INSPECTION OF PRESTRESSED CONCRETE ROAD BRIDGES BY ULTRASOUND 3D TOMOGRAPHER SYSTEM

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ABSTRACT

This article introduces ultrasound 3D Tomographer system and its application in inspection of prestressed concrete bridges. The ultrasound 3D Tomographer system enables a graphic reconstruction of the internal structure of a tested object and locating of poorly or non-injected tendon ducts. In addition the ultrasound 3D Tomographer system enables a precise location of casting defects, prestressing steel, rebars, pipes etc which exist in the concrete. Ramboll engineers have already successfully applied the use of the ultrasound 3D Tomographer system in about 20 different inspection cases of prestressed bridges.

Nowadays there are at least dozens of thousands of aging post-tensioned bridges built mostly the 1960-70's. In part of the bridges the prestressing system was applied in a faulty manner due to various reasons. In some cases, when stresses from the environment were added to faulty construction works, bridges have collapsed.

As many of the post-tensioned bridges have already reached their renovation time the condition of the bridges should be assessed. Usually, this is done by performing bridge special inspections. Unfortunately, “traditional” inspection techniques do not provide clear indication regarding the condition of the prestressing system which constitutes an internal system inside the reinforced concrete member. The ultrasound 3D Tomographer system enables to perform exactly this crucial task.

1. BACKGROUND AND THE CURRENT SITUATION

First of all, when discussing the inspection of prestressed concrete bridges we refer mostly to post-tension bridges. In the post-tensioning system we induce compressive forces in a concrete structure by tensioning steel tendons/strands/bars which are placed in ducts embedded in the concrete structure. The tensioning steel will be tensioned after the concrete structure has been sufficiently cured and has reached the designed level of compressive strength. In the end of this process the ducts will be injected by cementitious based grout and tensioning steel will be cut at anchorage points.

At present there are dozens of thousands (if not more) of aging post-tensioned bridges globally. They are often located in major transportation routes and sometimes spanning at great heights over rivers, valleys or other routes. Maintaining and monitoring the condition of those structures should be a great concern for safety and economical reasons.

Condition estimation of prestressed bridges is already a first priority task and challenge in the world due to the following main reasons:

The prestressing technique started being widely used during the 60-70's and was not always implemented successfully. Also the techniques, different materials and quality control measures at that period were not of sufficient level. The time for renovating those bridges has already come and the renovations need to be carried out now and in the near future. In Finland as well as in other countries in the world severe durability problems regarding the condition of prestressing steel have already been discovered. In some cases in the USA, England and elsewhere, the durability problems resulted in collapses of bridges.

Conventional bridge inspection methods do not provide estimation regarding the condition of grout injected ducts. As will be explained later on, in case ducts injection is faulty, i.e. there are voids in the duct, corrosion of the strands might occur and significantly endanger the durability of the bridge. There are also structural functionality aspects to faulty grout injection.

As appears from the above mentioned paragraphs the need for efficient systems allowing the “look inside” ducts of prestressing systems is real and urgent.

Ramboll Finland engineers Guy Rapaport and Tuomo Koskela have already successfully implemented the use of ultrasound 3D Tomographer system in nearly 20 prestressed bridge condition estimations, especially of the anchoring zone of the tendons which is the most difficult for inspection and yet the most subjected to environmental stresses such as de-icing salts.

The ultrasound 3D Tomographer system and its implementation in inspection of prestressed bridges will be presented in this article.

2. RISKS AND TYPICAL DURABILITY PROBLEMS OF PRESTRESSED BRIDGES

The most influential factor which affects the long term durability of post tension steel is the quality and integrity of the cement grout injection into the ducts. The injected grout has two main roles:
1) Providing of permanent protection to the post-tensioned steel against corrosion, i.e. preventing ingress of water, chlorides and air into the duct.
2) Constituting the actual bond between the post-tensioned steel, the duct and the surrounding structural concrete.

In order to enable sufficient protection, the grout should be of a proper quality and integrity as well as of thick enough layer. That requires also sufficient correlation between the diameter of the duct and the amount of prestressing steel inside it. Of course also a proper injection work method and equipment are critical for the success of the injection.

Common durability problems, especially regarding post-tensioned bridges, are caused by environmental stresses such as de-icing salts and construction faults such as faulty grout injection, quality of used materials etc. Usually when damage occurs it is the result of a combination of the above mentioned factors.

