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ADVANCED GEOPHYSICICAL TECHNIQUES FOR DAM AND CANAL NETWORK SAFETY ASSESSMENT

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ABSTRACT

Water is a crucial resource for economic growth and sustenance of a country. A large number of dams have been constructed all over the country to store water. To take this water to end consumer points, a large network of canals exists. With time, dams and canal networks deteriorate. To realize continued economic benefits, it is imperative that these structures are not only functional but also safe to operate. In Indian context, maintenance of these structures is neglected. As the same time,a large amount of water is lost through leakages and seepages. Repairs, wherever undertaken, are often a haphazard firefighting measure. The visual and functional manifestation of structural deterioration in these structures happens much after internal weakening. Due to sheer size of dams and canals, it is very important to precisely pinpoint location and cause of seepage and leakages so that targeted and cost effective repair and rehabilitation measures can be undertaken.

Paper discusses various geophysical methods utilized for investigation of dams and canal networks. The primary motivation for using geophysics is their versatility and low cost, as a tool for mapping and pinpointing zones of deterioration in dam structures and identification of seepage zones in canals/water channels.

INTRODUCTION

Water and its efficient delivery to end users is important for economic activities and sustenance for any country. Dams and canal networks therefore form part of basic infrastructure of a nation. The importance of dams and canals makes it mandatory to concentrate on scientific management for sustained availability in long term. With each passing year, construction of new dams and canals is becoming nearly impossible. With increasing demand and shrinking per capita water availability, efficient use of these assets is assuming greater importance with each passing day. Surface water management has two distinct components- storage and distribution. Besides design losses in storage and distribution system, an alarmingly large amount of water is lost through seepages in dams and canals.

Geophysics techniques can be used to very effectively in assessing internal condition of dams and mapping of seepage paths in dams and canals. Based on areas identified which have deteriorated, accurate and targeted repairs can be done for cost effective repair and rehabilitation.

Application of geophysical techniques has been prevalent in hydropower, highway and tunnel industry for many years in India but use of these tools is still very limited, mainly due to lack of awareness. In many cases poor use of the geophysics resulting in misleading or wrong results has also contributed to the negative opinion about applicability and efficacy of these powerful tools.

GEOPHYSICS BACKGROUND

Geophysical methods are sensitive to contrast in the physical properties in the subsurface. Different methods respond to different physical properties, like material strength, material conductivity (linked to water saturation), fluid movement (seepage), change in density etc. Most of the development in the field of geophysics has been for deeper targets, typically for oil and natural gas. The developments for shallow subsurface have been little, especially in India. Over the past few years geophysics is being used for civil engineering, mining, infrastructure and water resources in a limited way. The shallow geophysics deals with investigations usually restricted to depths of 250m below the surface of the Earth. Specific applications of the near-surface geophysics include mapping the depth and thickness of overburden, mapping the aquitards or confining units, locating preferential fluid migration paths such as fractures and fault zones and mapping contamination to the groundwater such as that from saltwater intrusion.

Different methods are based on principle of identifying various lithological units depending on difference in their physical properties like conductivity, density etc. A successful investigation program generally uses a combination of techniques to arrive at unique solution.

CRITICAL FACTORS OF GEOPHYSICAL SURVEY

The success of a geophysical program primarily depends on three factors- timing of the survey, choice of techniques and capabilities of geophysical agency conducting the survey.

Ideally geophysics should be used in the initial phase of the project to have maximum benefit from the investigations. Geophysical techniques have the advantage of being economical in terms of cost and time. Findings from a carefully planned geophysical campaign is useful for designing an optimized and targeted borehole investigation program.

Success of geophysical investigations depends on careful interpretation and integration of these results with geological and hydrogeological data for the site. Only then will the geophysics be a success. Geophysics is typically used in one of two ways. Either it is used to project an interpretation of the geology and hydrogeology from boreholes and surface exposure into a formation or the geophysics is used in an area of unknown geology and hydrogeology in order to better focus the direct sampling program. For both the uses, if the geophysics is discussed early in the proceedings then the most appropriate techniques can be found and used in the most cost effective manner. A parallel for groundwater development can be found in the hydrocarbon world where successful use of an integrated geophysical program is seen at all stages of developing a hydrocarbon reservoir. First a geophysical regional recognizance study is conducted with potential field methods (gravity and magnetics). This is followed by regional seismic program and exploration wells. Based on these results, more detailed local 3D geophysical surveys are made and the surface geophysics is tied to the subsurface geology by borehole geophysics. Ultimately high frequency borehole geophysics is conducted for reservoir modeling purposes.

THE RIGHT APPROACH

A successful geophysical survey design should start from the definition of a clear set of objectives and the choice of appropriate methods. The objectives must be based on reasonable, achievable criteria using geophysical tools. It is important to note that geophysical investigations reveal physical properties and objectives should not include parameters not achievable by these techniques. The site conditions should be carefully observed to confirm feasibility of conducting geophysical investigations. Available data on the site should be collected and studied to refine the objectives. Various factors like approach to site, prevailing conditions, and surroundings should be considered. The client must specify early in the proceedings what the ultimate results will be used for and what format they should be provided in. This will ensure that the geophysical results are fully integrated into the project as a whole. For if the results are not presented in a manner that the client can fully understand and utilize then they are as good as useless results.

Choosing the appropriate geophysical methods and applying the methods in an appropriate manner is also critical to a successful survey. Only once the objectives have been clearly defined and agreed on by both the client and the contractor can the appropriate geophysical methods be chosen. Incorrect choice of technique and inexperienced personnel conducting the investigation has been cited as primary reason for the failure of many geophysical surveys. Strict quality control should be maintained during the entire project. Field quality control includes basic equipment calibration procedures, accurate field reporting including field printouts of digital data, checks for digital data recording and up-loading to computers and repeat measurements at base or calibration sites. During processing this quality control will include manual calculations of computer-processed data, documentation of processing steps and separate data reviews by an independent person not directly involved in the project.

