



**CLIMATE-RESILIENT DAMS AND  
HYDROPOWER INFRASTRUCTURE  
INTEGRATING  
ENVIRONMENTAL SUSTAINABILITY  
IN PLANNING AND DEVELOPMENT**



**From Visual to Digital Intelligence  
UAV & AI-based Digital Condition Assessment  
for  
Dam Safety & Hydropower Infrastructure**

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**Technical Advisor & National Level Expert, NWRWS&K Dept., Govt. of Gujarat  
(Hydraulic & Water Resource Engineering)**



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Dam Safety Review Panel (Govt. of Gujarat)

Technical Advisor & Consultant - Indian Institute of **Technology** (IITGn) Gandhinagar

Technical Advisor & National Level Expert, NWRWS&K Dept., Govt. of Gujarat

(Hydraulic & Water Resource Engineering)

## Comprehensive Inspection of Over 240+ Dams & Water Retaining Bodies India & Abroad

**Domain:** Dam, Hydropower, Pumped-Hydro Power Projects, Barrage, Canal, Power, Water, Irrigation and Renewal Energy, Tunnel, Metro, Railways, Bridges & Flyovers, Powerhouses, Critical Infrastructure, Underground Utilities and Urban Flooding Smart

- Dam Safety Expert | Instrumentation (GeoTech, Seismo, Geodetic, HydroMet) |
- Dam Inspection, Surveillance & Monitoring | SCADA/IoT Gate & Canal Automation (ARMAC) | Dam Break Analysis, EAP/ERP & Early Warning Systems
- Structural Health Assessment
- Flood Forecasting & Disaster Management | Geotechnical & Geophysical Investigations
- UAV/ROV Survey, Bathymetry & Sedimentation | SOP, O&M, Digitalization &
- Procurement & Tender Engineering (NCB/ICB, GeM) | Dam Safety Act-2021
- Water Management & Accounting | IT, ICT, Cybersecurity & Forensics
- Empaneled Lecturer & Professor of Practice (PoP)



## FROM VISUAL TO INTEGRATED DIGITAL INTELLIGENCE: A MULTI-LAYER DIGITAL CONDITION ASSESSMENT & TECHNOLOGY-ENABLED INSPECTION FRAMEWORK USING UAV & AI/ML BASED DATA FUSION FOR SAFETY EVALUATION OF DAMS AND HYDROPOWER STRUCTURES

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*Panel Member, Dam Safety Review Panel (DSRP), Govt. of Gujarat*

*Technical Advisor & Senior Consultant, Indian Institute of Technology (IITGn) Gandhinagar*

*National Level Expert and Consultant for Narmada Water Resource Water Supply and Kalpsar Department (NWRWS&K Dept.), Govt. of Gujarat*

*(Specialist in Dam Safety| Inspection & Investigation |Instrumentation| IT, ICT & Automation | SHM | Surveillance| [Water Resources & Hydraulics Engineering]*

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### SYNOPSIS

The maintenance of global civil, especially the critical infrastructure including bridges, dams, culverts, and maritime structures represents a major engineering and economic challenge of the twenty-first century. These assets are continuously subjected to mechanical loading and aggressive environmental conditions, leading to progressive material deterioration. Conventional inspection practices, primarily based on manual visual observations and tactile techniques such as hammer tapping and chain dragging, remain widely used but are inherently subjective, labor-intensive, costly, and often expose inspectors to significant safety risks, particularly in hazardous or difficult-to-access environments.

Digital Condition Assessment (DCA) has emerged as a paradigm shift toward objective, data-driven structural health monitoring. A critical enabler of this transition is the deployment of Unmanned Aerial Vehicles (UAVs) integrated with multi-modal sensing technologies, including high-resolution RGB photogrammetry, infrared thermography, LiDAR, and acoustic-based systems. These technology-enabled “fly-by” inspections allow rapid, non-contact data acquisition and facilitate the creation of high-fidelity digital twins for remote identification and quantification of both surface and subsurface defects.

This study examines the technical foundations, system integration frameworks, and diagnostic capabilities of UAV-based multi-sensor platforms for detecting a wide range of concrete pathologies, from cracking and spalling to complex deterioration mechanisms such as alkali-aggregate reaction and reinforcement corrosion. The integration of UAV-acquired datasets with artificial intelligence and machine learning techniques enables automated defect detection, anomaly recognition, trend analysis, and predictive maintenance, significantly enhancing inspection reliability and decision-making. Recognizing the limitations of traditional visual inspections particularly for ageing dams and hydropower infrastructure exposed to climate-induced extremes, this paper proposes an integrated, multi-layer digital intelligence framework for comprehensive condition assessment. The framework systematically combines multi-scale UAV inspections, ground-based and embedded instrumentation, historical performance records, and advanced data fusion techniques within a unified digital ecosystem. AI/ML-driven analytics are employed to assess structural, geotechnical, hydraulic, and electro-mechanical components, enabling early-stage distress identification, risk prioritization, and proactive maintenance planning.

Digital Condition Assessment offers a scalable, objective, and repeatable approach for strengthening dam safety management in India by facilitating a transition from reactive inspections to predictive, risk-informed asset management. The proposed framework can be readily adapted to Indian dam safety practice by aligning consequence classes with national hazard classifications, integrating digital inspection outputs into Dam Safety Reports, Emergency Action Plans, and instrumentation programs, and correlating deterioration trends with hydrology, seismicity, gate operations, and reservoir management data. Case studies referenced in this study demonstrate the practical implementation of UAV- and AI-enabled digital inspections, the seamless integration of heterogeneous datasets into decision-support systems, and a measurable shift from qualitative assessments to quantitative, performance-based lifecycle management across diverse dam types.

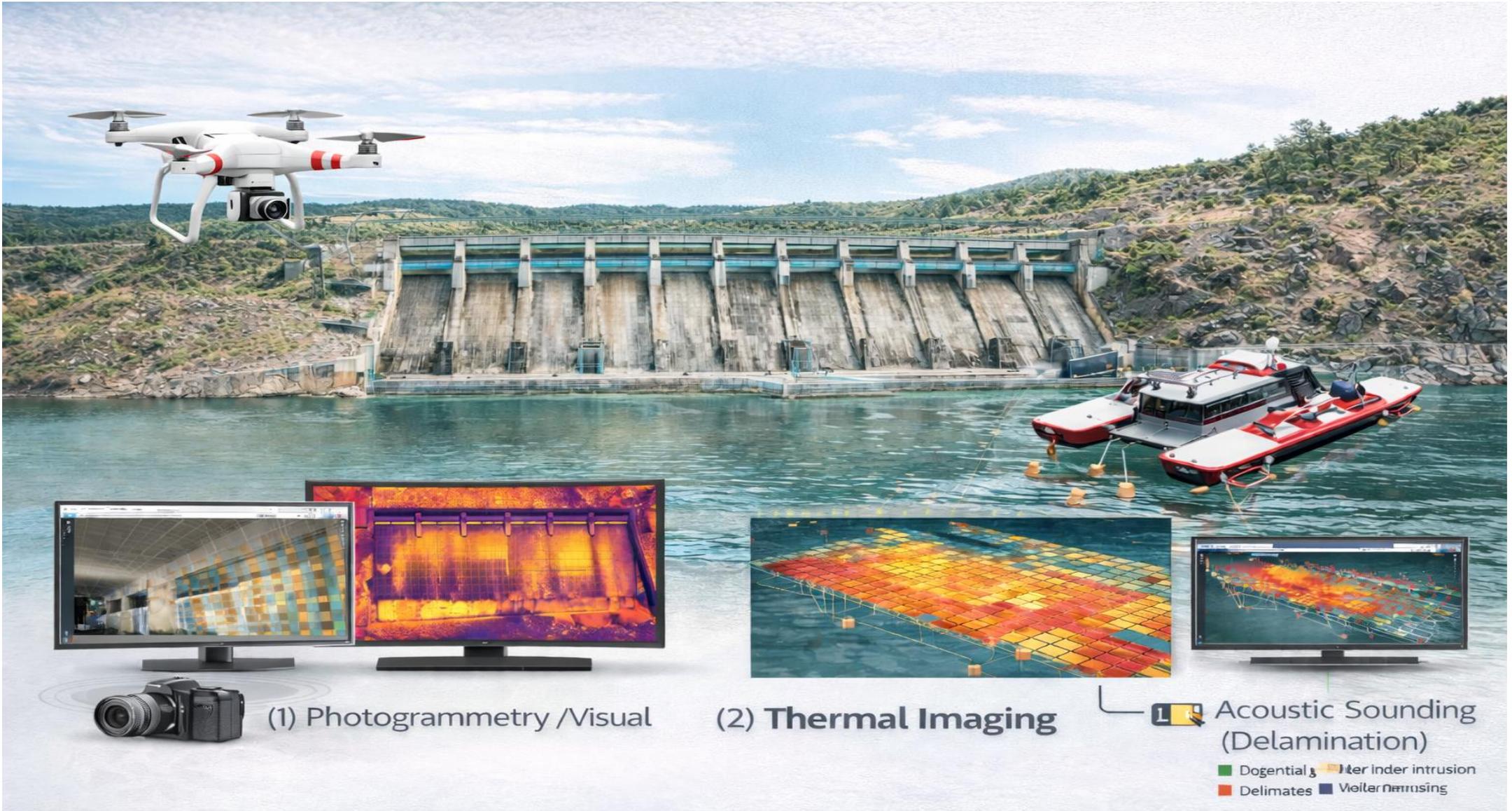
**Key Words:** #CriticalInfrastructure #CivilInfrastructure #DamSafety #HydropowerInfrastructure #AgingInfrastructure #DigitalConditionAssessment #StructuralHealthMonitoring #DamSafetyIndia #RiskInformedAssetManagement #PredictiveMaintenance #LifecycleManagement #NonContactInspection #UAVInspection #DroneBasedInspection #MultimodalSensing #RGBPhotogrammetry #InfraredThermography #LiDARScanning #AcousticSensing #DigitalTwin #ArtificialIntelligence #MachineLearning #DataFusion #AutomatedDefectDetection #DecisionSupportSystems #ConcreteDeterioration #CrackDetection #Spalling #ReinforcementCorrosion #AlkaliAggregateReaction #ClimateResilientInfrastructure #EmergencyActionPlan #DamSafetyReports #InstrumentationAndMonitoring



**DIGITAL DAM INSPECTION - UAV/AUV THERMAL MAPPING**

-10°C -10°C 10°C 10°C 10°C 10°C 30°C 30°C 30°C 30°C 80°C 80°C 80°C 60°C 60°C+

# Multi-Layer Digital Condition Rapid Health Assessment



(1) Photogrammetry / Visual

(2) Thermal Imaging

Acoustic Sounding (Delamination)