The most acute durability problems are usually present at the prestressing system anchoring zones near the bridge abutments. A potential and a dangerous damage mechanism at the anchoring zone is described here:

The anchoring zones are located almost immediately under the expansion joints in the heads of the bridge deck. In case an expansion joint is not water tight, water or water containing de-icing salts (chlorides) will run on the surface of the second stage concrete cast which is targeted to protect the anchors heads. As the second stage cast is often

cracked at the construction joint with the prestressed girder (for example due to shrinkage) water and chlorides might penetrate to the anchors heads area causing:
1) Corrosion of the anchor heads and of the protruding strands at the anchors heads.
2) In case some ducts are not fully injected by grout, water and chlorides might penetrate into the ducts causing dangerous corrosion to the prestressing steel.

The main difficulty in these cases is that the corrosion process occurs inside the “internal prestressing system” and is not noticed by normal visual observation from near the bridge. Results of the above presented damage mechanism are shown for example in figure 1. In this photo it is possible to see pitting corrosion (relatively mild) of prestressing steel in an anchor unit due to chloride penetration (confirmed). The photo was taken from the demolished Mälkiä channel bridge in Finland.


”Figure 1 – Mälkiä channel bridge, corroded prestressing steel”

In addition, as the anchoring zones are heavily reinforced in order to withstand significant compressive and shear forces, the compacting of the concrete is very difficult and thus potential for air pockets or poorly compacted concrete is great. Because where air is present so moisture is likely to be, if it occurs adjacent to a duct (especially to a poorly injected one) corrosion of the prestressing steel will be possible.

When discussing the “mid-zones” of a post-tensioned bridge the problematic locations would be non-tight construction joints between segments allowing water and chlorides to penetrate close/into the prestressing system and the extreme low and high points along the ducts due to grout injection difficulties and direct contact between the prestressing steel and the duct which mean that almost no protection of injection grout will exist at those locations.

The risk level due to corrosion of post-tensioned steel, especially due to presence of chlorides which cause pitting corrosion, is of a severe gravity because the steel is usually concentrated in a small amount of tendons which have the key role to provide the load carrying capacity of the bridge. If a few tendons fail that could trigger a catastrophic occurrence such as a bridge collapse. Unfortunately this sort of events have already occurred and will probably keep on occurring more frequently in the future unless the right condition evaluation and monitoring measures will be taken.

3. AVAILABLE "TRADITIONAL" SPECIAL INSPECTION TECHNIQES

None of the so called "traditional" special inspection techniques are able to effectively and safely indicate what is happening inside the prestressing steel system, i.e. what is the condition of the prestressing steel and how well the ducts are injected.

Corrosion detection techniques such as the half-cell potential measurement and the electrical resistivity measurement are effective for evaluating the corrosion process of normal soft reinforcement. The half-cell potential technique requires a physical contact with the steel to be assessed, which is an almost impossible task regarding prestressing steel. Even if connection has been established, the presence of the soft reinforcements will affect in unknown way the potential measurements. With resistivity measurement the problem will be it measure the concrete electrical resistivity but not of the cement grout which form together with the prestressing steel an own internal system inside the concrete structure.

Extraction of core samples and opening of ducts are very dangerous and difficult to perform if the exact location and depth of the duct is uncertain. Deep concrete cover meters can assist to some extent in this matter, but not sufficiently. It should be remembered that ducts are not always embedded in the concrete as precisely as detailed in the construction plans. In addition the extraction of a core sample is completely blind and ineffective as there is no way to predict if the drilling location is the logical one. Extensive extraction of cores is not recommended as it damages/cuts some of the soft reinforcements and breaks the compressed concrete.
Drilling of small bore holes into the ducts for void detection and for sample taking of pulverized cement grout is ineffective and will almost certainly damage the prestressing ducts.

When viewing the above mentioned "traditional" special inspection techniques it is obvious that they do not provide sufficient clarification regarding the condition of the prestressing system which is the key factor of post-tensioned concrete bridges. Thus, it is obvious we need to be assisted from another direction and that will be from the NDT (Non Destructive Testing) field.

4. THE ULTRASOUND 3D TOMOGRAPHER SYSTEM

The ultrasound 3D TOMOGRAPHER system (hereunder referred to as "3D TOMOGRAPHER") has been chosen for the task of performing evaluation of grout injection into ducts of prestressed bridges and in general, for estimating the quality of the surrounding concrete structure. The main reasons for choosing this system are among others the ability to perform fast, accurate and sufficiently deep scanning from only one surface of the concrete structure and due to the possibility to interpret the scanning results on site and rapidly.

Hereunder the description of the 3D TOMOGRAPHER system:

4.1. Purpose and applications of the 3D TOMOGRAPHER System

The 3D TOMOGRAPHER is a state-of-the-art instrument for creating a three-dimensional representation (tomogram) of internal defects that may be present in a concrete object. The detection is done almost in real time and in situ.

