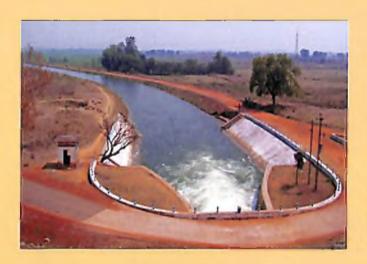


#### Government of India

भारत सरकार

Ministry of Water Resources, River Development and Ganga Rejuvenation जल संसाधन, नदी विकास और गंगा संरक्षण मंत्रालय





Technical Memorandum

# SEEPAGE MAPPING METHODS IN DAMS AND CANALS

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केंद्रिय जल और विद्युत अनुसंधान शाला, पुणे निदेशक: स. गोविंदन Edited by

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भारत सरकार जल संसाधन , नदी विकास और गंगा संरक्षण मंत्रालय



GOVERNMENT OF INDIA
MINISTRY OF WATER RESOURCES
RIVER DEVELOPMENT & GANGA
REJUVENATION

केन्द्रीय जल और विद्युत अनुसंधान शाला, पुणे CENTRAL WATER AND POWER RESEARCH STATION, PUNE

Technical Memorandum on

# SEEPAGE MAPPING METHODS IN DAMS AND CANALS

May 2015



निदेशक : स. गोविंदन

Director: S. Govindan

#### **PREFACE**

Excessive seepage in Dams and Canals may intimidate their safety and stability, in addition to massive loss in water resources. In spite of adopting appropriate care in planning, designing and execution, there are incidences of distress in dams and canals due to seepage related problems. As such, it becomes essential to identify and analyse the complex problem of seepage using possible and suitable techniques to achieve the most appropriate controlling measures. Regular monitoring of seepage facilitate in deciding suitable and economical remedial measures for dams and canals taking into account extent and quantity of seepage and feasibility and economy of the control measures.

Central Water & Power Research Station, Pune, is a premier hydraulic research institute offering wide range of R&D services. In the past few decades, C.W.P.R.S has developed expertise in providing cost effective and viable solutions for seepage control in hydraulic structures i.e. dams and canals by conducting field and laboratory investigations. This document provides comprehensive information on various aspects of seepage, its investigation and control through Hydraulic Structures with specific reference to dams, and canals. Several problems of seepage undertaken and successfully completed by C.W.P.R.S are also provided for the purpose of illustration.

This document is organized into six chapters, with Chapter I giving a general introduction about causes of seepage, investigations for monitoring and detection of seepage and various remedial measures for seepage in dams and canals. Chapter II illustrates the various causes of seepage through dams (i.e. Earthen, masonry and concrete) and canals.

Different conventional and non conventional methods which are widely adopted in investigation of seepage through dams and canals, like the hydrogeological methods, geophysical methods, borehole logging and tracer techniques are discussed in chapters III and IV with illustrations.

Studies related to seepage detection through dams and canals are highlighted with illustrations as C.W.P.R.S experiences in Chapter V. Chapter VI summarizes the important aspects like detecting the seepage using different methods and then employing suitable

remedial measures to mitigate the seepage, highlighting importance of seepage investigation and remedial measures in dams and canals.

The document is expected to be of great help to practicing engineers, researchers, scientists, consultants and other authorities of Water Resources project planning and execution, to identify and mitigate seepage related problems in dams and canals.

**Editor** 

R.K.Kamble Scientist 'E', C.W.P.R.S

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The authors would like to express their special gratitude and thanks to various project authorities for rendering their support during the laboratory and field studies.



#### CHAPTER - I

#### INTRODUCTION

R.K.Kamble (Scientist E)

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.

An ideal site for construction of the hydraulic structure should be geologically and structurally undisturbed area with unfissured, unweathered rock totally exempt 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-Omosh, et. al, 2008).

The causes of seepage for different types of structures are discussed below: All "Earthen Dams" are subject to seepage through the embankment, foundation, and abutments. In earth dams the principal failure modes are 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.

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.

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).

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.

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:

- 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
- 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 futures 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 dams and canals along with various causes of seepage, consequences of occurrence of seepage, different methods for analysis and measures adopted for controlling seepage in different types of dams and canals. The related case studies are discussed in the Technical Memorandum.



#### SEEPAGE THROUGH DAMS AND CANALS

R.K.Kamble (Scientist E)

#### **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. Fig.2.1 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.

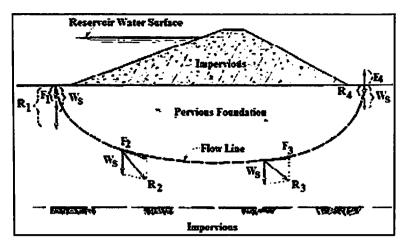


Fig 2.1: Seepage Forces

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.

#### **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 these 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 dams 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.

#### **IRRIGATION CANALS**

An irrigation canal is a waterway, often man-made or enhanced, built for the purpose of carrying water from a source such as a lake, river, or stream, to soil used for farming or landscaping. One of the difficulties with irrigation canals is providing a reliable flow of water. When the canal is directly connected to a water source like a lake or a river, the water supply is fairly reliable, but care must be exercised to avoid using so much water that other areas suffer. Seepage is the most dominant processes by which water is lost

in the canal. Thus, for the effective operational planning and management of an irrigation system, a dependable forecasting of the seepage is very important. Seepage rates are obtainable either by direct measurement or by estimation. The exact analysis of seepage loss from the canals is quite complex.



#### **CHAPTER-III**

#### **CONVENTIONAL METHODS**

Sudipta Bhowmick (Scientist B) Dr. Rolland Andrade (Scientist B)

Seepage is a common problem of dams and other hydraulic structures and is a function of hydraulic head (Jami et al, 2000) i.e. as the reservoir approaches maximum capacity at flood stage, rate of seepage is also expected to be maximum. Seepage being an important factor in hydraulic structures, engineering geologist has to be apprehensive of the geology of the dam site including the foundation to ensure the water tightness of the foundation as well as the geology of the area to be occupied by the reservoir once the dam is completed. Anomalous seepage often occurs along preferential paths created within the dam. These include fracture zones, solution channels and cavities, poorly mixed fill in the embankment, and paths created along buried drainage pipes or electrical lines. Typical dam safety surveillance consists of visual inspections supported by limited instrumentation. Seepage control is necessary to prevent excessive uplift pressures, sloughing of the downstream slope, piping through the embankment and foundation, and erosion of material by loss into open joints in the foundation and abutments. Most of the seepage control remedial measures are to be planned and executed with a complete understanding of the problem.

Investigations related to dam seepage include study of the proposed site geology using various geophysical and geotechnical methods, water balance studies, assessment of seepage potential of the foundation and analysis of dam instrumentation data. Integration of different methods enables a better understanding of the problem and offer cost effective solutions. Other non-conventional methods like tracer techniques, borehole logging, geophysical methods, hydro geological methods and remote sensing techniques are often used in conjunction with other techniques to have a better understanding of the sub-surface properties. The chapter describes the details of the methods and their potential in assessing seepage through hydraulic structures.

#### **Geological Studies**

Primary objective of geological and geotechnical site investigations for a dam is to gather information about different parameters which are required to be incorporated during design and construction process in order to design a safe and economic structure. Some dam sites may be relatively uniform in their geology having one rock mass type with less discontinuities and a regular pattern of weathering. However, more often, the geology can be complex with several rock types having different physical

properties such as strength, durability and susceptibility to weathering etc. For design of hydraulic structures related to water storage and transmission, following parameters need to be ascertained with a view to understand site specific seepage characteristics.

- Characteristics of foundation rock and rock mass of recharge area.
- Engineering properties of the foundation rock types such as density, porosity, strength, deformability, water absorption and durability.
- Geological structure of the foundation such as jointing, faulting and folding. A
  full description of the defect pattern in the rock mass such as orientation,
  spacing, extent or persistence and aperture need to be included.
- Permeability of the rock mass of the foundation.
- · Groundwater table and their fluctuations.
- · Aquifer characteristics of the site.
- Information regarding precipitation and surface discharge.
- Delineation of seepage path through foundation.

Although most of the dam site investigations will employ different methods, the exact bouquet of methods and their execution sequence needs to be customized to suit the particular geological problems of each individual dam site.

#### WATER BALANCE STUDY

Water balance study is essential for making decisions regarding water conservations and water management. It accounts for all water volumes that enter and leave a 3-dimensional space over a specified period of time considering the changes in the internal water storage. Both the spatial and temporal boundaries of a water balance must be clearly defined in order to compute water balance. A complete water balance is not limited to only irrigation water or rainwater or groundwater, but includes all water that enters and leaves the spatial boundary. The water balance of a dam or water storage over a specified time interval may be expressed as:

$$Q_{in} + P + \Delta D = Q_{out} + S + E$$

where  $Q_{in}$  is the inflow, P is precipitation,  $\Delta D$  is the change in level measured,  $Q_{out}$  is the outflow, S is seepage and E is the evaporation rate (all in mm/day).

