Myndighet og regelverk
Konstruksjoner
Konstruksjonsteknikk
15. mars 2021

Statens vegvesen

Etterspente betongbruer Inspeksjonsmanual

FoU-programmet Bedre bruvedlikehold
2017-2021

STATENS VEGVESENS RAPPORTER Nr. 718

Foto – Dekra Industrial AB
Illustrasjon – Gaute Larsen, SVV

Statens vegvesens rapporter

NPRA reports
Norwegian Public Roads Administration

Tittel
Etterspente betongbruer
Inspeksjonsmanual

Undertittel
FoU-programmet Bedre bruvedlikehold 2017-2021

Forfatter
DEKRA Industrial: A. Karlsson, E. Boström, P. Jilderda

Avdeling
Konstruksjoner

Seksjon
Konstruksjonsteknikk

Prosjektnummer
L10114

Rapportnummer
Nr. 718

Prosjektleder
Bård M. Pedersen

Godkjent av
Bård M. Pedersen

Emneord
Etterspente betongbruer, ikke-destruktiv testing (NDT), inspeksjonsmetoder

Sammendrag
Statens Vegvesen, SVV, sendte i 2018 ut en forespørsel om utredning av metoder, muligheter og begrensninger for inspeksjon av etterspente betongbruer. Ulike ikke-destruktive teknikker (NDT) ble studert i detalj for vurdering av tilstanden til spennsystemet i etterspente betongbruer, og muligheter og begrensninger ved bruk ble oppsummert og diskutert i SVV rapport 699. Denne rapporten er en manual for inspeksjon av etterspente betongbruer basert på utredningen i SVV rapport 699.

Antall sider 37

Title
Post-tensioned concrete bridges
Inspection manual

Subtitle
R&D program Better Bridge Maintenance 2017-2021

Author
DEKRA Industrial: A. Karlsson, E. Boström, P. Jilderda

Department
Structures

Section
Structural Engineering

Project number
L10114

Report number
No. 718

Project manager
Bård M. Pedersen

Approved by
Bård M. Pedersen

Key words
Post-tensioned concrete bridges, Non-Destructiv Testing (NDT), inspection methods

Summary
In 2018, the Norwegian Public Roads Administration, NPRA, issued a request for a study of methods, possibilities and limitations for inspection of post-tensioned concrete bridges. Various non-destructive techniques (NDT) were studied in detail for assessing the condition of the tensioning system in post-tensioned concrete bridges, and possibilities and limitations of their use were summarized and discussed in SVV report 699. This report is a manual for inspection of posttensioned concrete bridges based on SVV report 699.

Pages 37

Forord

Denne rapporten er utarbeidet av FoU-programmet Bedre bruvedlikehold (2017-2021). Bedre bruvedlikehold skal gjennom ny kunnskap bidra til at Statens vegvesen kan optimalisere ressursbruken knyttet til inspeksjon, vedlikehold og forvaltning av bruer.

Bedre bruvedlikehold består av fire prosjekter:

- Prosjekt 1: Forvaltningsverktøy for bruer
- Prosjekt 2: Armeringskorrosjon i betong
- Prosjekt 3: Alkalireaksjoner i betong
- Prosjekt 4: Vedlikehold av stålbruer

Bedre bruvedlikehold ledes av Bård Pedersen, Vegdirektoratet.

Denne rapporten tilhører Prosjekt 2: «Armeringskorrosjon i betong» som ledes av Karla Hornbostel. Prosjekt 2 er rettet mot drift og vedlikehold av betongbruer med armeringskorrosjon. Mål for prosjektet er å utarbeide anbefalinger for inspeksjonsmetoder for å utrede omfang av skader på grunn av armeringskorrosjon samt å utvikle verktøy for å kunne bedømme konsekvenser av armeringskorrosjon for bruens levetid. Prosjektet skal også utarbeide et beslutningsgrunnlag for valg av reparasjonstiltak og anbefalinger for gjennomføring av tekniske gode og økonomisk effektive reparasjonstiltak.

Rapporten er skrevet av Dekra Industrial AB og er utarbeidet i delprosjekt 2.4 «Spennarmering», som ledes av Lise Bathen. Prosjektet har søkelys på kartlegging av skader og konsekvenser av dette på både føroppspent og etteroppspent armering. Rapporten er en inspeksjonsmanual for undersøkelse av etteroppspente betongbruer med ikke-destruktive metoder (NDT-metoder) og baserer seg på SVV rapport 699.

Post-tensioned Concrete Bridges

Inspection Manual

March 2021

DEKRA Industrial

Andreas Karlsson, Erik Boström, Pieter Jilderda

Preface

In autumn 2018, the Norwegian Road Authorities (Statens Vegvesen) issued a request for a study of methods, possibilities and limitations for inspection of post-tensioned concrete bridges. DEKRA Industrial AB in Sweden was awarded the assignment, which was carried out in cooperation with Luleå University of Technology, Division of Structural Engineering. The project started in winter 2019 and was finished in March 2021.

As a result of the abovenamed study, a technical report was issued in December 2020 entitled: `Post-tensioned Concrete Bridges – Study of methods for inspection´

This inspection manual constitutes the second and conclusive part of the assignment, where inspection methods are specified based upon the findings described in the technical report.

Cover Photo: Visual inspection of tendons, Heroysundsbron, Nordland fylke, Norway. Photo: Dekra Industrial AB.

www.dekra-industrial.se
tel. +46 10 455 10 00
Gamlestadsvägen 2
SE-402 51 Gothenburg

Table of content

1 Scope of application

This manual is intended to be used as a tool for planning, execution and evaluation of inspection with the use of non-destructive testing. It primarily applies to locating air- and water filled voids and poor grouting of injection mortar in tendon ducts by NDT, followed by visual inspection of exposed tendons to evaluate potential corrosion or breakage.

2 Terms and definitions

ASR	Alkali-silica-reaction
CM	Cover Meter
ES	Endoscope
GPR	Ground Penetrating Radar
UPR	Ultrasound Pulse Response
IE	Impact Echo
LET	Lead Engineering Team, as defined in §5.1
NDT	Non-destructive Testing
VI	Visual inspections
BI	Bridge inspector

3 Guiding documents

3.1 Governing document

Karlsson A, Holmqvist M, Jilderda P, Strand J, Johansson B Å, Täljsten B. (2021). Utredning av metoder for inspeksjon av etterspent armering i betongbruer (Statens vegvesens rapporter Nr. 699). Statens vegvesen, Norge.

3.2 Manuals

Statens vegvesen. (2017) *Håndbok N401-Bruforvaltning fylkesveg.* SVV.
Statens vegvesen. (2018) *Håndbok R411-Bruforvaltning riksveg*. SVV.
Statens vegvesen. (2014) *Håndbok V440-Bruregistrering*. SVV.
Statens vegvesen. (2014) *Håndbok V441-Bruinspeksjoner*. SVV.
Statens vegvesen. (2016) *Håndbok R210-Laboratorieundersøkelser*. SVV.
Statens vegvesen. (2018) *Håndbok R211-Feltundersøkelse*. SVV.
Highways England. (2020) *CS465-Management of post-tensioned concrete bridges*, Highways England.

3.3 Standards

ISO 16311-2:2014, Maintenance and repair of concrete structures – Part 2: Assessment of existing concrete structures.
ISO 13822:2010, Bases for design of structures – Assessment of existing structures.
ASTM C-1383:2015, Standard test method for measuring the P-wave speed and the thickness of concrete plates using the impact echo method.

4 General framework for inspection

The overall purpose of the inspection is to investigate the condition of post-tensioned bridges regarding defects that might influence structural load capacity, durability and safety. Inspection is focused on detecting hidden defects such as air- and water filled voids, debris, and honey combing in grouting mortar inside the tendon ducts. Investigations to find hidden defects can either be undertaken as special inspection or be integrated in recurrent inspection routines according to current Norwegian practice.

This inspection should be undertaken according to the flowchart in fig. 4.1. After a decision has been made on undertaking a special inspection of a post-tensioned bridge, drawings should always be examined carefully. A lead engineering team must be consulted prior to inspection to evaluate construction type, design, critical sections and choice of inspection methods. Important information shall be transferred to a bridge inspector.

A bridge inspector functions as the person who provides the NDT team with test plan and suitable information regarding the bridge. He/she is also responsible for all the practical matters that enable an inspection, e.g. accessibility of the bridge, electricity, lights, traffic etc.

The NDT team performs the inspection and all tests included. After the inspection has been completed, the results are delivered in a test report with analysis and condition assessment.