- Dogential
- Water under intrusion
- Delimites
- Veiter nrrsing

# Current Practice of Inspection: Completely Visual





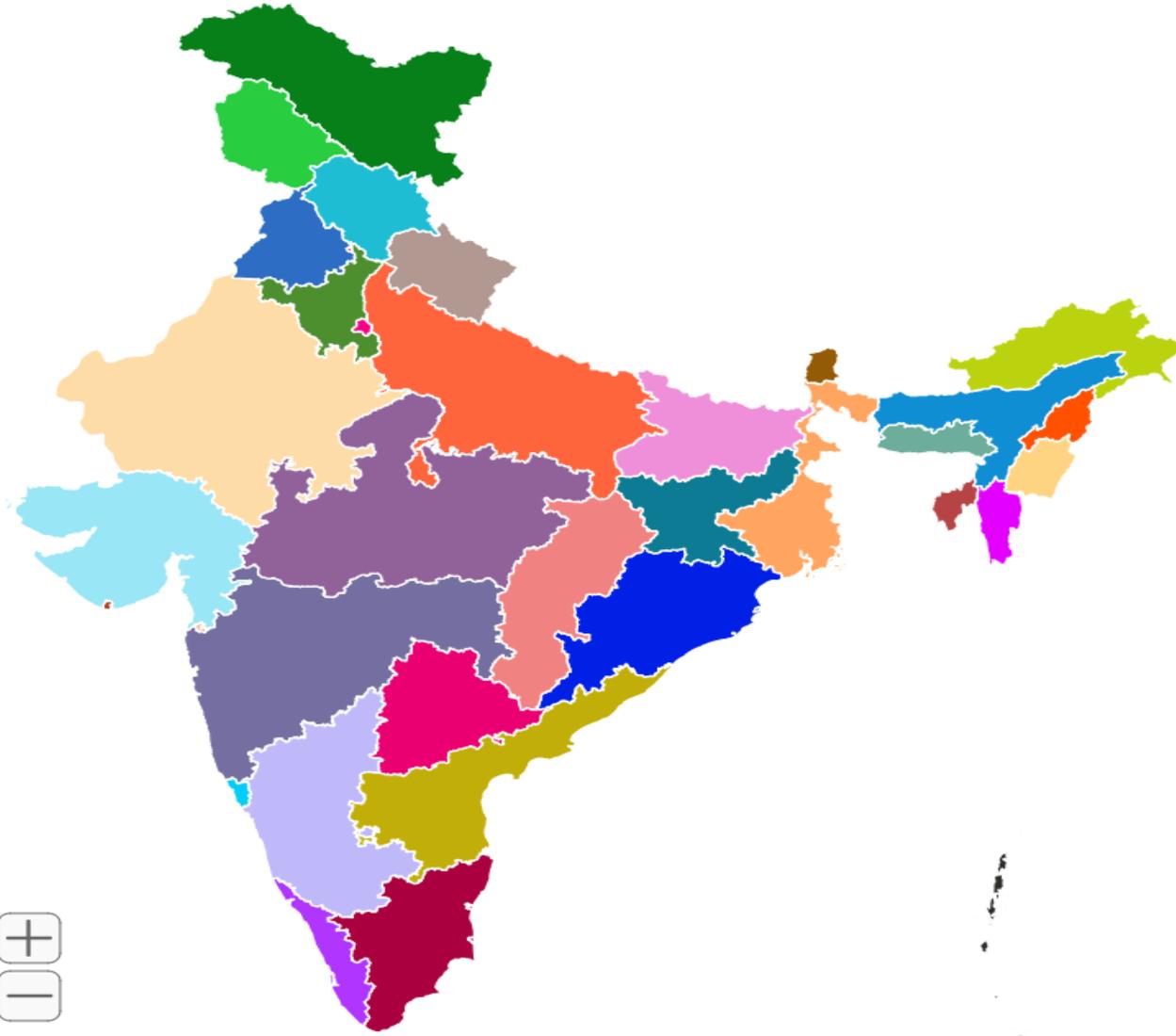
# Total No. of 6,628 Specified Dam in India as per April 2025 NRLD



Select State ▼



**DHARMA**  
Dam Health And Rehabilitation Monitoring Application



**6628**  
Total No. of Specified Dams in India

**330020.00 MCM**  
Gross Storage

**265545.00 MCM**  
Live Storage

**291**  
Dams Age Above 100 Yrs.

**1390**  
Dams Age 50 - 100 Yrs.

**2754**  
Dams Age 25 - 50 Yrs.

**2110**  
Dams < 25 Yrs.

**2460**  
Height (10-15m)

**3440**  
Height (15-30m)

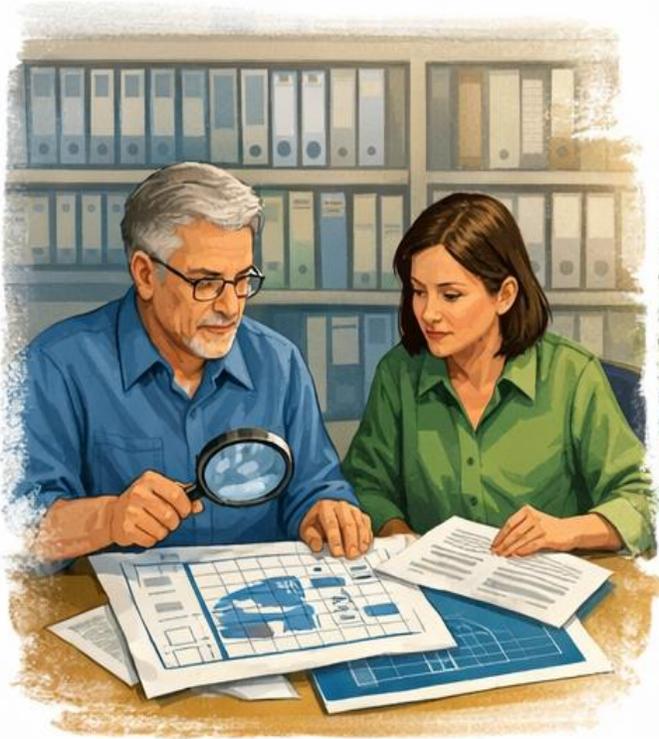
**702**  
Height (30-100m)

**26**  
Height (>100m)

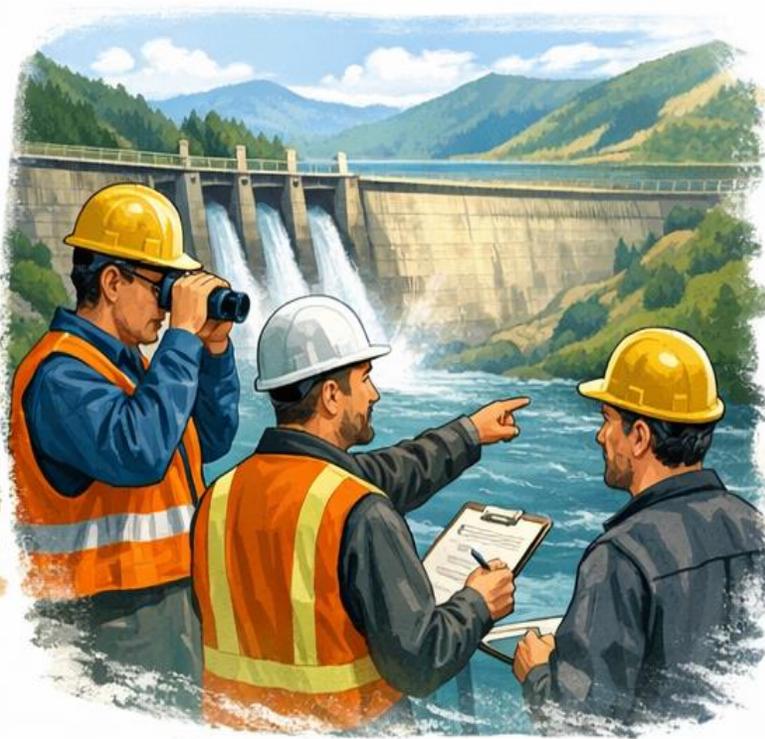
Updated as on Date: April 2025



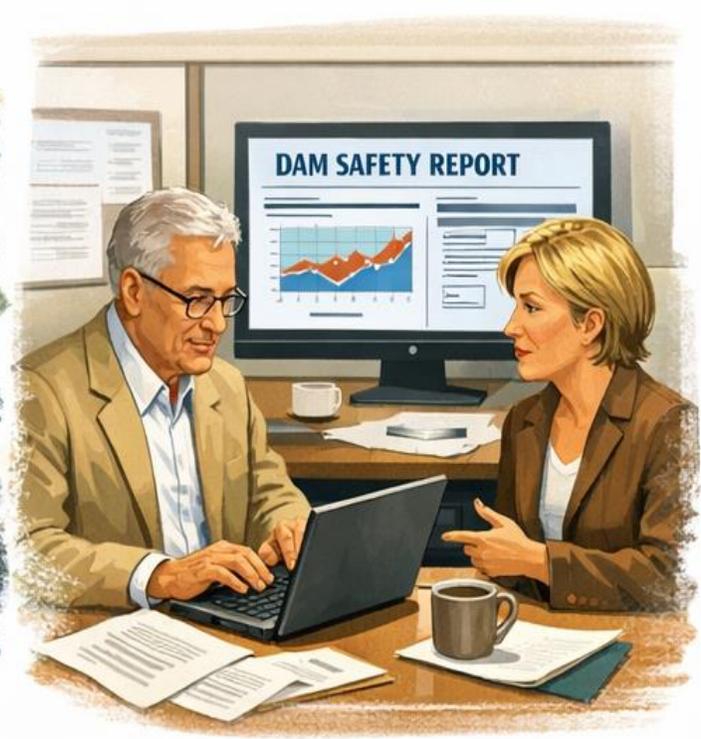
# How DSRP Committees Work



**1. Project Documents Studies**



**2. Dam Site Visit & Comprehensive Inspections**



**3. Report Preparations & Submissions**

# Let Take 3 Minimum Scenarios...

## Comprehensive Inspection of Dam (Visual) by DSRP Committee as per CWC Guideline 2018 up to Report Submission

Scn.	Task	No. of Dams (Specified Cat)	No. of Days per Dam (Max to Min.)	Total Days	Months	Total Years	Nos. of DSRP Active Committee in India (If So)	Period of Yrs required
1	From Visual Inspection up to Report Submission by DSRP Committees	6628	60	3,97,680	13,256	1,104.67	30	36.82222
2	From Visual Inspection up to Report Submission by DSRP Committees	6628	45	2,98,260	9,942	828.50	30	27.61667
3	From Visual Inspection up to Report Submission by DSRP Committees	6628	30	1,98,840	6,628	552.33	30	18.41111

This is applicable only if the DSRP Committee commences work **without any leave or gaps** between days, ensuring a continuous process covering Project Study, Field-Level Inspection, and Report Submission.





