detected using conductivity meters (figure 2(a)), which measure the ionic conductivity of salts in the water they flow through. Dyes introduced as tracers are detected by Fluorometer as shown in figure 2(b). Fluorescence is a physical property of certain atoms and molecules. It is a molecules ability to absorb light energy at one wavelength, and then instantaneously re-emit light energy at another, usually longer wavelength. Each compound that fluoresces has a characteristic excitation wavelength (wavelength of light that it absorbs) and a characteristic emission wavelength (wavelength of light that it emits when molecules relax and return to their ground state). These excitation and emission wavelengths are referred to as the compounds "fluorescence signature".

A Fluorometer, is a device, in which, the light from a lamp is passed through an excitation filter that transmits light of wavelength range specific to the sample compound being measured. The light passes through the sample, which emits light proportional to the intensity of the exciting light. The emitted light is then passed through an emission filter that selects for the appropriate wavelength range, which is then detected by a photo-multiplier tube, where a readout device indicates the relative intensity of light reaching it figure 2(c).

Thus with different light sources and filter combinations, the Fluorometer can discriminate between different fluorescent materials. The methods used for detection and measurements of radioactive tracers are based on ionisation or excitation of atoms during passage of tracers through a medium.



Fig. 2(a) Conductivity Meter with probe **Fig.2(b):** Image of *Laboratory Fluorometer* used for detection and analysis of dye tracer

The ionisation principle is applied as a working principle for photographic methods, ionisation chambers, proportional counters, GM counters, while the excitation of atoms with subsequent emission of ultraviolet and visible light is used in scintillation detectors. Special scintillation detectors are available for alpha, beta, gamma and neutron detection. ZnS (Ag) and CdS (Ag) are used as alpha detectors while NaI(Tl), CsI(Tl) are used as gamma detectors. Low-level measurements of beta particles emitting isotopes namely Tritium (^3H) and ^{14}C are detected by Liquid Scintillation Systems that can measure a large number of samples.

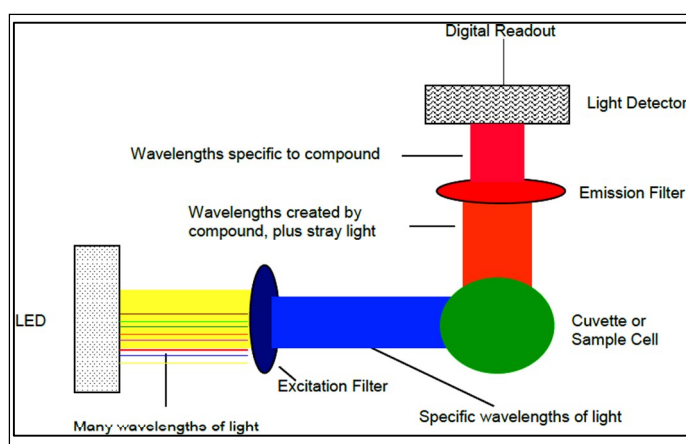


Fig.2(c) Image of working principle of *Laboratory Fluorometer*

4.0 METHODOLOGY

Tracer techniques are adapted by injecting a predetermined quantity of tracer into a borehole or suspected seepage entry points and monitoring the dilution of tracers at the places of leakage points:

The tracer techniques can be employed by utilizing two methods.

- i. Single Well or Point Dilution Technique

ii. Multiwell Technique

4.1 Single Well (Point Dilution Technique)

The aim of the method is to obtain a direct measurement of filtration velocity i.e. the amount of subsurface water flowing per unit area per unit time in a water bearing formation under natural or induced hydraulic gradient (Halevy et. al. 1967). The concentration of a tracer decreases as a result of horizontal flow of water or by diffusion. The interconnected fissures/cracks can be located by tracer dilution and filtration velocity can be determined which in turn would give quantity of flow and permeability of masonry / concrete / formations. When a tracer like common salt or organic dye or any radioactive water-soluble tracer is introduced in a borehole, the decrease in the concentration of the tracer is related to the filtration velocity of the undisturbed ground water flow as shown in figure 3.

A change in the concentration of the tracer is caused either by flow or by diffusion. The flow in the borehole consists of horizontal flow, vertical flow, density currents and flow due to artificial mixing. If only steady horizontal flow is dominant and the tracer is homogeneously distributed throughout the volume at all times, then the relation between apparent dilution rate and the concentration of the tracer is given as:

$$V_a = -\frac{V}{Ft} \ln \frac{C}{C_0} \dots\dots\dots (1)$$

Where:

V_a = apparent velocity

V = volume of water in the borehole in which dilution takes place

F = Area of cross section of measuring volume perpendicular to the direction of the undisturbed groundwater flow

t = time required for concentration to fall from C_0 to C

The horizontal flow pattern is distorted due to the presence of borehole. Thus, the measured velocity (V_a) has to be related to actual filtration velocity (V_f) by some additional terms, which account for the hydrodynamic distribution (Kaufman et al 1969). The correction factor ϕ , which accounts for the distribution of the flow lines due to the presence of the borehole, is given by.

$$\phi = Q_h / Q_f \dots\dots\dots (2)$$

Where Q_h = horizontal flow rate in borehole in cm/sec

Q_f = the flow rate in the same cross section of formation in the absence of Bore hole.

If only horizontal flow exists then, V_f is given by

$$V_f = -\frac{V}{Q_f t} \ln \frac{C}{C_0} \dots\dots\dots (3)$$

If packer system is used with a detector probe, then

$$V_f = -\frac{d^2 - d_s^2}{4Qt} \ln \frac{C}{C_0} \dots\dots\dots (4)$$

Where d & d_s are diameters of boreholes and detector probe respectively.

In this technique, the tracer is injected into the borehole by different methods like pouring it through a thin pipe, using a special syringe or a pump or by crushing an ampoule in the borehole at any desired depth. The tracer is then thoroughly mixed and then in situ measurements made at desired depths. Alternatively, samples are collected and then dilution of tracer is measured. A typical curve showing the change in tracer concentration with time for point dilution technique is depicted in figure 4.

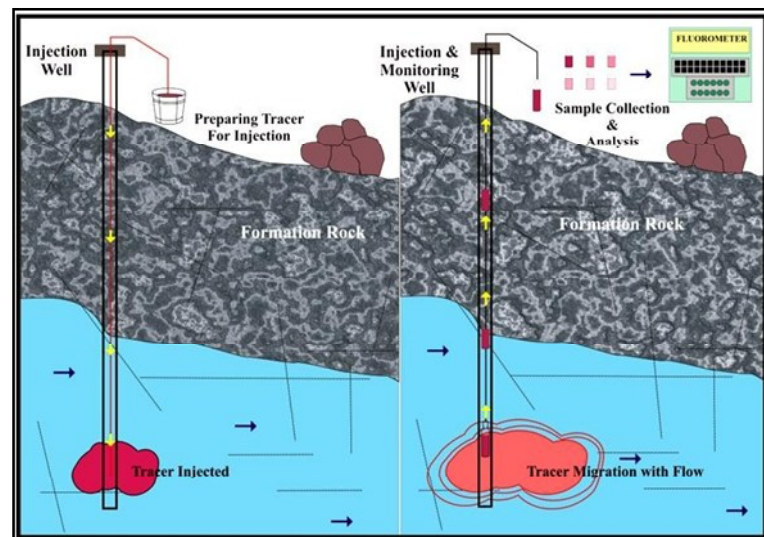


Fig.3 Conceptual model showing the tracer migration in single well injection test

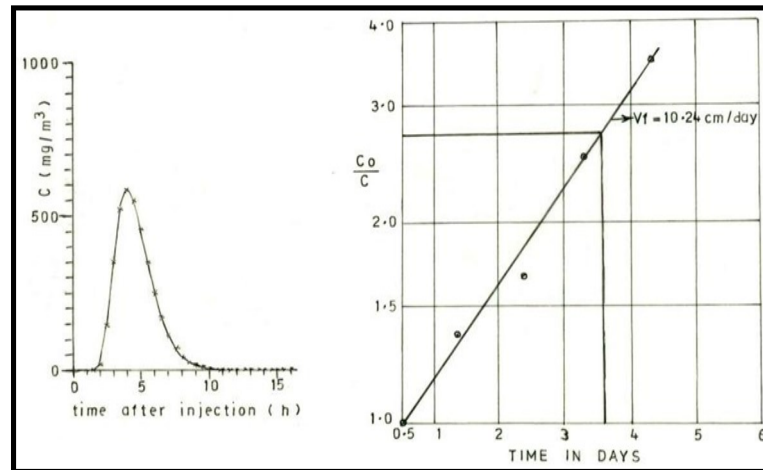


Fig.4 Tracer Arrival curve for single well; concentration (vs) time

4.2 Multiwell Technique

The method involves injecting a predetermined quantity of tracer in the form of a solution in one of the boreholes and monitoring its appearance in a number of boreholes located at the downstream, in the anticipated direction of flow. The injected quantity of tracer should last long enough to detect in the monitoring boreholes. The method is used to determine direction of flow and seepage velocity through porous medium. The seepage velocity can be determined by knowing the arrival of the peak in the concentration versus the time curve and the distances between the injection and observation holes. Thus hydraulic interconnection between two water bodies, if any, can be established as shown in figure 5.