#### **GEOPHYSICAL METHODS**

Geophysical methods in general address three objectives namely mapping of geologic features, monitoring of seepage, and in-situ determination of engineering properties. Typical geological features may include faults, bedrock profile, discontinuities,

voids and groundwater. Monitoring includes long time observations of intensity of seepage and engineering properties that can be determined in-situ include deformation modulus, electrical resistivity including magnetic and density properties to a lesser extent. Monitoring as well as in situ testing to determine various parameters applying geophysical methods need to be conducted keeping in view of the seasonal variations.

#### **Electrical methods**

Generally two types of electrical methods a) self-potential and b) electrical resistivity methods are employed for seepage investigation and monitoring.

#### a. Self Potential Method

The self-potential (SP) method is a passive technique used to measure small naturally occurring electrical potentials generated by fluid flow, mineralization, and geothermal gradients within the earth. This is the only one of the geophysical techniques that responds directly to fluid flow (Brosten et al 2005). Water flowing through the pore space of soil generates electrical current flow. This electro kinetic phenomenon is called streaming potential and gives rise to SP signals that are of primary interest in dam seepage studies.

Fig. 3.1 illustrates the concept of an SP survey set up along the crest of a dam and the recorded anomaly caused by seepage flow. For seepage investigations, a single survey line can detect and locate an anomaly caused by a seepage path. For best data quality, fixed-reference SP surveys need to be deployed, where measurements are taken between the fixed-base electrode and the measuring electrodes placed perpendicular to suspected seepage flow lines (Corwin 1989). Comprehensive SP investigations include survey data sets gathered at different reservoir levels. Cross-comparing of these data sets isolates the SP response to changes in the pattern of seepage (i.e., varying reservoir levels cause different groundwater seepage flow paths and volumes) to reveal the flow path. The SP method is a cost-effective passive technique that has found an increasing role in geotechnical investigations and has successfully located seepage paths within embankment dams, levees, and reservoir systems. The increasing role of SP has initiated research on SP algorithms to quantify flow volume and to develop the SP technique as a comprehensive investigative tool in seepage assessment projects (Sheffer and Howie 2003).

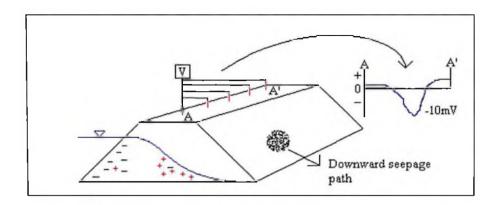


Fig. 3.1 Illustration of an electrode array set up along the crest of a dam and the SP anomaly generated from downward seepage

#### b. Resistivity Method

The resistivity method is used to measure the electrical resistivity of the geological section in both the lateral and vertical sense. In general, most soil and rock types are considered electrically resistive and the flow of current is influenced by moisture filled pore (or fracture) spaces within the subsurface. Zones of low resistivity values are predominantly controlled by the porosity and permeability of the system, the degree of saturation of the subsurface, and the concentration of dissolved solids within the saturated subsurface. Both "profiling" and "sounding" resistivity techniques are applied.

**Profiling** provides a means of delineating lateral resistivity contrast within the subsurface electrical properties. Resistivity sounding yields characterization of vertical resistivity contrasts and provides an estimate of the "depth layering" within the subsurface. The purpose of the resistivity survey is to delineate zones of suspected increased permeability and groundwater flow paths as potential sites for borehole drilling and subsequent monitoring well installation. The correlation of known seepage areas with resistivity anomalies is extrapolated to defining areas of suspected increased subsurface flow. The direct current resistivity method has well-established data acquisition and interpretation techniques for standard survey configurations. Resistivity surveys are conducted by laying out electrodes along a survey line. Current is introduced into the ground through a pair of current electrodes (C1 and C2), and two potential electrodes (P1 and P2) measure the voltage difference (Fig.3.2A). As the spacing of the current and potential electrodes increase, the depth of investigation also increases. By measuring voltage differences as the electrode spacing increases, a 2-D profile of the

subsurface is created. Geological interpretations of the subsurface are then made based on the resistivity observations. Ground resistivity is related to geologic variations such as the mineralogy, fluid content, porosity, and degree of water saturation in the rock. Electrical resistivity profiling provides a 2-dimensional (2-D) model interpretation of the subsurface resistivity distribution in the vertical and horizontal direction along a survey line. From the 2-D model, a subsurface distribution of the geologic variations can be inferred.

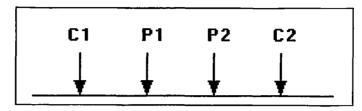


Fig. 3.2 A conventional four electrode array to measure the subsurface resistivity

Soundings provide a 1-dimensional (1-D) model of true layer resistivity and thickness beneath the center of the electrode array. In this method, the centre point of the electrode array remains fixed, but the spacing between the electrodes is increased to obtain more information about the deeper sections of the subsurface. To interpret the data from such a survey, it is normally assumed that the subsurface consists of horizontal layers. In this case, the subsurface resistivity changes only with depth, but does not change in the horizontal direction. Despite this limitation, this method has given useful results for geological situations (such the water-table) where the one dimensional model is approximately true. Numerous array configurations can be chosen, with advantages and disadvantages for both profiling and sounding. Some of the commonly used arrays in resistivity surveys and their geometric factors are shown in Fig.3.2 B. The best array for the survey is dependent on the type of geologic materials being investigated, desired depth of investigation, signal strength, array sensitivity to vertical and horizontal resistivity changes in the subsurface and the probable background noise.

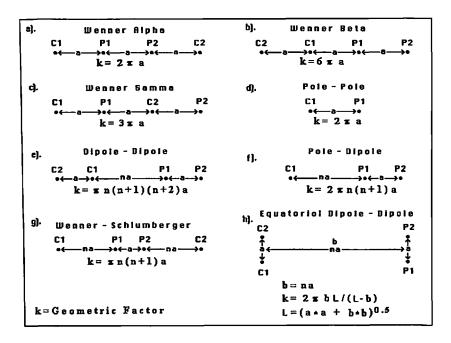


Fig.3.2 B Common arrays used in resistivity surveys and their geometric factors

The greatest limitation of the resistivity sounding method is that it does not take into account horizontal changes in the subsurface resistivity. A more accurate model of the subsurface is a two-dimensional (2-D) model where the resistivity changes in the vertical direction, as well as in the horizontal direction along the survey line. In this case, it is assumed that resistivity does not change in the direction that is perpendicular to the survey line. In many situations, particularly for surveys over elongated geological bodies, this is a reasonable assumption. 2D resistivity surveys are usually carried out using a large number of electrodes, 25 or more, connected to a multi-core cable. Typical setup for a 2-D survey with a number of electrodes with constant spacing along a straight line attached to a multi-core cable and a laptop microcomputer together with an electronic switching unit being used to automatically select the relevant four electrodes for each measurement is shown vide Fig.3.3.

The sequence of measurements to take, the type of array to use and other survey parameters (such the current to use) is normally entered into a text file which can be read by a computer program in a laptop computer.

Application of resistivity method to dam seepage investigations is two-fold. The method may be used to monitor spatial and/or temporal variations in electrical resistivity in response to changing soil conditions caused by internal erosion and anomalous seepage. For seepage investigations, resistivity targets generally include fracture zones and solution features created through preferred seepage paths. Resistivity profiling is a primary method used in seepage investigations and was successfully delineated seepage paths in past studies (Butler and Llopis 1990, Karastathis et al. 2002, Panthulu et al.

2001, Sirles 1997). Since, embankment and reservoir conditions are dynamic, fluctuations in lake levels, seasonal temperatures, and total dissolved solids etc affect the electrical properties of the embankment, particularly its electrical resistivity. Hence, a long-term monitoring may help an increased sensitivity to temporal changes and enable more effective identification of local changes that may be linked to the development of internal erosion.

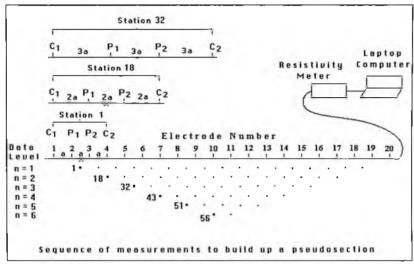


Fig. 3.3 The arrangement of electrodes for a 2-D electrical survey and the sequence of measurements used to build up a pseudo-section

#### OTHER GEOPHYSICAL METHODS

In recent times, applications of techniques such as Ground Penetrating Radar (GPR) and Seismic Refraction Method have resulted in fast and accurate analysis of geological parameters. A brief discussion is given in the following paragraphs.

