Intelligent Satellite Dam Monitoring

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The dam industry in the UK is in changing, interesting and challenging times. The incident at Toddbrook Reservoir in 2019 has led to the drafting of new guidance for Undertakers (dam owners and operators), Reservoir Engineers and others, as well as the potential for legislation change. This will shape future UK dam industry requirements and is challenging the way we undertake reservoir safety.

Developing technology of the 21st century can assist us in managing our historic assets going forward, whilst complementing our existing data sets, processes and activities. The Intelligent Dam Monitoring System (iDMS) harnesses the power of satellite technology to proactively manage reservoir safety and address these challenges. It enables dam owners to understand their assets, improve risk management, deliver strategic objectives and realise operational and commercial benefits, bringing long term resilience to dam safety strategy.

By establishing a detailed understanding of the basal rhythm of the dam the system can provide early detection of anomalous change. It will allow for a better-informed analysis of risk across a portfolio of assets and will allow owners to demonstrate a duty of care by avoiding potentially catastrophic incidents through long-term planning and proactive risk management.

The system is currently being piloted by the Canal and River Trust (CRT) at two of their reservoirs. This paper will outline the practical implementation and operation of the system, some of the findings and ongoing developments, which include tailoring the system to the CRT's own individual requirements.

DAMS FEELING THE STRAIN

It is noticeable that within the last decade or so headlines around the world associated with dams have been about failures which have sadly led to loss of life, for example Patel Milmet Dam, Kenya in 2018 killing 48 people, or major damage caused by significant weather events, for example Tiware Dam, India in 2019 killing 19 people and Edenville Dam/Sanford Dam in 2020 in the USA.

With climate change predicting increasingly volatile weather; both drier and hotter summers, more intense and frequent rainfall events and long-term temperature increases, it is clear our assets will continue to be under even greater strain going forward. In this context it is important to utilise technology to provide as much information as possible, such that risks are minimised and our dams are resilient going forward.

21ST CENTURY TECHNOLOGICAL DEVELOPMENTS

A technological revolution generally increases productivity and efficiency, and there have been a number of such revolutions throughout history:

1. Financial-agricultural revolution (1600–1740)
2. Industrial revolution (1780–1840)
3. Technical revolution or Second Industrial Revolution (1870–1920)
4. Scientific-technical revolution (1940–1970)
5. Information and telecommunications revolution, also known as the Digital Revolution or Third Industrial Revolution (1975–2021).

Many of our dams in the UK were constructed during the Industrial Revolution to provide power for various mills and mines and to supply canals for transportation of goods across the UK. Subsequently dams were constructed in the second Industrial Revolution for public health to provide water supplies to our major cities.

We are currently in the Third Industrial Revolution, which is the Digital Revolution. It is exponential in its speed of development and the impacts it has on our society. Benefits are not always quantified, with technology developed for one purpose subsequently having multiple uses elsewhere. There is an argument to say that we are actually in a fourth industrial revolution, which is an age were physical, digital and biological fields are being challenged by digitalisation. Artificial Intelligence technologies, data analytics and personal connection devices are changing how industries operate across the globe.

Existing Technology

Within the dam industry our structures have typically been constructed in previous technological revolutions, with subsequent developments incorporated retrospectively. Think of the installation of vibrating wire piezometers; telemetry read firstly off dataloggers and subsequently from mobile phone signals in real time; actuation of penstocks; SCADA and alarm systems and more recently bathymetric surveys, ROVs, CCTV monitoring of spillways/inlets/outlets and drone surveys.

What Next?

It is inevitable that these developments will continue with more technology becoming standard within the realms of dam monitoring. So, what is next?

Satellite technology is the natural development and is in fact already here, but how can this provide benefits to the dam community and add to the suite of monitoring systems we already have, to allow us a better understanding of our dams and how they react over time?

This paper outlines one of the developments using satellite technology and how it is being applied to reservoir sites within the Canal and River Trust portfolio.

