Piloting innovation in the waters of Boston

JONNAS JACQUES, PE, Kleinfelder, Boston, Massachusetts
AMY SCHOFIELD, Boston Water and Sewer Commission, Boston, Massachusetts
DAVID PETERSON, PE, Kleinfelder, Boston, Massachusetts

ABSTRACT | Drone technology has rapidly expanded into the commercial market in recent years. Drones, more formally known as unmanned aerial vehicles (UAVs), have been integrated into the data collection and inspection services of many firms around the world. The development of smaller-scale drones has facilitated the implementation of drones as remote-controlled inspection tools. Their use has been seen predominantly in building envelope and overland transmission pipeline evaluations. Only a few instances are found of this technology being used for assessing underground pipelines, culverts, and conveyance conduits such as combined sewer overflow (CSO) outfalls. This article discusses the two-part illicit discharge detection and elimination inspection that reimagined the use of UAV technology to investigate illicit connections within the Boston Water and Sewer Commission's Fort Point Channel CSO 070 outfall.

KEYWORDS | Drones, UAV, illicit discharge detection and elimination inspection (IDDE), pipeline inspection, tidal influence

INTRODUCTION

A 2014 study of Boston's Fort Point Channel (FPC) found the channel to be degraded by contamination from sewage, bacteria, oils, grease, and floatables. Because of these contaminants, the FPC did not meet the water quality objectives of a Class SB combined sewer overflow (CSO) receiving water as defined by the Massachusetts Surface Water Quality Standards. The study found that during dry-weather conditions, sampling site SW1 (see Figure 1) at the upstream (southern) end of the FPC exceeded the water quality standard for *Enterococcus* (104 MPN/100mL) 65 percent of the time over the 143 samples taken. The remaining downstream sample locations in the FPC (SW3-SW8, see Figure 1) complied with the standards between 92 percent and 100 percent of the time. The study found the CSO 070 outfall to be the primary contributor to the FPC's dry weather water quality issues. Furthermore, the study recommended that the Boston Water and Sewer Commission (BWSC) investigate the CSO 070 combined sewer system for illicit sources of bacterial contamination.

Two large outfall pipelines—the Roxbury Canal conduit (RCC) and the Dorchester Brook conduit (DBC) in the BWSC CSO 070 combined sewer system that drains into the FPC—were constructed in the 1960s. These pipelines are reinforced-concrete box culverts that convey a combination of groundwater base flow, storm flow from the local drainage catchment, and combined sewer flow during large storm events to the FPC through the CSO 070 outfall as illustrated in Figure 2. The RCC/DBC pipeline dimensions vary from a 15 ft (4.2 m) wide by 10 ft (3 m) high, single-barrel culvert at the upstream end of the RCC to twin-barrel culverts, each 20 ft (6.1 m) wide by 15.5 ft (4.7 m) high at the CSO 070 outlet to the FPC. Water levels within the conduits are greatly influenced by tide fluctuation, as the FPC is hydraulically connected to Boston Harbor.

The FPC project area is divided by Interstate 93 (I-93), an elevated, congested highway, and numerous railroad tracks that shepherd daily commuters to Boston's South Station. The area includes various municipal, commercial, industrial, and institutional sites that require access for inspection to be coordinated. This highly developed, urban environment within about 1 mi (1.6 km) of the FPC overshadows the relatively flat nature of the local topography. Grades rest at an elevation of approximately 17 ft (5 m) on the Boston City Base (BCB) datum, and the RCC and DBC pipeline crowns are buried roughly 7 ft (2 m) below grade. Between their single- and double-barrel configurations, the RCC and DBC pipelines extend more than 12,000 lf (3,658 m).

