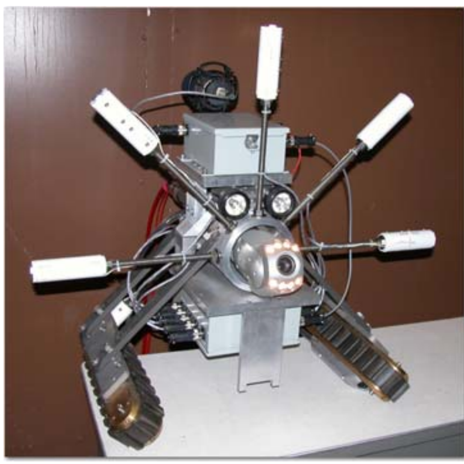
RECLAMATION

Managing Water in the West

Water Operation and Maintenance Bulletin

No. 225

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U.S. Department of the Interior
Bureau of Reclamation

September 2008

This *Water Operation and Maintenance Bulletin* is published quarterly for the benefit of water supply system operators. Its principal purpose is to serve as a medium to exchange information for use by Bureau of Reclamation personnel and water user groups in operating and maintaining project facilities.

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Cover photograph *(left) Front view of a prototype system.*
(right) Prototype system in a pipe model.

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Field Application of PAM for Canal Seepage Reduction[1]

by Del Smith

Traditional methods of controlling canal seepage include concrete lining, compacted clay, and geomembrane lining. These proven methods of reducing canal seepage are effective but often cost prohibitive for most water districts and canal companies. In the late 1990s, the Uncompaghre Valley Water Users Association (UVWUA) started experimenting with the flocculent polyacrylamide (PAM) to reduce canal seepage. They worked with the Bureau of Reclamation's (Reclamation) Western Colorado Area Office to conduct some bench scale tests in wooden test troughs. After seeing initial success, they expanded their applications to small canal laterals that were known to have high seepage losses. By 2003, there was a significant number of PAM applications occurring in western Colorado, largely being encouraged by anecdotal evidence of seepage effectiveness and support by the Natural Resources Conservation Service.

Reclamation made a decision that this new application of PAM needed to be thoroughly evaluated on several fronts, including, in addition to water savings, potential human health and environmental effects. The following represents why Reclamation is concerned about what is put in our waters:

> "Reclamation is the largest water wholesaler in the country, providing 10 trillion gallons of water to more than 31 million people and irrigating 10 million acres that produces 60 percent of the nation's vegetables and 25 percent of its nuts and fruits." (Reclamation, 2005)

Reclamation collaborated with the Desert Research Institute to provide answers to the following seven questions:

1. What are the ecological and human risks of the use of PAM and any trace substances in PAM formulations, particularly acrylamide (AMD), when used in unlined earthen canals for seepage control?

2. Does PAM degrade to the monomer, AMD? If so, does the amount present a significant risk for contamination of surface water or groundwater?

3. What is the relative significance of residual AMD in the original polymer versus AMD as a PAM degradation product (if it is generated)? Are there other potential or known degradation products of PAM that are of toxicological concern?

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[1] This paper was presented at the USDA-ARS-Western Regional Research Center on February 26–27, 2008.

4. What is the fate (including biodegradation) and transport of AMD (and/or PAM and product components) in surface water, soil, and groundwater systems? What data gaps exist specific to this application?

5. How do field application practices (e.g., application of PAM to dry soil versus water in a flowing ditch) affect the risk of use of PAM? What field practices can be used to reduce risks of PAM application?

6. If residual PAM is released into receiving waters, what are the ecological risks and issues associated with PAM in surface water (e.g., armoring channel morphology, bioaccumulation, etc.)?

7. Are there any other issues regarding the human and ecological risk of use of PAM that should be considered?

Measuring Canal Seepage

To accurately measure canal seepage in flowing canals is not an easy task. To improve the accuracy of measurements, the following are necessary:

- Collect frequent stage data
- Measure between diversions
- Conduct measurement during steady-state flow
- Long enough reach (typically 2+ miles)
- Need good cross-sections/canal geometry

The site selection we used incorporated the following:

- Magnitude of seepage loss (needs to be sufficiently high)
- Controllable or stable inflows
- Minimum number of turn-outs
- Length of canal
- Presence of an upstream control reach
- Presence of background data
- Ability to collect downstream water chemistry

Canal Application

From 2005 to 2007, Reclamation, Desert Research Institute (DRI), and Colorado State University (CSU) conducted 17 LA-PAM field application experiments. The 2005 and 2006 applications can be summarized as providing excellent data on short-term seepage loss and excellent data on LA-PAM release into water column, but difficult to evaluate seasonal seepage. The 2007 studies focused on obtaining significant background data and gaining a better understanding of naturally occurring changes in seepage. PAM was applied as dry granular PAM at a rate of approximately 10 lbs/acre based on wetted perimeter and direction from downstream to upstream in flowing water.

The concentration of PAM Applied – Based on Phase II Rule National Primary Drinking Water Regulations issued by the U.S. EPA (40 CFR 141.111) asserts an acrylamide polymer maximum use level of 1.0 mg/L and an AMD concentration of 0.05% in the polymer, or equivalent, for a carryover of not more than 0.5 ug/L of AMD into the finished water.