THE RIGHT GEOPHYSICAL INVESTIGATION AGENCY

Most of the failures of the geophysical survey are due to bad choice of the survey technique, lack of experience and bad quality control. The agency chosen to perform the geophysical investigations must therefore have a wide range of techniques available for the geophysical survey. In the absence of access to geophysical techniques appropriate for a given project, the agency would try to use whatever is available with it. The end result would not be meeting end-user expectations. Besides the hardware, the geophysical agency should also have sufficient experience in the related field to overcome the challenges during the field data acquisition and data interpretation.

SURVEY TECHNIQUES

There are number of geophysical techniques available. In the present paper a brief description has been provided, without getting into the detailed theory of these techniques. All geophysical techniques measure variations in a material's physical properties. For soils and rocks the properties can be divided into a framework of matrix component and the pore content component. Different materials exhibit different parameter signatures such as their resistivity or its inverse conductivity, acoustic velocity, magnetic permeability and density. These parameters are influenced by the mineral type, grain packing arrangement, porosity, permeability, and pore content (i.e. gas or fluid type). In general no one property is unique to any material. A range of each property describes a material. In most geophysical surveys it is important that changes in the geophysical parameters are measured and compared.

For groundwater investigations, the most significant parameters that have been used for describing an aquifer system are ones that relate to the porosity and permeability of the aquifer and surrounding aquitards. Electrical conductivity or its inverse resistivity is the proportionality factor relating the electrical current that flows in a medium to the applied electric filed. It is the ability of an electrical charge to move through a material.

Seismic velocity for both compressional waves and shear waves is related to the elastic moduli and the density of a material. Compressional wave velocity has also been correlated with porosity and used for determining fluid content.

The successful use of each geophysical technique is dependent not only on the careful design of the survey but also on the consideration of a number of key geological and cultural factors together with the geophysical data:

Nature of the target : The target geophysical signature must be different to that of the background geology or hydrogeology.

Depth of burial of target : The depth of burial of the feature of interest is important as different techniques have different investigation ranges. The depth range is technique dependent however there is always a trade off between penetration depth and resolution of the technique with respect to the feature of interest. A technique that will look deep into the earth generally has lower resolution than a technique that is only looking to shallow depths.

Target size : An estimation of the target size is necessary prior to selecting appropriate techniques. The target size should be considered in conjunction with the depth range for individual techniques.

Measurement station interval : This will depend on the burial depth, target size and technique selected. Geophysical surveys have traditionally been conducted along line profiles or on grids and therefore the station spacing along the lines must be calculated together with the line separation in order to not miss a particular target size. A rough rule of thumb is that a geophysical anomaly will be approximately twice the size of the object causing the anomaly so this will give the maximum line and station spacing.

Calibration of the data : The key to success of any geophysical survey is the calibration of the geophysical data with both hydrogeological and geological ground truth information. Calibration data may be provided by both down-hole geophysical logs in boreholes, samples derived from boreholes by continuous sampling and by measuring what goes into and comes out of a system.

Following section discusses are various techniques available for seepage/leakage path investigations.

ELECTRICAL RESISTIVITY IMAGING

2D Resistivity Imaging uses an array of electrodes (typically 64) connected by multicore cable to provide a linear depth profile, or pseudosection, of the variation in resistivity both along the survey line and with depth. Switching of the current and potential electrode pairs is done automatically using a laptop computer and relay box. The computer initially keeps the spacing between the electrodes fixed and moves the pairs along the line until the last electrode is reached. The spacing is then increased and the process repeated in order to provide an increased depth of investigation.

Basic Principle:

Measurement of ground resistivity involves passing an electrical current into the ground using a pair of steel or copper electrodes and measuring the resulting potential difference within the subsurface using a second pair of electrodes. These are normally placed between the current electrodes. Fig 1 shows field arrangement for ERI.

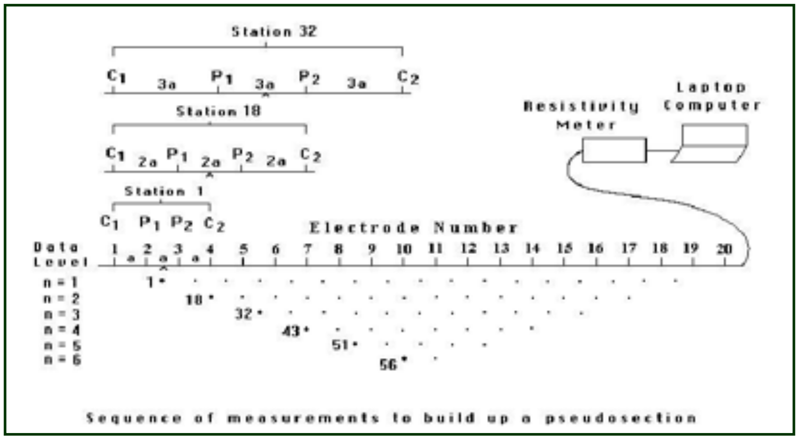

Fig. 1 : Field Arrangement for ERI

Unlike conventional resistivity sounding and lateral profiling surveys, 2D resistivity imaging is a fully automated technique that uses a linear array of up to 64 electrodes connected by multicore cable. The current and potential electrode pairs are switched automatically using a laptop computer and control module connected to a ground resistivity meter (that provides the output current). In this way a profile of resistivity against depth ('pseudosection') is built up along the survey line. Data is collected by automatically profiling along the line at different electrode separations. The computer initially keeps the spacing between the electrodes fixed and moves the pairs along the line until the last electrode is reached. The spacing is then increased by the minimum electrode separation (the physical distance between electrodes which remains fixed throughout the survey) and the process repeated in order to provide an increased depth of investigation.

The maximum depth of investigation is determined by the spacing between the electrodes and the number of electrodes in the array. For a 64 electrode array with an electrode spacing of 5m this depth is approximately 60m. However, as the spacing between the active electrodes is increased, fewer and fewer points are collected at each 'depth level', until on the final level only 1 reading is acquired (Point 56 in Fig 1). In order to overcome this the array is 'rolled-along' the line of investigation in order to build up a longer pseudosection.

