

PARADIGM SHIFTS IN MONITORING LEVEES AND EARTHEN DAMS: DISTRIBUTED FIBER OPTIC MONITORING SYSTEMS

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ABSTRACT

Earthen embankments including levees, tailings dams, and earthen dams present many challenging problems for Civil Engineers, particularly in verification of their structural integrity and capacity, operation and maintenance (O&M), inspection, and safety. The sheer size and scale, age, and uncertainty of materials in these sometimes mammoth structures, all combine to present a difficult array of parameters for the levee professional to navigate when analyzing a new or existing levee or dam.

To make things more difficult, there is an ever growing number of assets and lives these structures protect downstream or in the “flood plain,” and more and more emphasis is being placed on the vulnerability of these structures. Also, in the wake of flood disasters associated with Hurricane Katrina and others, a complex regulatory environment has emerged; requiring engineers to certify structural and geotechnical fortitude, and levee and dam asset owners and engineers are exposed to more liability than ever.

Recent advances in instrumentation technologies and applications are providing new ways the Civil Engineer examines these structures, and present engineers with a set of monitoring tools never thought possible. Distributed fiber optic technologies create sensors that are of scale and size to finally match the dam or levee, and present an interesting, reliable, cost effective way of monitoring these structures.

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THE CHALLENGES PRESENTED BY EARTHEN LEVEES AND DAMS

Levees

A levee is a natural or artificial slope or wall to regulate water levels. It is usually earthen and often parallel to the course of a river or the coast. Artificial levees are made of many different materials, but are generally made of soil or earth including organic and inorganic materials with varying particle sizes and geotechnical properties. Many levees are constructed in areas that provide compressible, weak foundations. In most levees, due to their large size and age, little information is known about their construction, materials, or structural capacity.

Levees are critical components in flood protection and resource management throughout the United States and the world. Heavily populated and developed portions of the US` rely on these systems, and as evidenced by Hurricane Katrina, failure of these structures can result in heavy financial tolls, property damage and the loss of life. According to the American Society of Engineers (ASCE) 2009 Report Card on Infrastructure:

LEVEES D-

More than 85% of the nation's estimated 100,000 miles of levees are locally owned and maintained. The reliability of many of these levees is unknown. Many are over 50 years old and were originally built to protect crops from flooding. With an increase in development behind these levees, the risk to public health and safety from failure has increased. Rough estimates put the cost at more than \$100 billion to repair and rehabilitate the nation's levees.

Levees have many different failure modes as depicted in Figure 1. Many of the most common failure modes have indicators (erosion, seepage and/or settlement) that are, for the most part, undetectable to the human eye during inspection. Relying on visual inspection, weaknesses in these structures remained undetectable, until a catastrophic failure occurs during a storm or surge event.

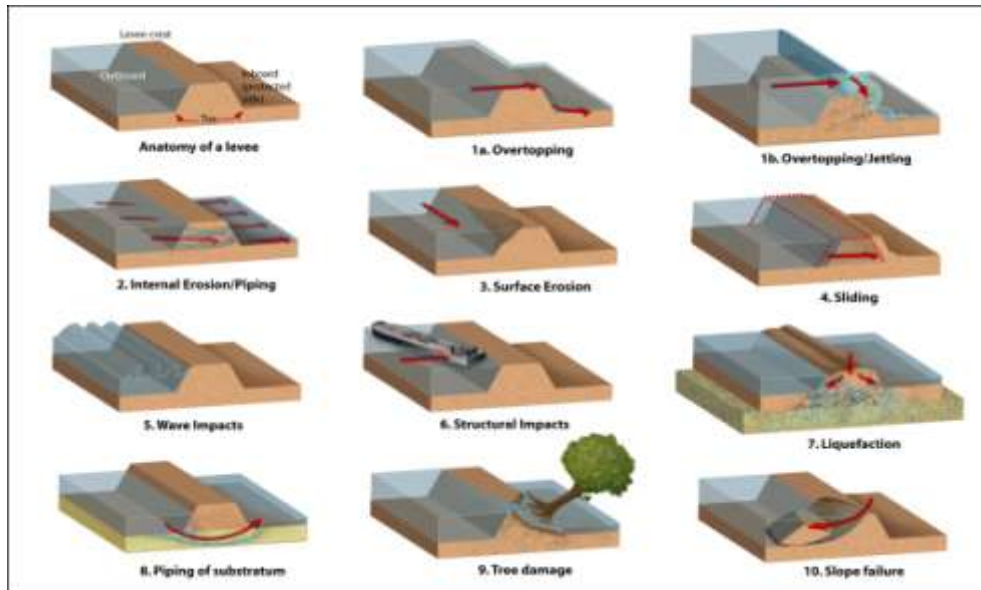


Figure 1 - Examples of Levee Failure Modes, Graphic by the National Science Foundation (all of these failure modes are detectable with the DiTEST®)