#### Ground-Penetrating Radar (GPR)

GPR, in principle, identify seepage either by detecting underground voids created by the seeping water as it erodes the material or by detecting anomalous change in the properties of the material due to saturation. Advantages include good spatial resolution and high acquisition speed. However, GPR's primary disadvantage is its extreme sensitivity to site conditions. Areas with high clay or water content within the shallow subsurface can attenuate the GPR signal, making it virtually useless. The penetration depth depends on soil properties but also on the emitted frequency. Different antennas

are therefore used for various applications. A long frequency gives a high penetration depth but a low resolution due to the low wavelength. Internal erosion affects the porosity of material in the core and increases the water content. Radar measurements can detect these changes since they influence the radio wave velocity.

If the contrasts in electrical properties (e.g. changes in permittivity) are relatively simple, then the GPR time-distance record can be viewed as a two dimensional pseudo-image of the earth, with the horizontal axis as the distance along the surface, and the vertical axis being the two-way travel time of the radar wave. The two-way travel time on the vertical axis can be converted to depth, if the permittivity (which can be converted to velocity) is known. The GPR time-distance record is the simplest display of GPR data that can be interpreted in terms of subsurface features.

#### **Seismic Refraction Method**

Refraction seismic method is utilized to delineate the contact between the unconsolidated material and underlying bedrock. In seismic refraction method, compression wave (P-wave) is generated using a near-surface impulsive energy which propagates through the subsurface media and is refracted along stratigraphic boundaries. The impulsive energy source is selected based upon the length of the seismic line, the resolution desired and the environmental suitability of the seismic source. Fig.3.4 shows the simple two-layer case of the site profile and the propagation of P-waves generated from the impact source that travel along the seismic line. The Fig shows how the rays go downward to the boundary and are refracted along the boundary and return to the surface to impact the detectors (geophone) deployed along the ground surface. If the time of first arrival is plotted on a time-distance curve such as Fig.3.5, the rate of change of arrival times between detectors is seen to be proportional to the velocity of the material. This method can be effectively used to delineate the weak zones in the bedrock and in the foundation of the dam which may be the prospective zones for the seepage.

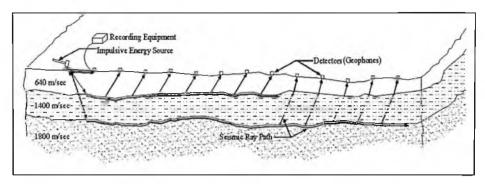


Fig. 3.4 Schematic of Seismic Refraction Survey

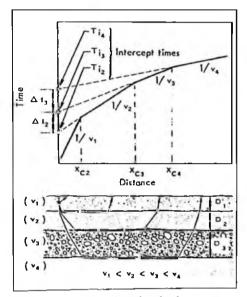


Fig. 3.5 Schematic of multiple-layer case and corresponding time-distance curve



#### **CHAPTER - IV**

#### **NON CONVENTIONAL METHODS**

Dr. Rolland Andrade (Scientist B) Govind A Panwalkar (Scientist B)

In the recent past these non-destructive and non-conventional methods are finding increasing application in seepage detection of hydraulic structures. These techniques are discussed in detail in subsequent chapters.

#### Nuclear Logging

Borehole logging investigations represent an economic, noninvasive alternative and can provide insitu assessment of the engineering properties of the subsurface, potential seepage pathways, lithological variations, and solution activity (e.g. Black and Corwin, 1985, Al-Saigh et al., 1994). Application of these methods has demonstrated cost savings through reduced design uncertainty and lower investigation costs.

A borehole log is a continuous record of measurement made in bore hole that responds to variation in some physical properties of rocks through which the bore hole is drilled. The subsurface geologic conditions and engineering characteristics can be determined directly or indirectly from the properties measured by these techniques. Further, borehole logs can be run in cased/uncased and fluid filled boreholes and can be repeated a 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 chapters, the different logging techniques like nuclear logging, acoustic logging and caliper logging techniques that are most important for detection of seepage in hydraulic structure are discussed.

#### Tracer Techniques

Tracer techniques are widely used in different fields as advanced techniques to solve different kinds of problems. The major use of these techniques is in the field of medical science, bio science (viz. agricultural fields), oil sector, industry, hydrology and hydro geology, civil engineering etc. In the civil engineering field, tracer techniques are mainly used to solve seepage related problems through hydraulic structures viz. dams, reservoirs and canals.

A tracer is 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. The system or medium within which tracer is applied should be a dynamic one.

In seepage studies, "Tracers" are innocuous (nonhazardous and nontoxic) chemical compounds, salts and dyes that behave exactly similar to the materials to be traced but differ from them by a particular property that may be physical, chemical including radioactive (Moser. H, 1995). An ideal tracer is nontoxic, inexpensive, unique passive-type, easily soluble in cold water, moves with the fluid in contact, easily detectable in trace elements at low concentrations, does not alter the natural flow direction, is chemically stable and sensitive for the desired length of time and for most purposes is neither filtered nor sorbed by the solid medium through which the fluid moves (Flury and Wai, 2003).

The major applications of tracer techniques in seepage studies are:

- Determination of hydraulic connection, direction, velocity and the pattern of subsurface flow
- Determination of aquifer characteristics like filtration velocity, porous velocity, porosity, permeability, transmissivity etc.
- Stratification of aquifers
- Interconnection between solution cavities in karst areas
- Seepage through hydraulic structures
- Assessment of seepage losses through irrigation canals
- Selection of sites for waste disposal
- Estimation of infiltration for recharge studies.

#### **TRACER STUDIES**

Tracers have become a primary tool for process investigation, qualitative and quantitative system analysis and integrated resource management in the hydrology. A Tracer is 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 applied purposely 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). 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, temperature or isotopes (Ancid, 2000). The need for tracers is mainly a consequence of the large variability with time and space of relevant parameters of water systems. This variability frequently makes it difficult to obtain reliable values of the parameters which are responsible for the behaviour of water in the system under investigation, especially when precise information is absolutely necessary. In these cases, the use of tracers may provide the only available solution (Plata-Bedmar. A, 1988). The change of permeability of the dam body media is interpreted as a result of interaction with seeping water after reservoir impoundment (Hien. P. D et. al, 1996). The tracer method can be adapted in the best way to the hydrological problem and situation, but there are limitations regarding the size of the investigation area and the time period of the experiment (Moser. H, 1995).

By definition, tracers are chemical compounds, salts and dyes that behave exactly similar to the materials to be traced but differ from them by a particular property that may be physical, chemical including radioactive. 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 (Markus Flury, et. al, 2003, Aeby, P, et. al, 2001) and must be detectable at low concentrations to ensure high recovery rates, as well. Tracer must be sufficiently economical but not alter the environment or subject to leaching, abrasion or other alteration; or hazardous to public health or the environment. The tracer has low background concentration and is clearly discernible from the background of the system. The tracer is detectable either by chemical analysis or by visualization. The tracer generates a low toxicological impact on the study environment.

Ideal tracer has properties such as no loss, no delay and having the same compound as traced fluid. An ideal tracer is 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 (H. Moser, 1995, Hotzl, H. et. al., 1992, Peters, N. E, et. al, 1993).

#### **OBJECTIVES**

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 behaviour, assessment of the influence of man-made structure on sediment movement, wastewater treatment process studies etc.
- Estimation of infiltration for recharge studies.

#### **TYPES OF TRACERS**

Depending on application, tracer can be used to characterize properties of large subsurface volumes or investigate small-scale transport phenomena (Craig E, et. al, 2005). 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

#### **CONVENTIONAL TRACERS**

Conventional tracers include strong electrolytes like Sodium Chloride (NaCl), Ammonium Chloride (NH $_4$ Cl) and organic dyes like Sodium Fluoroscene, Rhodamine-B, Rhodamine-WT, etc (Olaf Huseby, et. al, 2009) which moves with the same velocity as the ground water, and its concentration is affected only by hydrodynamic dispersion. Major ions such as chloride and bromide have been used as they behave conservatively and rarely sorb onto geological material.

Dye tracers (viz. Sodium fluorescein) are successfully used in karst and other high-permeability terrains where other types of tracers have limited use (Mull, D.S, et. al, 1988). Dyes or organic dyes have proven to be powerful tracers (Davis et al., 1980) due to their low toxicity, detectability at low concentrations and over long distances, relatively low sorption tendencies, good solubility in cold water and low cost, as well (Aeby, P. et.al, 2001). Since dye tracer is water soluble, the tracer response curve reflects the flow model in the porous media and dilution processes in the in-situ water.

The dye provides information on the nature of the groundwater flow that is not produced by more conventional tracing methods. Sodium Fluoroscene is orange in color, low toxicity, sensitive to Ultra-violet light and characteristic bright yellowish green colour in dilute concentrations (Divine C. E, 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 Fluoroscene.

#### **METHODS OF APPLICATION**

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 best injection point is at the well head or on the injection flow line very close to the wellhead.

The tracer techniques can be employed by utilizing two methods.

- i. Single Well or Point Dilution Technique
- ii. Multiwell Techniques

#### Single Well Technique (Point Dilution Technique)

The aim of point-dilution method is to inject a tracer into a well, monitor one or more down-gradient wells by collecting and analyzing ground water samples, 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 faster the ground water flow, the faster the tracer is swept from the well bore.

