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# Development and deployment of instrumented microtunnelling jacking pipes for the Athlone Main Drainage Scheme, Ireland: practical aspects and lessons learned

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ABSTRACT: Microtunnelling or pipe jacking (PJ) is an increasingly popular means of installing utility pipelines in congested urban environments due to its minimally-disruptive nature and reduced carbon footprint compared to traditional approaches. Since the PJ total force requirement for any drive is site-specific and its estimation is not well served by existing design methods, instrumented pipes (IPs) can enable a better understanding of pipeline performance in critical projects. Three reinforced wet-cast concrete jacking pipes were instrumented with some combination of fibre Bragg grating strain sensors, vibrating wire strain gauges and multi-axis fibre optic load cells for deployment within two drives as part of the Athlone Main Drainage Scheme in Ireland. This paper consolidates the practical considerations and lessons learned from the instrumentation process and deployment of the three IPs, including the placement/orientation of sensors on the reinforcement cage of each pipe, the development of watertight enclosures for housing data loggers within the tunnel, logger power supply, considerations for 'zeroing' the sensors

This paper aims to serve as a frame of reference for tunnelling engineers considering instrumentation in PJ schemes.

KEYWORDS: Microtunnelling, pipe jacking, instrumentation, fibre Bragg grating strain sensors, vibrating wire strain gauges

## 1 INTRODUCTION

During the development of underground infrastructure, there is always a risk of unexpected outcomes due to the complex behaviour of the soil/rock mass (Deng *et al.,* 2022). Instrumentation may be deployed in such projects with a view to reducing risk, measuring some combination of (i) the structural response to the construction process (e.g. strain sensors), (ii) ground movements (e.g. displacement sensors), (iii) soil-structure interaction (e.g. multi-axis load cells) and (iv) pore water pressures (e.g. piezometers).

Microtunnelling, also known as pipe-jacking (PJ), is a trenchless technique used for the construction of utility pipelines in which a series of pipes is advanced from a launch shaft to a reception shaft while a tunnel boring machine (TBM) excavates the soil ahead of the pipe train, as illustrated in Fig. 1. Key considerations in PJ drives include the structural response of individual pipes, the volume and pressure of the injected lubricant, the development of frictional resistance along the outer surface of the pipeline and settlements or heave especially if the pipeline is negotiating sensitive urban environments. Instruments are increasingly utilised in critical PJ projects to monitor some combination of the aforementioned behaviours (Wadood *et al.,* 2025b). Most of the studies reported in the literature incorporating instrumented pipes (IPs) in PJ projects (e.g., Zhang *et al.,* 2022; Feng *et al.,* 2023) do not offer a detailed account of the instrumentation process and associated challenges.

As part of the Research Ireland *SMART-PIPE* project, three instrumented pipes (IP1, IP2, and IP3) were deployed within two of the PJ drives constructed for the Athlone Main Drainage Scheme upgrade in Ireland. Instruments used in the three IPs included fibre Bragg grating (FBG) strain sensors and vibrating wire strain gauges (VWSGs) to monitor pipe strains, multi-axis fibre optic (FO) load cells installed flush with the pipe outer surface to monitor normal and shear stresses, and pressure transducers distributed along the tunnel length to monitor lubricant pressures in the overcut. This paper details the instrumentation and deployment process of the IPs including the installation of sensors, the development of watertight enclosures for housing the data loggers within the tunnel, logger power supply, considerations for 'zeroing' the sensors for data analysis and real-time monitoring. In doing so, this paper aims to serve as a reference point for future research studies involving instrumentation and field monitoring in PJ and other subterranean infrastructure.

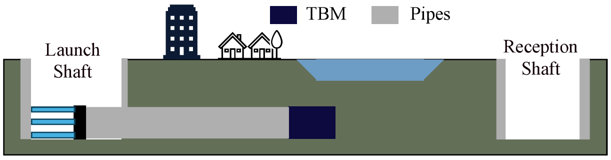

Figure 1. Simple schematic illustration of the pipe jacking process.

## 2 ATHLONE MAIN DRAINAGE SCHEME

### 2.1 *Project overview*

The Athlone Main Drainage Scheme (ATHMDS) upgrade, which commenced in 2023, involved the construction of a 2.8 km long sewer network and two new stormwater overflows in Athlone, Ireland. These upgrades aim to reduce sewer overflows into the River Shannon and increase the capacity of the sewer network to support anticipated population growth. Ward and Burke Construction Ltd. (W&B) was the design-and-build contractor for the project.