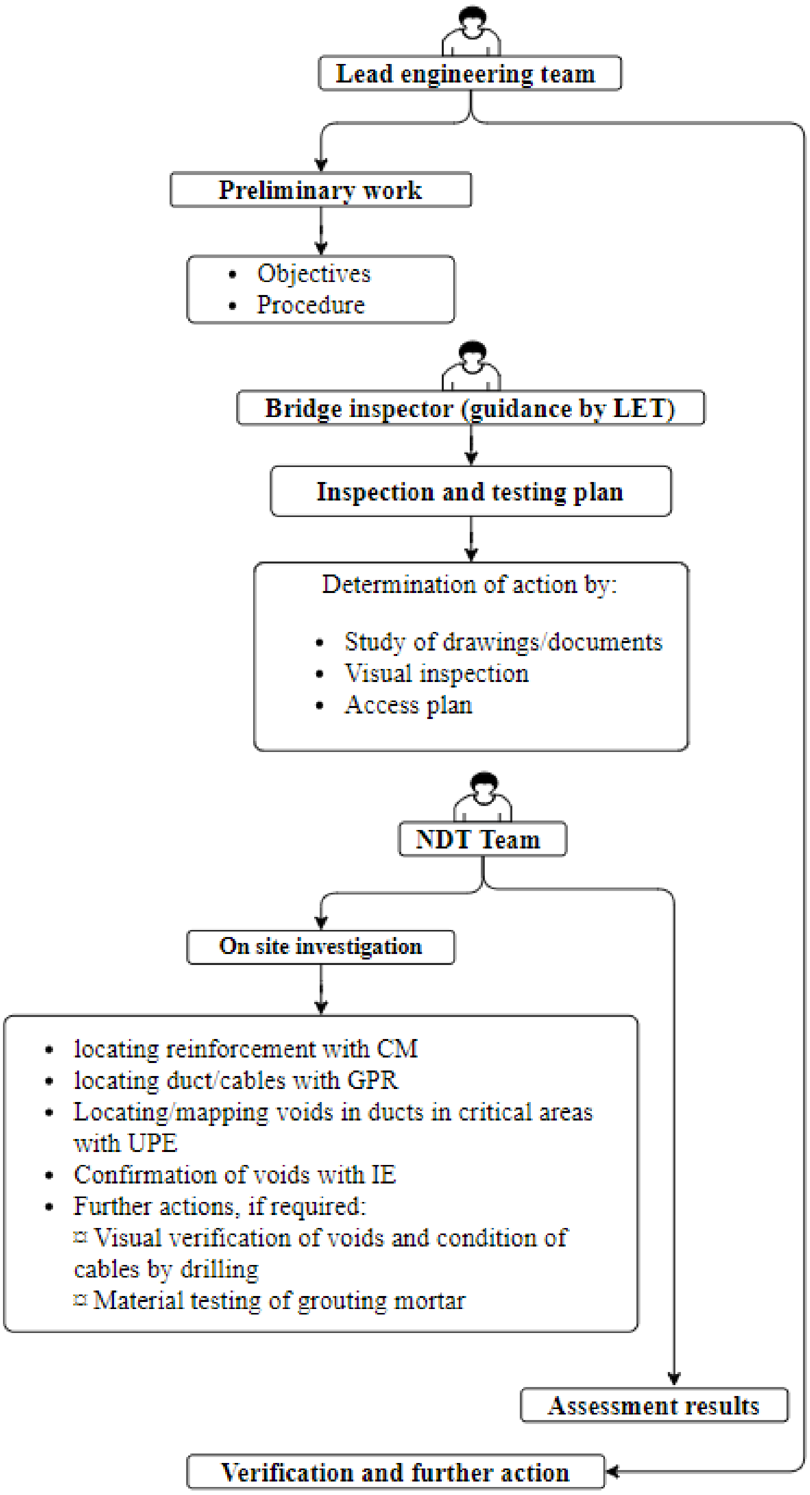

Fig. 4.1 Flowchart for inspection of post-tensioned concrete structures.

5 Requirements on personnel

5.1 Lead engineering team

The NDT inspection should be managed by a lead engineering team assigned by Statens Vegvesen with extensive knowledge of the design and possible deficiencies of post-tensioned bridges. Furthermore, the lead engineering team should have good knowledge of available testing methods and their application and limitations. The lead engineering team is responsible for specifying the required testing with respect to overall locations, choice of suitable methods and rough scope of testing.

As part of the testing program, intrusive actions such as drilling may be required / desired. The lead engineering team shall always be consulted prior to execution of any intrusive actions.

5.2 Bridge inspector

A bridge inspector assigned by Statens Vegvesen should be present on-site during inspections. The bridge inspector shall introduce the NDT coordinator and share his knowledge of the specific bridge by informing of known defects/weaknesses and other specific findings during earlier inspections. Preferably, the bridge inspector reports to the lead engineering team.

The bridge inspector may also be responsible for establishing over all conditions which allow for inspection e.g. access to bridge (scaffolding, boat, lift), redirection/closing of traffic, electricity and lighting. Otherwise, a separate site manager may have to be appointed for this.

5.3 NDT team

The NDT inspection team should consist of at least two technicians consisting of one NDT operator and one NDT coordinator.

The degree of expertise required for usage of the different NDT techniques and equipment varies, for example a lower degree of expertise is required for testing and evaluation of results with cover meter and ground penetrating radar (GPR), whilst testing and evaluation with ultrasound pulse echo (UPE) and impact echo (IE) requires a higher degree of expertise and understanding.

5.3.1 NDT coordinator

The NDT coordinator should have extensive experience and good understanding of inspection of concrete structures with all of the below mentioned methods, both in singular use and in combination. He/she shall have a profound education within concrete construction, preferably concrete engineer or have a proven equivalent knowledge level.

NDT coordinator is responsible for:

- Managing NDT inspection
- Final evaluation of test results.
- Establishing inspection report

5.3.2 NDT- operator

The NDT operator shall have a basic knowledge of concrete structures. He/she should have some experience and basic understanding of concrete testing. He/she shall have a good knowledge of the equipment used and be able to understand each technique utilized for obtaining results. The amount of required experience is dependent on the testing method used, as listed below. NDT operator is authorized to carry out:

- Measurements and tests with applicable NDT techniques under supervision of NDT coordinator.
- Preliminary evaluation of test results.

Cover meter

Operator should have basic knowledge and some experience of inspection and evaluation of results with cover meter.

Ground penetrating radar (GPR)

Operator should have some experience of inspections and evaluation of results with GPR. He/she shall be able to handle software programs implemented in the equipment including export of data to other sources.

Background: There are a handful of manufacturers of GPR equipment. The majority of them are supplied with software that is manageable with low to medium degree of knowhow, i.e. Microsoft Windows etc. The results however can in some cases be difficult to assess and evaluate.

Ultrasound pulse echo (UPE)

Operator should have relative extensive experience of inspections and evaluation of results with UPE. He/she shall also have a good understanding of post-tensioned concrete structures. He/she shall be able to handle software programs implemented in the equipment including export of data to other sources.

Background: UPE differentiates from GPR regarding requirements for inspectors. It takes quite extensive experience to be able to interpret the results obtained. The measured values are obtained as signals, or echoes, which must then be interpreted in order to be able to draw the right conclusion.

Impact Echo (IE)

Demands as for UPE. Besides that, the operator should have good knowledge of evaluation of results with IE.

Background: Impact Echo is an acoustic method. Readings are produced in raw data of curves (Hz) and require profound knowledge and experience to understand and interpret the results.

www.dekra-industrial.se
tel. +46 10 455 10 00
Gamlestadsvägen 2
SE-402 51 Gothenburg

6 Placement of post-tensioned tendons and ducts.

Location and type of reinforcement may differ depending on the type of construction of the bridge. Below is a selection of typical bridge constructions and principal placement of post-tensioned reinforcement. However, it should be emphasized that there are bridge types of special design which may deviate from the general rules listed below. Therefore, construction drawings must always be consulted to define the exact placement of post-tensioned reinforcement. In fig. 6.1 a number of common defects in post-tensioned concrete bridges are displayed, the upper figure displays defects in the cross section and the lower figure in longitudinal section.