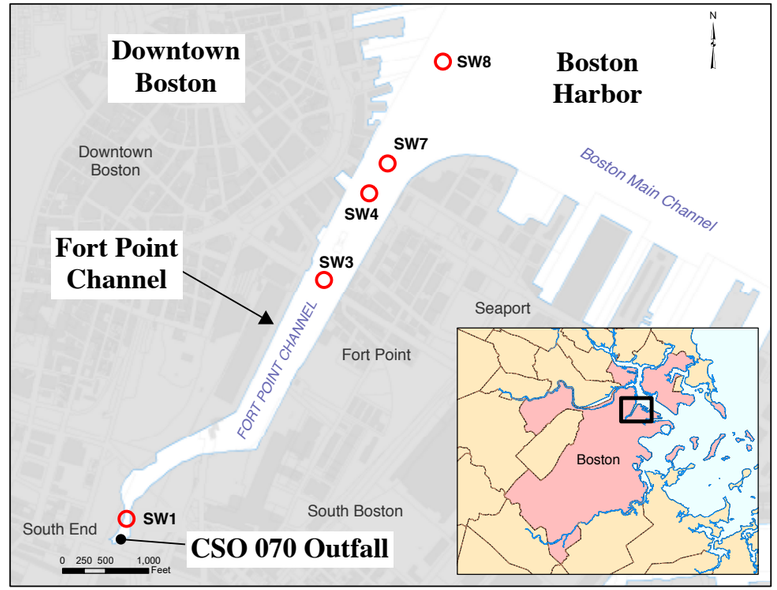

Figure 1. Fort Point Channel sampling sites

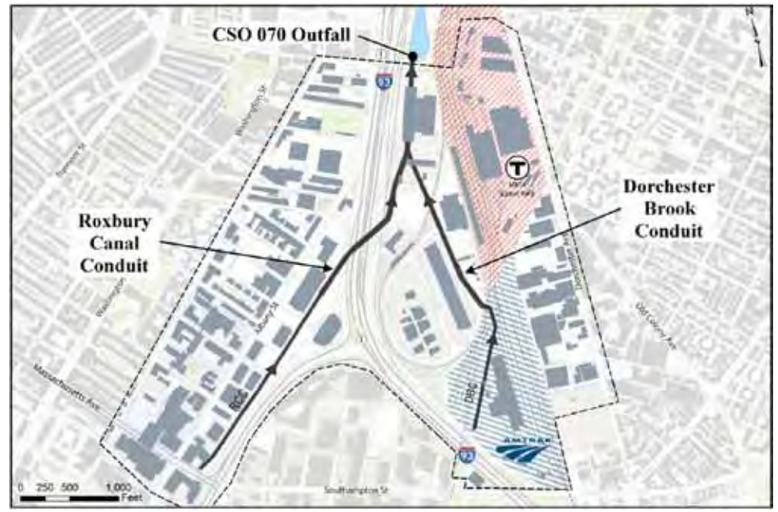

Figure 2. Fort Point Channel project area

DESCRIPTION OF WORK

An illicit discharge detection and elimination (IDDE) program, known as the FPC CSO 070 project, was developed in 2017 to investigate these water quality issues and their sources of contamination within the CSO 070 combined sewer system. The project's objectives are as follows:

- Improve the BWSC's understanding of the CSO 070 collection system configuration, connectivity, and functionality
- Identify specific source(s) of illicit connections, direct cross-connections, or indirect connections between the sanitary and storm-drainage networks contributing to water quality issues
- Develop recommendations for eliminating confirmed illicit connections and, if needed, identify areas for additional study

The CSO 070 system investigation included pipeline inspections, building inspections and dye testing, and manhole water quality grab sampling for laboratory analysis. Central to the pipeline inspections were obtaining internal digital video information of the RCC and DBC pipelines (see Figure 3—next page) and confirming their connectivity to the rest of the drainage system. Although the BWSC's mapping was relatively accurate, these inspections were to identify and inspect any undocumented, existing connections.

Early on, the BWSC understood that conventional inspection would be difficult given the limited access into the conduits, the conduit configurations, and the complex behavior of the tidally influenced water levels. Records of the conduits show that concrete access panel slabs were constructed every 1,000 ft (300 m) or so along each pipeline's alignment. Field reconnaissance found these slabs to be deteriorated and unusable for inspection. Furthermore, access manholes were constructed every 300 ft (91 m) along the pipeline alignments, flanking the conduits at either side as depicted in Figure 4 (next page), and the non-centered location of the manholes limited access into the center of the pipelines.