Earthen Embankment Dams

Earthen embankments, including tailings dams, are typically created by the placement and compaction of various compositions of soil, sand, clay and/or rock. Earthen dams can have many thousands of square feet of surface area, and can be mammoth in both height and length.

Typically, an earthen dam will include spillways designed to handle the 500-year storm event. Sustained hydraulic force and pressure outside of the spillways can cause eventual failure of the dam. Additional sources of failure for earthen embankment dams include:

- Weak foundations,
- Seismic events,
- Excessive water level and rising rate,
- Overtopping,
- Piping,
- Slurry waves,
- Silt pressure.

TRADITIONAL LEVEE AND EARTHEN DAM TOOLS: VISUAL INSPECTION, SURVEYING AND DISCREET SENSORS

Historically for levees and earthen dams, O&M has relied heavily on visual inspection and surveying. Visual inspection and surveying are vital parts to any levee management program, and neither can be replaced; however, current inspection practices have the following limitations:

- Levees and dams are too large in scale (many miles long, very wide, very tall) to thoroughly inspect visually and consistently survey
- Differential settlement, structural weakness, and warning signs can be nearly impossible to detect with visual inspection
- Many structural failures originate underground with no surface changes
- Many levee “warning signs” are not intuitively obvious and difficult to detect even by the most well trained inspectors

Traditional Discrete Instrumentation

Many different types of discrete instrumentation for dams have been available to Civil Engineers for many decades. These systems incorporate many different types of technology, and include piezometers, inclinometers, settlement plates, and others.

Levees traditionally have excluded sensors, but occasionally rely on traditional point sensors for limited data gathering for a specific location or to investigate a specific defect. For such extended structures, deciding where to install point sensors becomes a challenge by itself. Since defects and failures can be located anywhere, the real challenge of instrumentation becomes the localization of such events, rather than their quantification. Installing a large network of discrete sensor, as hypothetically shown in Figure 2, is not a viable approach.

Earthen embankments and tailings dams have traditionally incorporated galleries of instrumentation, usually an array of point sensors, including piezometers, inclinometers, settlement plates, tilt, vibration sensors and others.

Rarely, if ever, are these discrete sensor systems incorporated into a real time warning system and rarely provide actionable data for O&M programs.

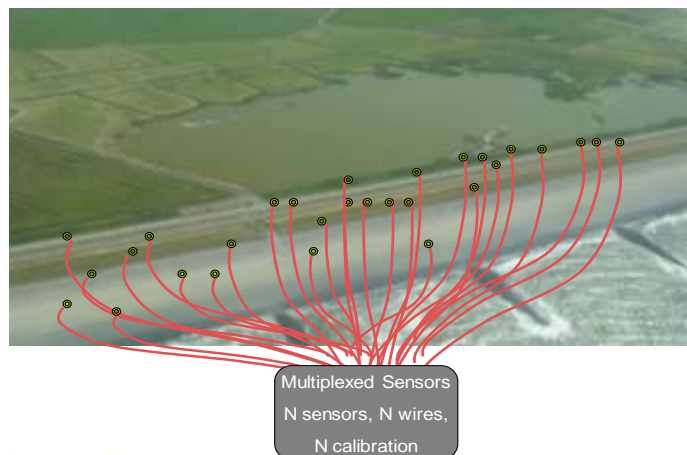


Figure 2 – Traditional Discrete Sensors. Discrete monitoring systems are unreliable for maintenance and inspection systems, and generally considered unreliable as warning systems.