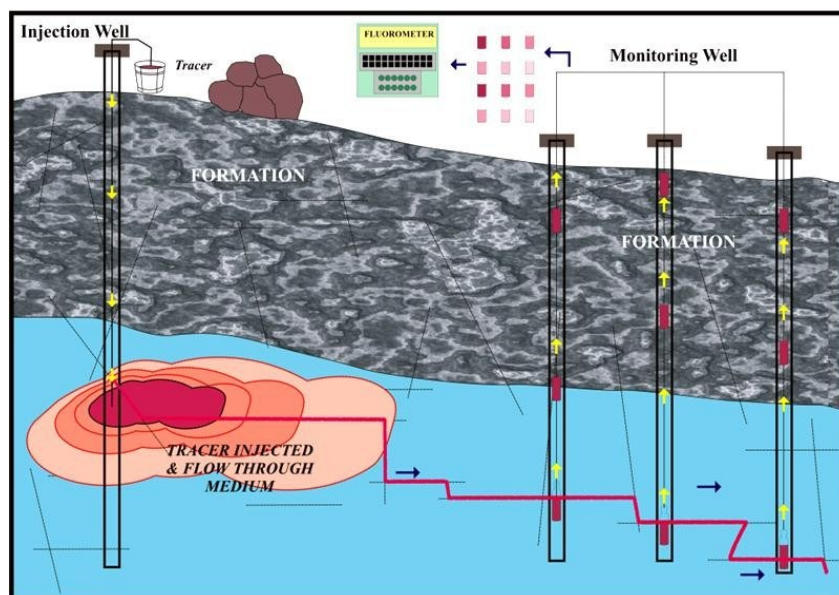


Fig.5: Conceptual model showing the tracer migration in multi well injection test

Tracer injection studies in dams are usually carried out by injecting a predetermined quantity of tracer, preferably dye tracer like Rhodamine-B ($C_{28}H_{31}ClN_2O_3$) or Sodium Fluorescein ($C_{20}H_{10}Na_2O_5$) at specific depth within the reservoir or in borehole drilled through the body of the dam. The depth at which the tracer is to be injected is deciphered based on borehole logging test results and or any other NDT (Non Destructive Test) results. Predetermined quantity of desired tracer is tied to a weight (cylindrical pipe or rod) and is lowered to the desired depth either in the reservoir or borehole drilled through the body of the dam.

A typical graph depicting the tracer (Sodium Fluorescein) arrival at a known seepage location at different times is shown in figure 6. The velocities were calculated from the peak concentration and the seepage losses were estimated.

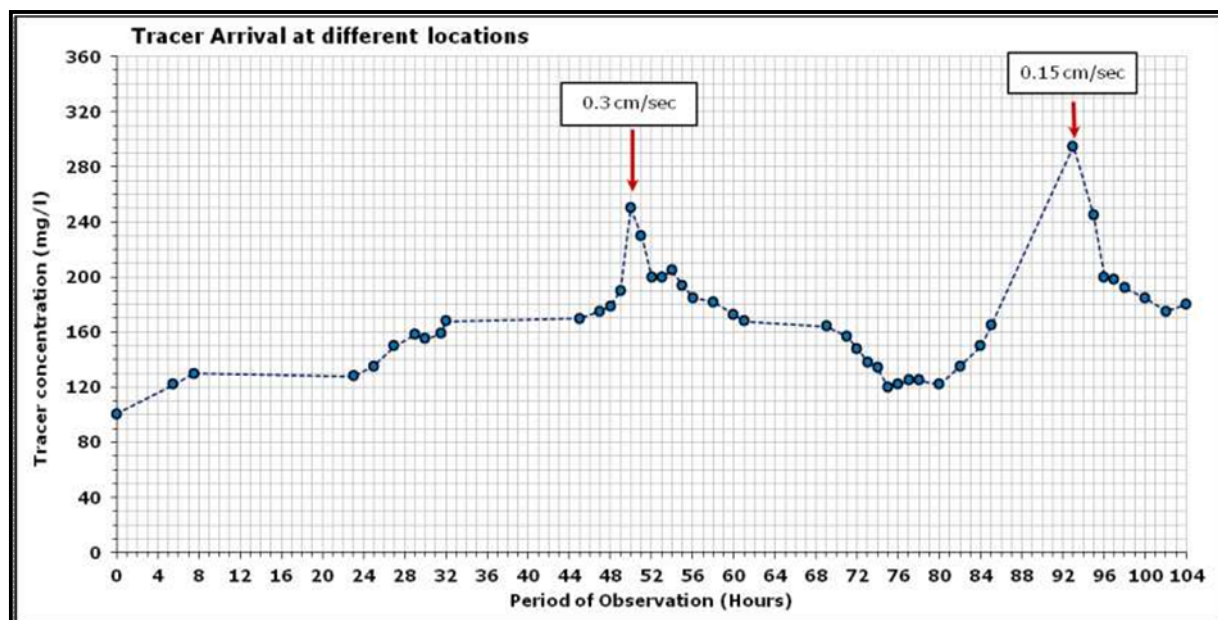


Fig.6 Tracer Arrival curve; concentration (vs) time

5.0 SIGNIFICANT STUDIES WITH SUCCESSFUL OUTCOME

Isotope Hydrology (IH) Division was established in 1979, under the United Nations Development Programme (UNDP) aided project for Applied Earth Science Divisions, to cater to the needs of the clients, requiring specific studies to be carried out towards the delineation of seepage in hydraulic structures, foundation studies of power plants and assessment of seepage losses through irrigation canals using Tracer Techniques and Borehole Logging. Almost every project undertaken by IH division pertaining to seepage investigation was

uniquely significant. A few case studies are mentioned in this memorandum as a separate chapter to elaborate the significance of tracer and borehole logging as a non-destructive technique (NDT) in deciphering seepage through hydraulic structures.



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CWPRS is actively involved in seepage investigation for dams and canals since 1962 and had given solution and remedial measures to several intricate problem related to dam seepage, structural audit studies, foundation studies etc. A few typical and important case studies are cited below to provide insight and approach to the seepage problem in the dams using trace and nuclear logging.

1. TRACER STUDIES FOR DETECTING LEAKAGE THROUGH HILLOCK AT UPPER MANAR MEDIUM PROJECT, NANDED, MAHARASHTRA

The Upper Manar Medium Project is a composite dam across River Manar, a tributary of River Manjara (a major tributary of River Godavari) near village Limboti, Tal. Kandhar, Dist. Nanded. The dam stores 68.093 M Cum of water at FRL and irrigate 862 Hectares of land. The project consists of a 1000 m long Earth dam on the left flank (RD 0 to RD 1001.75m), Non-Overflow (NOF) section on the left flank (RD 1001.75 m to RD1051.50 m), masonry portion on the right flank with 180 m Overflow section (RD 1051.50 m to RD 1270 m), and 30 m NOF section on right flank (RD 1270 m to RD1300 m). The key wall at the junction of earthwork and masonry structure was necessary to provide good bond between the earthwork and masonry work. The main canal on left bank is 58 km long. It was observed that there were a few leakage spots in the hill at the right flank just near the earthen junction. It was therefore necessary to check whether there was any connection between this flow and the reservoir water (fig. 1).



Fig. 1. View of the Spring Discharge on the Right-Hand Side of the Dam

During the preliminary site investigations, locations were selected for drilling of boreholes for conducting tracer studies. Drilling was attempted by using high pressure compressor rotary drilling with variable diameter but the same frequently failed. It was also observed that the drainage gallery was flooded and inaccessible. Seepage through the wall was also visible near the entrance. Based on the above physical observation's boreholes were required for taking up tracer studies. In order to establish the interconnection between reservoir and seepage observed at spring discharge site (right bank of the dam) tracer studies were conducted. The four boreholes available for tracer studies were termed as BH - 3 and BH - 4 (key wall), BH- 5 (Nr. Spring) and BH-6 (Hillock) for convenience. The depth of the boreholes varied from 25 m to 38 m. Tracer Injection was carried out at three borehole locations, two on the Key-wall section (BH-3 & BH-4) and one on hillock (BH-6) adjacent to key-wall at a higher elevation. At the time of injection of tracer in a particular borehole, the other boreholes and spring discharge location were treated as seepage monitoring points.

