Expansion of Existing Monitoring System on Great Man-Made River Project Using Acoustic Fibre Optic Technology

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Abstract Acoustic monitoring has played a major role in the management of one of the world's largest civil engineering projects. After experiencing failures on their pipeline between 1999 and 2001, the Great Man-Made River Authority (GMRA) undertook an aggressive condition assessment program. This program led to the development of a comprehensive Pipeline Risk Management System (PRMS), making the Great Man-Made River Project one of the best managed pipelines in the world. The planned expansion of the existing acoustic monitoring system, a key component of the PRMS, will allow for monitoring of over 700km of pipeline. This paper will discuss steps taken to-date, the acoustic monitoring technology and the expansion of this key component to the management strategy for the pipeline.

Keywords: Acoustic Monitoring, Prestressed Concrete Cylinder Pipe

PROJECT BACKGROUND
Located in Libya, the Great Man-Made River pipeline is the one of the largest water projects in the world, with more than 4000km of mainly four metre diameter prestressed concrete cylinder pipe (PCCP) in operation. Water is extracted from underground aquifers deep in the Sahara desert and is conveyed to coastal areas where over 90% of the population lives.

Phase I or the Sarir-Sirt/Tazerbo-Benghazi (SS/TB) conveyance of the project consists of two lines and involves conveying two million cubic meters of water per day, from well fields in Sarir and Tazerbo to end reservoirs at Sirt and Benghazi (Figure 1). The total length of PCC pipes used is 1900 kilometers, the majority being four meters in diameter. The system is designed to ultimately carry a flow of 3.5 million cubic meters per day in the future, with the additional water being drawn from a well field at Kufra.

Phase II of the Great Man Made River Project involves conveying two million cubic meters of water from well fields at East Jabal Hasouna and North East Jabal Hasouna to Tarhouna and Tripoli. Two hundred eighty-seven production wells at the East Jabal Hasouna well field will produce 1.4 million cubic meters of water per day and 153 production wells at North East Jabal Hasouna will produce a total of 0.6 million cubic meters per day.

The Gardabiya-Sedada system links Phases I and II, enabling bi-directional flow. In addition to the Kufra expansion underway in the Phase I system, two other major phases are either under construction or design. Once complete, the entire project will be capable of transporting over six million cubic meters of water per day.
Pipeline ruptures
The SS/TB conveyance system had a series of five ruptures on four meter diameter pipes while in service. The first pipe ruptured on August 19, 1999 on the SS line. The second rupture was on September 4, 1999 on the parallel TB line. Three more ruptures, two on the TB line and one on the SS line, occurred between January 2000 and April 2001. On-site investigations and studies carried out by GMRA experts concluded that the ruptures were attributed to chloride induced corrosion of the pre-stressing wire of the PCC pipes. These ruptures resulted in emergency unplanned shutdowns, which were not acceptable by GMRA since the project is supplying all domestic water requirements for the entire population of the coastal strip.

Need for management
To minimize the risk of occurrence of more rupture events and maintain the uninterrupted flow of water, GMRA adopted a full-scale rehabilitation plan that involved installing a cathodic protection system on the entire SS/TB pipeline, and conducting a condition assessment program based on non-destructive inspections to identify and repair corroded pipes. The extent of the problem was then assessed and it was found to affect only some of the uncoated pipes in the conveyance. The SS/TB conveyance consists of 60% uncoated pipes and 40% coated pipes. These were coated with coal tar epoxy and used in areas originally deemed as corrosive.

To help in determining which pipes needed to be repaired and/or replaced, a simplified and initial Pipeline Criticality Index (PCI) was established and used in classifying the distressed pipes according to their criticality. The said program enabled GMRA, at the beginning of the problem, to conduct a successful selective and preventive maintenance.
As the pipeline was put back into operation, GMRA installed acoustic monitoring equipment to track deterioration on the remaining pipe sections. Initially able to monitor approximately 40km, the system has been expanded since 2000 and now covers almost 100km of pipeline.