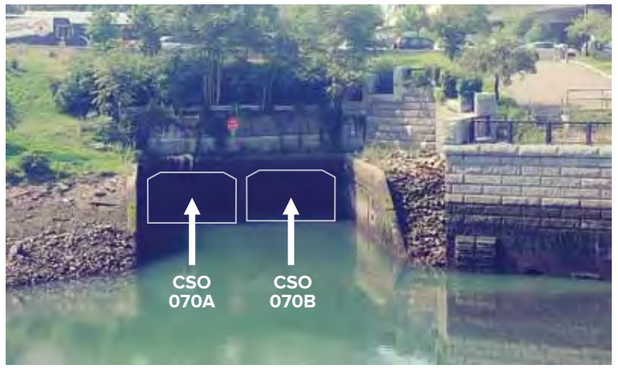

Figure 3. Boston's Fort Point Channel looking upstream into CSO 070

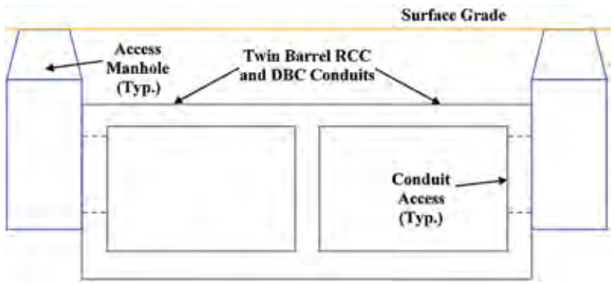

Figure 4. Sketch of Roxbury Canal and Dorchester Brook conduits

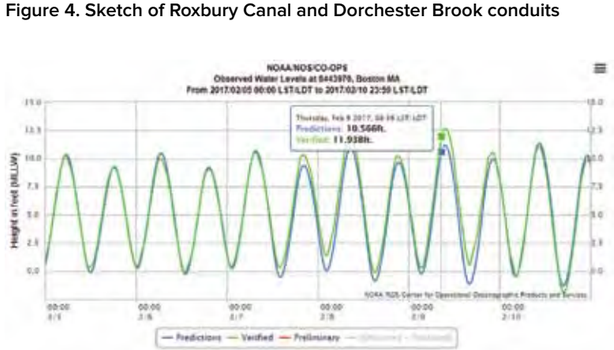

Figure 5. NOAA tide charts for Fort Point Channel/Boston Harbor

The outfall pipelines are hydraulically connected to Boston Harbor and have no tide gates. Confined-space entry (CSE) investigations of the conduits identified the complex behavior of the tidally influenced water levels. The water levels within the outfall pipelines change constantly with the daily tide cycle, varying up to approximately 13 ft (4 m) vertically from a BCB elevation of roughly 11.5 ft (3.5 m) to -1.5 ft (-0.5 m). As shown in Figure 5, during high tide, both outfall conduits are effectively submerged and inaccessible. The CSE investigation found that crews had roughly 4 to 5 hours for insertion and extraction before the workspace within the conduits was submerged by tidal waters.

In addition to the challenge posed by the tidal waters, the outfall pipelines also contain several feet of sediment, consisting of sand and gravel washed down from the drainage and organic backwash from the Boston Harbor, that has built up over more than 50 years of operation. The sediment changes from loose sludge to hard-packed deposits over the length of the two outfall pipelines. Given the challenges to inspection described above, an innovative approach was needed.