The studies were carried out using sodium fluorescein as tracer and samples were collected and monitored every 10 minutes and further the samples were analyzed using fluorometer. The tracer breakthrough curves at each observation point were plotted as concentration Vs time as shown below in fig.2. These curves provided critical insights into tracer arrival times, peak concentrations with reference to the baseline data, and were used to infer subsurface potential preferential pathways. The analysis of the trends of tracer dilution curves for boreholes BH-5 (near the spring) and BH-4 (RD 1325.6) indicate significant differences in tracer arrival times, peak concentrations, and dilution behaviors for the two monitoring points. At BH-5 near spring, it can be observed that the tracer arrived rapidly, with a sharp initial peak concentration at approximately 40 minutes after tracer injection, indicating a direct and high-permeability flow path with minimal dilution. The concentration then declined sharply but exhibited secondary peaks around 150 minutes and remained high and steady from approximately 250 minutes onward. This is indicative of multiple flow contributions or a highly connected fracture system. The tracer arrival at BH-4 was observed by a notable rise in concentration with a peak around 150 minutes, indicating a more dispersed and diffused tracer movement along the pathway.

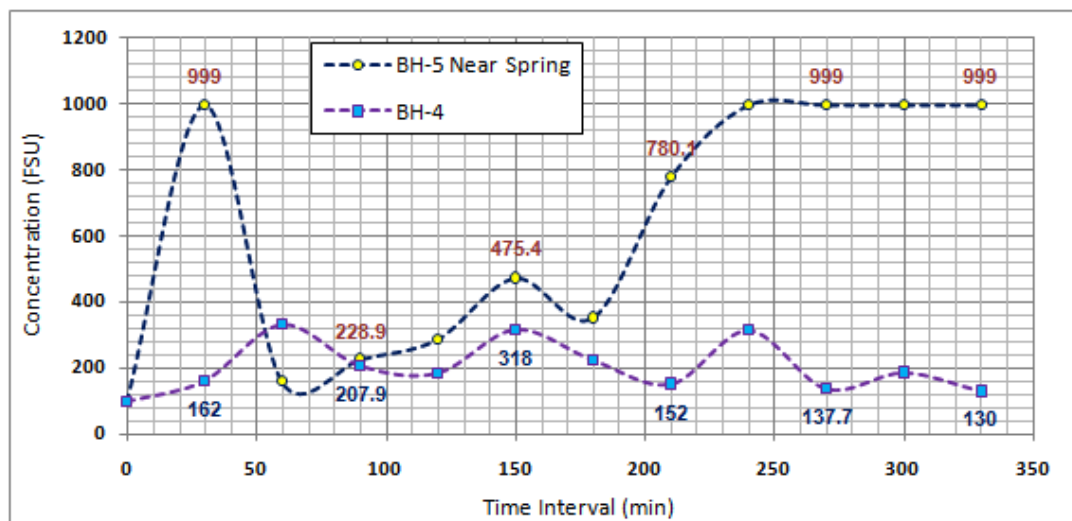


Fig. 2. Tracer Breakthrough curves for Injection in BH-1 (RD 1318) on Dam top

Similarly, the second tracer injection was carried out after ensuring that the earlier tracer had been completely washed out and again obtaining a background sample for calibrating the fluorometer. The tracer arrival was monitored at the sampling locations viz. i) the spring and ii) borehole BH-5 located 20 m downstream near the spring. The general trend of tracer dilution curve in fig 3 is indicative of initial fluctuations followed by a gradual increase in concentration. The peaks and troughs could be indicative of mixing effect in flow variations due to complex flow paths. The final increase from 250 – 400 minutes could be indicative of continuous tracer dispersion, with increasing concentration. This is indicative of complex circuitous non-uniform flow paths suggestive of fractures and voids as tracer slowly seeps through alternate pathways.

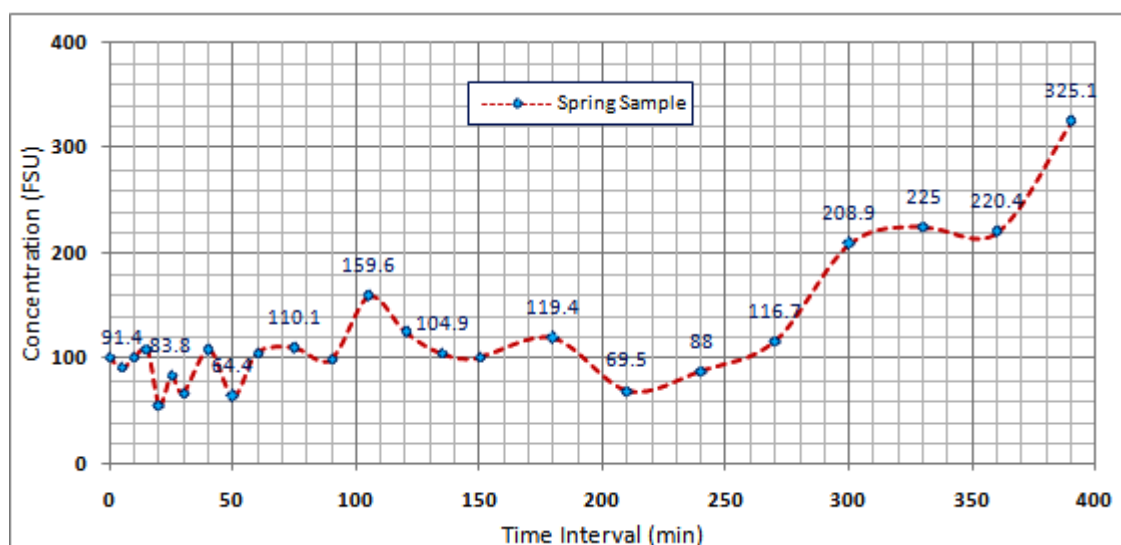


Fig.3. Tracer Breakthrough curves for Injection in BH-4 (RD 1348) on Hillock

In order to reduce / stop the seepage, the following recommendations are suggested:

- Since the major seepage is through the junction between the key-wall and abutment it may be treated with grouting. If seepage persists, the copper plate needs to be checked or replaced.
- The abutment is getting recharged by reservoir water. This may need established by monitoring reservoir level and measuring discharge through seepage point. The particular level of reservoir for which maximum discharge is observed needs to be noted and abutment may be treated suitably with bentonite grouting / sand piling at that level.

2. TRACER STUDIES FOR DELINEATION OF SEEPAGE IN THE SPILLWAY PORTION & DIVIDE WALL OF TAIL RACE CHANNEL AT KADANA DAM, GUJARAT

Kadana Dam is a composite earthfill and masonry structure with a height of 66 m, length of 1500 m and spillway with 21 radial gates, constructed on the Mahi River in Mahisagar district, Gujarat, India. The dam was constructed in 1979. The dam holds a storage capacity of 1545 hm³ to extend irrigation facilities to 11,492 ha through a direct canal on the left bank besides firming up irrigation in the existing system covering 2,71,000 ha on the right bank under the pick-up weir 65 km downstream. Seepage through the dam body and foundation strata has been observed in the masonry portion of the dam. It was observed that water was ponding in the scour formed in downstream beyond end seal in front of spillway gate no 17 and 18 and also in the plunge pool area. It was suspected that, there could be possibility of seepage through the interface of dam foundation and also through foundation rock, which could be likely due to the presence of anomalies/ fissures / fractures if any in the foundation rock and this perhaps may be the cause for ponding of water. Seepage was also suspected from the power canal on left side of the dam which is entering the plunge pool and scour area. In order to identify the probable path of water loss leading to seepage, tracer studies were conducted at different reservoir levels. Tracer technique is basically adopted by doping/injecting a predetermined quantity of tracer into the reservoir directly or through borehole located on the dam top as shown in fig. 4.