Figure 1: Satellite over the UK

SATELLITES

The number and variety of satellites that have been launched into orbit in recent times is substantial: Elon Musk's Starlink satellite fleet and Amazon's Project Kuiper grab the headlines but the NASA and European Space Agency (ESA) continue to lead the way with the ESA Copernicus Programme Sentinel Satellites. The Sentinel 1 data is produced/refreshed every 6-12 days, Sentinel 2 every 5-10 days. The satellites operate in pairs, so data updates are every 5-6 days.

Relevance

Traditional methods to monitor dams have been based on survey measurements being taken once or twice a year from a limited number of predefined points, and building an understanding from that.

Satellite-based systems can provide a platform that can collect a wide range of data over the whole of the dam. This can then be used (via appropriate analysis) to aid the understanding of a dam's overall condition.

Available Data – Movement, Vegetation Vigour and Moisture

An established method of interferometry is used with movement detected by analysing the phase wave of synthetic aperture radar (SAR) from a sensor on Sentinel 1. The associated phase wave is 55mm long, so by comparing the change in location on the phase wave across two acquisitions, a measurement for change in vertical movement in millimetres can be obtained.

Optical data is used to monitor trends in vegetation vigour and moisture as a proxy for seepage. This is from a sensor on Sentinel 2. An orthogonal index compares moisture and vigour (or greenness). Vegetation responds positively to moisture availability in normal conditions. There will be a relationship between the two that represents a seasonal trend. Vigorous vegetation suggests optimal soil moisture and unusual moisture regimes may indicate seepage.

INTELLIGENT DAM MONITORING SYSTEM (IDMS)

One system that has been developed to use satellite technology is the iDMS monitoring system. This uses geospatial Artificial Intelligence (AI) techniques, developed by Rezatec, to provide information that is used to establish a dam's behaviour from a long-term retro perspective data, creating a complete digital signature, or a dam's unique 'basal rhythm' of movement.

Readings from satellites build up a clear picture of the dam's behaviour, using synthetic aperture radar, combined with interferometry. In this way iDMS is able to identify trends and anomalies across the whole dam structure. This, alongside knowledge of moisture content, provide valuable insights for dam owners with respect to the status of the dam.

Within the system the dam is divided into sections or hexagons. For each hexagon the trend can be established for rate of movement, as well as seasonality changes. Hexagons have 9m long sides, with an average area of 230m^2, and are used because:

- They provide insights over the entire area of interest, (AOI), not just the crest of the dam.
- The multi-resolution feature provides a better way to visualise AOI without losing information.
- The circularity of a hexagon grid allows it to represent curves in the patterns of data more naturally than square grids (according to ESRI.com).

The visual presentation of the information on a web-based monitoring system is simple and a user can quickly and readily establish areas of concern that may warrant additional investigation to prevent risks developing. Support to interpret the information is given by Binnie's reservoir staff with appropriate experience and knowledge.

CANAL AND RIVER TRUST - PILOT

The Canal and River Trust (CRT) decided to pilot the iDMS system in 2020. Prior to the pilot a review was undertaken of CRT's reservoirs to determine those which would have the best satellite coverage and should be considered for the pilot, with the sites graded as green (good coverage), amber and red.

It is important to note that not all sites are suitable and it depends upon the satellite coverage, orientation and the dam's physical characterises. Brent (London) and Rotton Park (Birmingham) reservoir were selected.

Process – 3 years retrospective data

Once the sites were selected, a review of three years of retrospective data was undertaken for the sites. This revealed that full coverage of Brent Reservoir could not be provided and so it was decided to select another site. It had originally been hoped that Toddbrook Reservoir would have suitable coverage, but initial analysis indicated this might not be possible. A more detailed review was undertaken and it was concluded that Toddbrook was indeed viable and it was subsequently added to the pilot.

Table 1: CRT Reservoirs in Pilot

Reservoir	Date	Description
Rotton Park	1828	Cat A / High Risk Designation, 14m high, 350m long embankment dam.
Toddbrook	1837-40	Cat A / High Risk Designation, 24m high, 310m long embankment dam.

The three years' retrospective data (movement, vegetation vigour and wetness) was added to iDMS website and logins provided to key CRT staff - typically the Supervising Engineer (SE) and other reservoir team staff.