Remember this is Repetitive Exercise after Every 3, 5 and 10<sup>th</sup> Year

# VISUAL INSPECTION OF DAMS

Repetitive Task Scenario of Dam Inspections by DSRP Committees as per Regulatory Compliance

**EVERY 3 YEARS**

Periodic Inspection by DSRP Committee



**EVERY 5 YEARS**

Periodic Inspection by DSRP Committee



**EVERY 10 YEARS**

Periodic Inspection by DSRP Committee



**AS PER REGULATORY COMPLIANCE**

**DSRP COMMITTEE**

ENGINEERS, GEOLOGISTS & SAFETY OFFICIALS



**CHECKING  
CRACKS & SPILLWAYS**



**MONITORING  
SEEBAGE & CONCRETE**

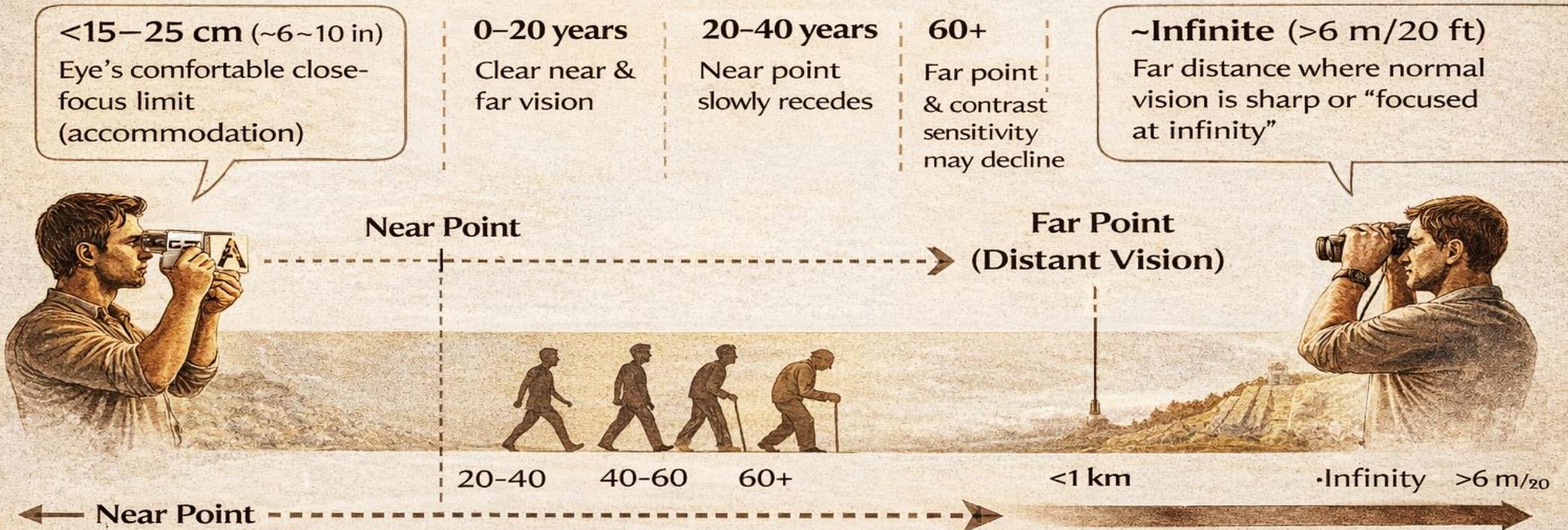


**EXCLUDING SPECIAL INSPECTIONS IN CASE OF HIGH FLOODING OR EVENT OF EARTHQUAKE**



Climate-Resilient Dams and Hydropower Infrastructure: Integrating Environmental Sustainability in Planning and Development

# Human Visual Distance: Near & Far Points (With Age-Related Changes)



<math>< 15-25 \text{ cm}</math> (<math>\sim 6-10 \text{ in}</math>)  
Eye's comfortable close-focus limit (accommodation)

0-20 years  
Clear near & far vision

20-40 years  
Near point slowly recedes

60+  
Far point & contrast sensitivity may decline

<math>\sim \text{Infinite}</math> (>6 m/20 ft)  
Far distance where normal vision is sharp or "focused at infinity"

← Near Point

→ Far Point (Distant Vision)

20-40    40-60    60+

<math>< 1 \text{ km}</math>    ·Infinity    >6 m/20

- Age progression for 1:0'0"y1
  - 1 arcminute detail discernible at distance
  - Readable letter height at 1 km: ~30 cm

## Age-Related Changes

- Near point recedes (presbyopia)
- Far vision may decline due to cataract, macular degeneration
- Contrast sensitivity drops

\* Near & far limits assume 20/20 vision

# Inspection of Dam & Infrastructure Engineers

- **Long-Range Human Observation:** Effective up to ~500–1000 m for large objects; limited for small cracks or seepage detection.
- **Short-Range Inspection:** Minimum focus ~25–30 cm for fine features.
- **Aging Inspectors:** Near vision may require magnifiers or corrective lenses; far observation may need binoculars or scopes (*Very Few Inspectors are using such smart Gadgets*)
- **Implication:** Human Visual Inspections alone are limited in range and precision ~ need **Multi-Layer Digital Inspection and Sensing Technologies, UAVs, and Satellites** for Dam Health Inspection



# Why Digital Condition Assessment (DCA)?

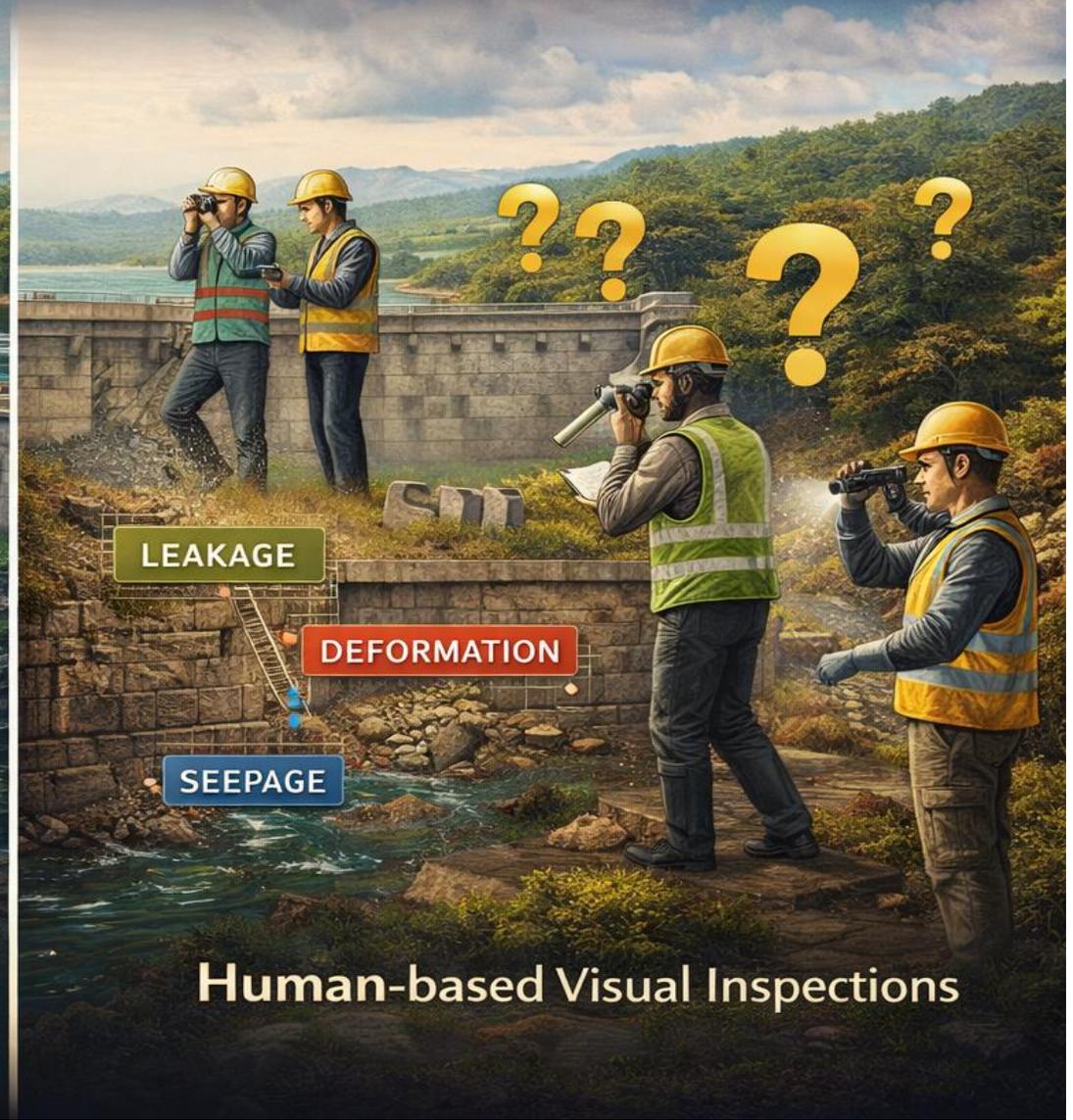
- ✔ More than 6,800+ Specific Dams in India, Many Aging Beyond 40 - 60 Years
- ✔ Manual Inspections are Subjective, Risky, and Non-repeatable and Purely an Individual Driven
- ✔ Time Taking limitation with Risk Involvements in Many Critical Section
- ✔ No Upstream (Reservoir-RIM) & Many Sections Inspection unattained
- ✔ Climate Extremes Demand Frequent, Objective, and Data-driven Inspections
- ✔ Digital Condition Assessment bridges this Critical Gap
- ✔ Repetitive and Historical Data Driven system in compliance of DSA 2021

# Why A Multi-Layer Digital Condition Health Assessment & Technology-Enabled Inspection Framework is needed to Dam Vs Human based Visual



## Digital Condition Health

Assessment & Technology-Enabled Inspection Framework



## Human-based Visual Inspections



# Integrated Smart Monitoring Workflow

Nature-Inspired Sensing



Modern Sensors (UV, Thermal, Multispectral, ADCP)



Ground Instrumentation  
(Piezometers, Inclinometers, Crack Meters)



Satellite Integration (Cartosat, RISAT, Oceansat)



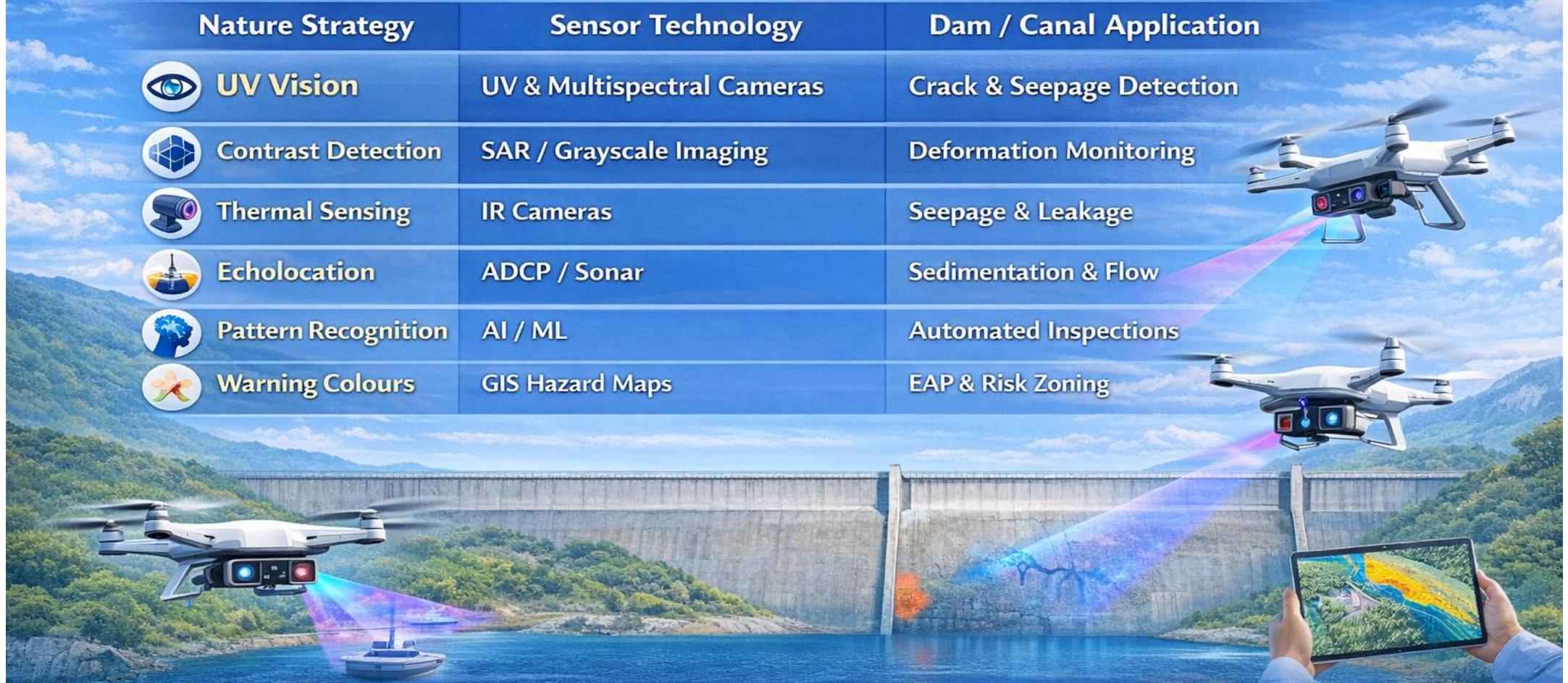
AI / ML Decision Support (Anomaly Detection, Trend Analysis)