The raw data is initially converted to apparent resistivity values using a geometric factor that is determined by the type of electrode configuration used. Many 2D resistivity imaging surveys are carried out using the Wenner Array. In this configuration the spacing between each electrodes is identical. Once converted the data is modeled using finite element and least squares inversion methods in order to calculate a true resistivity versus depth pseudosection. Fig 2 below shows a resistivity profile.

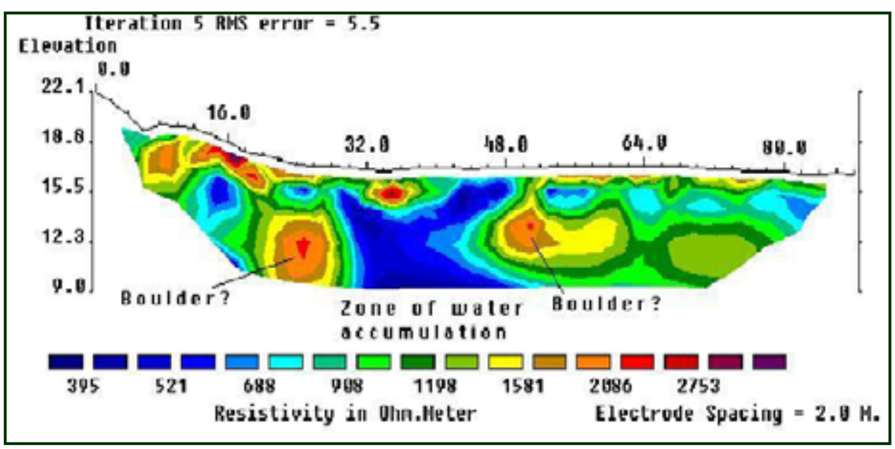

Fig. 2 : Resistivity Profile

STREAMING POTENTIAL SURVEY (SP)

The streaming potential method consists of measuring the electrical potential by flowing water within a structure or subsurface. Self-potential (SP) is a passive technique that measures naturally occurring electrical potentials in the ground.

Water flowing through the pore space of soil generates electrical current flow. This electrokinetic phenomenon is called streaming potential and gives rise to SP signals that are of primary interest in dam seepage studies.

SP is measured by determining the voltage across a pair of non-polarizing electrodes using a high-impedance voltmeter. Interpretation of SP measurements to infer seepage patterns and concentrated seepage flows ranges from simple qualitative to more advanced quantitative numerical modelling approaches.

Most common application of SP study is to identify the zones in the dam body through which seepage is taking place. The results are correlated with resistivity sections. Fig. 3 below shows combined ERI and SP profiles to indicate seepage zones.

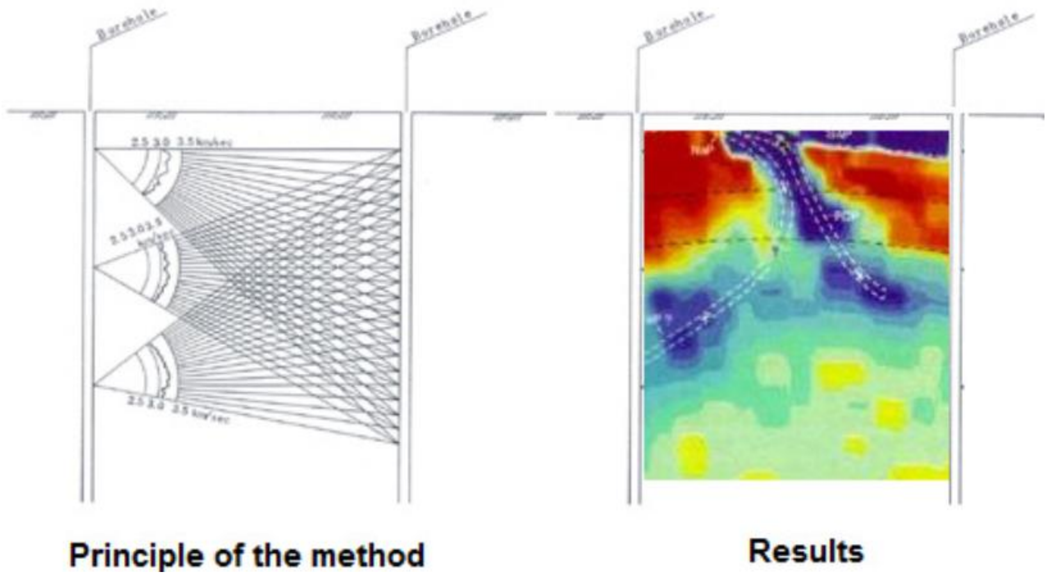

Fig. 3 : Sonic Tomography between Boreholes

SEISMIC TOMOGRAPHY

Sonic method's principle is based on generation of elastic energy using various sources which is propagated through the investigated structure. The elastic waves are recorded by specific sensor in the form of electric signals. Velocity analysis consists of an estimation of time needed by the elastic impulse to cover the distance between the transmitter-receiver couple. Therefore the second step consists of time-distance processing of data set to calculate sonic velocity distributions and to estimate a tightly linked parameters with elastic properties of investigated area. Seismic tomography can be applied between boreholes or between 02 faces. Fig 4 below illustrates tomography principle.

Sonic tomography survey provides maps (called tomograms) that show the velocity distributions of elastic waves and their attenuation of crossed material along plane sections. This process starts from arrival time measurement of longitudinal waves along high number of ray tracks which reciprocally cross each other within the area between transmitter and receiver position. Tomography resolution and then the final results accuracy are dependent upon numbers of ray paths acquired and how well does it cover the anomalous zones.

The data acquisition process is done by acquisition of each signal transmitter point related to different receiver points. In this way is possible to realize the data grid necessary to next data processing phase. As previously mentioned, every receiver and transmitter points coordinates are determined by an appropriate geometry mapping.

In processing stage, the investigated section is divided by a rectangular grid cells where velocities are calculated for each single node, assuming bilinear velocity variation along the cells. Cell dimensions are chosen in order to be compared either with signal wave length and relative distances between consecutive transition and receiver points. Such discretization is also aimed to calculating process adopted but is justified by the assumption that sonic waves mediate the characteristics of the investigated materials, having length different by zero, in a finite width portion (first Fresnel Zone). Starting from a velocity model described at the beginning of the process, an iterative inversion progressively minimizes the gap between the times measured along the different measuring paths and those computed on the basis of the velocity model defined at the previous step. The processing algorithm used, for the computation of the path times between transmitter and receiver, takes into account the effects of the refraction of the sonic rays along the path, using a "pseudo-bending" "ray -tracing" procedure (Um and Thurber, 1983), which enables the reconstruction of the rays path as a function of the velocity field.