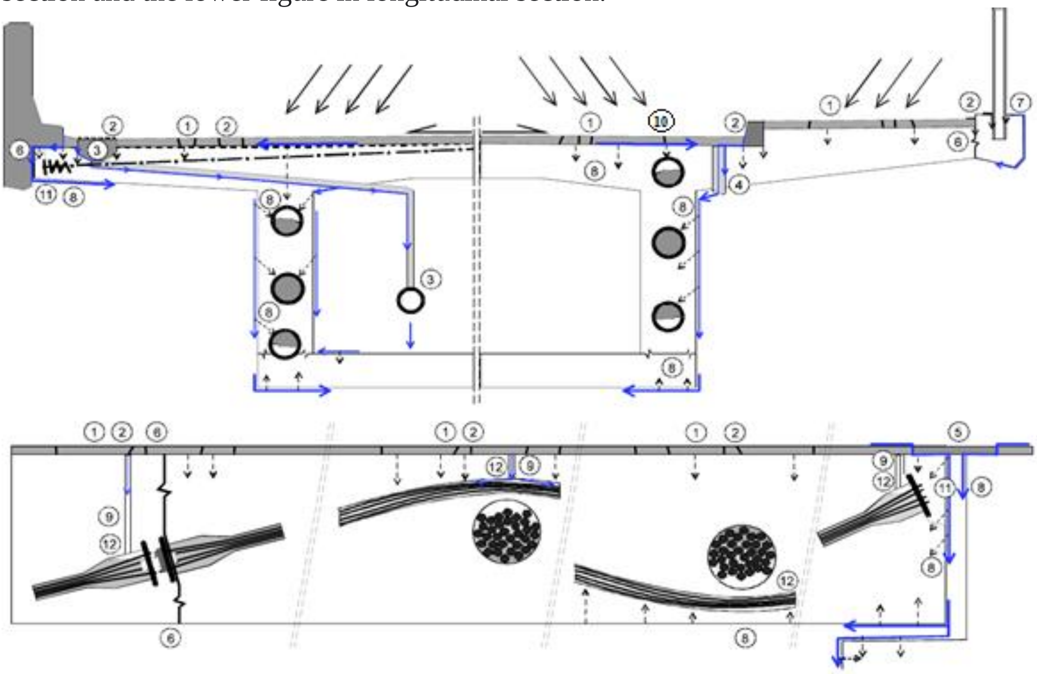

Fig.6.1 Hazard scenarios for post-tension steel in a typical box girder bridge. Indication of potentially weak points where water (possible with chlorides) can gain access to the tendons and cause corrosion (Matt, 2000).

Failure of external barriers

1 Defective wearing course (e.g.cracks)

2 Missing or defect waterproofing membrane

3 Defective drainage intakes and pipes

4 Wrongly placed outlets for the drainage of wearing course and waterproofing

5 Leaking expansion joints

6 Cracked and leaking construction or element joints

7 Inserts (e.g. for electricity)

8 Defective concrete cover

Failure of tendon corrosion protection system

9 Partly or fully open grouting in- and outlets

10 Leaking, damaged metallic ducts mechanically or by corrosion

11 Cracked and porous pocket concrete

12 Grout voids at tendon high, couplings and anchorage.

Possible no voids in low point as indicated in the sketch

Post-tensioned cables in concrete bridges

The layout of post-tension cables can vary significantly from one bridge to another, and an inspection must always be based on relevant construction drawings.

Common post-tension cables layout in *ordinary slab/beam or box girder bridges*:

1. The cables are normally placed in the lower part of the cross section in the spans, in the upper part over the support and around mid-height at free end supports.
2. There may be (approximately) horizontal cables in the upper part of the cross section (bridge plate of box girders) in the support areas. There may also be (approximately) horizontal cables in the bottom plate of box girders in the spans.
3. The cables are located inside ordinary reinforcement.

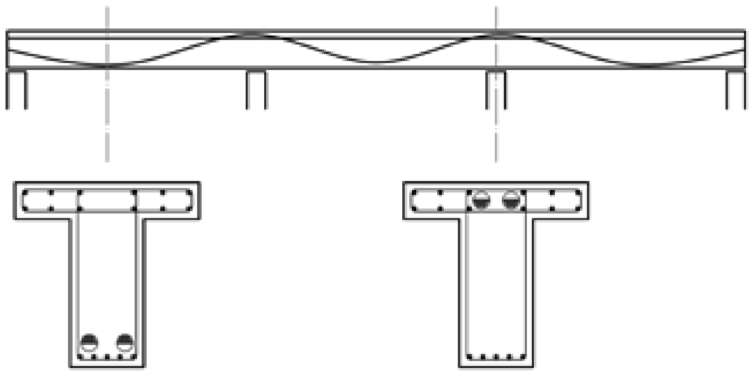

Fig. 6.2 - Ordinary slab/beam bridge.

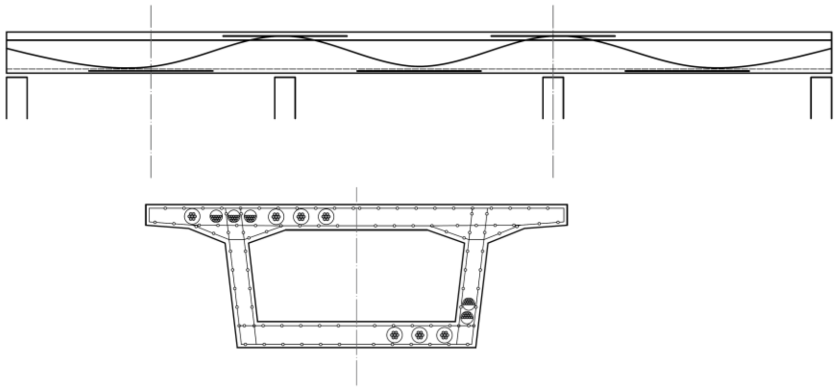

Fig. 6.3 - Box girder bridge.

Free cantilever bridges are variable height post-tension box girder bridges constructed as self-balancing free cantilevers from the main axes columns.

Common PT cables layout in free cantilever bridges:

1. One or two pairs of bridge plate cables are anchored in every construction joint, basically every 4-5 meters in each direction, and bridge plate cables cover the entire length constructed as free cantilevers. Cables are distributed laterally over the cross section, but the anchors are located near the webs.
2. Bottom plate cables symmetrically about mid-span and with variable length are anchored at corbels.
3. The cables are located inside ordinary reinforcement.

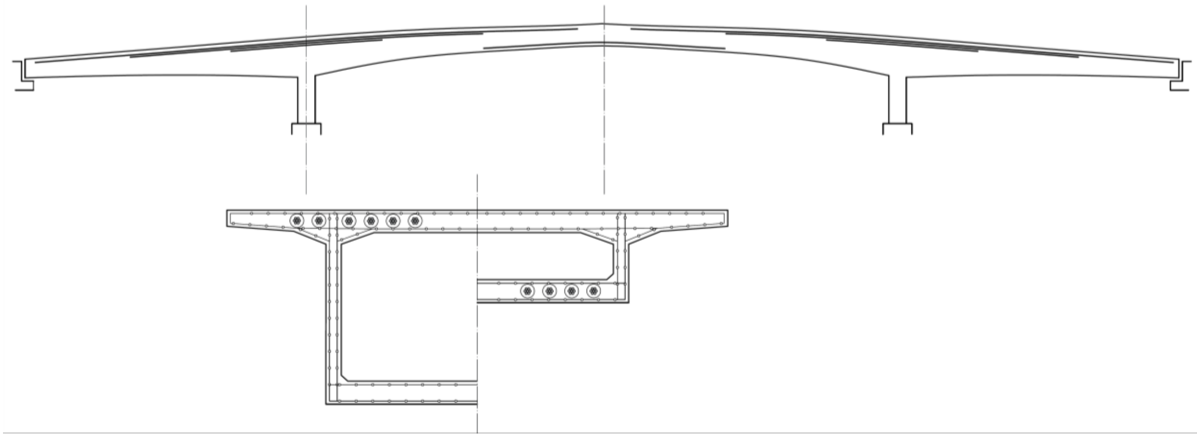

Fig. 6.4 - Cantilever bridge.

7 Planning of inspection and testing

7.1 General

Planning of inspection should be executed according to the following chapter together with overall planning according to *"Håndbok V441 Bruinspeksjon, (paragraphs 2.1-2.2)"*.

Many defects on post-tensioned bridges are normally not visible, therefore a structured approach to the investigations is of essential importance. It is impractical and uneconomical to uncover all hidden components for inspection and many competing factors must be considered before undertaking actions. Planning of inspections must be carried out in consultation with the Lead Engineering Team.

Where it is not possible to inspect all hidden components within the normal cycle of recurrent inspections, those of greatest risk should be prioritised. Selection of number and placement of test areas should be made based on thorough planning.

7.2 Study of drawings/documents

Information regarding ducts and strands can often be obtained by studying drawings. Drawings should always be studied and function as the primary basis before an inspection. Questions to consider before inspection:

- Is the component critical for the safety of the structure?
- What are the consequences of failure of the component?
- May this result in damage to the structure or the component itself?
- Could this lead to long-term durability issues with the structure?
- Can investigation be justified economically? Estimate price and benefit

Suitable locations for inspection areas might include:

- Cable high points e.g. over supports (due to gravity, it is more likely that there are voids of air and water in high points)
- Aeration pipes
- Areas close to anchors
- Critical areas (what would a breakage of tendon mean regarding bridge safety in a certain key point)

7.3 Visual inspection

As a first step, visual inspection should be carried out with emphasis on visual signs of degradation. All vital parts of the bridge should be made accessible to the greatest possible extend. When accessibility does not allow for a closer inspection due to location, lack of scaffolding etc. preliminary visual inspection may be carried out with e.g. drone or with binoculars.