The 3D TOMOGRAPHER is based on the ultrasonic Echo method and uses an antenna composed of an array of dry point contact (DPC) transducers, which emit shear waves into the concrete. The transducer array is under computer control and the recorded data are transferred wirelessly to a host computer in real time. The computer takes the raw data, analyses it and creates a 3D image of the reflecting interfaces within the concrete object.

Even though the development of the above mentioned technique was initiated in the early 90's, only in recent years its usage has become effective due to availability of sufficient computer power, mostly of laptops.

The 3D TOMOGRAPHER system has been successfully implemented for the following applications:

- Detection of voids in grouted tendon ducts (prestressed bridges)
- Estimation of structural part dimensions, i.e. thickness measurement
- Detection of poor quality bond in overlays and repairs
- Detection of delaminations
- Detection of voids (casting defects) and honeycombing in concrete members
- Assessment of cement injection into massive concrete/stone structures
- Locating of prestressing steel and reinforcement
- Locating of pipes inside concrete members
- General concrete quality estimation

Scanning depth:
Up to 1-1,5 m in heavily reinforced structures and up to 2 m in lightly reinforced structures.

4.2. The 3D TOMOGRAPHER system components

The components of the 3D TOMOGRAPHER system are presented in figure 2.
The 3D TOMOGRAPHER components are:
1. The 3D TOMOGRAPHER system has a phased antenna array which is composed of a 4 by 10 array of dry point transducers (DPC) and a control unit that operates the transducers. The transducers act as transmitters and receivers in a sequential mode.
2. Laptop with the 3D TOMOGRAPHER software, a SAFT (Synthetic Aperture Focussing Technique) algorithm based software.
3. The power unit of the antenna equipped with a wireless net-transmitter.

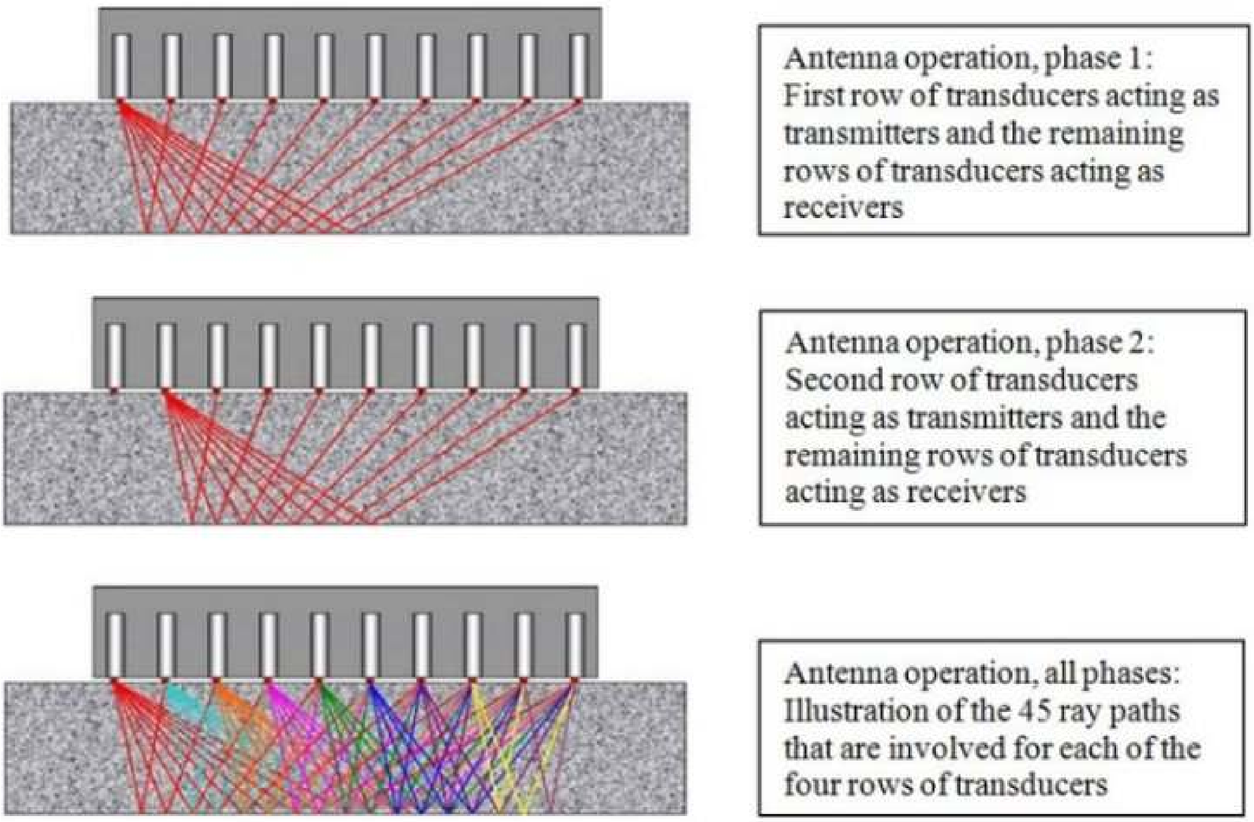
"Figure 2 – The 3D TOMOGRAPHER components"