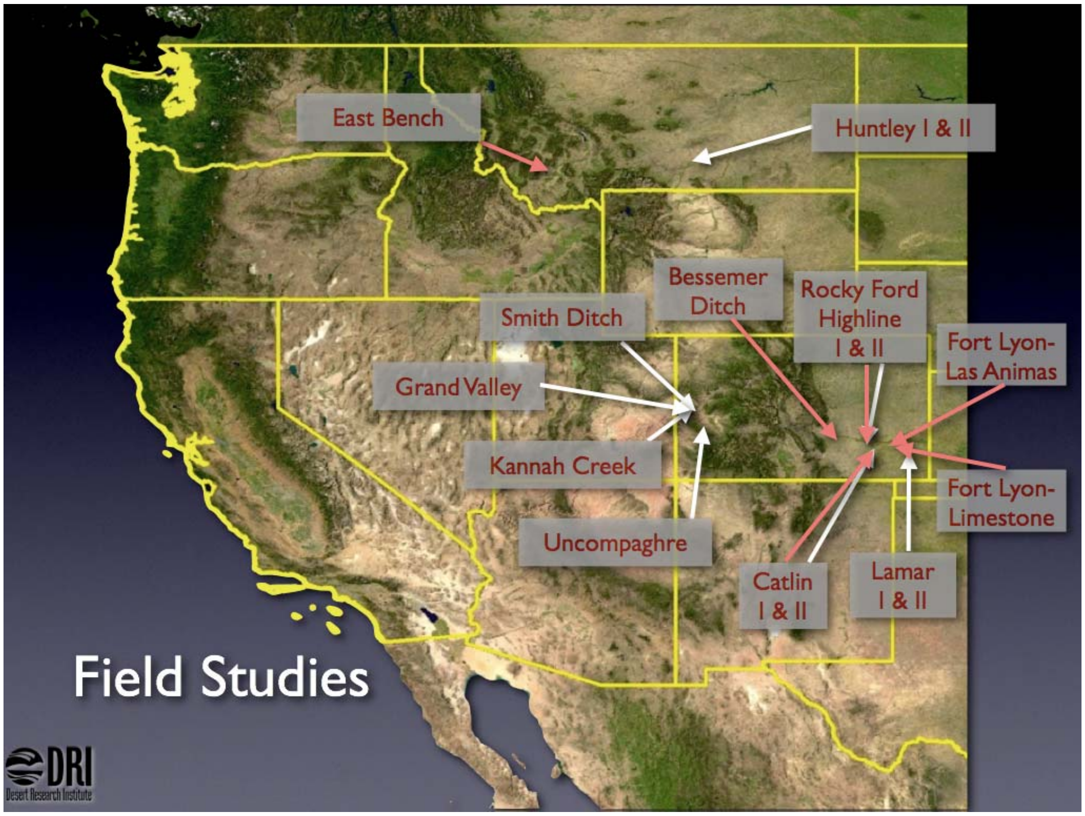
We sought to apply LA-PAM to achieve a canal water concentration of less than 1.0 mg/L.

Variables that control effectiveness of seepage reduction include:

- Travel time
- Hydration time
- Suspended solids concentration in water
- Water temperature
- Water velocity
- Water chemistry
- Ability to hit target reach
- Mixing

Seepage Reduction

Seepage reduction ranged from 0 to 99 percent, but where the conditions were favorable, the range was typically from 30 percent to 90 percent and lasted throughout the irrigation season (up to 5 months). Followup measurement during successive years indicates that PAM would need to be reapplied on canals that are allowed to dry out over the winter.


East Bench
Huntley I & II
Bessemer Ditch
Rocky Ford Highline I & II
Smith Ditch
Fort Lyon-Las Animas
Grand Valley
Kannah Creek
Fort Lyon-Limestone
Uncompaghre
Catlin I & II
Lamar I & II
Field Studies
DRI
Desert Research Institute

Alternatives to PAM Framing Research Directions[1]

by Chuck Hennig

The mission of the Bureau of Reclamation (Reclamation) is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public. By its mere presence and ownership of facilities, Reclamation directly influences water use and supply patterns in most major western river basins. Reclamation owns 348 reservoirs that store 245 million acre-feet of water, which provide $9 billion in agricultural benefits. More than 90 million people each year visit 308 public recreation areas. Reclamation owns 254 diversion dams and approximately 16,000 miles of canals delivering water for irrigation and more than 31 million people for municipal and industrial use. This makes Reclamation the largest municipal water wholesaler in the United States. Six million homes are powered by 58 hydropower facilities, and more than $12 billion in flood damages have been avoided since 1959.

Problem

A 1978 study indicated 30,300 miles of western “off-farm” canals seeped as much as 1.1 million acre-feet each year. Reclamation has approximately 14,000 miles of unlined canals. A desired benefit from a polyacrylamide (PAM) alternative that Reclamation seeks for our project beneficiaries is a less expensive alternative to reduce seepage losses in water delivery canals. Traditional seepage control measures typically cost $9 to $18 per square yard.

How does PAM reduce canal seepage? Flocculates sediment are entrained in canal waters forming a seepage reduction barrier along the canal invert. The seepage reduction effectiveness has been measured between 0 to 90 percent and depends on the following site-specific factors:

- Amount of sediment in the water
- Water temperature
- Amount of PAM
- Application method
- Porosity characteristics of the canal invert

[1] This paper was presented at the USDA-ARS-Western Regional Research Center on February 26–27, 2008.

The duration of seepage reduction has been measured to last the entire irrigation season or as short as 1 month. Natural settling of sediments has been measured to reduce canal seepage, but it is typically more gradual and not as long lasting.

Where Do Canal Seepage Losses Go? Not all canal seepage is a loss to the watershed; some of it recharges groundwater and may return to the downstream surface waters. Canal seepage is a loss of beneficial use to the water right. Other impacts of reducing seepage are site specific but can result in:

- Reducing groundwater supplies
- Reducing downstream return flows
- Making wetlands less “wet”
- Flushing less salts from the soils

Human Health Concerns

Water delivery canals, directly or indirectly, are a source of water for human use. It is not good to throw anything potentially toxic in water used for human consumption or swimming in the absence of regulation or product labeling for such uses. PAM contains acrylamide (AMD), which the U.S. Environmental Protection Agency (EPA) classifies as a class B2 animal carcinogen, is a known neurotoxin and a genotoxin. Studies of fate and transport of PAM and AMD in the environment indicate a rapid degradation. However, degradation by-products are not well understood.

In March 2004, the U.S. Department of Health and Human Services convened an expert peer review panel that documented AMD as having potential human reproductive and developmental effects. In March 1994, the Food and Drug Administration developed an action plan for AMD in food. In June 2002, the World Health Organization started evaluating the health implications of AMD in food. EPA is updating a risk analysis of AMD in 2008. The European Union, academia, and others scientific entities are evaluating the human health effects of AMD.

Recent and ongoing studies to further evaluate AMD risks in food and form sensible public health advice is proving difficult. More studies and investigations are needed to better understand human risk, uncertainties, and risk management considerations.

Public Perception and Exposure to Litigation

In the absence of regulations and environmental studies, it is difficult for water managers to protect themselves from perceived risks. Applicators wearing protective clothing, including eyewear and dusk masks, indicate to the public that what is being applied is dangerous. There is also the risk that what is being applied may be potentially toxic to aquatic species and/or may adversely impact aquatic habitat. The methods to manage risk for applications of PAM do not yet exist like they do for applications of herbicides and pesticides used in canal environments. These are regulated by EPA and States and are labeled accordingly for specific applications to waters. Where PAM is used in drinking water treatment, there are trained applicators and it is performed in a controlled engineering environment where there is a well defined risk-risk tradeoff.

How could risk of using PAM in canals be appropriately managed?

- Implementing customized and proven application protocols
- Having a regulatory entity implement and administer application protocols
- Having trained and certified applicators

What are some of the associated challenges?

