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Technical note

Piezoelectric wave generation system for condition assessment of field water pipelines

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ABSTRACT
The condition assessment of pipelines is central to the management of water systems but is only conducted sporadically due to the limited range and practical constraints of current technologies. This paper describes the successful international field trial of a new condition assessment approach that was tested in live water pipeline networks of large cities during peak water demand and traffic conditions. The system, referred to as PIPE SONAR (PCT/EP2015/059540), uses a piezoelectric actuator capable of generating customized, small amplitude ($<$ 0.4 m) pressure signals. The field trial involved 1600 individual field tests covering 31 sites of water networks in New Zealand and China, across nine different pipe materials and pipe diameters ranging from 100 mm to 600 mm. The results of the condition assessment were independently confirmed using hydrant tests, low frequency transient tests, and direct inspection through excavation.

Keywords: Acoustic signals; condition assessment; pipe wall; valves; water pipelines

1 PIPE SONAR system

Active pipeline condition monitoring using fluid transients requires the generation of highly controlled pressure signals in the field, often against significant system back pressure and a confusing array of background traffic and fluid turbulence noise (Colombo, Lee, & Karney, 2009). Since most water pipelines run alongside traffic routes, the generation of the signal should be carried out quickly, non-intrusively and with a minimal loss of water. This combination of requirements poses significant challenges for researchers in the field (Brunone, Ferrante, & Meniconi, 2008; Stephens, Lambert, Simpson, Vítkovský, & Nixon, 2005; Stephens, Simpson, & Lambert, 2008).

This paper applies the existing transient fault diagnostics techniques on signals generated by a new type of actuator consisting of a vibrating ceramic element. This actuator, referred to as PIPE SONAR (PCT/EP2015/059540), can create small pressure fluctuations of an order of 0.1 m in typical water distribution pipelines. The minute signals from the actuator are combined with signal processing methods proposed in Lee (2005) to allow for their detection above the noise band at a range greater than 265 m metres in a 300 mm diameter pipeline network. Pressure signals are generated by a custom built piezoelectric actuator driven by a linear power amplifier and an impedance matching unit. The actuator has an operational frequency range of 40–8000 Hz and the signal from the actuator

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is captured using high-speed, dynamic piezoelectric transducers (PCB ICP©) with a response frequency of 200,000 Hz. One pressure sensor is located at the actuator (known as the "local" station) and another is attached to another hydrant upstream or downstream (known as the "remote" station). The data recording is GPS synchronized between pressure sensors and data are recorded onto a laptop computer via a 16 bit, 400 kS s^{-1} National Instrument (Austin, TX, USA) data logger at each station. The data acquisition system is capable of a sampling rate greater than 100 kHz for long durations and has a sensitivity of $+/-200$ mm. Each station is powered by a portable power supply consisting of an inverter and rechargeable lithium ion batteries. The system is compact and is able to be transported and set up by one or two people.

The actuator is capable of generating customized signals and Fig. 1 shows an example of one of the signal sequences that have been used in this field trial. Figure 1 shows the input signal to the actuator with the y-axis of the plot as the normalized electrical input. The signal consists of a sequence of evenly spaced, identical chirps to Fig. 1 with a frequency sweep from 100 to 300 Hz. Chirp sequences such as these are commonly used in the SONAR system as they are broadband and yet temporally compact; and able to contain a wide range of frequencies within a short signal duration.

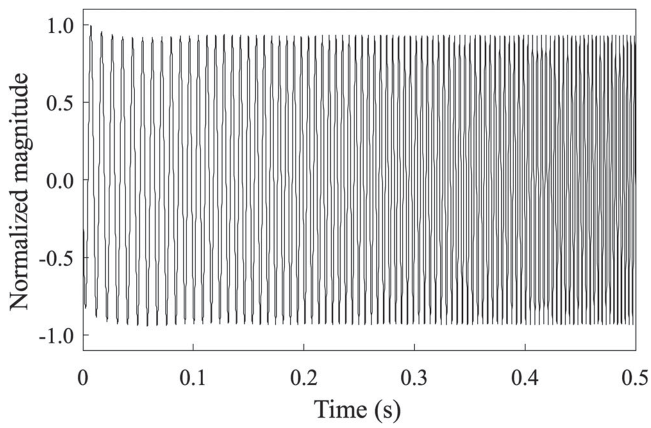

Figure 1 Example of simple PIPE SONAR signal consisting of a 100–300 Hz chirp

One significant advantage of the piezoelectric actuator is that the signal can be adjusted to suit the field conditions. Figure 2a shows the average background pressure noise spectrum taken from 25 different live water networks. The x-axis is the frequency (f), measured in Hz. The noise spectrum is the average determined from 100 s of pressure data sampled at over 20 kHz at each site during the time of testing. Figure 2a shows that this background noise is concentrated at the low frequencies with much of the energy below 50 Hz. Previous publications have shown that the energy of manual valve closure signals is concentrated below 60 Hz, and the signals overlap directly with the background noise band (Lee, Vitkovsky, Lambert, & Simpson, 2008). The positive identification of a valve closure signal in the field requires a signal that is significantly larger than the noise band, often as large as 30 m head in some systems.