4.3. Principle of the 3D TOMOGRAPHER system technique and the system operation

The 3D TOMOGRAPHER is based on the ultrasonic echo method using transmitting and receiving transducers in a "Pitch-Catch" configuration which means that one transducer sends out a stress-wave pulse and a second transducer receives the reflected pulse. The time from the start of the pulse until the arrival of the echo is measured. If the wave speed C is known (it is acquired by performing calibration process on test-object) and naturally the distance between the transducers is known, the depth of the reflecting interface can be calculated. This article will not deal with physical and mathematical equations related to the technique.

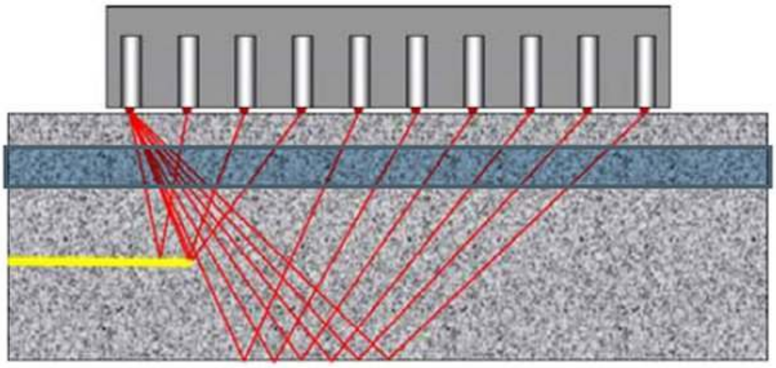
Description of the of the 3D TOMOGRAPHER antenna operation:

The control unit within the antenna activates one row of transducers to send a pulse and the other rows of transducers act as receivers. Then the next row of transducers is sending a pulse and the remaining rows to the right act as receivers. This process is repeated until each of the first nine rows of transducers has acted as transmitters. The duration of each scanning point including complete data acquisition, processing and transfer takes less than 3 seconds. The antenna operation process is illustrated in figure 3.



“Figure 3 – The 3D TOMOGRAPHER antenna operation”

If a defect within a concrete object exists in the form of a sufficiently large concrete-air interface, a portion of the stress pulse will be reflected by the defect and the reflected pulse will arrive at the receiver sooner than reflections from the back wall. The SAFT based signal processing software (the 3D TOMOGRAPHER software) determines the location of a defect in the tested object by analysing the arrival times of the reflected pulses. Figure 4 is illustrating the locating of a defect.



Antenna operation:
Illustration of ray paths when
detecting a defect in an object

“Figure 4 – The 3D TOMOGRAPHER antenna operation – detection of a defect”