- Protocols based on risk characterization, not a detailed risk analysis, using available information and limited testing.

- Lack of controlled setting (i.e., there exists a wide and unpredictable range of site-specific physical, environmental, human, and institutional factors across Reclamation’s 14,000 miles of unlined canals).

- Equipment being used for applications is not designed to facilitate consistent applications.

- Easy to overdose – so little product is needed that it is easy to overdose canals. It is also not cost-prohibitive to overdose; it introduces the temptation to add more for good measure.

Bureau of Reclamation Decision – March 2007 Memorandum

In the absence of a regulatory framework or product labeling for PAM applications to reduce canal seepage, Reclamation will not support or allow the use of PAM in Reclamation-owned facilities.

Reclamation will continue to actively explore improved ways to reduce canal seepage losses:

- Reclamation will collaborate with USDA – Agricultural Research Service and industry to pursue the development of alternative biodegradable flocculants (i.e., green alternatives to PAM).

- Use new methods to more accurately measure and locate seepage so that spot treatments using conventional alternatives such as concrete and geotextiles is more practical and effective.

Detecting Voids Behind Conduits Using Acoustic Technology

by Fred A. Travers[1] and William F. Kepler[2]

Abstract

The presence of voids in the fill around conduits through embankments is a recognized problem. Detection and location of these voids is difficult until a void becomes so large that the integrity of the structure is at risk. A research effort has been mounted to explore the viability of using acoustic technology to detect such voids before they imperil the embankment. Using a technique similar to tapping on a wall and listening to the sound to locate a stud, a system has been developed that taps on the inside of a pipe and records the sound made while it moves through the pipeline. An automated analysis of the recorded sounds has shown potential as a means of detecting and locating voids.

Introduction

Piping in an earthen structure can have catastrophic consequences. Once flow is established through a structure, it can increase dramatically in a short time. The uniform compaction of the bulk structure is essential to preventing piping. Conduits running through structures are particularly problematic because uniform compaction around them is sometimes difficult to achieve. Furthermore, leaks from a conduit can cause voids in an otherwise sound structure.

It has been recognized that piping around conduits through embankments represents a major and growing problem. As dams and the conduits through them age, the problem of seepage around conduits is getting worse. The Bureau of Reclamation (Reclamation) has many structures containing embedded conduits and, therefore, has a vital interest in methods of detecting voids around them. If voids can be detected, located, and quantified, a variety of techniques can be employed to repair them and avert potential failures. To this end, Reclamation's Dam Safety Office is funding the research effort described herein.

Detection of voids in the fill outside a conduit is difficult because the conduits are buried and are opaque. Visual indications of a problem are often not evidenced before a problem is quite severe. A sinkhole over a conduit, or seepage at its end,

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would indicate a severe problem. A visual inspection of the inside of a conduit might show sagging into a void, cracking of a concrete conduit, or joint separation, but if the conduit is large and rigid, this might not be evident until the void is of significant size. For a detection and location technique to be viable, it must operate from the ground surface over the conduit or from inside the conduit itself.

Existing Void Detection Technologies

Some void detection technologies currently exist; however, none of them are without limitations that preclude their general use.

Ground Probing Radar (GPR) has been widely used in geophysical applications to obtain images of subsurface features. GPR works by directing radio waves into the ground using a specially designed antenna. Discontinuities in the dielectric properties of the ground cause reflections of the radio waves that are detected by the antenna. Like the name implies, it works very much like the radar systems used for tracking aircraft. In GPR, the antenna is moved along the ground, and the data collected are used to generate an image that represents a cross-sectional view of the subsurface. Because GPR relies on discontinuities in the dielectric properties of the medium through which it travels, its range and capabilities are a function of the moisture content and conductivity of the soil. The range can vary from a few inches to tens of feet. Metal objects reflect nearly all of the radar pulse and, consequently, seeing past such objects is not practical. Given these limitations, this technology is best suited to finding voids around non-metallic pipes. This type of pipe would allow inspection from the inside and could show voids at all locations around the circumference as the antenna is moved around the inside of the pipe. Inspection of a metallic pipe or a heavily reinforced concrete pipe could not be performed from the inside because the radar waves could not travel through the pipe. Inspection from the outside would be possible if the soil conditions were suitable and the depth not excessive, but it would not be possible to inspect under a metallic pipe.

Acoustic emission technology uses passive “listening” devices to detect the low-amplitude, high-frequency noise emitted by leaks in high-pressure pipelines. A void will likely develop where a leak exists. While this technique would be applicable in some industries, the types of conduits of interest to Reclamation would not benefit from this.

Another possible void detection method would be the use of infrared thermography. This technology employs a sensitive infrared temperature detector to measure the surface temperature of an object. The surface temperature is displayed as a picture of the surface with the color indicating the temperature. Viewing the inside surface of a conduit in this way would show temperature differences that could indicate voids outside the conduit. The technique assumes that the inside surface of a conduit would have temperature differences between where the fill is in intimate contact with the conduit and where there is no contact because of a void. Reclamation currently has a parallel research effort exploring the use of this technology.

An Acoustic Resonance Void Detection Method

A unique concept for void detection is being studied that uses the acoustic resonance of the conduit wall to detect voids. It involves a simple concept similar to that used to find a stud inside a wall. By tapping on a wall and listening for differences in the sound made by the tap, the location of a stud can be found. It was reasoned that a similar method could be used to detect the presence of voids in the fill around a buried conduit. If the pipe wall is excited so that it vibrates, where it is in direct contact with well-compacted fill, it will vibrate very little. If there is a void next to the pipe wall, it will vibrate more readily. By detecting differences in the vibration characteristics of the pipe wall, variations could indicate the presence of a void in the fill. The investigation and implementation of this technique is the subject of this research.

To test the viability of this concept, a brief test was conducted on a corrugated metal pipe (CMP) under a roadway. The pipe wall was excited by tapping it with a hammer at several locations and recording the sound. Where the pipe was completely covered by fill, the sound produced was a uniform thud. At the end of the pipe, where it protruded from the soil, the sound was markedly different, having a ringing quality. In the lab, a spectral analysis of the recorded sounds showed marked differences between the two areas. This preliminary testing suggested that further investigation was justified. Application was made for a patent titled, "Void Detector for Buried Pipelines and Conduits Using Acoustic Resonance." In May 2002, U.S. Patent Number 6,386,037 was granted.

Void Detection System Requirements

When tests suggested that an acoustic void detection system might be possible, the requirements were outlined:

1. The device must operate on the inside of a pipe to be capable of impacting it.

2. Impacts must be made at several locations around the circumference to test the entire pipe.

3. The device must be capable of recording the location of each impact so that the pipe response can be correlated with the location of the impact.