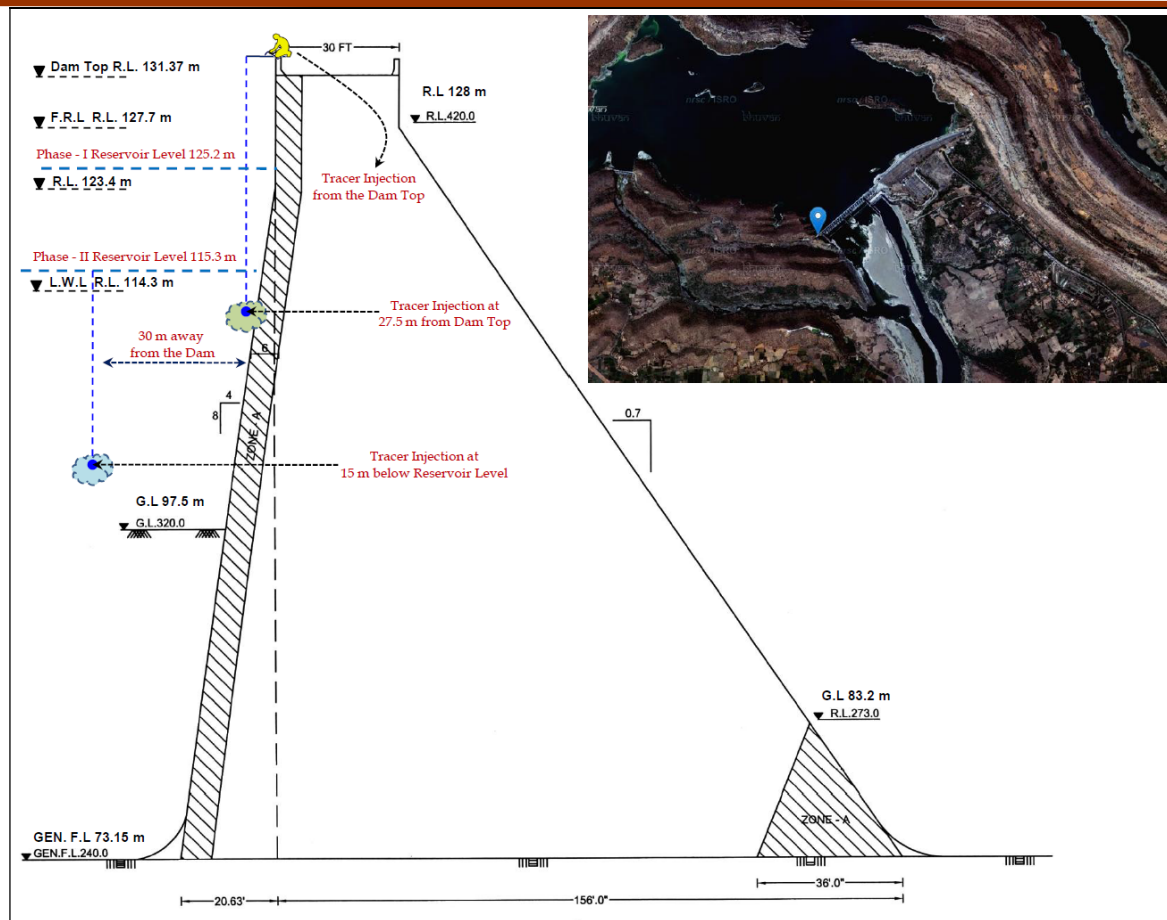


Fig.4 Cross Sectional (map not to scale) view of the Dam illustrating tracer injection.

Tracer studies were conducted by injecting a pre-determined quantity of sodium fluorescein and rhodamine dye tracers (50 gms. each) in the reservoir at different depths. Sampling points were identified with the assistance and presence of the dam authorities within the foundation gallery and also along the downstream portion of the dam (Plunge Pool) to ascertain the interconnectivity through the foundation.

The samples were labeled and then subjected for analysis using Fluorometer manufactured by M/s Turner Designs, USA. The analysis was carried out with reference to the background sample(s) collected. Arrival of tracer was confirmed based on higher concentration of tracer in samples collected from seepage points in gallery and also from Plung Pool (fig.5).

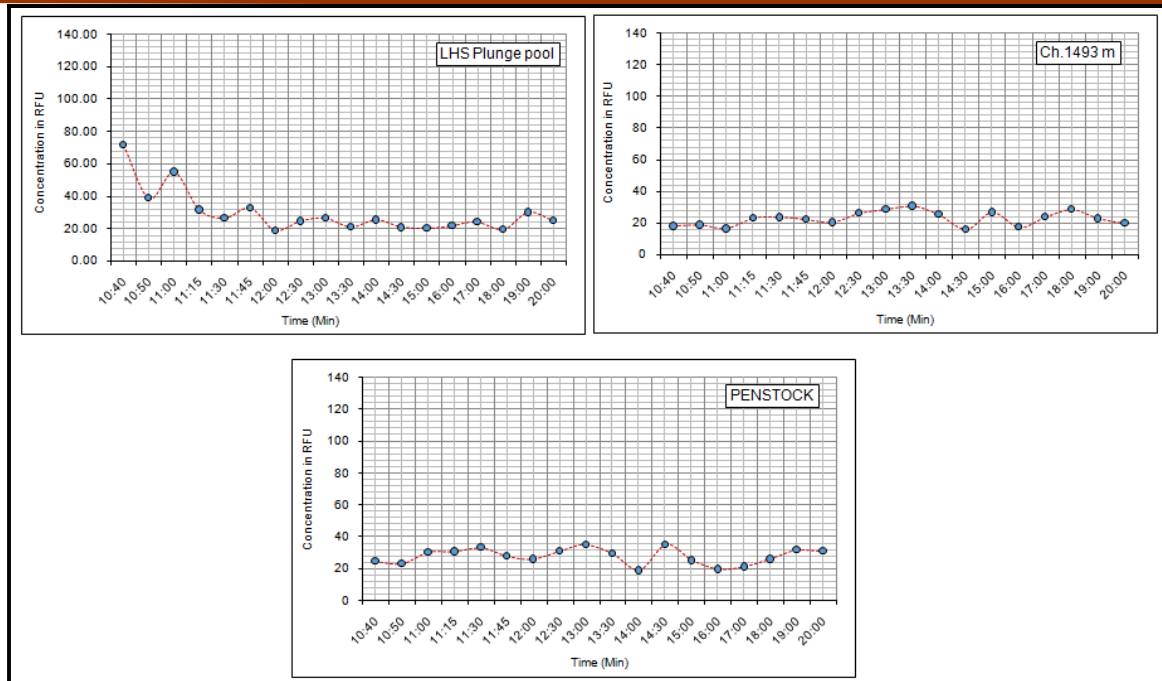


Fig.5 Breakthrough curves of tracer test conducted at NOF-OF Block Joint (LHS)

Tracer was injected at 27.5 m (RL 103.87 m) from the dam top in the reservoir. Samples were then collected from LHS Plunge pool, near penstock and at Chainage No. 1493 in the foundation gallery. Samples were collected and labeled for 8 hours and then subjected for analysis using Fluorometer. Indication of tracer arrival was not seen at any sampling point; and the same is shown in fig. 6.

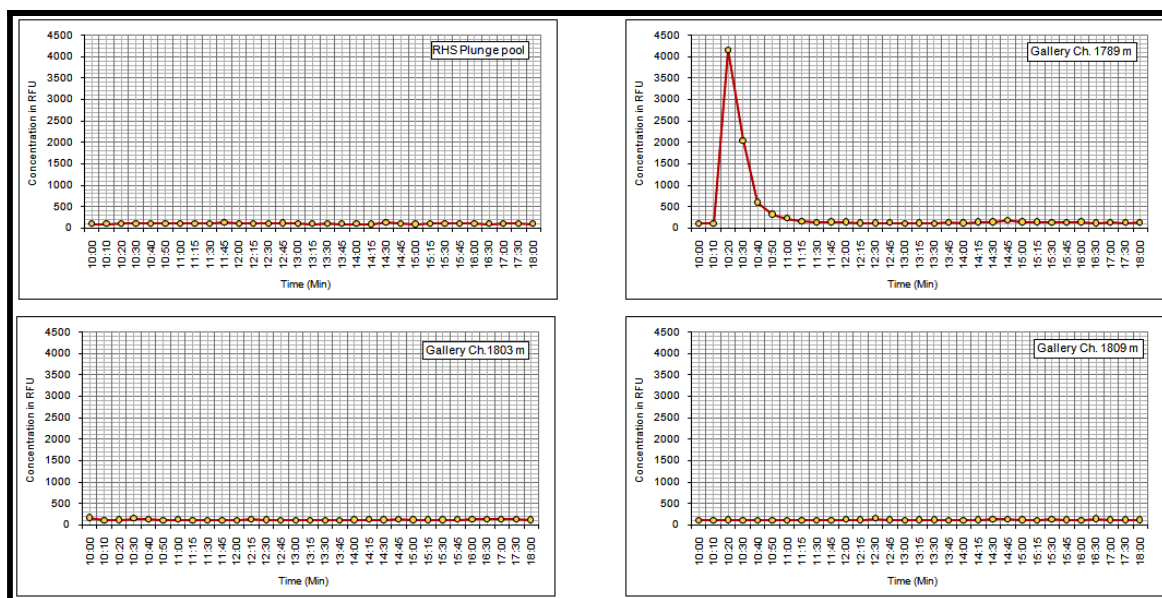


Fig.6 Breakthrough curves of tracer test conducted at Ch.1808 m

During the first phase, tracer injected at 27.5 m (RL 103.87 m) from the dam top in the reservoir did not show any trace of tracer dye arrival at any sampling points. Whereas tracer injected from the dam top at 45 m (RL 86.37 m) at Ch 1808 m in the reservoir showed the tracer arrival in Ch.No.1789 m near cable duct within 15 to 20 min after injection. During the second phase of tracer studies, it was decided to inject a predetermined quantity of tracer at deeper level compared to the first phase of study. In order to decipher the seepage path through the foundation (if any); which was seen in plung pool area, on the downstream. However, the depth as desired could not be met due to the presence of apron above the gallery on the upstream side of the dam. Tracer was injected 30 m away from the upstream face of the dam at a depth 15 m from the reservoir level, at Ch 1451 m in the reservoir but no sign of tracer arrival was seen at any of the sampling points in the gallery.

