THE IMPORTANCE OF

# Wireline Logging for Dam Safety

**Dams have been an essential part of the development of human civilisation for centuries and operate mostly with quiet efficiency for a variety of purposes.**

They are often compound structures with complex ownership models operating within diverse regulatory frameworks. The objective of dam safety is to avoid dam failure whereby the cost of inspection and subsequent geotechnical investigation is minor when compared to the potential cost of catastrophic failure.

## Wireline Logging

Globally, most dams were built before the widespread availability of wireline logging for geotechnical investigation. Any significant new dam construction should include a programme of drilling and wireline logging for geotechnical and hydrogeological analysis. For any civil engineering project, the ground conditions represent the single biggest unknown which is especially relevant for dams due to the creation of artificial hydraulic pressures and the consequences of catastrophic failure. Wireline logging can provide valuable ground characterisation data for the design process and will form a permanent record of conditions before the dam was constructed.

Once a dam becomes operational, routine inspection and maintenance of the dam and its associated structures will be necessary to ensure the ongoing safety of the dam. This is applicable for all dams, though the level and frequency of inspection may be dictated by the size or criticality of the particular dam. Whether identified from routine inspection or in response to changes it may be necessary to conduct detailed ground investigation including drilling and the collection of wireline derived data to determine risk or aid rehabilitation. Any engineering assessment of a dam should include geotechnical analysis, as it is estimated that 70% of concrete dam failures are due to geology and 40% of embankment dam failures are due to foundations.

Wireline logging can provide unique data sets in three key areas of ground characterisation for dams, pertaining to structure, strength and hydrogeology.

For structure, televiewers produce orientated images of borehole walls with geological features, notably bedding planes and fractures, delineated in terms of dip angles and direction.

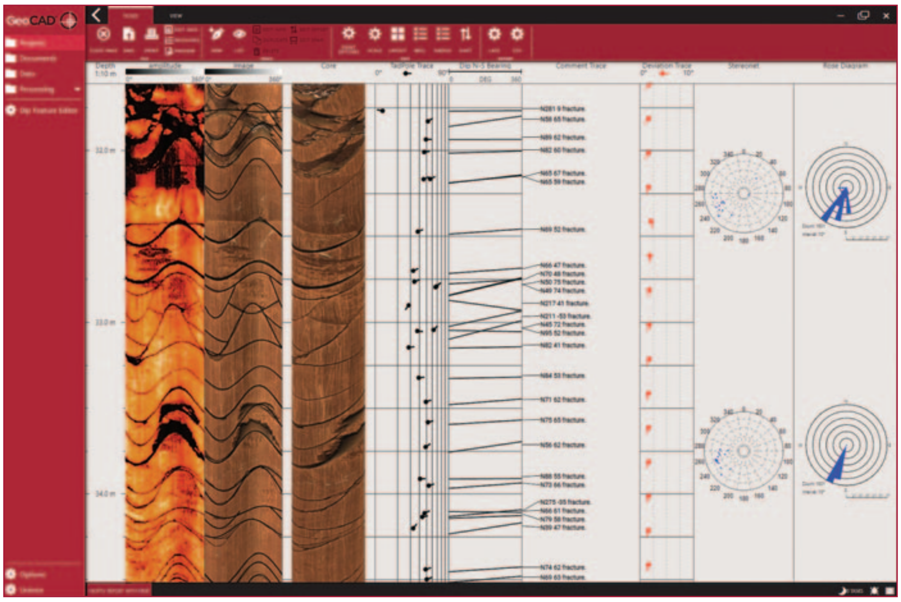
Potential hazards can be identified such as thin shear zones, weak or continuous joints, weathered bedrock, solution features, fault zones, bedrock profiles and volcanic rocks. The image on the right shows an example of the high-resolution images that can be obtained using an optical televiewer showing bedding layers, fractures and wash-out zones indicative of weak formations.

If there is a lack of historical information regarding how foundations were constructed, or if problems with foundations are suspected, televiewers can provide permanent records which are informative and legally binding. For concrete and masonry dams test boreholes can be drilled into parts of the structure to allow for video inspections to detect cracks or other signs of deterioration.

Ground strength can be determined by measuring P and S wave velocities using a sonic probe, and by combining this with density measurements small strain moduli can be calculated in formations and foundations. A borehole geometry probe with x-y callipers can be used for stress analysis which can be useful for characterising hazards such as shear zones or shrink/swell.