Compliance & Reporting  
(BIS 4994:2002, BIS 1893:2016, CWC Guidelines [\[1\]](#), Dam Safety Act)

# Multi-Sensor Monitoring Frameworks for Digital Health Assessments using UAV

Nature Strategy	Sensor Technology	Dam / Canal Application
 <b>UV Vision</b>	UV & Multispectral Cameras	Crack & Seepage Detection
 <b>Contrast Detection</b>	SAR / Grayscale Imaging	Deformation Monitoring
 <b>Thermal Sensing</b>	IR Cameras	Seepage & Leakage
 <b>Echolocation</b>	ADCP / Sonar	Sedimentation & Flow
 <b>Pattern Recognition</b>	AI / ML	Automated Inspections
 <b>Warning Colours</b>	GIS Hazard Maps	EAP & Risk Zoning

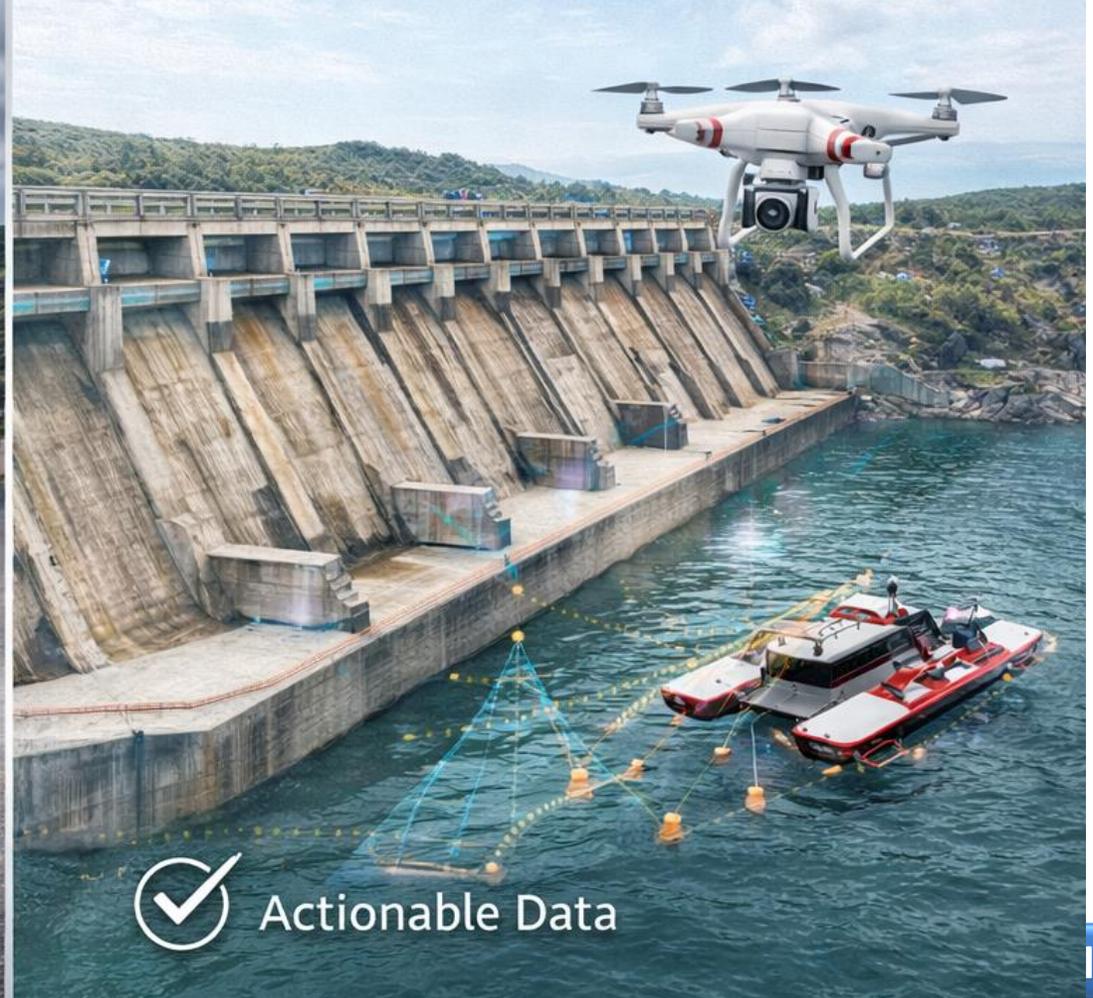


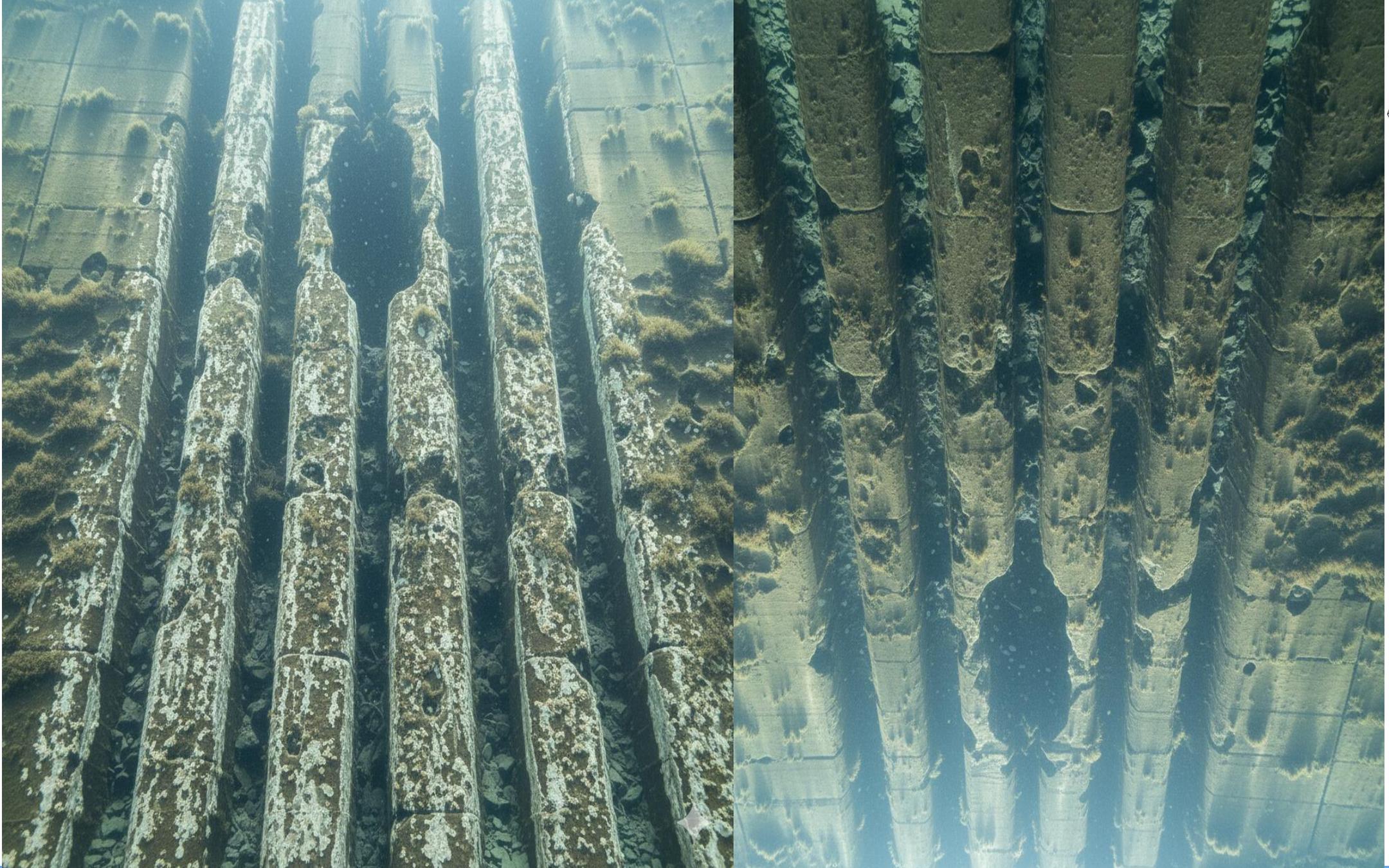
## MULTI-SENSOR MONITORING FRAMEWORKS for DIGITAL HEALTH ASSESSMENTS using UAV