**Pipeline Risk Management System**

Because the initial PCI could not be considered accurate since it involved estimation and personal judgment based on practical experience and historical data, GMRA developed a long-term management tool that would facilitate more comprehensive repair and maintenance decisions. This in turn can lead to extend the service life of its enormous and complex pipeline network at a significant level of cost savings and management. This management tool, which is known as the Pipe Risk Management System (PRMS), compiles the massive amount of data available such as pipe design and manufacturing data, corrosion survey data (close interval potential surveys, soil resistivity, chloride levels, etc.), material test data (mortar porosity, mortar chloride levels, pre-stressing wire properties, etc.), operational data (cathodic protection, operating pressure, water flow rates, etc.), and inspection and monitoring data (electromagnetic, acoustic, visual investigations, etc.) to estimate the level and rate of pipe deterioration. Finally, the remaining service life of each pipe is estimated using structural, chemical and statistical analyses included in the expert model of the system. Figure 2.1 shows a sample of the optimistic and pessimistic curves for the remaining life of a certain 7.5m section of pipe on the SS/TB conveyance.

![Figure 2.1 Screenshot from PRMS Software](image)

**ACOUSTIC MONITORING**

The SoundPrint® acoustic monitoring system is a proven technology for assessing the condition of PCCP; it has been used in both short and long-term monitoring programs. The major advantage of acoustic monitoring over other methods is the availability of real-time information on the deterioration rate of the pipe. This dynamic data is important to the PRMS and its expert model.

When a tensioned wire embedded in a piece of PCCP fails, its stored energy is released suddenly, causing a dynamic response in the section of pipe. Other ambient events may also cause a response. Events that meet pre-set criteria are recorded and transmitted to a processing facility in Ajdabiya, located in an Operations and Maintenance Facility for the
pipeline. Acoustic analysis software is used to process data and generate reports summarizing the time and location of the recorded wire break events. The existing monitoring system on the project uses hydrophones and surface mounted sensors connected to data acquisition systems using both wired and wireless communication protocols.

The original monitoring configuration employed by GMRA consisted of hydrophone assemblies installed in three consecutive manhole or air valve structures 600 meters apart (Figure 3.1). Each station therefore spanned approximately 1.2 kilometres and was controlled by a single SoundPrint® data acquisition system. Using the hydrophone station approach, it was initially possible to monitor a total length of approximately 40 kilometres at any one time on the SS-TB lines. Because of the wide distribution of distressed pipes along the line, it was not possible to monitor all distressed pipes with the available equipment.

![Figure 3.1 Hydrophones are installed in existing manhole or air valve chambers](image)

In order for GMRA to monitor remaining uncoated pipe sections on the SS/TB conveyance during and following the rehabilitation programs, additional acoustic monitoring equipment was required. Whilst electromagnetic inspections detect broken wires, they do not detect presence of corrosion. Even though the repair program was not limited to distressed pipes, with many adjacent pipes containing evidence of corrosion also being removed, there still remains a real danger of corroded pipes being present in areas that had not been excavated. The Authority decided to implement a program of staged acoustic monitoring of 160 kilometres of uncoated pipe sections. The monitoring program is still underway, and is adjusted based on results from the monitoring and input from the PRMS.

The extra acoustic equipment raised serious practicality issues related to the cables connecting the hydrophones to the loggers and in the manual collection of data from the loggers. In the first instance the laying of the cables is time-consuming especially when taking into account the additional amount of hydrophones. In addition, the cables are prone to damage during relocation of the sites. Secondly, the acoustic monitoring stations would be spread out over an area of approximately 400 kilometers, and sending teams to collect data from the loggers would be impractical.

Instead, most sites now have data relayed from the hydrophones to the loggers and from there to the main processing center at Ajdabiya using wireless transmission. This effectively eliminated the need for cabling and manual data collection, and allowed great flexibility in the location and re-location of hydrophones in either the SS or TB line anywhere along the
400 km. distance. Furthermore, the capacity of the existing data loggers was increased from four channels to sixteen channels using a proprietary multiplexing system to accommodate the increased number of hydrophones. Each site can now monitor up to 8km of pipeline.

Results from the PCI and then PRMS were used to rank various locations along the pipeline in order of criticality. Areas considered critical were the first to be monitored using the acoustic equipment. Interventions on the pipelines were only undertaken if certain deterioration rates or total number of wire breaks were reached as dictated by the criteria of the management systems.

Acoustic monitoring stations that show no significant levels of activity are relocated together with the sites where repairs have been carried out after an intervention. During the period between November 2001 and September 2003, there were three interventions on the SS line all based on acoustic monitoring results and the Authority was able to avert potential failures. Another intervention took place in January 2005, again based on data from the acoustic monitoring system. The 2005 intervention is discussed in more detail below. It is important to note that the interventions mentioned above were all scheduled to be carried out within the time constraints afforded by the project’s reservoir storage capacity.