METHODOLOGY

Closed-circuit television (CCTV) has been the primary method in the United States of visually inspecting and capturing photographic data of a pipeline's interior. Advancements over the years in pipeline traversing units, camera systems, and inspection software have further enhanced this technology. These advancements include the following:

- **Laser scanning**: recording pulses of light to measure the internal pipeline
- **Sonar inspection**: measuring sediment levels under the pipeline's flow line
- **Thermal imagery**: sensing temperature readings of the pipeline's surface and objects within
- **3D rendering software**: processing captured imagery of the pipeline into a 3D model

These advancements, however, have increased the cost of using CCTV technology. Typically, contractors rely on their volume of pipeline inspection work to make advanced inspection technology cost-effective, with only limited, occasional use of it in larger, more-complex systems to inspect a small part of the network. The higher cost is typically driven by the need for personnel to enter these larger pipelines to perform manual inspections and equipment deployments. One innovative—and safer—alternative to manned-entry inspections is drone technology. Drones can perform similar inspections to conventional equipment, and they offer more-versatile maneuverability in these more complex and dangerous environments.

Drone technology is not new to pipeline inspections, having been used in the oil and gas pipeline industries for both internal and external inspections. Drones have been used, however very rarely, to inspect water resource infrastructure pipelines around the world. One example is in Spain where the Spanish firm Fomento de Construcciones y Contratas, S.A. (FCC) is using drones to inspect the 938 mi (1,500 km) sewer system in Barcelona (Freyberg, 2017). Another example is in Melbourne, Australia, where drones are being used in regional drinking water infrastructure inspection and maintenance (Goldsmith, 2015). And now in the United States, the FPC CSO 070 project is among the first in this country to similarly pilot drones for pipeline inspection.

APPROACH

Implementing any of the conventional approaches to inspect the RCC and DBC conduits would have been difficult given the conditions; hence, drones were piloted as one potentially viable and cost-competitive alternative to conventional CCTV pipeline assessment. Three approaches, using a combination of technologies, were devised:

1. The project team attempted to pilot a drone through the conduits with just the bare necessities for accessories: a camera and a lighting system. An onsite crew provided additional lighting.
2. The project team constructed a remote-controlled boat, affixed with its own camera and lighting system, to supplement the drone inspection approach. The lighting crew was not used during this inspection attempt.
3. The project team strung a wire rope through the conduits that would be tethered to a pontoon-mounted camera and lighting system and pulled throughout the conduits.

The drone used for the inspections (photo 1) was provided by the operator. When using these technologies, it is important to provide for safe access through a limited number of locations, to work around sediment levels, and to accommodate a shortened work window due to tidal conditions. Each approach used to inspect these conduits had benefits and opportunities for improvement, and the successes identified in one approach could be used to alleviate the challenges of another approach. In turn, this sharing of information improved the technical feasibility and cost-effectiveness of all approaches used.

The objectives of the drone/remote-controlled inspection approaches included the following:

- Gain access and make a safe entry into RCC and DBC conduit manholes
- Understand the tidal influence on the conduits
- Photograph the inside of the conduits, including piped connections
- Test multiple approaches to lighting the interior of the conduits
- Demonstrate that a quadcopter drone can fly within the conduit
- Develop a 3D model of the conduit, if conditions permit

Through these drone inspection demonstrations, the project team anticipated using the drone's versatility to meet other IDDE objectives. If active flow was detected coming through a lateral during dry weather, the drone could perform a close-up inspection of the lateral piping for illicit indicators. The drone would also allow for the visual inspection and documentation of conditions from various angles. In the event of debris or obstructions, the drone could maneuver in and around areas of interest to obtain point-specific data.

Photo 1. Drone used for inspections (typical)

Photo 2. Lateral detected through drone inspections

Drones also can be outfitted with any combination of advanced pipeline inspection tools, including laser scanning, sonar, thermal imaging, and 3D rendering. Software would compile the digital photography and video data from the drone inspection to generate a 3D model of the inspected pipeline. The FPC project team intended to use the model of the RCC and DBC conduits to determine the locations of any detected laterals. If necessary, the project team could perform follow-up IDDE investigations upstream of these identified laterals to determine dry-weather, illicit sources.