Understanding the hydrogeology beneath and in the vicinity of dams is vital to ensure stability, as the artificial hydraulic pressures can induce detrimental effects such as uplift or unwanted seepage and erosion. Hydrogeologists have an array of probes available to them to characterise the subsurface conditions including electric probes to measure resistivity, neutron probes to measure porosity, NMR probes to measure porosity, permeability and transmissivity, temperature/conductivity probes and flowmeters to identify flows and video inspections to investigate ducts and cavities. A combination of these probes can be used to characterise potential hazards including solution features, shrink/swell potential, settlement, and slide potential.

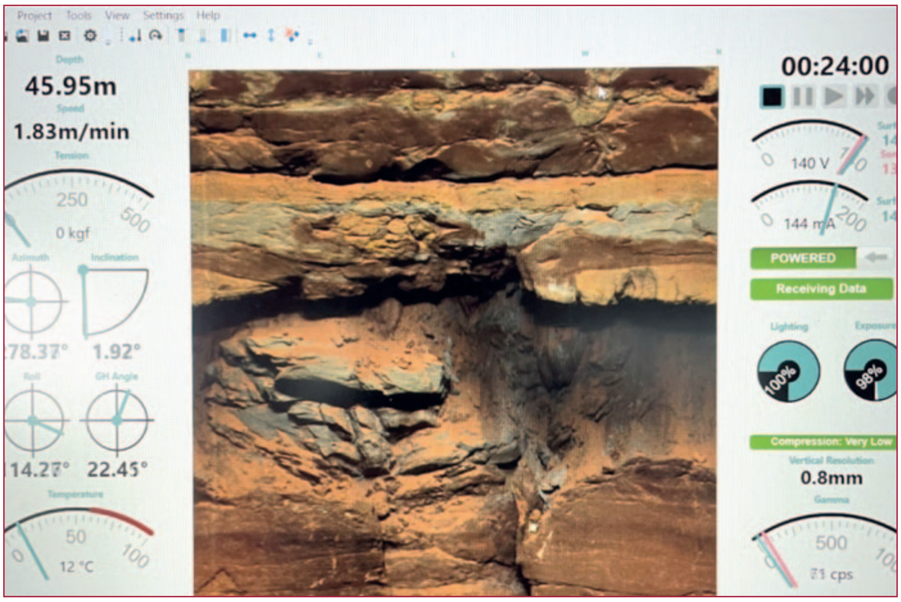
Due to sometimes complex hydraulic pressure profiles, any drilling programme conducted in the vicinity of a dam needs a comprehensive risk assessment to be conducted by a competent body to consider the potential for drill induced problems such as artesian blowout, hydraulic fracturing, erosion, contamination, and heave. This should also include recommendations for drill completion and grouting once the borehole investigation is finished.




*GeoCAD® output showing oriented features from HI-OPTV® and HRAT® televiewers.*

## Dams through Time

The earliest building of dams is attributed to Mesopotamia and the Middle East for control of water levels, with the oldest known being the Jawa Dam in modern day Jordan circa 3,000BC. The use of dams gradually spread across the ancient world to Egypt, India, Yemen, Turkey, and China. By the second century AD the Romans had taken the concept of dams a stage further by creating reservoir dams that would retain permanent water supplies for population centres, aided by their




*The clarity of the Hi-OPTV® as illustrated in the above image can clearly identify fractures, voids, bedding, and the changing geology at given depths below ground level.*


*Evening view of the Hoover Dam in Boulder, Nevada, USA.*

development and widespread use of concrete and waterproof hydraulic mortar. Early uses for dams also included providing hydropower for raising water and milling. By the 12th century AD the Netherlands had begun a programme of dam building to manage water levels and to provide protection from sea water ingress in their low lying country. In the nineteenth century advances in materials and the application of mathematical techniques allowed for the construction of masonry and subsequently concrete arch dams. Population expansion in the twentieth century saw the proliferation of large dams throughout the world with notable examples being the Aswan Dam in Egypt (1902) and the innovative Hoover Dam (1936) in USA. Currently it is estimated that there are over 800,000 dams worldwide with around 58,000 being classified as large dams (usually over 15m height).

## Classification of Dams

The purpose of a dam is to store or restrict water, wastewater, or liquid materials for any of the following uses: flood control, water supply, irrigation, energy generation, containment of mine tailings, recreation, inland navigation and pollution control. The classification of dams is important, not only for statistical purposes, but also for the potential impact on funding available for investigation and rehabilitation. Dams can be classified in three categories: function, structure, and construction materials.