The results of the processing are plotted as colored tomograms, which show the variations of the P waves velocity field, along with the representation of the measuring paths as obtained from the ray-tracing processing. The selection and location of seismic source and receivers is decided based on the shape of structure, access to various parts and distance between two boreholes or faces.

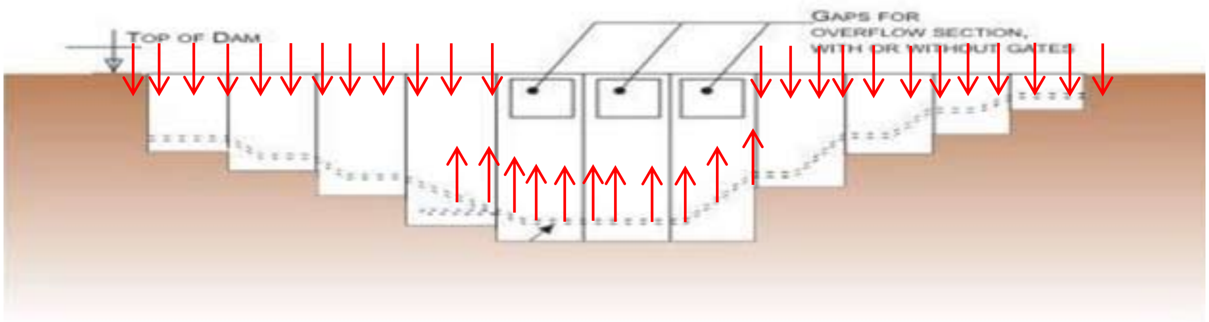

Fig. 4 : Arrangement for ERI on a dam top.

GEOPHYSCIAL INVESTIGATIONS FOR DAMS

The table given below provides a quick reference of techniques that can be used for internal condition assessment of dams.

GEOPHYSICAL METHODS	ISSUES AND CONCERNS						
	CONCRETE DAM		EARTH EMBANKMENT DAMS			MASONRY DAMS	
	CRACKS	DEGRADATION	WATER LEAKS	LANDSLIDE	SINK HOLES	WATER LEAKS	STRENGTH
Electrical Resistivity							
Streaming Potential							
Seismic Tomography							
ReMi							

For deciding upon survey geometry and scope of work, cross section and L-section drawings are sufficient. Additional information like known problems, site photographs and seepage data are also helpful in fine tuning scope of work.

ELECTRICAL RESISTIVITY IMAGING (ERI)

2D Resistivity Imaging uses an array of electrodes (typically 64) connected by multicore cable to provide a linear depth profile, or pseudosection, of the variation in resistivity both along the survey line and with depth. Switching of the current and potential electrode pairs is done automatically using a relay box. The computer initially keeps the spacing between the electrodes fixed and moves the pairs along the line until the last electrode is reached. The spacing is then increased and the process repeated in order to provide an increased depth of investigation.

The field work involves planting of electrodes on the dam top. The inter-electrode spacing is decided by depth of investigation required. If the dam does not have a spillway, one profile can cover entire length of the dam. In case of spillways, the profiles are on Non-Over-Flow (NOF) sections. To cover spillway section, the profiles are done by planting electrodes in the dam gallery roof. If the dam top is more than 5-6m wide, more than two parallel profiles are undertaken. Fig 5 below shows typical arrangement for ERI on a dam top.

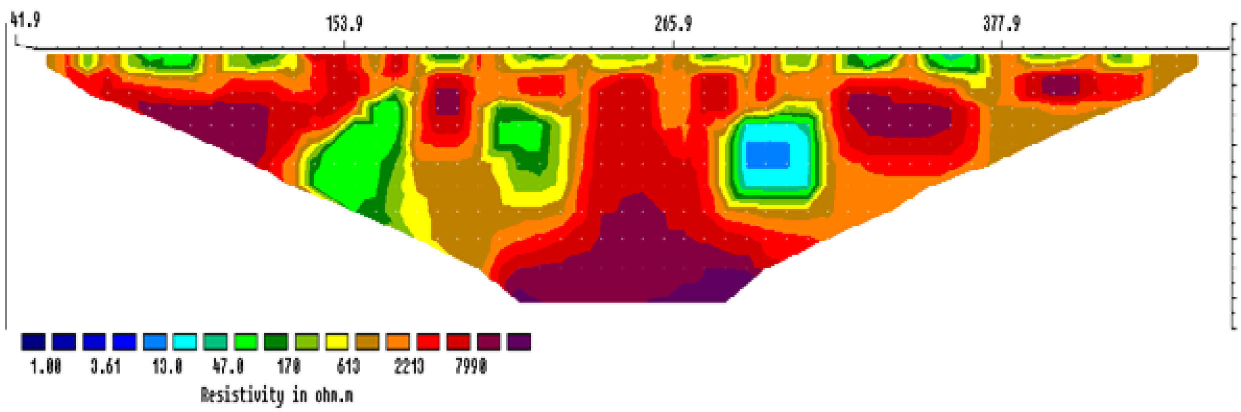

Fig. 5 : Resistivity Profile of a Dam

The maximum depth of investigation is determined by the spacing between the electrodes and the number of electrodes in the array. For a 64 electrode array with an electrode spacing of 2m this depth is approximately 20m. However, as the spacing between the active electrodes is increased, fewer and fewer points are collected at each 'depth level', until on the final level only 1 reading is acquired (see figure). In order to overcome this, the array is 'rolled-along' the line of investigation in order to build up a longer pseudosection.

The results of electrical surveys carried out on the crest of a dam are presented as vertical sections showing the electrical properties of the dam materials. Electrical currents travel along preferential pathways in the most conductive materials such as dam core composed on fine grained materials. Fig 6 below shows resistivity profile of a dam body.