RESULTS

Through these drone demonstrations, both the UAV and remote-controlled boat methodologies showed they could successfully inspect large outfall pipelines when other traditional methods are unavailable. Photo 2 illustrates a lateral inspected by the UAV. The first and second drone demonstrations inspected 300 ft (91 m) and 250 ft (76 m) of conduit, respectively. The limited production from these approaches was due to unforeseen circumstances with available equipment and the tides. Proper

Table 1. Cost comparison of pipeline inspection approaches

Inspection Type	Total Daily Cost ($)	Inspection Length ft (m)	Unit Cost $/ft ($/m)	Required Production ft (m)	New Unit Cost $/ft ($/m)
Drone demo #1	8,760	300 (91)	29.20 (95.80)	>1,850 (564)	<4.73 (15.52)
Drone demo #2	5,100	250 (76)	20.40 (66.93)	>1,100 (335)	<4.63 (15.19)
Pontoon*	4,750	1,000 (305)	4.75 (15.58)	n/a	n/a

*Vendor-quoted price and production

planning was critical to maximize the work windows between high-tide cycles. Other findings from the drone demonstrations included the following:

- The video quality output depended on adequate lighting while maintaining a centered and stable camera position within the conduits. Powerful lighting systems affixed to the drone are needed to capture quality video and photo data.
- The drone could easily eclipse inspection speeds of 30 ft/min (9 m/min) and greater.
- The slight air flow within the conduits caused the drone to rotate horizontally on its own. The changing air flow conditions were related to the tidally fluctuating water levels.
- The sediment within the conduit was a fine, loose material that prevented stable footing, and the debris build-up throughout the conduit was apparently from leftover construction. Inspections using conventional crawler equipment would not have been feasible.
- During the beginning and end of the 5-hour tidal work window, the water levels were found to rise and fall at a rate of roughly 1 ft (30 cm) every 30 minutes.
- Owing to the uniform concrete conduits and lack of distinguishing marker points, the 3D rendering software could not develop a model of the conduit pipelines.

Ultimately, the decision to implement the drone inspection approach would be driven by cost, regardless of the drone's capabilities. In Table 1, the costs to perform the two drone demonstrations are compared to the unit cost to perform the inspections using a pontoon camera system. As depicted, the unit price to perform the drone inspections decreased between the first and second demonstrations following some adjustments. However, the drone inspection unit costs were still an order of magnitude greater than those of the pontoon camera. Thus, further attempts to refine the drone inspection approach were dismissed in lieu of the quoted pontoon inspection method. Nonetheless, an increase in the daily production rates of the drone approaches is feasible with proper planning and refinement and, therefore, a drone inspection can be cost-competitive with conventional inspection methods.

The drone demonstrations accomplished the IDDE objective of pipeline inspection, and, with future advancements to the technology, more opportunities will arise to incorporate drones in other water resource assessments. The drone approach demonstrated a cost-competitive alternative to conventional inspection methods, and, with enough initial investment, water utility providers may add drone technology to their system-management tools.

DISCUSSION

To foster continuous learning and innovation, recommendations for consideration in drone inspection include the following:

- **Site Inspections**. Crews should perform field reconnaissance to confirm the condition of pipelines planned for inspection. Drone inspection should address the challenges of each pipeline. Also, access into the pipelines should be evaluated as it may require additional scaffolding and staging equipment to establish a safe work area.
- **Pipeline Conditions**. Stormwater and combined sewer outfall pipelines hydraulically connected to tidally influenced waterbodies will experience fluctuating water levels. Similarly, the flow conditions within these pipelines should be evaluated so that the proper controls may be in place to safely perform drone inspections.
- **Drone Accessories**. Various advanced inspection tools that may be necessary for successful pipeline inspection projects, and the drone itself should have the necessary features to gather the intended data. The drone demonstrations found lighting critical to successful data capture during inspections. For large pipelines and conduits, drones should have a heavy-duty lighting system for proper illumination (greater than 1,000 lumens is recommended).
- **Data Collection/Telemetry**. The underground environment is not always conducive to relaying signals for GPS/video telemetry. Accessories for repeating signal data or boosting signal strength may be required given the pipeline configuration. When possible, the data collected should be relayed and stored on the drone pilot's controller. Data stored directly within the drone risks being lost due to a drone failure or crash.
- **3D Modeling**. Developing a 3D model is difficult when only photogrammetry is used. The uniform appearance of underground pipelines hinders the 3D software's capability to stitch video and photographic data together in order to render a complete model of the pipeline. Instead, laser scanning and/or defined marker points along the pipeline in tandem with digital photo capturing may improve 3D model development.