A thorough visual inspection of the concrete surfaces provides information on potential locations of damage of the unstressed and/or stressed reinforcement. The visual indicators might include:

- Discoloration (e.g. rust strains)
- Water flow
- Spalling, delamination
- Honeycombing
- Cracking e.g. in load bearing concrete elements or top of the bridge deck.
- Irregularities in roadway e.g. cracks or potholes in asphalt
- Colouration e.g. lime precipitation, colour differences, rust, moist areas
- Structural deviations

7.4 Access plan

- In which way can the component be exposed safely?
- What impact would the investigation have on the operation of the structure e.g. traffic?
  - Redirecting closing or restrictions on traffic.
- Accessibility to areas for inspections.
  - Scaffolding
  - Boat
  - Lift
- Power supply
- Lighting
- Facilities for personnel

8 On site investigations

8.1 Step 1; Locating reinforcement with cover meter (CM)

In order to obtain the best possible conditions for locating the tendon ducts, the placement of slack reinforcement should first be identified. It is especially important to precisely locate the slack reinforcement along the area which will be tested because the slack reinforcement can shade encapsulated objects when testing with GPR and UPE.

Fig. 8.1 Cover meter (CM)

8.1.1 Testing sequence CM

1. Make settings according to manual from manufacturer
2. Locate reinforcement in area for inspection → mark with chalk or other
3. Make notes on concrete cover, c/c, (if known, dimensions)

Fig.8.2 ***Step 1;*** *Scan and mark out reinforcement in both x- and y-direction in the area intended for inspection.*

8.2 Step 2; Locating ducts/cables with ground penetrating radar (GPR)

8.2.1 General

The easiest and most efficient method to locate tendon ducts is by using the GPR. It can locate both metal- and plastic tendon ducts. The GPR enables an accurate measurement of the position in plane and in depth of the tendon ducts.

With GPR it is not always possible to distinguish between slack reinforcement and ducts, the signals are often similar. However, careful examination of construction drawings combined with good knowledge of structural engineering will in most cases enable the inspector to identify tendon ducts. Also, the concrete cover is usually larger for ducts, if the depth of reinforcement and ducts should be similar, the arc of the signal from a duct should be more flat and wide than the signal from a rebar due to the larger dimension of the duct (fig 8.3)

Concrete surface

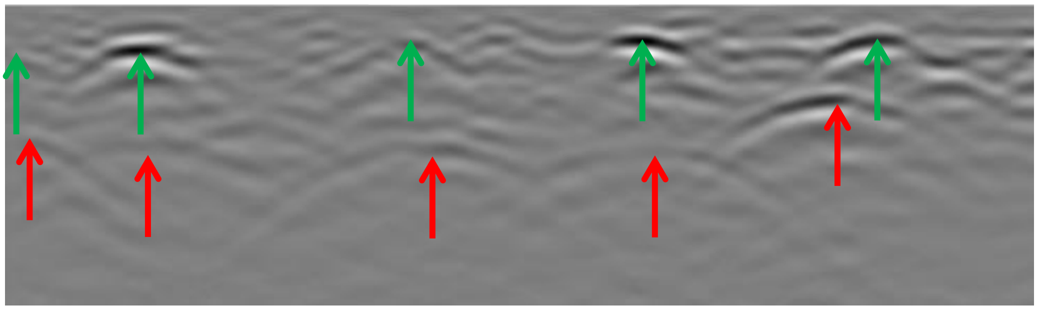

Fig.8.3 Example of "non-migrated-view" with GPR (line scan mode). Each reflected signal is visualized with an "arc". The larger the dimensions, the wider and more flat the arc. **Red arrows** = *tendon ducts,* **Green arrows** = *reinforcement*

Fig.8.4 Ground Penetrating Radar (GPR)

GPR has a measureable depth limit of up to 600-800 mm depending on the amount of reinforcement. A densely reinforced structure can lower the expected measuring depth and if for example a second layer of ducts is placed directly below an object of metal (e.g. a duct), it cannot be seen with GPR.

There are two different types of scans that can be carried out with GPR, (1) line scan (2D) or (2) area scan (3D). The easiest and quickest way to locate tendon ducts is by using scanning mode "Line scan" (2D). Line scan is carried out in single scans directed perpendicular to the tendon duct intended for inspection (fig 8.5)

8.2.2 Testing sequence GPR

1. Make settings according to manual from manufacturer for "line scan".
2. Carry out single scans in a 90 degree angle from the direction of the tendon duct(s) according to instructions from LET (fig 8.5). If results are unclear, make scans in areas between reinforcement.

Fig. 8.5 ***Step 2****; locating tendon ducts with GPR; scanning for localization is carried out in transverse direction relative to the tendon duct.*

3. Evaluate results in user software (tablet/PC/device). Readings can be displayed in different views such as "Migrated heatmap view", "Non-migrated view", "Time slice view".
4. Mark out placement of ducts with chalk or other, preferably in different colour than for reinforcement.

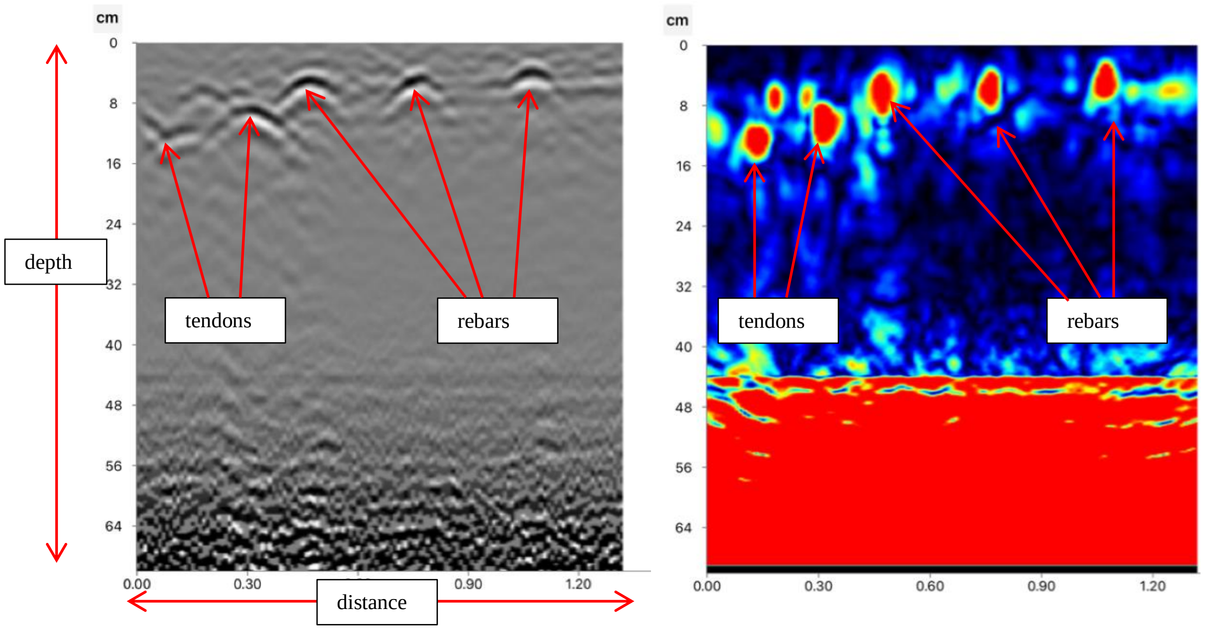

Fig. 8.6 Example of results from line scan GPR in "non-migrated-view" (left) and "migrated heat map view" (right). Test images shows results from the same scan after adjusting visualization mode.

8.3 Step 3; Locating voids in tendon ducts with ultrasound pulse echo (UPE)

8.3.1 General

Since ultrasound signals are not transported in air, enclosed air in concrete or ducts is clearly visible. Many factors may influence the signals and consequently the quality of the results. Among them, most importantly the quality of the concrete (enclosure of air, density, homogeneity), presence of delamination, presence of reinforcement bars above the ducts, etc. Behind any objects/defects, the signal is shadowed and no results can be obtained.

Although scanning with UPE is considered the fastest method to detect voids in ducts it is a time-consuming method that requires an experienced inspector to obtain and interpret the results. Images are analyzed afterwards with the aid of computer software.

A scan with UPE consists of several different segments called B scans. The results from each individual scan are reported as a slice of the concrete. When this is processed in the computer, several B scans are put together into a 3D image. Therefore, in order to find a void in the duct, scanning must be performed along the duct in a systematic manner.