**Acoustic Monitoring Verification Case Study**

Data from the acoustic monitoring system has been used by GMRA several times since inception to assist in management decisions and to help prevent further ruptures on the pipeline. One such example was a pipe section located at Station 279+750 on the TB line, which was not considered for replacement or repair based on results from the baseline condition assessment performed in 2001. However, a monitoring system installed in December 2003 started to record wire breaks on this pipe section, and after one year of monitoring over 100 wire breaks had been recorded (Figure 4.1).

![279+750 Wire Breaks by Month](image)

**Figure 4.1** Wire breaks per month for pipe section at 279+750

Based on the criteria established by GMRA’s Pipeline Risk Management System, a decision was made to repair the deteriorating pipe section. Forensic investigations of the exposed pipe showed that the acoustic monitoring results were accurate in both location and quantity. The
acoustic monitoring system was therefore credited with preventing a likely rupture. Figure 5.1 shows photos of the pipe section exposed prior to its repair, divided by metre.

![Figure 5.1 Pipe section at 279+750 prior to repair](image)

As shown in Figure 6.1, the pipe section was repaired using external post-tensioning. This procedure eliminated the need to dewater the pipeline and replace the pipe section.

![Figure 6.1 Repair of pipe section at 279+750 using external post-tensioning](image)

EXPANSION OF ACOUSTIC MONITORING PROGRAM

Despite the aggressive rehabilitation program and preventative measures in place along the pipeline, an extensive monitoring program is planned to track further deterioration. It is recognized that continuous monitoring is critical to the long-term sustainability of the project. Evidence has also shown that acoustic monitoring is an effective way to detect pipes in advanced states of distress.
New developments in acoustic monitoring have yielded a fibre optic sensor that is more cost-effective for long reaches of pipe. Typically deployed in pipelines while shutdown and dewatered, the Acoustic Fibre Optic (AFO) system will be deployed in the Great Man-Made River while the pipeline is in operation using a parachute to pull the cable into place. A typical cable exit and splice location detail is shown in Figure 7.1.

![Figure 7.1 Typical cable exit detail and splice location for AFO system](image)

This monitoring configuration is capable of monitoring up to 40km from one data acquisition system. Sensors consist of four or more glass fibres bundled with a strength member and encased in a protective sheathing. Cable will be installed through new valves in existing manhole chambers, and lengths of cable will be spliced together at approximately 5km intervals.

A laser is used to project light down the fibre and a data acquisition system monitors reflections generated by the acoustic activity in a pipeline. The entire fibre cable acts as a sensor, so the sensor is never further than a pipe diameter from a wire break. Another advantage of the system is that no electronics are placed in the water flow, so monitoring system noise is nearly eliminated.

The initial phase of this program consists of 280km of cable and seven monitoring sites, each monitoring up to 40km of pipeline. An additional 375km of cable will be installed, facilitating staged monitoring of up to 650km of pipeline, in addition to the existing hydrophone equipment monitoring 100km. The end result will be the largest structural monitoring system of its kind in the world.

The AFO systems will focus on pipeline segments that cannot be dewatered for inspection using the other techniques previously mentioned. Specifically, the coastal lines between Benghazi and Sirt will among the first to be monitored using the technology. These coastal lines have only coated pipes, but lack the redundancy of the Ajdabiya-Sarir segment of the pipeline, so have not been internally inspected since commissioning.

Data from all acoustic monitoring sites (including the existing 100km using hydrophones) will be processed from the Ajdabiya processing centre. Wire break results will continue to feed the Pipeline Risk Management System, and assist GMRA in prioritizing future repairs.
CONCLUSION
Data has been collected by more than 100 sites since GMRA started using acoustic monitoring as part of their management strategy. This has provided valuable information on hundreds of kilometres of pipeline, and in several instances has been used to likely prevent pipeline ruptures. In fact, since April 2001 when GMRA started implementing the strategies detailed above, to-date, there have been no further pipe failures and in addition water supply to the consumers has remained uninterrupted throughout this period. The planned expansion of the acoustic monitoring system using the new AFO technology will further assist GMRA in assessing the condition of the pipeline.

References