Research Project Plan

A plan was developed for proof of concept testing. The goals included: (1) assess the current state of void detection techniques, (2) perform laboratory testing of the acoustic resonance technique to evaluate its viability, (3) develop a device suitable for field testing a conduit, (4) perform field testing using the device, (5) confirm field test results, and (6) complete development of the system to make it viable for field use.

Developing repair techniques for voids in the fill was not included as part of the research effort. Several repair options are available that can be used to repair voids once they are located.

To accomplish the project goals, a list of tasks was established:

a. Conduct a literature search for work on subsurface void detection techniques.

b. Build a model in the laboratory for use in evaluating the viability of the technique and the test apparatus.

c. Perform tests on the laboratory model to confirm the ability of the technique to detect voids under various conditions.

d. Design and build an apparatus capable of traversing the length of a pipeline while testing for voids.

e. Test the prototype apparatus in the laboratory model and modify as required.

f. Analyze the laboratory test data to quantify the performance and capabilities of the technique.

g. Test the apparatus at a suitable field site and confirm the test results.

h. Finalize development of the system to make it suitable for field use.

Project Constraints

To limit the scope of the project to a manageable size, two constraints were established:

(1) The type of conduit to be used for initial testing would be limited to CMP. While conduits through embankments are constructed using many different types of pipe, for the proof of concept, it was decided to limit the research to one type of pipe. By doing so, the effort and

resources could be concentrated on a complete evaluation of the technology rather than spreading resources thin to evaluate the technology on several different types of pipe. CMP is commonly used in this application and would be easily incorporated into a laboratory model. It was also considered to have the greatest chance of success because of its inherent resonant characteristics. If the system proves viable for CMP, testing can be expanded to include other types of pipe.

(2) A further constraint was the use of a single pipe size. It was assumed that an evaluation of the technology on one size could be extrapolated to other sizes. A 36-inch-diameter size was selected so that it would be convenient to work in, but not so large that it would be difficult to incorporate into a laboratory model. For the field test phase of the project, a conduit of the same size would be sought.

Literature Review

A literature search was conducted and resulted in a list of only nine citations. None of nine citations were specifically related to void detection using acoustic resonance methods. This was not surprising because the patent search would have found existing uses of the technique. The citations found could be grouped into three broad categories: (1) leak detection, (2) ground probing radar, and (3) acoustic emission. The usefulness of these technologies for this application has previously been discussed. The conclusion from the literature search was that no previous work employing acoustic resonance existed.

Laboratory Test Model

A laboratory model of an embedded conduit would first serve to provide a test bed for evaluating the viability of the technique and, second, for developing a system that could traverse a pipe and be capable of testing one in the field. The model would be constructed with areas having well-compacted fill and other areas having voids.

A 3-foot-diameter CMP, 15 feet long, was used as the conduit for the model. A wooden box was constructed that measured 8 feet wide by 6 feet tall by 12 feet long. The box was constructed using 2” x 6” framing lined with 3/4” plywood. The pipe was located 12 inches from the floor of the box and centered side to side. The box was partitioned into three test sections of 4 feet each and is shown in figure 1.

Figure 1.—Laboratory test model.

The box was filled with “roadbase” material in a way to provide several test conditions. The material was placed in 12-inch lifts in a moist condition, then compacted using a vibrating plate compactor. The first lift was installed, and the pipe was then inserted into the box directly on top of it. Subsequent lifts were added and compacted to bring the level to the middle of the pipe, taking care to ensure good compaction around the pipe. Partitions were then constructed at 1/3 points along the length of the box to define three sections. Each section was then filled to different heights to simulate various void conditions. The two end sections were used as references. The height of the fill in the left section was stopped at the mid-line of the pipe. The right section was filled to the top of the box, completely encasing the pipe in well-compacted fill. The center section was filled in various configurations to simulate several locations and sizes of voids.

Initial Laboratory Tests

Impact Tests

After completion of the model, testing was conducted on the pipe. At this stage, the best type of exciter had not been determined. Several options were considered. The most obvious was impacting with a hammer. Another possibility was some type of chain drag, similar to that used to detect disbonded areas in concrete slabs. An intense acoustic impulse was also considered. It was decided that for initial testing and evaluation, impacting the pipe using a hammer would provide an adequate data set for evaluation.

The first phase of the preliminary tests used several different types of hammers as impulse exciters. These included two different sizes of ball-peen hammers, two sizes of claw hammers, a dead blow hammer, a plastic-faced mallet, a rubber mallet, and a modally tuned impact hammer with four different tips. The impacts were made in the center of the left and right sections at the top of the pipe.

The impacts were evaluated qualitatively by ear. The audible differences between the two sections were easily discerned. The differences between steel-faced hammers and those with softer faces were also obvious. The qualitative assessment of which hammer produced the most suitable impacts concluded that the modally tuned impact hammer provided the best range of impact types and was therefore used for all subsequent testing. This hammer had the additional benefit that it is instrumented with a load cell and accelerometer, making it possible to quantify the magnitude of the impact to the pipe. Its interchangeable tips provided varying rigidities so that this factor could be evaluated as well.

Impact tests with the impact hammer were done and the results recorded using an omnidirectional microphone. Impacts were made using each type of hammer tip. The impacts were made at the top of the pipe, in the center of left and right sections, which modeled void and non-void conditions, respectively. The four hammer tips included soft rubber, harder rubber, nylon, and steel. The microphone was located in the center of the pipe within 12 inches of the impact location. The microphone, accelerometer, and load cell outputs were recorded using a data acquisition system at a 50-kHz sampling rate. Multiple impacts were made at each location with each hammer tip type. The data from each impact were recorded.

Data Processing

The response waveforms were examined in many ways to find the method that emphasized the differences between the void and non-void areas the best. The analysis showed that there was good correlation between the magnitude of the acoustic signal and that of the load cell and accelerometer. This made recording the load and acceleration signals unnecessary.

The responses for the different hammer tips were analyzed, and it was found that the harder the tip, the better the response. It was concluded that the sharpness of the impact from the steel tip gave a better excitation of the pipe structure.

The peak amplitude of the time domain waveforms correlated well with the void and non-void locations. The amplitude of the response was larger, and of longer duration, in areas adjacent to a void. This agrees with intuition—hitting something solid produces a dull thud, and hitting something that is free to vibrate produces a louder ringing sound. Figure 2 shows a comparison of the average of five impacts in the two locations.

