A smart geosynthetic for early detection of potential transportation substructure failure

Kurt Rudahl & Sally E. Goldin
King Mongkut's University of Technology Thonburi, Thailand

Abstract: Highways, railways, airport runways and levees (dikes) consist of multiple structural layers which ultimately rest on an earthen subgrade. Over time, erosion, nearby construction, weather, seismic activity and other causes can weaken or create gaps in the lower layers including the subgrade. Initially there is no sign of damage on the surface, until the structure subsides, buckles, or even collapses. At present there is no practical way to routinely monitor the condition of the earthen subbase which supports a road, railway or airport runway.
In this paper we describe a "smart" geosynthetic which addresses this problem. Our Smartroad Tools™ geosynthetic can be embedded under pavements and other geotechnical infrastructure during construction or reconstruction. Subsequently, an easy-to-use and inexpensive sensor array can be used to verify the integrity of the subgrade. This process can provide alerts regarding immediate threats to public safety, as well as longitudinal data for optimizing preventive maintenance budgets and activities. We present the results from our laboratory prototypes and full-size materials testing, and also describe plans for further stages of testing.

Keywords: dike failure, runway failure, railway failure, road failure, construction error, subsurface imaging, geosynthetic, smart material

1 BACKGROUND

Railways and highways form a major part of any nation's infrastructure, and their construction and maintenance are a major part of the nation's budget. They are used every day by almost everyone, and are the backbone of transportation for commercial goods. Airport runways, likewise, are crucial to a nation's economy. In this paper we will refer to roads, highways, airport runways, railway tracks, and also 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 beneath the road can develop due to floods, gradual erosion, and other geological and hydrological forces. Leaks of fluids and foreign substances from landfills or hazardous waste dumps can also cause problems.

Figure 1. Road collapse example (Depositphotos)

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. 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 subbase. In some cases, the collapse may cause the road to be closed for an extended period requiring travel and shipping to be rerouted. In extreme cases such as following severe storms, towns can become isolated due to one or multiple failures. In addition, property damage and even loss of life may occur.

2 CURRENT TECHNOLOGY

Surveys are made periodically on important roads to detect pavement distress, and railway staff are continually monitoring the state of the track. Modern rail companies are now outfitting rolling stock with sensors and instrumentation to monitor and detect distortion of the rails and pending failures in wheels. Similar instrumentation for the surface of highways is being actively developed. However, subsurface degradation can occur without visible pavement distress or track distortion. There do not appear to be any methods currently available for frequent periodic inspection to discover subsurface failures.

2.1 *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 require the use of specialist personnel and tend to be quite disruptive.

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 cm 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 ground or road at the location to be tested, which limits testing to a small number of locations per day. Thus, such geophysical survey methods are not useful for routine monitoring of an entire road.

2.2 *Radar and other non-contact methods*

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

The U.S. Federal Highway Administration (FHA 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 (Cardamona 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.

Attempts to use optical remote sensing from satellites or airborne instruments for assessing road condition have not yet been effective even for discovering pavement surface conditions. One report said that it is difficult to even find and measure the width of roads (Qihau 2008).

Lidar, which uses laser pulses to accurately measure elevation, is a possible approach to remote sensing of road 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 above are looking for anomalies in the road structure rather than looking for 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.

3 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 subsidence or collapse. We would like this examination to be easy, fast, convenient, and not 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 put a road in danger).

The system we have designed meets these criteria, provided that our smart geosynthetic (such as a geogrid or geotextile) has been embedded into the road during construction or reconstruction. Once embedded in the road, this geosynthetic is entirely passive. It does not require any power or external electrical connections, either permanently or during use.

Our technology is suitable for use with railway, highway, and international airport use. In particular, it is consistent with the objectives of the U.S. FAA Airport Technology Research Planning for the NextGen Decade (FAA 2012). As stated in Section 5 of that document, "Due to the increasingly limited availability of access to airport pavement because of operational and maintenance constraints, a method for accurately assessing pavement condition in a minimum amount of time will continue to be a pavement management necessity. This pavement evaluation will be required to take place in off-hours for airports such as over night. Therefore, this technology will require high-speed, accurate, and repeatable data acquisition without the benefit of sunlight." In particular, our technology can provide an input into PAVEAIR, the FAA's public, web-based application designed to assist organizations in the evaluation, management, and maintenance of their pavement networks.