TECHNOLOGICAL ADVANCES

Through advances in structural health monitoring (SHM) and civil engineering instrumentation, new monitoring technologies and applications have emerged that are challenging the traditional methods engineers use to evaluate, inspect and levees and earthen dams. New and versatile monitoring systems are capable of diagnosing levee and dam problems before they are visible to inspectors and before catastrophic failures occur. The fiber optic distributed strain/temperature (DiTEST®) monitoring system can provide actionable operation and maintenance (O&M) information, provide powerful inspection and assurance tools, and provide warning to engineers and asset managers about failures before they occur, increasing safety for all dam and levee shareholders.

Until recent developments in fiber optic technologies, the sheer length, scale and magnitude of the levee or dam made monitoring systems ineffective. Engineers in charge of instrumenting these extended structures were faced with the age old problem of “where to place the sensors.” Placing traditional, discrete sensors made monitoring more akin to locating a needle in a haystack, and was seldom considered a cost effective method. Now engineers have cost effective tools to seamlessly monitor levee segments in lengths up to twenty miles, with no breaks or gaps, allowing 100% coverage. These distributed sensors allow engineers to both localize and quantify movements and leakages. In addition, earthen tailings dams can be hundreds of feet high, and also can share this same coverage.

Levee owners, engineers and managers have greater risk and liability than ever, stemming from the Federal Emergency Management Agency (FEMA) Levee Certification Requirementsⁱ³ and limited financial resources. No longer is it acceptable for civil engineers to provide certification for these structures using theoretical calculations and modeling, when hard empirical data is available with relatively inexpensive means. Levee professionals are ethically required to rethink these assets, and deploy reliable systems to safely manage these critical structures.

³ Federal Emergency Management Agency (FEMA) Certification Requirements

Levee owners are required to seek accreditation (certification) of their levee by providing FEMA the documentation and data as outlined in 44 CFR 65.10. 44 CFR 65.10 specifically requires levee owners to demonstrate adequate structural design and that operation and maintenance (O&M) systems are in place that provide reasonable assurance that the levee offers protection up to a base-flood event.

All levees must be certified by a registered professional engineer or a federal agency responsible for levee design. FEMA, for the purposes of the National Flood Insurance Program (NFIP) will only recognize in its flood hazard and risk mapping efforts those levees that meet, and continue to meet, minimum design, operation, and maintenance standards that are consistent with providing protection from the base-flood.

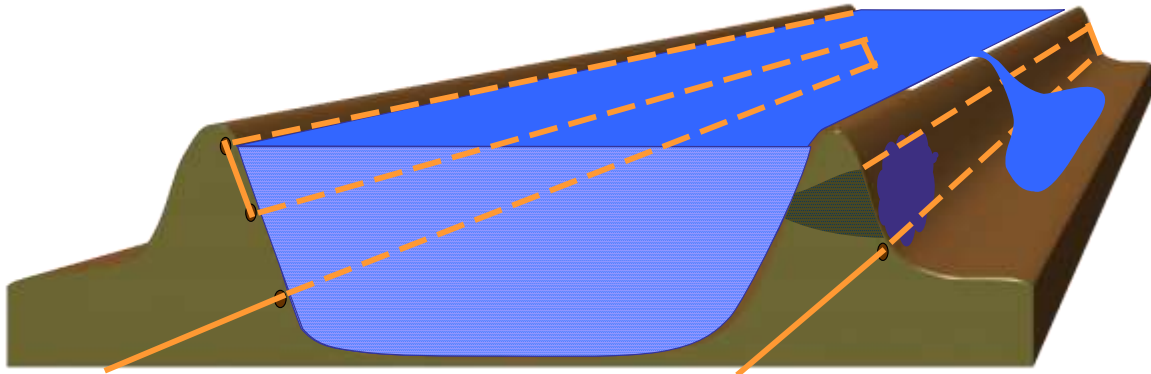


Figure 3[h2] – Distributed fiber optic sensors (depicted in orange) are installed along a levee at different heights. Multiple cables can be interconnected for a single chain of sensors. Sensors identify strain produced by local settlements or other movements and temperature sensors detect leakages.

Distributed Monitoring Systems

A distributed fiber optic monitoring system consists of one or more unique sensor cables (fiber optic) and one unique readout device (see Figure 4). The area of coverage can be up to 20 continuous miles in length with one split system. The sensor cables can easily be deployed either during construction or after construction, and is possible to retrofit on existing structures. The readout system can monitor strain and temperature, along the entire length of cable, and is able to detect the following failure modes:

- Structural movement or failure,
- Overtopping,
- Under levee seepage[h3],
- Through seepage
- Piping (internal erosion),
- External erosion,
- Differential settlement, and
- Landslides.