CONCLUSION

As the feasibility of using drone technology for pipeline inspections progresses, applications exist today that may be considered. For water utility providers, these include CSO storage tunnels, stormwater outfalls, and water transmission aqueducts. Although suitable for inspections in less complex pipeline systems, drone inspections show the most apparent benefits in larger systems with more-complex pipe networks. Drone inspection technology may alleviate the risks in performing maintenance on these large, critical infrastructure elements of our water resource systems. In general, the conditions in which implementing a drone inspection should be considered include pipelines 60 in (150 cm) in diameter or greater that have the following attributes:

- Stagnant flows, no flow, or flows difficult to bypass
- Tidal influences
- Sediment build-up
- Odd cross-sections
- Limited access points

In summary, proper planning and preparation are key to successful drone inspections. These inspections can be cost-competitive with conventional pipeline inspection technologies when high production rates are met. Drones used in underground pipeline inspections should be outfitted according to the environment where the inspection occurs. Advancements in pipeline inspections are driven by the challenges faced when investigating the unique pipeline infrastructure of the modern world. With that in mind, the future holds many opportunities for the use of drone inspection technology to become more widespread.

REFERENCES

- CUES, Inc. (2018). CUES Broadest Product Line in the Industry. Available from: www.cuesinc.com/Products.html. Accessed September 21, 2018.
- Freyberg, T. (October 2017). Game of Drones for Barcelona Sewer Inspection. Water & Wastewater International. waterworld.com/articles/wwi/2017/10/video-game-of-drones-for-barcelona-sewer-inspection.html.
- Goldsmith, M. (February 2015). Aerial Drones: the Future of Asset Inspection. Utility. utilitymagazine.com.au/aerial-drones-the-future-of-asset-inspection.
- Iseley, T. and Behbahani, S. (May 2018). TTC Leads the Way in Advancing Pipeline Condition Assessment (PCA) with Drone Technology. Trenchless Technology Center, Louisiana Tech University.

ABOUT THE AUTHORS

- Jonnas Jacques is a project engineer at Kleinfelder with experience in the assessment, design, construction, and rehabilitation of municipal, water resource infrastructure. He is knowledgeable in the effective application of various traditional and trenchless technologies, with a focus on wastewater and stormwater pipeline rehabilitation. Mr. Jacques is OSHA HAZWOPER and confined-space-entry certified. He also has been trained through National Association of Sewer Service Companies' (NASSCO's) Pipeline Assessment Certification Program (PACP), Manhole Assessment and Certification Program (MACP), and Cured-in-Place Pipe (CIPP) Inspector Training and Certification Program (ITCP) certification programs. Mr. Jacques holds a Bachelor of Science in Civil Engineering from Northeastern University.
- Amy Schofield is a project manager at the BWSC where she has been employed for 30 years. She has a Bachelor of Science in Geography from Bridgewater State University. She holds a Mass Grade 2 Drinking Water Distribution license and a Mass Grade 4 license in wastewater treatment. Ms. Schofield has been managing illicit discharge detection and elimination and water quality sampling projects for the BWSC for more than 25 years, including the recent investigation to identify illicit sanitary connections in the CSO 070 system.
- David Peterson is a project manager at Kleinfelder. His entire career has focused on municipal wastewater engineering and consulting. His experience has been in planning, design, and construction of new or rehabilitated wastewater collection system infrastructure and wastewater treatment plants. Mr. Peterson has managed numerous wastewater facility and pipeline assessments, infiltration/inflow studies, IDDE studies, capital improvement plan development, and design and construction of upgrades.