The sewer network was constructed using three different methods: traditional open cut excavation, directional drilling and pipe-jacking. The three IPs had inner and outer diameters of 1200 mm and 1490 mm respectively and were 3000 mm in length. For the two drives incorporating the three IPs, a Herrenknecht AVN 1200 (slurry shield machine) TBM with a cutter head outer diameter of 1541 mm was used, providing an overcut thickness of 25.5 mm.

### 2.2 *Drive 1*

Drive 1, incorporating IP1, was 297 m in length and traversed the town centre of Athlone under existing roadways and in close proximity to buildings. The depth to pipe crown varied from 6.41 m at the start of the drive to 2.55 m at the end of the drive. The tunnel was constructed at a constant upward gradient of 1:58 and incorporated a horizontal curve of radius 500 m between chainages of 90.72 m and 264.3 m. The tunnel negotiated alluvial clays and silts for the majority of the drive and granular glacial till towards the end.

The objective of IP1 installation was to monitor the mechanical response of pipes in curved PJ drives. A conventional instrumentation scheme was adopted for IP1 with four axial and four hoop embedded FBG strain sensors at the pipe cardinal points (N, S, E, W), as illustrated in Fig. 2a. Robustness of the FO cables was ensured by specifying a 1 mm layer of glass fibre reinforced polymer (GFRP) and a 0.5 mm layer of high-density polyethylene (HDPE) coating. Additionally, two pairs of embedded VWSGs with thermistors (one axial, one hoop) were installed at the S and E cardinal points of the pipe (Fig. 2a) to enable comparison with the FBG strains. IP1 was installed as pipe #31, 99 m behind the TBM cutter face.

### 2.3 *Drive 2*

Drive 2, incorporating IP2 and IP3, was 303 m in length. The drive alignment incorporated two horizontal curves of radius 200 m and one vertical curve of radius 750 m, and traversed beneath commercial and residential buildings as well as existing roadways. The first horizontal curve extended from chainage 45.9 m to 121.3 m, while the second extended from chainage 147.5 m to 195.7 m. The drive was constructed at varying upward gradients: the first 131.6 m at 1:400, followed by the vertical curve between chainages 131.6 m and 143.0 m, with the remainder at a gradient of 1:50. The depth to pipe crown varied from 3 m to 11 m. Drive 2 negotiated granular and cohesive glacial till.

A preliminary analysis of data from IP1 (Wadood *et al.,* 2025a) indicated that the pipe underwent compression on the inside of the curve and tension on the outside. In order to gain more detailed insights into the effect of curvature on the pipe's mechanical response, eight strain sensing points were used around the cross-section of IP2, involving twenty FBG and four VWSG embedded strain sensors using the same sensor specifications as IP1. Three FBGs were placed at each cardinal point in a strain rosette configuration (axial, hoop, and 45º). A pair of FBGs was also placed at the intercardinal points of the pipe (NE, NW, SE, SW) in the axial and hoop orientations. Four axial VWSGs with built-in thermistors were placed at the four cardinal points. Additionally, four multi-axes FO load cells were installed flush with the pipe's outer surface at the pipe cardinal points to monitor normal and shear stresses during the construction process. The instrumentation scheme in IP2 is shown in Fig. 2b. IP2 was placed as pipe #10 in Drive 2, 36 m behind the TBM cutter face.

IP3 was instrumented with twenty-four FBG and four VWSG embedded strain sensors. Unfortunately, the FO cable in IP3 was only coated with a 0.5 mm GFRP layer and snapped during the concrete pour, rendering the FBG sensors useless. The four VWSGs were installed in the axial orientation and were placed at the cardinal points of the pipe. IP3 was initially intended for a drive that traversed beneath the River Shannon, however, after the FBG cable got damaged, it was redeployed as pipe #19 in Drive 2, 63 m behind the TBM cutter face. The two IPs separated by 27 m would enable the distribution of frictional resistance along the drive to be ascertained, i.e. using the average axial compressive force on the pipes from the axial strain readings in conjunction with the total jacking force and steering cylinder data to estimate the frictional resistance ahead and behind the IPs.

