THE GROUND BENEATH OUR FEET: ENABLING SUBSURFACE SENSING

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ABSTRACT: Remote sensing using satellites, planes, and drones is a well-established technology which has been extensively explored and developed. However, for the most part, remote sensing data stops at the surface of the Earth. Information about conditions below the surface is difficult and expensive to obtain—yet it is very important. When the ground we stand on is unstable, we are in grave danger.

This paper reports on a technology which permits monitoring soil conditions to a depth of one to two meters below the surface. The focus of our current research is applying this technology to protect transportation infrastructure such as roads, rail and airport runways. Disruption of this infrastructure due to weaknesses in the supporting earthen foundation can cause severe economic loss and human hardship. However, at present there is no practical way to monitor the condition of these structures on a regular schedule. Subsurface degradation or cavities which form in the subbase are not detectable from visible symptoms. Techniques such as ground-penetrating radar, which allow indirect examination of subsurface structural conditions, are not appropriate for routine, repeated use by untrained personnel.

In this paper we describe a "smart" material that addresses this problem. This material, which we originally targeted for highway use, can also be applied below railway tracks, airport runways and levees. After including the material during construction or reconstruction, an inexpensive, easy-to-use sensor assembly is used to verify the integrity of the hidden earth subbase. Using this technology, disasters can be averted and expenditures for normal maintenance can be optimized.

We describe the theory and design of the material and sensor, and the computer processing used to create images of potentially hazardous regions. We then describe a simple setup we used for testing the material in the laboratory, and present the positive results of this testing. We also describe plans for the next stages of testing, which will require incorporating the material into a full-sized in-laboratory construction followed by an extended testing program under real-world conditions.

INTRODUCTION

Subsurface Remote Sensing

Remote sensing, in customary usage, refers to observation of the earth's surface from a distance, generally using reflected radiation. In many cases the radiation is reflected sunlight; in other cases it may be radiation which is actively supplied, as in Lidar, and it may be non-optical, as in various radar technologies. In general, however, the observations reveal the condition of the earth's *surface* (whether the surface is considered to be soil or treetops), or can penetrate the surface only slightly.

Detection of conditions below the surface is successful in only a few special circumstances. Heng Thung (Thung, 1994) used analysis of surface imagery to discover the history of the Angkor Wat hydrology system as indicated by subsurface remnants. In the Peruvian Amazon, leaves of canopy trees growing in abandoned oil spill locations were detectably different in color from trees in non-polluted areas. This difference permitted the use of optical remote sensing to discover subsurface spills from leaking oil pipelines (Fraser, 2016).

Ground penetrating radar and acoustic seismology use an alternative approach, where pulses of energy are applied downwards from the earth surface. Measurement of the reflected energy, together with the time delay in receiving the reflection, make it possible to acquire information about the earth structures beneath the instruments. The quality of the imaging is limited by the complexity of soil types and structures, and the resulting "imagery" can be difficult to interpret.

All of these traditional technologies have been based on ever more sophisticated sensing instruments. Although the sensors become more sophisticated, they are observing terrain which has not been augmented by any technology which assists in the observation. Recent developments in materials have changed the economics of electronic circuitry, to the point where it is practical to consider deliberately placing very large numbers of electronic elements in known positions, within constructions or beneath the surface. Subsequently, changes in their positions or behavior can be detected and used to form an image of subsurface conditions.

Subsurface Threats to Essential Infrastructure

Railways form a major part of any nation's infrastructure, and their construction and maintenance are a high priority for any country. Highways, likewise, are crucial to a nation's economy. In this paper we will refer to airport runways, highways, railway tracks, and river or ocean levees and dikes collectively as "roads".

The structure of modern roads has evolved gradually since the 17th century into a complex set of layers, whose details vary depending on the materials available, the environment, and the intended use. Well-known engineering principles provide a high level of confidence in the properties and stability of these structures.