Unlike the “discrete monitoring systems” there are no longer coverage “gaps” between sensors, providing seamless coverage. The system collects data day and night, 24 hours a day. Using current internet technologies, effective warning systems can be integrated into current management methods.

Sensor cables can be retrofitted on existing levees and dams by means of trenching the cable into the face of the structure, on either the upstream or downstream side. Often trenching is only necessary to a depth of protection for the protection of the cable itself, and can be as little as 4” deep.[h4] The location of the cable will depend on many different factors that must be carefully considered by the engineer. These considerations are site specific and vary greatly, but the following considerations should be taken account in any design:

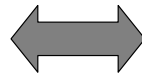
- Minimizing impact to the structural integrity of the current earthen system
- Rodents, insects and vandalism
- Maximization of potential early detection locations

- Accessibility of installation location
- Optimization of the location of the data collection system

Location of the sensor cable is critical for detecting both strain (settlement) and seepage (temperature change). With regard to strain, the sensing cable must be placed where changes in the shape of the structure will physically occur, directly transferring strain to the cable. The same is true for seepage. The sensing cable must be placed in a location where water is moving around the cable, creating trends in temperature directly to the cable.



○ One fiber optic sensor provides thousands of point sensors.



Remote monitoring

Figure 4 – Thousands of Sensors in One Continuous Cable

Recently, in conjunction with a European textile consortium, products are being developed with distributed sensors woven into geotextiles. Based on the principle similar to the way a spider uses its web to detect local movement, textiles offer an interesting possibility for enhancing the localized coverage area of fiber optic sensors. Geogrids and “geotextile sensing tubes” with fiber optic sensors, in some cases woven directly into the geotextile, are presenting many new application possibilities in civil engineering and elsewhere.

System Focus: O&M, Inspection and Surveying, and Warning System

O&M: A levee or dam is in many ways like a chain, only as strong as its weakest link (or lowest point). An individual levee can be many miles long and can meander through urban, rural, remote, inaccessible and sometimes dangerous areas. Vegetation, sheer size and scale, can limit levee access and mask indicators from even the most well trained inspectors. Areas of structural weakness, even when relatively obvious, are difficult to identify when looking directly at these areas. The DiTEST® [h5] system can not only detect structural failures, but also detect very slight differential settlements that can be considered as early warning of future issues.

Through algorithms based on strain detection, differential settlement locations can be detected along levee segments up to 20 miles in length, with a special resolution of 2 linear feet, with actual differential settlement values (elevation changes) as low as 2 mm. These systems can actually deploy coverage of longer or shorter lengths of levee, depending upon cable configuration and levee monitoring requirements. Over time, the DiTEST® system will be able to help engineers predict the ongoing rate of differential settlement in remote areas, and verify elevation changes with empirical data from the specific location.

Through algorithms based on temperature change, the DiTEST® system can detect water movement underneath the surface of the levee. Water movement can indicate piping, erosion, and other warning signs that the levee is moving, prior to strain indicators being triggered.

The DiTEST® system can be programmed to generate work orders based on detection indicators that will allow operations and maintenance crews to respond to areas while maintenance requirements are relatively minor, and repair these areas before catastrophic failures (and costly repairs) begin.

Inspection and Surveying: No monitoring system will ever replace visual inspection and surveying required by a properly maintained levee. Monitoring tools can only work to enhance these necessary processes, and help confirm and validate these management systems.

The DiTEST® system can be programmed to send alerts to inspection and surveying crews when changes occur, allowing them to focus their efforts on problem areas and areas where changes are occurring.

Warning System: Never before has technology been available that will allow seamless, definitive coverage of many miles of levee structure. With sensitive data gathering, and powerful algorithms, every failure mode in figure 2, or combination thereof, is detectable with this system. And, perhaps even more powerful, is the system's ability to detect failure warnings before the failure actually occurs.

