

An Advanced Method of Condition Assessment for Large-Diameter Mortar-Lined Steel Pipelines

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Abstract

This paper describes the development and application of an advanced method of condition assessment for large-diameter, cement mortar-lined steel pipelines operated by the Hetch Hetchy Water and Power Project of the San Francisco Public Utilities Commission.

The most accurate method of pipeline condition assessment is in-line inspection (ILI) using advanced nondestructive electronic methods to scan the full circumference and length of the pipeline for damage by corrosion and other causes. This technology, commonly known as 'smart pigging', has become relatively straightforward in unlined steel pipelines used in the oil and gas industry. However, the presence of mortar lining in water pipelines has, until now, limited the accuracy of ILI inspection and hindered development of practical ILI methods for large diameter, mortar-lined steel pipelines.

This ILI project was conducted over a 3-year period and included development of magnetic flux leakage (MFL) tools, a caliper tool, and propulsion equipment to move the tools through the pipeline. Two full-scale field inspections using the equipment were conducted on a total of 13-miles of historic pipeline. The results were of immediate use in managing the pipeline asset.

The benefits of using this advanced method of condition assessment are compared to the traditional method using records and indirect indicators of pipeline condition.

Introduction

The Hetch Hetchy Water and Power Project (HHWP) of the San Francisco Public Utilities Commission (SFPUC) operates approximately 142 miles of large diameter water transmission pipelines. These pipelines convey water across the San Joaquin Valley in central California and are known as the San Joaquin Pipelines (SJPLs). Approximately 120 miles of pipeline are constructed from cement mortar-lined steel pipe and have a replacement value on the order of \$1 billion.

The SJPLs range in size from 56- to 78-inches in diameter. They have been in service for 40 to 80 years. During that time, HHWP has conducted a variety of investigations, studies, and repairs to maintain the pipelines. In recent years, condition assessment of the SJPLs has increased in importance as the SFPUC has evaluated and improved its water supply system.

Preliminary condition assessments of the SJPLs were based on traditional methods such as review of maintenance records and excavation of the pipe for inspection. However, HHWP recognized that the most accurate method of pipeline assessment is in-line inspection (ILI) using advanced nondestructive methods to scan the full circumference and length of the pipeline for damage by corrosion and other causes. ILI has become relatively straightforward in unlined steel pipelines used by the oil and gas industry. However, the presence of mortar lining in water pipelines complicates ILI and hindered development of practical methods for large diameter, mortar-lined steel pipelines.

The SFPUC authorized a project to develop and apply ILI to the SJPLs so that their condition could be accurately assessed. The result of the project was the development of an advanced method of condition assessment for large-diameter mortar-lined steel pipelines (Slide 1). The authors believe that the approach described in this paper is unique and that no equivalent system is in use in the water pipeline industry at this time. This paper describes the development and implementation of ILI for the SJPLs (Slide 2).

The SFPUC and HHWP retained CH2M HILL to assist with condition assessment of the SJPLs. Electromechanical Technologies, Inc. (Emtek) was retained as ILI expert, and Yuerba Buena Engineering was selected to provide construction services for the project (Slide 3).

Magnetic flux leakage (MFL) was the method of nondestructive evaluation (NDE) selected for this project (Slide 4). Validation of ILI results was completed by examination of excavated pipe and also by automated ultrasonic thickness testing (AUT). An advanced electronic ILI system such as the one described in this paper is often called a 'smart pig'.

Pipeline Description

The SJPLs are comprised of 3 parallel pipelines in a common alignment that is 47.5 miles in length (Slide 5). The pipelines have combined nominal capacity of 300 million gallons per day (MGD) and convey water to approximately 2.4 million people. Flows are by gravity with operating pressures up to approximately 250 pounds per square inch (psi). The pipeline alignment crosses the foothills of the Sierra Nevada Mountains and the relatively flat San Joaquin Valley. The pipeline alignment crosses land used for a variety of purposes including grazing, agriculture, and urban development.

The SJPLs are constructed from a variety of pipe materials (Slide 6).