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.4.1. A change in the concentration of the tracer is caused either by flow or by diffusion (Rao. S. M, 1984). The flow in the borehole consists of horizontal flow, vertical flow, density currents and flow due to artificial mixing.

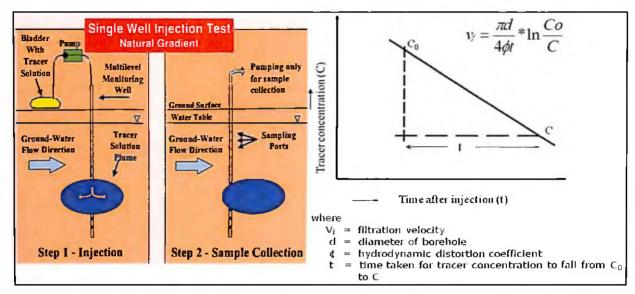


Fig. 4.1 Conceptual model showing the tracer migration in single well injection test

In a single borehole, many hydraulic coefficients, such as flow velocity, direction of flow, vertical flow etc., can be obtained by using isotope tracer method. There are three conditions if a fissure intersects a borehole: vertical, parallel and tilt. According to each different condition, the formulation of flow velocity deduced by isotope dilution method is different (Moser, H., et. al, 1989).

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:

$$Va = -\frac{V}{Ft} \ln \frac{C}{C_0} \tag{1}$$

Where:

V<sub>a</sub> ≃ 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  $\emptyset$ , which accounts for the distribution of the flow lines due to the presence of the borehole, is given by.

$$\emptyset = Q_h / Q_f \tag{2}$$

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

 $Q_{\text{f}} = \text{the flow rate}$  in the same cross section of formation in the absence

of

borehole.

If only horizontal flow exists then, V<sub>f</sub> is given by

$$V_f = -\frac{V}{Q_f t} \ln \frac{C}{C_0} \tag{3}$$

If packer system is used with a detector probe, then

$$V_f = -\frac{d^2 - d_s^2}{4Ot} \ln \frac{C}{C_0}$$
 (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 insitu measurements made at desired depths. Alternatively, samples are collected and then dilution of tracer is measured (Lamontagne S, et. al, 2002). A typical curve showing the change in tracer concentration with time for point dilution technique is depicted in figure.4.2.

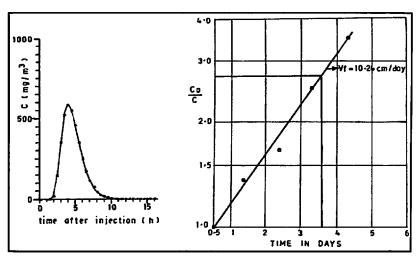


Fig. 4.2. Tracer Arrival curve for single well; concentration (vs) time

#### **Multi-well Technique**

Tracers used for Multi-well Technique may be chemical or radioactive. However, radioactive tracers are suitable for small volume injection. This multi-well approach can yield a direct estimate of ground water flow velocity.

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. Use of tracers through inter-well tracer testing has been established and proven as an efficient technology to obtain information on well-to-well communication, heterogeneity and fluid dynamics (Olaf Huseby, et. al, 2009, Moser, W., et. al, 1989), determine direction of flow and seepage velocity through porous medium etc. The injected quantity of tracer lasts long enough to be detected in the monitoring boreholes. 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.4.3.

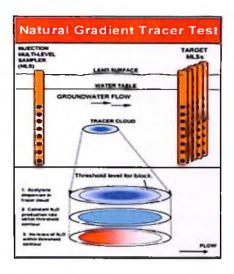


Fig. 4.3. Conceptual model showing the tracer migration in multi well injection test

#### ADVANTAGES AND LIMITATIONS IN USE OF CONVENTIONAL TRACERS

Advantages of conventional tracers are already discussed earlier. Chemical and dye tracers are generally affected by absorption and adsorption processes. While detecting these tracers diffusion, dispersion, are predominant and therefore many times exact detection is not possible (Rao. S. M, 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.

#### **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. M, et. al, 2003); so their nuclei are stable and their masses remain the same. However, they may themselves be the product of the decay of radioactive isotopes. This alters the mass of the atom but not its chemical nature. The most commonly occurring isotope has the lowest mass in the case of  $^{13}$ C,  $^{2}$ H,  $^{18}$ O as well as  $^{15}$ N. Stable isotopes include environmental isotopes while unstable isotopes are radioactive (e.g.  $^{3}$ H,  $^{51}$ Cr,  $^{60}$ Co,  $^{82}$ Br, and  $^{131}$ I) (Gaspar et. al, 1972, Gibson, et.al, 2005).

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 (Y. Yurtsever, et.al., 1993, Kendall, C. et. al., 1998).

#### **ENVIRONMENTAL ISOTOPES**

Human-applied tracers are different than environmental tracers. Isotopes which are naturally produced and incorporated into the hydrological cycle or are released inadvertently to the environment through human activities, are often referred to as "Environmental Isotopes" (Markus Flury, et. al, 2003, Pritchard, J, et.al, 2000). Environmental isotope techniques are based upon measurements of the variations in the environmental isotope compositions of natural water. They cannot be controlled by man, but can be observed and interpreted to gain valuable regional information on the origin, turnover and transit time of water in the system which often cannot be obtained by other techniques (Coplen T.B, 1993). Analysing and interpreting the chemistry of water can provide valuable insights into groundwater-surface water interactions. Dissolved constituents can be used as environmental tracers to track the movement of water. This relies on the measurement and interpretation of background concentrations of the chemical constituents of water, such as major ions, stable or radioactive isotopes.

The application of environmental isotope 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 subject 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, Y. Yurtsever, et.al , 1993, Clark and Fritz, 1997; Scanlon et al., 1997; Ka"ss, 1998).

## RADIOACTIVE (UNSTABLE) ISOTOPE TRACERS

Radioactive isotopes spontaneously emit radiations and in a chain process, it is transformed to atoms of other radioactive elements, till a stable atom is formed. 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 (Plata-Bedmar. A, 1988). The example of radioactive tracers is Bromine-82, Iodine-131, Cobalt-60, Rubidium, Hydrogen-3 (Tritium) etc. Injected radioactive tracers like Tritium,  $K^{131}I$ ,  $NH_4^{82}Br$  and  $K_3[^{60}Co(CN)_6]$  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. L, 2001). As gamma emitters can be detected in situ,  $^{82}Br$  is the most commonly used artificial isotopic tracer in view

of its short life span (36 hrs) and high-energy gamma emission. Sometimes, radioactive tracers (<sup>198</sup>Au and <sup>140</sup>La) are removed from the water and adsorbed on the soil matrix as the water enters the soil during seepage and are particularly useful to locate areas of high seepage (Kamble et al., 2003, Gibson, et.al, 2005).

Radon gas can be used as a natural tracer of ground water seepage as the groundwater has a higher concentration of <sup>222</sup>Rn than surface water (Kraemer et.al, 1998).

Radioactive tracer techniques present advantages:

First, their concentration can be measured with detectors located outside pipes or vessels. Second, measurement of samples taken from a flow is simple and independent of the matrix of samples. Third, a radioactive tracer is unique for labeling specific elements or chemical species.

#### **METHODS OF APPLICATION**

The different methods of application of radio-active isotope tracers are

- 1. Point Dilution Technique
- 2. Point Injection Technique
- 3. Labeling of whole water column
- 4. Radioactive Cloud Migration Method
- 5. Radioactive Tracer Adsorption Method

among which only Point Dilution and Point Injection methods are discussed here.

(1) Point Dilution Technique: The Point Dilution Technique, the horizontal component of the groundwater flow velocity is obtained from the decrease in the concentration of the tracer injected into the borehole due to the flow perpendicular to its axis, as a function of time.

In principle, the method is based on (1) the groundwater flow at the borehole site is in a steady state, (2) tracer concentration at any given moment in all points within the volume is same, (3) absence of significant losses of tracer (Lichner. L, 2001).

(2) Point Injection Technique: This method is based on the execution of tracer injection at different points of the seepage prone area and measurement of the eventual break through curves at the existing spring or downstream boreholes. Each tracer injection provides information of the water leakage corresponding to a small area close to the injection point (Kimball,

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B.A., 1997). This technique is particularly useful in quantifying sources of pollutants that may be entering the stream from tributaries, seeps, or from ground water.

#### ADVANTAGES OF ISOTOPE TRACERS

The unique properties of isotopic tracers make them an ideal tool to trace the water movement in hydraulic structure, used for flow measurements in rivers and canals and estimate groundwater velocities, as well. The ability to study widespread effects has generally made naturally occurring tracers more useful and more environmentally accepted than artificially introduced tracers.