Additionally, four pressure transducers were installed in Drive 2 in order to monitor and maintain sufficient pressure in the overcut to prevent excessive surface settlements that could potentially damage nearby buildings. One sensor was installed immediately behind the TBM, and one each in the N lubrication ports of pipes #7, #31, and #54. The installation process for these sensors is detailed by Phillips (2023).

The instrument configuration in the IPs was based on best practices identified in the review by Wadood *et al.* (2025b). FO-based sensors were used because of their benefits over traditional sensors used in previous W&B research (Phillips *et al.,* 2019) and other studies reviewed by Wadood *et al.* (2025b), such as immunity to water ingress, corrosion and electromagnetic interference. Moreover, traditional strain sensors can be difficult to manage as separate gauges are required at each sensing location. In contrast, FO strain sensors facilitate multiple sensing locations along a cable length.

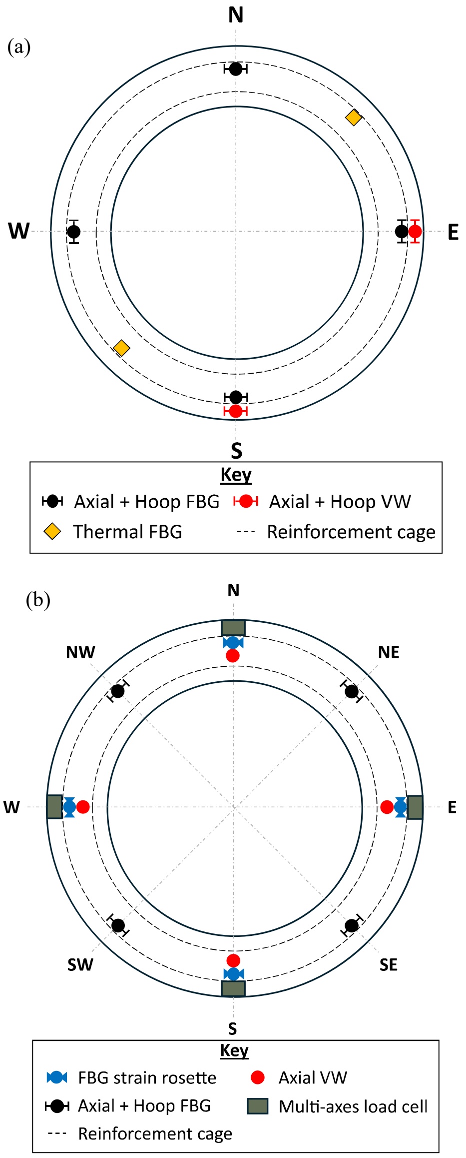

Figure 2. Instrument layout (a) IP1, and (b) IP2.

## 3 PIPE FABRICATION

All jacking pipes utilised in the ATHMDS were supplied by Tracey Concrete, Enniskillen, and were fabricated using the 'wet cast' method, i.e., using self-compacting (SC) concrete. Selected concrete mix details are summarised in Table 1. The pipe fabrication process can be summarised in the following steps with supporting photographs:

1. Placement of inside mould and the reinforcement cages (Fig. 3a)
2. Placement of the outside mould (Fig. 3b)
3. Concrete casting
4. Removal of moulds after a minimum of 12 hrs after the concrete pour (Fig. 3c)
5. Concrete curing for a minimum of 28 days