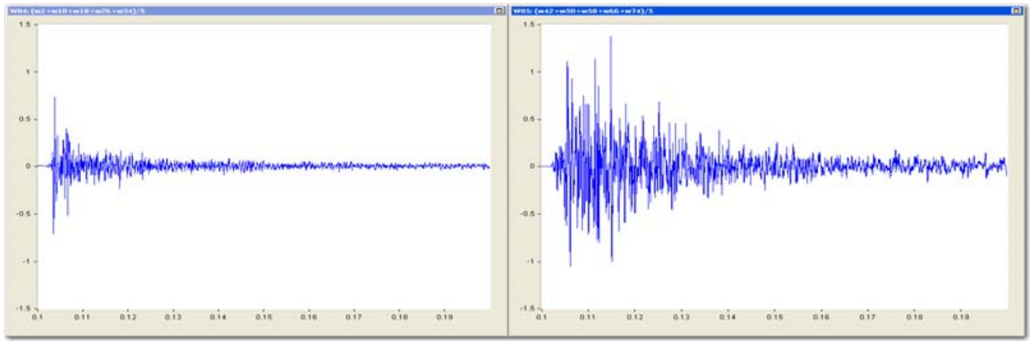

Figure 2.—Comparison of the magnitude of pipe response to hammer blows. The left graph shows the response for well-compacted fill, and the right graph shows the response for a void.

In addition to the difference in magnitude, the sound of the response was markedly different. A spectral analysis was made of the response signals, and this showed distinct differences between the void and non-void locations. Figure 3 shows the response spectrums for the two locations. The differences are easily observed.

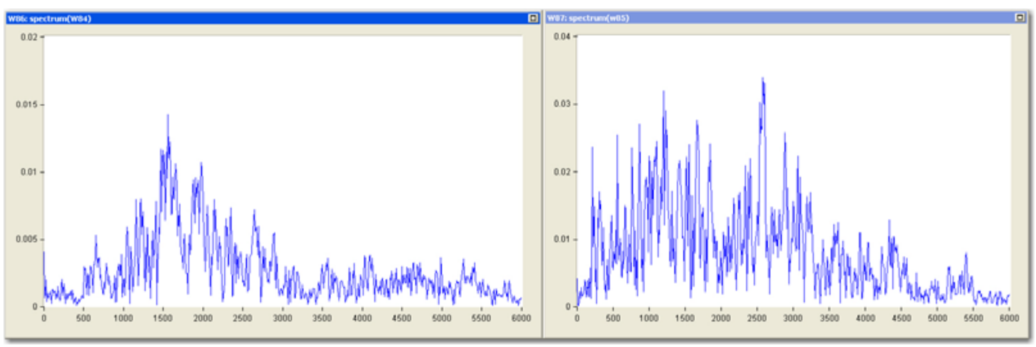

Figure 3.—Comparison of the response spectrums for well-compacted fill on the left and for a void on the right.

Initial Results

Based on the hammer impact tests, it was concluded that the technique was viable for the location of voids. These preliminary tests showed that the acoustic response of a CMP in well-compacted soil was easily distinguished from that of a pipe section adjacent to a void. The response differences could be detected using two different criteria: (1) the response magnitude and the (2) response spectrum. These results justified further work to determine if the technique was applicable for use in the field.

Pipe Testing Apparatus

All testing to this point was conducted manually to obtain enough data to evaluate the technique. Based on the promising initial results, the decision was made to proceed.

To provide a viable testing device for field use, it would be necessary to mechanize and automate the impacting and response recording functions. This phase of the project addressed this need in two ways. First, a device would be required that could traverse the length of a pipe. It would need to incorporate an exciter to stimulate the inside wall of the pipe at several points around the circumference. Second, a recording system would record the response of each impact and correlate it with the location of the impact.

Transport Device

Several schemes were considered for the transport device to move the exciter, listening device, and recording system through a pipe. The ideas considered included:

1. *A pull cart*. This would be a manual system and the easiest to implement. An operator would pull the device through the pipe and mark the location of suspected voids as they are detected by the apparatus. While easily implemented, it would greatly limit the size of pipes that could be tested. Even a 3-foot-diameter pipe would be difficult for a person to walk through for any distance, and it would also have significant safety considerations if the pipe were very long.

2. A similar scheme would use a cable to pull the cart through the pipe from one end. This would eliminate the human safety factors, but would have the problems of how to insert the pull-cable into the pipe and how to negotiate corners.

3. Remotely operated, self-propelled pipe crawlers are currently used by Reclamation for visual inspections of many types of conduits. These crawlers are equipped with video cameras for visual inspection and can be steered around corners. This type of device could bring a pull-cable through a pipe or could be the platform to which the test equipment would be mounted.

The limitations of the first two options and the advantages of the pipe crawler made selection of the third option obvious. Several key features were defined:

1. The ability to operate in several sizes of pipe. While this system was to be used specifically for verification of the concept in a single pipe size, 36-inch diameter, it could eventually be incorporated into a field-deployable system that would need to adapt to several pipe sizes.

2. The ability to negotiate slopes and turn corners.

3. Remote control of the device from outside the pipe. A 500-foot range was considered adequate for the initial testing.

4. An onboard video system to assist the operator in operating the crawler and to provide visual pipe inspection capabilities.

5. The system should have waterproof components.

A pipe crawler meeting the above requirements was purchased and is shown in figure 4. It can be configured to operate in pipes as small as 8 inches in diameter and as large as 36 inches in diameter. It employs two rubber-tracked crawling units with heavy lugs on the tracks. The unit is electrically powered and controlled through a 500-foot umbilical cable that is pulled behind the unit. The remote control box allows the operator to control the crawler’s speed, forward and backward movement, and turning. A separate control box is used for the integral camera unit and lighting system. The camera controls include lighting intensity, camera focus (manual or automatic), zoom, and camera direction. The camera is fully articulated and can be turned to look in nearly every direction both in front of and behind the crawler.

Figure 4.—Pipe crawler with integral video camera and lighting system

Pipe Exciter and Response Recording System

With the transport system selected, design was started on a system to excite the pipe and record the response. The exciter system and instrumentation package would be mounted on the crawler. The size of the package would be mainly limited by the pipe in which it would be used. For the prototype system, the size was not a major constraint because of the 36-inch diameter of the pipe. If the system proved viable, the size and configuration could be adjusted to accommodate other pipe sizes. Weight, also, was not a major consideration; the crawler is very strong, and more weight provides better traction.

The system is comprised of four main components: (1) the pipe exciter, (2) a response transducer, (3) a pipe distance transducer, and (4) the response recording system.