Isotopes are suitable for studying most sorts of pollution because of wide range availability. Sometimes they are a quite unique tool with significant advantages in comparison with other tracers. One important advantage of isotope techniques is that they provide the chance to estimate, qualitatively and quantitatively, what are called "retardation parameters" of geological media with respect to the movement of pollutants (Dubinchuk, et.al, 1990).

Isotopes for hydrological studies include the stable isotopes of water (180, 2H), exhibit systematic spatial and temporal variations of isotope fractionations that accompany water-cycle phase changes and diffusion. Isotope fractionation produces a natural labelling effect within the global water cycle that has been applied to study a wide range of hydrological and climatic processes at the local, regional, and global scales (Gibson, et.al, 2005).

## **CANAL SEEPAGE**

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 (Zechner. E , et. al, 2004). The canal seepage can be calculated using empirically developed formulae or solutions derived from analytical approaches

### METHODS FOR MEASUREMENT OF CANAL SEEPAGE

The seepage occurring from canal can be estimated by following methods;

- Inflow-Outflow method
- Ponding method

- Seepage meter method
- Remote sensing
- Tracer Technique

Out of these four methods, only tracer technique is discussed here.

#### TRACER TECHNIQUES FOR CANAL SEEPAGE

Seepage losses in the canals using tracers can be assessed in several ways. Environmental tracers provide an excellent opportunity to address water movement in the subsurface (Clark and Fritz, 1997). Tritium (3H) is particularly useful for understanding near-surface ground water flow.

Radioactive tracers can be adopted to the purpose and duration of the investigation by choosing suitable chemical compounds and their half-lives. The filtration velocity of seepage is measured using radioisotopes. The Radioactive tracer such as AU-198 (gamma emitter) is added in the canal water and the gamma activity is monitored at the canals walls and its bottom. The areas of maximum leakages can be spotted as the gamma emitter will be filtered and absorbed in the soil. Yet, another approach could be by using a soluble tracer, which is not absorbed by the earth and could be detected by suitable probe in the seepage water at some distance from the canal.

In the tracer technique, a tracer is injected in one or more bore holes located near the banks of canal and observing either the dilution of the tracer in the injection bore holes itself or by detecting its arrival in the observation bore holes located near the injection boreholes in the probable direction of seepage (Tanaka. T, et.al , 1999).

In canal seepage studies also, Point Dilution and Multiwell techniques are used. The formulae and filtration and seepage velocity equations used in dam seepage investigations are also used in assessment of canal seepage losses. However, the above velocity is, average macroscopic ground water filtration velocity. The average microscopic (interstitial) filtration velocity ( $V_a$ ) is obtained by dividing  $V_f$  by the fractional porosity (P) (Kaufman et al, 1969).

i.e. 
$$V_s = V_f/P$$
 (5)

After the interstitial velocity,  ${}^{w}V_{s}'$  is determined by the above equation the seepage losses from the canal can be calculated using the relation (Dhillon et al 1980)

$$q = 2.Vs D. \theta. Cosec \theta$$
 (6)

Where q = Seepage losses per unit length of the canal

D = Half bed width of canal.

 $\theta$  = Angle in radians which the phreatic line makes with the normal at the injection borehole.

Critically, the time of tracer travel should be calculated from the time displacement of the center of gravity of the concentration time propagation for the injection and observation points. However, considering the variable seepage rates and the dispersion of the tracer wave, the time of travel are estimated from the peak concentration. Seepage losses from the entire wetted surface can then be obtained by dividing 'q' by the wetted perimeter of the canal.

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.

#### **DAM SEEPAGE**

Dams have been a part of the economic development model of almost all nations of the world. At some stage of their development, most countries with water resources that can be economically exploited have built dams for energy, irrigation, and drinking water. In developing countries like India, constructing dams form a critical component in building the infrastructure of the nation. There are approximately 5125 large dams (4728 completed and 397 under construction) and several thousand smaller dams. However, like all pieces of structures, dams age and deteriorate, posing a potential threat to life, health, property, and the environment. Although, in India a sound foundation was laid for a nation-wide systematic dam safety surveillance programme in 1979, and maintenance and upkeep of the dams have been started recognizing dam safety as an important activity, significant funds are not provided for dam safety rehabilitation.

The hydraulic structures viz. dam, reservoir, canal etc. are although designed not to seep or leak, still minimum seepage or leakage occurs through these hydraulic structures when founded on pervious foundations.

#### **BOREHOLE LOGGING TECHNIQUES**

#### Introduction

Borehole Logging methods provide a wealth of information that is critical in gaining a better understanding of the subsurface. These methods enable us to investigate the subsurface non-destructively, efficiently and effectively. They measure the in-situ properties and structural characteristics of earth materials (e.g., bulk density, porosity, shear modulus, electrical resistivity, depth to bedrock, fault location). The use of these methods has resulted in cost savings through reduced design uncertainty and lower investigation costs. Borehole logging techniques are being increasingly used in solving a number of problems related to seepage in hydraulic structures. The text discusses methodology of borehole logging techniques, instrumentation and case studies on the applications of these techniques for dam seepage at some major projects.

Borehole log is a continuous record of measurement made in bore hole that responds to variation in some physical properties of rocks through which the bore hole is drilled. It includes techniques of lowering sensing devices in a borehole and recording some physical parameters that may be interpreted in terms of the physical and chemical characteristics of the rocks and the fluids contained in them. The subsurface geologic conditions and engineering characteristics can be determined directly or indirectly from the properties measured by these techniques.

### **OBJECTIVES OF BOREHOLE LOGGING**

The main objective of borehole logging is to obtain more information about the sub-surface than can be obtained from drilling, sampling and testing (US Army Corps of Engineers, 1995). Borehole logs provide a continuous quantitative set of data along the entire length of the borehole. Furthermore, a number of physical and chemical properties of surrounding rock and fluids contained therein can be investigated. Logs can be run in all boreholes including those cased with metal or plastic casing and filled with water, brine, mud or air. Borehole logs also provide information that can be directly used for standardization and calibration of parameters. Borehole logs can be interpreted to determine the lithology, geometry of the formation, resistivity, bulk density, porosity, compressional and shear wave velocities ( $V_p$  &  $V_s$ ), moisture content, water bearing strata and movement of water (Scott Key, 1971).

# INSTRUMENTATION

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, acoustic velocities, 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. A schematic setup of borehole logging is shown in fig.4.4.

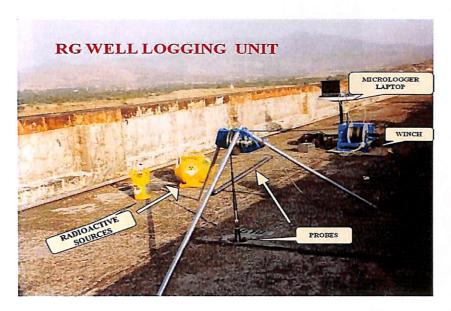


Fig. 4.4 Schematic Setup of Borehole Logging

#### **MICROLOGGER**

The micro logger is a portable, powerful high speed data acquisition unit . It has a USB interface for the recorder and communicates with the recording unit and the probe (Fig.4.5A).



Fig.4.5 (A) Micro Logger

#### **CABLE & WINCH SYSTEM**

The winch is lightweight and compact. It is battery operated and includes a speed and depth indicator. The multi-conductor armored cable supplies electric signal to the probe and the recorder (Fig.4.5B).



Fig.4.5 (B) Cable and Winch system

#### TYPES OF BOREHOLE LOGGING

Based on the parameter to be measured, borehole logging is classified into various types. Table-I shows the various logging methods and the parameters measured to characterize the subsurface.

Table - I Types of Logs

Logging Method	Parameter Measured
<ul> <li>Resistivity</li> <li>Spontaneous potential (SP)</li> <li>Natural Gamma-ray</li> <li>Gamma-Gamma</li> <li>Neutron</li> </ul>	<ul> <li>Electrical resistivity</li> <li>Electrical potential</li> <li>Natural gamma radiation</li> <li>Bulk density</li> <li>Porosity</li> <li>V<sub>p</sub> &amp; V<sub>s</sub> , Mechanical properties of</li> </ul>
<ul><li>Sonic</li><li>Temperature</li><li>Caliper</li></ul>	rocks  Fluid Temperature  Borehole diameter

#### **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 posses appreciable penetrating power and are measured in nuclear/ radioactive logging (Mayers, 1992). The commonly used nuclear logs are Natural gamma, Gamma-gamma and Neutron. Nuclear logs have a fundamental advantage over most other logs; they may be run in either cased or open holes that are filled with any type of fluid.

#### **Natural Gamma Log**

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 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. Natural Gamma detector is generally installed in density and neutron probes.

#### Gamma-gamma (Density) Log

Gamma-gamma logs are records of 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. The main use of gamma logs is for the measurement of bulk density and porosity of rocks.