4.4. Main key special technological features of the 3D TOMOGRAPHER

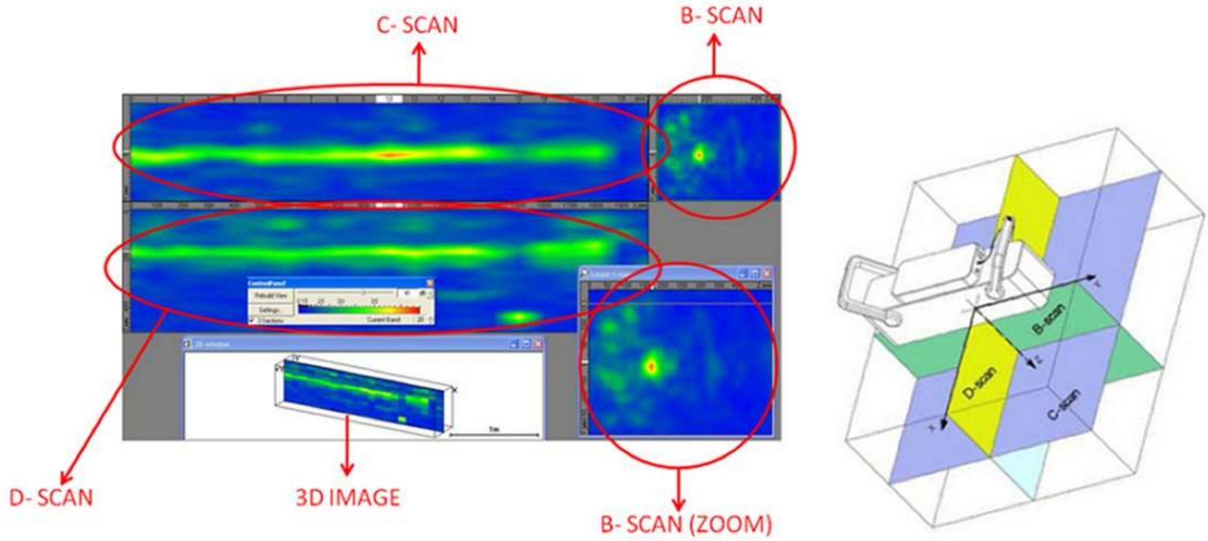
- The 3D TOMOGRAPHER antenna uses dry point transducers (i.e. no a coupling medium is needed to be spread on the tested surface) to introduce into the concrete short duration pulses of shear waves with a nominal center frequency of 50 kHz which is a low frequency.
  SHEAR WAVES (S- waves) are high energy waves with strong ray reflection signature at certain angles. The transducers function as transmitters and receivers results in multiple ray paths in each scanning operation which makes it also possible to detect flaws located one under another.
  LOW FREQUENCY shear waves are proved to be suitable for testing heterogeneous material such as concrete.
- Scanning by the 3D TOMOGRAPHER is done only from one side of object surface. In addition, the transducers are spring loaded to conform to an irregular surface (up to 8 mm for the area of the antenna).
- The transducer array (antenna) is connected wirelessly to the host computer, thereby eliminating the need for long cables.

4.5. The 3D TOMOGRAPHER data visual presentation

The signals captured by the antenna are transferred automatically to the host computer, where the Synthetic Aperture Focusing Technique (SAFT) is used to reconstruct a 3D model of the internal structure of the concrete. The visualization software allows views of different slices / cross-sections of the reconstructed internal structure as shown in figure 5.

The system is using a predetermined x-y-z axis system allowing clear orientation in the scanning process and in the interpretation of the reconstructed views. Distances between testing points can be predetermined for systematic and accurate scanning. The system user can zoom and measure the precise location of different interfaces inside the tested object, for example, of voids (air) or steel.

Some explanation regarding the color scale: the more red color the more intensive wave reflections are, i.e. presence of different material interface (such as steel, air etc.). As air reflects more than 99.99% of the wave energy it will reflect intensively.



“Figure 5 – The 3D TOMOGRAPHER antenna operation – detection of a defect”

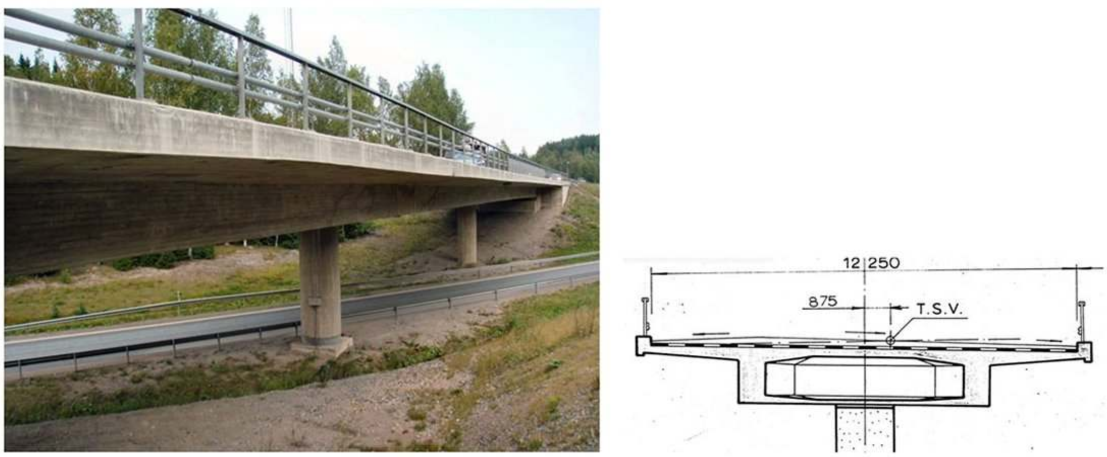
5. TEST CASES – THE ACTUAL USAGE OF THE 3D TOMOGRAPHER SYSTEM

The 3D TOMOGRAPHER system is frequently used by Ramboll engineers for assessing the condition of the prestressing system at the anchoring zone of prestressed bridges. It refers mainly to detection of voids in grouted tendon ducts.