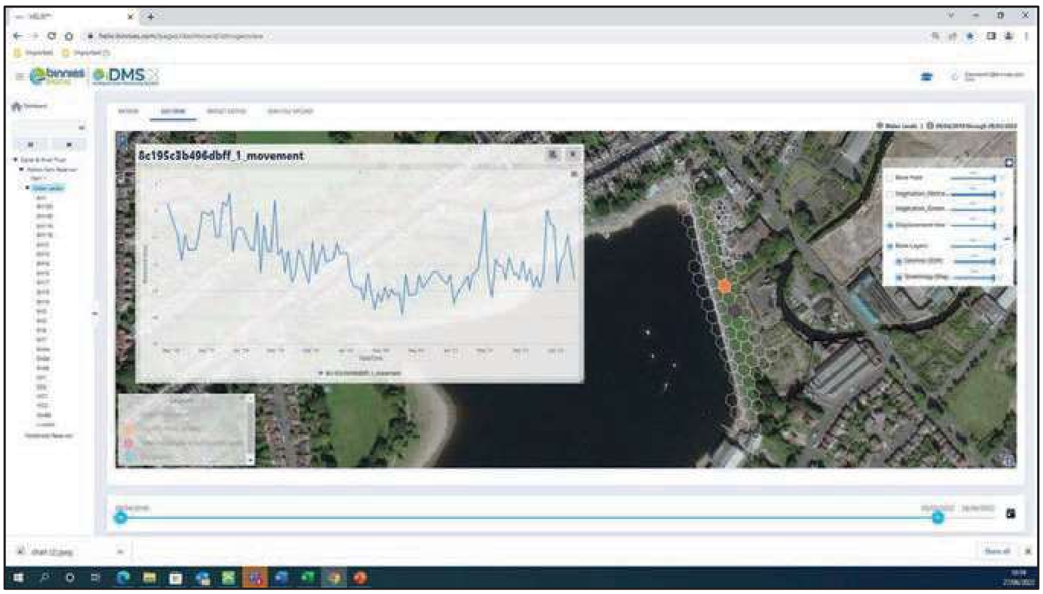

Figure 2: Screen shot from the iDMS portal of Rotton Park with three years' retrospective data – showing movement data graph associated with one hexagon.

Process – continuous monitoring

Once the retrospective data was uploaded it could be viewed via the portal. The three years' data provided an insight into the normal behaviour of the dam, allowing a datum to be set. Subsequently continuous monitoring started and satellite data is uploaded on a regular basis.

Two rules are written into the software that allow the new satellite data to be added and compared with:

- the previous reading for the individual each hexagon,
- the original (first) reading taken for the hexagon.

If there is a variation outside the levels that have been set (which are set individually for each reservoir following analysis of the three years' retrospective data and discussion with the SE), then the hexagon changes colour to amber, or red. For example, on Rotton Park the movement levels have been set to:

- Previous value comparison - from 0.00mm -> 5.00mm -> 8.00mm
- Start of range comparison – from 0.00mm -> 6.00mm -> 10.00mm

This gives a very quick visual indication of the status of the whole dam as soon as you log in, with any changes immediately identified.

Process – additional data

Dam owners will typically hold historic data on their reservoirs; some taken weekly, some monthly or even annually. This will be in a multitude of forms including SCADA. CRT is no exception and as part of the process additional data has been integrated into the system for Rotton Park as follows:

- Water Level
- Rainfall Data
- Piezometer readings
- Drainage flows
- V notches readings
- Crest Pins.

Process – Myview and analysis

In order to facilitate analysis of the data, specific items can be set up in a 'Myview' to be monitored. For example, on Rotton Park initial indications were of some degree of movement around the spillway greater than that experienced elsewhere on the dam. Therefore, a specific view was set up to monitor this area and provide dials for minimum and maximum movement.

Comparison of the satellite information with the existing data CRT provided is undertaken on a regular basis, bringing various elements of data together to highlight trends and identify any issues. This can then be combined with knowledge the client possesses or other historical data, for example: construction details, previous works, asset inspection reports, as-built drawings, plus existing monitoring data; water levels, rainfall data, piezometer readings, drainage flows.