- SJPL1 ranges from 56- to 72-inches in diameter. SJPL1 was built in the early 1930's, when welding was in the early stages of development. Welded joints were used in several miles of pipeline, but most joints were riveted. Individual pieces of pipe were made from rolled plate with one longitudinal weld. SJPL1 was coated with bitumen (asphalt), and in some areas the bitumen was covered with a cement mortar jacket. SJPL1 is lined with cement mortar which was installed in the 1950's after the original bitumen lining reached the end of its useful life.
- SJPL2 is 61-inches in diameter and was built in the 1950's. Sections of the pipeline with higher pressure and directional changes are constructed from cement mortar-lined and – coated steel pipe with welded joints. The remainder of the pipeline is constructed from reinforced concrete cylinder pipe (RCCP) with rubber gasket joints.
- SJPL3 is 78-inches in diameter and was built in the late 1960's. Most of the pipeline is constructed from steel pipe with welded joints and coal tar enamel coating. The original pipe lining was coal tar enamel which is still in place in some areas. The remainder of the steel pipeline has cement mortar lining that was installed in the 1980's. A portion of the pipeline was constructed from prestressed concrete cylinder pipe (PCCP).

The ILI project described in this paper was conducted on SJPL1, although condition assessment studies are in progress on all 3 pipelines.

Condition Assessment

Condition assessment of buried metallic pipelines requires collection and analysis of data, followed by an engineering evaluation and, ultimately, decisions on whether to repair, replace, or take some other action to maintain reliable service (Slide 7). Data collection usually consists of finding and assessing the extent of metal loss due to corrosion and damage by other causes such as third party construction or agricultural equipment. For historic pipelines, it is also important to find and document old repairs and modifications that may not have been fully documented in records. An engineering evaluation of the collected data is necessary to determine the leak-tightness and pressure capacity of the pipeline to ensure that service goals can be met.

Experience suggests that traditional methods of condition assessment have accuracy that is moderate at best (Slide 8). This may be sufficient for distribution pipelines that have redundancy, but a more precise method is desirable for key structures such as transmission pipelines. Advanced methods of condition assessment by ILI involve scanning the full circumference and length of the pipeline under study to identify all defects. This approach is in use in the oil and gas pipeline industry. Advanced methods have the potential for high accuracy in condition assessment that is most desirable for large-diameter water transmission pipelines.

The first step toward an advanced method of condition assessment for the SJPLs was to evaluate ILI technologies based on the literature and state-of-the-art in the oil and gas pipeline industry (Slide 9). Three possible methods were evaluated: ultrasonic thickness gauging; remote field eddy current; and magnetic flux leakage or MFL, which was ultimately selected based on the expected accuracy and practical considerations for ILI.

MFL technology is relatively simple in concept (Slide 10). Permanent magnets are used to temporarily magnetize the steel pipe and the effect is observed. The magnetic flux is uniform if there are no flaws in the wall of the pipe. If internal or external flaws are present, the magnetic flux is distorted, and this distortion or 'leakage' can be measured by Hall Effect sensors.

Although MFL is simple in concept, its application to large-diameter, mortar-lined pipe posed several challenges (Slide 11): Powerful magnets are necessary to magnetize the pipe wall; precision electronics are required to acquire and retain data; and signals must be correctly interpreted. In addition, all ILI equipment was designed to be placed into the pipeline through existing manholes, assembled, operated, and then removed by the reverse process.

Project Description

Work on the HHWP ILI project to date has been completed in two phases (Slide 12). Phase 1 included design and construction of prototype systems, followed by full-scale field testing on a section of pipeline. Phase 2 consisted of revisions to ILI systems previously constructed and subsequent full-scale field testing on another section of pipeline. Future work is anticipated to consist of refinement of ILI systems and application to other sections of pipeline.

Phase 1

Phase 1 had an ambitious scope (Slide 13). The project included conception, design and fabrication of equipment for ILI by MFL. All systems were shop-tested to prove form and function, including verification that all components would fit through the 14-by-16-inch elliptical manholes in SJPL1 and could be properly assembled inside the pipe.

An inspection run of up to 4 miles of pipeline was planned, although 6 miles were actually inspected. The project also included analysis and correlation of the MFL data to determine locations of suspected metal loss ('anomalies'). These locations were subsequently investigated by excavation and examination of the pipeline, a process known as 'validation'.

-Blind Test

One key shop test conducted in Phase 1 was a 'blind test' (Slide 14). A length of 24-inch diameter steel pipe was machined so that it contained 28 simulated 'pits' in 7 groups designed to evaluate the resolution of the MFL tool and data analysis system. After machining, the simulated pits were filled with epoxy, and the pipe was coated so that there was no visible evidence of their locations. The ILI tool was passed through the pipe, with the magnets and sensors held 1/2- to 3/4-inch from the pipe surface to simulate the thickness of mortar lining. The results indicated by MFL were compared to actual measurement data, and excellent correlation was obtained.

