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16. Abstract <p>This report documents the research project “Investigation of Ground-Penetrating Radar (GPR) Technology for the Health of Bridge Decks: Phase I – Feasibility Testing.”</p> <p>Primary deck damages and problems of bridges in California are, according to the reviewed literature, cracking (subsurface), spalling of concrete, air-filled delamination, rebar corrosion, moisture content, and other physical states of the concrete, e.g. scaling. Secondary features and damages are, for example, pavement thickness, concrete surface location, rebar covering, rebar locations, and locations of other structures or parts.</p> <p>Ground Penetrating Radar (GPR) is a strongly developing nondestructive evaluation (NDE) method, which can be successfully used for the initial mapping and specifying of damage locations in bridge decks.</p> <p>During the research project it was found that in many cases the damages and features of bridge decks and structures cannot be measured using only one measurement technique. Hence, the use of more than one measurement technique to determine the current health of the bridge deck is recommended. Such additional measuring techniques could be, for example, digital imaging, 3D laser scanning, thermal measuring, interferometry, 3D sonar measurements and other non-contact sensing technologies.</p> <p>This report provides background on GPR for bridge decks, along with results from a bridge deck GPR scan in Finland. These results also include 3D laser scanning data.</p>					
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Advanced Highway Maintenance and Construction Technology Research Center

Department of Mechanical and Aerospace Engineering
University of California at Davis

Investigation of Ground-Penetrating Radar (GPR) Technology for the Health of Bridge Decks: Phase I – Feasibility Testing

Rauno Heikkilä, Kin Yen, Bahram Ravani &
Ty A. Lasky: Principal Investigator

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ABSTRACT

This report documents the research project “Investigation of Ground-Penetrating Radar (GPR) Technology for the Health of Bridge Decks: Phase I – Feasibility Testing.”

Primary deck damages and problems of bridges in California are, according to the reviewed literature, cracking (subsurface), spalling of concrete, air-filled delamination, rebar corrosion, moisture content, and other physical states of the concrete, e.g. scaling. Secondary features and damages are, for example, pavement thickness, concrete surface location, rebar covering, rebar locations, and locations of other structures or parts.

Ground Penetrating Radar (GPR) is a strongly developing nondestructive evaluation (NDE) method, which can be successfully used for the initial mapping and specifying of damage locations in bridge decks.

During the research project it was found that in many cases the damages and features of bridge decks and structures cannot be measured using only one measurement technique. Hence, the use of more than one measurement technique to determine the current health of the bridge deck is recommended. Such additional measuring techniques could be, for example, digital imaging, 3D laser scanning, thermal measuring, interferometry, 3D sonar measurements and other non-contact sensing technologies.

This report provides background on GPR for bridge decks, along with results from a bridge deck GPR scan in Finland. These results also include 3D laser scanning data.

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LIST OF ACRONYMS AND ABBREVIATIONS

AHMCT	Advanced Highway Maintenance and Construction Technology
API	Application Programming Interface
BAM	Federal Institute for Materials Research and Testing
Caltrans	California State Department of Transportation
COTS	Commercial-Off-the-Shelf
DRI	Division of Research and Innovation
EMPA	Swiss Federal Laboratories for Materials Testing and Research
FHWA	Federal Highway Administration
FRA	Finnish Road Authority
GB	Gigabyte
GIS	Geographic Information System
GNSS	Global Navigation Satellite System
GPR	Ground-Penetrating Radar
GPS	Global Positioning System
GSSI	Geophysical Survey Systems, Inc.
HERMES	High-Speed Electromagnetic Roadway Measurement and Evaluation System
HMI	Human-Machine Interface
IDS	Ingegneria Dei Sistemi
IE	Impact Echo
IR	Infra-Red
IRIS	Incorporated Research Institutions for Seismology
LCPC	Laboratoire Central des Ponts et Chaussées
LLNL	Lawrence Livermore National Laboratory
LTBP	Long Term Bridge Performance
MB	Megabyte
MEMS	Micro-Electro-Mechanical Systems
MPH	Miles Per Hour
NDE	Nondestructive Evaluation
NDT	Nondestructive Testing
OS	Operating System
PDA	Personal Digital Assistant
PERES	Precision Electromagnetic Roadway Evaluation System
RAM	Random Access Memory
RH	Relative Humidity
RTK	Real-Time Kinematic
UCD	University of California-Davis
UIT	Underground Imaging Technologies, Inc.
USB	Universal Serial Bus
USDOT	United States Department of Transportation
XML	eXtensible Markup Language

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CHAPTER 1: INTRODUCTION AND BACKGROUND

The bridges in California are aging, and inspection and maintenance are critical to the safe and effective operation of this vital element of the transportation system. Pro-active health-monitoring of bridge decks, including internal health, is essential. Existing methods, e.g. chain-dragging, cannot provide the level of information needed for optimal quantitative data-driven maintenance. Effective bridge inspection using Ground-Penetrating Radar (GPR) is also important to clearly understand the state of bridge decks before issuing contracts for bridge maintenance; otherwise, projects can be at risk due to unforeseen conditions arising during the execution of the maintenance. GPR was evaluated to show great promise for bridge deck health evaluation, and should be investigated for application within California.

GPR uses discrete radar pulses with central frequency from 10 MHz – 2.5 GHz to find location and dimensions of electrically distinct layers and objects below the surface. A part of the transmitted pulse is reflected back by an electric interface, and the GPR displays this as a waveform showing amplitude and time elapsed. When the measurements are repeated (currently up to 1000 scans/second) and the antenna is moving, a continuous profile is obtained across the target [20].

Propagation and reflection is determined by the material's electric properties: magnetic susceptibility, relative dielectric permittivity, and electrical conductivity. Electrical conductivity contributes to attenuation, and in part to reflection. In GPR surveys of roads and bridges in cold climate areas, the presence of deicing salts are a major factor affecting the electrical conductivity of the materials. The most important electrical property affecting GPR survey results is dielectric [20].

Objectives

The objective of the research project was to study the applicability of Ground-Penetrating Radar (GPR) technology to the measurement tasks of existing bridge decks in order to determine the health of California's bridge decks.

To facilitate the research, the main object was divided to six more specific tasks:

1. Execute a literature review and a technology scan, i.e., to summarize previous research and current technology related to GPR for investigation of the health of bridge decks (i.e. the current interim report).
2. Identify bridge test candidates and GPR vendors.
3. Develop the applicability criteria and test methodology.
4. Execute feasibility tests.
5. Analyze test results.
6. Report the study.

In the project kickoff meeting, the research emphasis was shifted focus primarily on task number one. Feasibility tests were eliminated from the research, as reflected in this final report. The funds originally targeted for feasibility testing were returned at the end of the project. However, preliminary feasibility tests were performed via cooperative research efforts with Finland.

CHAPTER 2: MATERIALS AND METHODS

Literature Review

According to Saarenketo [20], GPR was first used in bridge deck surveys in the early 1980s. Later research and development was focused on developing automated or semi-automated GPR data analysis as well as multi-channel GPR system for mapping bridge deck deterioration. During recent years the focus has been on collecting reflection amplitude data from bridge decks and preparing maps that present damaged areas in the bridge structures.

Using GPR the following features can be measured [11]:

- pavement thickness,
- thickness of single pavement layer,
- pavement damage,
- spacing between reinforcement bars,
- position of tendons or tendon ducts,
- concrete damage, and
- concrete and pavement properties.

Parry and Davis [14] prioritized parameters that can be obtained via GPR. Priority 1 parameters were: pavement thickness, rebar covering, debonding, delamination, and scaling. Priority 2 were: chloride content, moisture content (free moisture), and moisture content (bound in concrete). Priority 3 were: surface cracking and subsurface cracking. The primary cause of deterioration in bridge decks in North America was evaluated to be corrosion of the steel reinforcements inducing concrete cracking, which frequently results in delamination. The corrosion is mainly due to deicing salts. Another source of deterioration is freeze-thaw cycles in chloride-contaminated concrete [21], also called spalling. According to Manning and Holt [13], deterioration can be rapid if the cover layer over the top reinforcements is too thin. A third damage type found on bridges is debonding which takes place when an asphalt or concrete overlay separates from the concrete bridge deck [20].

According to Saarenketo [20] both high-frequency ground-coupled and air-coupled antennas can be used in bridge deck surveys. Ground-coupled systems can provide very detailed information about the bridge deck's structures and reinforcement bars; however, current systems must be used at slow speed for data collection so that bridge lanes have to be closed during the operation. As such, the use of air-coupled antenna systems, which can perform data collection without causing major traffic problems, is highly recommended especially on high traffic volume roads.



**Figure 1: An example of Bridge GPR deck measurement executed in Finland 2008
(courtesy of Roadscanners Oy)**

Bridge deck deterioration mapping has increased in recent years. Romero and Roberts [17,18] used a dual-polarization horn antenna to remove the effect of longitudinal reinforcement bars. Shin and Grivas [22] applied statistics to evaluate accuracy of GPR results on bridge decks, finding that rebar reflection data detects defects at 75% true detection rate with a 15% false detection rate. There is still some controversy concerning the reliability of GPR especially in detecting delamination in bridge decks. Some research has attributed this difficulty to GPR resolution problems [2,16], which is why higher frequency antennas have been tested and recommended for use in these surveys [12,20].

Based on these issues, Saarenketo concluded that GPR alone cannot provide sufficient information on the damage in the deck [20]. However, it provides the initial mapping so that other non-destructive evaluation methods and limited ground-truth (core sampling) testing can be used to verify the problems. Figure 2 illustrates such an application. GPR can also be used for quality assurance regarding placement, density, and pattern of steel reinforcement, and to detect voids in post-tensioned concrete beams. Dérobert et al. [3] have tested several NDT methods in testing post-tensioned bridge beams and suggest that the best combination of current techniques is GPR before gammagraphy [20], an NDE method based on gamma radiation.

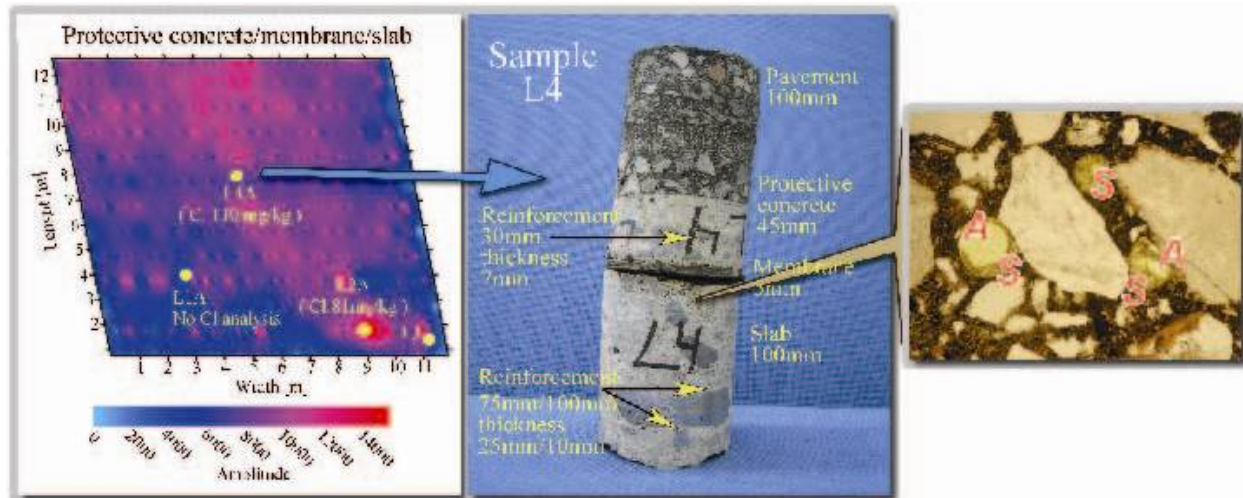


Figure 2: Case from the Långsvedjan bridge in Sweden shows how GPR can be used to predict problems in the early phase in bridge decks (Courtesy Saarenketo [20]).

GPR has been used to detect scour around bridge piers [5,6,8,23]. The best results are obtained if the conductivity of the river water is less than 1000 $\mu\text{S}/\text{cm}$ (micro Siemens per centimeter) [6].

In a laboratory experiment Hugenschmidt and Loser [10] showed that both moisture and chlorides have a measurable influence on the reflection amplitudes of radar signals at the concrete surface and at an aluminum sheet situated below the concrete specimen.

Huston et al. [12] studied three sensor types to assess bridge deck condition: electromagnetic (GPR), acousto-elastic wave (impact echo and chain drag), and electrochemical (half-cell) measurements. The main finding was that no single current technology, on its own, can be used to quickly and accurately assess a concrete bridge deck or detect small delaminations without shutting down the lane of traffic. One approach to resolving this difficulty is to fuse the data from several sensor types to estimate the potential for damage.

According to Rhazi, Dous, and Ballivy [16], radar antenna technology has progressed significantly in recent years, but it is still impossible to detect delamination clearly and without ambiguity. They also proposed and validated an alternative GPR data processing method using determination of the variation of moisture and salts content in the concrete, which gives information very comparable with that given by the half-cell potential test.

Barnes, C. L. & Trottier J.-F. & Forgeron [1] showed that for exposed reinforced concrete bridge deck, decreases in GPR signal reflection amplitude measured from the transverse bars in the top mat of deck reinforcement resulting from variations in cover depth can have a significant effect on the interpretation of GPR data for the purposes of deck condition evaluation. A linear regression model fitted to the 90th percentile amplitude values for subsets of the total range of measured two-way travel time appears to remove these depth-dependent variations and provide reflection amplitudes with improved correlation to the chain drag and half-cell potential survey methods.

Technology Scan

GPR Technologies developed, used and tested in USA

In the US, there are two different measurement technologies available for GPR measurement:

- Geophysical Survey Systems, Inc. (GSSI), USA – the biggest manufacturer in the world
- Sensors & Software, Toronto

According to GSSI, bridge professionals use GPR for:

- Bridge deck condition assessment
- Determining concrete cover depth on new structures
- Measuring bridge deck thickness
- Inspecting concrete – locate metallic and non-metallic targets
- Detecting voids and location
- Inspecting other reinforced concrete structures

**Table 1: Antenna frequency, approximate depth penetration and appropriate application
(Courtesy of GSSI)**

Depth Range (approximate)	Primary Antenna Choice	Secondary Antenna Choice	Appropriate Application
0-1.5 ft 0-0.5 m	1600 MHz	900 MHz	Structural Concrete, Roadways, Bridge Decks,
0-3 ft 0-1 m	900 MHz	400 MHz	Concrete, Shallow Soils, Archaeology
0-12 ft 0-9 M	400 MHz	200 MHz	Shallow Geology, Utilities, UST's, Archaeology
0-25 ft 0-9 m	200 MHz	100 MHz	Geology, Environmental, Utility, Archaeology
0-90 ft 0-30 m	100 MHz	Sub-Echo 40	Geologic Profiling
Greater than 90 ft or 30 m	MLF (80, 40, 32, 20, 16 MHz)	20 m	Geologic Profiling

According to the recent studies of the Rutgers University evaluation [7], GPR provides rapid evaluation of deteriorated deck sections. However, it does not necessarily address delamination. Rutgers University has tested the use of complementary Impact Echo (IE) measurement (IE is a seismic technique that can detect delaminations as reflectors of elastic waves). They have found that IE provides accurate assessment of the position and degree of delamination of the deck. The method has, however, been found to be relatively slow. Their conclusion was that it is possible to

use the speed of GPR testing to evaluate broad areas. After that the more accurate IE measurement was recommended to be executed.