In addition, we believe the technology can be used to monitor for incipient failure in earth-supported flood control dikes and mine tailings containment lakes.

4 TYPICAL USE CONFIGURATION

Our system consists of a material, a geosynthetic, plus a sensor apparatus for real-time monitoring and detection of subsurface failures of a road, highway, airport runway, railway track, river or ocean dike, mine tailings dike or similar construction which is earth supported.

The smart geosynthetic consists of a standard geosynthetic with added electronic components. We have been working with a geogrid as the base geosynthetic because of the ease of attaching the electronic elements. However, we have been advised to consider using a felt type of geosynthetic because this type would be more likely to be already in use for the construction (Camise 2018). We are discussing with various vendors and users which type would be most appropriate.

We are working with two alternative types of electronic elements to add to the geosynthetic. In both cases, they are passive in nature (i.e. no power or permanent connections are required), and they respond to radio-frequency queries from above the highway surface or railway.

The geosynthetic must be built into the highway either inside or between pavement layers or above the subbase, in such a way that the fabric will stretch, tear or be damaged by any collapse in pavement layers or subbase. The geosynthetic is engineered such that electronics in the vicinity of the damage will also be damaged and will not respond to the queries. There is no requirement for physical access to the geosynthetic after road construction and the fabric is entirely passive except during examination. This examination permits discovery of damage to the subsurface structure before damage becomes apparent on the surface through subsidence or collapse.

Examining the condition of the substructure is done by passing the sensor assembly along the surface, for example by attaching it to a car or truck as shown in Figure 2. When the sensor assembly probes the fabric remotely, damage to the fabric becomes apparent. This damage is assumed to imply weakness or possible failure of the road structure. The pattern of damage can be shown visually as an image or automatically processed using conventional image-processing techniques. The sensor assembly should be suitable to identify potential failures across the full width of a highway lane or railway track bed.

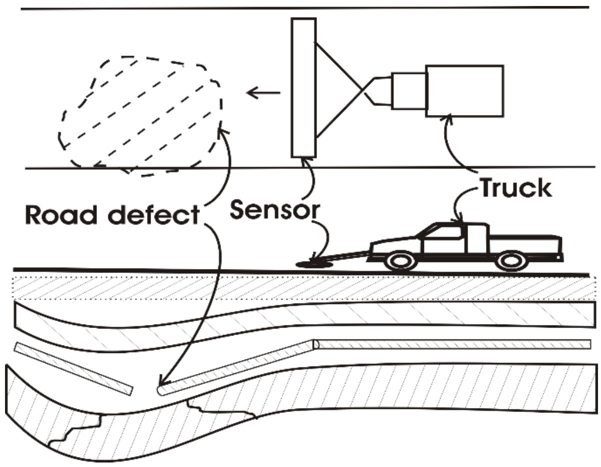


Figure 2. Road and sensor configuration

5 VALIDATION OF BEHAVIOR

5.1 *Research questions*

The questions to be answered by testing our geosynthetic are as follows:

1. Will the smart geosynthetic layer in fact show the expected sort of damage when subjected to stress similar to that which would occur with subgrade disruption?
2. Can a sensor traveling along a road-like surface, constructed of realistic materials, reliably detect the presence or absence of intact electronics components?
3. Can the sensor accurately determine the locations where components fail to respond?
4. How does the detection accuracy vary with the depth at which the fabric is buried?
5. How does the detection accuracy vary with the speed which the sensor array travels?
6. To what extent is the fault detection impacted by environmental considerations such as moisture?
7. To what extent is the geosynthetic with electronics impacted by normal road stresses?

We have identified four stages of testing which, if successful, will bring the technology up to Technology Readiness Level (TRL) 7: ready for manufacture.