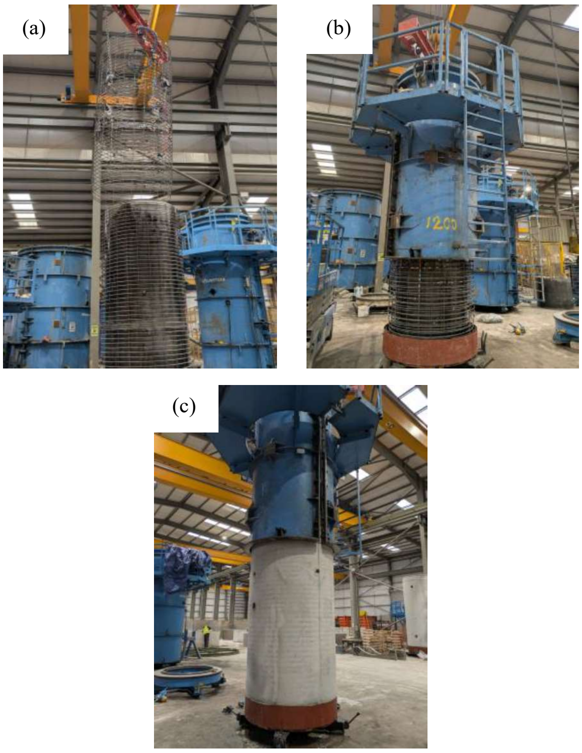

Figure 3. Wet cast pipe fabrication process, (a) placement of reinforcement cages, (b) Placement of inner and outer moulds, and (c) Removal of moulds.

Table 1. Properties of SC concrete used to produce the jacking pipes.

| Parameter | Value |
|---|---|
| 28-day cylinder strength | ≈ 63 MPa |
| Elastic modulus | ≈ 39.6 GPa (EN 1992-1-1: 2004) |
| 28-day density | 2430 $kg/m^3$ |
| Slump | 725 mm |
| Water-powder ratio | 0.33 |

## 4 INSTRUMENTATION PROCESS

### 4.1 *Strain sensors*

The FO cables utilised in IP1 and IP2 each comprised 5 FBGs, spaced 800 mm apart. Therefore, two cables were used for IP1 and four cables for IP2. In contrast, all twenty-four sensors in IP3 were etched onto a single FO cable. From a risk management perspective, distributing sensors across multiple cables is preferable, as damage to one cable will not compromise the others. However, the total number of cables is limited by the number of channels available on the FBG interrogator.

The strain sensor installation process is shown in Fig. 4 and can be summarised in the following steps. The FO cable(s) was looped to achieve the desired strain sensing configuration and secured periodically on the outer reinforcement cage using cable ties (Fig. 4a). For the FBGs oriented at 45°, a short piece of reinforcement bar was first cable-tied to the reinforcement cage at a 45° angle. The FBG was then attached to this additional bar (Fig. 4b).

FBG cable connectors were embedded in concrete, and FO patch cords were used to extend both ends of the FBG cables outside the pipe. While embedding connectors should generally be avoided (since they are irreparable if damaged within concrete), it was necessary here due to the insufficient length of the FBG cables. In order to protect the connectors during the concrete pour, they were taped to the reinforcement cage and encased in foam (Fig. 4c). Both ends of the FBG cables were extended outside the pipe for redundancy; in case of a fibre break at one end, data from all FBGs could still be acquired by connecting the opposite end to the interrogator.

Axial VW sensors were installed in the longitudinal orientation to the reinforcement bars using cable ties. For hoop VWSGs, similar to the 45° FBGs, additional bars were first attached to the existing reinforcement cage to which the VWSGs were attached using cable ties (Fig. 4a).

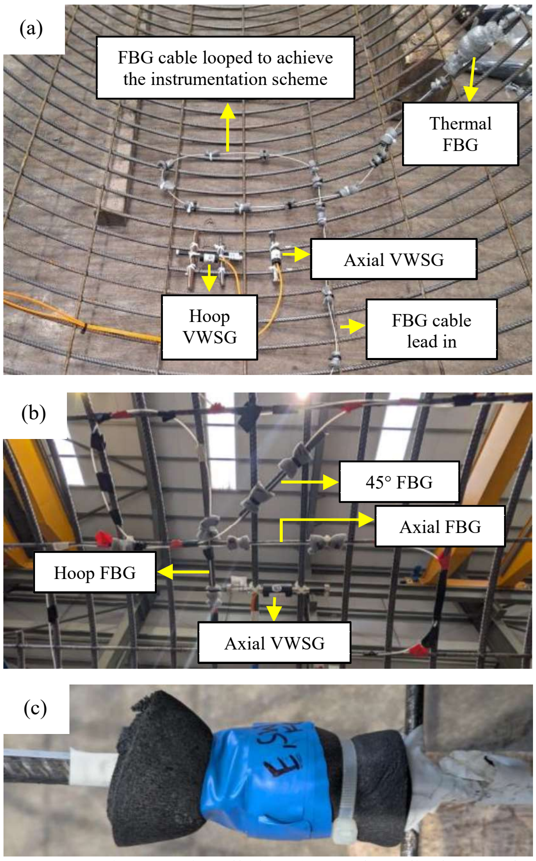

Figure 4. Strain sensor installation: (a) South cardinal point of IP1, (b) north cardinal point of IP2, (c) FBG cable connector taped to the reinforcement bar and encased in foam.

