

# Digital Integration for Condition Assessment for Water Tunnels in Hong Kong

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## ABSTRACT

Unbeknown to many, the supply of fresh water in Hong Kong is dependent on water conveyance through almost 200 km of water tunnels in conjunction with other waterworks installations managed and maintained by the Water Supplies Department (WSD). A significant number of these tunnels were constructed during the 1960's and 1980's, with over 50% now being more than 50 years in age and some even dating back to the late-1800's. Given the age and strategic importance of the tunnels, periodic condition and maintenance assessment works are required to enhance the asset management performance continuously so that water supply service of the highest quality is provided to the public. In the last complete round of asset-wide condition assessment for the tunnels, the development and use of digital inspection and data management tools were in the early stages and not ready for digital asset management. To address this and provide an integrated, structured and more usable dataset for asset management and future assessment works, a variety of digital approaches and tools have been explored, developed and implemented during the on-going round of condition assessment works. These have included the use of a central dashboard-based system for data management and access, together with trials of tools such as mobile apps, 360 imagery, laser scanning and UAV photogrammetry to aid with data collection, management and reporting for the tunnel inspection works. An outline of the findings from the trial of these approaches is provided herein, together with recommendations on the preferred solution for digital asset inspection and management as well as possible future developments that could be integrated to these.

## 1 INTRODUCTION

### 1.1 WSD Water Supply Network

To ensure the provision of high quality water in meeting the need of the public and economic activities in Hong Kong, the Water Supplies Department (WSD) operates and maintains a total of 17 impounding reservoirs, 20 water treatment works, over 190 pumping stations/houses, over 230 service reservoirs, about 120 km of catchwaters, about 200 km of water tunnels (including associated portals, shafts and shaft towers), and other miscellaneous installations, in addition to over 8,400 km of water mains and various associated valves and civil, mechanical & electrical installations.

### 1.2 WSD Water Tunnel Network

Integral to the distribution of water amongst WSD's various waterworks facilities is the functionality of their water tunnel network. This includes 168 water tunnels with a combined length of about 200 km, as well as various associated assets including 148 access portals, 44 access shafts and 8 shaft tower structures (Figure 1). The lengths of the individual tunnels vary from 35 m in the case of small connecting tunnels along catchwaters, to over 7,200 m for major fresh water supply tunnels. The average tunnel length is about 1,200 m. Similar variance exists for tunnel diameter, which ranges between 0.9 m and 10.2 m and averages 4.2 m. Most of the tunnels (>70%) were constructed between the 1960s and 1980s, when significant development and enhancement to Hong Kong's water supply system was undertaken. However, assets such as the Pok Fu Lam and Tai Tam Conduits date as far back as the 1880's and even include elements designated as declared monuments due to their historical significance. Some examples of the varying nature and typical condition of the tunnels in the network are shown in Figure 2.