A radioactive source such as Caesium-137 ( $^{137}$ Cs) or Cobalt-60 ( $^{60}$ Co), contained in this logging probe emits medium energy gamma rays into the formations. These gamma rays collide with the electrons in the formation. At each collision, a gamma ray loses some of its energy to the electron and then continues with diminished energy. This type of interaction is known as Compton scattering. Density probe is so designed that the tool response is predominantly due to this phenomenon (Fig.4.6). The back scattered gamma ray is usually captured by the scintillation detector in the probe. Gamma radiation attenuation is assumed to be proportional to bulk density of material it passes through (Keys, 1990). The instrument must be calibrated for different formation densities and hole diameter. The errors in bulk density obtained by this method are of the order of  $\pm$  5%. Porosity can be derived from bulk density by the relation

$$Porosity = \frac{Grain \ density - Bulk \ density}{Grain \ density - Fluid \ density}$$
(7)

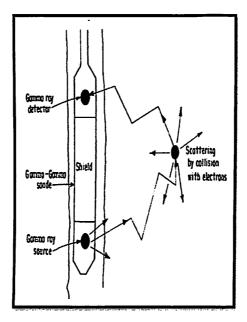


Fig. 4.6 Principle of Density Log

### **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 (Keys, 1990).

Fast neutrons are continuously emitted from a radioactive source such as Americium-241-Beryllium, which is mounted in the probe used for neutron logging. These neutrons collide with nuclei of the formation material; with each collision the neutron loses some of its energy. 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 largely on the amount of hydrogen in the formation. Within a few microseconds the neutrons are slowed down by successive collisions to thermal velocities, corresponding to energies of around 0.025 eV. They then diffuse randomly without losing any more energy until they are captured by the nuclei of atoms such as chlorine, hydrogen etc. which then emit characteristic gamma rays (Fig.4.7).

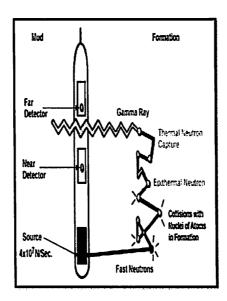


Fig. 4. 7 Principle of Neutron Log

Depending on the type of neutron logging tool, either these capture gamma rays (neutron-gamma) or neutrons (neutron-neutron log) themselves are counted by a detector in the probe. Modern neutron tools most commonly count thermal neutrons with a He-3 detector. 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. This results in a low count rate and is interpreted as an indication of high porosity and vice versa.

#### **CALIBRATION OF NUCLEAR LOGS**

The response obtained in gamma-gamma log is in terms of count rate (counts /sec) a unit or radioactive disintegration and it is required to be converted into known parameters like density, by calibrating the probe in the laboratory. Calibration of nuclear logs can be carried out either in standard pits constructed with materials of known density values or with laboratory calibration of the cores samples. In calibration pits the response of density probe for different known density values is obtained by filling the pits with soil, mourrum, sand etc. in various proportions by simulating field conditions. The calibration curve is then obtained by plotting density against counts /sec and applying best-fit equations. This calibration curve is used while evaluating density from gamma-gamma logs. In general, a low value of count rate corresponds to a high value of density and vice-versa.

#### **Radiation Safety Aspects of Nuclear Logging**

Although nuclear logs are highly reliable, accurate and valuable, some inherent precautions are required to be observed while handling radioactive sources like <sup>137</sup> Cesium and <sup>241</sup> Americium-Beryllium. The Atomic Energy Regulatory Board (AERB) monitors the use of these radioactive sources. For this purpose, the following precautions are to be observed.

- 1. Film badges are provided which should be worn by the personnel to maintain a record of the radiation exposure.
- 2. The badges are sent to AERB, Mumbai for quarterly monitoring of radiation exposure.
- 3. The radiation sources should be kept in isolated storage away from working place to minimize the exposure.
- 4. The sources should not be tampered with unnecessarily to avoid damage to them.
- 5. The movement of sources should be reported to AERB.
- 6. In case of an unfortunate accident, damage or loss of source in the borehole during field studies, the AERB authorities should be immediately informed and the area made inaccessible until it is proved to be safe.

#### **CALIPER LOG**

The caliper log provides a continuous record of changes in borehole diameter determined by a probe equipped with tensioned mechanical arms or an acoustic transducer. Caliper logs are one of the most useful and simple of all logs obtained in borehole geophysics. This log is essential in interpreting other logs that are affected by changes in borehole diameter (Keys, 1990). Caliper logs provide the physical size of a drill hole and should be run in all boreholes in which other logging is anticipated. Caliper logs provide indirect information on subsurface lithology and rock quality. Borehole diameter varies with the hardness, fracture frequency, and cementation of the various materials penetrated. Borehole caliper surveys can be used to accurately identify washouts or swelling or to help determine the accurate location of fractures or solution openings, particularly in borings with core loss. Caliper logs can also identify porous zones in a bore by locating the intervals in which excessive mud filter cake has built up on the walls of the borehole. One of the major uses of borehole caliper logs is to correct for borehole diameter effects. Caliper logs also can be used to place water well screens,

position packers for pressure testing in foundation investigations for dams or other large engineering structures, and help estimate grout volumes in solution or washout zones.

Mechanical calipers are standard logging equipment and available in one-, two-, three-, four-, or six-arm probe designs. Multiple-arm calipers convert the position of feelers or bow springs to electrical signals in the probe (Fig.4.8). The electrical signals are transmitted to the surface through an armored cable. Some caliper systems average the movement of all the arms and record only the change in average diameter with depth, and others provide the movements of the individual arms as well as an average diameter. The shape or geometry of the borehole cross section can be determined with the individual caliper arm readings.

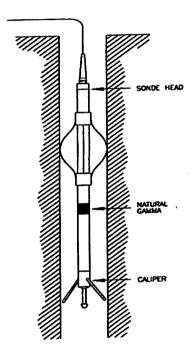


Fig. 4.8 Set up of Caliper Probe

#### **Advantages & Limitations of Borehole Logging**

Borehole logs have a number of advantages over the conventional core logs. They provide a continuous quantitative set of data as compared with the core samples. Borehole geophysical tools sample or investigate a volume of rock many times larger than core or cuttings that may have been extracted from the borehole. Some Furthermore, a number of physical and chemical properties of surrounding rock and fluids contained therein can be investigated. Logs can be run in all boreholes including those cased with metal or plastic casing and filled with water, brine, mud or air. Data from geophysical logs are also useful in the development of digital models.

Another advantage of borehole logging is that, it can be repeated many times in a borehole or series of boreholes adding a new dimension to the information obtained. Repeatability enables us to study the effects of remedial measures adapted to reduce seepage. Borehole logs also provide information that can be directly used for standardization and calibration of parameters. The graphical presentation of borehole logs also allows rapid visual interpretation at the site.

Borehole logging cannot completely replace sampling, because some information on the local geology is needed on each new area to aid log analysis. Therefore to maximize efficiency of logs, at least one core hole should be drilled in new area. Laboratory analysis of core is also required either for direct calibration of logs or for checking calibration carried out by other means. 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 answers sought.



#### CHAPTER - V

#### C.W.P.R.S EXPERIENCES

Govind A Panwalkar (Scientist B) Amol Chunade (Asst. Research Officer)

CWPRS is actively involved in seepage investigations for dams and canals since 1962 and had given solutions and remedial measures to the problems. Following are a few typical case studies, cited to provide insight and approach to the seepage problems in the dams and canals using tracers and nuclear borehole logging.

### 5.1 Delineating path of seepage in the masonry at Pawana Dam, Maharashtra

The Pawana Dam of height 38.1 m was constructed across River Pawana, Maharashtra. It is a composite dam comprising 414 m long masonry dam with overflow and non-overflow portion and a 903 m long earthen dam. Excessive seepage which was related with the rise of the reservoir level was observed in the drainage gallery and body of dam. Hence grouting at a few places and guniting of the entire upstream face was done to reduce the seepage which was actually reduced by about 50%. For the purpose of strengthening the dam and to raise the Full Reservoir Level by 0.5 m, tracer studies were carried out to delineate the path of seepage. Figure.5.1. shows the layout of dam and excessive seepage observed at drainage gallery and downstream of the dam. Seepage was observed like water jets on the downstream slope of Left Hand Side (LHS) of masonry between Ch.725 ft. and Ch. 849 ft. in monoliths 5, 6 & 7 and between RL 1935 ft and 2004 ft. The leakage was observed from a number of pores holes on the RHS gallery but no appreciable seepage was seen in the LHS drainage gallery. This is an example of seepage through structure. Tracer studies were carried out in two phases during the year 2003, viz. May-June when the reservoir level was between 1975 ft. and 1976.30 ft. and in September when lake level was around 2010 ft. The appearance of Potassium Permanganate dye tracer was monitored at downstream observation points at every 10 minutes interval for about two hours after injection.