According to Rutgers University [19], nondestructive methods make it possible to see inside a structure, where most deterioration starts. Some good examples of 3D information models measured by impact echo as well as 3D GPR have been provided by the Rutgers University.

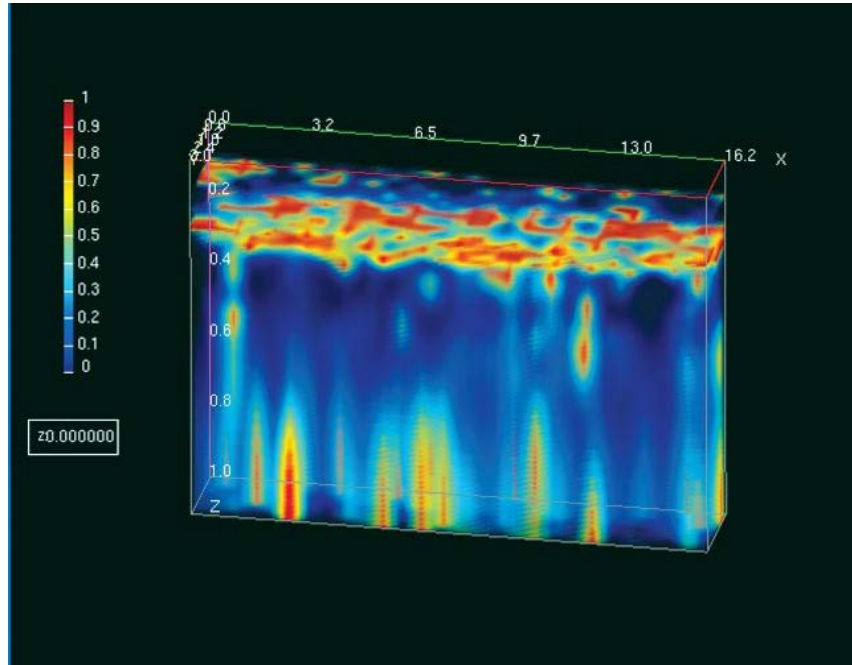


Figure 3: An example of 3D NDE measurement by impact echo method (Courtesy of Rutgers University)

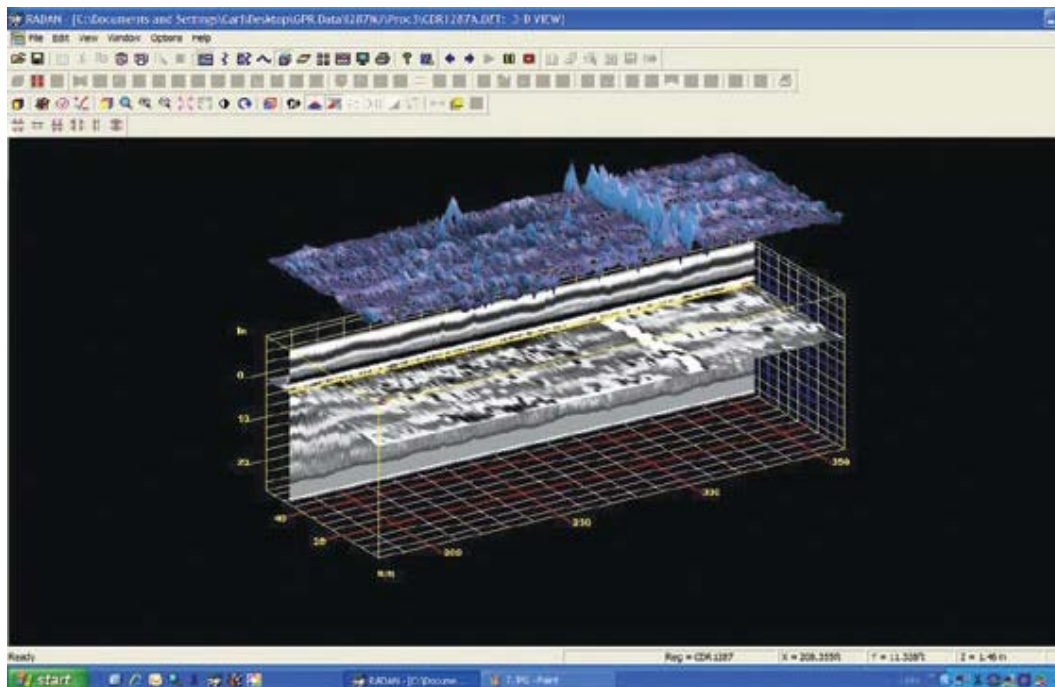


Figure 4: An example of 3D GPR result describing the severity of the damage to the structure (Courtesy of Rutgers University)

In California, a test of GPR measurement was executed by Resource International Inc. in 2006 [15] for Caltrans on the Vincent Thomas Bridge, shown in Figure 5. The test focused on the corrosion mechanism of the reinforcing steel. GPR was successful in identifying amount and locations of impending or advanced corrosion conditions that would cause corrosion of reinforcement, change in concrete integrity and chemistry, and damage (such as cracking, delamination, or spalling) to concrete. GPR data was collected at 30 MPH.



Figure 5: Vincent Thomas Bridge, Los Angeles, California

GPR Technologies developed, used and tested in Finland

A research and development project “*The measurement of seven bridges by GPR and 3D laser scanning as well as the execution of special inspection*” was executed in Finland in 2007 [4]. The aim of the project was to study the reliability of GPR measurement of concrete bridge decks and to map different suitability areas of these GPR measurements. The main idea was to compare the results of special inspections to the results of the GPR measurements performed. The bridges have been constructed in the years 1967-1984. Destia Oy (Mikko Rauhanen) reported the results to the Finnish Road Administration [4]. The special investigations were earlier made by Destia Oy, SiltaExpert Oy and WSP TutkimusKortes Oy, the GPR measurements by Roadscanners Oy (Dr. Anja Palli), and the 3D laser scans by Neopoint Oy, Finland. In addition, special borings and samplings for the quality control and calibration of the GPR measurements were executed. In the laboratory, thin-section research and chloride content measurements were executed. The laser scanning was made mainly for the initial data needs of the bridge design.



Figure 6: 2D GPR on the Sipoonlahti Bridge, Finland (Courtesy of Roadscanners Oy)

During the GPR measurements, weaknesses were observed in the 3D GPR measurements (Antenna Technology of 3D Radar AS, Norway, 16 antennas with the interval of 15 cm, 100 measurement/m, frequency range 150 MHz–2 GHz) and interpretation of the observations. Therefore also 2D GPR (GSSI Inc. SIR-20 Antenna, 1.5 GHz, frequency range 250 MHz - 3.75 GHz) measurement method was used in the research. All of the seven bridges, except one (Sipoonlahti U-1250 N), were measured by using both 3D and 2D GPR method. Compared to the aims, the following conclusions were made based on the experiences achieved in the research:

1) *The measurement and determination of the 3D form of upper surface of the concrete deck, i.e. to find where are possible holes (gathering water and causing damages) and what kind of slopes there are on the whole area of the deck.* This feature is still under development phase.

2) *The measurement and determination of the thickness of paving layers as well as concrete protection layer.* In Finland, a special concrete layer for protection of structural concrete slab has been used. This is a major difference vs. Californian bridges. According to the results, these thicknesses can be determined based on GPR measurements. The results of boring and sampling tests supported this conclusion. Based on the measured thicknesses, the real volume of asphalt as well as concrete material to be renewed can be calculated, thus enabling the accurate calculation of repair costs, which was found to be very important.



Figure 7: 3D GPR on the Sipoonlahti Bridge, Finland (Courtesy of Roadscanners Oy)

3) *The variety of moisture content in different areas and parts of the concrete deck.* This was found to be very difficult without the use of GPR measurement. Based on the thin-section research some individual and partial estimates can be made indicating also increased water moisture in that area. The use of 2D GPR was evaluated to produce reliable results.

4) *The locations of different drainage parts.* For example, drains and water tubes can be detected and measured by 3D GPR measurements (measurement interval of 150 mm was used, in near future it will be 100 mm). So these parts can be measured and transferred to bridge designer. Using 2D GPR measurement, the interval is only 500 mm, thus the accurate planning for the measurement lines is needed and open uncertainty of the detection and location determination remains. Also, the work will be slower.

5) *The determination of the damages of the concrete slab as well as the condition of water insulation.* The measurement using 2D GPR method was found to be quite reliable. The results were verified based on the boring and sampling results. The measurement using 3D GPR method was found to be unreliable based on the reference of thin-section research.

6) *The thickness of protective concrete of reinforcement.* The thickness of protective concrete of reinforcement can be roughly measured. More accurate, for example 35 mm thicknesses, were

not possible to measure. However, the approximate location of reinforcement can be measured indicating quite well the quality of assembly and casting work.

7) *The initial data for repairing design.* Using 3D laser scanning, an accurate and useful measured and dimensional model of the real bridge can be created. Also using GPR measurement, the volumes of different material layers can be determined.

8) *The improvement of the quality of bridge design.* Based on the more accurate and broader information, the quality of bridge design can be improved. Thus there are fewer changes needed and fewer surprises found in the construction phases of the repairing work. If also more range 3D laser scanning is done, a more detailed working area design can be planned.

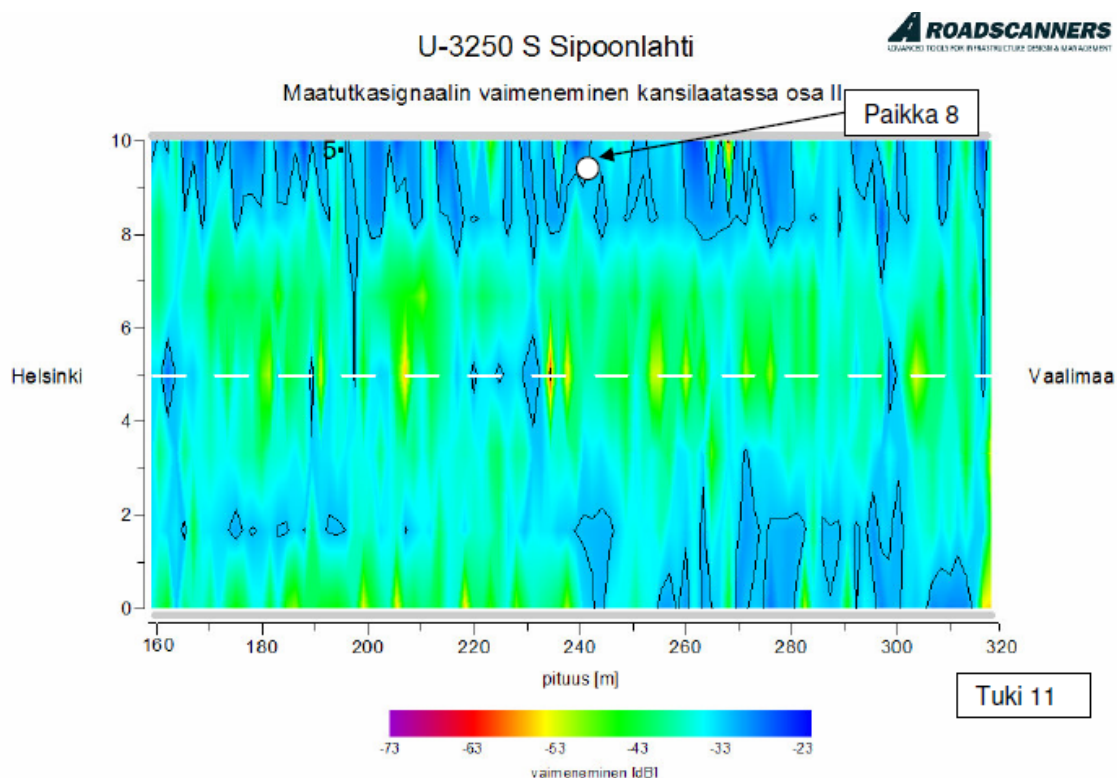


Figure 8: An example of the moisture content in the area of the concrete deck of U-3250 Bridge, measured by 2D GPR method, Finland 2007 (Courtesy of Roadscanners Oy)

In general and based on this research, 2D GPR measurement was found to be today the only possible alternative with which it is possible to study the quality of concrete decks of bridges. The GPR method needs the use of boring and sampling research, which makes the results more reliable. The development of the combination of both the GPR result and laser scanned result was strongly recommended. There are needed several experiments in different bridges, and a future goal is to develop a common description of the process in general. The following benefits of 3D laser scanning were concluded in this study:

- Possibility to provide accurate 3D information quickly and inexpensively
- Data acquisition is mainly automated

- Non-contact principle of measurement
- Measuring without any interruption to traffic
- Measurement of dangerous and difficult objects also possible
- Fully digital process
- High accuracy ± 4 mm/100 m
- Different derivative products available: point cloud, surface model, hybrid model
- Simple and reliable way to provide accurate information from old bridges and bridge surroundings.

In the study, an example of a general process for the repairing of old bridges was suggested to owners:

- 1) Programming of special inspections
- 2) Execution of GPR measurement
- 3) Checking the programming on account of the GPR measurement. If there was not observed any abnormal damage or moisture areas, the next special inspection is timed to the next future cycle
- 4) Execution of special inspection and 3D laser scanning, determination of the accurate points for boring and sampling research
- 5) Planning of repair designs
- 6) Request for bids, selection
- 7) Operation of repair and construction works
- 8) Work admittance examination.

The study included an analysis of measuring principles. The operating principle and current features of GPR measurement were found to need dry weather and at least two rainless and dry, warm days after last raining. During a very hot and dry summer time it is not possible to detect possible moisture areas in the concrete deck. The current measurement speed is about walking speed. Therefore, if there is heavy traffic, the lanes must be closed during the measurements. In Finland, where a special protective concrete layer is used, some damages can be hidden below the water drains. Thus, a multi-measurement principle method is recommended.