Tracer was also injected at a depth of 41 m, in the 150 mm diameter borehole on the dam top at Ch 1907 m in order to monitor interconnectivity if any between reservoir and plunge pool. There was no signature of tracer arrival at any of the sampling points. Arrival of tracer was seen at Ch. No.1789 m near cable duct in the gallery within 15 to 20 min after injection indicated the interconnectivity between reservoir and seepage point near Ch.No.1789 m. However, there was no sign of tracer arrival depicting interconnection between tracer injection points and plunge pool. Injection of tracer was attempted 30 m away from the upstream face of the dam at a depth 15 m from the reservoir level, at Ch 1451 m in the reservoir, as the desired depth of tracer injection from the dam top could not be achieved. There was no sign of tracer arrival seen at any of the sampling points in the gallery.

3. DETERMINATION OF IN-SITU DENSITY BY NUCLEAR BOREHOLE LOGGING AT TEMGHAR DAM, TAL. MULSHI, DIST. PUNE, MAHARASHTRA

Temghar dam is constructed across Mutha River (18° 27' 0" N and 73° 32' 0" E) in Pune district, Maharashtra mainly to provide domestic water supply to Pune city and irrigation of 1000 Ha of agricultural land through K.T. weirs. Hydro power is also contemplated at the foot of the dam. The project commenced during March 1997 and was commissioned in the May 2010. The 86.63 m high and 1075 m long, masonry dam comprises of a 72 m long spillway portion in the centre from RD 528 m to RD 600 m and a non overflow portion on either flank. The total utilization of 3.708 T.M.C. is planned for this project which is accommodated within 599 T.M.C. of Krishna water allocated to Maharashtra. The full reservoir level is RL 706.50 m and dam top RL is 711.40 m.

Geologically, the region is characterized by basaltic lava flows known as “Deccan-Trap” of upper Cretaceous to lower Eocene age. The rocks are predominantly basic in composition, very dark and grayish in color, hard, compact and are more or less uniform in composition and texture. Most of the bedrock portion is overlain by overburden with few visible rocky outcrops. Both amygdaloidal and compact basalt were found here. The compact basalt was found to occur as a thick flow up to 25m in thickness.

After completion of the project, leakages were observed in the dam and were estimated to have increased to about 2587 liters per second during the year 2016. Fig. 7 shows the foundation gallery with excessive seepage and leaching marks. This excessive seepage raised doubts about the dam’s safety. Hence there was the need for immediate action to be taken to reduce seepage/leakages and to look for safety of dam. The Dam safety committee suggested determination of in-situ density of the masonry, which is an inherent parameter required for to assess the stability of hydraulic structures.

Hence it was proposed to conduct nuclear borehole logging at four selected locations, to estimate the in-situ density and identify weak zones if any, susceptible for seepage through the body of the dam.

The nuclear logging studies were conducted in Temghar Dam, Maharashtra. All the Standard Operating Procedures (SOP) as per Atomic Energy Regulatory Board (AERB) protocols and regulations were strictly followed while conducting the studies. The studies were undertaken in four Nx size bore holes drilled at selected locations in the body of the dam at Ch. 481 m, Ch. 525 m, Ch. 507 m, Ch. and 472 m with depths varying between 26 m to 39 m. The L- section of dam (fig. 8) shows the borehole locations.



Fig. 7 Foundation Gallery showing seepage and leaching marks

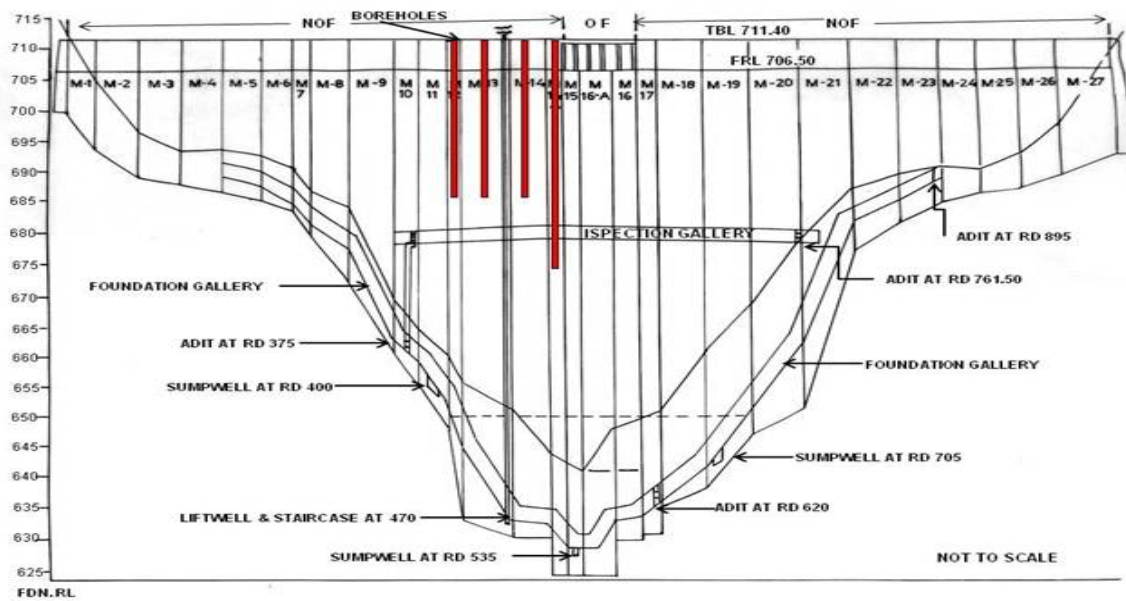


Fig. 8 L- Section showing BH locations

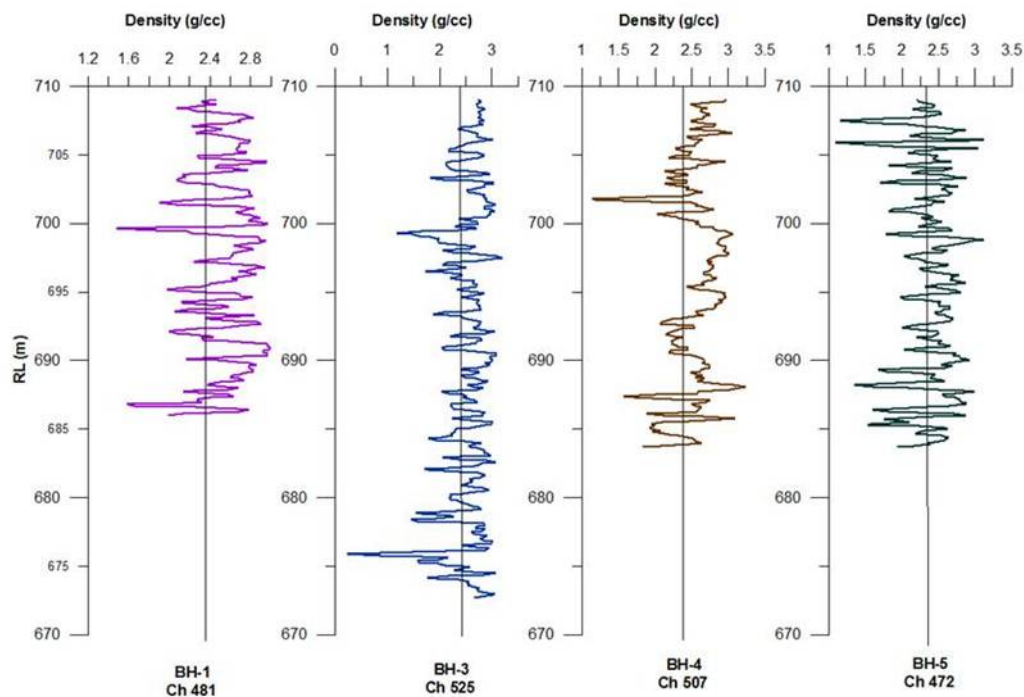


Fig. 9 Density logging plots showing weak low density zones

The densities plotted against the depth of boreholes and shown in fig. 9. The results indicated that in general, the density of masonry ranged between 1.14 gm/cm^3 and 3.10 gm/cm^3 . The density values that were observed below the design density of 2.35 gm/cm^3 (as marked by a vertical line in fig. 9) at certain depths may be attributed due to the presence of weak masonry.