There are four basic types of dams based on function: storage, diversion, detention, and cofferdams. Storage dams are the most common type and are used to store seasonal rainfall for water supply. Diversion dams have a low head and are used to divert water often into canals and ditches for irrigation. Detention dams are used for flood control by retarding downstream flows. Cofferdams are temporary structures designed to hold back water usually in construction sites. Dam structure can similarly be defined by four types: gravity, arch, buttress, and embankment. Gravity dams require solid foundations and are large structures which use the weight of the dam itself to resist horizontal water pressure and are often found in low wide valleys. Arch dams require solid foundations and sidewalls and are the most spectacular, using curvature to direct forces into steep valley sides. Buttress dams come in many variants, but they all comprise a sloping deck supported by buttresses. By far the most common type of structure is the embankment dam, which is constructed from natural materials, often sourced locally. For construction material the three dam types are: masonry, steel and timber, with the majority of dams of interest being masonry, which includes the use of rock, concrete and earthen materials.

## Dam Safety and Maintenance

The expected life of a dam is often measured in decades or centuries during which time many changes can occur which affect its reliable working. Gradual and rapid changes may push the dam beyond its design limits and in the worst case can lead to complete failure. Ultimately, the responsibility for maintaining a safe dam and avoiding catastrophic failure rests with the owner.

Inspection and maintenance of all dams is essential to avoid failure. Risk assessments, which may be a legal requirement for large dams, bring into focus the consequences of catastrophic failure which may include potential loss of life, destruction of property and disruption to businesses, urban areas and agriculture.

To maintain efficient and safe operation of dams, operators and owners should conduct regular inspections using approved dam safety specialists. The level and frequency of these inspections will be in accordance with any local regulations, and as a minimum will include a comprehensive visual inspection looking for changes that have occurred since the previous inspection. Depending on the size and complexity of the dam there may also be regular data collection, sometimes automatic, monitoring water levels, flow rates, structural movements and seismicity. Early identification of the pre-cursors to failure is essential.

The records kept by owners for their dams should include a documented routine inspection and maintenance plan, with data and results forming a legally binding part of a dam history file. In the event of a failure these records will come under scrutiny, whereby deficiencies may have severe legal and financial consequences.

Routine maintenance and inspections can identify potential problems and drive the need for further investigation including geotechnical methods. Geotechnical Engineers, Civil Engineers, Hydrologists and Hydrogeologists now have an array of investigative tools at their disposal, many of which were not available when the dam was built.

In addition to further assessment due to potential hazards identified from routine monitoring and inspection there are many other reasons why a geotechnical assessment may be required. Old dams may have little or no data available and further assessment may be a pre-requisite for proposed rehabilitation. Following an event or incident leading to a near miss or from a risk


*Polavaram, Andhra Pradesh / India - December 25th 2018 : National project Polavaram Dam under construction on the Godhavari river, India.*

assessment a need for data may be identified. Change of usage or increased local risks as well as non-local effects from climate change or seismicity may also drive the need for a geotechnical investigation. The resulting data can then add into the assessment of the dam's stability and its hydrology and hydraulic characteristics.

## Failure Modes of Dams

Dam failure can be defined as the collapse or movement of part of a dam or its foundation so that the dam cannot retain water and the avoidance of dam failure is the primary goal of any dam safety programme. By understanding and analysing the potential risks to a dam, measures can be put in place for mitigation. Potential Failure Mode Analysis (PFMA) is a common methodology used for this purpose. The benefits from PFMA may include recommendations for changes to monitoring programmes, identification of previously unconsidered failure modes, identification of potential failure modes due to mis-operation or human factors and identification of additional data required for the analysis of potential failure modes.

The most common failure mode is overtopping, which occurs when the water level exceeds the top of the dam which can be a precursor to complete dam failure. Water levels can exceed design parameters due to excessive rainfall, flooding and from storm effects caused by wind and waves. Inadequate spillway design or maintenance issues such as blockages may also lead to overtopping.

For embankment dams a common cause of failure is due to seepage. This can occur beneath the dam structure and cause problems due to erosion (piping) or heave from uplift due to the hydraulic pressure. Piping can also occur through the body of embankment dams caused by backward erosion of construction materials. Hydraulic fracturing can also occur if seepage takes place in supposedly impervious materials due to the hydraulic pressure.

For all dams, structural failure can be catastrophic and may be the result of poor design, use of substandard materials, poor workmanship or lack of supervision and maintenance. Structural failure can occur during normal operations but is more likely to result from a specific incident such as flooding, storm damage or seismicity or even during the construction phase or at time of first fill. As a dam ages settlement and the gradual deterioration of materials can increase the risk of structural failure.