Figure 9 shows a view of 3D bridge data. The topmost bar is the 3D GPR data from one antenna. On the right is a cross-section profile of the bridge. The two colored bars underneath the 3D GPR data are plane views of reinforcement in the concrete deck slab. Figure 10 provides data for pavement thickness of a bridge in Finland. The deterioration map of the concrete deck slab of

this bridge is shown in Figure 11. The pavement layer of the bridge is clearly worn out mostly in the left wheel paths. This is because the right wheel path is patched. Blue areas in the deterioration map of the bridge deck slab indicate possible moisture in concrete. The red areas indicate possible other damage like corrosion in the reinforcement. The green areas are found good. Moisture can be detected from both edges of the bridge and from both construction joints and from the abutments at 14 m and 35 m.

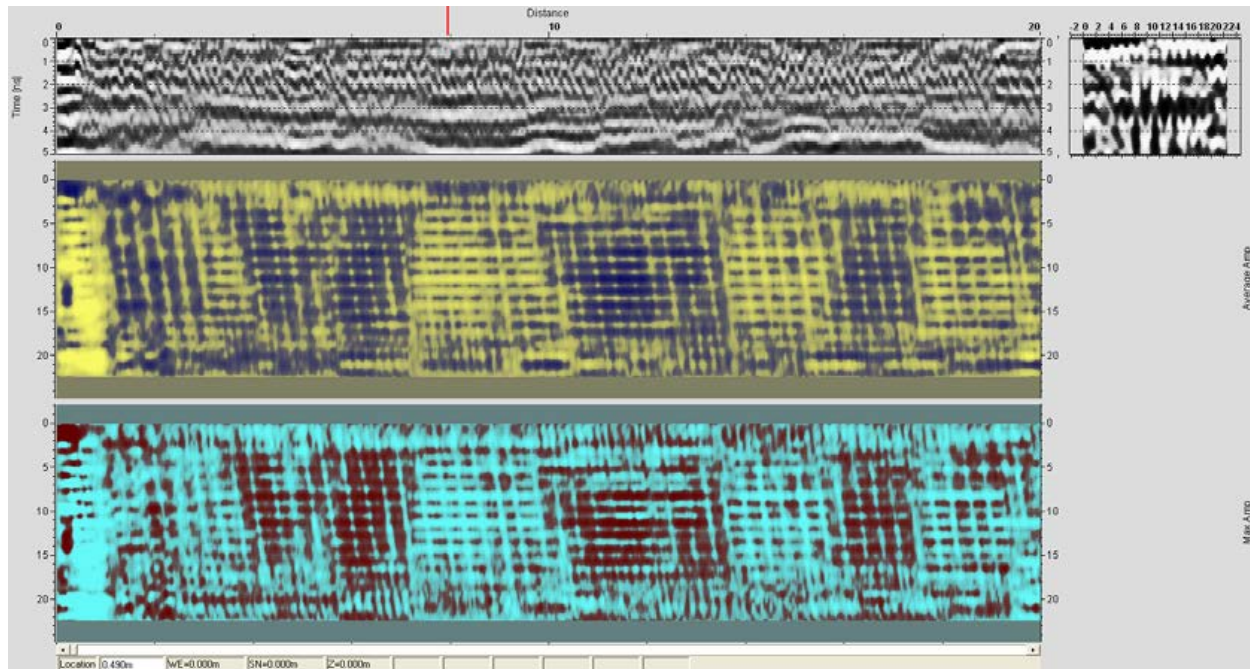


Figure 9: View of 3D bridge data. (Courtesy of Roadscanners Oy).

Roadscanners provides the following directions for executing bridge measurements:

- Dry weather
- Optimal conditions for measurements are about two clear days after rainfall. However the bridge deck should not be totally dry, because, in that case, possible moisture damage is difficult to detect from the results.
- Measurements are done at walking speed.
- Closure of the traffic lane is required on busy bridges.
- Bridges that have gravel filling are challenging for GPR, sometimes the concrete deck slab cannot be seen depending on the thickness of the gravel filling and the granular size.

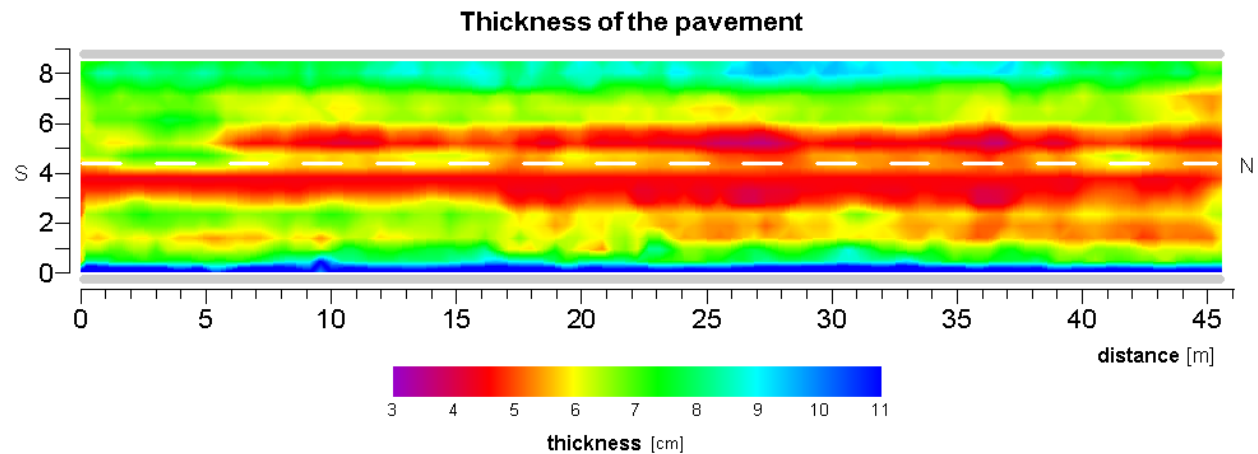


Figure 10: Pavement thickness of a bridge in Finland. (Courtesy of Roadscanners Oy).

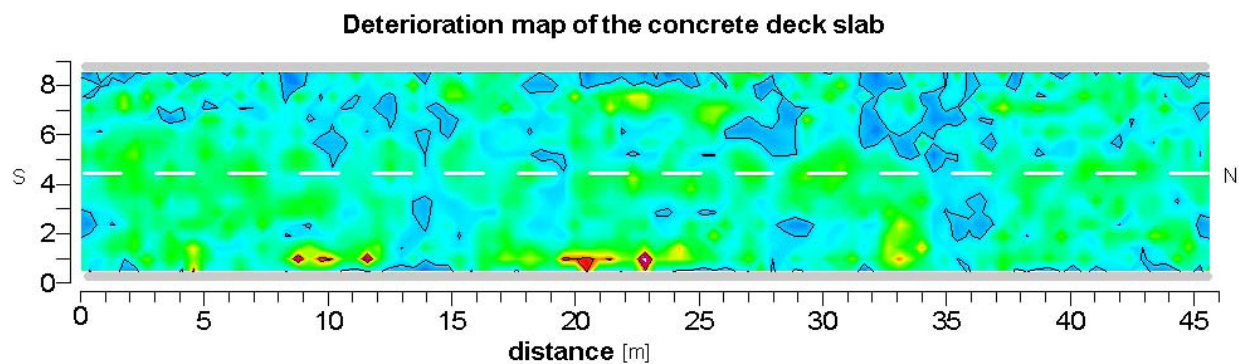
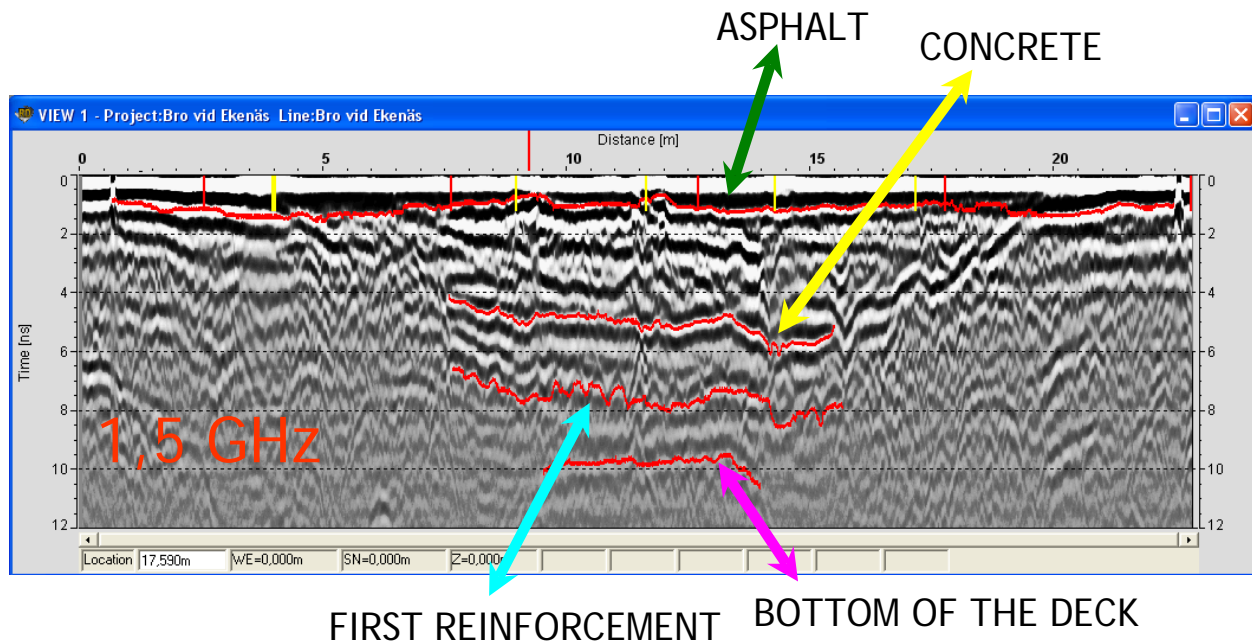


Figure 11: Deterioration map of the bridge deck slab. (Courtesy of Roadscanners Oy).

According to Roadscanners, when investigating possible deterioration indicators in a bridge, it is beneficial to combine GPR analysis from the bridge with core samples and visual observations. This method provides more accurate information about the condition of the deck slab compared to the situation when only a few core samples or just visual observations are used. GPR enables identification of deterioration indicators early enough that rehabilitation is still economical. It also enables more accurate rehabilitation planning. This enables major savings in rehabilitation costs and it cuts down on the amount of extra work during the rehabilitation work.

Examples of GPR imagery and deliverables from the BRO vid Ekenäs bridge measured in Sweden in 2008 by Roadscanners Oy are presented in Figures 12 – 14.



**Figure 12: BRO vid Ekenäs bridge: interpretation of the fundamental GPR quantities
(Courtesy of Roadscanners Oy)**

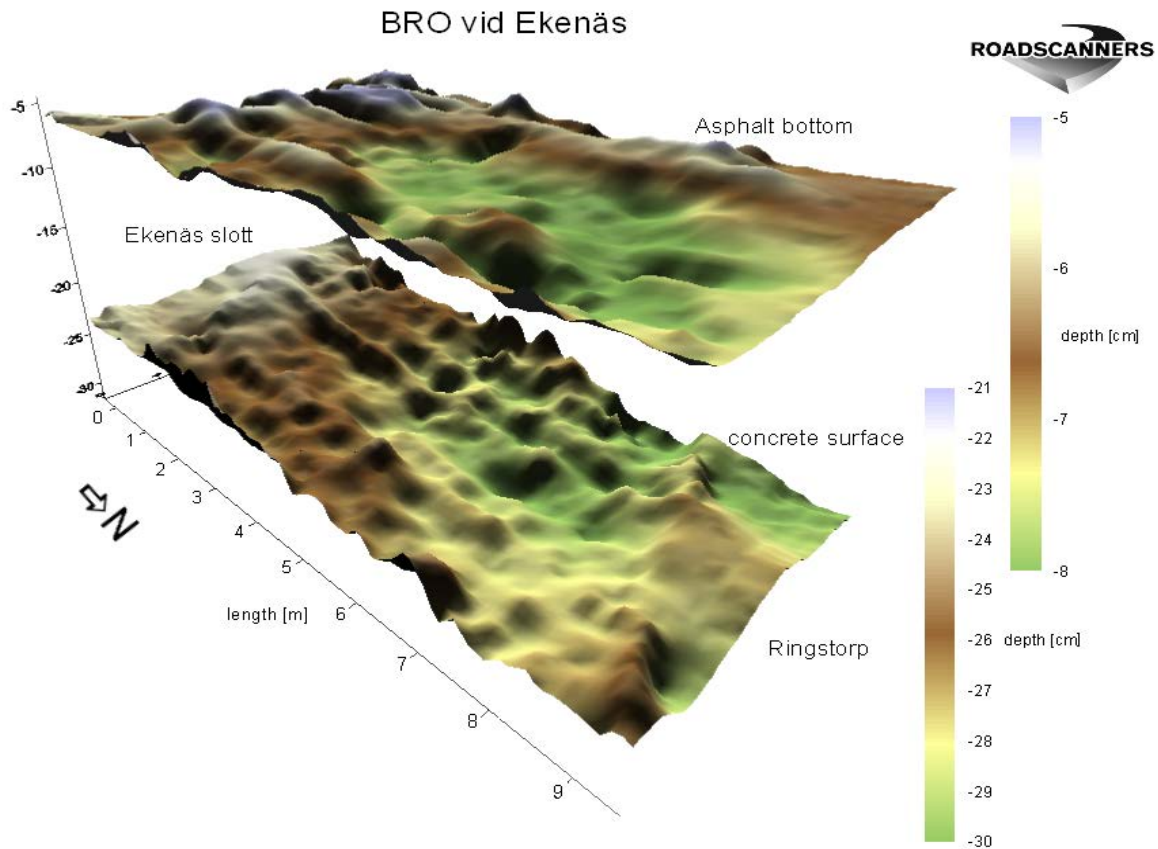


Figure 13: BRO vid Ekenäs bridge: derivative quantities of the surfaces of asphalt bottom and upper concrete layers. (Courtesy of Roadscanners Oy)