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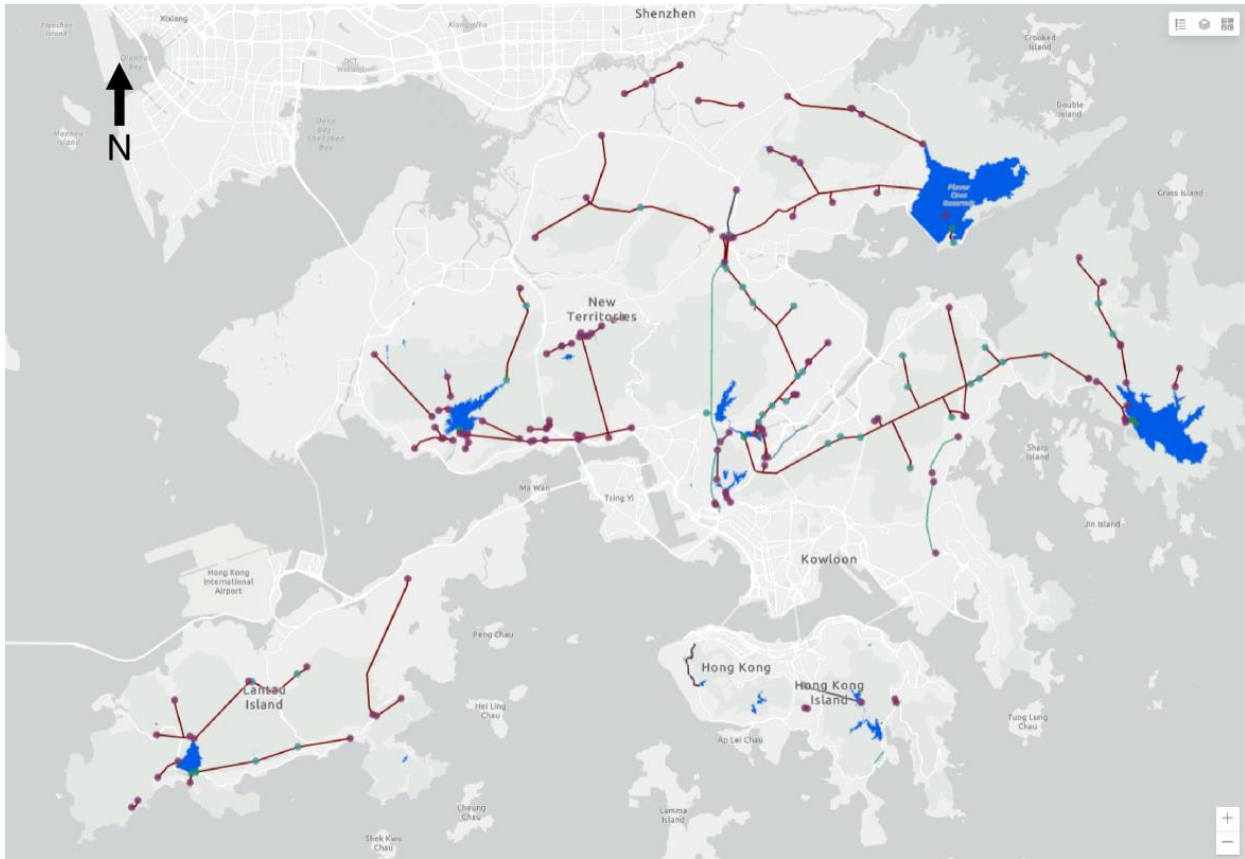
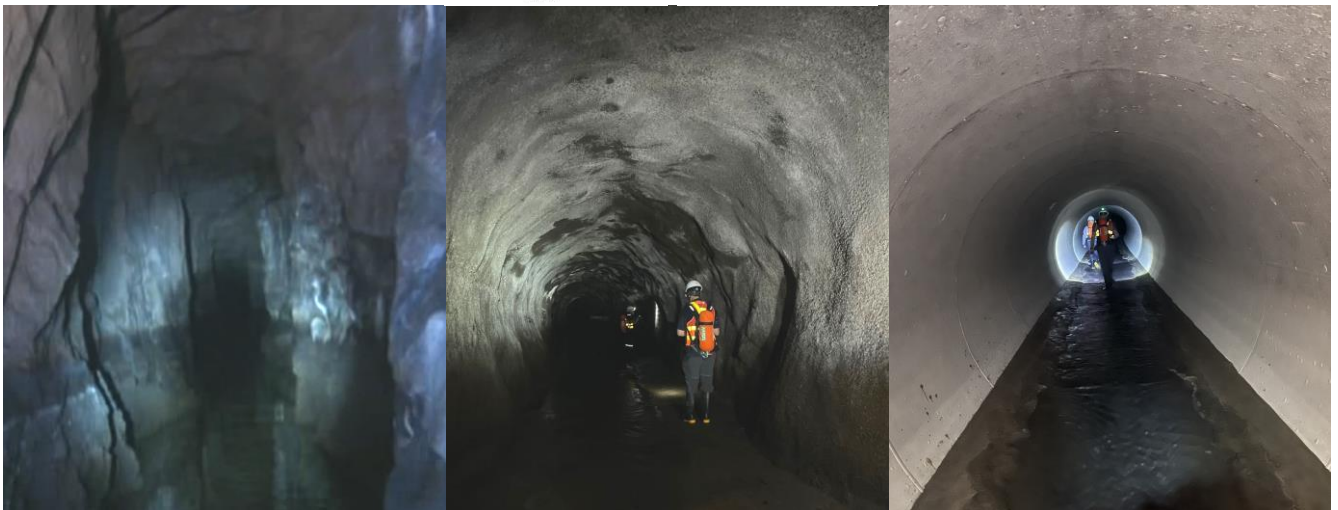
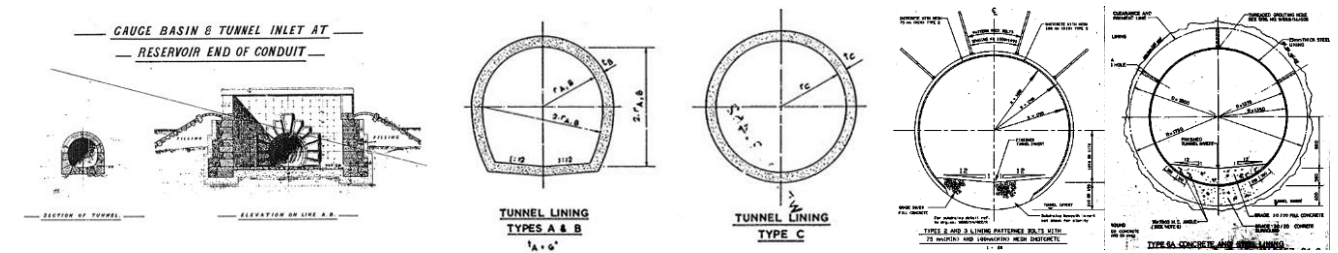


Figure 1: WSD Water Tunnel Network



Historic Water Tunnel (1880s)  
- Tai Tam Conduit

Typical Water Tunnel (1960s to 1980s)  
- High Island Eastern Tunnel

Recent Water Tunnel (post-1980s)  
- Silvermine Bay Aqueduct

Figure 2: Examples of Typical Tunnel Nature and Condition

## 2 EXISTING DATASETS

### 2.1 Asset Register

To assist with the asset management of the water tunnels, WSD had established a GIS-based dataset containing the following basic information for the tunnels:

- Asset ID Number
- Tunnel Diameter
- Responsible Region of WSD
- Name (English & Chinese)
- Installation Date
- Asset System (Fresh or Raw Water)
- Length (Tunnels) / Depth (Shafts)
- Drawing No.

### 2.2 Previous Inspection Records

With a view to conducting detailed condition assessments of water tunnels, consultants commissioned by WSD undertook the first round of on-condition monitoring of their tunnel assets from 2010 to 2012 and collated the following datasets for each asset:

1. As-constructed Records from the original construction contracts;
2. Condition Assessment Forms detailing the overall condition level for key aspects of the asset;
3. Performance Risk Assessments detailing the performance level of assets where physical inspection was not feasible;
4. Asset Improvement Forms outlining the specific maintenance and/or enhancement works requirements identified during the on-condition monitoring; and,
5. Photo and video (in some cases) records from the inspection works.

The data stored for each of the above datasets comprised either a Word or PDF file following the standard proforma layout defined in the Surface Asset Management (SAM) Manual (WSD, 2010) (see Section 3.3) for details, supplemented with the raw image and, where available, video files.

## 3 CONDITION ASSESSMENT REQUIREMENTS

### 3.1 Assessment Guidelines

In order to assist with the on-going management and assessment of asset functionality, the WSD has prepared the SAM Manual detailing the overall service delivery strategy, the policies, assumptions, obligations and targets relating to water supply, as well as the detailed methodologies and procedures for the classification, inspection, assessment, maintenance and management of all assets within the water supply network. An overview of the workflow relating to the condition assessment of subsurface tunnel assets (and associated surface facilities) per the SAM Manual requirements is shown in Figure 3. This workflow covers the full spectrum of works from asset selection through criticality assessment, performance risk assessment and on-condition monitoring to the development and prioritisation of any necessary maintenance or asset enhancement works from failure risks, criticality and cost-effectiveness.