-Field Trial

After the 'blind test' and manufacturing of the MFL tool were completed, a full-scale ILI field trial was planned and undertaken on SJPL1 (Slide 15). Difficulties were encountered during tool movement, especially in locations where the bore of the pipe was smaller than anticipated due to deflection of the pipeline or the height of riveted and mortared joints. The propulsion vehicle had difficulty towing the MFL tool, and supplemental winching was used to move the tool through the pipe. Other difficulties were encountered that were ultimately overcome.

After some trial and error, the 'anomalies' indicated by the MFL analysis were correlated with the actual condition of the pipeline (Slides 16, 17 and 18). The indications were validated by excavation and examination of the pipe. One immediate benefit of ILI was the discovery of deep corrosion pits in the bottom of the pipe at the locations of 'grade stakes' that were installed during original construction. The grade stakes damaged the protective coating on the bottom of the pipe and allowed corrosion. The corroded areas were repaired, and possible future leaks were prevented at those locations.

The Phase 1 ILI project was successful. Inspection identified several corroded areas or defects that varied from 30 to 90 percent through the wall, and over 800 defects that were recognizable but not critical. The inspection also indicated that the majority of the pipe surfaces had relatively minor amounts of metal loss considering the age of the pipe.

Phase 2

Phase 2 of the ILI project also had an ambitious scope (Slide 19). The project included extensive hardware and software modifications based on the experience of Phase 1. A full-scale field MFL inspection of SJPL1 was planned, and ultimately 7.4 miles of pipeline were inspected. Validation of MFL indications in Phase 2 was conducted from inside the pipeline using automated ultrasonic thickness testing (AUT) to avoid the time and expense of excavation.

-Geometry Inspection

After encountering the difficulties with constrictions in pipeline bore during Phase 1, the scope of Phase 2 included design and construction of an ILI caliper device (Slide 20). This 'geometry tool' was used to verify the adequacy of the pipeline bore for the MFL tool and also to physically locate openings and features for use in conjunction with MFL data. The geometry tool was towed with one propulsion unit, which was completely new and improved from the one used in Phase 1. Both the propulsion unit and geometry tool worked well, and only minor problems were encountered.

Analysis of the measurement data from the geometry tool showed that the minimum bore of the pipe joints ranged from 54- to 57-inches in most cases, and that all joints were of sufficient size to accommodate the MFL tool (Slide 21). The ovality of each piece of pipe was also determined to assess deflection or out-of-roundness (Slide 22). Results showed that the deflection was less than 1-percent in most cases, and less than 2-percent in all but 3 locations. For reference, AWWA Manual M11 ([Steel Pipe- A Guide for Design and Installation](#)) suggests a maximum allowable deflection of 3-percent for new pipelines constructed with mortar linings and flexible (dielectric) coatings.

-MFL Inspection

The MFL inspection was also successfully completed (Slide 23). It was a more complex operation due to the larger number of components and heavier weight of the MFL tool compared to the geometry tool. Two propulsion units were used; one unit in front and one in the rear of the MFL tool. Coordination between the drivers of the front and rear propulsion units proved to be a key factor in progress of the inspection. Improvements made in the data handling and analysis systems prior to the field trial also paid off in increased reliability and

reduced effort. Full redundancy in data storage was maintained as a precaution against loss of data.

The results of the Phase 2 MFL inspection were definitive (Slide 24). The total length of pipeline inspected was 39,027-feet including 1,346 joints. A total of 229 locations were identified with metal loss attributed to external corrosion. Other findings included 59 existing patches, 24 butt-strap joints and 14 mill anomalies in the manufactured pipe.

Analysis of the pattern of metal loss indicated two locations where the pipe wall was penetrated by corrosion to a depth of 72-percent of the original thickness (Slide 25). Another 10 locations were found with indicated metal loss of 35- to 45- percent of original wall thickness. The other indicated locations of metal loss were less than 35-percent of original wall thickness. It should be noted that the tested section of pipeline has a mortar jacket over the bitumen coating, according to construction records. Observations made on other sections of the pipeline that have this coating suggest that the mortar jacket protects the bitumen coating from deterioration by contact with the soil and thereby reduces the probability of corrosion of the pipeline. These observations are supported by the ILI findings of Phase 2.