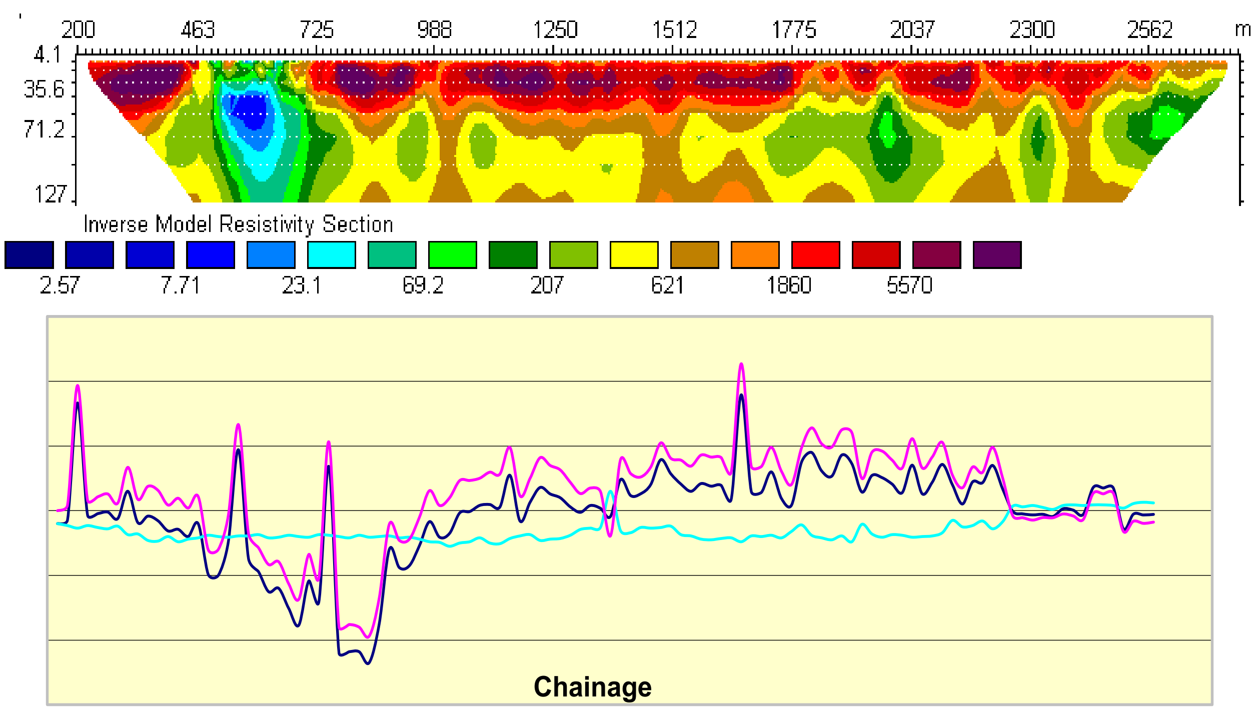

Fig. 6 : Combined ERI and SP Profiles to indicate seepage zones.

STREAMING POTENTIAL SURVEY (SP)

SP is measured by determining the voltage across a pair of non-polarizing electrodes using a high-impedance voltmeter. This inexpensive and deceptively simple data acquisition procedure requires special care and attention in order to reliably interpret and correct for sources of electrical noise that can mask the signal of interest. All noise sources – including time-varying telluric currents associated with solar and atmospheric activity, stray currents, and the corrosion of buried metal – must be recognized and measured. These noise sources can mask the relatively small signals associated with seepage anomalies. For this reason, telluric measurements and magnetic surveys should be carried out to assist in interpreting the SP data. Typically, SP anomalies on the order of tens of millivolts are associated with seepage anomalies of interest, although anomaly amplitudes largely depend on site-specific conditions.

Interpretation of SP measurements to infer seepage patterns and concentrated seepage flows ranges from simple qualitative to more advanced quantitative numerical modeling approaches.

Most common application of SP study is to identify the zones in the dam body through which seepage is taking place. The results are correlated with resistivity sections.

For earthen dams, more ERI and SP profiles are done to assess seepage paths. Fig 7 below depicts various options for ERI and SP profiles.