Alternatively, the PIPE SONAR system can create customized pressure signals that have most of their energy outside the background noise spectrum. Figure 2b shows the spectrum for the PIPE SONAR chirp signal in Fig. 1. Most of the signal energy lies above 100 Hz and there is little overlap between the signal and the spectrum of the background noise band. The PIPE SONAR system can create highly controlled signals of different frequency bands to avoid specific noise sources on each site and this presents a powerful advantage over the manual or mechanical means of signal generation. The clear separation between the generated signal and noise bands meant that the analysis can be carried out using signals that are as small as 0.10 m in head and this signal can be detected hundreds of metres away from the actuator.

The PIPE SONAR system is attached to existing hydrants through flange connections. Fire hydrants provide the ideal connection points for the assessment of potable water supply networks as they are spaced within 150 m in urban areas and the fittings are standardized across administrative regions (Stephens

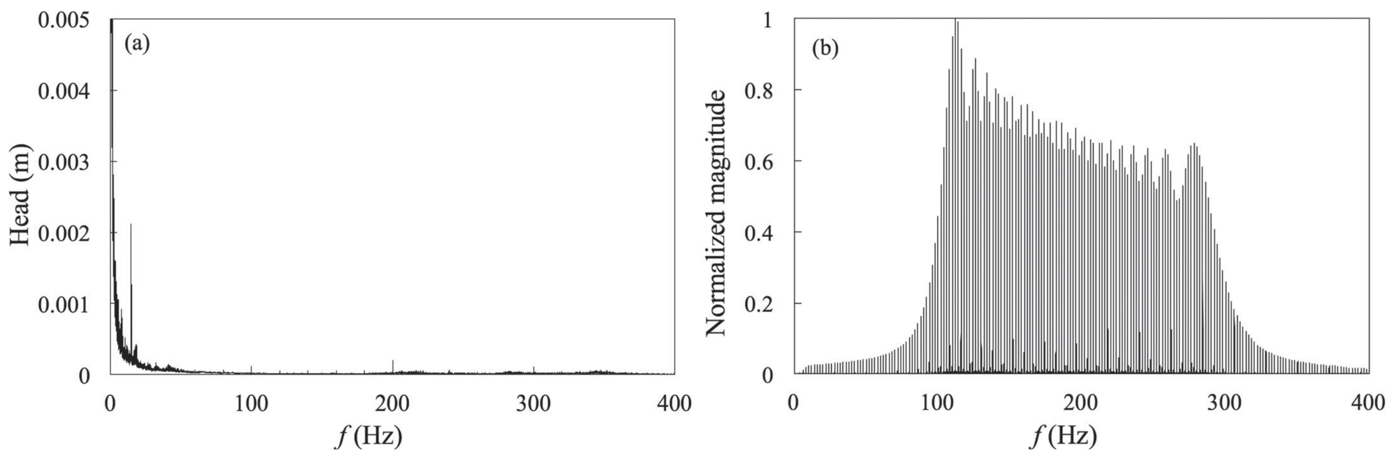

Figure 2 (a) Background noise spectrum collected from 25 different sites in live water supply networks; (b) Power spectrum of a typical chirp signal from the PIPE SONAR system et al., 2008). The PIPE SONAR system has been tested on two types of fire hydrants: below-ground hydrants typical in the UK, Australia and New Zealand; and above-ground hydrants in USA, China and mainland Europe. For the below-ground hydrants, a stand pipe is used to mount the equipment above the manhole to avoid submergence. As a comparison to the piezo-electric signal, a 25 mm ball valve was also used at each site to create manual valve closure signals. All tests were measured at a sampling frequency of 20 kHz and this oversampling (relative to the signal bandwidth) is required to provide an accurate measurement of the signal arrival time.

2 Field testing scope and programme

The PIPE SONAR system developed at the University of Canterbury, Christchurch, New Zealand through funding from the Royal Society of New Zealand (Marsden Grant M1153) is field trialled with the assistance of Veolia (Shanghai, P.R. China), who operates water pipeline networks across the globe. Field-testing was undertaken on 31 sites on four operational water networks in China and New Zealand. The networks included the on-campus water network at the University of Canterbury; and three large-scale municipal water networks: one in New Zealand (city population 400,000), and two in China (city population 3–4 million); which are operated and managed by Veolia.

Pipe materials tested included steel, cast iron, ductile cast iron, reinforced concrete, asbestos cement, fibrebond, medium/high density polyethylene and polyvinyl chloride. Pipe diameter ranged from 100 mm to 600 mm (Table 1). In total over 1600 field tests were conducted on live water supply networks. The tests were conducted under live system conditions and no restrictions or alterations to the network were imposed. In many cases, the tests were conducted on main roads during peak hours. The signal was observed to lose 50% of its magnitude per 100 m of travel and this is typical of the head loss observed in typical transient events in the field.