### 4.2 *Temperature measurement*

In IP1, thermal compensation of the FBG strain measurements was accomplished by reserving two FBGs for temperature measurements, hereafter referred to as thermal FBGs. To isolate them from mechanical effects, the technique proposed by Hensman and Sheil (2024) was adopted, whereby thermal FBGs were encapsulated within aluminium blocks (Fig. 5a). To eliminate spurious strain readings arising from the difference in the coefficients of thermal expansion (CTE) of aluminium and concrete, the aluminium blocks were isolated from the surrounding concrete using bubble wrap (Fig. 5b).

Although this method was successful in isolating the thermal FBGs from mechanical effects, temperature measurements from the thermal FBGs plotted slightly lower than those measured by the thermistors due to the insulating effect of the bubble wrap (detailed in Wadood et al., 2025a). Furthermore, all thermal sensors (FBGs and thermistors) in IP1 were placed in one half of the pipe (Fig. 2a). Wadood *et al.* (2025a) concluded that this arrangement was not ideal and suggested using at least four temperature sensors at the pipe cardinal points for accurate thermal compensation of the strain measurements. Ideally, if FBGs are to be used as thermal sensors, the blocks should be made of the same material as the structure, in which case wrapping the thermal FBGs in foam (which was problematic in IP1) would not be required. Since concrete blocks could not be sourced, VWSGs with thermistors were used for temperature measurements in IP2 and IP3.

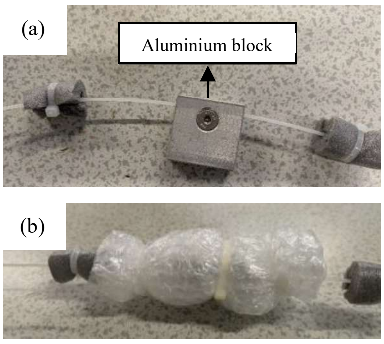

Figure 5. Thermal FBGs (a) encapsulated in an aluminium block, and (b) wrapped in bubble wrap.

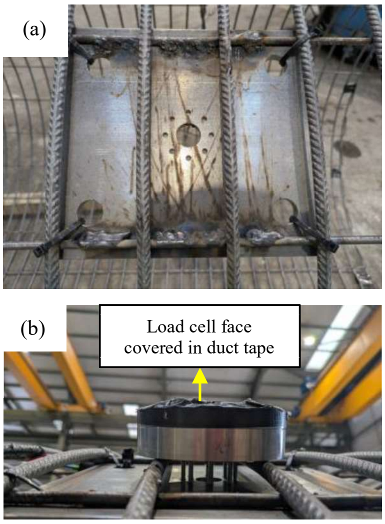

Figure 6. Load cell installation process, (a) steel plate welded to the outer reinforcement cage, and (b) load cells held to the plate by eight bolts.

## 4.3 *Load cells*

To ensure that the load cells were installed flush with the outer surface of IP2, the thickness of the load cells was specified to match the cover depth of the pipe. Therefore, each load cell measured 34 mm in height and 110 mm in diameter, with a sensing face diameter of 55 mm. The load cells had eight threaded holes on the side opposite the sensing face. Bespoke steel plates with holes aligning with those on the load cells were first welded to the outer reinforcement cage of the pipe (Fig. 6a). Eight bolts were screwed in the threaded holes to fix each load cell in place (Fig. 6b). The face of the load cell flush with the pipe's outer surface was covered with duct tape (Fig. 6b) to protect it from potential damage during casting.

From a practical perspective, it is preferable to use load cells with a small diameter sensing face, so that they remain less sensitive to curvature of the pipe's outer surface. The 55 mm sensing face diameter was adequate for the 1490 mm outer diameter pipes in this study. For smaller pipe sizes, smaller load cells should be selected.