The condition evaluation of the prestressing system is carried out by performing ultrasound 3D Tomographer scanning of a chosen area close the prestressing anchors and by a careful opening of a chosen duct in the most suspicious point according to the 3D TOMOGRAPHER scanning. The exposed prestressing steel condition is evaluated and samples from the concrete and the injected cement grout are extracted for chloride content evaluation. Before scanning the theoretical location of the ducts to be scanned is marked on the bridge girder.

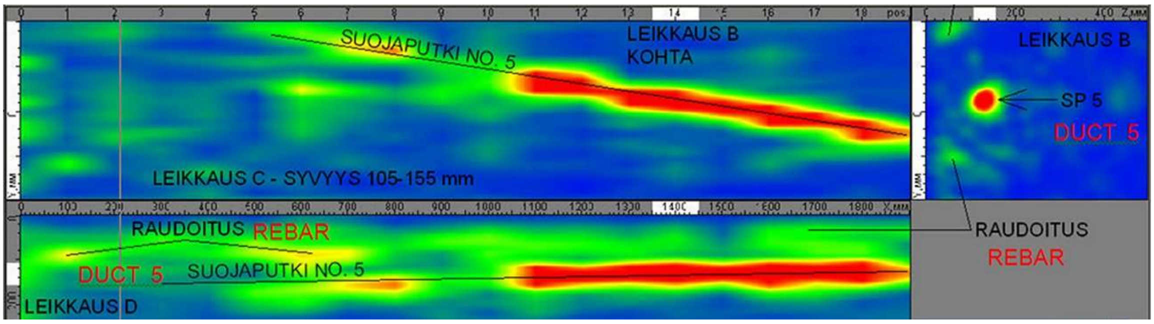
5.1. Test case no. 1 – Lieviö overbridge

Lieviö overbridge is located in the south of Finland on motorway no. 1 between Helsinki and Turku. The bridge type is continuous prestressed concrete box-girder bridge and it was constructed in the year 1971. The bridge overall length is 102,0 m. The bridge general side view and the bridge cross-section are presented in figure no. 6.

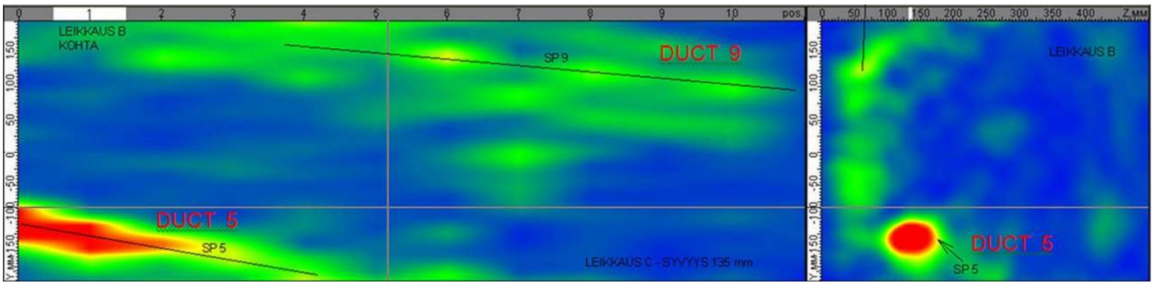


“Figure 6 – Lieviö overbridge side view and cross-section”

The 3D TOMOGRAPHER scanning of duct no. 5 revealed intensive and continuous wave reflections as shown in scan's print screen 1 at figure 6. The intensity of the wave reflection became more obvious while scanning the upper duct to duct no. 5 (duct no. 9). In a short section of the scanned area both ducts were "visible" on the same 3D TOMOGRAPHER scan. As the reflection of duct no. 9 was weak duct no. 5 has reflected waves very intensively. See scan's print screen 2 at figure 7. Both ducts are located at about the same depth from the girder surface, which is about 160...180 mm and both contain the same amount of strands.



"Figure 6 – 3D TOMOGRAPHER scan print screen 1, Lieviö overbridge"



"Figure 7 – 3D TOMOGRAPHER scan print screen 2, Lieviö overbridge"

On the basis of the 3D TOMOGRAPHER scan it was decided to open duct no. 5 of visual inspection at a distance of 1000 – 1100 mm from the head of its anchor.

Opening was carried out by diamond drilling till touching the duct. The duct was opened by lighter drilling and chiselling equipment.