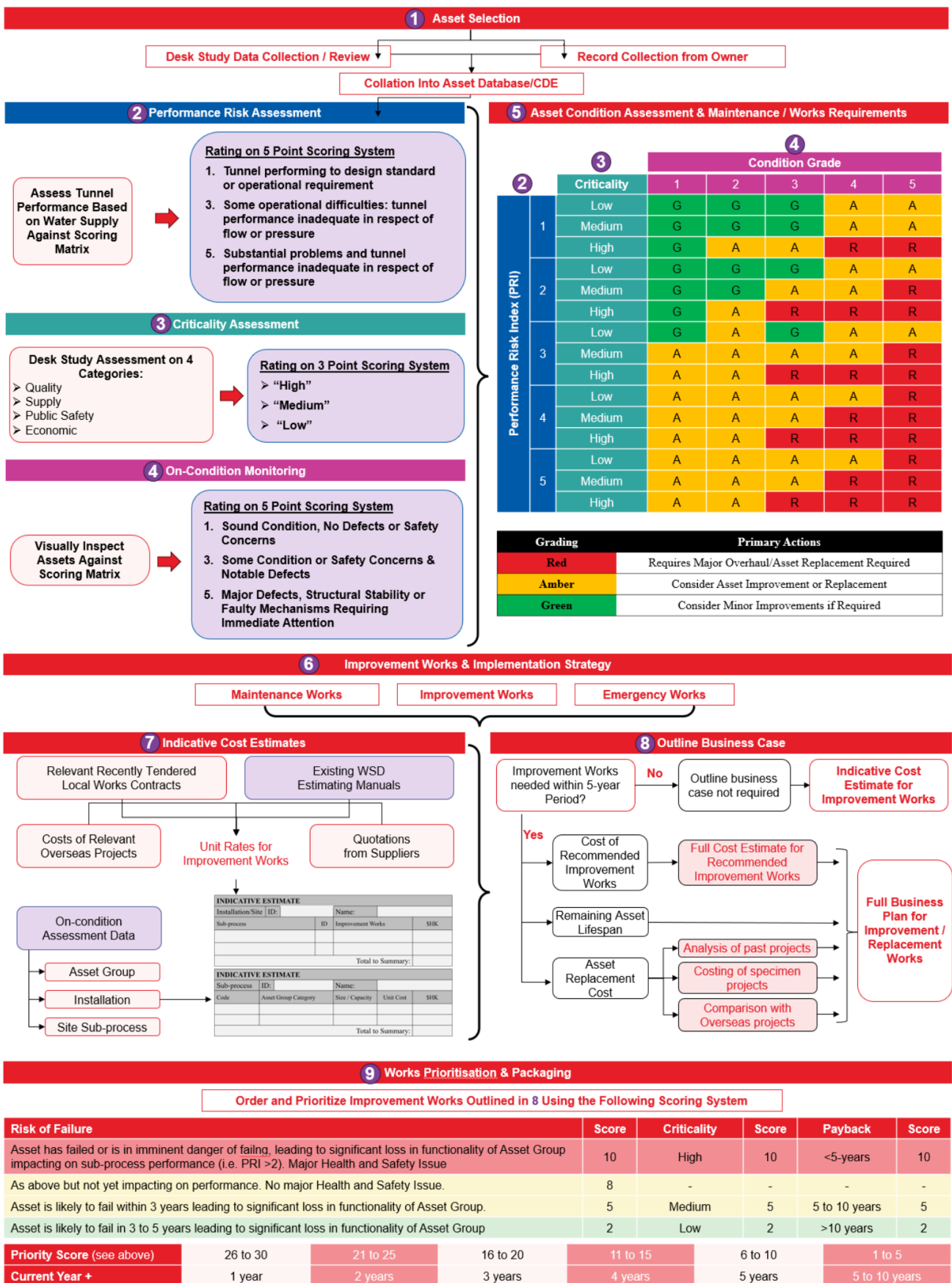


Figure 3: Workflow for Condition Assessment of Subsurface WSD Assets

### 3.2 Inspection Guidelines for Water Tunnels

The core part of the condition assessment workflow for the water tunnels (and associated assets) comprises the on-condition assessment of the assets themselves. These primarily comprise physical inspections of the assets to review and assess the condition status according to the various criteria shown in Figure 4.

Task	Information	Assessment Criteria	
<b>Tunnel Condition</b>	Observe damage to the rock face or tunnel lining through walkthrough inspection.	Major damage to rockface or lining	5
		Some damage or deposits	3
		Sound condition	1
<b>Tunnel Deformation</b>	Observe ovalisation or displacements of tunnel lining and/or rock face by walkthrough inspection and measurements.	More than 10% of the surface area deformed	5
		Some deformation	3
		No deformation	1
<b>Tunnel Siltation</b>	Observe siltation build up walkthrough inspection and clear before resuming service.	20% or more of the tunnel depth	5
		< 20% of the tunnel depth	3
		No significant problems	1
<b>Flow Control Structures Condition</b>	Observe mechanism, seals and other aspects by visual inspection.	Seized or missing systems	5
		Significant defects	3
		No significant problems	1
<b>Shaft Condition</b>	Observe damage to the rock face or shaft lining by visual inspection.	Major damage or blockage	5
		Some damage or deposits	3
		Sound condition	1
<b>Shaft Tower Condition</b>	Observe condition and security of towers	Major movement, settlement or security problem	5
		Some signs of movement or settlement	3
		Sound condition	1
<b>Tunnel Portal Condition</b>	Observe condition of the portal and surrounding areas by visual inspection.	Major movement, settlement or deterioration	5
		Some movement, settlement or deterioration	3
		Sound condition	1
<b>Other Issues</b>	Record any significant issues, in particular safety related issues, that may endanger the tunnel or operating flexibility		

Figure 4: On-condition Assessment Criteria for Water Tunnel Assets

### 3.3 Reporting Standards

The findings of the inspections are documented according to reporting formats defined within the SAM Manual, which includes standard proforma forms for the reporting of on-condition assessment findings, as shown in Figure 5.