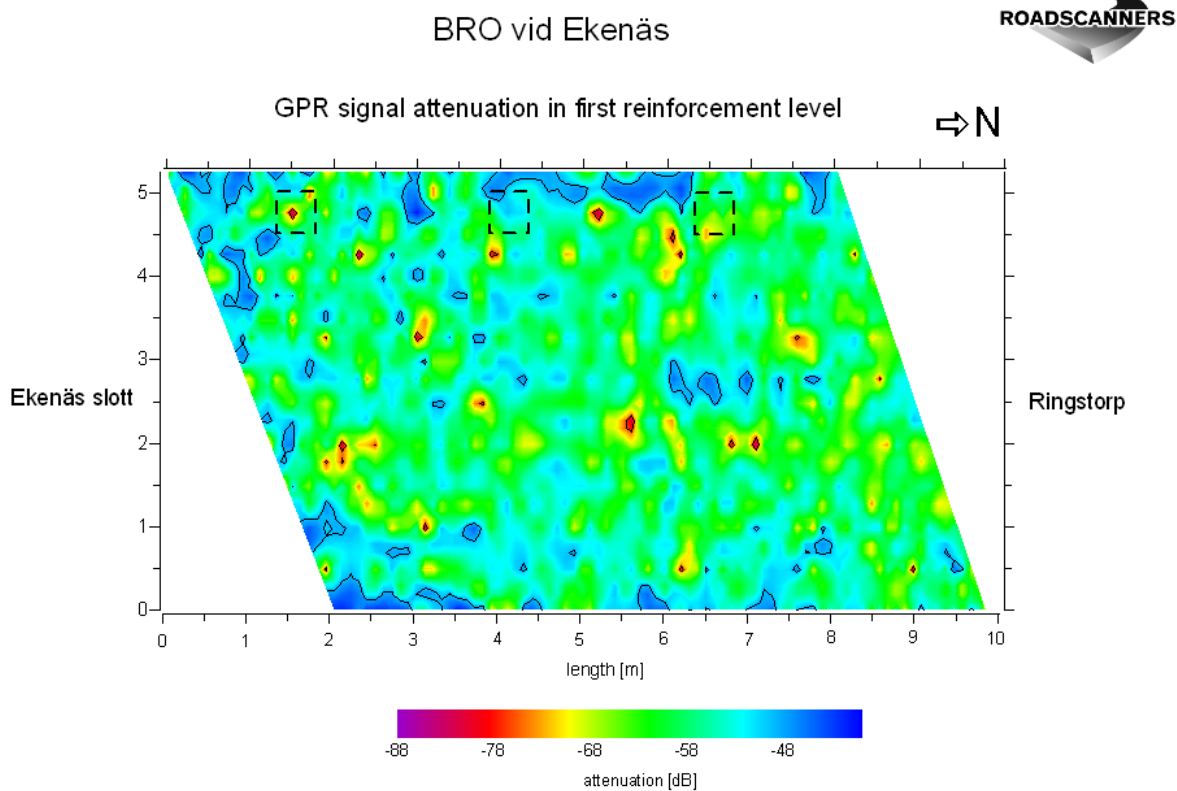


Figure 14: BRO vid Ekenäs bridge: signal attenuation in the first reinforcement level. (Courtesy of Roadscanners Oy)

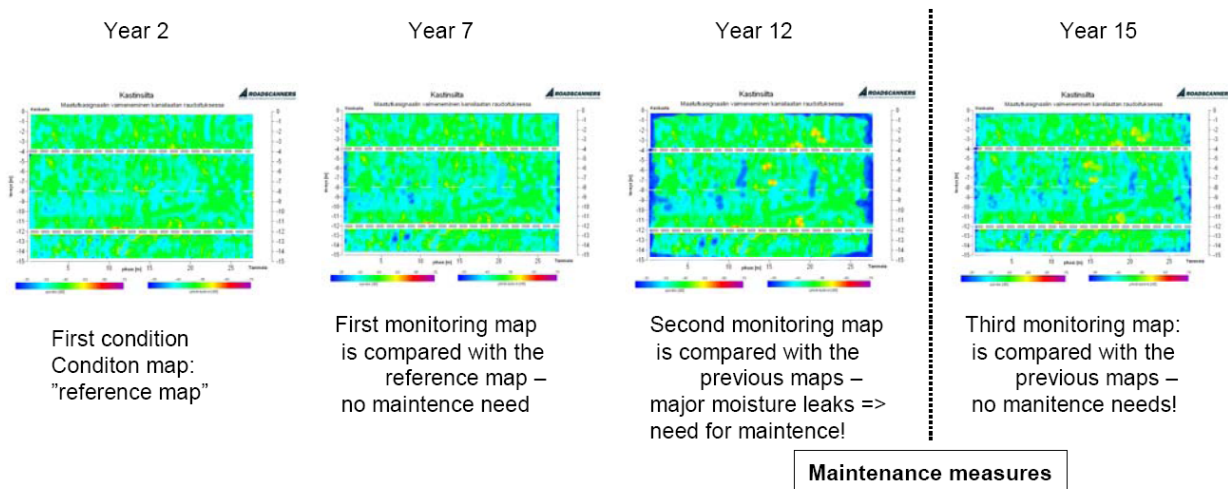


Figure 15: Concept for long-term health monitoring with GPR (Saarenketo, Roadscanners Oy)

GPR Technologies developed, used and tested in other countries

During the last two years an Italian company IDS (Ingegneria Dei Sistemi) has developed a Fast Wave Antenna Technology for GPR measurement. The antenna technology is based on the Dipole-Dipole method. The new IDS solution has several single antennas beside each other with the intervals of 12.5 cm. The width of the measurement beam is 1 m. Maximum measurement speed is today about 10 km/h. In Finland, Roadscanners Oy has during late Winter and Spring 2009 started the first tests using the antennas of IDS. According to Roadscanners, the first results have been very promising.

Towards Sensor Fusion - Newest Related Surveying Technologies and Methods

During the research project it was found that in many cases the damages and features of bridge decks and structures cannot be measured using only one measurement technique. Hence, the use of more than one different measurement technique to determine to current condition of the structure is recommended. In addition to GPR measurement, the following measurement or observation methods can be used:

- Digital photos
- 3D laser scanning
- Thermometer measuring
- Interferometry
- 3D Sonar measurements or
- Other non-contact sensing technologies.

Field Cases

During this project we were not able to make experiments in California. To facilitate experimental validation, and to maximize the benefit of the current research partnership, results are presented here for a University of Oulu research project, “*Calibration of Bridge GPR Measurement in 3D (3D GPR)*” [9]. The research was scheduled 2008-2009 and consists of experiments on the Kajaani Varikko Bridge in Finland. An accurate 3D laser scanning was used as a reference for GPR evaluation. One aim was to create a combined 3D digital measured model incorporating GPR as well as 3D laser scanning. The experiments were carried out during Summer 2009. The idea of this experiment was to study the measurement and consider the utilization of the accurate and complementary 3D measurement of a bridge deck. In the construction phase of the experimental bridge, also the reinforcement of the bridge was scanned by the laser scanning system. The research collaboration with the Bridge Research Project of the AHMCT Research Center at the University of California, Davis, was accepted by the Finnish funder of the 3D GPR project.

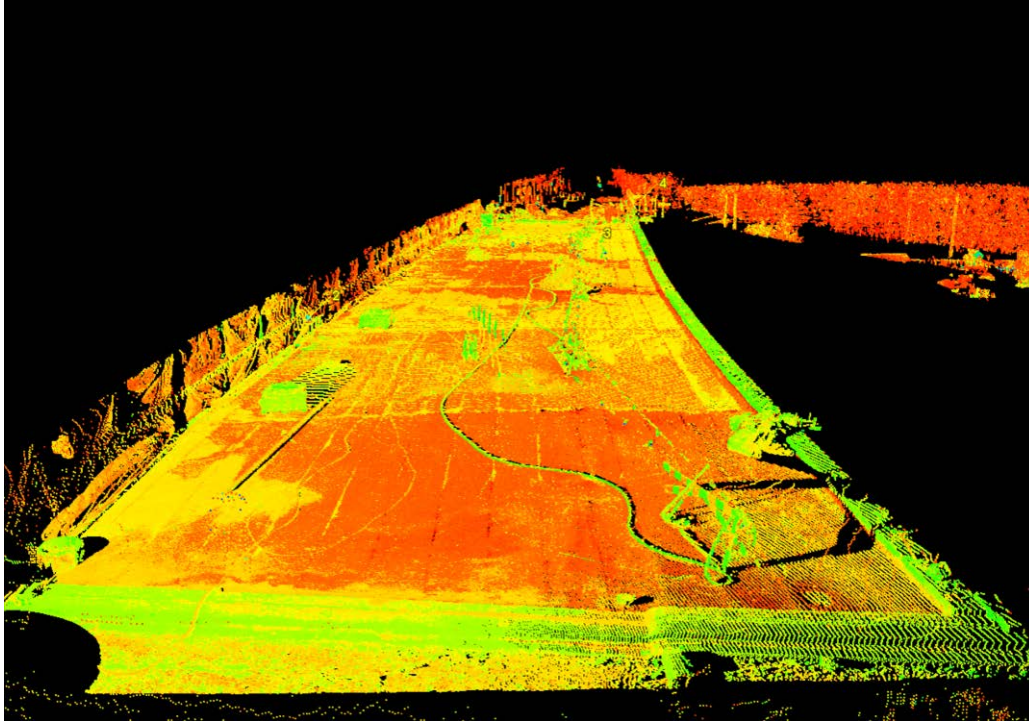


Figure 16: A laser scanned 3D point cloud of the concrete deck surface of Kajaani Varikko Bridge, Finland.

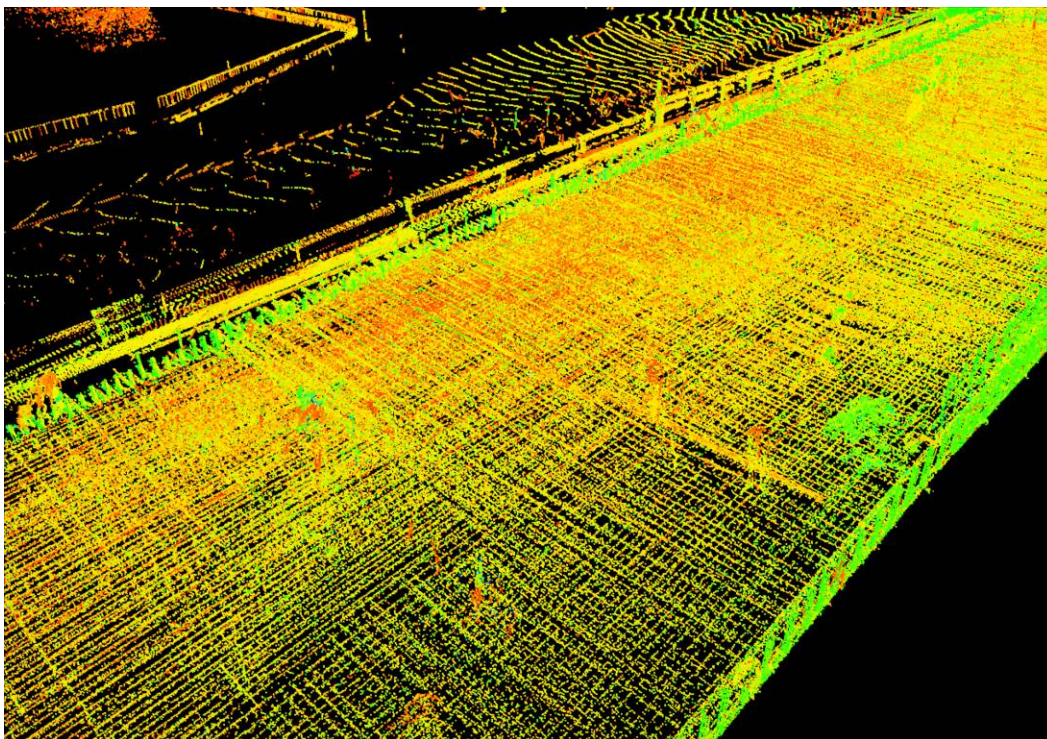


Figure 17: A laser scanned 3D point cloud of the reinforcement of Kajaani Varikko Bridge

Execution of laser scanning

The geometry of the bridge was measured by laser scanning the visible surfaces by a Zöller & Fröhlich Imager 5006 laser scanning system (see Figure 19) (measurement speed 500,000 points/s, maximum range 79 m, accuracy of single point measurement varies typically $\pm 2... \pm 7.5$ mm depending the distance as well as color of the object). Nineteen (19) different scans were executed up and down the bridge deck. The point clouds measured were transformed to the coordinate system of the bridge using target points. The registration was made by Laser Control software of the Zöller & Fröhlich system. The results were compared to the earlier laser scans made in 2007 during the construction phase of the bridge.

The coordinate transformation to the site coordination system was determined by measuring the three fixed points using Leica TCRP 1200 total station (Figure 18). The same points were also measured by the Trimble R8 RTK-GNSS system to determine the same transformation to the GPR measurement system.



Figure 18: Leica TCRP 1200 total station



Figure 19: The laser scanning was executed using the Zöller & Fröhlich Imager 5006 system by a measurement consultant (Mitta Oy)



Figure 20: Measuring under the bridge deck



Figure 21: One of the target points of the laser scanning system



Figure 22: Laser scanning on the bridge deck

Execution of GPR measurement

The measurement object was the rebuilt part of the deck of Kajaani Varikko bridge. The measurements were made using the system of Geophysical Systems Inc.'s (GSSI) GPR device with 1.5 GHz and 2.6 GHz antennas. The GPR device was positioned in 3D using the RTK-GNSS-method and the Trimble R8 GNSS system of the University of Oulu. The length of the bridge was 66.75 m, width 14.3 m and area 954.45 m². Measuring lines were determined with 25 cm intervals for the whole width of the deck. The measurement frequency was 100 measurements/m. Also a new system developed by IDS (Ingegneria Dei Sistemi Inc.) using a special dipole-dipole antenna construction was tested. The frequency was 2 GHz and the antennas were spaced at 10 cm intervals.

The results of the GPR measurements were transformed to the coordinate system of the bridge using the seven parameter Helmert transformation. The interpretation of the GPR observations was made by Roadscanners using Road Doctor software.



Figure 23: The GPR measurement was made using the GPR system of GSSI (this photo is from a different bridge, Courtesy of Roadscanners Oy)



Figure 24: The deck was also measured using the new system of IDS (Ingegneria dei Sistemi Inc., Roadscanners)

Combination of the measurement results

The GPR measured as well as laser scanned point clouds and surface model were combined together to create a 3D digital model. The laser scanned point cloud was compared with the earlier point clouds scanned in 2007 during the construction work. The point clouds and surfaces of the GPR measurements were compared to the 3D surfaces measured by the laser scanning system.

CHAPTER 3: RESULTS

Results of Laser Scanning

According to the laser scanning results, the deck of the bridge has settled when comparing to the results made in 2007. The deformation and tracking due to the traffic can be observed from the laser scanned point cloud.