The package would be subject to the environment on the inside of the pipe. While the crawler is fully submersible, it was not considered necessary that the exciter and instrumentation meet this standard. Flowing and standing water would typically be in the bottom of the pipe, and the package could be configured to stay above this. Initial plans were to use a laptop computer to provide the necessary control and recording functionality; however, the pipe environment would not be compatible with a laptop PC. Since the crawler required an umbilical cable for its power and controls, it was decided to locate the response recording system with the crawler controls outside the pipe. Locating it there would give the added advantage of being able to monitor the progress of the test and proper operation of the exciter/response system. Two additional umbilical cables were run with the crawler cable—one for the analog microphone signal and one for all digital signals and power.

Pipe Exciter

The preliminary testing found that a steel-tipped hammer gave the best impact. The pipe testing apparatus would need to be equipped with a system that would provide hammer-type impacts at several locations around the circumference of the pipe while it is moving through the pipe. Electrical, pneumatic, and spring-loaded mechanical devices were considered. It appeared that electrical solenoids would provide the required sharp impulse and would be easily implemented. An array of eight solenoids around the circumference of the pipe, one every 45 degrees, would provide good coverage for a 36-inch pipe. Smaller diameter pipes would require fewer impact locations.

Response Transducer

As described earlier, the initial tests used a microphone to "listen" to the response of the pipe. While this appeared to be the transducer of choice, other options were considered.

Any transducer that could measure the vibration of the pipe wall, or the sound generated by it, would be suitable. Accelerometers, eddy current probes, optical displacement transducers, and others were considered, but rejected, because of implementation difficulties or cost. The need to make measurements on an undulating surface while in motion eliminated most options.

In the end, a microphone was selected as the best compromise for measuring the response of the pipe. It would be mounted in an acoustic microphone suspension to isolate it from the mechanical noise generated by the crawler. A preamplifier for the microphone would be mounted on the crawler to ensure an adequate signal is transmitted back to the data acquisition system through the dedicated umbilical cable.

Pipe Distance Transducer

Determining the location of the crawler in the pipe is critical for knowing the location of suspected voids. As response records are recorded, they must be annotated with the location in the pipe at which the impact occurred. A rubber-tired wheel mounted on a rotary optical encoder was selected. The wheel rides on the bottom of the pipe and turns the encoder. The encoder generates electrical pulses that are counted. The pulse count correlates directly to the distance traveled.

Response Recording System

The initial testing used a digital audio tape recorder to record the pipe response sound. After testing was completed, the tape was played into a data acquisition system for processing by a computer. A better solution is to connect the microphone directly to a data acquisition card in a laptop computer, thereby eliminating the intermediate tape recording. Further, the data acquisition card also counts the pulses from the distance encoder for location information. A digital I/O card in the PC controls the exciter solenoids.

A laptop computer was configured as described, and software was written in LabVIEW to control operation of the pipe excitation and response recording system. To conduct a test, the crawler is started in motion. The PC operates the solenoids and records the responses. Each solenoid is operated sequentially, and the response from the microphone is recorded at a rate of 50,000 samples per second. The encoder count is converted to distance and is stored with the digitized response and solenoid number in a data file. A delay between excitations prevents cross-contamination of the response records. The pulsing and data recording runs automatically once started, leaving the operator free to "drive" the crawler. When the desired pipe length has been tested, the data acquisition system is stopped and the crawler is backed out of the pipe.

Prototype Testing

A prototype system was assembled as shown in figure 5. The prototype was configured to operate in the laboratory test model described above. Figure 6 shows the system in the pipe and ready for testing.

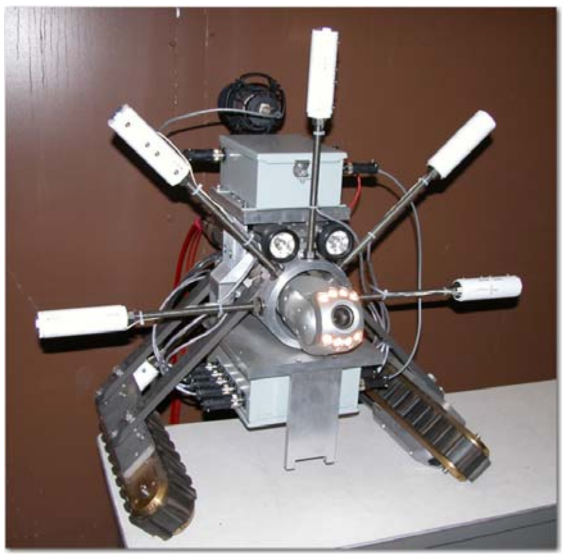

Figure 5.—Front view of the prototype system.

Figure 6.—Prototype system in the pipe model.

The crawler traversed the pipe in the laboratory model as expected. Adjustment of the exciter solenoids proved to be critical. The distance between the end of the solenoids and the pipe wall was important because the limited travel of the solenoid plunger would not impact the bottom of a trough in the corrugated pipe if it was not adjusted properly. The intensity of the impact varied depending on where the plunger impacted the pipe. If the impact was perpendicular, the impact was more intense. If the pipe wall was at an angle, the intensity was less. This did not appear to affect response characteristics adversely.

As described previously, the model could be configured to accommodate several void and non-void conditions. Data were collected for multiple runs of each of eight configurations.

After testing, a re-design of the exciter solenoid housing was undertaken to allow it to follow the contour of the pipe wall. Figure 7 shows the revised configuration. A wheel follows the pipe wall to keep the end of the solenoid a fixed distance from the wall.

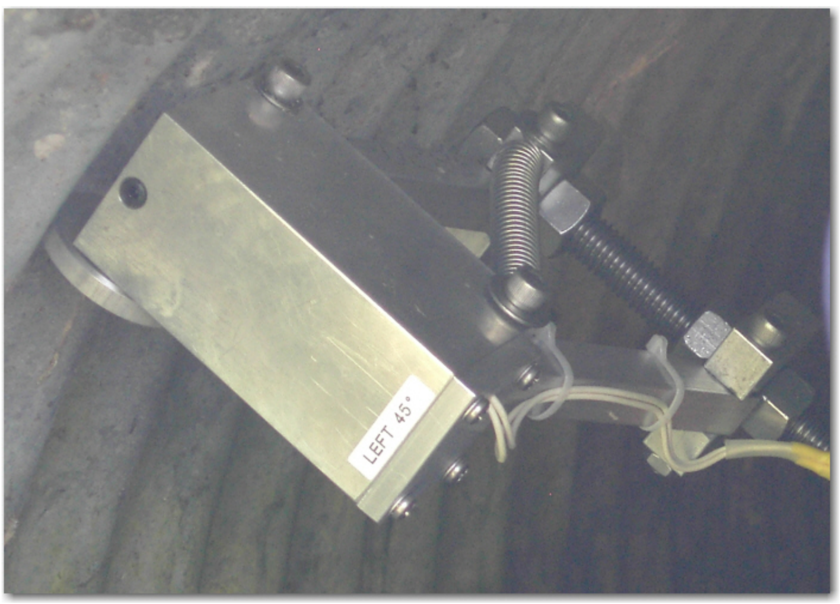

Figure 7.—Revised exciter solenoid assembly with pipe-following wheel.