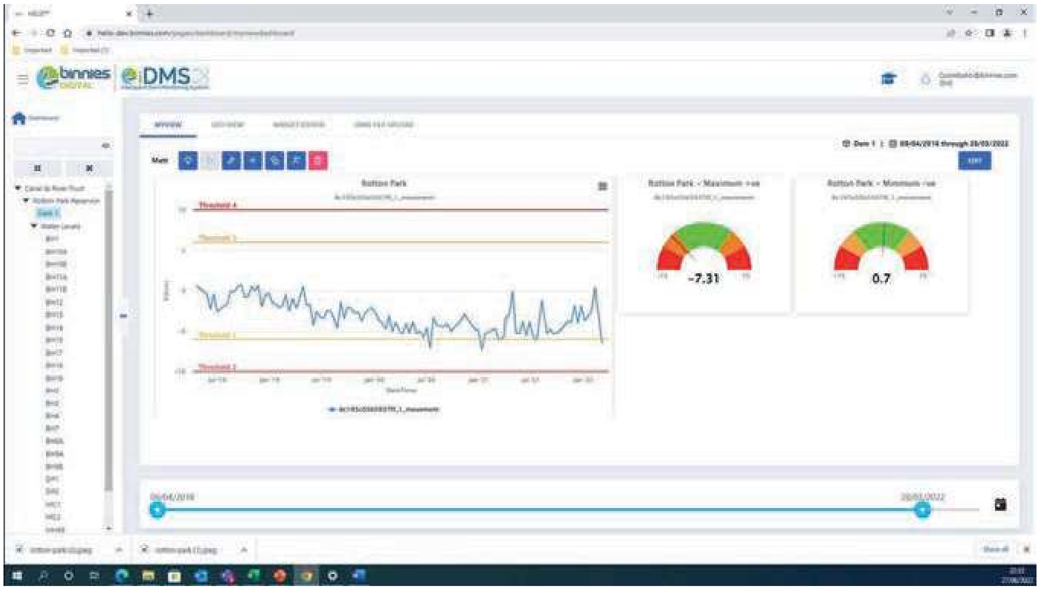

Figure 3: Screen shot from the iDMS portal of Rotton Park with Myview set up to indicate max and min levels of movement at a specific Hexagon.

Process – results to date

The analysis of Rotton Park to date has resulted in:

- Indications that there is more movement in two key areas of the dam compared to the rest of the embankment. There appears, over a period of time, to be more movement here than in other locations.
- That the movement appears to correlate with periods when the dam has been full for longer periods and has had a more significant drawdown, as would perhaps be expected.
- That the movement is increasing over the last three years, but has now recovered and appears to be transient. This correlates with the increased filling and greater drawdown level periods. This also correlates with increased flow in the drainage system (0.75 l/s – 2.00 l/s), although these fluctuate with changing levels and seasons.
- There is an overall trend across the dam of negative movement from 2019 to 2021, but there are signs that this is reversing in 2022.
- Overall, that the movement data indicates that movement identified across the dam is fairly minimal.
- The vegetation vigour data indicates a maximum variation in 2018, which appears to correlate with an extreme weather event that occurred in Birmingham that led to a slip on another reservoir.

- Comparison of the movement data with recently installed Survey Ops crest pins (Sept 2021) indicates comparable levels to those provided by iDMS. Only 9-12 survey pins are present within each Hexagon and very little movement that has occurred over the Survey Ops period. However, taking into account the increasing number of points the satellite data provides you would expect iDMS to be slightly different from the Survey Ops data. Note that the +/- state matches i.e. when iDMS is positive so is Survey Ops, when iDMS is negative so is Survey Ops.