5.2 *Stage 1: desktop prototypes (to TRL 4)*

As a desktop test of this technology, we created a model of a single-lane road as reported earlier (Rudahl and Goldin 2014). Later we replaced that with a new, more sophisticated model using a simulated railway track and vehicle. The model vehicle and sensor assembly are shown in Figure 3. The sensor assembly is about 34 cm wide. In use, it communicates with a computer running our middleware using Ethernet Our testing is being done on a simulated track about 2 m long with a 11-cm gauge, and with a simulated fabric below the track.

Figure 4 shows the results of several experimental runs. On the left there are no damaged areas in the simulated geosynthetic. The center frame shows a moderate level of damage indicating a region which should be tested again soon, and on the right, a more severe level of damage which should be evaluated immediately.

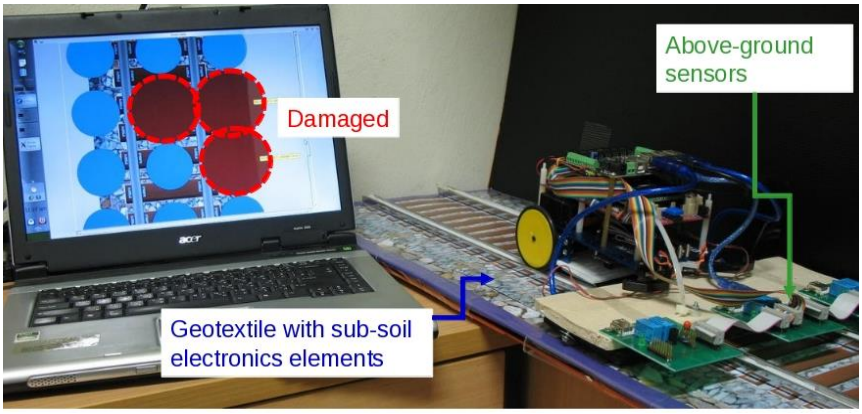


Figure 3. "Railway car" prototype

5.3 *Stage 2: validation of materials and components*

We have built two test rigs in our lab. One of them is designed to test the physical behavior of a candidate geosynthetic under stress. The manufacturers typically provide certifications of the material's resistance to failure and maximum amount of stretch. However, these numbers do not appear to detail how much force produces how much stretch and, even more important, over what time period. The time period is important because we do not anticipate that a void under a road will appear suddenly, but rather will develop as a progressive failure over days or months. We found that a weight of 40 kg applied for 24 hours caused a stretch of about 5% to 10% for different samples. Additional time did not increase the stretch.

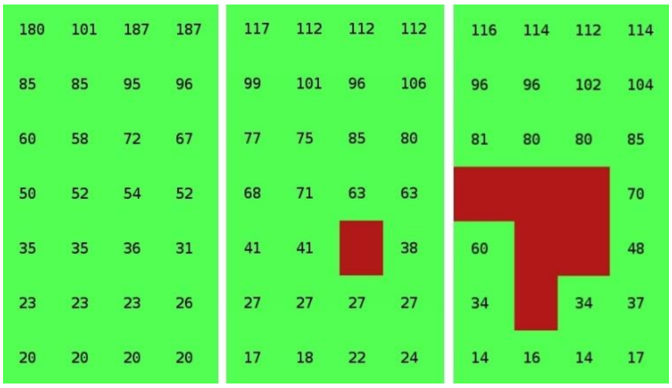


Figure 4. Detected damage

The other rig is used to test the behavior of a larger geosynthetic sample (1.5m square), either with or without attached electronics. The geosynthetic is spread horizontally across the frame and secured at the edges. Weights (sandbags) are placed on the geosynthetic to simulate the weight of the overlying pavement layers. With each weight increment, we test that the electronics on the geosynthetic can be detected. Eventually the textile stretches so that the electronics cease to respond. We found that a weight of about 40 kg above the unsupported geosynthetic/electronics was sufficient to stretch the geosynthetic and render the electronics inoperable.

We also have access to the sandbox shown in Figure 5, through the help of the KMUTT Department of Civil Engineering. This apparatus consists of a metal frame 180 cm long, 80 cm high, and 40 cm thick. Transparent sides permit observing a sample of pavement and underlying layers while subjecting them to varying force from above.