C5: TUNNEL CONDITION ASSESSMENT	
Installation ID & name:	<input type="text"/>
Sub-process ID & name:	<input type="text"/>
Asset Group ID & name:	<input type="text"/>
1. Condition of tunnel including rock (or lining) deterioration, deposits, slimes, rockfalls and seepage	
Defects to Rock or Lining:	<input type="text"/>
Signs of seepages:	<input type="text"/>
Signs of Rockfalls:	<input type="text"/>
Attachment / Supplementary Information:	
Condition Grade:	<input type="text"/>
2. Deformation of the tunnel	
Deformation of Tunnel:	<input type="text"/>
Attachment / Supplementary Information:	
Condition Grade:	<input type="text"/>
3. Siltation of tunnel invert / sediment traps	
Degree of Siltation:	<input type="text"/>
Attachment / Supplementary Information:	
Condition Grade:	<input type="text"/>
4. Condition of control structures / flow measuring devices	
Visible Defects to Flow Control Structures and Measuring Device:	<input type="text"/>
Flow Control Structures and Measuring Device Operable:	<input type="text"/>
Attachment / Supplementary Information:	
Condition Grade:	<input type="text"/>

C5: TUNNEL CONDITION ASSESSMENT	
5. Condition of Shafts	
Major Blockages to Shaft:	<input type="text"/>
Attachment / Supplementary Information:	
Condition Grade:	<input type="text"/>
6. Condition of Shaft Towers	
Signs of Instability, Movement and Settlement:	<input type="text"/>
Attachment / Supplementary Information:	
Condition Grade:	<input type="text"/>
7. Condition of Tunnel Portals	
Signs of Deterioration, Movement and Settlement:	<input type="text"/>
Attachment / Supplementary Information:	
Condition Grade:	<input type="text"/>
<b>SIGN-OFF</b>	
Overall Grade	<input type="text"/>
Assessment Engineer:	<input type="text"/>
Assessment date:	<input type="text"/>
Time in months to next assessment:	<input type="text"/>
Number of Asset Improvements attached:	<input type="text"/>
SAMP form: DC3.1/12-5	

Figure 5: On-condition Assessment Report Proforma

## 4 ENHANCED DIGITAL APPROACH

### 4.1 Overall Approach

The previous round of on-condition monitoring for the water tunnels in early 2010 was conducted at a time when the development and use of digital inspection and data management tools were in the early stages and not ready for digital asset management. Works at that time were generally conducted in a manual format. Although following a well-established filing structure, the approach meant that the saved data was manually input and extracted from each file, which cannot completely prevent data inconsistencies or errors. The approach also used a tree format data structure, which was less efficient for the user to navigate and trace the output files from the original core data sets.

To address this and provide a more integrated, structured and connected approach to data management and future assessment works, an overarching digital approach was established early in the current round of on-condition monitoring. This approach was developed around the use of centralized secure online servers (e.g. a Common Data Environment or “CDE”) that could host the existing datasets collected either directly from the Client or through desk study searches, as well as all new datasets (e.g. inspection data, records and performance calculations) generated by the on-going works. Through the implementation of standardized filing conventions and structures, the datasets could then be used to populate dashboards for easy visualization and progress tracking as well as the semi-automated generation of inspection reports and other deliverables as shown in Figure 6:

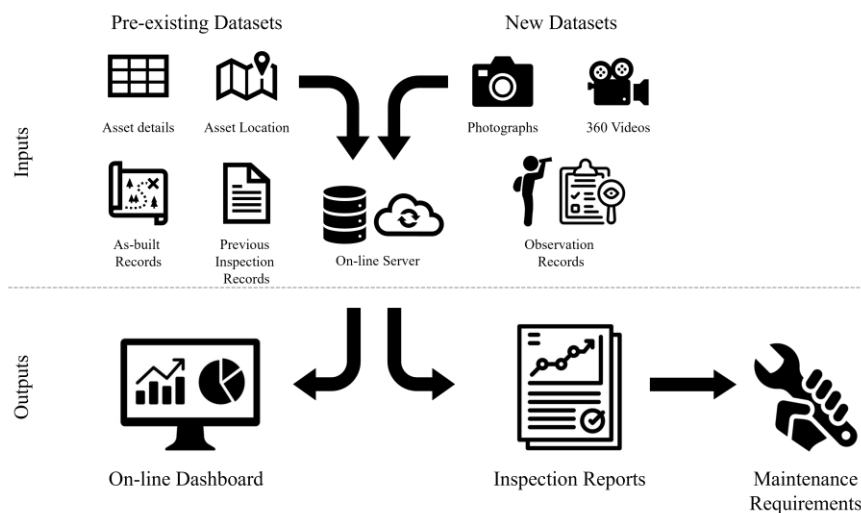


Figure 6: Overall Approach to Data Management and Use

### 4.2 Centralized Asset Register

To facilitate enhanced management of the available data for each of the assets, key information from the various available asset datasets was collated and input to a single, simple on-line excel spreadsheet (Figure 7) that included the following information.