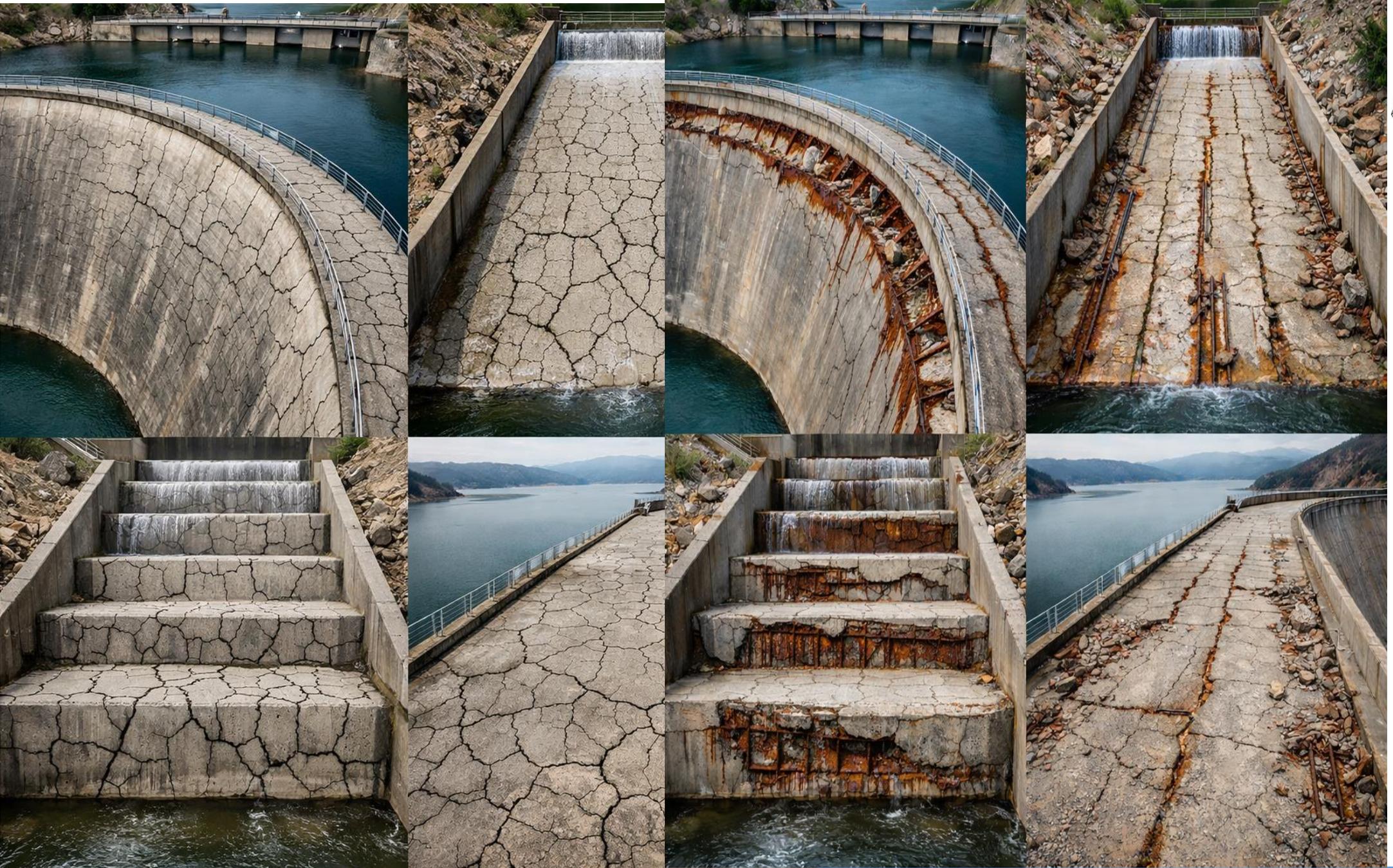
# EPISODIC COMPLIANCE INSPECTIONS



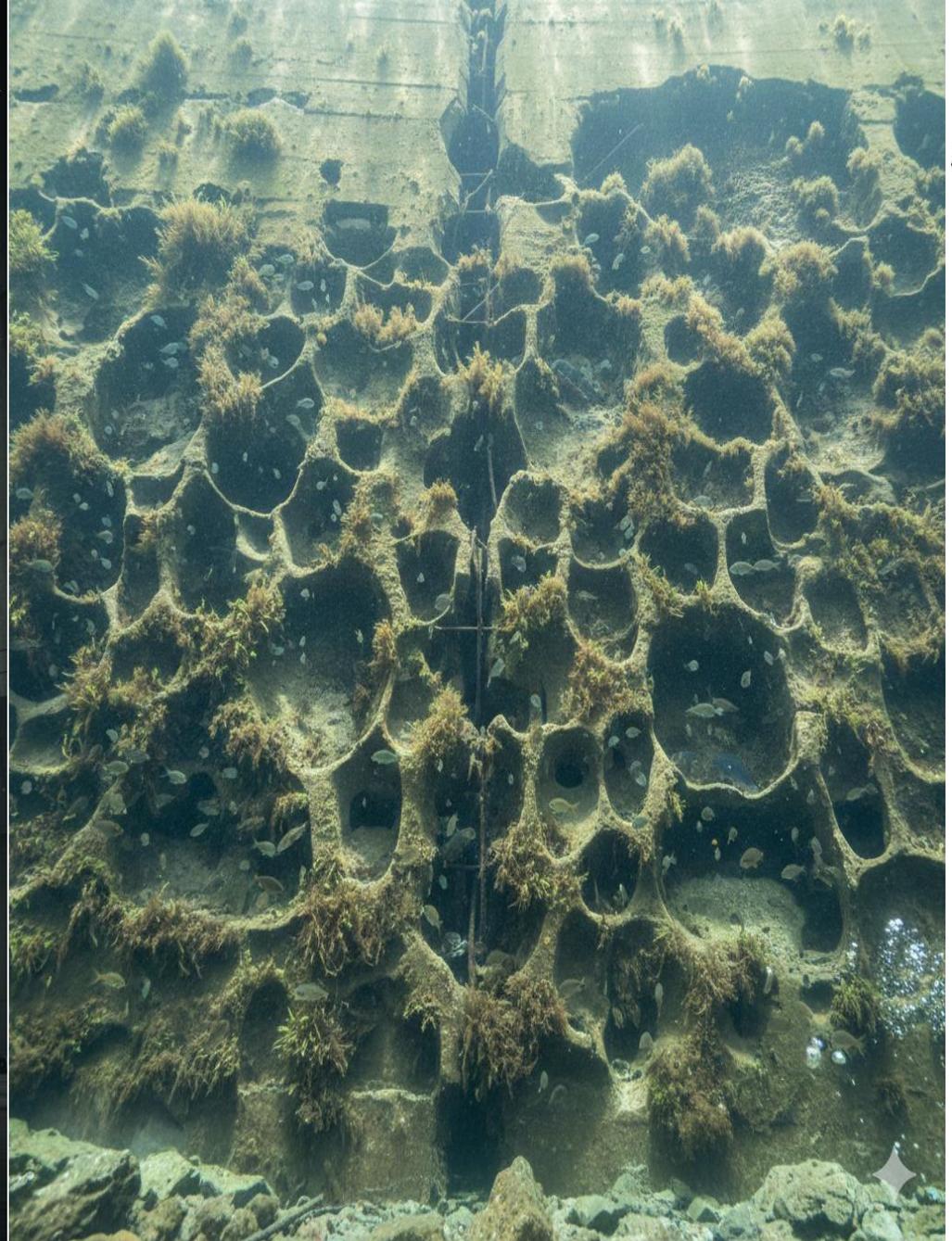
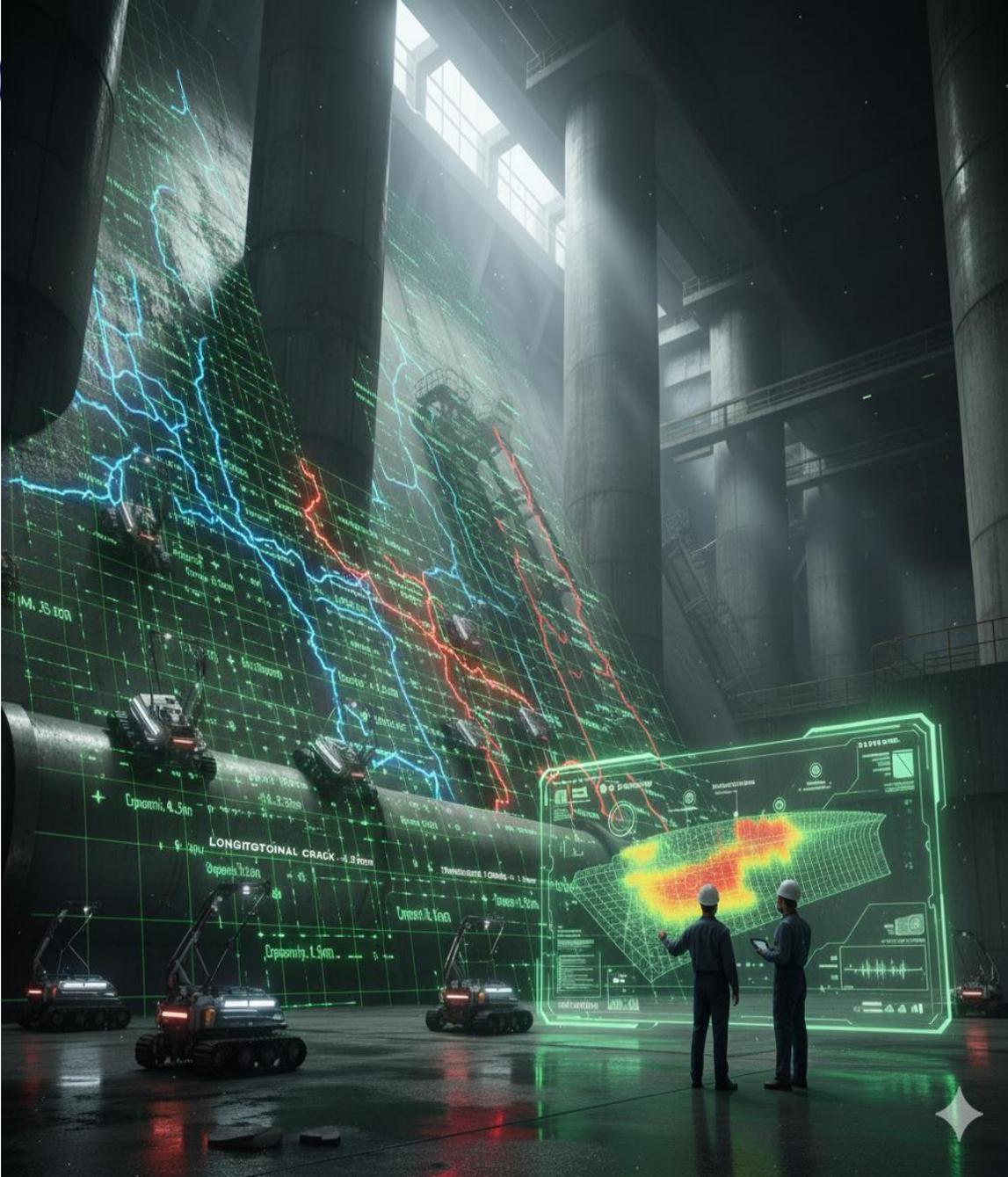
# CONTINUOUS ASSET INTELLIGENCE











# Evolution of Dam Inspection Paradigm

Manual Visual  
Inspection



UAV-Based  
Inspection



AI-Driven  
Digital Intelligence

Transformation from Episodic, Qualitative Inspections to  
Continuous, Quantitative and Predictive Condition Assessment

# Key Benefits from Evolutionary of Dam Inspection Paradigm

- Sub-Millimeter Crack Detection
- High-Density 3D Point Clouds and Orthomosaics
- High-Density 3D Point Clouds and Orthomosaics
- Identifies Delamination and Voids
- Detects Seepage and Moisture Retention Zones
- Spalling Volume and Area Computation
- Identifies Delamination and Voids
- Detects Seepage and Moisture Retention Zones
- Passive & Active Thermography Supported
- Thermal Anomalies Reveal Hidden Deterioration