## 4.4 *Cable management*

All instrument cables were routed out from one end of the pipe (Fig. 7a) and they were encapsulated in insulation foam at the exit point (Fig. 7b) to protect them and to enable access to connect them to the data loggers during the concrete pour (Fig. 7c). Once the pipe was struck, the insulation foam was 'peeled off' (Fig. 7d and e). Due to the large number of sensors in IP2, routing out all cables from one exit point was not possible, so two exit points were used (Fig. 7e). The placement of exit points should be planned carefully to avoid: (i) interference with the additional slurry lines placed when the pipe is installed in the tunnel, and (ii) disruption to construction activities during the pipeline construction process.

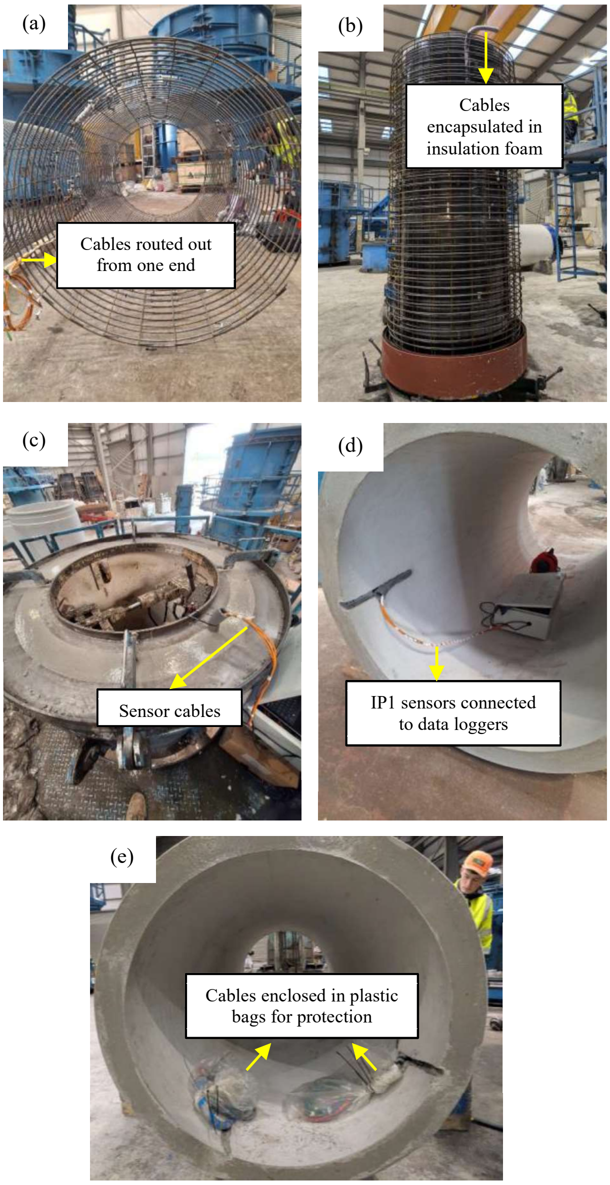

Figure 7. (a) Sensor cables routed out from one end of the pipe, (b) cables wrapped in insulation foam, (c) concrete pour, (d) data logging during concrete curing (IP1), and (e) cables enclosed in plastic bags during concrete curing (IP2).

IP1 was allowed to cure in the manufacturer's yard, during which the sensors were continuously logged (Fig. 7d). For IP2 and IP3, the sensor cables were enclosed in plastic bags to protect them from moisture and dust (Fig. 7e) during curing and transport to site.

## 5 SITE DEPLOYMENT

### 5.1 *Data acquisition system*

Fig. 8a shows a simplified schematic of the data acquisition (DAQ) system used for IP1, with the equivalent photograph in Fig. 8b. The DAQ system comprises the data loggers, a miniature computer with a screen, a 12 V battery with a charger, and an electrical distribution board. For the FBG sensors, the SM130 4-channel interrogator (Luna Innovations, Inc.) was used. The VW sensors were connected to the Linx series loggers (Geosense Ltd). Both data loggers were connected to the computer to record data from the instruments. The computer was connected to the internet using an Ethernet cable which ensured that the data were accessible in real time, from outside the tunnel, during the pipe-jacking process.