One disadvantage with UPE is that a tendon duct without voids can be difficult to locate during processing, as only a minor part of the signal is reflected on the duct. This can be dealt with in place by adapting the settings or in retrospect by comparison with the results from GPR. Failure to locate the duct during data processing may cause doubts as to whether the scan was performed at the correct location. Therefore, it is of great help to be able to compare afterwards with a scan from GPR.

Ultrasonic Pulse Echo (UPE) is the primary method to locate voids in tendon ducts. The instrument allows for a relatively fast mapping of potential voids in cable ducts over longer distances and/or larger areas.

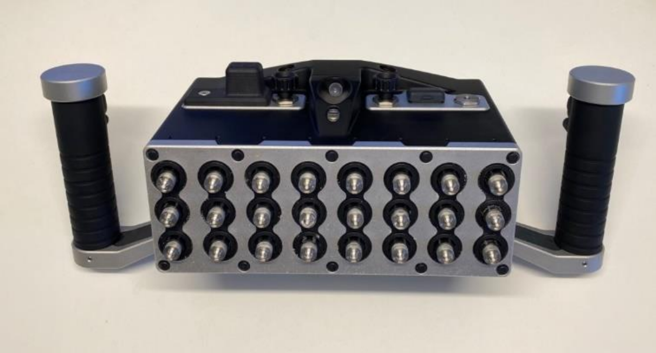

Fig 8.7 Ultrasound Pulse Echo

8.3.2 Testing sequence UPE

1. Make settings according to manual from manufacturer.
2. Adjust "Measuring presets" (pulse velocity, analog- and time gain compensation) to set optimum signal strength before scanning. Make adjustments whilst transducers are in contact with the concrete surface in an area with solid concrete and known thickness of the element. If thickness unknown, follow instructions according to manufacturer's manual for "calibration of pulse velocity".
3. Make scans in a longitudinal direction along the duct(s) but with the device in a transverse direction (fig 8.8).
4. Locate and identify centre line of duct meticulously for further measurements with IE and potential drilling.

Fig. 8.8 ***Step 3;*** *scans are carried out along the tendon duct with the instrument in a transverse direction relative to the tendon duct(s). Scanning requires a relatively smooth surface.*

5. Evaluate results in user software on tablet/PC/device (fig. 8.9).
   Adjust values for "Digital gain (dB)" to optimize image visualization and to locate voids → mark ambiguous/non-ambiguous areas with chalk or other on the bridge for further testing with IE and visual intrusive inspection, if required.

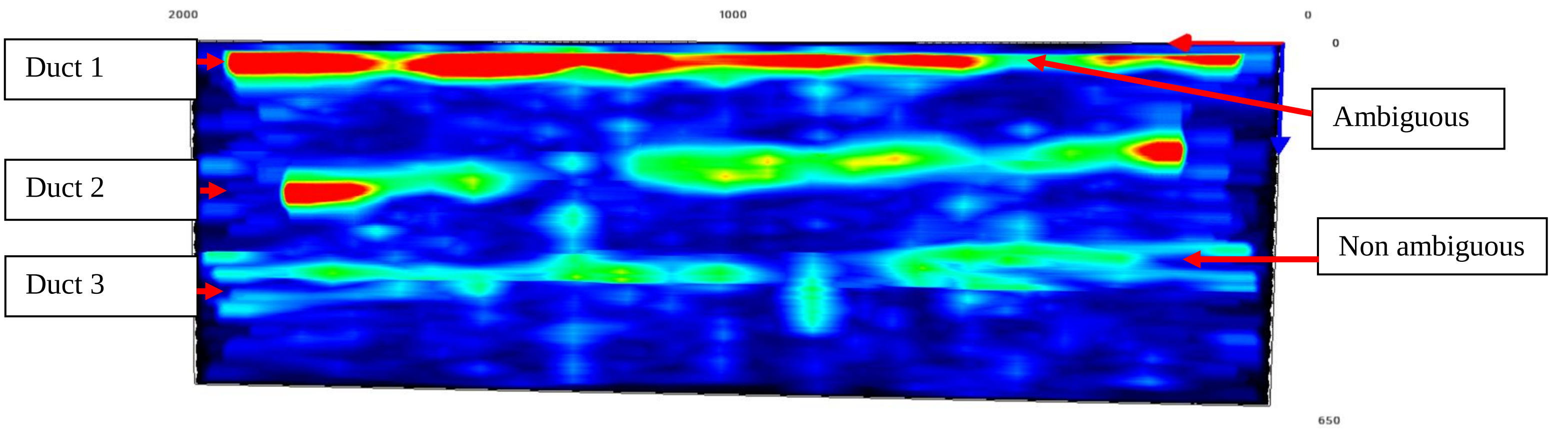

Fig. 8.9 Results from scanning with UPE in 3D. The red-marked duct in the upper part of the figure indicates voids of air and/or water. (Visualization of the results can be obtained in different views, colors, 2D and 3D by adjusting the input values in the software.)

8.4 Step 4; Confirmation of void with Impact Echo (IE)

Test areas for verification of results should be chosen with care and discussed between all concerned parties involved in the inspection. Final decision is made by the LET.

Fig. 8.10 Impact echo equipment

8.4.1 General

The impact-echo method is based on monitoring the periodic arrival of reflected stress. The P-wave produced by impact from a small steel spherical impactor is able to obtain information on the depth of the internal reflecting interface or the thickness of a solid member (fig 8.11)

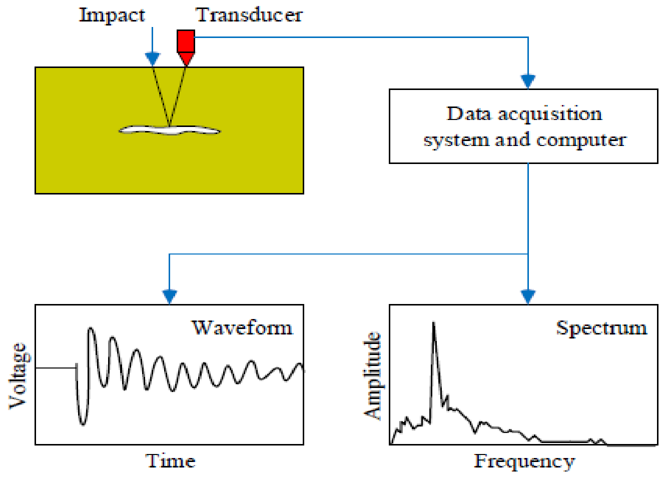

Fig 8.11 Simplified diagram of the IE-method (from www.ndt.net)

A short-duration stress pulse is introduced into the member by mechanical impact. This impact generates three types of stress waves that propagate away from the impact point. A surface wave (R-wave) travels along the top surface, and a P-wave and an S-wave travel into the member. In impact-echo testing, the P-wave is used to obtain information about the member.

When the P-wave reaches the back side of the member, it is reflected and travels back to the surface where the impact was generated. A sensitive displacement transducer next to the impact point picks up the surface displacement due to the arrival of the P-wave. The P-wave is then reflected into the member, and the cycle restarts. Thus, the P-wave undergoes multiple reflections between the two surfaces. The recorded waveform of surface displacement has a periodic pattern that is related to the thickness of the member and the wave speed.

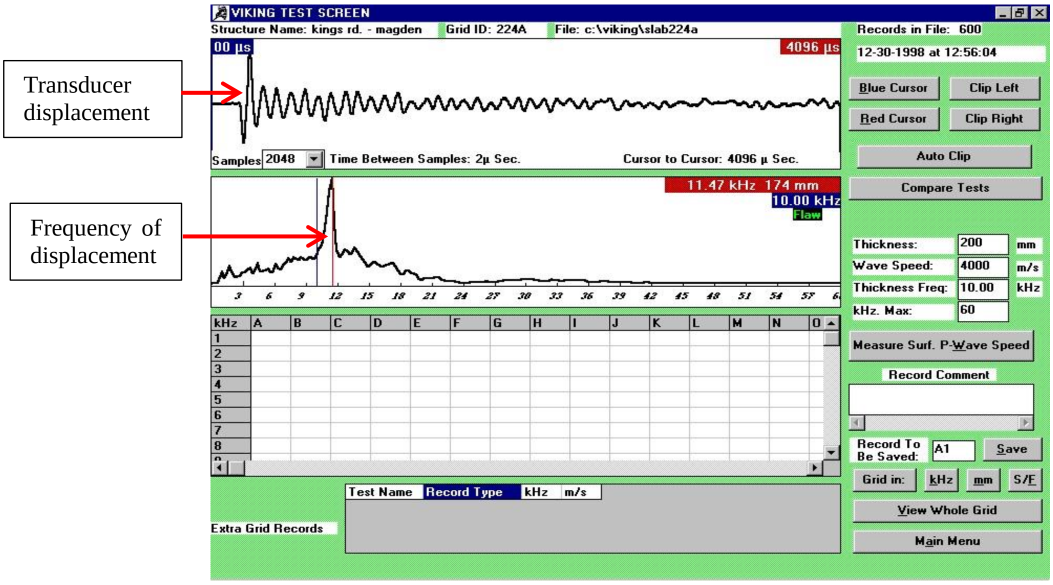

Fig 8.12 Test example (from http://germann.org)

The transducer displacement waveform (upper window, fig 8.12) is transformed into the frequency domain to produce an amplitude spectrum which shows the predominant frequencies in the waveform (lower window, fig 8.12). The frequency of P-wave arrival is determined as the frequency with a high peak in the amplitude spectrum. The thickness (T) of the member is related to the thickness frequency (f) and wave speed (*Cp*) by this simple approximate equation:

$$T = \frac{C_p}{2f}$$

The same principle that applies to reflection from an internal defect (delamination or void), applies for a pulse encountering air. In both cases, a drop in the first modal frequency will be observed (example in fig 8.15).