- |                                    |                               |                                     |
|------------------------------------|-------------------------------|-------------------------------------|
| 1. Asset ID;                       | 2. Sub-process ID and Name;   | 3. Asset Group ID and Name;         |
| 4. Asset Name (English / Chinese); | 5. WSD Region;                | 6. WSD Responsible Team;            |
| 7. Up/Downstream Assets Reference; | 8. Tunnel Length/Shaft Depth; | 9. Tunnel/Shaft Diameter;           |
| 10. Water Type (Raw/Fresh);        | 11. Year Asset Constructed;   | 12. Asset Age;                      |
| 13. Asset Design Life;             | 14. Asset Remaining Life;     | 15. As-built Record Drawing No.(s); |
| 16. P&I Manual Reference;          | 17. O&M Manual Reference;     | 18. Date of Last Inspection;        |
| 19. Date of Current Inspection;    | 20. On-condition Grade;       | 21. Asset Criticality;              |
| 22. Performance Risk Assessment;   | 23. Risk of Failure Score;    | 24. Replacement Cost;               |
| 25. Modern Equivalent Value;       | 26. Maintenance Strategy;     | 27. Priority Score;                 |
| 28. Asset Prioritisation.          |                               |                                     |

Batching				General Data										
Batch (Actual)	Region	Responsible WSD Team	Installation No.	Installation Name	Waterworks Installation Ref. No. 1 (u/s)	Waterworks Installation Ref No. 2 (d/s)	Length (km)	Diameter (m)	Lining Type	Raw/ Fresh/ Catchwater	As-Built Records	Data Sheet Completed?	Tunnel able to be Isolated for Inspection	
1	K	HW1	TL020	Tai Po Road WTW Raw Water Inlet Pipe Tunnel	TP058	TP059	0.105	5.4	Concrete	R	W05877_0000	Y	Y	
1	NTW	HW3	TL027	Tai Lam Chung Catchwater J Tunnel 05	TP073	TP072	0.148	2.21	Shotcrete	C	W02522_0000	Y	Y	
1	NTW	HW3	TL029	Tai Lam Chung Catchwater J Tunnel 06	TP077	TP076	0.339	2.21	Shotcrete	C	W02522_0000	Y	Y	
1	NTW	HW3	TL030	Tai Lam Chang Catchwater LMNO Tunnel 02	TP079	TP078	0.777	3.2	Shotcrete	C	W06102_0005	Y	Y	
1	NTW	HW3	TL031	Tai Lam Chang Catchwater LMNO Tunnel 03	TP081	TP080	0.167	3.6	Shotcrete	C	W06102_0005	Y	Y	
1	NTW	HW3	TL032	Tai Lam Chang Catchwater LMNO Tunnel 04	TP083	TP082	0.221	3.6	Shotcrete	C	W06102_0005	Y	Y	

Figure 7: Simple Online Excel-based Asset Register

The asset register was hosted on a secure Microsoft Sharepoint server to allow for integration to various tools within the digital data management system. To effectively integrate GIS map data with the inspection records and Excel database, the “Atlas” tool (Figure 8) was used to facilitate real-time data updates and ensure that the project team were working on the correct and most up-to-date data possible.

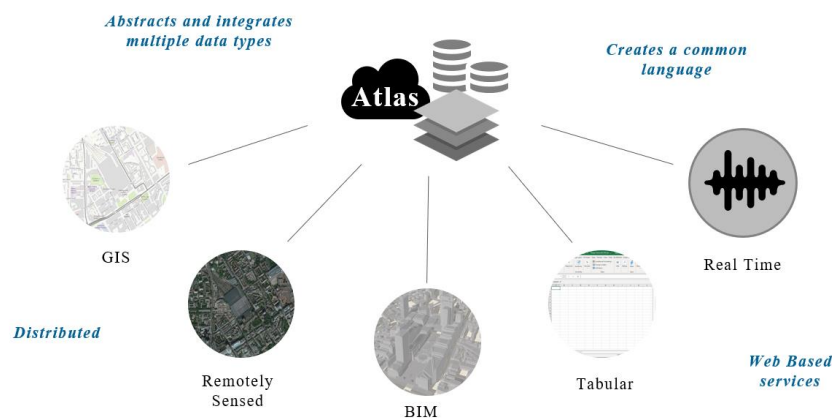


Figure 8: Atlas Database System

### 4.3 Data Collection App

The on-condition monitoring requires manual inspections to be undertaken for all physically accessible assets. Throughout the course of the inspections, the inspecting personnel would be required to identify, photograph and record the location and details of various different types of maintenance defects including, but not limited to lining damage, cracks/fractures to lining, rockfalls, seepages, and siltation of the invert. They would also need to record the general tunnel condition at regular intervals to capture a complete picture of the tunnel condition along its length. Typically, the inspections would need to be undertaken in confined space settings that were unlit, poorly ventilated, damp and wet, and deep underground thus lacking cellular signal connectivity.

To enhance the ease with which data could be collected, recorded and managed in an integrated, structured and systematic manner, decisions were quickly made to develop a bespoke tunnel inspection application that could be loaded to a mobile phone, could easily be operated one-handed and that would be capable of working in an off-line environment, syncing the collected data back to the central server once network connectivity resumed. To facilitate app development in a cost-effective manner that allows for direct integration with Microsoft Sharepoint, a relatively low-tech approach was adopted using Microsoft PowerApps. This app (Figure 9) allows the user to load a “light database” to their phone handset when connected to the internet before the inspection. The user could then select the desired asset for inspection without signal before and easily collects on-site observations through the simple pre-set interface which includes tunnel chainage, tunnel element (e.g. crown, left/right wall, or invert), the observation type (e.g. fracture, seepage, siltation, rockfall, damage, or other) and then takes a photo through using the app interface. This approach means that all key information for a photo is saved as structured metadata that could be directly shared to the online server and immediately integrated in the online data management platform.