## Resources and Funding

The construction of large dams raises complex financial questions regarding who will pay the costs. There is no single model for the financing and most commonly each dam will involve a unique approach. Depending upon the scale and impact of the proposed dam many stakeholders may be involved including government, local government, banks, including the World Bank, friendly foreign governments, corporations, and private businesses. In all cases, once constructed, the dam will have an owner who is thereafter responsible for the ongoing safety of the dam.

| Acronym | Organisation | Provision |
|---|---|---|
| ASDSO | Association of State Dam Safety Officials | Resources for dam safety and funding |
| USACE | US Army Corps of Engineers | Owns and operates over 700 federal dams |
| NID | National Inventory of Dams (USACE) | Reference list of USA dams |
| IWR | Institute for Water Resources (USACE) | Resources for water management |
| FEMA | Federal Emergency Management Agency | Grants for hazard mitigation |
| USSD | United States Society on Dams (ICOLD) | Resources for dam safety |
| FERC | Federal Energy Regulatory Commission | Licenses and inspects hydroelectric projects |
| NDSP | National Dam Safety Program (FEMA) | Grants for dam safety |
| HHPDR | High Hazard Potential Dam Rehabilitation | Grants programme administered by FEMA |
| ASCE | American Society of Civil Engineers | Resources for civil infrastructure |

*Figure 1: Focus on Funding for Dam Safety in USA.*

Ownership of dams lies in the hands of many types of organisations, from national governments through to private individuals. There will national differences in regulatory frameworks and classifications which may affect what resources are available for dam rehabilitation. So how do dam owners find out how to access potential funds available?

For the largest of dams, defined as over 15m in height or between 5m and 15m in height with a capacity over 3 million cubic metres, they will most likely be registered on the International Commission On Large Dams (ICOLD) database. ICOLD has affiliated national committees in over 100 countries, 40 of which have their own websites. ICOLD and these national sites provide useful information and links to partner organisations concerned with dam safety and funding.

The level of grants available for dam safety and rehabilitation will usually be a government decision, though the allocation process can be complicated with allocations often through government and local government organisations and programmes. The qualification for funding may require specific classification, risk analysis and the drafting of an emergency action plan. The need for rehabilitation is often identified by routine inspections by qualified dam safety experts and appointed engineers. These personal may be able to advise on funding available. In most cases the national or local government and regulatory authorities would be a good place to commence enquiries about funding.

For the United States dam owners seeking funding for dam safety improvements and rehabilitation should initially contact their state government's dam safety office for advice. The Association of State Dam Safety Officials (ASDSO) also provides information and guidance on funding. Further resources can be found in the table of organisations above.

With 90,000 dams in the USA and an average age of 60 years the need for federal assistance for rehabilitation has been recognised with funding being made available through the Bipartisan Infrastructure Law. The package is worth $1.2 trillion over 5 years, but the amount available for dams remains unclear, while awards will likely be on a project-by-project basis. ASDSO have estimated that the cost of rehabilitation of the nations non-federal dams is $76 billion. Over the next five years, the Federal Emergency Management Agency (FEMA) will award $733 million through the Bipartisan Infrastructure Law in dam safety grants to states and territories to enhance dam safety and rehabilitate or remove aging dams.

An ongoing allocation of grants available to states is through the High Hazard Potential Dam Rehabilitation programme (HHPDR) administered by FEMA. "High Hazard Potential" is a classification standard for any dam whose failure or mis-operation will cause loss of human life and significant property destruction. This programme provides technical, planning, design and construction assistance in the form of grants for the rehabilitation of eligible high hazard potential dams, with $22 milion awarded in 2022.

The Dam Safety Group (DSG) brings together a group of member companies, both instrument OEMs and service contractors, ideally positioned to use proven geophysical technologies, services and products for Dam site investigation and monitoring together with seismic monitoring via earthquake early warning and evaluation systems.

**Further information can be found at the DSG website: www.damsafetygroup.com**

| Company | Technology | Website |
|---|---|---|
| Robertson Geo | Wireline Logging | www.robertson-geo.com |
| Iris Instruments | Resistivity Imaging | www.iris-instruments.com |
| Geometrics | Seismic Tomography | www.geometrics.com |
| GSSI | Ground Penetrating Radar | www.geophysical.com |
| Kinemetrics | Seismic Monitoring | www.kinemetrics.com |

*Figure 2: The Dam Safety Group.*