The signal from the pressure measurement at the remote station is converted into an approximation of the impulse response function, $I(t)$, using the technique in Lee et al. (2008):

$$I(t) = F^{-1}\left(\frac{F\left(\lim_{T_0\to\infty}\int_{-T_0/2}^{T_0/2} x(t)y(t+t^*)\mathrm{d}t\right)}{F\left(\lim_{T_0\to\infty}\int_{-T_0/2}^{T_0/2} x(t)x(t+t^*)\mathrm{d}t\right)}\right) \tag{1}$$

where $x(t)$ is the signal at the local station (actuator) and $y(t)$ is the signal measured at the remote station (receiver). The cursive "F" represents the Fourier transform and the "-1" superscript represents the inverse Fourier transform. This equation is

Table 1 Wave speed comparisons between signal generation methods and theoretical range

Site ref.	Material	Diameter (m)	Install date	Length (m)	Wave speed, value (m s^{-1})	Wave speed, pipe SONAR (m s^{-1})	Theoretical wave speed range (m s^{-1})	Assessed condition
A1	PVC	100	2008	39.70	371	375	387–460	✗
B	AC	100	1971	72.10	1037	1022	1059–1070	✗
C	AC	100	1981	84.50	1042	1019	1059–1070	✗
D1	FB	100	1963	128.00	1061	1055	1059–1070	✗
D2	FB	100	1963	77.50	1001	1002	1059–1070	✗
E1	AC	150	1960	114.00	1008	997	967–978	✓
F1	AC	300	1991	91.20	1074	1073	972–984	✓
F2	AC	300	1991	88.70	1054	1044	972–984	✓
F3	AC	300	1991	267.10	1054	1055	972–984	✓
G	CIP	100	1956	68.30	1102	1079	1311–1395	✗
H	CIP	100	1956	60.40	1128	1098	1311–1395	✗
I	CIP	225	1956	201.10	1111	1107	1199–1329	✗
J	DCIP	100	1992	37.78	1206	1194	1301–1349	✗
K	DCIP	200	2009	68.71	1233	1231	1188–1263	✓
L1	DCIP	300	2013	114.11	1211	1202	1134–1215	✓
L2	DCIP	300	2013	118.40	1216	1227	1134–1215	✓
L3	DCIP	300	2013	116.34	1227	1224	1134–1215	✓
M1	DCIP	500	1999	107.97	1081	1080	1073–1155	✓
M2	DCIP	500	1999	110.88	1113	1098	1073–1155	✓
N	DCIP	500	1995	56.43	982	978	1073–1155	✗
O1	DCIP	300	1993	79.21	1194	1204	1134–1215	✓
O2	DCIP	300	1993	179.67	1143	1156	1134–1215	✓
P	S	100	2009	108.88	1152	1140	1301–1323	✗
Q	RCP	600	2004	101.59	1183	1147	1148–1210	✓
R	S	400	2000	128.53	1248	1264	1181–1213	✓
S	S	600	1995	122.12	1183	1181	1112–1149	✓

derived from the single input, single output linear system extraction theory, with the inclusion of a matched filter to enhance the detection of the transmitted signal.

In this field trial, the PIPE SONAR system was used in two well-established pipe diagnostic approaches: the determination of pipe wall condition through wave speed measurements (Bhimanadhuni, 2014; Bracken & Johnston, 2013; Carlson, Henke, Duppong, & Buonadonna, 2013; Gong et al., 2013; Hachem & Schleiss, 2012; Liu, Kleiner, Rajani, Wang, & Condit, 2012; Nestleroth, Flamberg, Condit, Battelle, & Wang, 2012; Nestleroth et al., 2013; Stephens et al., 2008, 2013; Tuck & Lee, 2013) and the determination of valve condition through wave transmission tests (Meniconi, Brunone, Ferrante, & Massari, 2011a, 2011b; Stephens et al., 2005). As pipelines age the pipe wall can undergo subtle changes in its material properties. These physical changes will lead to observable changes in the system wave speed. The wave speed within a pipeline is given as (Wylie & Streeter, 1993):

$$a = \sqrt{\frac{K/\rho}{1 + [(K/E)(D/e)]c_1}} \tag{2}$$

which is a function of the pipe effective wall thickness (e), nominal diameter (D), elastic modulus (E), the fluid bulk modulus (K) and density (ρ). The restraint conditions on the pipe are given by the factor c_1 (Wylie & Streeter, 1993). The wave speed of the pipeline at its originally installed state can be determined using Eq. (2) and pipe parameters from manufacturing specifications. Using the PIPE SONAR system the *in situ* wave speed of a pipeline can be determined from the distance between the two stations and the observed time required for the signal to travel from the actuator to the remote station. The difference between the field measured wave speed and the theoretical wave speed in Eq. (2) is an indication of the deterioration of the pipe from its original state.

The second application of PIPE SONAR in this field trial was the testing of isolation valve seals. Isolation valves are critical for the protection of pipeline networks and can minimize damage in the event of a major burst or disruption to users during system maintenance (Bouchart & Goulter, 1991; Jun, Loganathan, Deb, Grayman, & Snyder, 2007; Stephens et al., 2005; Walski, 1993). These valves are often left untested throughout a lifetime spent buried underground, such that the sealing capabilities of these valves are often unknown and can be negatively affected by sedimentation, tuberculation or corrosion over time. The transmission strength of a transient wave through a valve (or any local loss element) is a function of the constriction and energy loss imposed by the valve (Wylie & Streeter, 1993). A well-sealed valve poses a large restriction on the propagation of the transient wave and a significant reduction in the transmission strength of the signal should be observed downstream. A comparison of the transmission of the signal through the closed valve with the transmission through the fully open valve will determine the amount of flow restriction imposed by the valve.