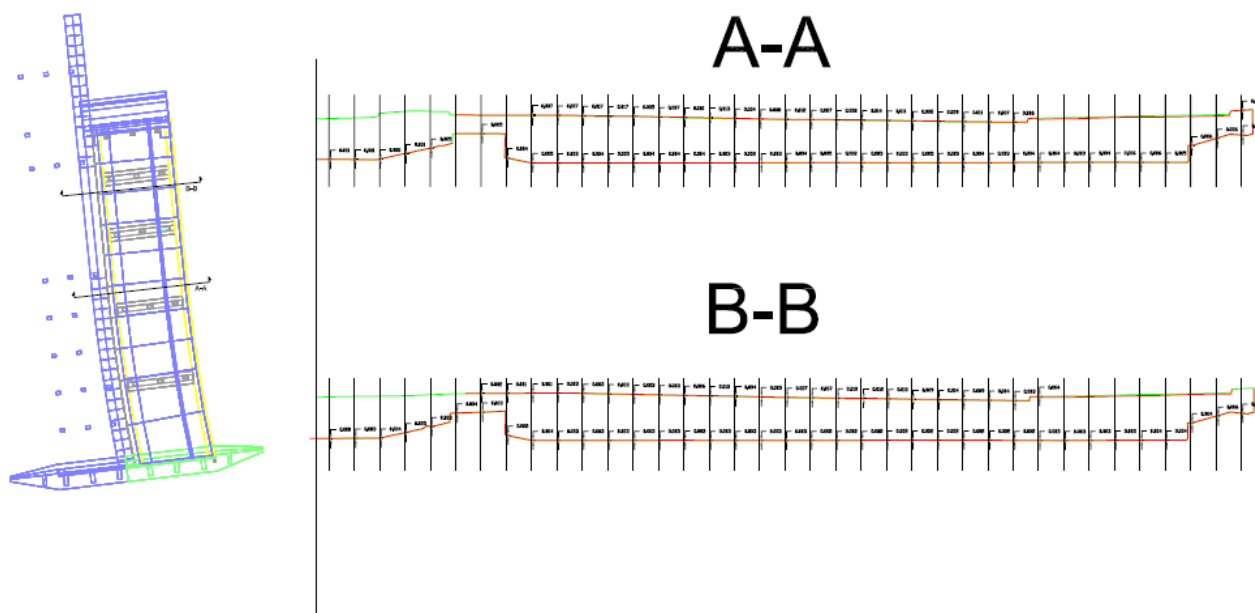


Figure 25: The comparison of the laser scanned results (cross sections A and B) measured in 2009 and 2007

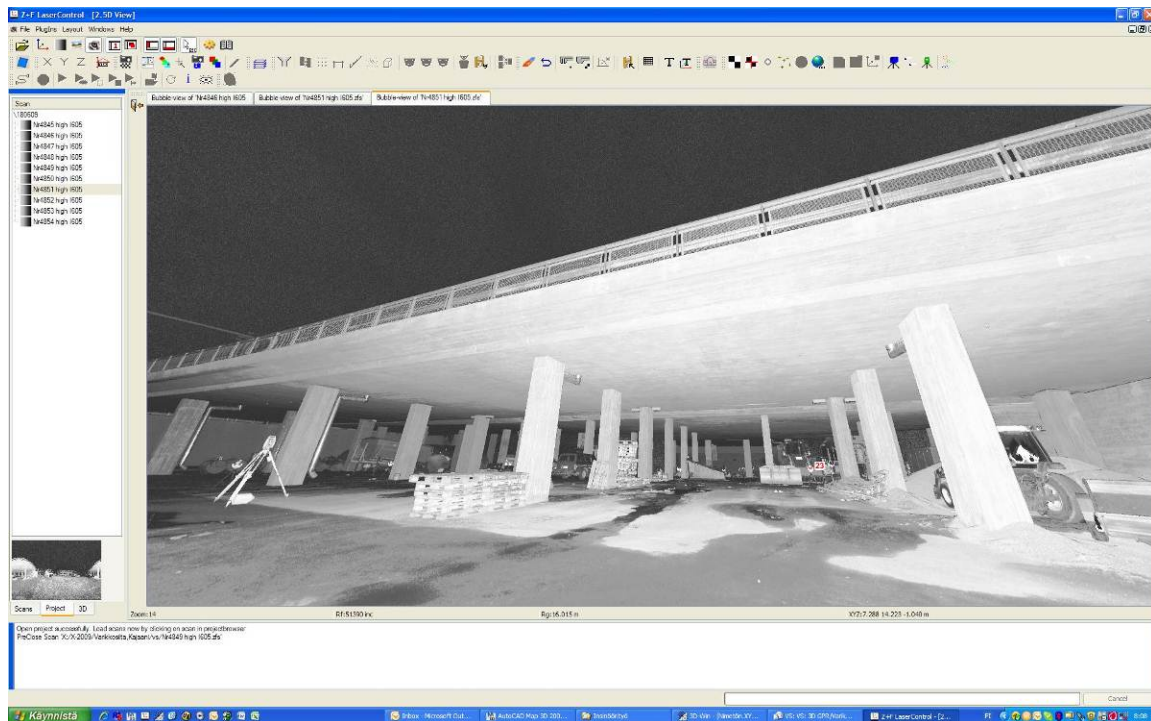


Figure 26: A photo taken by the camera of the laser scanning system

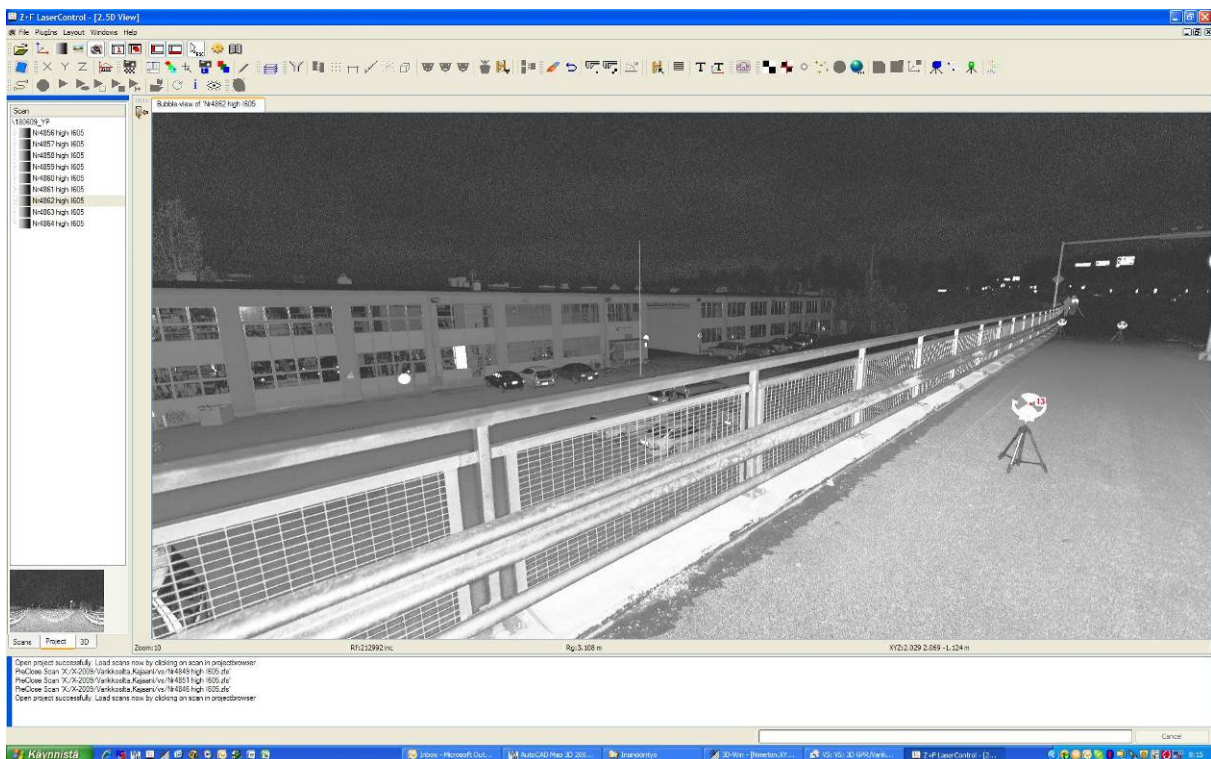


Figure 27: A photo taken by the camera of the laser scanning system

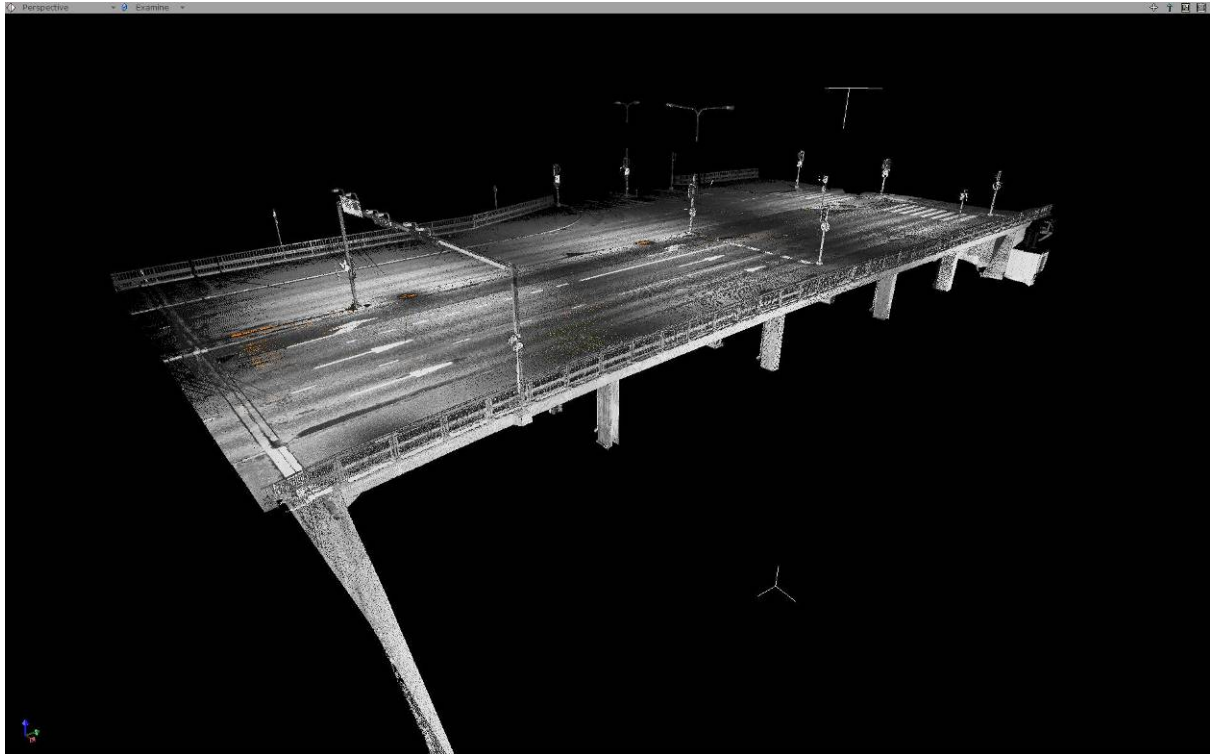


Figure 28: The registered point cloud of the new 2009 measurement

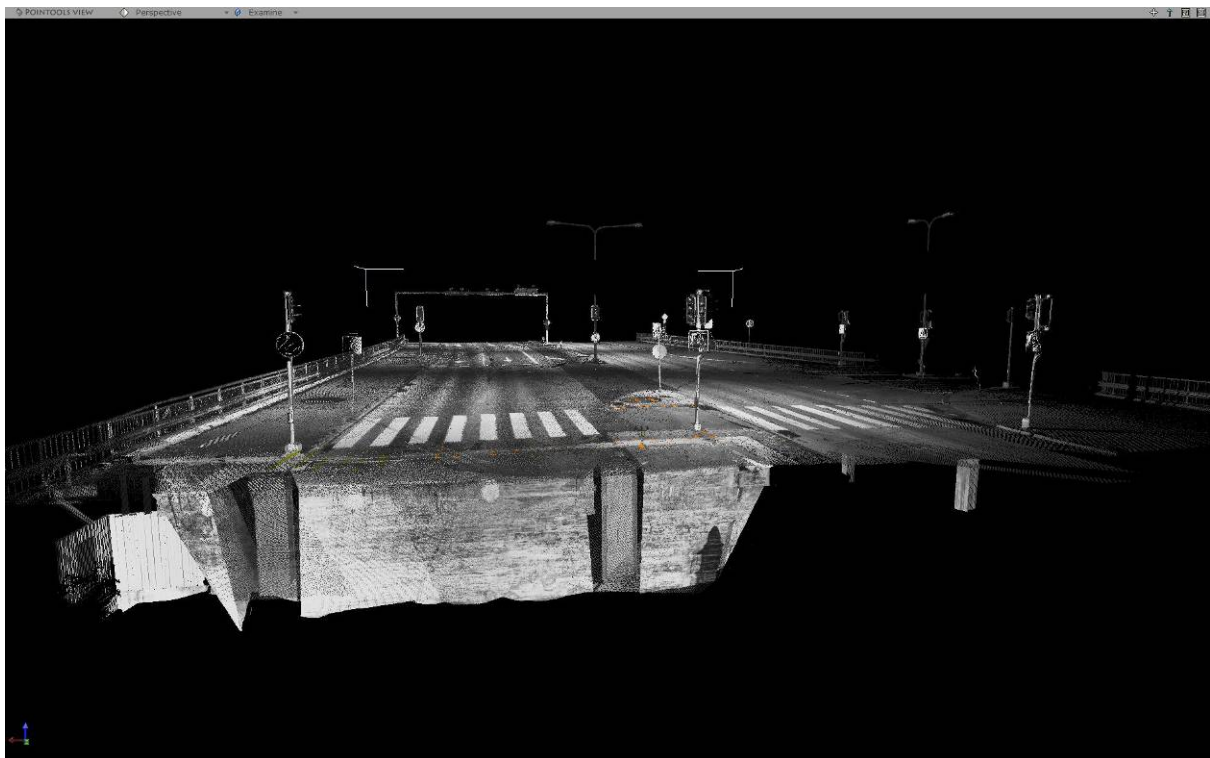


Figure 29: The final point cloud of the new 2009 measurement



Figure 30: The final point cloud of the new 2009 measurement

Results of GPR Measurements

From the raw data the thickness of the asphalt layer and the upper reflexes of reinforcement were analyzed. The signal absorption of the reflexes of reinforcement were calculated and illustrated onto the map picture below so that possible damaged areas can be positioned. The results are calculated from the results of 1.5 GHz and 2.6 GHz observations. For the interpretation the laser scanning report and some extra pictures were utilized.

According the results, the thickness of the asphalt layer was 9-11 cm. The thickness of the west lane was only 5-6 cm. The most thickness was observed from the East lane, where it was 12-14 cm. On the sidewalks the thickness was only 3-4 cm.