Hexagon (in iDMS)	**Survey Ops (15/09/21 baseline)**	**iDMS adjusted 19/09/21 (closest data date)**
8c195c05b4b57ff	• Min -3.5mm • Max +1.2mm Total variation therefore of 4.7mm	• Min -1.79mm • Max +1.43mm Total variation therefore of 3.22 mm
8c195c05b4b19ff (closer to spillway)	• Min -2.9mm • Max +1.8mm Total variation therefore of 4.7mm	• Min -3.18mm • Max +3.32mm Total variation therefore of 6.5mm

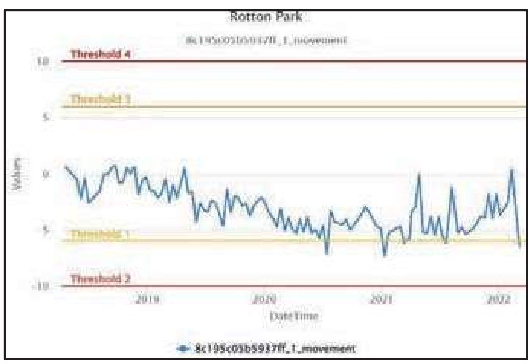

Figure 4: Movement at one specific hexagon at Rotton Park.

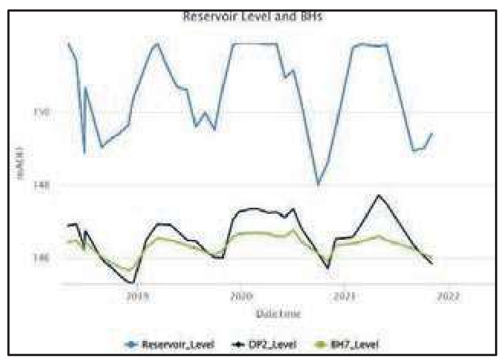

Figure 5: Water level and piezometer information at Rotton Park.

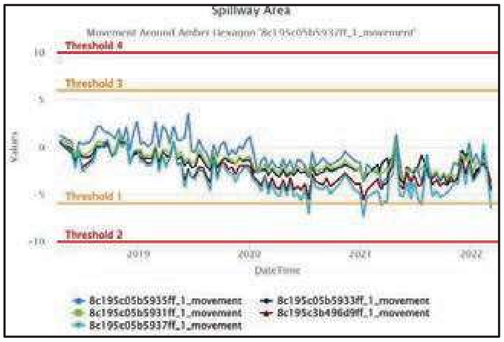

Figure 6: Movement data comparing one specific area to the majority of the dam (orange), demonstrating the movement is worth investigation.

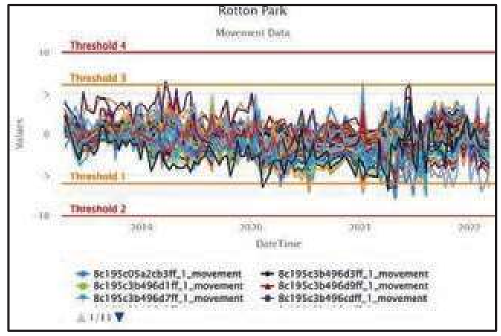

Figure 7: Movement across the whole dam. Showing an overall (small) down trend from 2019-2021 but a subsequent increase back to previous levels in 2022.

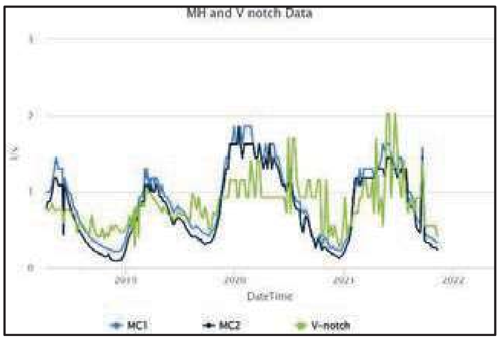

Figure 8: Manhole and V-notch flow data Rotton Park.

ONGOING DEVELOPMENTS

A number of additional facilities are currently being discussed to add to the system (on the CRT monitored sites):

- Year-on-year comparison of data – this has been added.
- Live SCADA data – being uploaded live into the system. It has been verified that this is possible but it has yet to be completed.
- Automatic Alerts to SEs via the CRT mobile phone system.
- An automatic run-through of all data to show hexagon colour variation, giving a visual ebb and flow of the dam over time.