3 Field determination of pipe condition through PIPE SONAR wave speed measurement

The operation of the PIPE SONAR system for wave speed measurement is illustrated in Fig. 3 using the tests from an 84.5 m stretch of 100 mm diameter asbestos cement pipe and another from a 114.1 m stretch of 300 mm diameter ductile cast iron pipe.

Figure 3a and c show the estimated impulse response functions for the pipelines using the PIPE SONAR system. The impulse response functions are calculated using Eq. (1) and the measured pressure signals at each station. The y-axis is the dimensionless magnitude of the response function, normalized by the maximum response. Note that the actual value of the response function is not relevant for the applications shown in this paper and the normalizing process allows the impulse responses of different pipelines to be directly compared. The PIPE SONAR signal begins transmitting at $t = 0$ and the occurrence time of the signal within the response functions in Fig. 3a and c is the time taken to travel between the local and remote stations. The first impulse in the response function appears with oscillations on either side of the main spike, and is an intrinsic numerical artefact created by the oscillatory chirp signals used in this study. The largest positive spike within the oscillation train is the time of actual transmission of the signal and these are identified as 0.085 s and 0.0107 s for the 100 mm and 300 mm pipes respectively.

To confirm the PIPE SONAR wave speed measurement, a low frequency transient signal was sent from the local station through the manual closure of a 25 mm ball valve and the results are shown in Fig. 3b and d. The pressure signals at both the local and the remote stations are shown. The results show a signal transmission time (measured as the time for the remote station to detect a signal) of 0.083 s and 0.011 s for the 100 mm and 300 mm pipes respectively. These transmission times are within 0.3% of the PIPE SONAR measurement and this result confirms the applicability of the PIPE SONAR system for wave speed measurement.

The results of the same wave speed analyses carried out over 25 different sites are summarized in Table 1, showing that the PIPE SONAR system produced very similar results to the valve closure tests. The average difference between the PIPE SONAR and manual valve measured wave speed is 0.56%. Each PIPE SONAR result in the table is the measured wave speed at each site repeated over 60 individual tests, with a total of over 1600 transient tests across the field testing programme. It is important to note that the PIPE SONAR system uses a signal that is smaller than 0.4 m in pressure head compared to the valve signal, which ranges up to 30 m. The PIPE SONAR system is able to achieve the same outcome as the traditional valve closures but using a