We use this equipment to verify that the selected materials and components can work together in combination with realistic building materials to detect simulated subsoil failures.

Figure 5. Civil engineering sandbox

A section of pavement structure is built inside the sandbox, using a standard sand for modeling the subgrade and the subbase layers. Figure 6 shows a cross-section side view. The base layer is modeled by crushed-rock. An asphalt concrete layer is then placed right on the base. Two layers of sensing geosynthetic are installed, one at the interface between the subbase and base layers and the other at 20 cm below this interface.

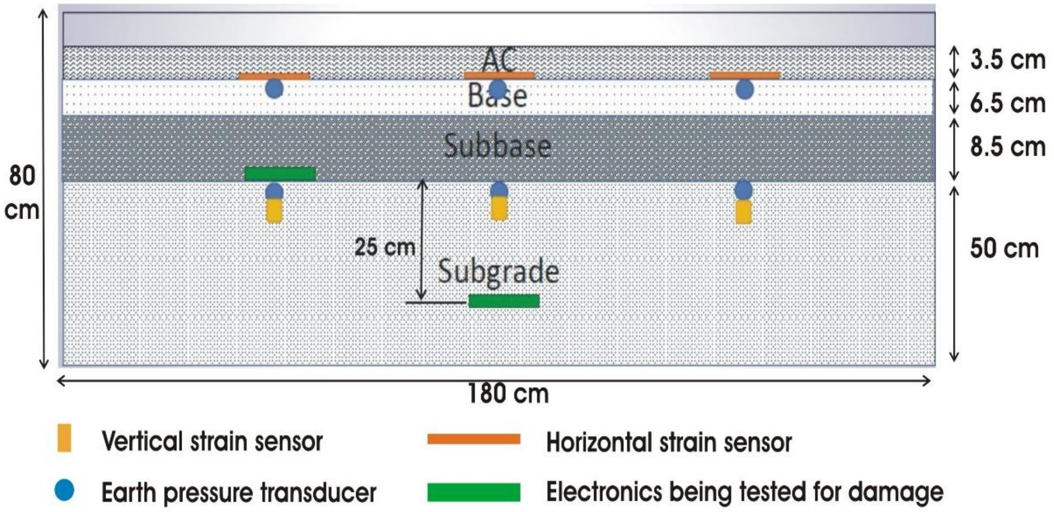


Figure 6. Sand box side view

Simulation of traffic loading is modeled by applying a vertical force cyclically to the pavement at either one or three locations. Figure 7 shows the force applied. Horizontal strain gauges are placed below the two geosynthetic layers such that they are directly beneath the location of each footing. Earth pressure transducers, used to locally measure the vertical stress, are also placed at the same vertical level as the strain gauges but horizontally offset from them

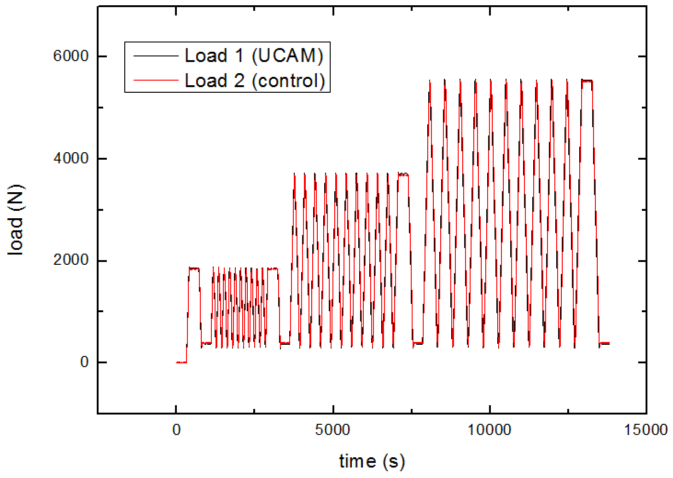


Figure 7. Force applied to samples in sandbox

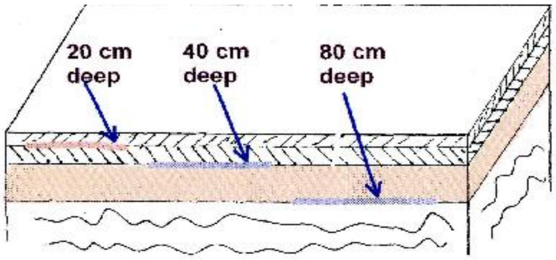
5.4 *Stage 3: full-size laboratory testing (to TRL 6)*