The results of nuclear logging revealed that the density of the masonry in general varied between 1.14 gm/cm^3 and 3.10 gm/cm^3 . The low density values (below the design density of 2.35 gm/cm^3) indicated the weakness in the masonry may be due to leaching of cement mortar. It was observed that the result of borehole in-situ density logging corroborated well with data of core sample logged as well as the neutron logs. Based on the result of these studies, extensive grouting has been recommended in the dam body. These logging techniques are thus an important aspect to be considered for assessing the safety of hydraulic structures and their rehabilitation, and also offer cost effective solutions to specific problems.

4. DETERMINATION OF IN-SITU DENSITY BY NUCLEAR BOREHOLE LOGGING AT MASSANJORE DAM, WEST BENGAL FOR M/S WAPCOS LTD., KOLKATA

Massanjore Dam is also called as Canada Dam, which has a hydropower plant generating capacity of 4 MW across the River Mayurakshi located at Massanjore, Dist. Dumka, Jharkhand. The dam is of 47.25 m in height and 661.58 m long masonry gravity dam. It has an overflow section of length 225.60 m comprising of 21 bays with a width of 9.144 m each. Distresses were observed in the dam body in the form of seepage and also leaching in the foundation gallery. This might have resulted in reduction of mass and strength parameters of the structures due to aging. As a part of structural audit studies, it was proposed to conduct geophysical nuclear gamma (γ) logging at selected locations in the body of the dam to estimate the in-situ mass density variation with depth and also to identify weak zones if any, in the body of the dam. The seepage and leaching marks in the foundation gallery is shown in fig.10.



Fig.10 Impression of seepage and leaching of mortar seen in the foundation gallery.

Nuclear gamma (γ) logging was carried out in the four Nx (76 mm diameter) size bore holes drilled at selected locations in the body of the dam at Ch. 319 m, Ch. 278.5 m and Ch. 576.5 m. In monolith No. 23, two boreholes, 11.48 ft apart have been drilled at same location i.e. at Ch. 576.5m (one is on u/s side and the other is on d/s side). Logging was carried out in all the boreholes throughout the depth varying between 14 m to 33 m. Nuclear gamma (γ) logging response was recorded continuously against the depth for all the boreholes in terms of count rate. Later the count rate responses were converted to corresponding bulk density values using calibration curves obtained in the laboratory. The density values were digitized at every 0.25 m interval and plotted against the depth of boreholes. A typical borehole log is shown in fig.11. The results indicated that the density of masonry ranged between 1.50 gm/cm^3 and 3.00 gm/cm^3 . The density values that were observed below the design density 2.35 gm/cm^3 of masonry were demarcated as weak zones, susceptible for seepage and maybe attributed due to the presence of weak masonry. The results of logging showed several weak zones which corroborated very well with the Rock Quality Designation (RQD) of the drilled boreholes.

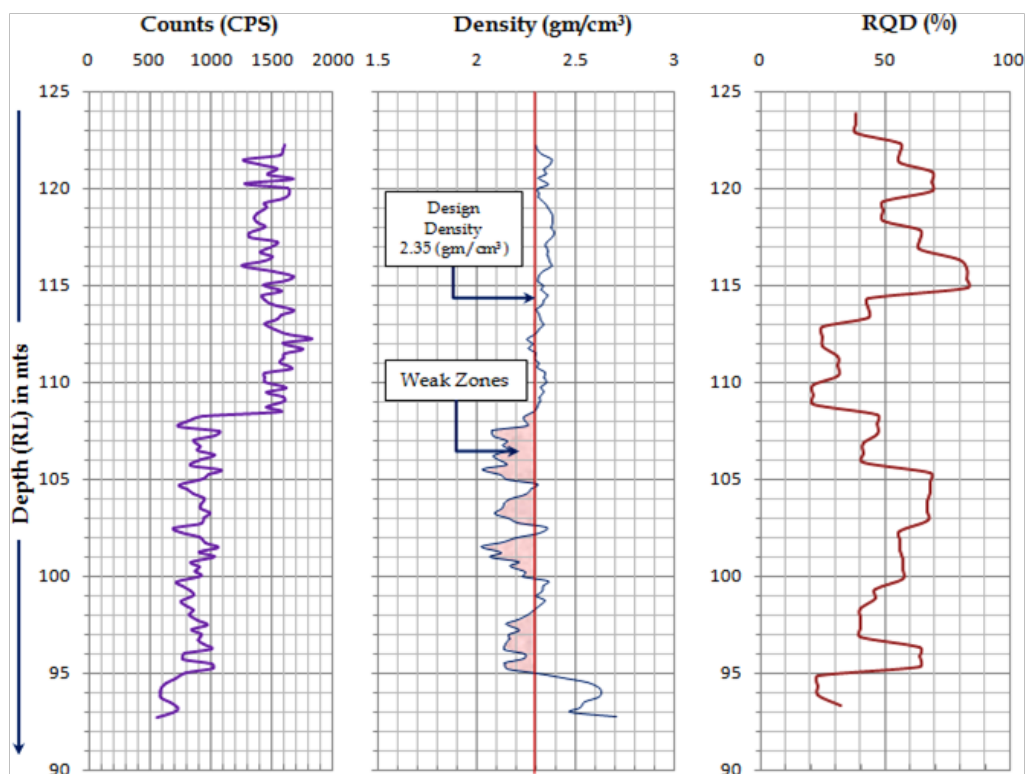


Fig.11 Typical plot depicting weak zones in corroboration with RQD.

5. DELINEATING PATH OF SEEPAGE TO THE DAMAGED PORTION OF TAIL CHANNEL AT BHAMA – ASKHED IRRIGATION PROJECT, MAHARASHTRA

Bhama-Askhed Irrigation Project envisages the construction of a dam on Bhama River, a right bank tributary of Bhima River near village Waki Tal. Khed, District Pune, Maharashtra with a side spillway, 14 km long left bank and 105 km long right bank canal. The earthen dam and spillway portion are partially completed. During the monsoon of 2005, it was observed that 13 RCC panels (7 m x 11 m x 0.30 m) were lifted up and displaced in the EDA portion and tail channel area (fig 12). The preliminary observations revealed that between RD 58 m and RD 91 m the RCC panels were lifted up and dislocated and the underlying rock exposed. Continuous oozing of water was observed in the chute channel at RD 83m (fig 13). The project authorities, therefore, approached CWPRS for conducting necessary studies to ascertain the cause of the dislocation of panels and suggest suitable remedial measures.



Fig.12 Spillway Along with Damaged Portion of Tail Channel



Fig. 13 Oozing of Water at Rd 83m

Accordingly, tracer studies and nuclear logging were carried out for identifying the path of seepage to the damaged portion of the tail channel to ascertain whether seepage / leakage observed could be directly responsible for dislocation of RCC panels. For this purpose three boreholes were drilled 6m below the foundation level so as to ascertain the interconnection, if any, between the foundation rock and the leakage / oozing of water observed in the downstream tail channel. These boreholes also utilized for the purpose of injection of tracer for delineating the seepage path.

Tracer studies were carried out to identify the leakage, if any, from (i) the interface between structures and foundation, (ii) the structure (iii) the foundation and (iv) Groundwater from Left Hand Side (LHS) of Energy Dissipation Assembly (EDA). For this purpose, Sodium fluorescein dye was injected at two locations in the reservoir, i) at the junction of Non - Over

Flowing (NOF) and Over Flowing (OF) section of spillway, and ii) the intersection of spillway and dyke.

Logging was conducted in three boreholes drilled to identify weak and porous zones, which are susceptible for leakage. Fig.14 shows result of density logging indicating a weak and permeable zone at depth of 34 m in the borehole. Accordingly permeable zones were identified in the boreholes Sodium fluorescein dye was injected in the boreholes at RD 0 at the foundation level (34 m) RL 639.4 and RD 80m downstream on the LHS at 16m (RL 650.4) depths. The samples were collected at the adjacent borehole (RD 40m downstream on RHS) and at RD 83m in tail channel where oozing of water was observed. Fig. 15 shows typical tracer arrival plot.

The studies revealed that oozing of water in the EDA is inter-connected with the permeable zone formed by weak red breccia in the foundation of the dam. The studies did not confirm the possibility of leakage through structure and also through the structure-foundation interface and thus the possibility of likely seepage occurring through these portions could be ruled out. The studies also revealed that there was no contribution of groundwater from left hand side of the spillway to the oozing of water at RD 83m in the tail channel as interconnections of ground water was not established. The suitable remedial measures include providing proper drainage holes in the EDA to release uplift pressure.