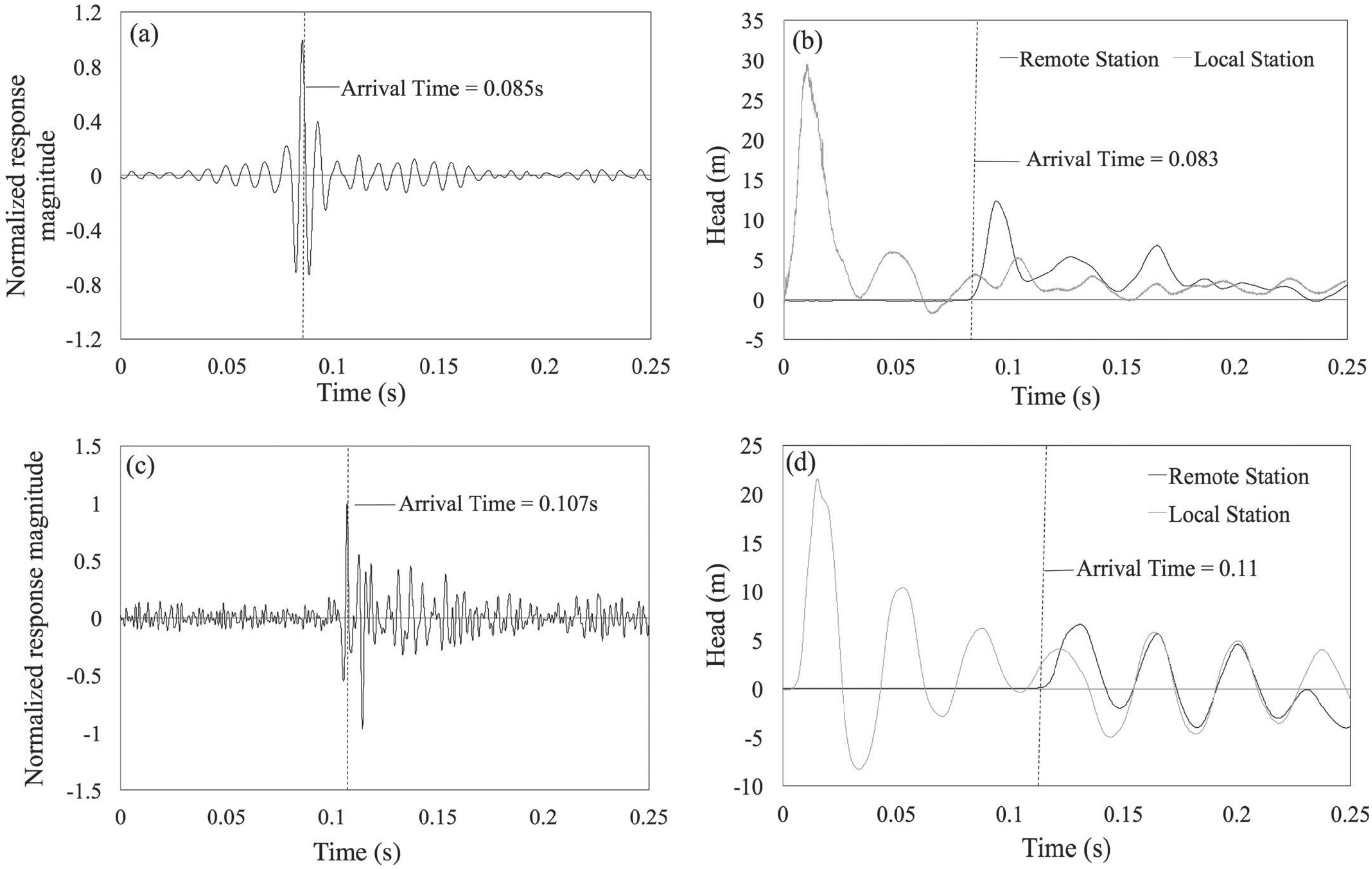

Figure 3 Arrival time analyses for a 84.5 m length of 100 mm asbestos cement pipe for (a) PIPE SONAR; (b) valve closure methods. Arrival time analysis for a 114.1 m length of 300 ductile cast iron pipe using (c) PIPE SONAR and (d) valve closure methods

signal that is only 1% of the valve closure signal magnitude. In addition to this, the tests were conducted without any loss of water, under peak background noise conditions and with no necessary system alterations or pipe isolation. The power required to create the pressure wave was 15 W (peak voltage 240 V) and could be achieved using portable batteries.

The condition of each pipe in Table 1 is assessed by comparing the measured wave speed with the expected wave speeds for the pipes when they are in perfect condition (Eq. (2)). The pipeline condition assessment considers the pipe has deteriorated (represented by a cross in Table 1) in cases where the measured wave speed is lower than the expected theoretical range. One of the pipes identified as being of poor condition (pipe "P") was excavated and a material test was conducted at the Veolia material laboratory in Changzhou, China. The results showed extensive and obvious corrosion of the pipe exterior with pitting depth of up to 1.0 mm, confirming the assessment through the PIPE SONAR system.

4 Pipe SONAR field determination of isolation valve seal condition

A testing programme was carried out on the capability of the PIPE SONAR system for identifying poorly-sealed isolating valves. A total of 800 individual tests were conducted on 13 different valves, spanning six material types and pipe sizes of 100 to 500 mm. The valves were predominantly gate valve types with two butterfly valves on the larger 400 and 500 mm pipes. A selection of the results is discussed in detail below and a full summary of the test sites and the condition of the valve is shown in Table 2. The aim of the testing programme is to identify valves that will not fully shut, allowing water to pass through even when the valve is set to a closed position. A poorly-sealed valve will maintain a hydraulic connection through the valve face. This hydraulic connection allows water, as well as pressure signals, to transmit through the device. On the other hand, a well-sealed valve will provide no hydraulic mechanism for water or pressure signal to pass and the signal transmission through the valve will be minimal (Wylie & Streeter, 1993).

The local (signal generating) station is at a hydrant on one side of the valve and the remote station is at another hydrant on the other side of the valve. A PIPE SONAR signal is generated at the local station and measured at the remote station for the valve in a fully open position as well as in various degrees of closure. The magnitudes of the transmitted signal at varying degrees of valve closure were compared with the magnitude of the signal transmission observed when the valve was fully open. The transmitted magnitude of the signal relative to the transmission when the valve is fully open is termed transmission strength

Table 2 Valve assessment summary

Site ref.	Material	Pipe diameter (m)	Valve type	Install date	Test range (m)	Transmission ratio (%)	Valve opening (%)	Valve assessment
D2	FB	100	Gate	1963	77.50	99%	> 1%	✗
G	CI	100	Gate	1956	68.30	5.60%	< 0.1%	✓
T	PVC	100	Gate	2003	80.86	< 1%	< 0.01%	✓*
A2	PVC	100	Gate	2008	105.30	< 1%	< 0.01%	✓*
A1a	PVC	100	Gate	2008	39.70	< 1%	< 0.01%	✓*
A1b	PVC	100	Gate	2008	39.70	< 1%	< 0.01%	✓*
E2a	AC, HDPE	150	Gate	1960s	67.00	33%	0.10%	✗
E2b	AC, HDPE	150	Gate	1960s	67.00	61%	1%	✗
E1	AC	150	Gate	1960s	114.00	63%	1%	✗
U	S, CIP	200	Gate	1987	81.74	38%	0.10%	✗
R	S	400	Gate	2000	128.53	13%	< 0.1%	✓
M2	DCIP	500	Butterfly	1999	110.88	17%	< 0.1%	✓
V	CIP	400	Butterfly	1995	285.71	82%	1%	✗*

*Valve assessment result supplemented by low frequency transient signal

and provides a measure of the sealing capability of the valve. A well-sealed valve will result in low transmission strength when the valve is fully closed. Based upon comparisons with a method of characteristic model and laboratory data, an estimate of the effective flow area through the fully closed valve to the cross-sectional area of the pipeline, τ^* is also given for each valve tested in Table 2. The valve condition assessment was made based on the level of valve sealing that would be sufficient for practical purposes.