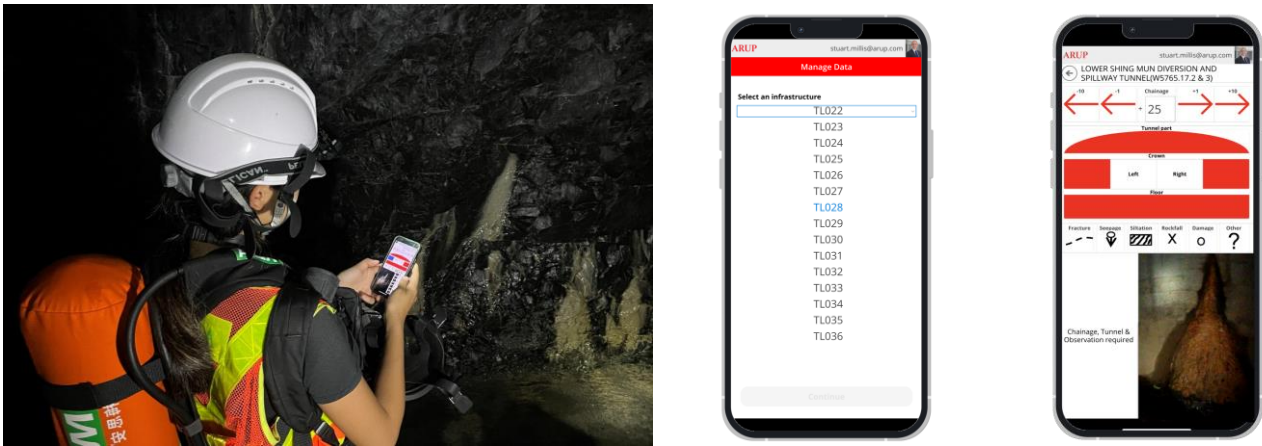


Figure 9: Data Collection App

#### 4.4 Data Management Platform

Central to the effective use of both the existing available digital datasets and the additional datasets generated during the on-condition inspections was the development of an online dashboard to facilitate data management, access and visualization (Figure 10). This was achieved using Arup’s in-house “Fuse” platform, which will be interfaced with the WSD Asset Management Information System (AMIS) via the Application Programming Interface and the relevant information will be stored in the WSD AMIS repository accordingly.

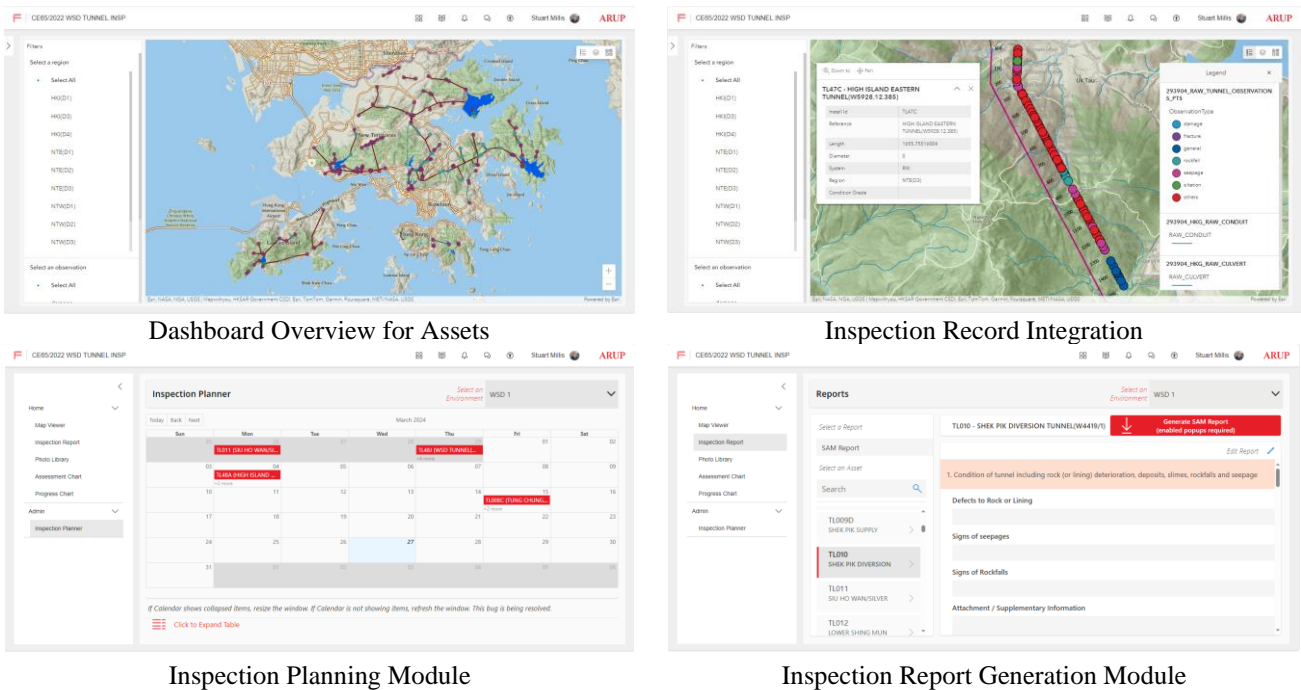


Figure 10: Data Management Dashboard

#### 4.5 Semi-automated Reporting

In addition to standard data management, the Fuse platform also enables the inspector to rapidly populate and generate inspection reports. This is completed using simple entry prompts in the dashboard environment that allows the inspector to select and annotate the appropriate images to be included in the report, provide inspection summaries and descriptions and easily report observation locations before generating the report.

The tool automatically creates the required reports according to the proformas in the SAM Manual, including all necessary written text fields, summary documents, photo records and drawings as appendices.