Testing with IE can be used for:

- Verification of results of voids obtained by UPE
- Confirmation of depth (concrete cover) to a duct intended for visual inspection by drilling.
- If an area is densely reinforced, it can also sometimes be an advantage to use IE where UPE fails as IE requires less contact surface for testing. Where most UPE equipment's require a test area of 20-30 centimeters (lengthwise) IE only requires a few centimeters. This allows for pin point measurements in small areas, e.g. between tightly placed reinforcement.

8.4.2 Testing sequence IE

1. Make settings according to manual from manufacturer and method ASTM C-1383. (thickness frequency, wave speed etc.)
2. Select area with a smooth surface for inspection. Grind area with cup stone, any grinder from the cup stone must be removed prior to testing.
3. Identify and locate center line of duct

4. Make a grid consisting of approximately 2 x 2 cm squares along the potential void and test systematically along the duct.
5. Carry out test according to manufacturer's manual in area(s) of interest (fig 8.13). If a drop in first modal frequency is observed, choose a smaller impactor to identify depth to defect.
6. Evaluate results in user software (fig 8.14).

Fig. 8.13 Executing test IE

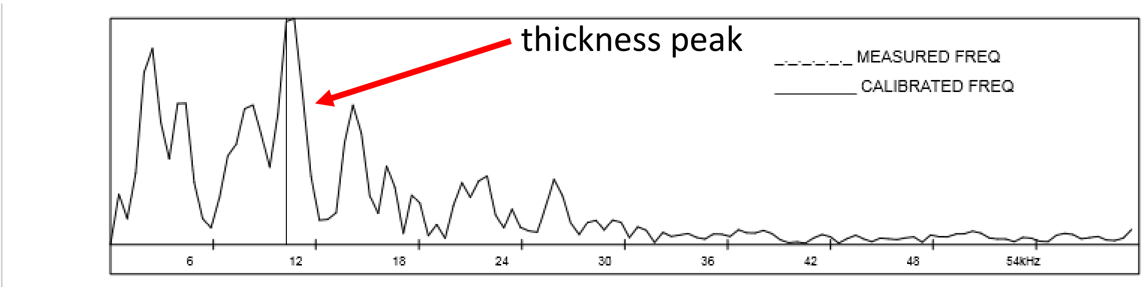

Fig. 8.14 Test result from Impact echo method in area with solid concrete without entrapment of air.

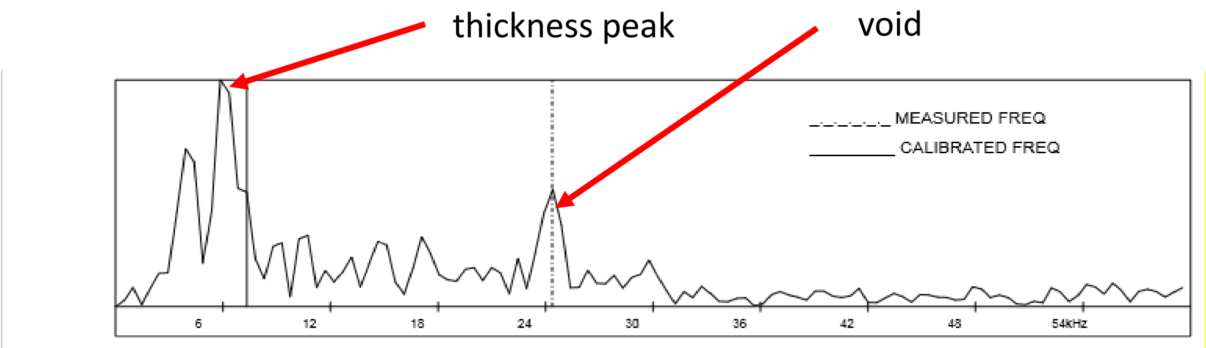

Fig. 8.15 Test result from Impact echo method in area with entrapment of air void in a tendon duct.

8.5 Step 5; Verification of results by drilling/core drilling

8.5.1 General

The results of non-destructive testing should always be verified by intrusive methods, such as drilling / core drilling, regardless of the fact if indications of entrapped air or water were found. Great caution should be taken with drilling, as tendons may be placed with little or no distance to the duct wall. It is of utmost importance to avoid damaging the tendons. Drilling can be made either with a (1) drill bit (Ø20-30 mm) or by (2) core drilling (Ø100-150 mm).

(1) Drilling with drill bit (Ø20-40 mm) is carried out in order to:

- Confirm results of air- or waterfilled voids from NDT testing (sometimes visual inspection requires using an endoscope (ES).
- Assess condition on post-tension system
  - Degree of corrosion on tendons and duct
  - Breakage of strands
  - Filling of grout (partly or completely missing)

(2) Drilling by core drill (Ø100-150 mm) is carried out in order to:

- Confirm results of air- or waterfilled voids from NDT testing
- Assess condition on post-tension system
  - Degree of corrosion on tendons and duct and confirm by polishing steel to remove surface corrosion (fig 8.18).
  - Breakage of strands
  - Filling of grout (partly or completely missing)
- Sampling of grout mortar for testing of:
  - Chloride content
  - Cement content

Fig. 8.16 Visual verification by drilling with a drill bit (Ø25 mm) into the duct wall.

Fig. 8.17 Heavily corroded tendon after visual verification of air void by drilling with drill bit.

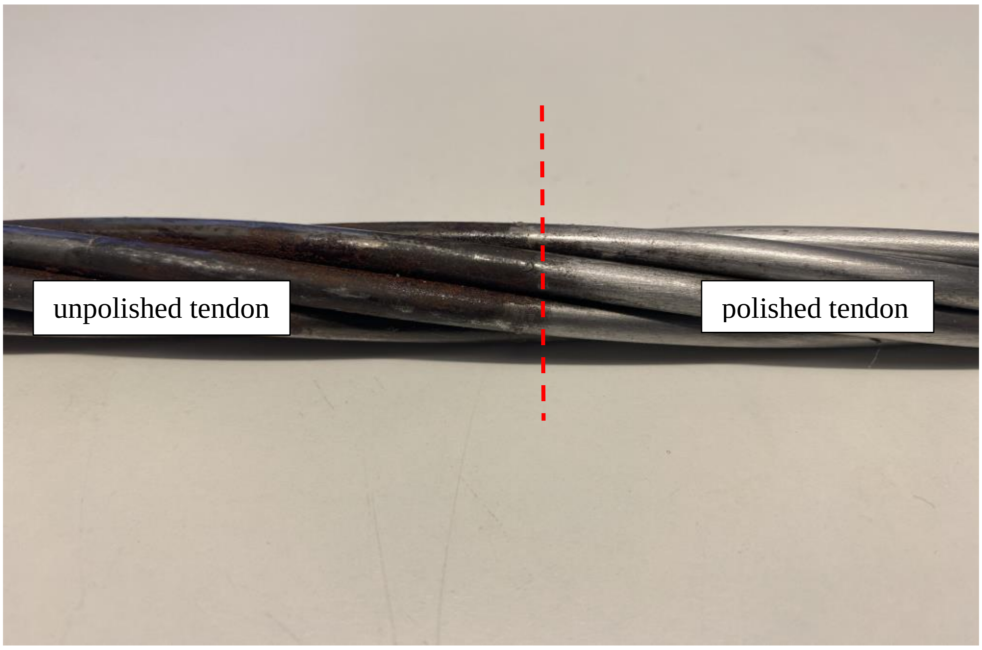

Figure 8.18 Polishing of tendons.

9 Reporting

Results shall be presented in a report established by NDT coordinator and delivered to the bridge inspector. Bridge inspector is responsible for handling and upload of the inspection report in Brutus in accordance with normal routines for bridge inspections.