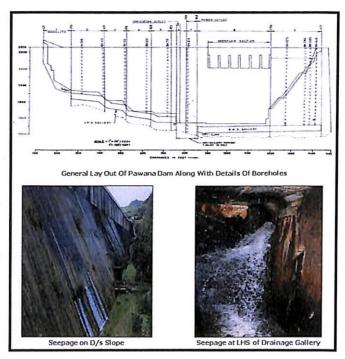


Fig. 5.1 Dam layout with visible seepage sites along the downstream

The results indicated that the tracer injected at Ch.225 m (RL 590 m) had a direct connection with water jet in the LHS drainage gallery and small quantity of tracers were also observed at the downstream slope for the tracer injections at Ch.250 m (RL 598 m & 594 m), Ch. 259 m (RL 598 m). The tracer injected at other locations has not arrived at the downstream monitoring points, indicating that there is no direct interconnection between these points. The direct arrival of dye for injection in borehole at Ch.247 m (RL 592 m, 594 m and 598 m) may be due to the presence of gaps in masonry dam. The tracer also appeared distinctly for the injection points in a well at Ch. 226 m (RL 609 m). It was observed that except for injections on the upstream face of dam at Ch. 226 m and Ch. 230 m, dye appeared at the remaining injection points. From the nuclear and caliper logging of boreholes, it was observed that in general, density of masonry varied from 2.3 gm/cm³ to 2.58 gm/ cm³ and presence of voids/ cracks were located in the boreholes.

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

# 5.2 Determination of the insitu bulk density of masonry at Dudhganga Dam, Maharashtra

Dudhganga masonry dam of 73 m height was constructed across river Dudhganga in the year 1987. The main objective of the dam was for irrigation and also generates electricity of 24 MW. Excessive leakage was observed in the drainage gallery and from the downstream face of the dam. Total leakage observed was about 350 lps. In view of the excessive leakage from the dam, doubts were raised about the safety of the dam. Therefore, studies were carried out to determine the bulk density of masonry as one of the parameters required for stability analysis of the dam.

For this purpose, nuclear logging was carried out in three Nx size boreholes drilled in the masonry to a depth of about 45 m from top of dam in monoliths 5, 6 and 7 where excessive leakage was observed (Fig. 5.2A). Caliper logging was also carried to identity deviation in diameter of boreholes and to identify locations gaps/voids present in the masonry due to leaching of binding material. The results of the studies indicated that the bulk density of masonry varied form 2.30 to 2.52 gm/cm<sup>3</sup>. Low-density values below 2.30 gm/cm<sup>3</sup> were also observed at a few stretches in all the three boreholes that were attributed to leaching of cement mortar due to excessive leakage. It was also possible to identify gaps in the masonry by caliper and density logs. Fig. 7B shows a typical plot of density logging in one of the boreholes. The studies were useful to the project authorities to plan suitable remedial measures for reducing excessive seepage.

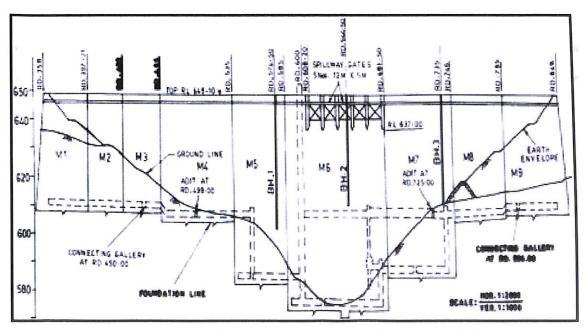


Fig. 5.2A L-Section of Dudhganga Masonry Dam showing Borehole Locations

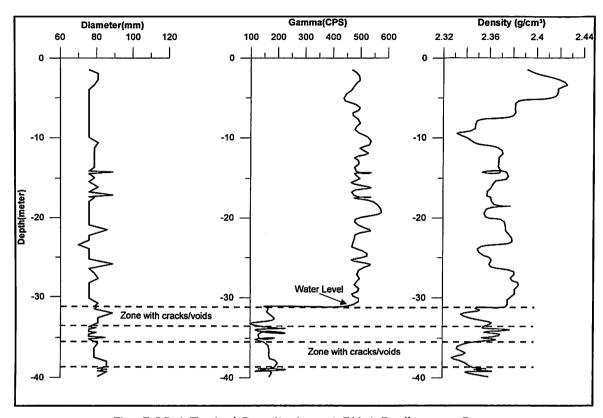


Fig. 5.2B A Typical Density Log at BH-1 Dudhganga Dam

# 5.3 Identification of seepage from the zone in the body of the dam at Indirasagar Project, Madhya Pradesh

Indirasagar Project on River Narmada, near Punasa village in Khandwa district Madhya Pradesh comprises of a 653 m long and 90 m 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. The project authorities on the basis of interpretation of data acquired from various dam instruments felt that there could be possibility of entry of seepage water and could pose problem to the structure. The piezometers installed in Block No. 25 at EL 208.85 m indicated high values of uplift pressure. 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.

Geologically, the Upper Vindhyan group of thickly bedded quartz arenites (Quartzite) and ferruginous sand stones inner layered with occasional lenses of silt/ clay

stone provided the foundation for the 92 m high concrete gravity dam. The beds have a general strike of N70 $^{\circ}$  East – South 70 $^{\circ}$  with dips of 10 $^{\circ}$  –25 $^{\circ}$  towards N 10 $^{\circ}$  – 25 $^{\circ}$  W. Four sets of joints were observed. The predominant bedding joints were open with filling of siltstone.

Nuclear logging comprising gamma-gamma density log, neutron log and caliper log were carried out in the six 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. Caliper logging was also carried out in the boreholes to identify the presence of gaps/voids in the masonry by measuring the variation in diameter of the boreholes and for applying correction in the density log data.

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. Fig. 5.3 shows a typical plot of nuclear logging showing permeable zones. 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 this depth.

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.

It appeared 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 measure.

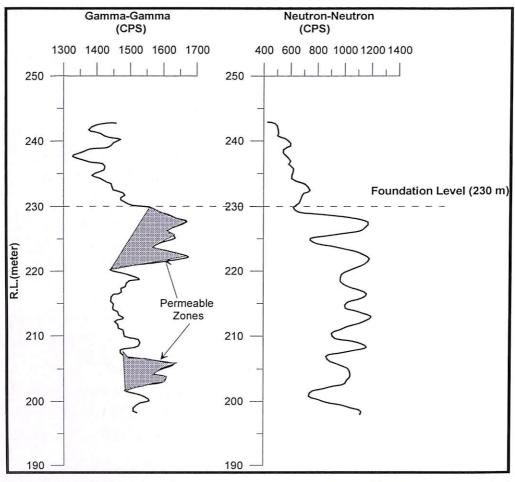


Fig. 5.3 Typical Plot of Nuclear Logging Showing Permeable zones at Borehole

# 5.4 Ascertaining seepage path in the foundation at Nagarjunasagar Dam, Andhra Pradesh

Nagarjunasagar dam constructed in the post independence era across the river Krishna in A.P is the largest (4868 m) and highest (1246 m) rubble masonry dam in the world. The masonry dam (3418 m in length) in the centre of the gorge flanked by earth dams. The reservoir formed upstream of the dam is the largest man-made lake in the country and third largest in the world (Fig. 5.4 A).

In 1989, a settlement was observed at Ch. 142.5 upstream of the right earth dam resulting in the formation of a cavity at RL 182.88 m. Technical Experts Committee (TEC) was appointed by A.P Govt. to examine the cause of the formation of the cavity. As suggested by TEC tracer studies were conducted for determining the interconnection if any, and the seepage velocity through the earthen dam. The area under study lies in the sedimentary terrain of Cuddapah group with quartzite as a predominant rock type.

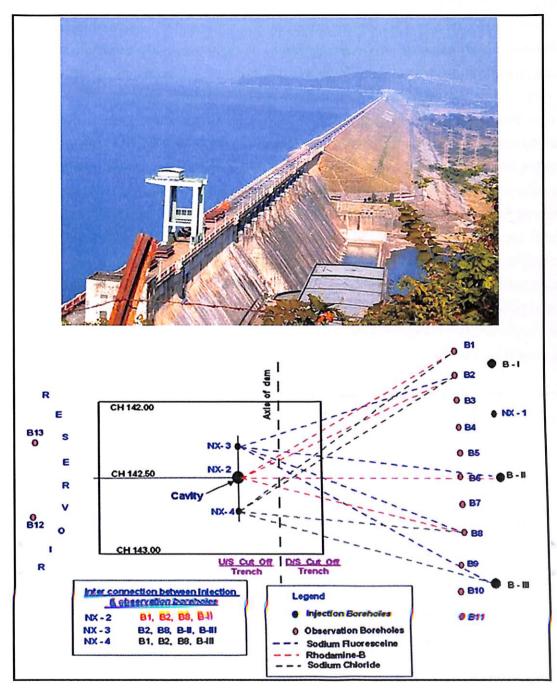


Fig. 5.4 (A) Plan of Location of Boreholes for Tracer Studies at Right Earth Dam, Nagarjunasagar Project, A.P.