4.1 *Example of well-conditioned isolation valve #1 (Site G)*

Site G consists of a 100 mm CI pipeline with a gate valve located between two hydrants. This section of pipeline was installed in 1956 and its condition was unknown prior to testing. The distance between the hydrants is 68.3 m and the valve is located 16.4 m from the PIPE SONAR actuator. The generated signal repeats every 0.5 s and transmission of the signal can be clearly identified by the presence of this pattern in the response function. The amplitude of the repeating pattern provides the strength of the transmitted signal and the severity of the valve leakage.

Figure 4a, c, e and g shows the impulse response measured at the remote station when the isolation valve was set to different degrees of closure; from fully open in Fig. 4a through to fully closed in Fig. 4g. The y-axis is the dimensionless impulse response magnitude normalized by the response when the valve was fully open. The strength of the transmitted signal is shown to decrease with the valve closure and at the fully closed valve position, the signal has decreased to 5.6% of the observed transmission strength when the valve was fully open. Through comparison with the outputs from a method of characteristics model, the flow area through the fully closed valve is estimated to be less than 0.1% of the pipe area. For the 100 mm diameter valve this is a flow area less than 10 mm^2, indicating the valve is well sealed for practical purposes.

To confirm the PIPE SONAR results, low frequency pressure waves are also generated through the closure of a 25 mm ball valve at the local station. The valve closure results are shown in Fig. 4b, d, f and h. The pressure trace at the remote station shows the arrival of the signal at 0.066 s after the creation of the signal at the actuator, which corresponds well with the travel time lag observed using the PIPE SONAR system. The closure of the valve resulted in a significant reduction in the size of the wave detected at the remote station, confirming that the valve is well sealed.

4.2 *Example of poorly-conditioned isolation valve #1 (Site D2)*

Site D2 consisted of a 100 mm fibrebond pipeline with an isolation valve located between two hydrants. This section of pipeline was installed in 1963 and its condition was unknown prior to testing. The distance between the hydrants is 77.5 m and the valve is located 64.6 m from the PIPE SONAR actuator. Figure 5a and b shows the impulse response for the fully open and fully closed isolation valve respectively. The transmission of the signal has suffered only a 1% drop in magnitude with the isolation valve fully closed compared to when the valve is fully open. Similar results for signals created through the rapid closure of a 25 mm ball valve at the actuator are shown in Fig. 5b and d. Analysis of the signal transmission indicates that the effective flow area of the 100 mm gate valve is greater than 100 mm^2 (similar to that of an open household tap). This indicates that significant hydraulic transmission is occurring through the closed valve and that the valve is in poor condition. The local water asset operations team conducted further section isolation testing of the valve and found the closed valve to be passing water. The valve was subsequently excavated and photos of the valve are shown in Fig. 6. The valve assembly contains significant tuberculation and the valve was in very poor condition, in line with the assessment found using the PIPE SONAR system.