However, all such constructions share a common weakness: they are not built with a rigid, self-supporting structure but depend for their support on the underlying ground. Despite the most careful design and the most exacting preparation, the ground behavior after the road has been completed is subject to forces and events which are known statistically but are unpredictable in detail. In particular, cavities and fractures in the underlying strata can develop due to floods, drought, gradual erosion, and other geological and hydrological forces. Leaks of fluids and foreign substances from landfills or hazardous waste dumps can also cause problems.

Subsidence of a railway track, which may not appear until it is put under load, can cause a train to derail, potentially resulting in serious injuries and great damage. The U.S has recently experienced several catastrophic accidents due to derailment of trains carrying fuel oil (Bowermaster, 2015). Structural weakness below an airfield runway or taxiway, if not detected, can cause ripples or sinkholes. If these were to appear when the runway is under heavy stress, such as when a plane is taking off or landing, the danger to aircraft would be extreme. A loss of strength in a dike can cause the dike to fail during a severe storm leading to property damage and possible loss of life.

The minimum implication of a failure such as shown in Figure 1 is a need for an expensive emergency repair, quite possibly during inclement weather since storms commonly trigger collapses due to pre-existing but undetected cavities or weaknesses in the subgrade. In some cases, the collapse may cause the facility to be closed requiring travel and shipping to be rerouted for an extended period.

Figure 1. Road collapse example. (photo from *123rf.com*)

CURRENT TECHNOLOGY

Surveys are periodically made on highways and runways to detect pavement distress. For railways, the staff are continually monitoring the state of the track. However, vulnerability due to subgrade or subsurface materials degradation is not related to visible pavement distress. Currently there do not appear to be any good means available to monitor for subsurface failures.

In this section we briefly review current technologies available for sub-pavement inspections, and highlight their weaknesses.

Geophysical Methods

Geophysical survey methods are used to evaluate geological conditions during the design phase, but their usefulness for subsequent maintenance of road works is uncertain (O'Flaherty, 2002). Typically they depend on physical manipulation of the region to be tested, for example by boring temporary holes. In any case these methods are expensive, require the use of specialist personnel, and cannot be applied over a wide area.

Seismic refraction is one such geophysical survey method (Daley et al., 1985). This methodology typically requires, at each location to be tested, a bore hole of several inches diameter filled with explosives. Approximately five locations per day can be tested.

2D resistivity imaging has also been used, especially for looking at possible collapsed mine shafts, and for karst regions. This methodology works on the principle that ground resistance changes when encountering a cavity. However, the nature of the change depends strongly on whether the cavity is water-filled. Also, this technique is only applicable in some soil types.

Measurement of flexible (typically asphalt, as opposed to rigid concrete) pavement structure is commonly done by subjecting the pavement at suspect locations to stress such as Benkelman beam, Dynaflect and similar falling weight deflectometers, to measure road deflections (Garber and Hoel, 2010). Although these methods can detect weaknesses, they are sufficiently time consuming and equipment-intensive that it is difficult to justify using them routinely.

All of the above methods require manipulation of the runway or road at the location to be tested, which limits testing to a small number of locations per day.

Radar and Other Non-contact Methods

Another category of methods uses equipment which does not require physical modifications to the road. Ground penetrating radar (GPR) is the most widely used.

The U.S. Federal Highway Administration (FHWA, 2011) says that by using GPR, highway engineers can assess subsurface conditions at a fraction of the cost of conventional methods, claiming that GPR systems can survey pavements quickly and with minimal traffic disruption and safety risks. However, users have found numerous difficulties in interpreting the GPR data (Cardimona, et al., undated). GPR produces a recording of patterns of dielectric constant changes beneath the measuring device. Interpreting this information requires pre-existing knowledge of the dielectric constants of all materials (both pavement and soil) which will be encountered during the survey. Use of GPR also assumes that the road itself is of consistent and continuous structure.