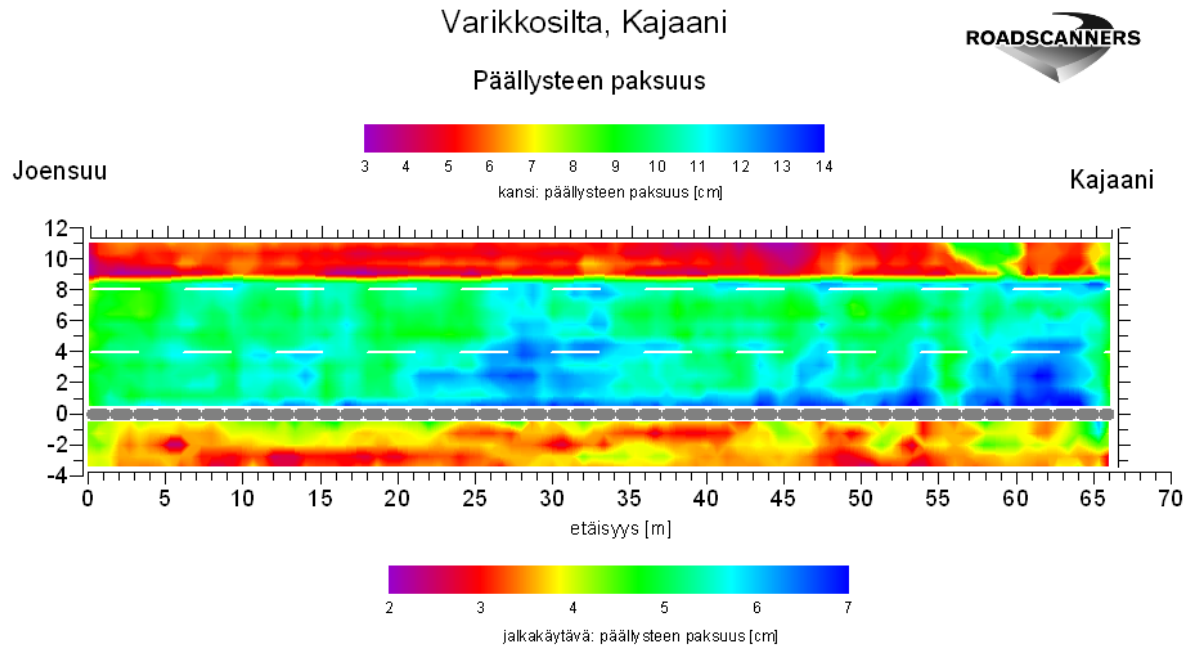


Figure 31: The thickness of the pavement measured by the GPR method (Courtesy of Roadscanners Oy).

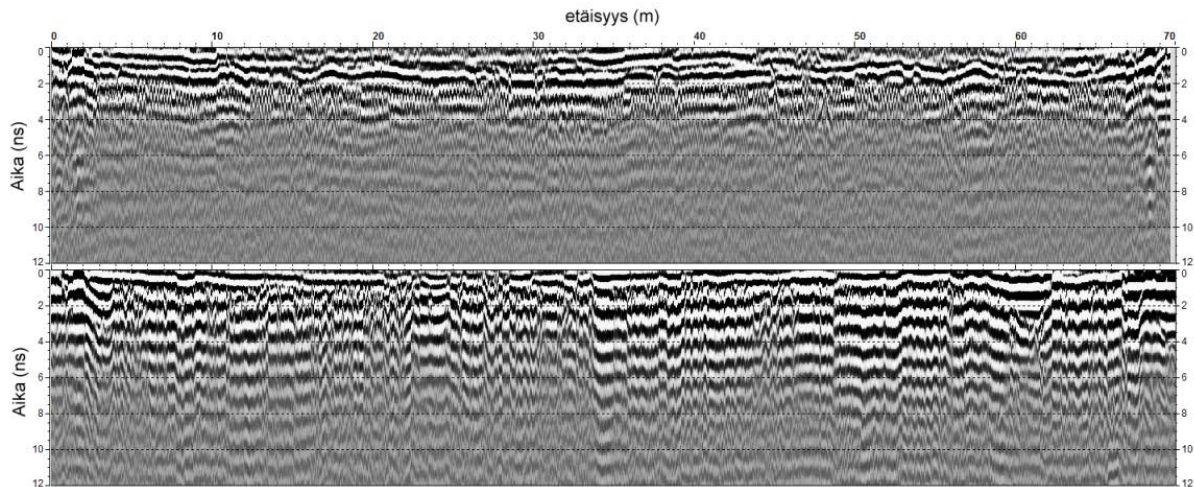


Figure 32: Two slitting from the GPR observations (frequency 1,5 GHz). The upper picture is from the right lane of the bridge (when driving towards Kajaani), and lower picture from the left lane including also larger noise among the observations making it difficult to observe different structures (Roadscanners Oy).

According to the GPR results, there can be possible moisture damage areas in the deck. The blue areas in the picture are indicating to have more moisture in the deck. There was more noise (random errors) among the observation of the left lane. The reason for that was unidentified.

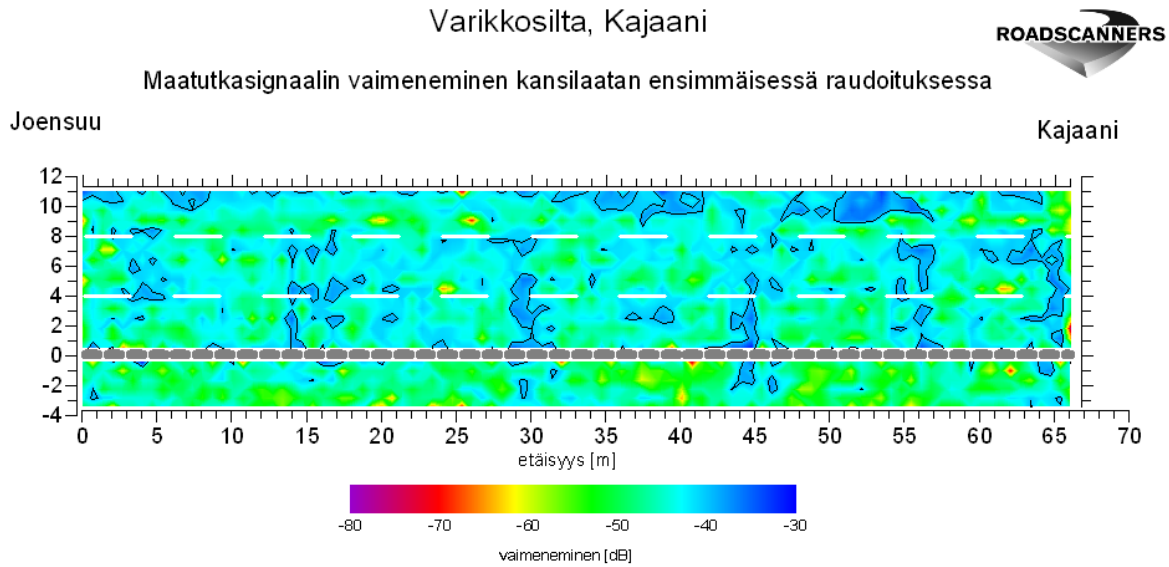


Figure 33: The absorption (degradation) of the GPR signal in the deck (Courtesy of Roadscanners Oy).

The absorption (degradation) of GPR signals were calculated using Road Doctor software. The first reinforcement was located 15 cm from the upper surface of the deck. The positions of the main foundations can be seen from the observations. In the left side of the left there was observed clear anomaly due to moisture or some other structure.

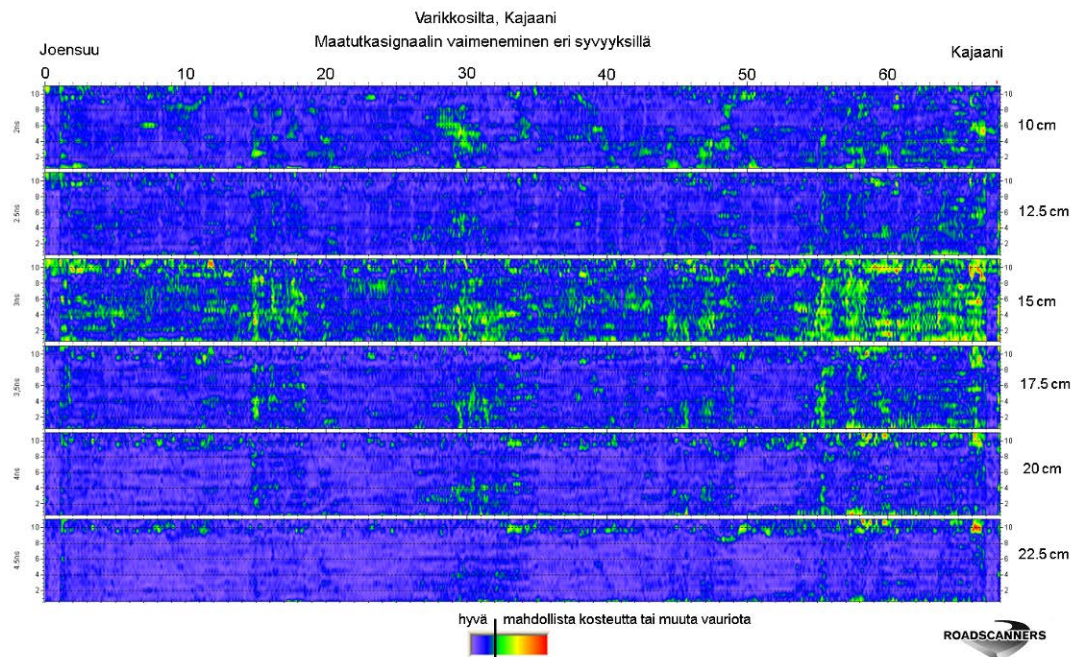


Figure 34: Absorption of the GPR signal at different depths in the deck below driving lanes (Courtesy of Roadscanners Oy).

The complete analysis of the IDS measurement results is not included in this report. The absorption (degradation) of some GPR signals by IDS was calculated by the Road Doctor software. According to the Roadscanners the results seemed to be very good and correlated also with GSSI results, but were even more accurate.

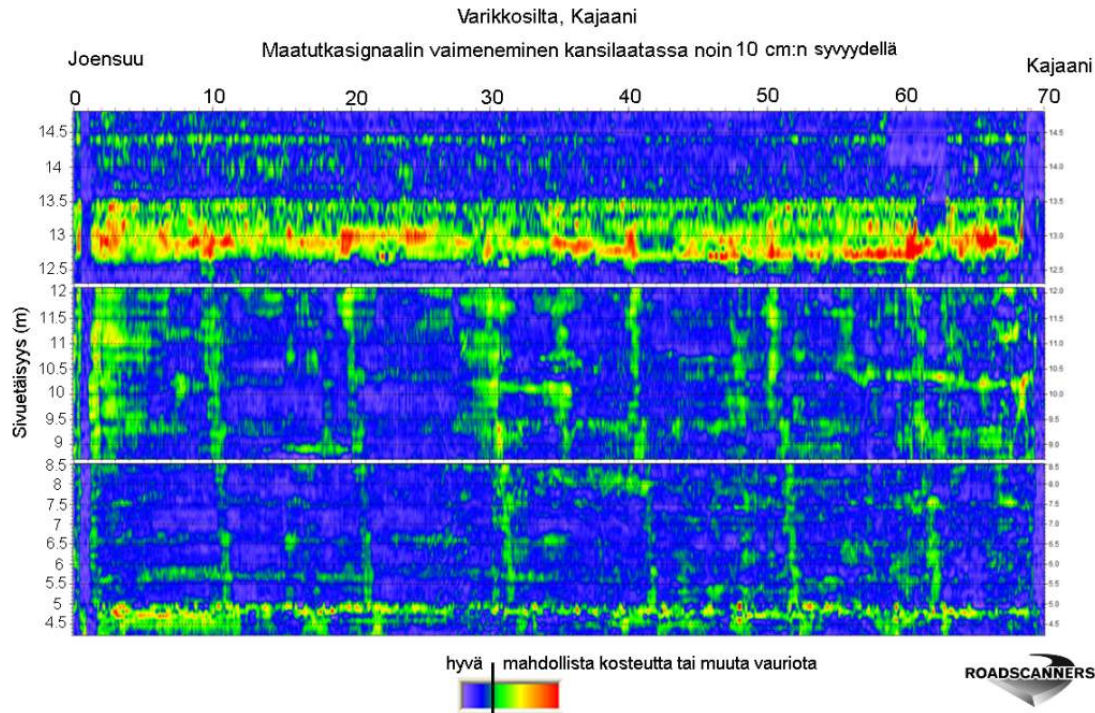


Figure 35: Absorption of IDS device GPR signal at different depths in the deck below driving lanes (Courtesy of Roadscanners Oy).

Combined measurement model

Different examples from the results of combined laser scanning and GPR measurements are introduced below. Based on the visual observations, the point clouds match each other with a fairly good accuracy.

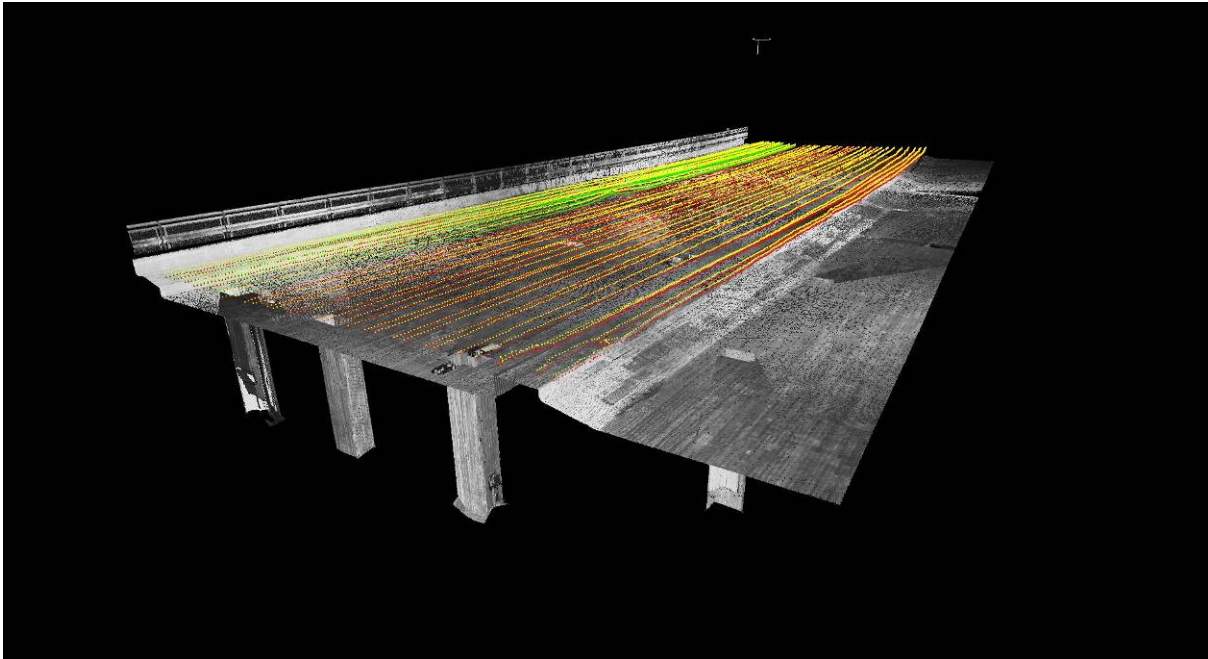


Figure 36: A combined 3D point cloud. The colored point clouds are from GPR measurements, the grey one from laser scanning.