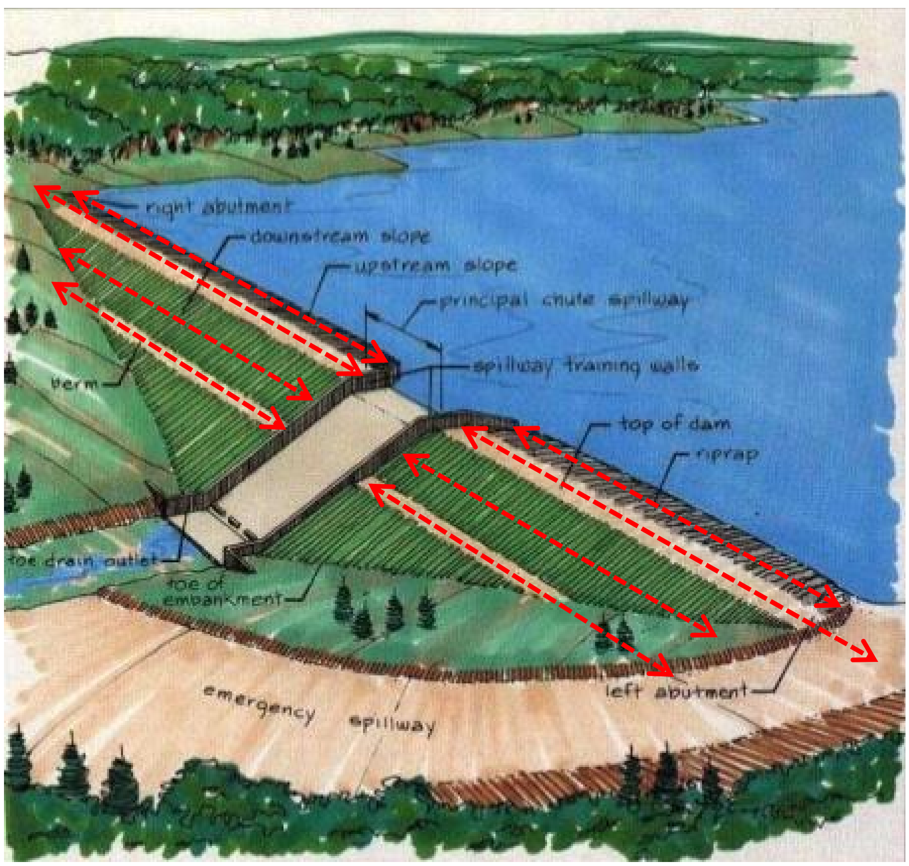

Fig. 7 : Various Options for ERI and SP Profiles on Earthen Dams

SEISMIC TOMOGRAPHY

Seismic tomography for dams is done along the length of the dam (L-section tomography). This is followed by cross face tomography and across downstream and upstream face of the dam. For L-section tomography, seismic energy is introduced through a hammer (with a hammer switch) from the dam top and receivers (high sensitivity vertical or 3600 geophones) are placed on dam gallery crown. Depending upon the length of the dam, the position of geophones is shifted to provide continuous data. Fig 8 shows shot points (points where seismic energy is transmitted) and receiver points in dam body.

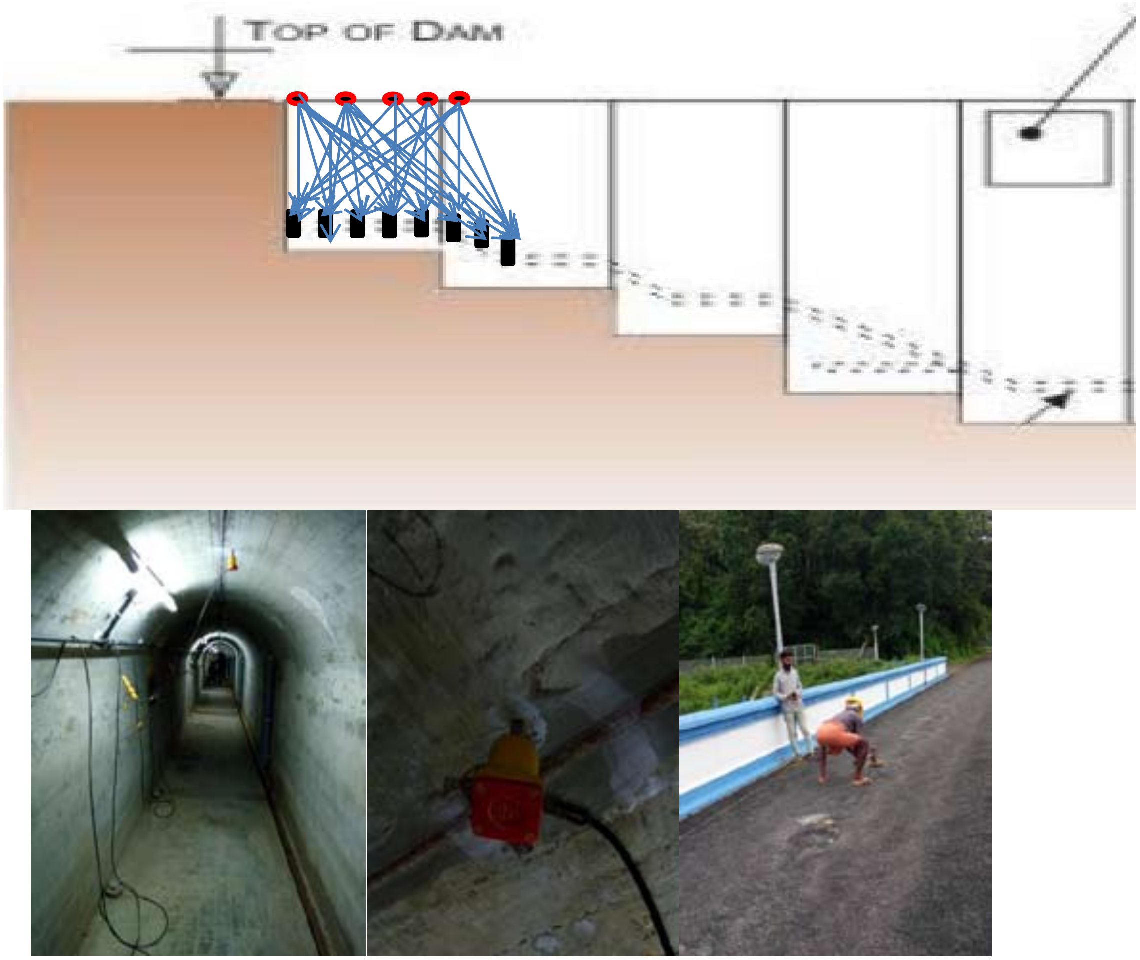

Fig. 8 : Shot Points and Receivers in a Masonry Dam

The results of L-section tomography are shown in Fig 9.

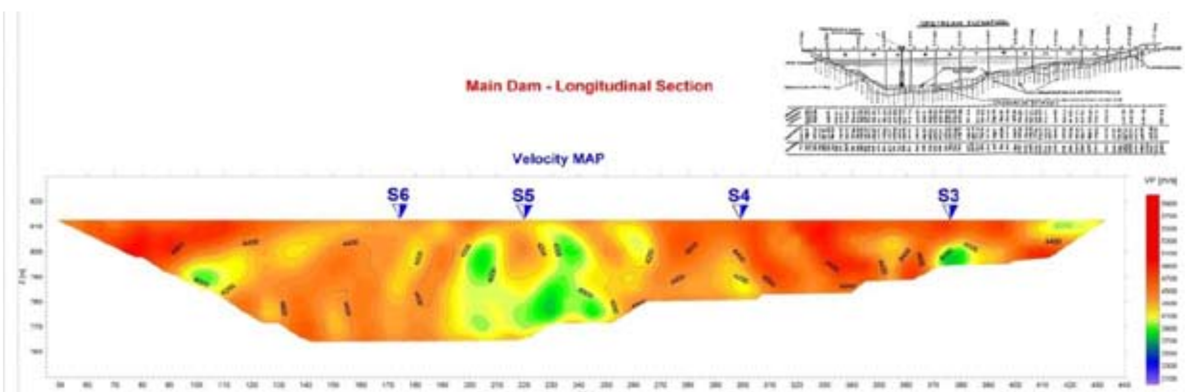

Fig. 9 : L-Section Tomogram of a Dam

Zones in lighter colors are having low P-wave velocity as compared to rest of the dam which is indicative of deterioration.