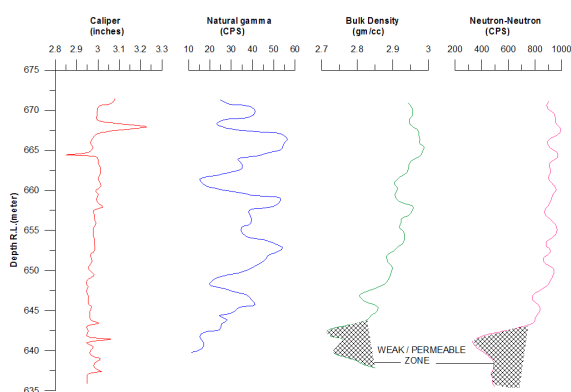


Fig. 14 Typical logging plot of BH-1 (10m D/s)

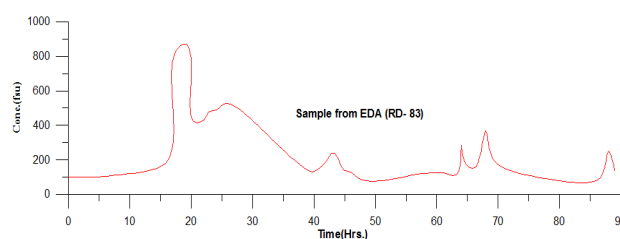


Fig. 15 Typical tracer plot at RD83

6. NUCLEAR LOGGING AND TRACER STUDIES AT INDIRASAGAR PROJECT, MADHYA PRADESH

Indirasagar Project on River Narmada, near Punasa village in Khandwa district Madhya Pradesh comprises of a 653-meter long and 90-meter-high solid concrete gravity

dam. In addition to irrigation, the project has a powerhouse with an installed capacity of 1000 MW consisting 8 units of 125 MW each. Fig.16 shows panoramic view of Indirasagar Dam. The project authorities reported the observations in respect of the dam instrumentation data stating that the piezometers installed in Block No. 25 at EL 208.85 m indicated high values of uplift pressure. On the basis of interpretation of data acquired from various dam instruments it was felt that there could be possibility of entry of seepage water and could pose problem to the structure. Hence, it was required to study the likely cause of seepage and to adapt remedial measures for reducing the seepage. In order to trace source and the path of the leakage, nuclear logging and tracer studies were undertaken at selected locations of dam and in the drainage gallery of Blocks 25, 26, 27, 28 and in the drift as well.



Fig. 16 Panoramic view of Indirasagar Dam

Nuclear logging comprising gamma-gamma density log, neutron log and caliper log were carried out in the boreholes drilled in the body of dam at Monolith Nos. 25, 26 and 27, abutment at Monolith No 28 and in the intake gallery at Monolith Nos. 32 and 33 for identifying weak, porous and permeable zones, if any, which may be susceptible for seepage. The nuclear logging indicated the presence of weak and permeable zones in the boreholes drilled in Block No. 25 and the borehole in the abutment at Block No. 28. Low density and more permeable zones were observed in the borehole at block No. 25 in the body of dam. Typical logging plot is shown in fig. 17.

Tracer studies were conducted by injecting the tracer in the reservoir at different depths corresponding to the weak and permeable zones in the boreholes, for confirming or ruling out the occurrence of seepage from these depth. The arrival of the tracer was

monitored by taking samples at one-hour interval round the clock; from seepage points observed in the drainage gallery, in the drilled holes and porous block holes. The result of tracer studies revealed that the borehole at Block No.25 was not directly interconnected with reservoir. The injection of tracer in borehole at Block No. 28 and its arrival in borehole at Block No. 25 confirmed that the path of seepage was from hillock to the borehole at Block No. 25. The tracer injected in the Head Race Channel near to abutment and its arrival at the seepage points in the adit/intake gallery, indicated that the path of seepage could be through the abutment / hillock. Typical tracer plot is shown in fig. 18.

It appears that when the reservoir level was maximum, the hillock / abutment could be getting recharged and there would be likelihood of seepage at Block No. 25 and in the drift. As the studies indicated that the likely path of seepage could be through the hillock suitable treatments such as silt grouting of abutment were suggested for reducing/stopping the seepage. Similarly, providing of proper drainage/ discharge of excess seepage in the drift was also recommended as remedial measures.

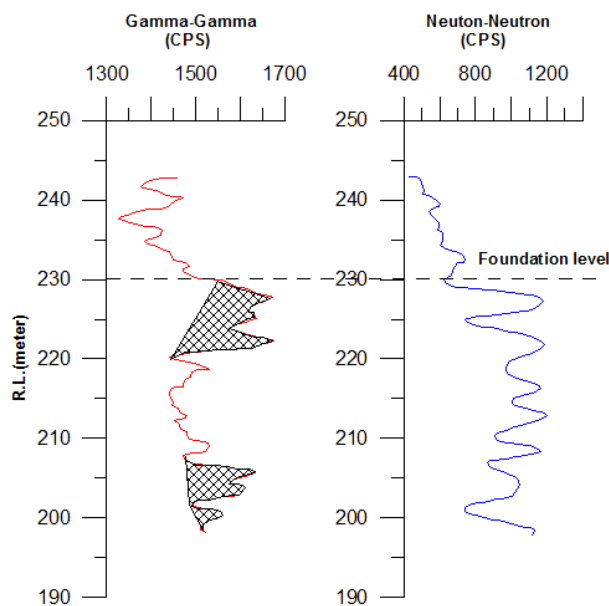


Fig. 17 Typical logging plot at BH-4 (Block -26)

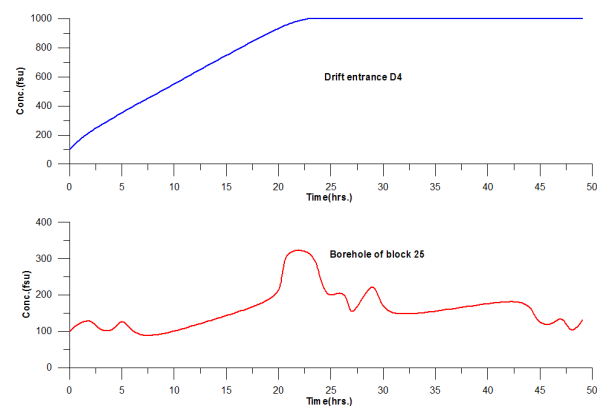


Fig. 18 Typical tracer plot in borehole of block 28



CHAPTER – VII

SUMMARY & CONCLUSION

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As water is very important part of living being, a huge amount of financial investment is made in planning, designing, construction, operation & maintenance of hydraulic structures for storage of water to meet the needs of water supply, irrigation and hydropower for socio economic development. Dams, however, are not unmixed blessings. They do pose a major hazard in the unlikely event of a failure. However, seepage through these structures is a cause of great concern since it is a potential threat to safety and stability of the structure. There are reported incidences of catastrophic dam failures in India and other parts of world due to excessive or uncontrolled seepage. In India, 75% of dam failures are due to seepage related problems.

Geological surprises, dam failures, occurrence of high magnitude earthquakes in geologically strong regions, advent of latest technology in the field of dam engineering and other regions enabled the dam engineers to make new safety guideline in the design of dams. Investigations conducted on dam failures, occurred in various countries have confirmed that a majority of these failures could have been avoided by proper design, construction and regulation of seepage. The main causes of seepage in hydraulic structures are aging of structure, presence of fracture, fault or shear zones in the pervious foundation, construction deficiencies, uneven settlement of structure, faulty design, etc. In a way, it can be said that occurrence of seepage is unavoidable owing to numerous reasons discussed in the preceding chapters. As such adoption of remedial measures to control and regulate seepage to acceptable limits is the only feasible alternative.

Investigations for seepage control or regulation start right from studies which involve understanding of site-specific geological characteristics. These comprise of geological, geophysical and hydrological investigations. It is mentioned that inadequate understanding of site-specific geological parameters related to foundation rock mass behavior has led to many dam failures in the past. Nonconventional techniques involving tracer techniques and borehole logging techniques play a key role in carrying out such investigations. Tracer techniques help in identifying the origin of the seepage its path and interconnection between two water bodies and also help to determine seepage velocity. Borehole logging investigations can provide in-situ assessment of the engineering properties of the subsurface, potential seepage pathways, lithological variations and solution activity. Geophysical methods, in general, address investigating and monitoring seepage and internal erosion in hydraulic structures such as mapping of geologic features and monitoring of

seepage. Remote sensing techniques can be used to identify potential seepage sites in conjunction with other spatial data.

Mathematical modelling by analytical and numerical methods provides a great tool for assessment of seepage through embankment dams and foundation. With the advent of high-speed computers and advanced softwares, these tools are being immensely popular. The effects of seepage through dam body and parameters such as seepage discharge, uplift, pore pressures, etc. are required to be continuously monitored by proper instrumentation. Periodical recording of instrument data, its analysis and interpretation is also equally significant.