Report shall include:

- Background
- Object/Scope
- Instruments/methods
- Test procedure
- Test areas
- Results (in text and displayed with images from software for each method)
  - CM
  - GPR
  - UPE
  - IE
  - Visual confirmation
  - Material analysis (if applicable)
- Damage assessment
  - Voids; placement and extent
  - Tendons; degree of corrosion, size, breakage
  - Ducts; degree of corrosion
  - Grout; composition, moist, degree of filling, cement content, chloride content
- Comments and conclusions
- Recommended measures
  - Repairs
  - Further testing
  - Monitoring
- Photo annex

Note that measures for repairing, further testing and monitoring specified in the report are recommendations and can be overruled by the Lead Engineering Team. They will take the final decision on how to proceed.

Authors

Name	Title	Expertise	Main contribution to this project
Andreas Karlsson, DEKRA Industrial AB	Concrete inspection engineer	Concrete expert, NDT operator (UPE, IE, CM and GPR)	Project management Concrete inspections Concrete testing
Erik Boström, DEKRA Industrial AB	Concrete inspection engineer	Concrete expert, NDT operator (UPE, IE, CM and GPR)	Concrete inspections Concrete testing
Pieter Jilderda, DEKRA Industrial AB	Manager materials, failure and concrete inspections	Mechanical engineer, Bachelor of science	Management, review-ing, coordination

References

Karlsson A, Holmqvist M, Jilderda P, Strand J, Johansson B Å, Täljsten B. (2021). Utredning av metoder for inspeksjon av etterspent armering i betongbruer (Statens vegvesens rapporter Nr. 699). Statens vegvesen, Norge.

Matt P. (2000). Durability of Post-tensioned Concrete Bridges in Switzerland. 16th Congress of IABSE.

Hurlebaus S, Hueste M.B.D, Karthik M. M, Terzioglu T. (2017) . Inspection Guidelines for Bridge Post-Tensioning and Stay Cable Systems using NDE Methods (NCHRP research report 848). National Cooperative Highway Research Program

Shaw P, Rasmussen J, Klit Pedersen T. (2004). A Practical Guide to Non Destructive Examination of Concrete. Nordic Innovation Centre / Force Technology

Petersen C.G. (2003). Injection quality of steel cable ducts evaluated by NDT. Germann Instruments A/S Copenhagen, Denmark

ISO 13822:2010, Bases for design of structures – Assessment of existing structures.

ISO 16311-2:2014, Maintenance and repair of concrete structures – Part 2: Assessment of existing concrete structures.

Appendix A – Properties of NDT equipment

Appendix A - Properties of NDT equipment

1 Cover meter

1.1 Specification

A low frequency magnetic field is applied on the surface of the structure; the presence of embedded reinforcement alters this field, and a measurement of this change provides information on the reinforcement. Cover meter surveys form part of most concrete condition surveys of buildings or structures. Cover meter surveys can also locate main and secondary reinforcement, determine bar sizes, spacing and cover thickness. The position of reinforcing steel and pre-stressing strands is sometimes also required, in order to circumvent them during core sampling or other tests which may be affected by their presence.

1.2 Capabilities and limitations of cover meter

Capabilities

- The equipment is normally handheld and will easily access most areas. However, for large areas the method can be time consuming.
- Internal ducts, provided duct is of metal and is within measure depth range.
- Measuring dept <100mm.

Limitations:

- CM cannot detect defects in concrete.
- The thickness of the concrete cover affects the accuracy of the method.
- In largely reinforced areas, the size and no. of reinforcement can be difficult to evaluate.
- CM cannot detect corrosion.

2 Ground Penetrating Radar (GPR)

2.1 Specification

This method applies electromagnetic waves by rolling an antenna over the concrete surface. It is important to note that if variation in the dielectric properties of the different materials is low, only a small amount of energy will be reflected. For example, electromagnetic waves cannot penetrate any metallic layer. The shape of the constructional elements (e.g. diameter of rebar) or material inhomogeneity's are difficult or not at all possible to estimate.

This method is often used for the inspection of the inner structure of structural elements made of reinforced or post-tensioned concrete, to detect and localise inhomogeneity's (voids, metal or wood inclusion), thickness of structures which are only accessible from one side, internal structure of complex elements, as well as to determine the moisture content and distribution.

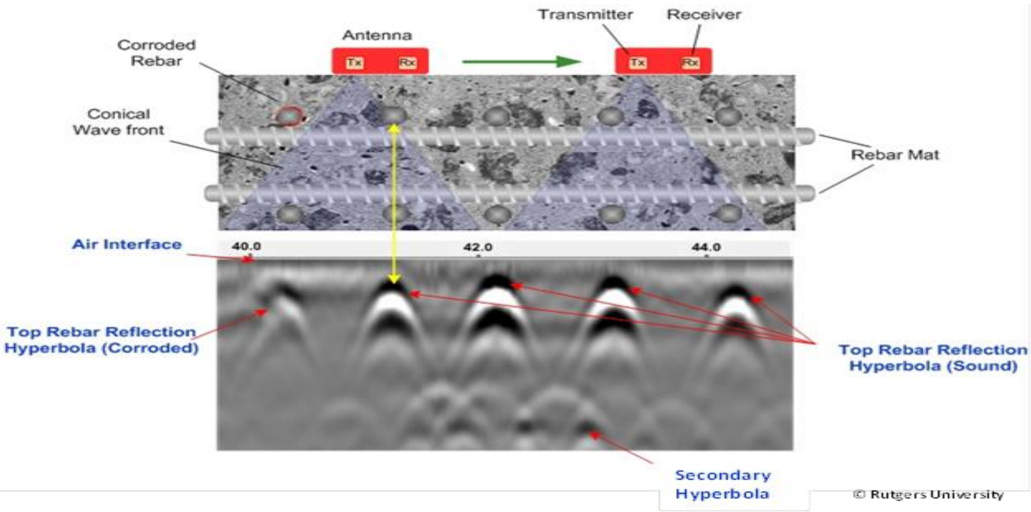

Fig. 2.1 Principle GPR technique (http://fhwaapps.fhwa.dot.gov/ndep/DisplayTechnology.aspx?tech)

2.2 Capabilities and limitations of GPR

Capabilities:

- GPR can detect defects in concrete such as e.g. air voids as well as casted-in objects such as, steel, plastic etc. Similar defects can be detected in external plastic ducts (HDPE), however with moderate accuracy. It is also possible to locate and distinguish between different materials, e.g. a plastic duct from a metal duct. The GPR technique is not suitable for detection of defects on strands.
- Can be used on either internal or external ducts.
- For locating ducts it can be used on both metal and nonmetal ducts
- For identifying defects: only on nonmetal ducts
- The effect of concrete cover is dependent on the scanning frequency. For high frequencies (~500–3000 MHz) penetration depth can typically exceed 600 mm but at the expense of reliable signals of smaller objects in greater depths. Measurements made with high or low frequencies affect the receiving signal. With higher frequencies comes an enhanced signal for smaller objects at smaller depths whilst measurements with low frequencies enable detection of larger objects at greater depths, however with a low resolution.

Limitations:

- Aligned layered ducts obstruct measurements.
- A considerable amount of steel reinforcement bars will impede measurements. Objects underneath the reinforcement will be hard to distinguish.
- Can possibly detect corrosion but needs larger areas. Results are difficult to evaluate and show a large uncertainty.
- Ground coupled GPR: For GPR inspection, it is required that the wheels of the device are in physical contact with the structure to ensure turning of the wheels which also acts as a distance meter.
- The creation of a 3D image requires either a 0,5 x 0, 5 m or 0,5 x 1,2 m manually accessible testing surface.
- Because of its robustness and relatively heavy weight air coupled GPR: is almost exclusively used on the bridge deck and therefore requires a bridge closed from traffic.