Cross face tomography is done in anomalous zones identified in L-section tomography. The fig. below shows arrangement of transmitter or seismic energy source (on upstream side) and receivers (on downstream side). The relative position of receiver and transmitter is interchangeable. For underwater upstream area, the seismic source is a sparker. Alternately, hydrophones can be used as receivers on upstream side. The choice of using sparker or hydrophone is dependent on site specific factors such as thickness of dam (particularly on lower side), depth of water etc. Fig 10 shows arrangement of receivers and transmitters across the dam faces. Planting of receivers and transmitters across the dam faces is a highly specialized activity requiring expert climbers who can move on steep dam faces.

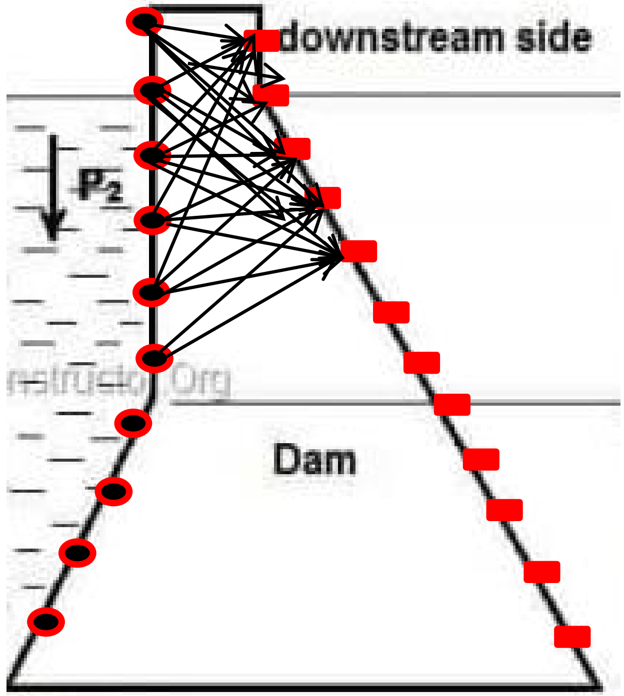

Fig. 10 : Arrangement of Receivers and Transmitters Across Dam Faces

Fig. 11 : Planting of Receivers and Transmitters Across Dam Faces

Results of cross face tomography are shown below. Zones showing low P-wave velocity are indicative of loss of strength and deterioration in the structure. Fig 12 shows a cross face tomogram of a spillway section.

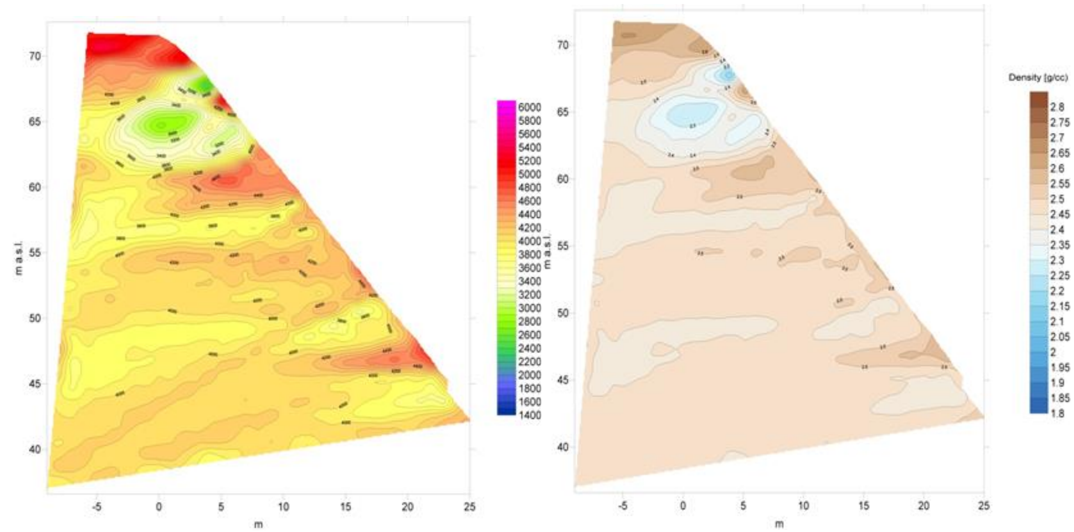

Fig. 12 : Seismic Tomography Across Spillway of a Masonry Dam

GEOPHYSCIAL INVESTIGATIONS FOR CANALS

Seepage of water through canal banks constitutes a major loss. According to a study undertaken in Kerala, these losses are as much as 40 to 50% as compared to designed losses of 13-15%. More often than not, the water does not reach the tail end user and full economic benefits of an irrigation project are never realized. In extreme cases, breach in a canal can lead to major catastrophe in inhabited areas adjacent to canals.

A typical canal length can be from few hundred meters to few hundred kilometers. In case of seepage being observed in any part of the canal, it is always beneficial to know seepage paths so that targeted repairs can be done. Precise knowledge of seepage zones is also necessary if there is a need to prioritize the repairs due to budget constraints.

A combination of ERI and SP along the length of the canal is used to identify active seepage zones. By doing a number of parallel ERI and SP profiles, it is possible to detect seepage paths. Depending upon whether the seepage in on both the banks or only one bank, the investigation can be planned. Fig 13 and 14 below show feasible arrangements of ERI and SP profiles. Fig 15 actual layout of ERI and SP profiles along a canal in Gujarat.