This next stage of testing is intended to provide field verification that the technology can be built into an actual road or rail segment and can detect artificially-created subsoil failures. This will be accomplished by including samples of the smart geosynthetic beneath a road or rail segment, as shown in Figure 8.

It is not feasible to expect to conduct a test beneath a working road, so access to a suitable test facility is required. This could be from a government agency or a research facility. We currently have been granted permission to perform this testing under a road segment at KMUTT, which is provisionally scheduled for 2018. The State Railway of Thailand has informally agreed to provide a site for rail testing, or we may be able to collaborate with the Korean Rail Research Institute for this testing.

5.5 *Stage 4: field testing (to TRL 7)*

Ultimately we need to perform long-term (six months to a year) testing under a highway or railway which is in actual use, in order to test whether the enhanced geosynthetic is robust enough to withstand environmental pressures including weather and traffic. We do not yet have a candidate location for this activity.



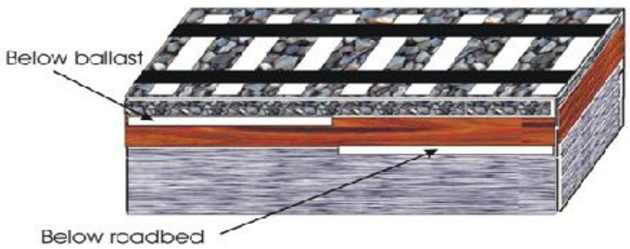


Figure 8. Testing beneath road or rail

6 FUTURE PLANS

This paper has described a new geosynthetic and sensor combination. While the sensor assembly we have tested is very similar to the expected full-size sensor, the geosynthetic was tested only in small sections. Before we can begin to use this to build real roads we need to test using large samples of the geosynthetic and the full sensor array in order to verify that the enhanced geosynthetic is robust enough to withstand environmental conditions including both weather and the forces of normal vehicular traffic.

The data collected using the methods described in this paper can be displayed as shown in Figure 4, but this is not very convenient for administrator use. We plan to create analytics software to aggregate data from multiple sensor runs into a database and present it in a geographic context such as shown in Figure 9. This data can be combined with geographic data such as soil type and slope, plus real-time data such as rainfall, to allow machine learning techniques to provide both short and long-term forecasts of maintenance needs. In Figure 9, the yellow circles indicate locations where some damage has been detected, while the red-orange 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 9 are entirely simulated, and do not indicate any actual damage to the rail network shown.