# Nature-Inspired Technologies for Surveying & Mapping (Biomimicry to Application)



**Biomimicry:** Evolving Nature perfected vision & sensing first → we adapted it for measurement

NATURE'S INSPIRED

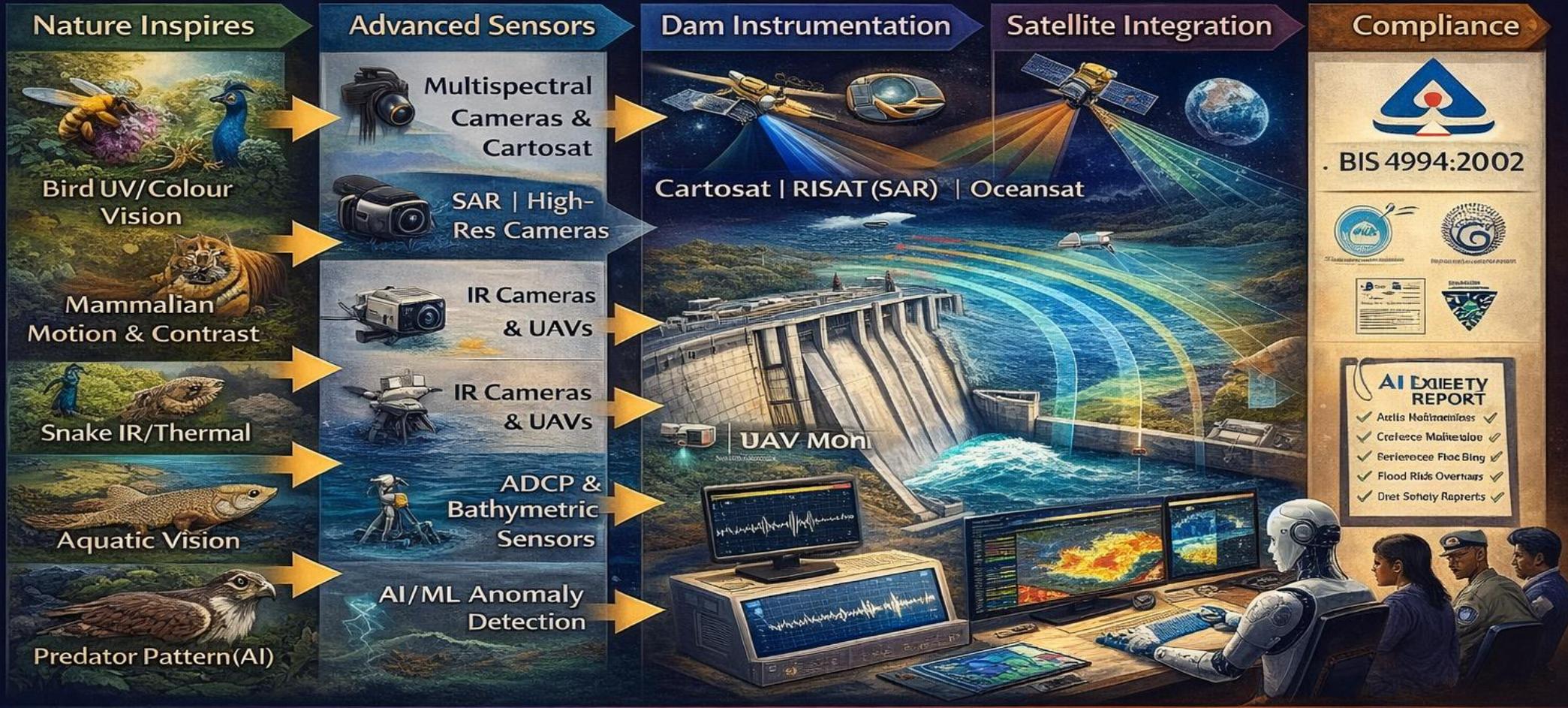
INDIAN MAMMALS

INDIAN RIVERS

INDIAN MARINE

INDIAN MARINE

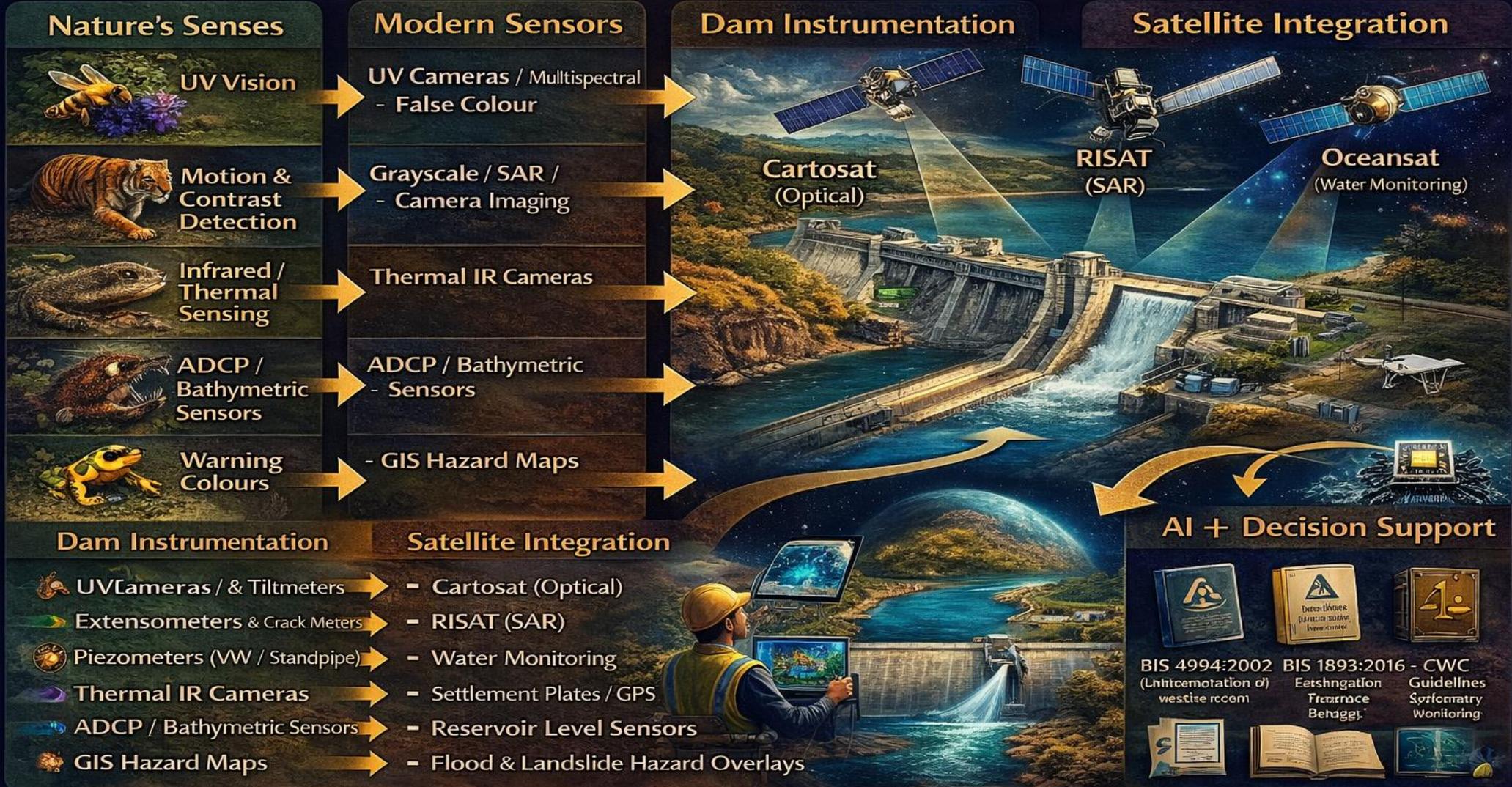




**Nature-Inspired Smart Monitoring of Dams & Water Infrastructure**  
 An integrated multi-sensor & satellite-based approach ensuring dam safety and security

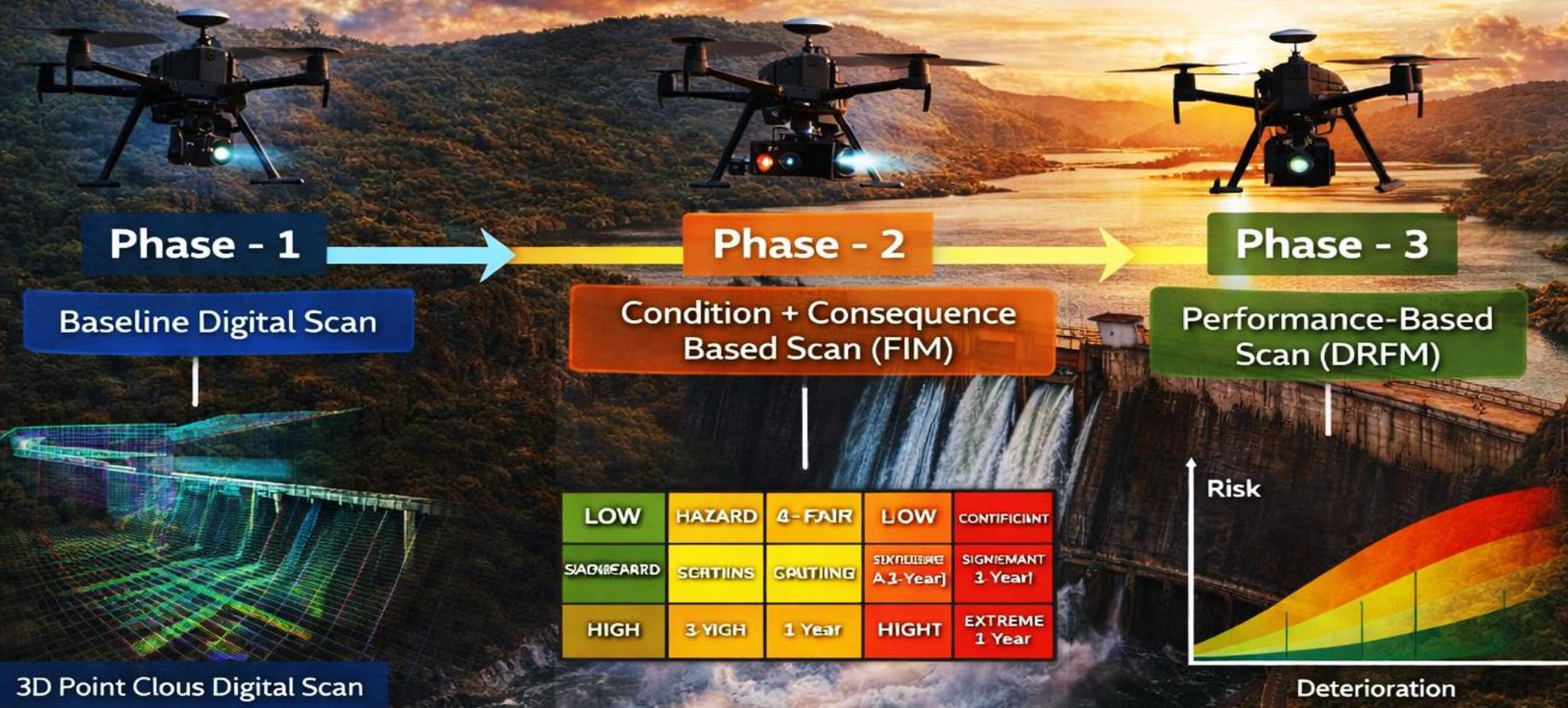
# Nature-Inspired Sensing for Dam Safety