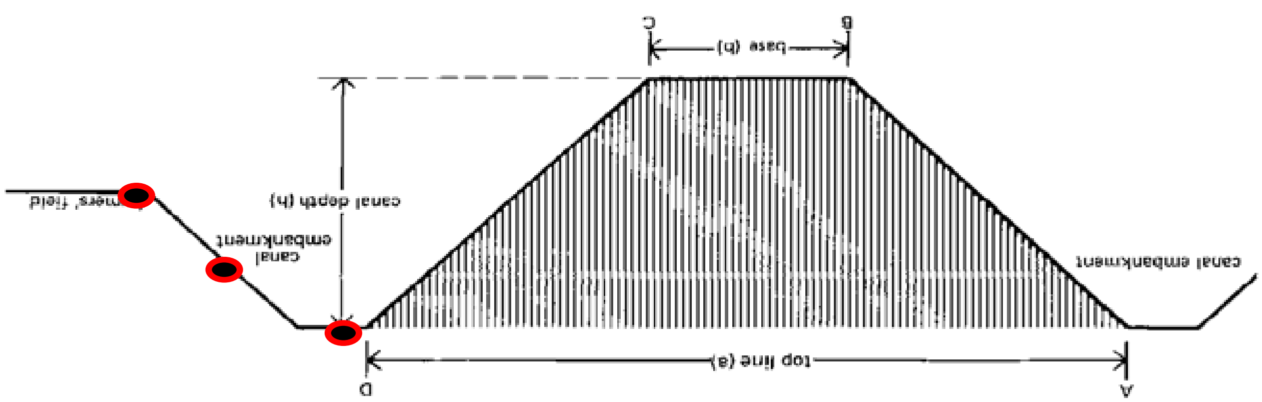

Fig. 13 : Arrangements of ERI and SP Profiles Along a Canal

Fig. 14 : Indicative ERI and SP Profiles Along a Lined Canal

Fig. 15 : ERI Profiles for canal seepage studies in Gujarat

The typical results of combined ERI and SP profiles are shown in Fig 16 below. A low resistivity saturated zone is observed in this profile from Chainage 1888m to Chainage 1904m (depth 9m to 18m)), associated with negative SP development. This is therefore an active seepage zone which should be treated to stop the seepage.

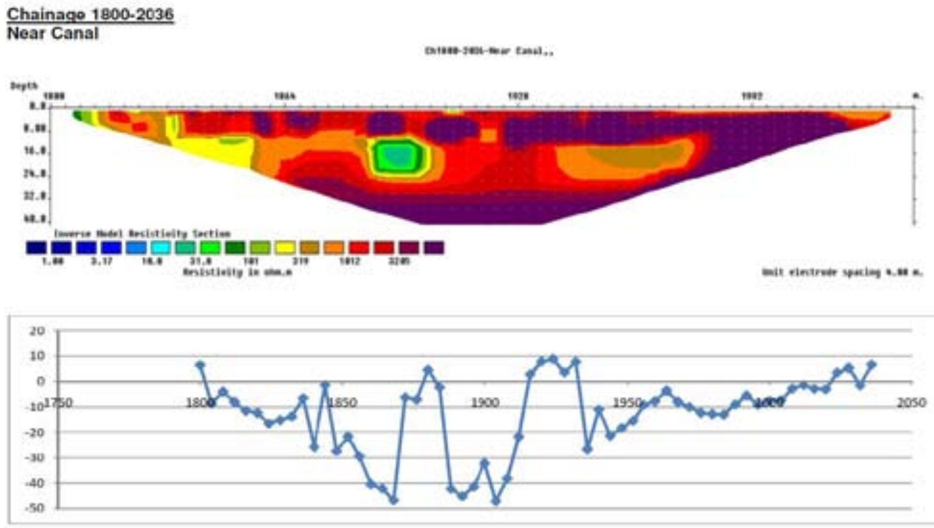

Fig. 16 : Results of Combined ERI and SP Profiles

INDIAN EXPERINECE

The remedial measures to address this enormous loss are done in a damage control mode. Starting from dams, very few dams have been investigated to establish the root cause of leakages and structural deterioration. This is despite the fact that there are many ambitious programs at Central and State levels to systematically rehabilitate and maintain the dams. Similar is the case with maintenance of canals. A large number of canals have transmission losses much in excess of design losses. There are many cases where water has not reached the tail-end even decades after construction of canals. This obviously means that full economic and social benefits of irrigation projects are not being realized. This also leads to dissatisfaction and negative perception about mega irrigation projects.

CONCLUSION

Our dams and canal networks are in urgent need of repair and rehabilitation. Going by the sheer size and enormity of this task, it is not possible to repair all these in a single go. Therefore prioritizing the remedial action is required. Geophysical techniques offer a very powerful tool which can be used be used to assess material state of dams & canals where the seepages and deterioration are very evident.

Contrary to popularly held notion, these geophysical investigations are very cost effective. With advancement in electronics and data handling capacities, geophysical instruments are becoming lighter and cheaper. This consequently makes geophysical investigations more versatile and economical to deploy. Based on the findings from geophysical investigations, a targeted and prioritized repair and rehabilitation action can be formulated. This will also allow planners and maintainers to take informed decisions rather than acting of hunch and gut feeling.

While the acceptance of geophysical investigations has been slow in India, there have been cases where these techniques have provided very good results. The need of the hour is to embrace these path breaking advanced techniques so that most optimal and judicious repair and rehabilitation actions can be adopted to conserve this precious gift from nature.

REFERENCES

1. Ms. K.D.Uchdadiya,Dr. J.N.Patel, Seepage losses through unlined and lined canals Int. Journal of Advanced Applied Maechanics. 2(2)(2014)88-91
2. Alison Saldanha, Bengaluru Wastes Nearly 50% Water Supply From Cauvery India Spend, 16 September 2016
3. G. Prabhakaran, Efficiency of irrigation projects only 40 p.c. The Hindu, 07 February 2003
4. Bikram Saha, A Critical Study of Water Loss in Canals and its Reduction Measures Int. Journal of Engineering Research and Applications, Vol. 5, Issue 3, (Part -4) March 2015
5. Vivek Kapadia, 6th Asian Regional Conference on Geo-synthetics November 2016
6. Sanjay Rana, Advanced geophysical Investigations for Dams International Dam Safety Conference, Trivandrum, India, February 2018