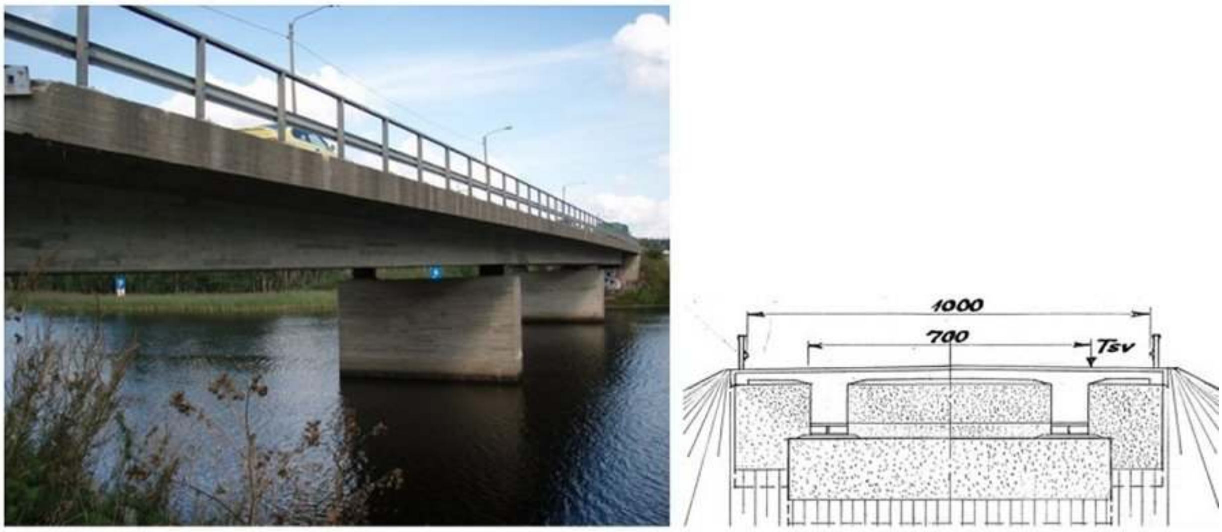
The opening of duct no. 5 revealed that the duct was completely empty of injection grout and the cables were severely corroded, yet only mildly pitted. See figure 8.

"Figure 8 – Exposed prestressing steel, drilling location in accordance to 3D TOMOGRAPHER scanning"

In addition, it was concluded base on comparison of the wave reflections between the two scanned ducts, the upper duct (duct no. 9) is probably well injected (not confirmed by drilling).

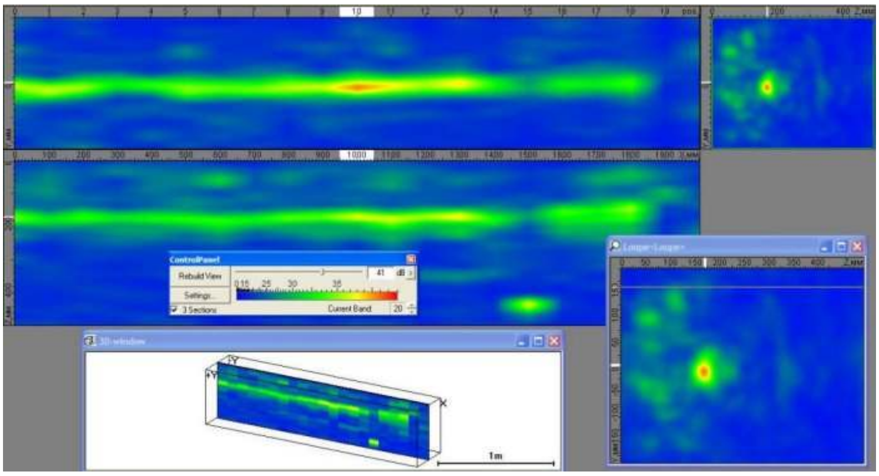
5.2. Test case no. 2 – Vanaja bridge

Vanaja bridge is located in the south of Finland on national highway no. 10 near the city of Hämeenlinna. The bridge type is continuous prestressed concrete girder bridge and it was constructed in the year 1965. The bridge overall length is 95,5 m. The bridge general side view and the bridge cross-section are presented in figure no. 9.



“Figure 9 – Vanaja bridge side view and cross-section”

The 3D TOMOGRAPHER scanning revealed no intensive and continuous wave reflections along the scanned ducts which might indicate of significant air existence in the ducts, see scan’s print screen 1 at figure 10.