Lidar, which uses laser pulses to accurately measure elevation, is a possible approach to remote sensing of pavement conditions. It is true that lidar can detect pavement subsidence which is too small to be seen by the unaided eye. However, lidar is a difficult and expensive technology. Furthermore, the presence or absence of subsidence is not a strong indicator of subsurface problems.

Finally, all of the techniques described are looking for anomalies in the road structure and the underlying geology, rather than actual early-stage damage. This is a problem because such anomalies may or may not indicate damage. The existing technologies cannot in themselves distinguish between benign and threatening situations.

Active Monitoring

A recent approach that has shown promise uses fiber-optics-based sensors buried under pavements to monitor subsurface deterioration (Briançon, 2006). As cavities develop in the layer under the sensors, the weight of the layers above increases the strain on these sensors. This in turn changes their optical properties. However, these solutions require connection to power, specialized skills for installation and measurement, and are too expensive to be used over large areas.

OBJECTIVES

What is needed is a system which permits examining, or visualizing, the current condition of a road structure before the degradation of the structure becomes externally visible in the form of a subsidence or collapse. We would like this examination to be easy, fast, convenient, and not to require specially trained personnel. It should be possible to perform this examination routinely (for example every month or year) or to meet a sudden demand (for example, a realization that extreme weather or seismic activities have created a danger). The system must be convenient and inexpensive enough to permit monitoring for damage over a wide area such as an entire road or rail network.

The system we have designed meets these criteria.

SYSTEM OVERVIEW

Our damage detection system consists of a material, the smart geofabric, plus a sensor apparatus for monitoring and detection of subsurface failures.

The geofabric must be built into the road either inside or between pavement layers or above the subgrade. There is no requirement for physical access to the geofabric after construction and the fabric is entirely passive except during examination. An examination permits discovery of damage to the subgrade before damage becomes apparent on the surface through subsidence or collapse.

To examine the condition of the infrastructure, the sensor assembly passes along the pavement surface. For example, it may be attached it to a car or truck as shown in Figure 2. When the sensor assembly probes the fabric remotely, damage such as a tear or stretch becomes apparent. This damage implies possible damage to the underlying supporting earth. The pattern of damage can be shown as a synthesized image or automatically processed using conventional image-processing techniques. The sensor assembly should be constructed to detect potential failures across the full width of a road or road lane, or across the keel of a runway.

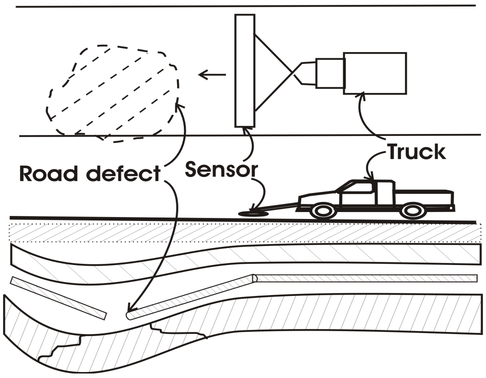

Figure. 2. Pavement and sensor assembly.

EXPERIMENTAL SETUP

As a laboratory test of this technology, we created a model of a single-lane road as reported earlier (Rudahl and Goldin, 2015). The present paper reports our work with a new, more sophisticated model using a simulated railway track and vehicle. The vehicle, sensor assembly and results display are shown in Figure 3.

The sensor, track, and cart for pushing the sensor along the surface are on the right, with simulated geofabric below the “track” The computer display on the left shows a blue circle where the sensor has found intact fabric and a brown circle where the geofabric is “damaged”. The geographic location of each damaged area detected is also shown (the yellow rectangles).

Our first proptoype used a sensor assembly which was manually stroked along a simulated road pavement, producing a motion which was quite unsteady and unrepeatable. The new version uses a sensor assembly mounted on the front of a standard robot cart running on a simulated track about 2 m long with a 11-cm gauge, and with a simulated fabric below the track. The cart speed is a steady 10 cm/sec. An instrumentation module is attached to the top of the cart.