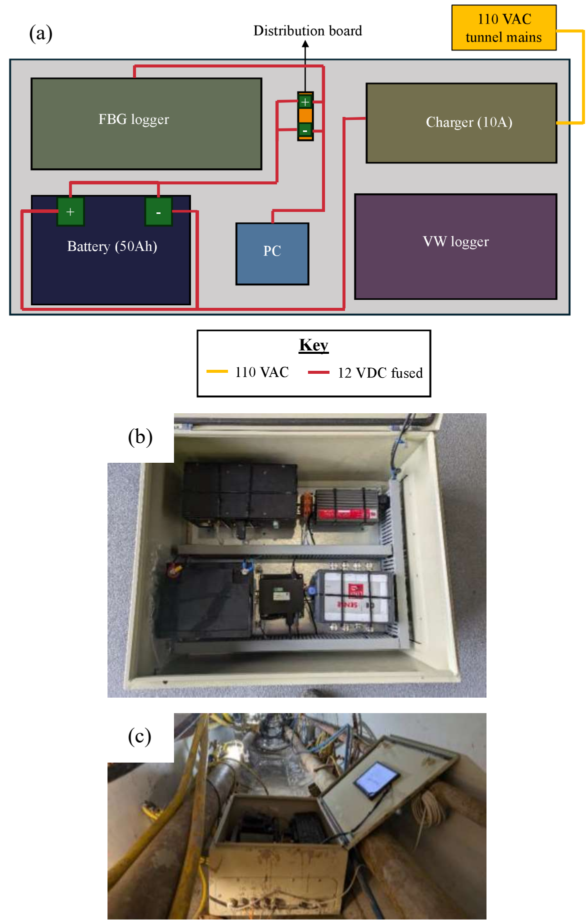

Figure 8. Simplified schematic and field implementation of the DAQ system used for IP1.

The DAQ system was powered by a 12-VDC, 50 Amp-hour deep cycle lead-acid battery which was charged using a 10-Amp charger connected to the 110-VAC tunnel mains. 12-VDC battery power was preferred over 110-VAC from the tunnel mains for the following reasons: (i) to ensure continuous power supply when the tunnel mains were disconnected (e.g., during construction stoppages or generator shutdowns) and (ii) to enhance operational safety, as lower voltage systems pose reduced electrical hazards.

Given the risk of the surrounding pressurised slurry/water entering the pipe, the DAQ system was placed in IP66 steel enclosures (Fig. 8b). Power and instrument cables running into the enclosures were fed through IP68 glands, installed at one side of the logging enclosures (Fig. 8c).

To prevent potential damage to the equipment and wiring caused by movements during construction activities, all components of the DAQ system were securely fixed in place within the logging enclosures. DIN rail was mounted on stand-off screws drilled into the steel plates of the enclosures. Stand-off screws elevated the DIN rail so that the components lacking a DIN rail mount could be fixed in place using cables ties. The components were mounted to the DIN rail rather than directly to the steel plates to avoid disturbing the entire enclosure in case of a component malfunction. With the DIN rail, cable ties could simply be cut to address the malfunctioning component. Alternatively, each component can be fitted with a DIN rail mount and clipped onto the DIN rail for simpler installation and replacement.

Due to the increased number of FBG-based sensors utilised in IP2, the Si255 Hyperion 8-channel interrogator (Luna Innovations, Inc) was used. Additionally, the battery size was increased to 95 Amp-hour because the logging system in IP1 shut down a couple of times due to unexpected power outages overnight. With the bigger capacity battery, the logging system could keep running for ≈20 hrs in the event of unexpected power outages. Moreover, a voltage monitoring relay was included to protect the battery from deep discharge, ensuring its longevity. Due to the greater battery and FBG interrogator sizes, the DAQ system for IP2 consisted of two enclosures. One housed the data loggers and the PC, while the other housed the battery, its charger and the voltage monitoring relay.

Larger capacity batteries, ideally Lithium-ion ones (due to their smaller size and lighter weight), or a parallel configuration of smaller capacity lead-acid batteries could be used to ensure the DAQ system keeps running during unexpected power outages over weekends or bank holidays. However, due to increased costs of such configurations, these were not considered in this research.

Since IP3 only incorporated four VWSGs, a WI-SOS 480 node (Geosense Ltd.) was used to log data from the sensors. The WI-SOS 480 is a battery powered, weather-proof (IP68) standalone data logger that stores measurements on its internal memory and, when configured with a gateway, can upload data to a cloud-based platform. However, a gateway was not utilised in IP3, and the data were manually retrieved from the node periodically. The VWSG cables were secured to the pipe wall (Fig. 9) to prevent accidental disturbance from workers during construction activities. After IP3 was installed in the tunnel, the node was fastened to the slurry lines using cable ties.