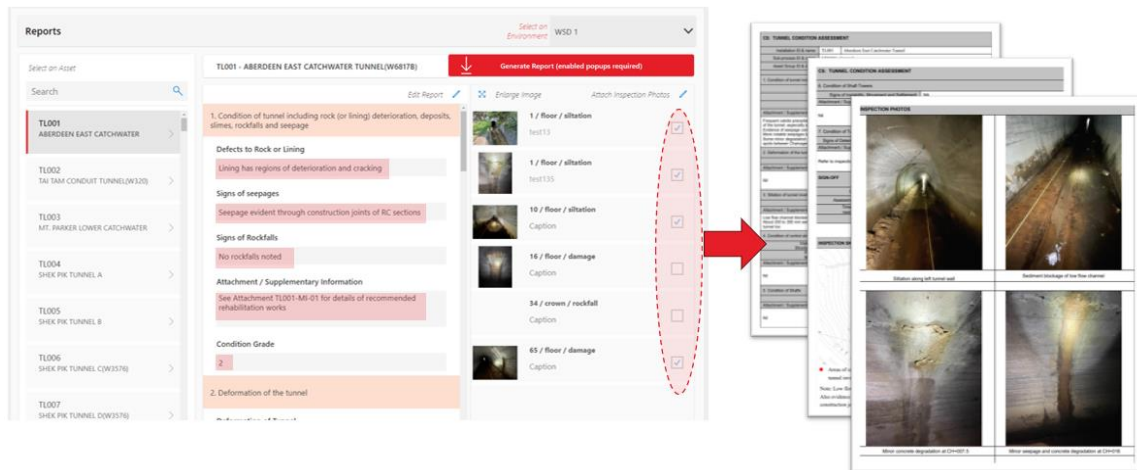


Figure 10: Semi-Automated Report Generation

## 5 SUPPLEMENTAL DIGITAL APPROACHES

### 5.1 360° Imagery and Videos

The photographs collected by the bespoke Mobile PowerApp are supplemented through the collection of additional 360° videos and images. These are captured using an Insta360 X3 camera mounted to a custom-made lighting rig that provides full 360° illumination of the main camera field of view (Figure 11). The collection of continuous and narrated 360° video footage enable the inspecting engineers to conduct virtual re-inspections of the assets to review and refine the findings documented using the Mobile PowerApp, whilst also allowing project participants not present during the physical inspections the chance to clearly observe and review the actual asset condition. This process acts both as a quality control measure and allows full internal audit capability to ensure that each inspection team is consistent with condition grading.



Figure 11: 360° Video & Image Capture Equipment

The 360° equipment has also been used to facilitate the inspection and defect identification/logging for vertical shafts in which no physical access is possible. This is achieved by lowering the equipment down the shaft from a tripod set up across the shaft top, with depth-time logs used to correlate the images captured to the location within the shaft, similar to the concept used by tethered CCTV crawler rigs (Figure 12).



Figure 12: Inspection of Inaccessible Shafts

### 5.2 UAV Surveys

To investigate the potential for unmanned inspection of water tunnels, a trial Unmanned Aerial Vehicle (UAV) survey was undertaken at the Lower Shing Mun Spillway Tunnel, a 326 m long, 5.5 m diameter concrete lined tunnel. The trial was undertaken by WSD’s Term Contractor, Ming Hing Waterworks Engineering Co. Ltd., using an Elios 3 UAV to conduct 3D-scanning by LiDAR, and collect 4k video footage and photographs of the tunnel condition as shown in Figure 13.

The inspection took less than 20 minutes to complete and yielded high quality photographs and videos in which all key defects identified during the physical survey of the same tunnel were clearly visible. To maintain sufficient signal to the pilot, the maximum line-of-sight distance for indoor UAV systems deployed in tunnels is effective over approximately 400-500m. This length would be considerably reduced if the tunnel has some curvature (breaking line-of-sight). Currently, the flight time is also not an uncommon challenge to the use of indoor UAVs, including the maximum flight time of approximately 20 minutes for Elios 3 UAV in this trial, which also acts as a constraint to the length of survey.

It should also be noted that in Hong Kong, the deployment of UAV systems for is subject to Civil Aviation Department law and when utilized for commercial settings, relevant flight restrictions must be adhered to.



Figure 13: UAV Survey Equipment and Data

On-going research on the use of indoor UAV devices for tunnel surveys identified some isolated examples of autonomous ‘unpiloted’ UAVs being used to conduct video and 3D scanning surveys of water tunnels up to 7 km in length. Should these devices become more readily available in Hong Kong, they would provide a highly effective tool for the collection of detailed tunnel survey datasets.

### 5.3 Laser Scanning Surveys

Similarly, trials were undertaken in the consultancy to explore the potential to collect detailed point cloud data of the tunnel geometry and condition using laser scanning technology. The trial included the use of both terrestrial tripod mounted scanners (Faro Focus Core Laser Scanner) as well as handheld scanning devices (FJD Trion S1 Portable Scanner) as shown in Figure 14.



Figure 14: Terrestrial and Mobile Laser Scanning

Data capture with the static (mounted) system was undertaken at intervals of 50 m to generate a series of continually overlapping point clouds that, due to the placement of survey spheres along the tunnel length, could be merged to cover the entire asset length. Data capture with the mobile system was undertaken using a ‘there and back’ loop for portions of an asset that could be covered in a 25-minute time interval, limiting the scanning distance of a single dataset to about 500 m. For assets exceeding this length, survey spheres were used with overlapping portions of adjacent scans to enable merging of the survey datasets.

Although only trialed on a limited number of assets, it is worthwhile to highlight the following findings of note about the suitability and effectiveness of laser scanning for water tunnels (Figure 15):

1. *Terrestrial Scanners:* Provided the survey is well-planned and adequate survey spheres provided across overlapping scan areas, tripod mounted scanners can yield very high-quality point cloud datasets for all tunnel lining types. However, such surveys can require considerable time to complete, in the case of the 326 m Shing Mun Spillway Tunnel this equated to about 30 minutes per 100 m of tunnel.
2. *Mobile Scanner:* Scanning of similar tunnel lengths using handheld mobile laser scanners required only about 10% of the time needed for tripod-mounted scans. However, the SLAM technology used by such devices means they are not capable of collecting data within tunnels of uniform and consistent profiles where insufficient variance exists for the device to distinguish between different locations within the tunnel. This provides a severe constraint for use within cast in-situ or segmentally lined concrete tunnels, in which scans typically fail within about 10 m from the last distinguishable geometric change or feature. However, reasonable quality datasets could be rapidly obtained from scans within shotcrete lined tunnels with irregular profiles and unlined rock tunnels.