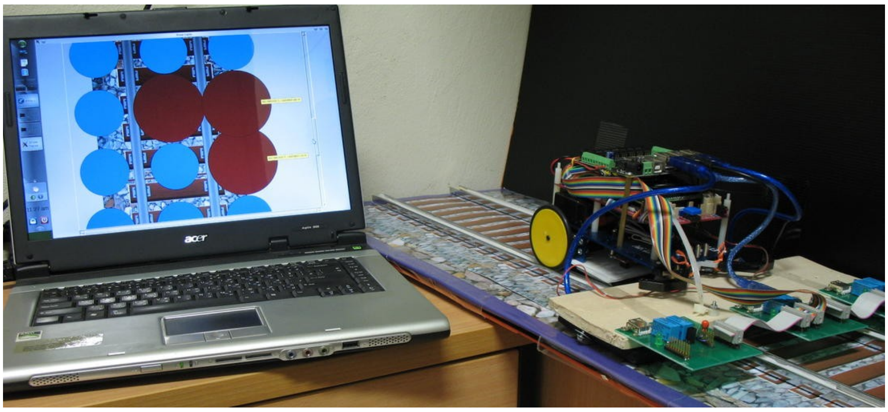

Figure 3. Railway "car" and sensor assembly.

Figure 4 shows a block diagram of the sensor system. In our test system we replaced the geographic positioning system (GPS) receiver by a sensor which allowed us to determine how far along the track the sensor system was located at any given moment. This corresponds to the odometer in a car.

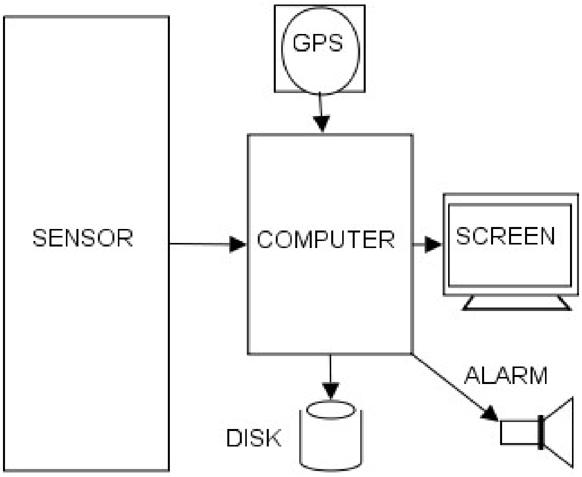

Figure 4. - Sensor system block diagram

The sensor measurements are converted to digital form and made available to a microprocessor (a laptop PC, in our case). The computer collects the measurements as the sensors move along the pavement surface. One set of measurements constitutes one line of data across the pavement. In a full implementation, each data line would be tagged with the exact time and location from a location sensor such as the GPS shown or an inertial system. Each data line would be saved to a disk file for later processing and/or displayed as one line of an image on a display and/or used to warn the operator with an alarm. In our test system, we simply tagged the data with the location and displayed the information on the computer screen as shown in Figure 3.

RESULTS

We conducted tests of the model in three situations: a) no damage to the geofabric indicating that the pavement subgrade is intact; b) slight damage to the geofabric indicating possible local damage to the subgrade which should be checked again in a few months; and c) extensive damage to the geofabric indicating a need for immediate repairs. In all three tests, the "damaged" and intact regions of the geofabric were correctly detected. The data for each run were saved to a disk file as the cart proceeded along the track, together with the "location" of the cart at that time. Because of the small scale of the model it was not possible to use GPS measurements to determine the location. Instead, the distance of the cart from the start of the track was calculated based on an assumption of constant cart speed. The results were correct except for test runs in which the cart was obviously slipping on the track. The results were displayed as shown in Figure 3.