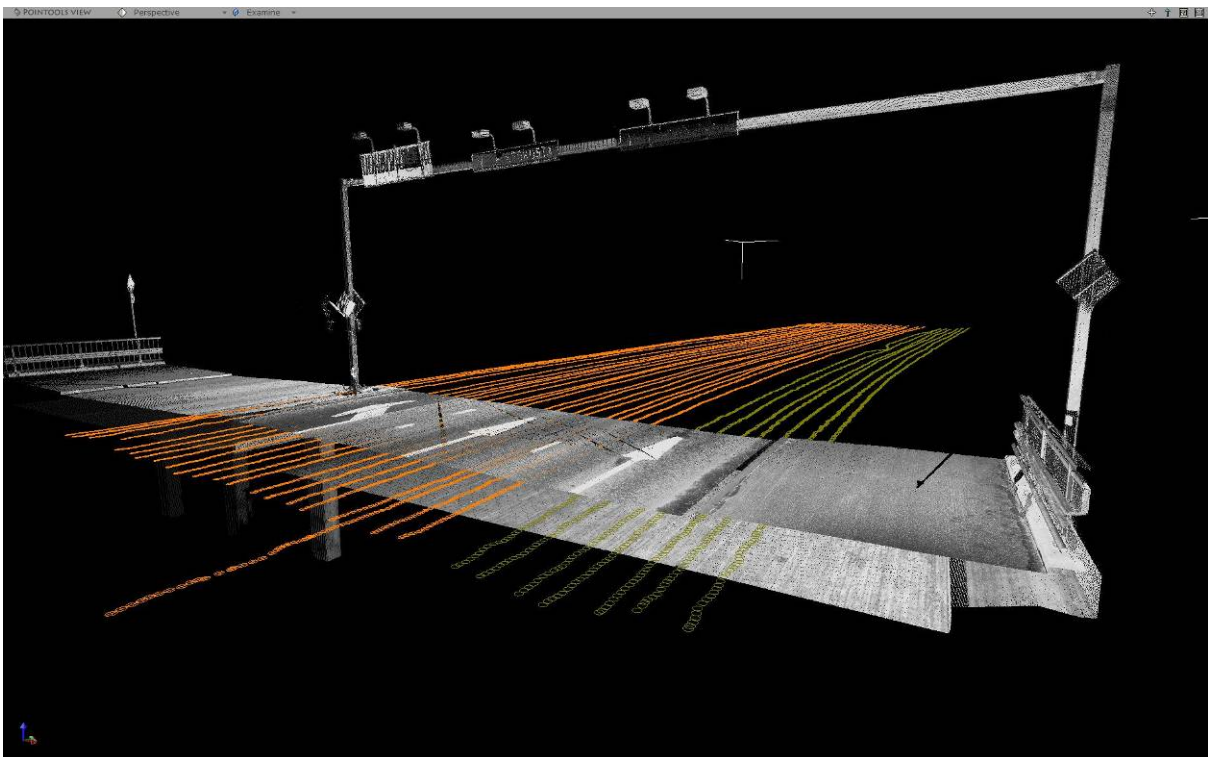


Figure 37: A combined 3D point cloud. The colored point clouds are from GPR measurements, the grey one from laser scanning.

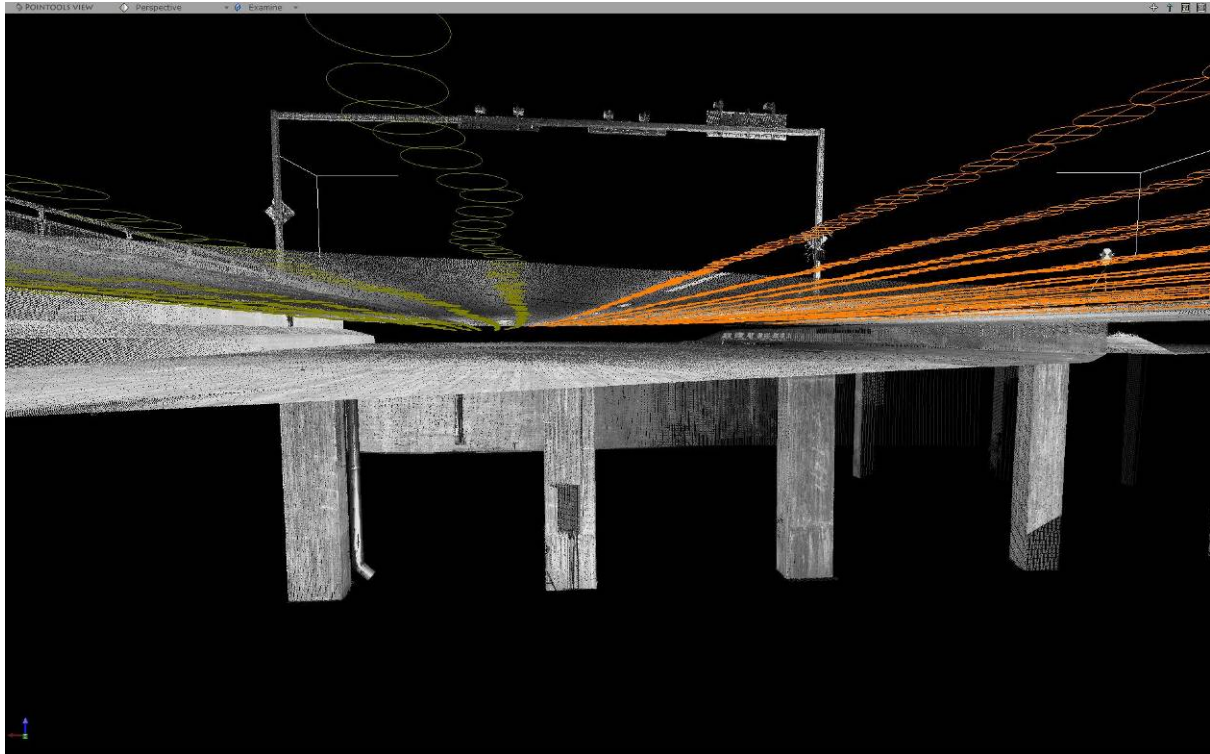


Figure 38: A combined 3D point cloud. The colored point clouds are from GPR measurements, the grey one from laser scanning.

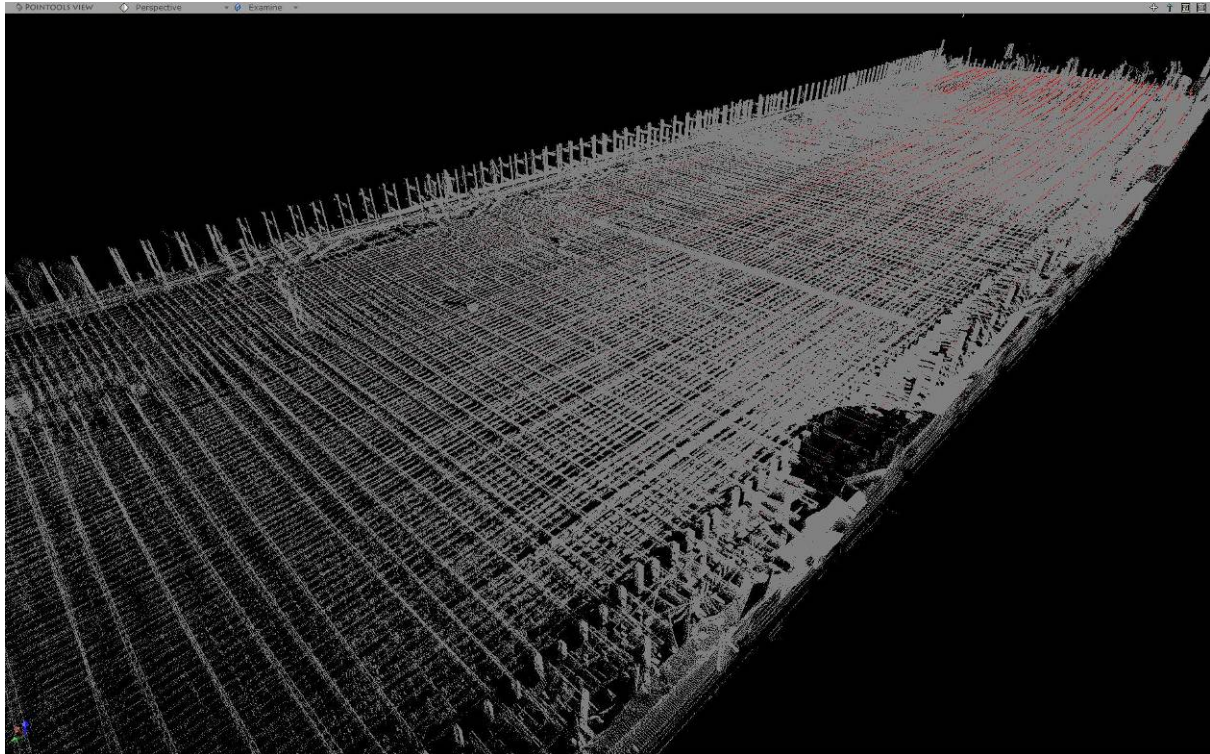


Figure 39: A combined 3D point cloud of the reinforcement. The red point clouds are GPR measured and grey one laser scanned.

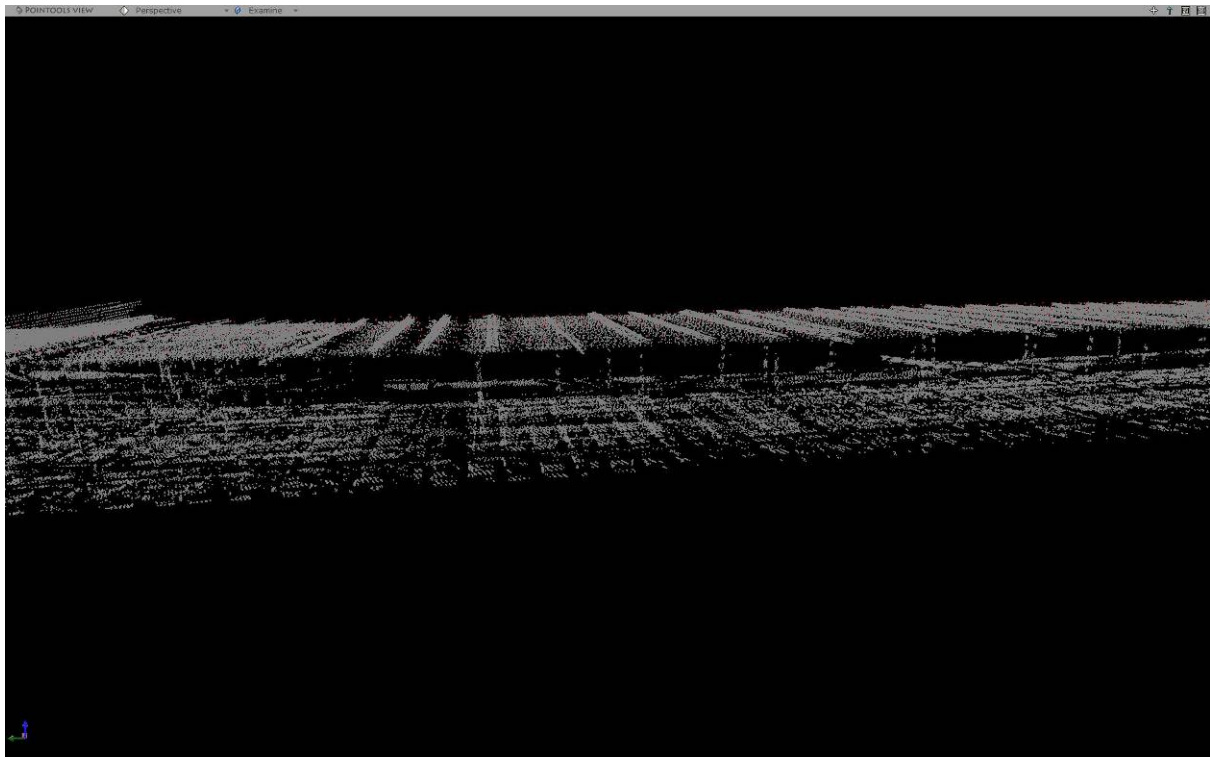


Figure 40: A combined 3D point cloud of the reinforcement. The red point clouds are GPR measured and grey one laser scanned.

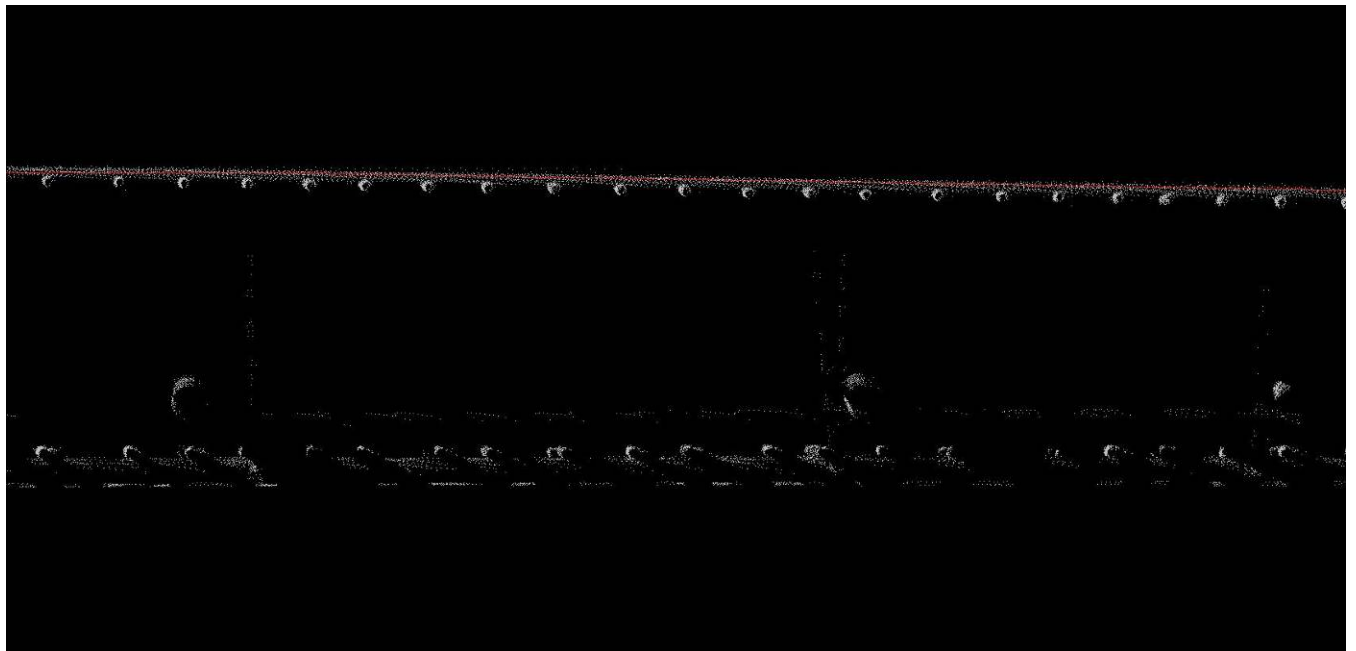


Figure 41: A combined 3D point cloud of the reinforcement. The red point clouds are GPR measured and grey one laser scanned.