## From Biomimicry to Compliance



**Biomimicry:** Evolving Nature perfected **vision & sensing** first → we adapted it for measurement

# Three-Phase Inspection & Implementation Framework



**Note: Inspection Frequency Dynamically linked to Risk and Deterioration**

# Inspection Frequency Identification Matrix (FIM)

## Condition State

	1 - GOOD	2 - FAIR	3 - POOR	4 - CRITICAL
Hazard Category	5-7 Years	5-7 Years	5-7 Years	1 Year
LOW	5-7 Years	3-4 Years	3-4 Years	[Annual 1 Year] 2 Year
SIGNIFICANT	3-4 Years	3-4 Years	3 Years	Annual to 3-Year
HIGH	3 Years	3 Years	Annual to 3-Year	Annual to 3-Year
EXTREME	1 Year	Annual to 3-Year	Annual to 3-Year	Annual to 3-Year

- ✓ Hazard Category × Condition State
- ✓ Extreme Hazard → Annual to 3-Year Inspections
- ✓ High Hazard → 3-5 Year Inspections
- ✓ Objective, Defensible Inspection Scheduling
- ✓ 30 Day (Smaller) 45 Days (Medium) & 60-70 Days for (Larger) Dams
- ✓ Historical Comparison DHA with Previous Data (7-10) Days (Maximum)

# Integrated UAV-Based Multi-Sensor Framework



## UAV Platform



**High-Resolution RGB Camera**  
(Cracks, Spalling)



**Thermal Infrared Camera**  
(Delamination, Seepage)



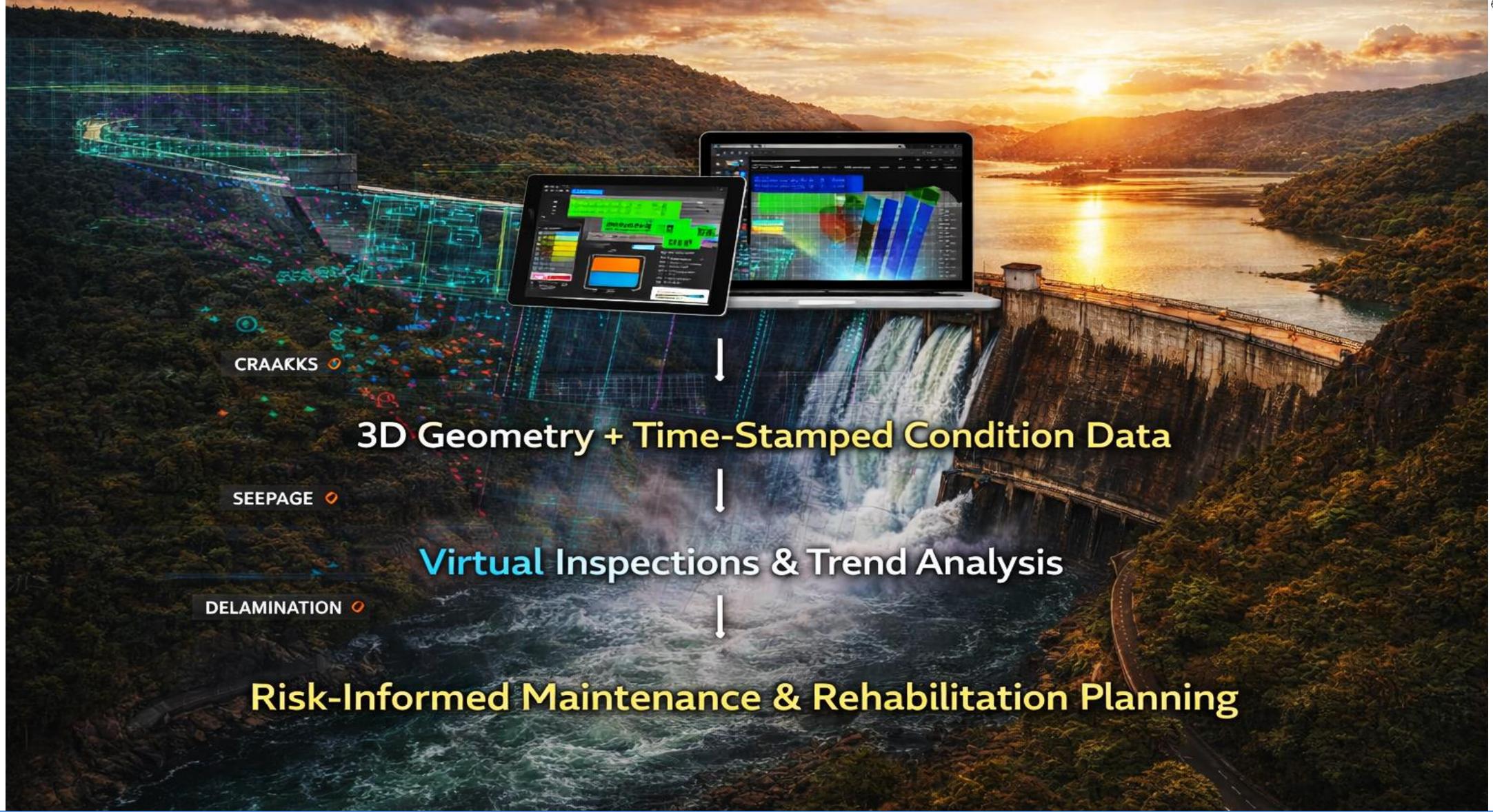
**Acoustic / Robotic Sounding**  
(Voids, Debonding)



**RTK-GNSS & IMU**  
(Georeferencing)

**Note: All Data Fused into a Single Digital Twin Environment**

# Semantic Digital Twin & Lifecycle Management



CRAAKKS

3D Geometry + Time-Stamped Condition Data

SEEPAGE

Virtual Inspections & Trend Analysis

DELAMINATION

Risk-Informed Maintenance & Rehabilitation Planning

# Acoustic & Vibro-Acoustic Sounding

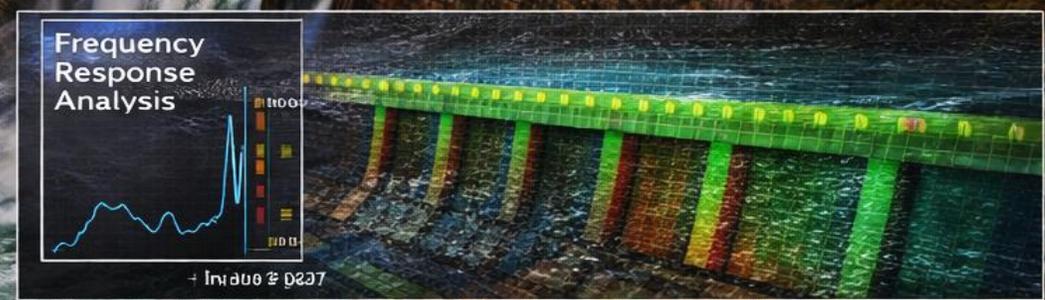


Mechanical Percussive Impactor



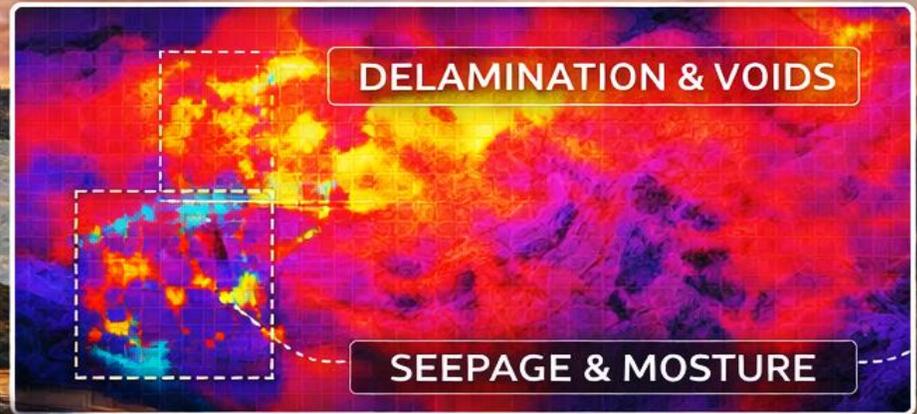
Electromagnetic Soundwave Emitter

- ✓ UAV-Mounted Percussive or Non-Contact Acoustic Systems
- ✓ Frequency Response Analysis (FFT, PSD)
- ✓ Detection of Hollowness and Debonding

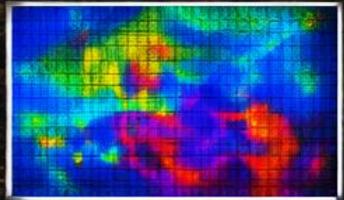


**Note: Complements Optical & Thermal Inspection**

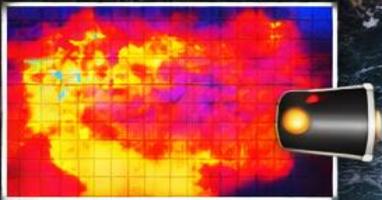
# Infrared Thermography – Subsurface Intelligence



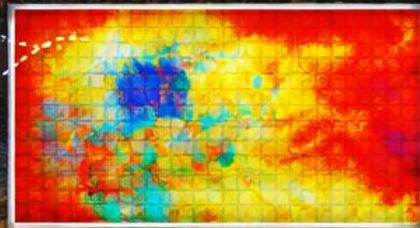
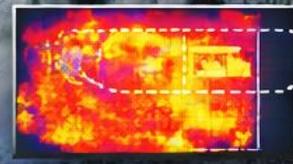
- ✔ Identifies **Delamination and Voids**
- ✔ Detects **Seepage and Moisture Retention Zones**
- ✔ **Passive & Active Thermography Supported**