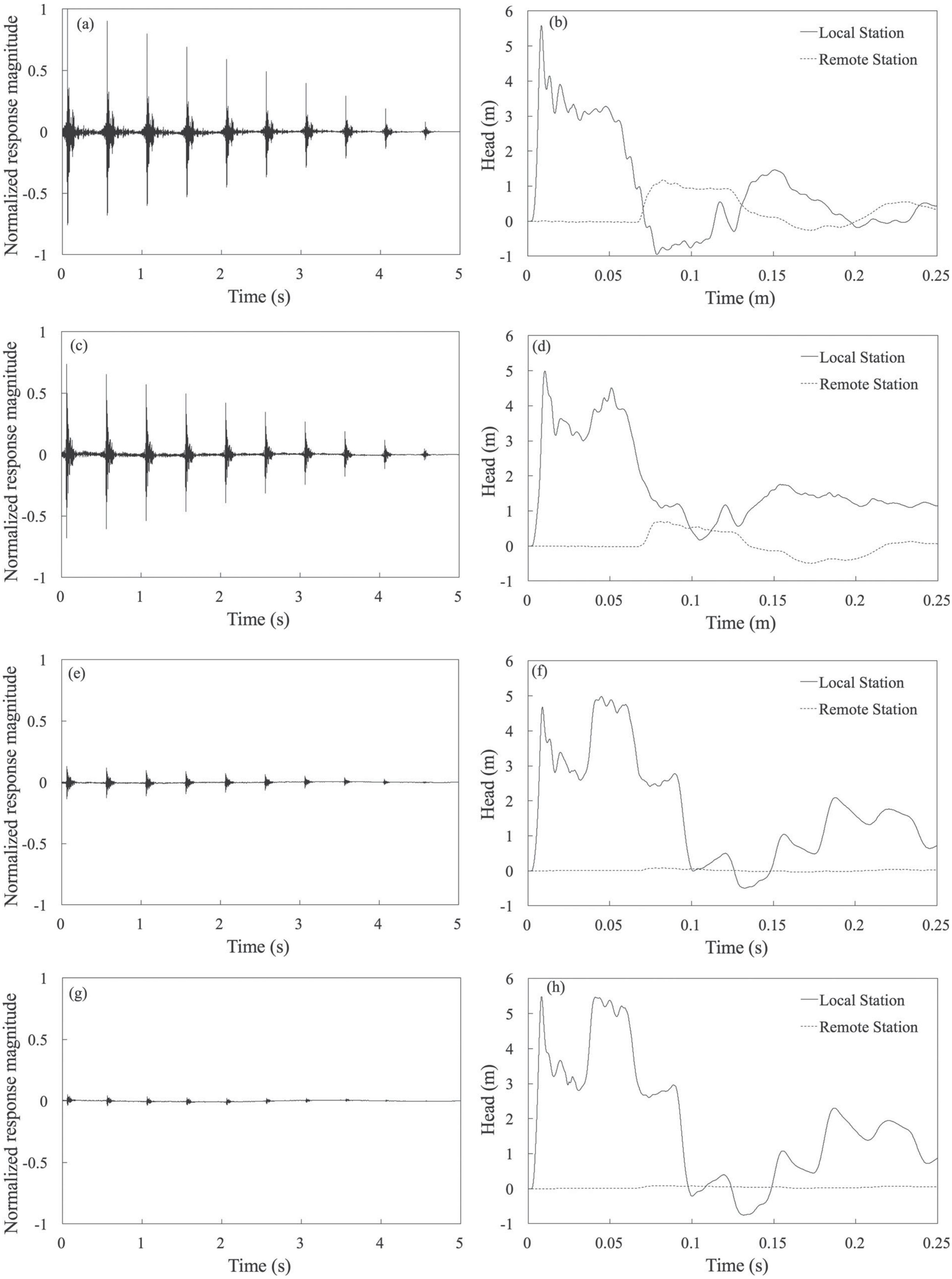

Figure 4 Processed response at the remote station for the (a) open valve ($\tau^* = 1$), (c) $\tau^* = 0.1$, (e) $\tau^* = 0.05$, (g) closed valve ($\tau^* = 0$). Measured response for a step wave signal at local and remote stations for (b) an open valve ($\tau^* = 1$), (d) $\tau^* = 0.1$, (f) $\tau^* = 0.05$, (h) a closed valve ($\tau^* = 0$)