The results of Phase 2 ILI were promptly evaluated for further action (Slide 26). After validation by AUT, one location with deep metal loss was excavated and repaired. The second location found with deep metal loss is planned for repair when an appropriate service outage can be scheduled. The 10 locations with indicated metal loss in the range of 35- to 45-percent were investigated to validate MFL indications and assess the need for repair.

Further analysis of the MFL metal loss data showed that 75-percent of the locations with metal loss were on the bottom half of the pipe (Slide 27). The rest were on the upper half of the pipe. This is consistent with general experience concerning corrosion of large-diameter pipe.

Analysis of the MFL data for specific locations disclosed other interesting features (Slide 28). These include metal loss in the vicinity of riveted joints, areas of extensive corrosion pitting, and stiffener rings on the exterior of the pipe. Riveted joints and butt-strap joints were found to have distinctive magnetic 'signatures' (Slide 29).

One location was found with deep metal loss due to corrosion on the top of the pipe (Slide 30). This was an unusual occurrence because of its location on the top of the pipe and lack of damage to the mortar jacket that would be expected if the pipe had been hit by other construction or agricultural equipment. The metal loss at this location was validated by AUT prior to excavation for repair.

-Validation by AUT

Investigation and validation of MFL indications of metal loss was performed by AUT (Slide 31). The AUT equipment is computer-controlled and makes many ultrasonic measurements of metal thickness in a closely-spaced grid over the designated area. Water is used for couplant between the transducer and the pipe surface. Validation of MFL data by AUT avoids excavation but is practical only if the pipeline can be entered and the indicated locations of the 'anomalies' found by MFL are precisely specified so that they can be measured and marked. Removal of the mortar lining is required for any form of ultrasonic thickness testing of the steel pipe.

The results of AUT produced clear images of the pipe wall thickness and metal loss in the areas studied (Slide 32). The location of the scan shown in the slide is the same as the excavated location described in the previous text.

The MFL inspection also revealed the presence and locations of pipeline features including old patches and unused openings in the pipe wall (Slide 33). Known features can be used to validate distances and orientation of MFL data. Features that are discovered can be documented for future reference or other appropriate action if necessary.

ILI Project Timeframe and Workforce

HHWP's ILI project began in 2007 (Slide 34). Phase 1 was completed in 2009, and Phase 2 is nearing completion in 2010. The majority of the time was spent in preparation for the field work and included planning, design and construction of the tools and propulsion units.

The field work phase of Phase 2 occurred over a 10-week period with 6-day work weeks during the service outage of SJPL1. This excludes the time required to drain and refill the pipeline. The basic work approach for the ILI field work was to assemble the geometry tool and conduct the geometry scan in one direction through the study area, then assemble the MFL tool and conduct the MFL scan in the opposite direction. During the tool changeover, the propulsion unit that towed the geometry tool was disassembled and reassembled facing the opposite direction for the return trip to the original starting point of the ILI.

The workforce for the field portion of Phase 2 consisted of 13 people (Slide 35). Of this workforce, 6 people were employed by the construction services contractor and were the ones who actually moved the ILI equipment through the pipeline. There were 4 ILI engineers and technicians who worked full-time assembling the tools, monitoring systems, and retrieving the data. The remainder of the workforce consisted of the chief engineer, resident engineer and measurement technician.

Summary

The ILI project conducted by HHWP and SFPUC developed and implemented an advanced method of condition assessment for large diameter, mortar-lined steel pipelines using ILI by MFL (Slide 36). The technology was proven by actual inspection of more than 11 miles of SJPL1 using the approach and equipment that was developed. The study greatly improved the understanding of condition and features in the full circumference and length of the inspected pipeline. In particular, locations of relatively weak points in the pipeline were identified for repair and mitigation to prevent leaks and help assure reliable service.

Perhaps most importantly, the ILI project determined that the pipeline studied was in generally good condition and that replacement was not required, thereby avoiding the associated costs. The opposite conclusion might have been reached if traditional methods of condition assessment had been used.

Based on the overwhelmingly positive results of the ILI project, future plans are under development (Slide 37). Anticipated activities include investigation of improved methods of joint inspection by MFL and inspection of additional sections of SJPL1, SJPL3, and possibly portions of SJPL2.

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