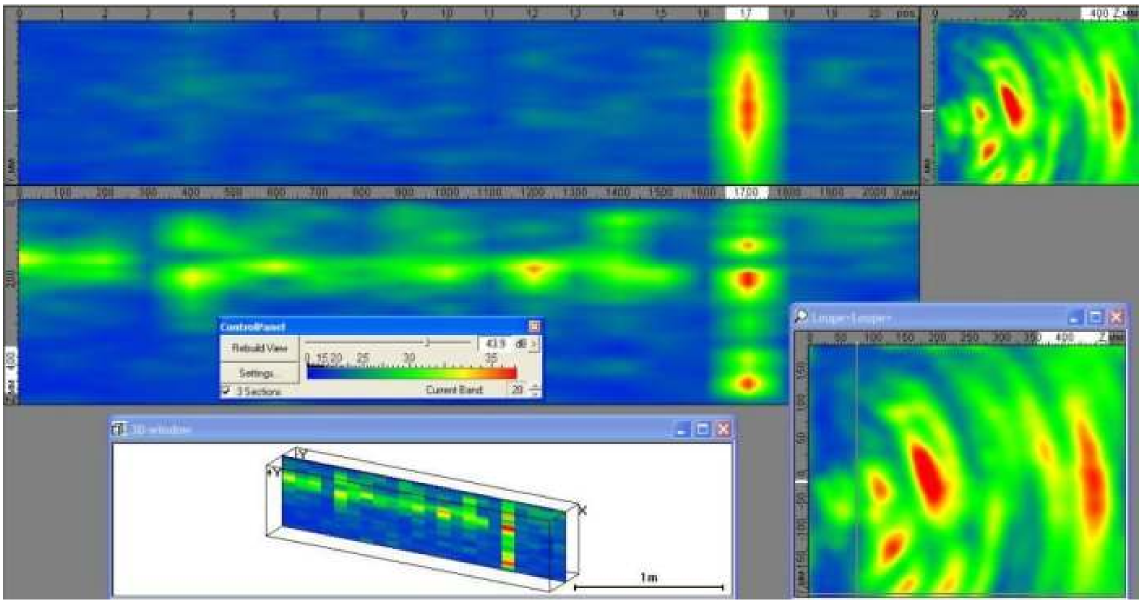


“Figure 10 – 3D TOMOGRAPHER scan print screen 1, Vanaja bridge”

The 3D TOMOGRAPHER scanning results were confirmed by opening (diamond drilling) of one duct in the relatively most suspicious point according to the 3D TOMOGRAPHER scanning. By the opening it was confirmed that the duct is injected by cement grout. No indication of air voids or moisture was found in the duct. The prestressing steel was only slightly corroded. Due to the relative small diameter of the duct and the large amount of prestressing steel in the duct, the injected cement grout layer was very thin, 0-4 mm. See figure 11.

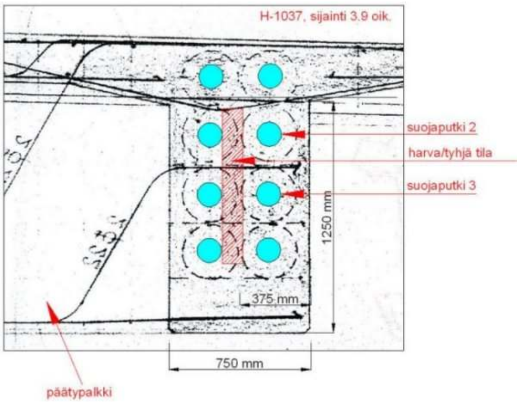
“Figure 11 – Exposed prestressing steel, drilling location in accordance to 3D TOMOGRAPHER scanning”

At a distance of about half a meter from the anchors heads the 3D TOMOGRAPHER scanning revealed intensive wave reflections at depth of about 400 mm from the concrete surface. Similar results appeared in several different scans, see scan’s print screen 2 at figure 12.



“Figure 12 – 3D TOMOGRAPHER scan print screen 2, Vanaja bridge”

When observing the bridge plans, it appears that the intensive reflections are located in between the columns of ducts. When taking into consideration the high amount of soft reinforcement together with the presence of the ducts, it becomes clear that the concrete compaction at this area is very difficult, and apparently in this case not successful. The mentioned intense reflections are probably due to existence of honeycombed concrete. See figure 13 (the cyan colored circles are the ducts and the red mesh-marked area is the probable honeycombed concrete location).



“Figure 13 – Honeycombed concrete in between the columns of ducts”

6. CONCLUSIONS

The ultrasound 3D TOMOGRAPHER system has been proved to be a powerful and effective tool for performing evaluation of grout injection in post-tensioned bridge ducts.

The 3D TOMOGRAPHER enables the bridge inspector to apply systematic and accurate scanning with fast results interpretation possibility on site and in real time

In addition to the use of 3D TOMOGRAPHER as described in this article, the system has been successfully used in various different tasks such as for evaluation of nuclear plant protective concrete structure, reinforced concrete bridges, assessing of bonding between overlays, assessing of cement injection into massive concrete-stone structure etc.

REFERENCES

1. Germann Instruments, Catalog NDT 2010, p 87-92.