Passive Thermography

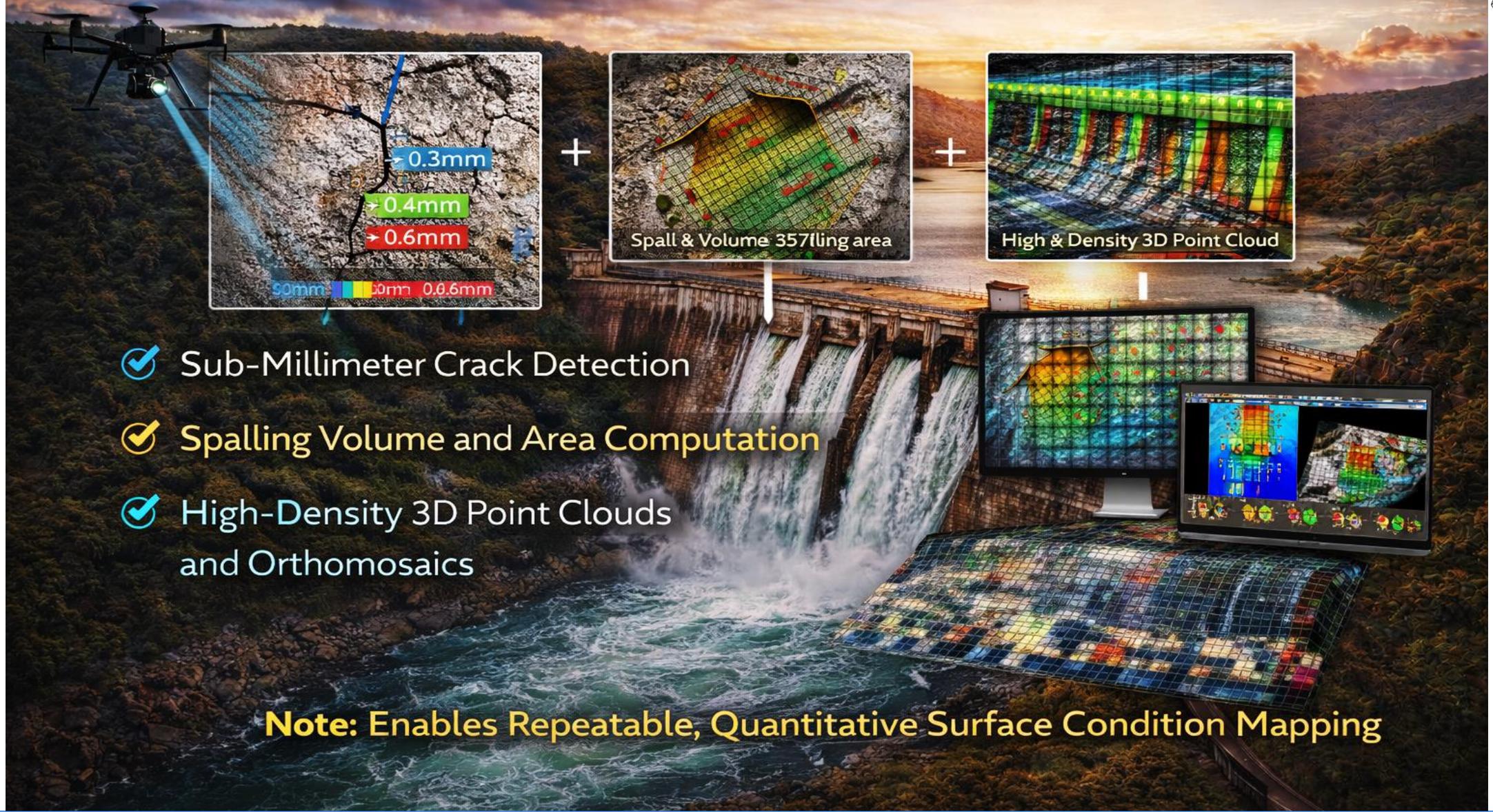


Active Thermography



**Note:** Thermal Anomalies Reveal Hidden Deterioration

# Photogrammetry – Surface Defect Quantification



- ✓ Sub-Millimeter Crack Detection
- ✓ Spalling Volume and Area Computation
- ✓ High-Density 3D Point Clouds and Orthomosaics

**Note:** Enables Repeatable, Quantitative Surface Condition Mapping

# Multi-Modal Data Fusion & AI

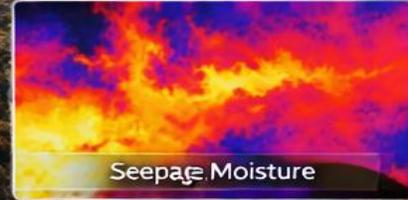
VISUAL

THERMAL

ACOUSTIC



+

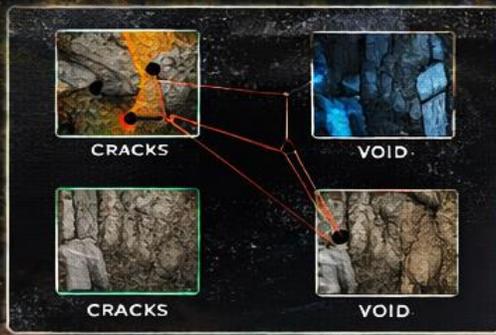


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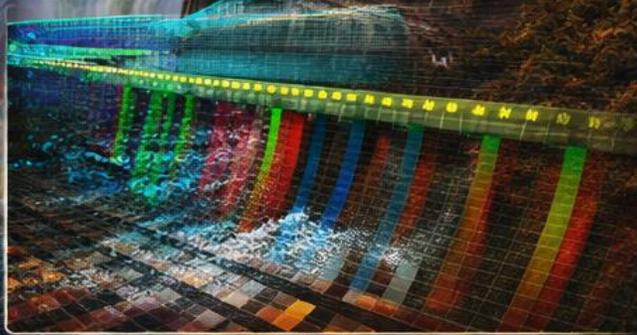


AI / ML Algorithms

Automated Defect Detection & Severity Classification



- Low
- Moderate
- Substantial
- Extensive
- Red



Predictive Deterioration Trends

# DIGITAL CONDITION ASSESSMENT OF DAMS, SPILLWAYS & OTHER AREAS

Photogrammetry-Based Visual Data using UAV / Drone



Orthomosaic



3D Photogrammetric Model



Under-Deck Inspection



Dam Crest



Spillway Wall & Floor



3D Mapping



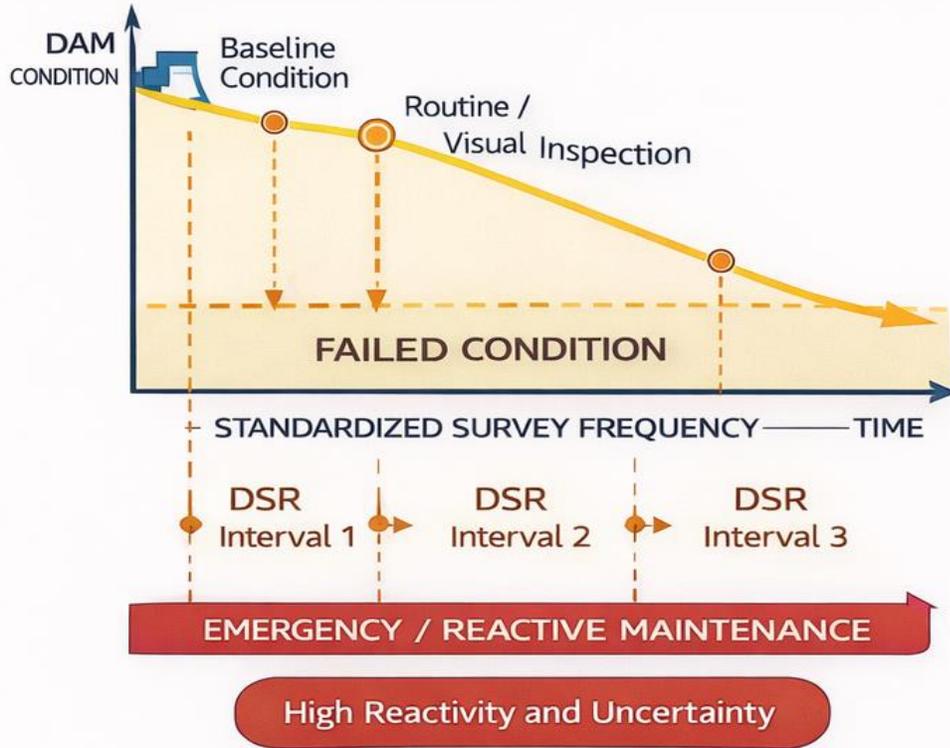
Defects Labeled

High Reactivity and Uncertainty

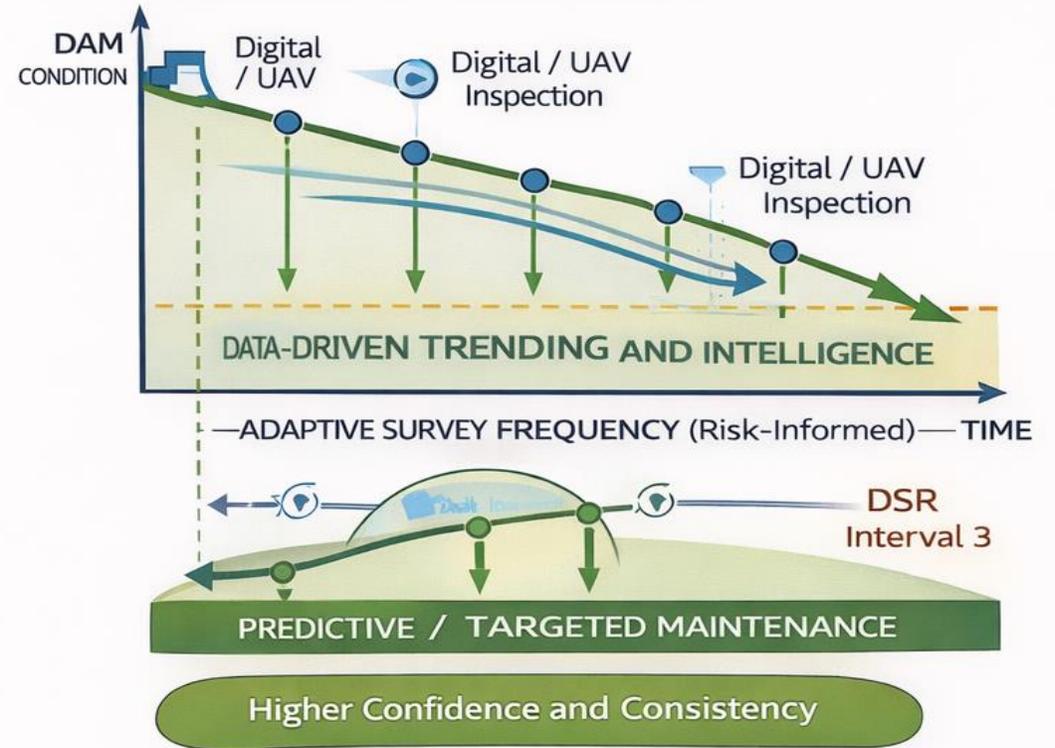
Higher Corpiitenc and Conesterry

# LIFE-CYCLE MANAGEMENT OF DAM ASSETS

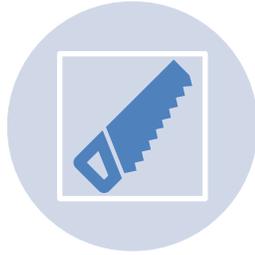
## CONVENTIONAL INSPECTION & MAINTENANCE APPROACH



## DATA-DRIVEN INSPECTION & MAINTENANCE APPROACH



# Key Advantages of DCA Framework



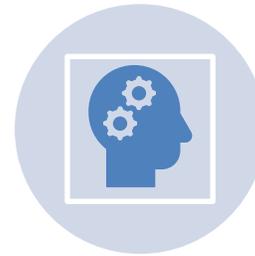
**Rapid, Improved Safety – No Rope Access or Scaffolding**



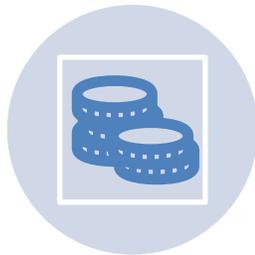
**High Accuracy and Repeatability**



**Early Detection of Hidden Defects**



**Historically Ready Digital Evidences for Future Ready Decision Support System**



**Cost-effective Lifecycle Asset Management**

# Regulatory Alignment

Dam Safety Act, 2021 (India)

CWC & NDSA Guidelines

ICOLD, USACE, FEMA Best Practices

Supports DSR, EAP, and  
Rehabilitation DPRs

# Conclusion...

**Digital Condition Assessment Transforms Dam Safety Management**

**Enables Predictive, Risk-informed Decision-Making**

**Fast, Safe and Scientifically Analyzed evidenced based Data**

**Lifeline & Historical Data Bank to Supports the Climate-Resilient and Sustainable Infrastructure**

**Ready for National-Scale Adoption in India for Prompt Action Taken**



# Ask Your Quiz



# Thank for Listing and Your Attentions