DiTEST® System Overview

The system is comprised of the following components:

- Fiber optic cables, up to 20 miles in length (possibly longer for certain applications)
- DiTEST® readout unit
- Windows based PC with the DiTEST® software system
- DiVIEW software (Data management and mapping tools)

The DiTEST® is a unique tool for the evaluation of distributed strain and/or temperature over several miles. It is a powerful diagnostic instrument for the identification and localization of potential problems. It allows the monitoring of local strain and temperature at thousands of locations by means of a single optical fiber and in just one measurement. Its inherent high stability and self-referenced principle of operation allows on-line or off-line long-term monitoring of large structures.

The cable can be trenched directly in an earthen embankment (see figure 5), cast in concrete along an “I Wall” or “T wall”, or placed under an embankment before construction begins.



Figure 5: Vibratory plow installation, fiber optic strain and temperature sensing cables.

Other benefits include:

- Cable can be repaired with standard fiber optic splicing equipment, and can be as simple as a call to the local cable utility.
- Cable comes in many different forms with options on cladding for various environments.
- Fiber optic cables are impervious to static, eliminating false readings and background noise.
- Fiber optic cables do not attract or conduct lightning strikes.
- Fiber optic cables are intrinsically safe.

Technical Description: The DiTEST® is a laser-based measurement system using an optical scattering measurement principle within the sensing fiber: Stimulated Brillouin Scattering. It can operate using standard single mode telecommunication fibers as sensing elements with specially designed cables. Stimulated Brillouin Scattering is an intrinsic physical property of the fiber material and provides information about the strain and temperature distribution actually experienced by the sensing fiber. The local characteristics of Stimulated Brillouin Scattering are measured thanks to an innovative and highly reliable configuration developed by the Metrology Laboratory of the Swiss Federal Institute of Technology of Lausanne in the 1990's. This measurement technique relies on the use of a single laser source and is therefore totally self-referenced allowing periodic measurements without any preliminary calibration. The system can operate in

two configurations: loop (with both ends of the sensing fiber connected to the measurement unit) or single-ended (with a mirror at the end of the fiber). Multiple fibers can be automatically connected to the instrument through an integrated optical switch.

Through the use of optional range extenders it is possible to monitor distances of up to 60 miles. The system includes an industrial PC with LCD screen and internal hard-disc storage, allowing great versatility in terms of connections: LAN, wireless, remote control/configuration/maintenance. The integrated software is user-friendly and allows an easy setup of the parameter through the use of self-configuration wizards. Data retrieved from multiple measurements can be simultaneously displayed and compared on screen. When pre-defined warning levels are exceeded, the system can generate alerts, activate relays (optional) and the location of an event can be located on a map (see Figure 6). The system can operate interactively or in automatic mode, gathering data according to a schedule.