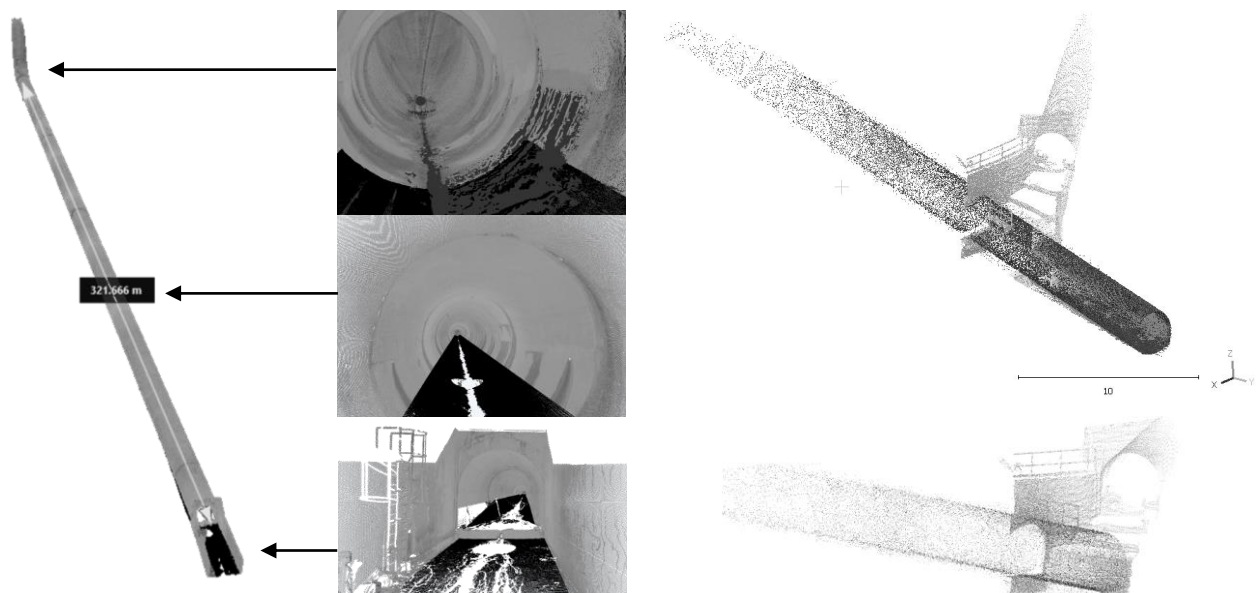


Figure 15: Examples of Point Cloud Datasets from Terrestrial (left) and Mobile (right) Laser Scanning

### 5.4 Arup Loupe 360 Tool

Arup Loupe 360 (Figure 16) is a tunnel inspection visualization and analytics platform that leverages 360° imagery and computer vision to enable visualization and asset analysis, supported by machine learning (ML) and artificial intelligence (AI) for defect detection, inventorying and condition rating analytics. Initially developed in the UK to facilitate the rapid and semi-automated inspection of segmentally lined railway tunnels, the platform is customizable and can integrate high-quality 360-data for any tunnel asset. Trial integration of regularly spaced 360 images from several of the WSD tunnels was therefore undertaken. The trials showed that the tool provided an ideal platform for conducting ‘Google Street View’ style walkthrough inspections, allowing the user to navigate their way quickly and easily through the available images for an asset. Regarding the use of AI for defect detection, the trial revealed that additional training of the ML algorithms would be required as the lining types and defect condition/classification used for the WSD tunnels differed notably from those in the segmentally lined tunnels on which the tool was originally trained. Such ML-training is considered entirely feasible and the trial provided a good proof-of-concept for further exploration when opportunity arises.

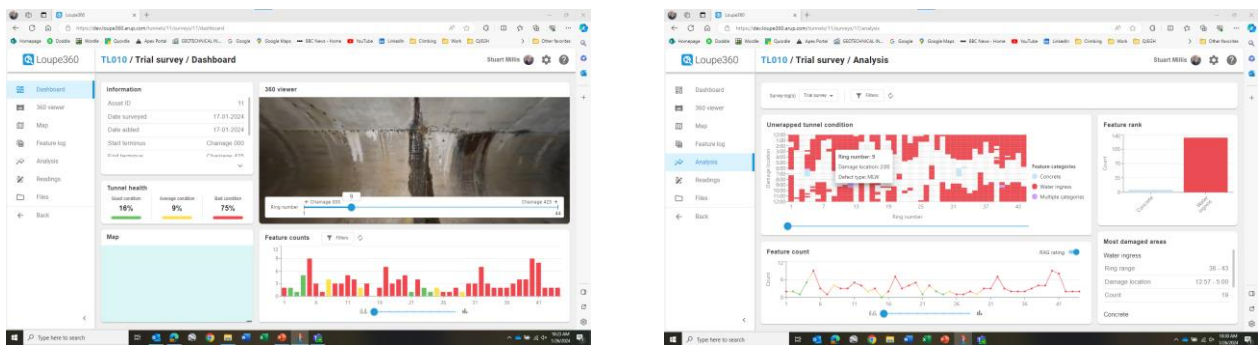


Figure 16: Data Integration within the Arup Loupe 360

## 6 SUMMARY

The Water Supplies Department (WSD) of Hong Kong owns, operates and maintains about 200 km of water tunnels, some of which are over 100 years old, as part of an extensive water supply network that must operate at considerable capacity, year-round, in order to facilitate the consistent supply of high-quality water to Hong Kong residents. As part of routine maintenance, condition assessments of these critical tunnels must be undertaken to ensure supply continuity. On behalf of WSD, Arup have completed these inspections utilising the latest technology and novel data collection and management methods to enhance every stage of the assessments including data management, on site data collection, condition assessment, dashboarding and reporting using the “single source of truth” approach. Extensive testing of various data collection methods and inspection tools and techniques was completed as part of the project to determine the most optimum condition assessment method for existing water tunnels. The conclusion of these trials is directly applicable to other, similar maintainers in the industry (e.g. drainage, electricity supply or gas networks). This approach is also being adopted by the WSD in which the data of the tunnel assessment could be retrieved in the WSD AMIS to facilitate future asset management under the WSD asset management policy.

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