Field Test

From the start of the project, an effort was made to coordinate with Reclamation's video inspection team to find a suitable site for field testing the pipe crawler. It was hoped that we could coordinate with this team on a joint field test. The ideal test pipe would be a CMP of the same diameter as our lab model.

When a pipe of the desired size was found, a field test was planned, although work on the test and data analysis software was ongoing. It was expected that a field test would be beneficial to work the bugs out and suggest areas for improvement. The data collected would be analyzed after the analysis software was complete.

The test pipe was located at a small dam in South Dakota. Information about the site indicated that the outlet works pipe was a 36-inch-diameter CMP, 50-100 feet in length. On arrival at the site, it was found that the pipe was actually 30 inches in diameter. With some difficulty, the crawler was modified onsite to allow it to allow it to operate in the 30-inch-diameter pipe.

Much was learned from the field test from the logistical standpoint. First, the crawler could be reconfigured to accommodate the smaller pipe size. Second, access to the outlet of the pipe made insertion of the crawler into the pipe very difficult. The pipe outlet was in a small ravine and had a continual flow of water. The end of the pipe was above the ground, with 18 inches of standing water below it. The weight of the crawler, the sloping ground on each side of the pipe, and the standing water at the end made inserting the crawler into the pipe very difficult. A hoist system was needed to help position the crawler for insertion into a pipe.

The subject pipe appeared to have been fabricated from pieced together scraps of corrugated metal. Instead of the expected continuous pipe with a joint every 20 or 30 feet, this pipe consisted of pieces of CMP that had been riveted together at random intervals and in random positions around the pipe. This presented a problem for the exciter solenoid assembly. The edges of the patched-in pipe pieces and rivets were perfect for catching on a solenoid plunger or the whole assembly. This happened numerous times and resulted in damage to one of the exciter arms and caused the crawler to become stuck at one point.

The third difficulty was the amount of water running through the pipe. It was expected that water would be present; however, the distance-measuring encoder was not able to withstand the amount of water it encountered. Soon after testing started, the encoder quit working.

While the data collected from this field test were of little use, the practical experience gained from operating in a field environment was very valuable. The problems encountered suggested modifications to the system that should make future tests more successful.

A second re-design of the exciter solenoid assembly was undertaken to minimize the potential problems with pipe surface variations. The new design is shown in figure 8. The size of the follower wheel is larger to allow it to roll over larger obstructions. The solenoid plunger impacts the follower wheel rather than the pipe itself, which will prevent it from binding on obstructions in the pipe. The impact energy is effectively transferred through the follower wheel into the pipe.

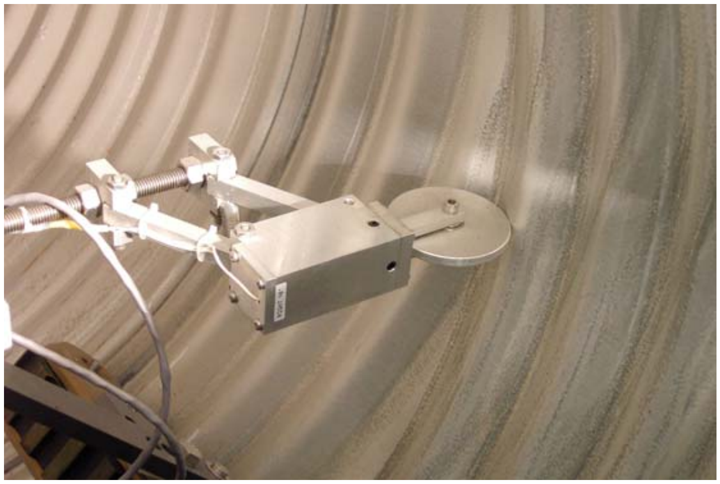

Figure 8.—Second revision of the exciter solenoid assembly.

Response Analysis and Data Presentation Software

The most critical part of the system is identification of suspected voids from the acoustic response records of the pipe. All initial testing relied on manual analysis of the test data. Once the crawler system was operational, the body of test data generated from testing the laboratory model amounted to thousands of data files. Manual analysis of this quantity of data was not possible. The data set from the laboratory testing, while large, would not compare to the quantity that would be acquired during a field test.

Three aspects of data handling needed to be addressed: (1) refinement of the algorithm used to identify suspected voids, (2) presentation of the data in a useful fashion, and (3) automatic data file processing.

Analysis of the Response Data

Early testing and analysis showed that the spectral analysis of a response record had features that could be used to identify a void. After the test apparatus became operational and a larger body of data was available, a second look at the data analysis algorithm was undertaken to ascertain if a better identification method could be found. DADiSP software was used to test various analysis techniques and algorithms. After looking at a number of techniques with several data sets, spectral analysis still appeared to give the best results. Specifically, the power spectral density (PSD) was used. Before the PSD is computed, the response waveform is normalized to the peak value of the record to reduce the effect of variations in the magnitude of the impact.

Data Presentation

The biggest problem with the system is the quantity of data it generates. A single run through a 20-foot pipe generates a response spectrum for each of eight solenoids for every foot of pipe length. Visually comparing 160 PSD plots is impractical. Various types of plots were tried. An analysis and plotting program was written in MATLAB to display the PSD graphs for each solenoid versus distance in a waterfall format as shown in figure 9. This display format provides a useful presentation of the data that highlights the contrast between void and non-void responses.