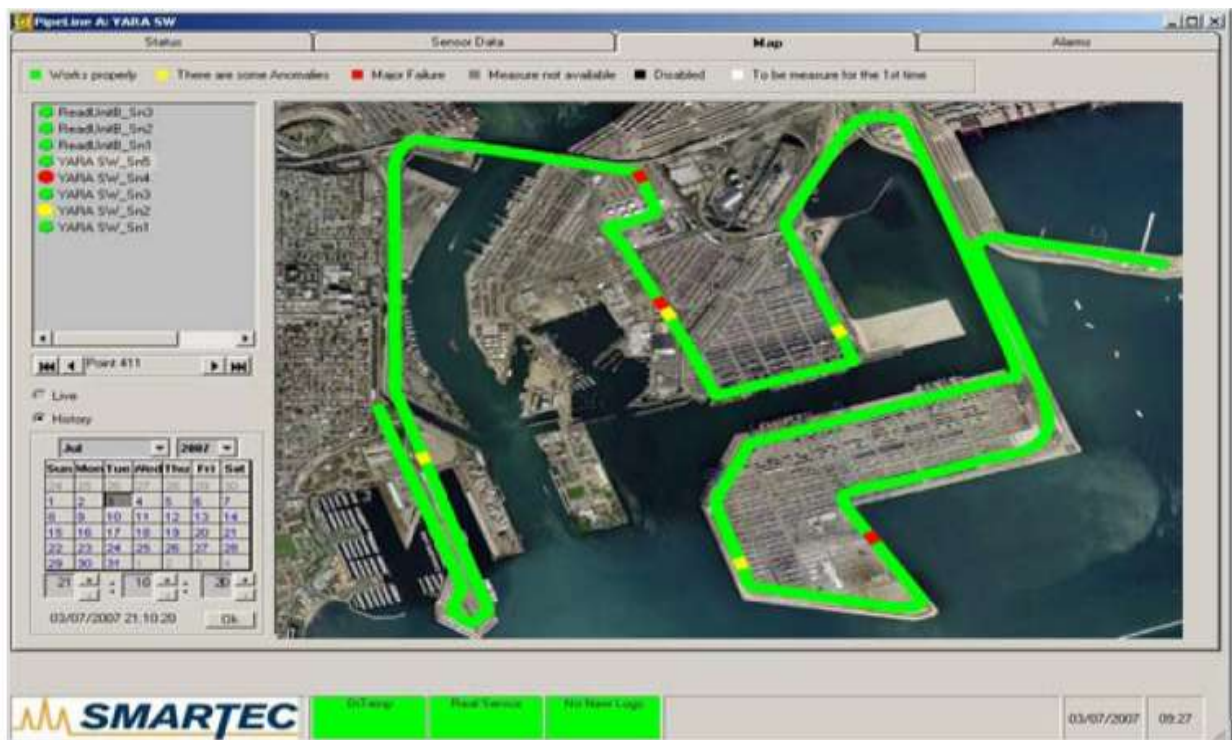


Figure 6 – Di-VIEW Data Management and Mapping Tool Example – Red and Yellow Warning Indicating locations that exceed warning levels.

Successful Civil Engineering Applications

While much of the potential for the distributed sensing system has been relatively unrealized by the dam and levee sectors, other sectors of civil engineering/monitoring have benefitted from the technology. While levee or dam systems may be considered new applications, the technology has been proven successful in many different and similar civil applications.

Pipelines have utilized the technology over the years, with many applications serving many pipelines in multiple countries. The detection cable can determine leakage in both gas and liquid pipelines through temperature change, and strain to determine other physical changes to the asset. Case studies of pipeline applications can be found in several locations, including the website <http://www.roctest-group.com/applications/pipelines>.

Bridges, both steel and concrete, have benefitted as well from the technology. Steel bridges have been retrofitted with the DiTEST® system to detect hairline cracking and micro-fissures in structural beams [h6]and deck elements. Concrete bridges have incorporated the system to measure internal responses from post-tensioning processes and long term monitoring considerations. Case studies of bridge applications can be found at <http://www.princeton.edu/~bglisic/>.

Sink hole monitoring is another application where the DiTEST® system has proven an effective detection system. On a remote site in the Midwest United States in 2010, approximately 2.5 miles of sensing cable was deployed to monitor a host of unpredictable earth settlement occurrences that were attributable to subterranean reductions in groundwater. Many obstacles to monitoring the settlement were identified including the large area of potential settlement, the relatively high occurrence of lightning, extreme temperature conditions, and the indigenous rodents in the area (mainly prairie dogs). A special textile buffering was designed by instrumentation engineers for these conditions, and also for installation by means of a mechanical trenching machine. The SMARTGeoTex Rope was produced to be located outside of the cladding, as seen in Figure 7. Smaller coils were required to meet installation requirements by the contractor.



Figure 7 – Production of sensing cable clad in SMARTGeoTex Rope

During field installation, the SMARTGeoTex was tested for continuity prior to backfill of the sensor with a continuity tester. The sensor was verified to be in working condition in the field, prior to placing backfill on the trench (Figure 8).

SMARTex Rope DiTest sensor , ER 21



Figure 8 – Onsite sensor verification prior to backfill placement.

CONCLUSIONS

As new monitoring tools emerge on the market, civil engineers entrenched in reactionary discrete sensor toolsets, must challenge and educate themselves to think in new ways to take advantage of remarkable, proven, readily available technologies. Potential structural failures associated with levee systems can now be detected in advance, and ethically, the burden of changing the current civil engineering mindset that surrounds these structures lies squarely on the civil engineering community as a whole.

Due to the scale and massive size of levee and dam systems, effective warning and monitoring systems have been unavailable for levee engineers, owners and stakeholders. With recent advances in fiber optic monitoring technology, and new applications in civil engineering, a new levee monitoring system has emerged that will provide effective, seamless coverage for identifying and localizing potential levee defects and failures. This technology, used with current levee practices, provides a tool for inspecting and supporting the levee certifying process, provides a tool for enhancing O&M procedures

and provides a reliable warning system for levee failure, thus increasing the safety of structures.

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