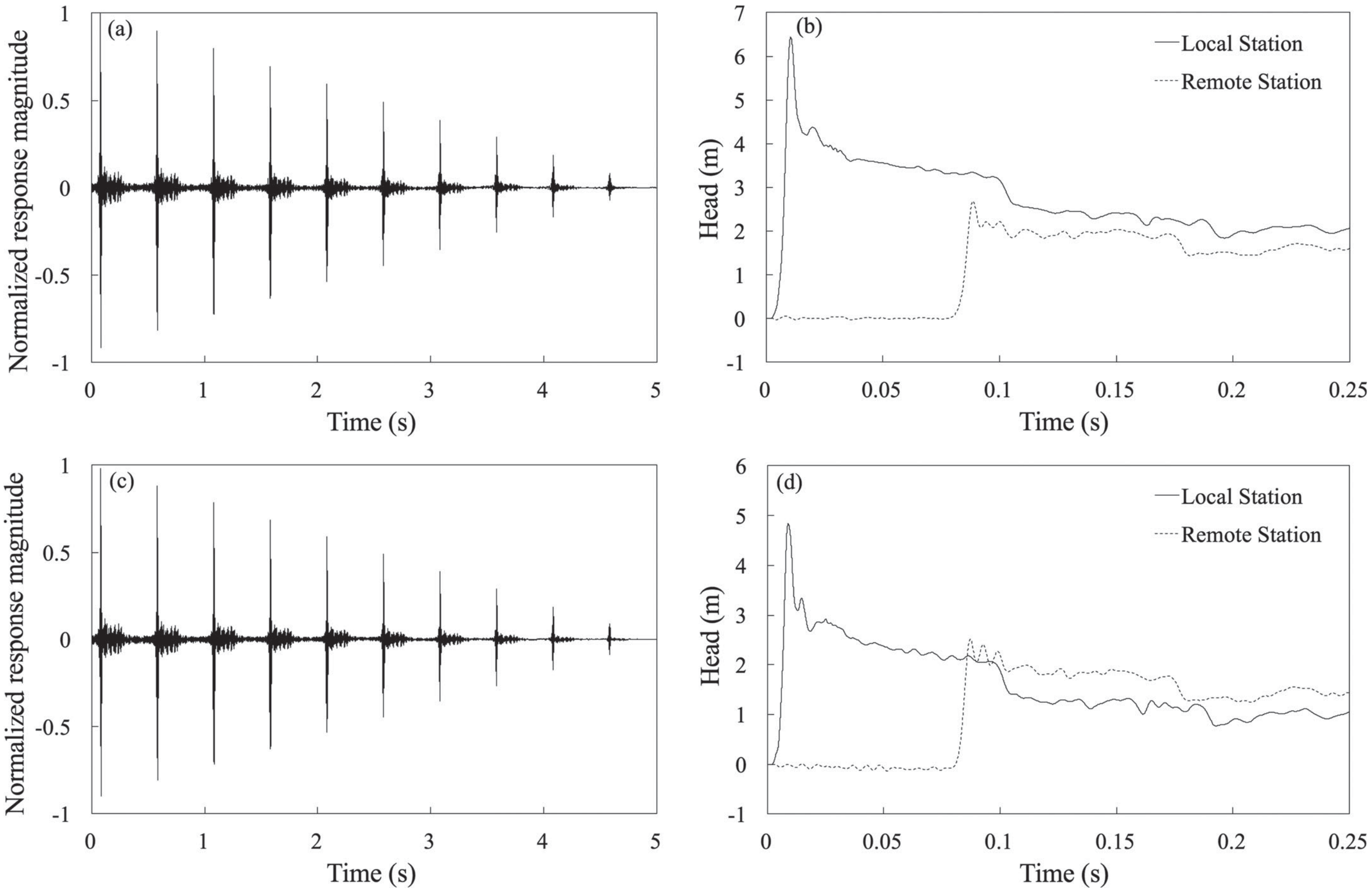

Figure 5 Site F2 (a) PIPE SONAR impulse response function a fully open isolation valve, (b) measured response for a valve closure signal for a fully open isolation valve, (c) PIPE SONAR impulse response function a fully closed isolation valve, (d) measured response for a valve closure signal for a fully closed isolation valve

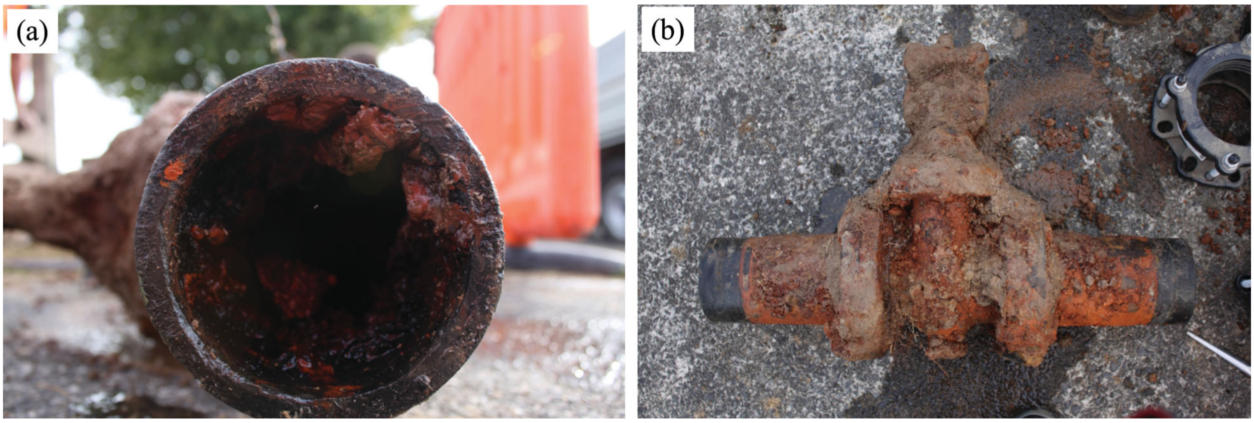

Figure 6 Internal (a) and external (b) views of the excavated isolation valve at Site D2

5 Conclusions

A novel transient signal generation system for pipeline condition assessment has been tested extensively in the field. The system, named PIPE SONAR (PCT/EP2015/059540), is a significant improvement over existing methods of transient generation for pipeline diagnostics, where a large and non-repeatable transient is created from manual closures of valves, often with a large loss of water.

The PIPE SONAR system can generate perfectly repeatable transients across different pipe sizes, materials and background pressure conditions with no loss of water from the system. The signal has an adjustable transmission range and the ability to design complex signal forms and signal bandwidth provides significant tolerance to ambient noise. The system was tested across 31 sites in four cities, in a field testing programme of over 1600 individual runs. In all tests, the pipeline network was under full operational status and in most cases the PIPE SONAR system was applied on main roads close to very heavy traffic. It was confirmed that the PIPE SONAR system does not require any system isolation or traffic diversion and there are no system base flow, topology or pressure requirements. The system easily attaches onto existing hydrants without any physical alteration to the system and is powered by batteries.

The PIPE SONAR method was applied to two well established pipeline condition diagnostic approaches, and the results from the PIPE SONAR method were compared to the results from manual valve closure signals. During the field trial, 13 isolation gate valves and 25 pipes were tested from which six valves were found to be faulty and 11 pipes were identified as being in a deteriorated state. Where possible these assessments were supported using independent methods, including flow isolation tests as well as physical excavation of a valve and a pipe section. The PIPE SONAR technique provided an accurate assessment of the pipe and valve conditions in all cases. The difference between the measured wave speeds from the PIPE SONAR systems and the manual valve closure signals was 0.56%. The ability of the PIPE SONAR system to replicate results from the traditional manual valve closure testing, but with a signal that is 99% smaller, without any loss of water and without any restrictions regarding nature of the network and ambient conditions, is a significant step towards the development of a real-time, permanent, active diagnostic system for water infrastructure networks.

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Notation

a = wave speed (m s^{-1})
D = pipe diameter (m)
E = elastic modulus (Pa)
e = pipe wall thickness (m)
I = impulse response function (–)
K = bulk modulus (Pa)
t = time (s)
x = measured signal at local station (m)
y = measured signal at remote station (m)
ρ = density (kg m^{-3})

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