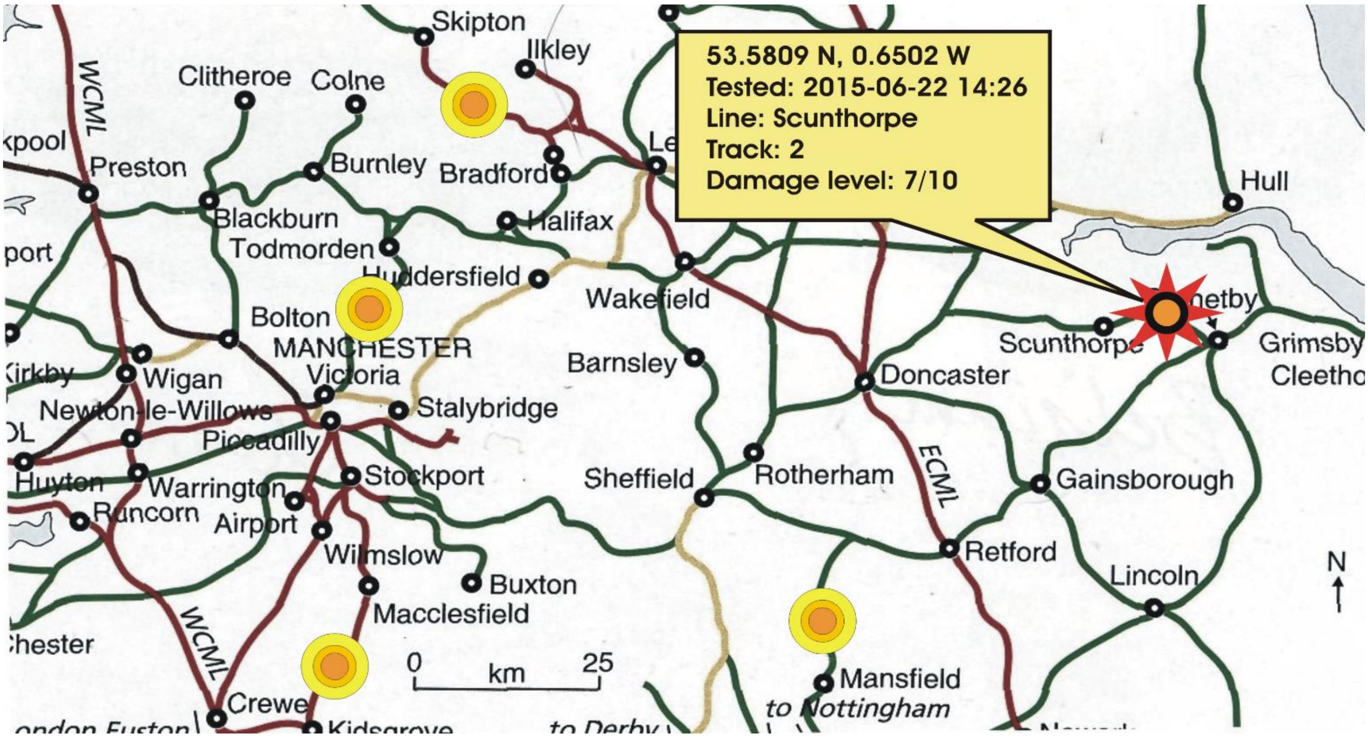


Figure 9. Maintenance administrator view of rail network damage

7 CONCLUSIONS

Deterioration of the subsurface structure of a road, highway, airport runway, 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 demonstrates an early warning system utilizing a smart geosynthetic and a sensor array which permits routine and inexpensive real-time monitoring and detection of such subsurface failures before the incipient failures become apparent at the surface. Use of this system will enable preventive measures to be applied at convenient and scheduled times, rather than waiting until a catastrophic failure mandates emergency repairs.

REFERENCES

Camise, R. (2018), personal communication.
Cardimona,S. et al, (undated), Ground Penetrating Radar Survey of Interstate 70 Across Missouri, The University of Missouri-Rolla, Department of Geology and Geophysics and the Missouri Department of Transportation.
Daley, M.A.,et al (1985), Seismic Refraction Data Collected in the Chugach Mountains and along the Glenn Highway in southern Alaska in 1984, United States Department Of The Interior Geological Survey USGS Open-File Report: 85-531.
FAA (2012), Airport Technology Research Plan ¡Kfor the NextGen Decade, Federal Aviation Administration.
FHA (2011), Priority, Market-Ready Technologies and Innovations: Ground-Penetrating Radar, Federal Highway Administration report FHWA-HRT-04-072.
Garber, N.J. and Hoel, L.A. (2010), Traffic and Highway Engineering, 4th Edition, Cengage Learning.
O'Flaherty, C.A. ed (2002), Highways: The Location Design, Construction and Maintenance of Road Pavements, 4th Edition, Elsevier.
Qihau Weng (2008), Remote Sensing of Impervious Surfaces, CRC Press.

Rudahl, K.T. and Goldin, S.E. (2014), A Smart Material for Imaging Highway Substructure Damage, Smart Materials and Sensors conference, Bangkok 2014.
Rudahl, K.T. and Goldin, S.E. (2014), A Smart Material for Imaging Highway Substructure Damage, Smart