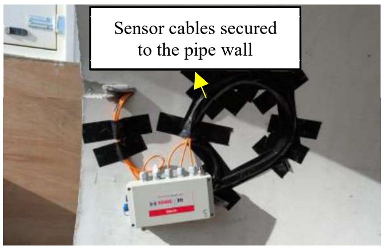

Figure 9. IP3 VWSGs connected to the WI-SOS 480 node.

### 5.2 *Considerations for zeroing the sensors*

Prior to the installation of the IPs into the tunnel, it was essential to monitor sensor data for a minimum of 24 hrs to establish stable baseline readings and to verify that the DAQ system was functioning correctly. This allowed any unexpected issues or malfunctions to be identified and resolved before the IP was installed in the tunnel.

Since strain sensors provide strains relative to a specified 'zero' value, it is crucial to zero the sensors when the test material is in an unstressed or minimally-stressed state. To compute strains during the curing period, the zero-stress state is clearly immediately before concrete is poured into the mould. For computing strains during construction, the best approximation of an 'unstressed' state is when the pipe rests on the ground prior to its installation in the tunnel. At this stage, any strains in the pipe arise from: (i) self-weight, which can be estimated analytically or via a finite element model and subtracted from the measured values, and (ii) temperature differences across the pipe cross-section.

The temperatures recorded by the four thermistors in IP2 are shown in Fig. 10. In this case, the strain sensors were zeroed approximately 5 hrs before the pipe was lifted and lowered into the launch shaft, at which time all four thermistors registered similar temperatures. Once the pipe was installed in the tunnel, the cross-sectional temperatures were nearly uniform (as seen in Fig. 10 after 21/03), so zeroing under uniform conditions ensured a consistent baseline for strain calculations.

The load cells were zeroed immediately before the pipe was installed in the tunnel.

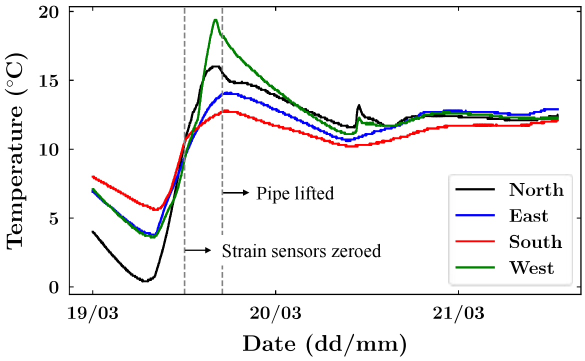

Figure 10. Temperatures recorded by thermistors in IP2.

### 5.3 *Real-time data access*

The FBG strain sensor and load cell data were plotted in real-time on the PC within the tunnel using the Enlight software. Remote access to the screen was achieved via the Chrome Remote Desktop application. Alternatively, an online dashboard could be developed to visualise the data real time, offering more accessibility than remote screensharing (Willis *et al.,* 2024). The logged data were downloaded periodically from the PC inside the tunnel.

Approximately one-third of the way through the construction of Drive 2, an unexpected flooding event occurred in the tunnel due to the failure of the water supply infrastructure at the construction site. As a result, the DAQ system of IP2 was damaged. While the VWSG data logger was replaced, a replacement for the FBG interrogator could not be sourced, resulting in no further FBG data acquisition from that point onwards. This incident highlights the importance of either periodically downloading logged data or backing it up to a cloud platform to mitigate the risk of data loss. To prevent such incidents in the future, it is recommended to install float switches that automatically activate pumps when rising water levels are detected.

## 6 CONCLUSIONS

This paper provides details of the instrumentation process for three concrete jacking pipes deployed in the Athlone Main Drainage Scheme in Ireland. It details the installation of strain sensors, thermal sensors, and load cells, as well as the development of logging enclosures, power supply arrangements, considerations for zeroing the sensors prior to deployment and real-time data access. Practical aspects and lessons learned from the instrumentation process are discussed, along with recommendations for future studies considering instrumentation in PJ or other underground construction projects. The data interpreted from the instrumentation in pipes IP1, IP2 and IP3 will be presented in future publications.

## 7 ACKNOWLEDGEMENTS

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