Three Nx size boreholes viz. Nx-1, Nx-2 and Nx-3 were drilled on the upstream side of the cavity area to facilitate injection of tracer. For monitoring the arrival of the tracers, eleven shallow boreholes (B1.....B11), three deep boreholes (B-I, B-II and B-III) and one Nx-1 borehole used for logging were used for sample collection at the toe of the right earth dam. In order to ascertain the direction of seepage towards the canal located

350 m downstream of the right earth dam , Nx-5 was drilled to monitor the flow of the injected tracer. B12 and B13 were drilled at the reservoir of upstream side to monitor movement of the tracer towards upstream. Tracers used were sodium fluoresceine, Rhodamine-B and common salt.

The tracer studies revealed that there was a hydraulic interconnection between the foundation rock and the toe viz. boreholes (a) Nx-2 and B1, B2, B8, B-II, (b) Nx-3 and B2, B8, B-II, B-III and (c) Nx-4 and B1, B2, B8, B-III. There was no interconnection between cavity and B12 and B13. The permeability of the foundation rock varying from  $4.93 \times 10^{-4}$  cm/sec to  $7.75 \times 10^{-4}$  cm/sec indicated that the rock permeability for rock in the cavity was higher than that for boreholes on either side of the cavity. High seepage velocity ranging between 3m/day to 7.8 m/day has also been observed as shown in figure.5.4 B. Borehole logging also revealed that the foundation rock below cavity (RL 544 - 539ft.) was prone to the excessive seepage. It was recommended that a suitable treatment should be given for the foundation at cavities zone to reduce the seepage through them.

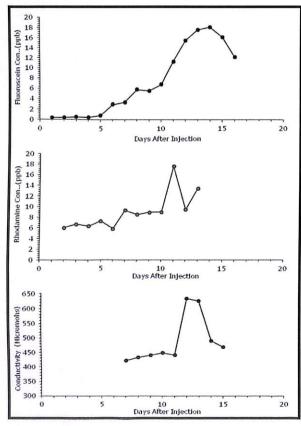


Fig. 5.4 (B) Arrival of Sodium Fluoroscein, Rhodomine and salt tracers in Nx Bore Hole B1 and B2 respectively

# 5.5 Indira Gandhi Main Canal, Rajasthan (IGMC), India

Indira Gandhi Main Canal (IGMC) is the largest desert area irrigation project in the north-western of Rajasthan, India, with a command area of 15.4 lac hectares covering five districts with main canal (195 km) and its branches. This area is an arid region of north Rajasthan with rolling topography, shifting dunes and interdunal flats. Though the main canal is lined with clay tiles, an excessive seepage and as a result the water logged area around the canal was noticed on both banks of IGMC between RD 0 and 100 covering a length of about 30 km. The location selected for estimation of seepage losses from canal and for measurement of subsurface seepage at the water logged area are shown in Fig. 5.5.

The point dilution method was adopted for the measurement of canal/subsurface seepage losses and filtration velocity in a water bearing formation using Sodium flouroscein dye, as well. Water samples, collected from all injection points at predetermined interval, and were tested for Sodium fluoresceine dye concentration using fluorometer for determining the rate of dilution of tracer.

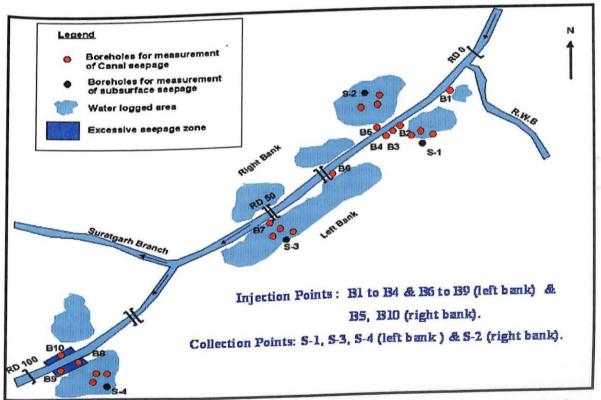


Fig.5.5 Plan of Indira Gandhi Main Canal, Rajasthan, Showing Locations of Boreholes for Canal Seepage Studies

The seepage losses measured by tracer methods were ranged from 0.34 to 9.99 m³/s/million sq.m. The identification of low, moderate and excessive seepage zones at both banks of the canal is based on the amount of seepage losses and these three identified zones are well matched with the value of the filtration velocity, as well. The excessive seepage zones at RD 96 might be due to damaged canal lining.

Measurement of seepage losses from subsurface due to irrigated water was achieved at several places. The calculated filtration velocity at each borehole along with permeability was varied between  $0.32 \times 10^{-7}$  m/sec to  $3.27 \times 10^{-7}$  m/sec. As the permeability (k) of the strata becomes the main parameter at the seepage prone area, it was computed upto a depth of about 3 m using the filtration velocity and hydraulic gradient and these values ranged from  $0.08 \times 10^{-4}$  m/sec to  $0.32 \times 10^{-4}$  m/sec. The high filtration velocity and permeability had been observed at the left bank near RD 96 but in general the values of filtration velocity indicated moderate subsurface seepage velocities which contribute to the water logging around the canal area. However, surface run-off would also contribute to the water logged condition during irrigation. Based on the studies, it was recommended to check the canal lining where high seepage losses (at RD 96) observed.



#### SUMMARY AND CONCLUSION

R.K.Kamble (Scientist E)

Enormous amount of financial investment is made in planning, designing, construction, operation and maintenance of dams and canals for storage and transportation of water to meet the needs of water supply, irrigation and hydropower for socio economic development. However, excessive seepage through these structures is a cause of great concern since it may cause direct potential threat to safety and stability of the structure. There are several reported incidences of catastrophic dam failures and canal breach in India and other parts of world, caused mainly due to excessive or uncontrolled seepage. In India, 75% of dam failures are due to unattended seepage related problems.

Investigations conducted on dams and canal failures, occurred in various countries have ascertained that a majority of these failures could have been evaded by proper design, construction, regulation of seepage and timely inspection. The main causes of seepage in dams and canals 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 this document under different 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 conventional techniques such as 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. Non-conventional techniques involving tracer studies and borehole logging techniques. Tracer techniques help in identifying the source of seepage, its path and interconnection between two water bodies and also help to determine seepage velocity. Borehole logging investigations can provide in-situ evaluation of engineering properties of the subsurface, potential seepage pathways, lithological variations and solution activity.

In the recent past the advent of mathematical modeling by analytical and numerical methods as a tool has provided a good result in assessing seepage through

dams and canals. With the arrival of high speed computers and advanced softwares, these tools are being immensely popular. The effects of seepage through dam body and across canals and the parameters such as seepage discharge, uplift, pore pressures, etc. are required to be continuously monitored by proper instrumentation.

Investigations of dam and canal seepage include through study of the proposed site geology using conventional methods, which comprise various geophysical and geotechnical methods, water balance studies, assessment of seepage potential of the foundation and analysis of dam instrumentation data. Integration of different methods enables in better understanding of the problem and offer cost effective solutions.

Apart from the conventional methods there are other non-conventional methods mentioned in this memorandum, like tracer techniques, borehole logging, geophysical methods, hydro geological methods and remote sensing techniques, 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.

Identification of seepage, its timely and efficient control is a skilled task. This should be based on sound background of geology of the area, investigations carried and analysis as regards to the occurrence of seepage, its location and amount. It is necessary to identify and locate the zones of defects/flaws in dams and canals which are susceptible for seepage by applying advanced and integrated methods for assessment of seepage. The cost of these investigations may not be more than 10% of total cost of repair of the structure. Suitable measures should be adopted to mitigate seepage so as to avoid future unpleasant consequences. Multidisciplinary techniques such as geological and geotechnical methods, geophysical methods, tracer techniques and nuclear logging for monitoring, detecting, analyzing seepage should be made use of effectively to arrive at an optimum solution for seepage problems. It is evident that effective application of these techniques not only helps in mapping the pathways of seepage but also ascertains the interconnectivity between source and seepage point.

Owing to their vast experience in conducting seepage studies involving multidisciplinary approaches comprising of field studies, laboratory investigations, analysis and advising on the remedial measures; authors have, over the decades, developed an expertise in providing cost effective and viable solutions for seepage related problems. A number of methods are available; however, identification of causes of seepage and implementing suitable remedial measures is a challenging job for

construction engineers as every problem involving occurrence of seepage or leakage is unique. A number of related case studies describing their objectives and methodologies adopted have been given with an aim that these would serve as a guide to construction engineers to resolve problems faced at site.

In India, many dams and canals have been constructed and are facing several structural deficiencies and short comings in operation and monitoring facilities. To reduce the risk of failures, regular health inspections are necessary to identify the defects and whenever severe deficiencies are observed, comprehensive remedial measures are required to be undertaken. To summarize, it can be stated that timely adoption of appropriate seepage monitoring, detection and analysis measures using conventional and non-conventional techniques and appropriate repair methodologies for rehabilitation of structures will surely lead to safe functioning of dams and canals throughout its design life.



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