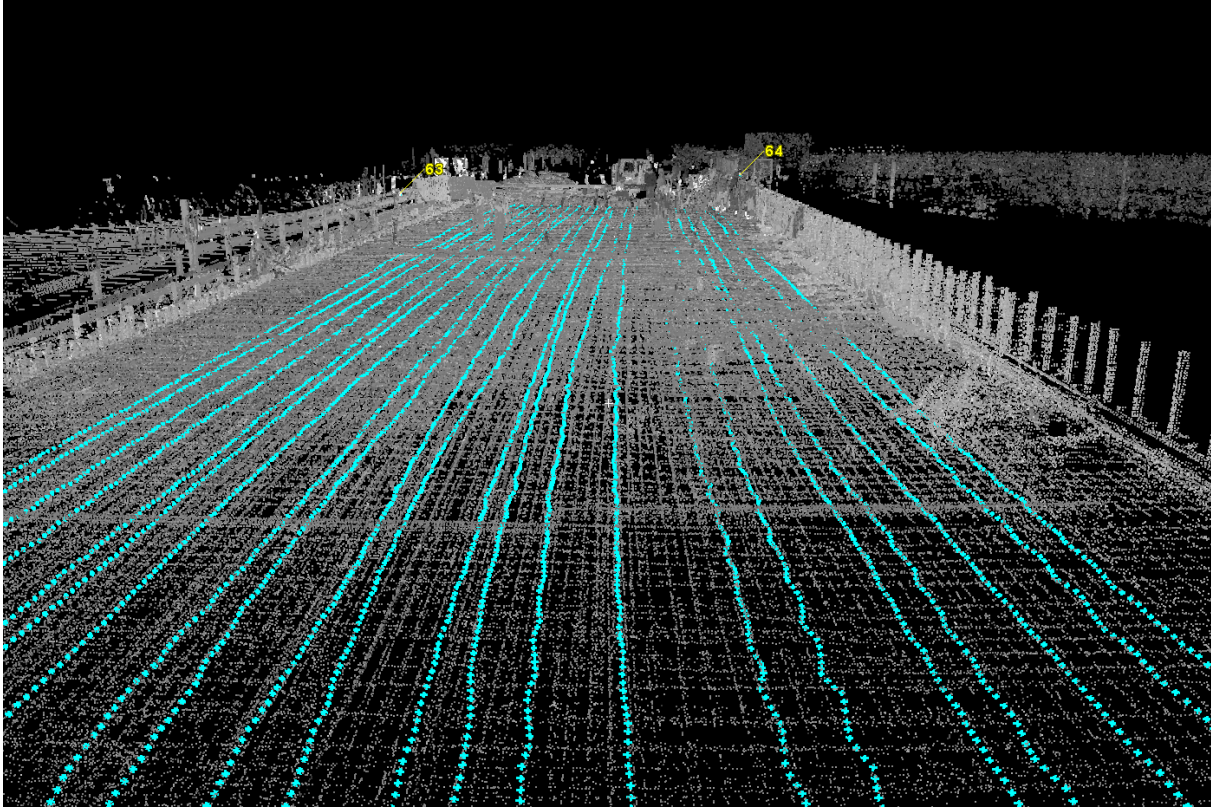


Figure 42: A combined 3D point cloud of the reinforcement. The cyan point clouds are GPR measured and grey one laser scanned.

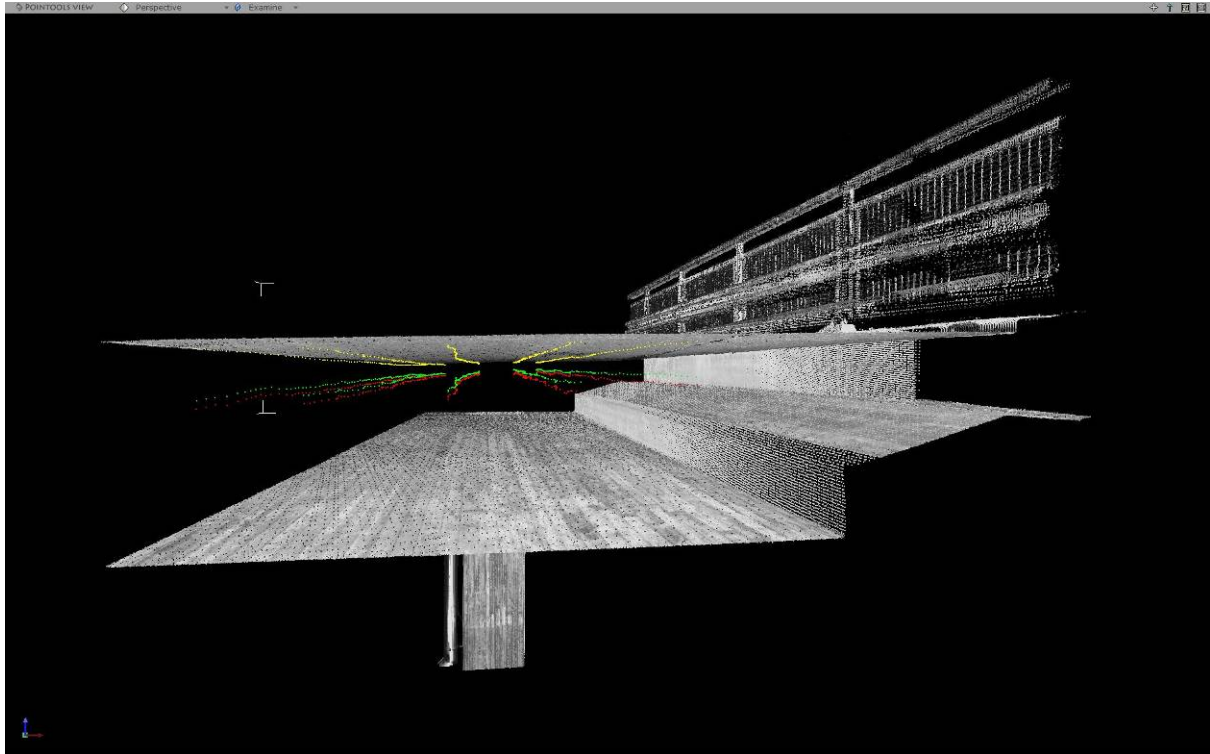


Figure 43: A combined 3D point cloud. The colored point clouds are from GPR measurements, the grey one from laser scanning.

CHAPTER 4: CONCLUSIONS

Primary deck damages and problems of bridges in California are, according to the reviewed literature, cracking (subsurface), spalling of concrete, air-filled delaminations, rebar corrosion, moisture content, and other physical state of the concrete (e.g. scaling). Secondary features and damages are, for example, pavement thickness, concrete surface location, rebar covering, rebar locations, and locations of other structures or parts.

From the information gathered from the other sources as well as from the 3D GPR experiment made in Finland, the GPR method still seems to be developing ahead also in the application area of concrete bridge deck measurements. In future, this type of measurements can also be done three-dimensionally and thus can be connected and compared with other 3D measurements and designed product models.

Currently it seems, as Saarenketo [20] has indicated, that GPR alone cannot provide sufficiently information on the damage in the deck. Instead, it can be an excellent tool for the initial mapping and specifying of locations where other non-destructive evaluation methods and limited ground-truth (core sampling) testing can be used to verify the problems.

According to Roadscanners, the main advantages of GPR measurement compared to impact echo measurements are low scattering and coupling, high acquisition rate, high-speed inspection, low reflection at the air to concrete interface, insensitivity to environmental conditions, and sensitivity to water and chloride conditions, promoting easily detecting delaminating.

The use of traffic speeds is naturally very important for the wider utilization of GPR technique; however, there is a group of open questions concerning the accuracy and reliability as well as the information extent of the measurements. There have been some GPR measurements with traffic speeds on bridge decks.

During the research project it was found that in many cases the damages and features of bridge decks and structures cannot be measured using only one measurement technique. Hence, the use of more than one different measurement technique to determine to current health of the bridge deck is recommended. In addition to GPR measurement, the following nondestructive evaluation (NDE) or measurement or observation methods can be used:

- Digital imaging
- 3D laser scanning
- Thermal measuring
- Interferometry
- 3D sonar measurements or
- Other non-contact sensing technologies.

This leads to numerous possibilities for future research, for example:

- how to simply connect digital photos to the laser scanned point clouds and surfaces?
- how to connect different GPR measured material features and moistures to the 3D point clouds and surfaces?
- how to use 3D laser scanned and GPR measured 3D information model in 3D model-based bridge design software?
- how to connect underwater 3D surfaces measured by sonar techniques to the laser scanned models?
- how to utilize thermal measuring to add more information and reliability into GPR analysis and interpretation?

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APPENDIX A: RESOURCES

Companies

- Geophysical Survey Systems, Inc. (GSSI), USA – the biggest manufacturer in the world
- Sensors & Software, Toronto

Service Providers

- Resource International, Inc.
- Roadscanners Oy
- Fugro
- Penetradar Corporation

Software:

- GSSI, Bridge Scan, RADAN (Radar Data Analyser for Windows NT)
- Ken Maser, own software, proprietary, not open for common use
- Karl Sandmaier, Reflex software, processing software, no maps etc.
- Road Doctor, Roadscanners Oy, Finland, may have the most features and functions.

GPR Experts and Measuring Consultants

- The BAM (Federal Institute for Materials Research and Testing), Berlin, Herbert Wiggensauser
- Empa, Switzerland, Johannes Hugenschmidt
- LCPC (Laboratoire Central des Ponts et Chaussées), France, Xavier Derobert
- Rutgers University, Nenad Gucinsky
- Francisco Romero, background in GSSI and UIT, nowadays working for the Rutgers University
- Ken Maser, Infra Sense, Bridge Alliance chief
- University of Vermont, Prof. Dryver Huston
- Lawrence Livermore National Lab (LLNL), California, IRIS, PERES
- Glenn Washer, Missouri, modeling expertise

APPENDIX B: GPR QUESTIONNAIRE TO ROADSCANNERS

The needed and useful tests to achieve the main goal of the study. Recommendations for:

- test methods
- GPR types to be tested
- Technologies to be use
- Companies with whom the tests are to be executed
- Software's to be used for processing, modeling, analysis
- etc.

The primary bridge deck problems in California are:

1. Cracking (strong majority)
2. Spalling
3. Delamination

SMSI is interested in any advancement above the state-of-practice in the US. Areas of interest include:

Question:

- Quality / capabilities vs. impact echo

Evaluation of Roadscanners:

- Low scattering and coupling unlike acoustic waves
- High acquisition rate
- High speed inspection
- The reflection at the air to concrete interface is low
- insensitive to environmental conditions
- sensitive to water and chloride conditions: easily detecting delamination

Question:

- Any ability to automate the analysis of GPR images. Any way to simplify the analysis.

Evaluation of Roadscanners:

- Semi-automated layer tracking, automated analysis is possible to program to Bridge Doctor (?)
- In a long term this is possible – but it has to be kept in mind that you have to process the data only once in bridge deck, after that software can compare the old interpretation and highlight changes

Question:

- Can GPR provide early indications of cracking? Same for spalling? Delamination seems like it can be done. What would GPR image provide if there were only cracking, but no de-bonding / delamination?

Evaluation of Roadscanners:

- Yes, if distance with parallel lines collected is kept small (10-15 cm). Requires possible also some reference method too??

- Vertical cracking should be identified easily but horizontal crack detection (early phase delamination) can have difficulties especially with lower frequencies. But you should be able to see indirect changes in concrete EM properties in these areas.

Question:

- Why use GPR instead of Impact Echo (IE). What conditions / bridge types favor one over the other? What pros / cons?

Evaluation of Roadscanners:

- See answers in the first question. GPR sees also through asphalt which IE cannot do. IE is also a point like method

Question:

- If did apply GPR in the field, how to really know what is there? Goes toward calibration, and other methods of validation (coring, chain dragging, etc.), and if these are required in any case, then why use GPR?

Evaluation of Roadscanners:

- GPR users must be experienced and have good training to do the job. Any reference data is good to have even results from visual inspections. GPR can be used as the first measurement to find locations of having some kind of problems. Core taking or some other point like measurement can then be better addressed to the right place to bring some more information. This way a lot of money is saved.
- More research on GPR is still needed – however GPR sees early phase “infections” i.e. areas that are not yet damaged but soon will be – this is an issue for bridge maintenance strategy

Question:

- Can it be done fast enough to avoid lane closure, but still provide sufficient image for analysis? Would like highway speed (say 40 – 60 mph), or at least fast enough for a moving / rolling closure.

Evaluation of Roadscanners:

- Depends on antenna system used and how many samples are collected and how deep we want to see. More samples more detailed information from the bridge. In general, highway speed is possible if using 1.0 GHz air-coupled antenna, but then the sample rate is quite low. Good quality data about 30 mph. With 3D system the measurement speed is about 5-10 mph, but interpretation is much faster and parallel lines can be collected in 10-15 centimeters interval.
- GPR data collection units develop fast and in the future this will not be a problem...

Question:

- What approaches can we as researchers provide to help out with calibration? E.g. (per RH), combining with laser scan.

Evaluation of Roadscanners:

- Information about materials used. Collect information about all other references available. Combining the results with laser scan would be very good.

Question:

- What advancements provided by Finland in general? Oulu? RoadScanners? Others?
Particularly on the analysis / automation of results, but anywhere else also.

Evaluation of Roadscanners:

- Roadscanners has done a lot of research on this topic and measured about 60-70 bridges in Finland and has tested several different GPR systems to find the best that works on bridges. Roadscanners also has good interpretation tool Bridge Doctor to interpret and analyze the data.