STATUS AND FUTURE PLANS

So far, we have performed two rounds of successful laboratory testing of the technology. While the sensor assembly tested is very similar to the expected full-size sensor, the geofabric was tested only by simulation.

Before we can begin to use this to build real railways or roads we need to test using a real geofabric, and using test pavements built with more realistic construction materials. In the next stage of testing we will bury a sample of our geofabric under real road materials, in a laboratory setup where we can intentionally undermine the supporting soil (for example, using water jets) to test that the geofabric will actually detect and report the ensuing damage. Following that, we need to create a test facility with dimensions comparable to an actual pavement, which must be long enough to permit using a GPS for tagging the location of defective regions (for example, 2 meters by 100 meters). Beneath this pavement we will bury samples of geofabric with intentionally-placed gaps to simulate failure conditions. With this facility we can determine:

1. Can a sensor traveling along a road-like surface constructed of realistic materials reliably detect the presence or absence of gaps in the geofabric?
2. Can the sensor accurately determine the locations where the gaps are located?
3. How does the detection accuracy vary with the depth at which the fabric is buried?
4. How does the detection accuracy vary with the speed at which the sensor array travels?
5. Are there factors in the field (such as moisture) which may affect the test results?

The data collected using the methods described in this paper can be displayed as shown in Figure 3, but this is not very convenient for administrator use. In the future, we plan to create software to aggregate data from multiple sensor runs into a database and present it in a geographic context such as shown in Figure 5.

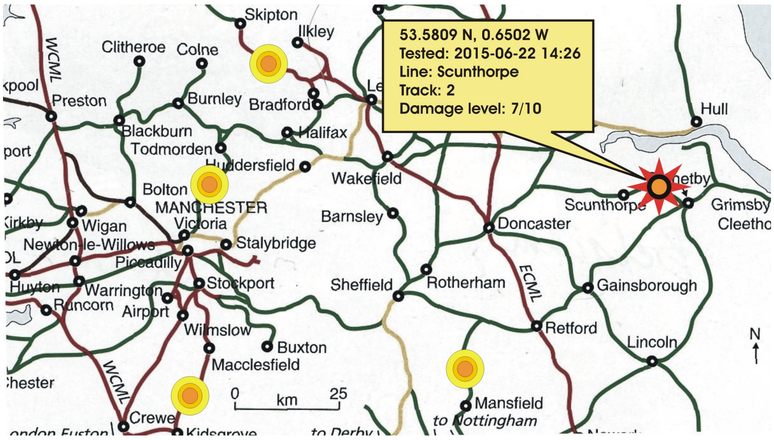
53.5809 N, 0.6502 W
Tested: 2015-06-22 14:26
Line: Scunthorpe
Track: 2
Damage level: 7/10

Figure 5. Global view of rail network damage

The yellow circles in Figure 5 indicate locations where some damage has been detected, while the red star denotes a location requiring immediate attention. A display like this will permit management personnel to understand easily where maintenance activity needs to be focused.

Note that the data shown in Figure 5 are entirely simulated, and the display does not imply there is any actual damage to the rail network shown.

CONCLUSIONS

Deterioration of the subsurface structure of an airport runway, highway, railway track, river or ocean dike, or similar construction which is earth supported can lead to unanticipated collapse, which in turn causes expenses to perform emergency repairs, economic losses due to traffic rerouting, possible destruction of property, injury to people or animals, and even death.

Our research provides a proof of concept for an early warning system which permits routine and inexpensive monitoring and detection of such subsurface failures, before the incipient failures cause damage at the surface. We have validated this technology in the laboratory, and are currently conducting additional experiments using realistic materials at full spatial scale. Use of this system will enable preventive measures to be applied at convenient and scheduled times, rather than waiting until a pavement failure mandates emergency repairs. Up-to-date knowledge of below-surface conditions will assist in optimizing maintenance budgets.

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