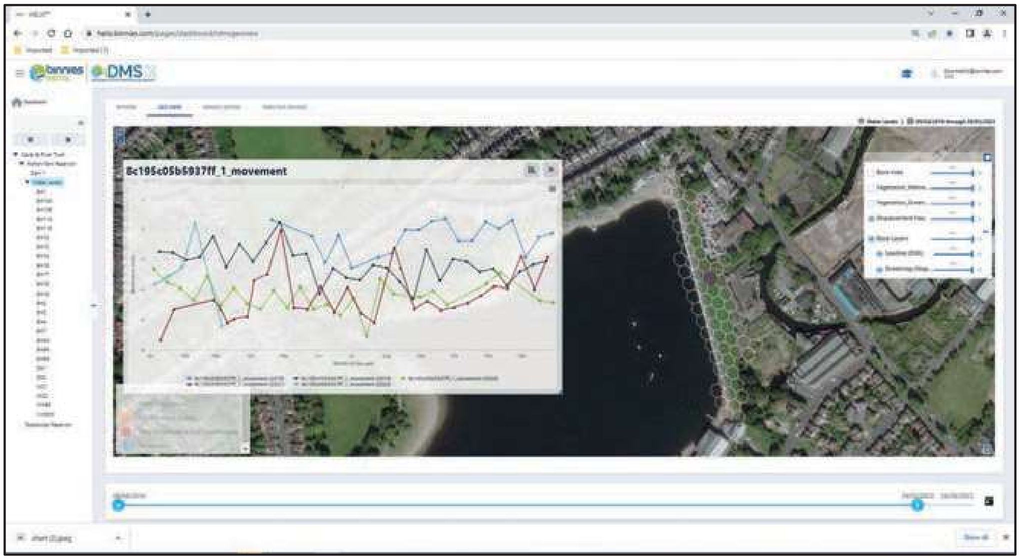

Figure 9: Movement data year on year comparison for one specific Hexagon.

The system that iDMS uses also allows for incorporation of the following in the future: Photographs, 360° views, Other Record Data, O&Ms, H&S Plans.

FUTURE ANALYSIS

The analysis of Rotton Park continues. Analysis of Toddbrook has now commenced and will continue with additional site-specific data provided by CRT. This will allow comparison of the technology to standard monitoring techniques to further validate the system.

BENEFITS

The system provides an overview of the whole of the reservoir embankment, providing continuous satellite monitoring and directly comparing this with historic information from the outset (three years' retrospective data).

It allows the 'basal rhythm' of the dam to be established and thus the normal levels of movement, vegetation wetness and vigour, which are then used to set alerts, providing early warnings if those levels are exceeded. It can also highlight the response of the dam to seasonality changes that may occur in the event of intense rainfall or drought.

Using satellites, the monitoring undertaken is completely remote. It does not require site visits, hardware (site instrumentation), or intervention/support from the dam owner.

It allows for a better-informed analysis of risk across a portfolio of reservoir assets, such that owners can demonstrate a duty of care via long-term planning and proactive risk management. Data can be used to prioritise future investment, and focus on measures to improve reservoir safety.

CONCLUSION

Technology in the 21st century is developing at an exponential rate and is continuing to do so. Satellite technology will become common place in the standard suite of dam monitoring facilities. It allows:

- a complete overview of the dam by monitoring its whole structure on a more continuous basis, rather than via periodic physical surveys,
- establishment of seasonal patterns and the dam's basal rhythm, to an extent which would not be possible with conventional systems,
- provides an early indication of elements of the dam that may vary outside of historic boundaries, which could indicate the development of an issue,
- with results displayed in a user-friendly way with rapid visual indication of issues without additional analysis,
- and facilitates the ability to undertake comparisons with existing data to then undertake analysis of issues to help analyse the primary cause.

The use of this technology provides dam owners with greater confidence with respect to the status of their dam, assurance that it is operating within normal boundaries and early indications of abnormal activity. This can then be investigated and resolved before it develops into more a serious, and more expensive, issue to resolve.