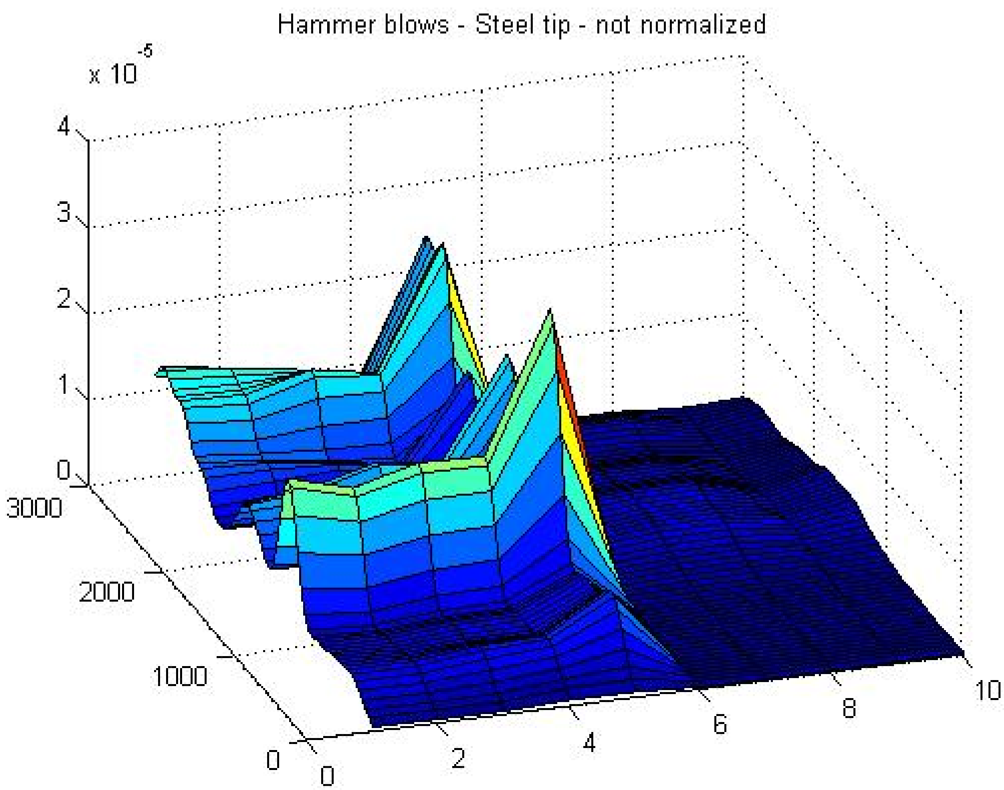

Figure 9.—Surface plot of hammer blows. The X-axis is the hammer blow number, the Y-axis is the response frequency, and the Z-axis is the response magnitude. Hammer blows left of blow 6 show a void, and blows 6–10 show well-compacted fill.

Rotating the plot of figure 9 to give a top-view perspective gives an intensity plot that is also an effective presentation of the data. This view is shown in figure 10.

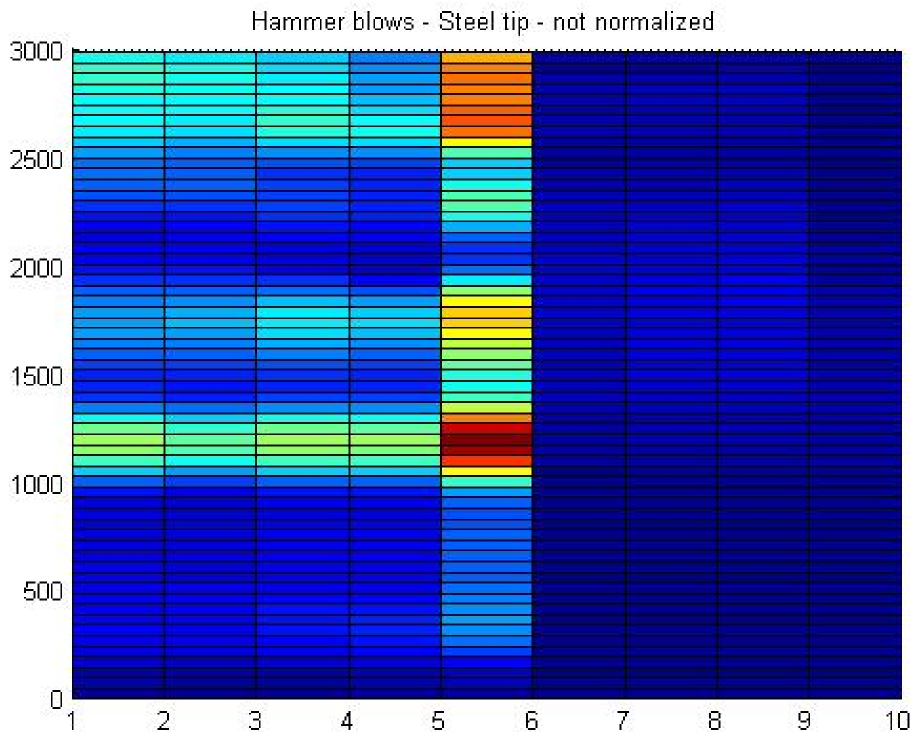

Figure 10.—Intensity plot view of the data set of figure 9. The X-axis is the hammer blow number, the Y-axis is the response frequency, and color is the response magnitude.

With this automated data analysis and presentation capability, it was possible to examine and compare the pipe response throughout its length. This "picture" of variations in the pipe response made it much easier to pick out anomalies that could make identifying suspected voids easier. With these improved tools, a more comprehensive look at the laboratory test data was conducted. This analysis showed much inconsistency in the identification of voids. It was concluded that at least part of this could be attributed to the fact that the set of test data had been acquired before refinements were made to the exciter solenoid assembly. It became obvious that it would be necessary to step back and do more laboratory tests to refine the analysis and identification algorithm.

A new model was designed, similar to the first, but somewhat larger. In addition to the test conditions the first model could simulate, the second model was designed to provide a section that could simulate air-filled voids, water-filled voids, and saturated soil. Construction of this model has been completed, and testing will start soon.

Conclusion

The concept of listening for voids while tapping on the inside of a pipe sounds simplistic; however, investigations have shown that this technique holds promise for use with CMP. Characteristics have been identified that can be used to detect the presence of a void in certain situations. A pipe crawling system has been developed for transporting the test equipment through a pipeline and making measurements as it travels. Continued work is being directed toward refining the identification and data presentation algorithms with the goal of making the system into a viable tool for field use. A further goal is to extend the applicability of this technique to other types of pipe materials.

LAST PRINTED ISSUE

This *Water Operation and Maintenance Bulletin,* No. 225, is the last to be printed in paper form. Since December of 1952, the bulletins have been printed and distributed, but in response to user requests, all future articles will be Internet based only.

Our Web site is still evolving, but all issues will be posted in Adobe Portable Document (PDF) format at <**http://www.usbr.gov/pps/WaterOandMBulletins**/>. The Adobe Reader program can be downloaded free of charge from this site.

We are currently updating the Bulletin Subject Index to show the latest topics, and we hope to have this accomplished soon.

We appreciate your use and comments throughout the years.

Sincerely,

Jerry Fischer
Managing Editor (now Bill Bouley)

We are going to the Internet!

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