Apart from the conventional method there are other non-conventional methods mentioned in this memorandum, like tracer techniques, borehole logging which are often used in conjunction with other techniques to have a better understanding of the subsurface properties. The details of individual methods and their potential in assessing seepage through dams and canals are briefly described. Nuclear well logging techniques are indispensable tools in subsurface characterization. By providing quantitative measurements of formation density, hydrogen index (porosity), and natural radioactivity, these logs enable geologists and Petro physicists to identify hydrocarbon reservoirs, quantify their potential, and make informed decisions regarding drilling, completion, and production strategies. Understanding the principles, applications, and limitations of each nuclear log, along with their synergistic use, is fundamental for effective formation evaluation.

Borehole geophysical logging and tracer techniques are two widely employed diagnostic studies to accurately identify the source and pathway of seepage, as well as to decipher the existence of potential weak zones within a dam's structure, which might contribute to seepage issues. Preliminary reconnaissance survey of the site, along with assessment of key site parameters as outlined in this manuscript, is mandatory. Judicious site selection plays a pivotal role in determining appropriate locations for drilling of Nx-size boreholes, which is necessary for conducting wireline geophysical well-logging investigations and also for tracer studies. Therefore, conducting a comprehensive site inspection is imperative to recommend optimal borehole drilling locations for effective wireline logging and tracer analysis in dams.

Once the occurrence of seepage, its source and amount are detected, decision is to be made to adopt suitable remedial measures for its control. There are two approaches for seepage control, first being to reduce the quantity of seepage and second to provide safe outlet to seepage water by proper drainage. The quantity of seepage can be reduced by interception of pervious zones by providing barriers in various forms, such as grout curtains, cutoff trenches, and diaphragms. It can also be achieved by lengthening the path of seepage

by providing impervious blankets. Remedial measures generally adopted for concrete and masonry dams are foundation grouting, body grouting, pointing, cable anchoring, concrete / mortar jacketing, geomembrane lining, steel jacketing, guniting, etc. In embankment dams seepage control is carried out using filters and drains to facilitate safe and quick seepage of water, however, optimum design of these structures should be ensured. The conventional lining methods have undergone transformation during the years with emerging new technologies and innovative materials. Off late, application of geosynthetics for seepage control is gaining wide popularity due to their inherent advantages.

To reduce the risk of failures, regular health inspections are necessary to identify the defects by applying advanced and integrated methods for assessment of seepage. The cost of investigations may not be more than 10% total cost of repair of the structure. Control measures should be adopted to mitigate seepage so as to avoid future consequences. As such timely adoption of seepage monitoring, detection and analysis measures using conventional and non-conventional techniques and appropriate repair methodologies for rehabilitation of structures should be undertaken. This will surely lead to safe functioning of the hydraulic structure throughout its design life.



The implementation of the “Dam Safety Act 2021”, has emphasized the importance of maintenance and rehabilitation of as an essential component of dam safety. The Act provides for the surveillance, inspection, operation, and maintenance of all specified dams across the country. The need to control water loss due to seepage underscores the importance of accurately diagnosing the root cause of the problem before initiating costly repair works. With an ever-increasing emphasis on dam safety, the need for continuous training, thorough examinations and proper evaluation cannot be overlooked. Investigation serves as a crucial phase, generating essential data for the safe, efficient and practical planning and design of hydraulic structures. Periodic visual inspections, adequate monitoring and rapid analysis of data recorded from dam instrumentation provide field engineers with valuable insights into the structural behavior of dams. Dam inspections are normally entrusted to highly qualified and experienced professionals who possess the expertise to identify potential issues. Before initiating rehabilitation measures for a distressed dam, it is essential to first understand the underlying causes of distress. Physical inspections, supported by “*detailed investigations*”, are necessary to identify probable sources of distress such as cracks, fissures, voids, or cavities within the dam body, foundation, or abutments. The following guidelines are to be followed as decision-making processes related to “*site selection*” for conducting borehole logging and tracer studies in dams.

Seepage Control and Analysis

Early investigation into the occurrence of seepage in any dam is critical for ensuring its long-term stability and safety. Periodic monitoring helps maintain accurate records of seepage points, flow quantity and content, zones of wetness, and any periodic variations. In the recent years with the advent of technological development, instrumentation has been playing a significant role in monitoring seepage. V-notch weirs offer a simple, cost-effective method for measuring flow rates, while piezometers may be used to determine the saturation level (phreatic surface) within the embankment. It is also recommended to perform periodic dye tracing tests to identify seepage pathways and conduct geophysical surveys, to detect anomalies within the dam structure. Proper training for field personnel in data interpretation and quick response protocols is crucial to address seepage issues swiftly and effectively.

Borehole logging and tracer studies are widely adopted to decipher the weak zones, seepage locations, interconnectivity and dimension of fracture/cracks/cavities, determination

of density, porosity, shear strength etc. Application of tracer and borehole logging techniques are currently used in dam operation and safety audit studies during the site assessment phase and operational phase. The major objectives of using tracer technique is to determine (1) seepage studies in dams and canals, (2) location of seepage entry zones, delineating seepage path, assessing the efficiency of remedial measures, examination of soundness of bedrock etc. (3) hydraulic parameters of subsurface flow or seepage through hydraulic structures (4) seepage losses through irrigation canals. Primarily before taking up the investigation a through site inspection (reconnaissance survey) is to be mandatorily conducted in order to access the actual severity of the site condition. Based on the site inspection, the selection criteria for *borehole logging* and *tracer studies* must consider the following site parameters as guidelines:

1. Geological and hydrogeological considerations:

- a) A thorough site investigation is necessary to evaluate the geology, soil characteristics, and other factors that can affect the safety and stability of a dam.
- b) Areas with known or suspected faults, fractures, or other structural discontinuities should be prioritized as they can be major seepage pathways through the foundation.
- c) Groundwater conditions near the dam site can affect the stability of the dam and the safety of the impounded water. Hence, suitable site investigation should be carried out to assess the groundwater conditions, including the depth to groundwater, hydraulic conductivity etc.

2. Hydraulic Consideration / Discharge measurements:

- a) Seepage measuring devices are mandatorily to be installed in order to measure the quantity of seepage through, around or under dams.
- b) Gallery drain outlets are commonly used as seepage measurements points using measurement devices i.e. V-notch weirs, Parshall flume, calibrated containers etc.

3. Dam Design and Construction (Cross Section and L Section):

- a) The study of Longitudinal section (L-Section) and cross section of the dam is important as they impart crucial information pertaining to dam i.e. location of gallery, rock line & ground line, depth to foundation, number and location of monolith w.r.t. chainage etc. it also imparts information regarding the dimension of gallery, Overflow and Non-Overflow section, key wall junction etc.

- b) These information's are extremely important while deciding the location for drilling of Nx size boreholes on the dam top and also to ascertain the feasibility of drilling of borehole inside the gallery.
- c) The material properties of the masonry and any construction materials used should also be considered, particularly in areas where different materials interface.
- d) Considerations must be given to identify seepage through the joints and cracks in the monoliths which is critical for finalizing the borehole drilling location for investigation.

4. Inspection of Gallery:

- a) Mostly dam galleries have slope along their entire length with small channels on both edges running along the galleries gathering seepage water that leaks through the dam body.
- b) The seepage through the dam body inside the gallery portion is noted with respect to Chainage and Monolith no. in order to facilitate in identifying the exact location for drilling of Nx size boreholes on the dam top and also inside the gallery.

5. Monitoring and Instrumentation:

- a) Instrumentation data often detect vital anomalies that serve as strong indicators for increased flow rates probably due to seepage issues. Cross-referencing data from multiple instruments is necessary as it provides a comprehensive understanding of seepage behavior.
- b) Regular monitoring and data collection will help in establishing baseline conditions which is crucial in defining normal operational parameters and identifying deviations.
- c) Long-term data analysis will help in identifying potential seepage issues. Sudden changes or persistent deviations from baseline conditions are suitable indicators for selection of borehole locations for further investigations.

Borehole geophysical logging and tracer techniques are two widely employed diagnostic studies to accurately identify the source and pathway of seepage, as well as to decipher the existence of potential weak zones within a dam's structure, which might contribute to seepage issues. Preliminary reconnaissance survey of the site, along with assessment of key site parameters as outlined in this manuscript, is mandatory. Judicious site selection plays a pivotal role in determining appropriate locations for drilling of Nx-size boreholes, which is necessary for conducting wireline geophysical well-logging investigations and also

for tracer studies. The case studies discussed in this manuscript demonstrate that site investigation, followed by strategic site selection for borehole drilling, has been instrumental in identifying critical in-situ physical parameters. These include filtration and porous velocity, as well as the bulk density of the formation. One such parameter, i.e. the in-situ mass density value is extremely useful for the designing of **grout mix composition** and also the density variations at different borehole locations, serve as an important input parameter for **structural safety review**. Therefore, conducting a comprehensive site inspection is imperative to recommend optimal borehole drilling locations for effective wireline logging and tracer analysis in dams.



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