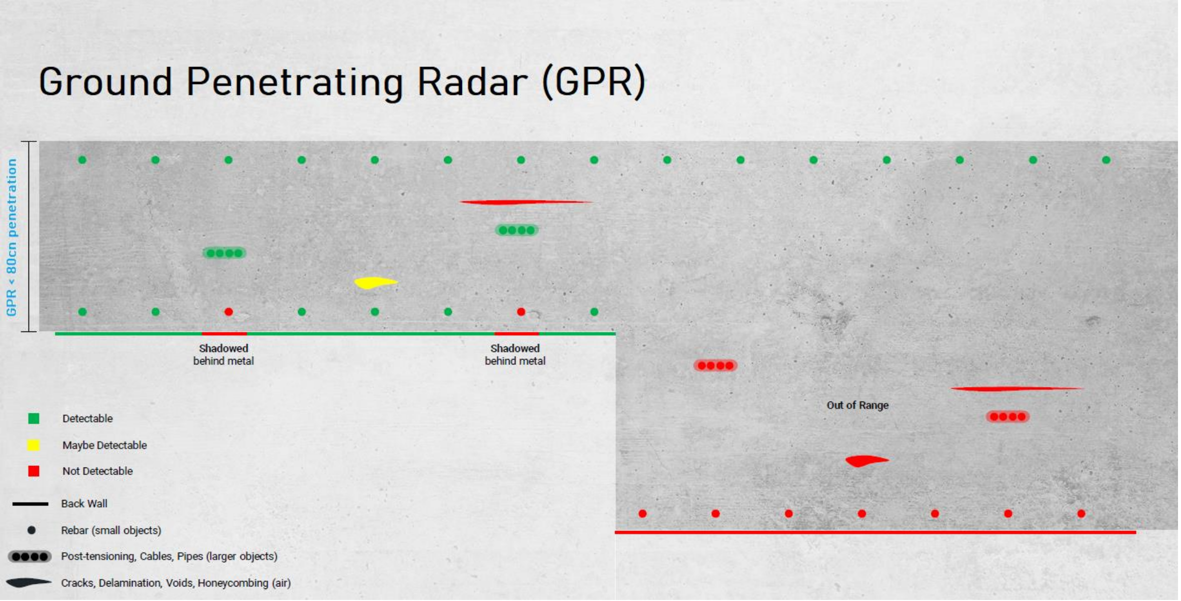

Fig. 2.2 Capabilities and limitations of the GPR technique. (Infrastructure and asset inspection GPR (PROCEQ))

3 Ultrasonic Pulse Echo (UPE)

3.1 Specification

This acoustical technique consists of the transmission (T) of ultrasonic pulses into concrete which are reflected by material defects or by interfaces between regions of different densities and/or elastic moduli, see a principal sketch in Figure 6.3. A receiver (R) coupled to the surface monitors the reflected waves. Point measurements are combined to visualise the reflection. It is worth noting that the propagation of ultrasonic waves is limited by layers containing air, e.g. concrete with large amounts of air pores and by very dense reinforcing bars. This method is used for the inspection of the inner structure of structural elements made of reinforced and post stressed concrete, rebar and tendon locations, compaction faults and voids. In the UPE method it has to be noted that a single measurement allows no conclusion about the position of a single rebar or duct. Only measurements along a measurement grid with a constant measuring point distance allow carrying out a reconstruction calculation with subsequent imaging of individual reinforcement bars or ducts. Compared to the radar method, the resolution here is often coarse due to the diffusion of signals at the aggregate.

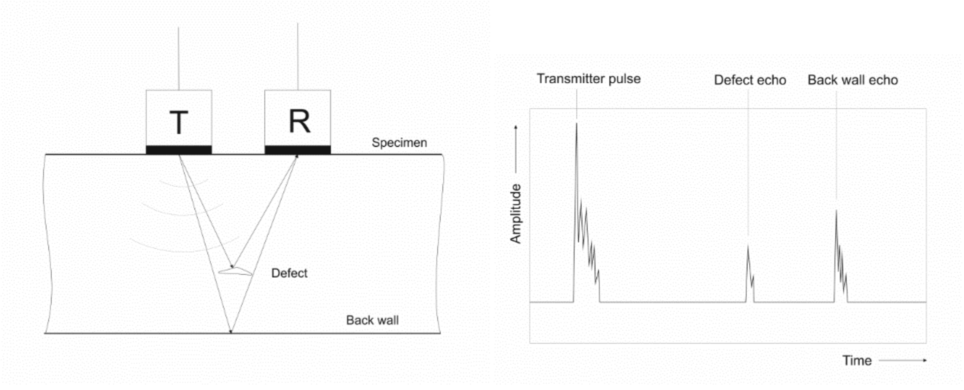

Fig. 3.1 Simplified diagram of the UPE-method (from www.ndt.net, zfp.cbm.bgu.tum.de)

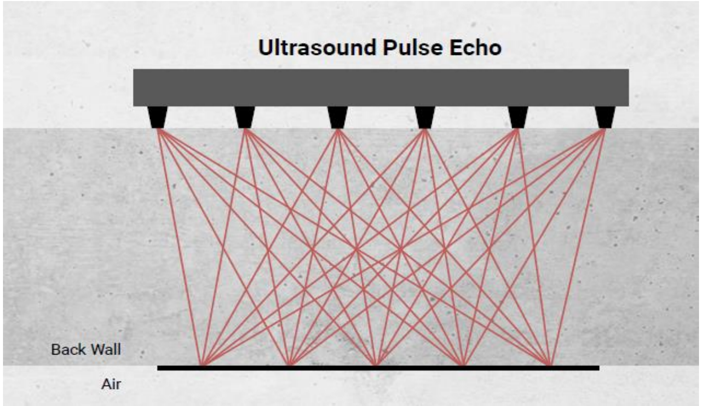

Fig. 3.2 Principle of UPE technique with multiple transducers. Each transducer coupling functions as both transmitter and receiver. (from "Infrastructure and asset inspection GPR (PROCEQ)")

3.2 Capabilities and limitations of UPE

Capabilities:

- UPE can locate voids in concrete and grout defects (enclosed air/water) in internal ducts with moderate accuracy.
- UPE can locate both metal and non-metal internal ducts.
- Typical concrete covers do not obstruct UPE inspection, though signals are attenuated with increasing depth. Depending on the concrete composition and required accuracy of results, the maximum possible thickness to inspect is up to 1,8 m.
- Ducts behind other ducts can in certain cases be distinguished using UPE. The position of the two transducers can be varied, which aids in mapping out the volume of the defect.
- Can in some cases distinguish a partly filled duct from e.g. a completely empty duct.

Limitations:

- A considerable amount of steel reinforcement bars will impede measurements, as they reflect acoustic waves. Objects underneath the reinforcement will be hard to distinguish.
- It is not possible to detect corrosion or broken strands using UPE.
- For UPE devices, the width required for scanning is about 300 mm. The surface must be relatively smooth to enable sound to penetrate into the material.
- Can sometimes be hard to distinguish partly filled ducts from completely empty ducts depending on the placement of the partly voided area in reference to the pulse direction.

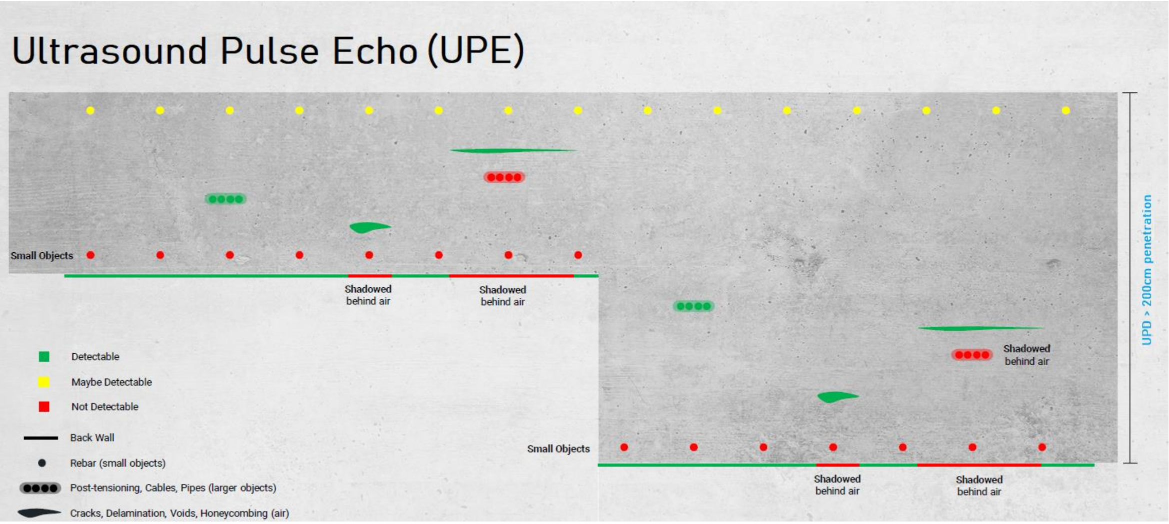

Fig. 3.3 Capabilities and limitations of UPE (from "Infrastructure and asset inspection UPE (PROCEQ)")

4 Impact Echo

4.1 Specification

Impact Echo is an acoustic method based on sending out a wave by an impact on the concrete surface and recording the response (wave energy) with a transducer. The signal will reflect on essential boundaries, such as enclosed air or objects with a distinct difference in density. Due to a relatively low attenuation, the method is particularly suitable for thick concrete elements. Internal defects such as voids or objects with a high density such as tendons can be identified.

A transducer records the surface displacements caused by multiple reflections of the waves versus time. These displacement signals are subsequently transformed into the frequency domain.

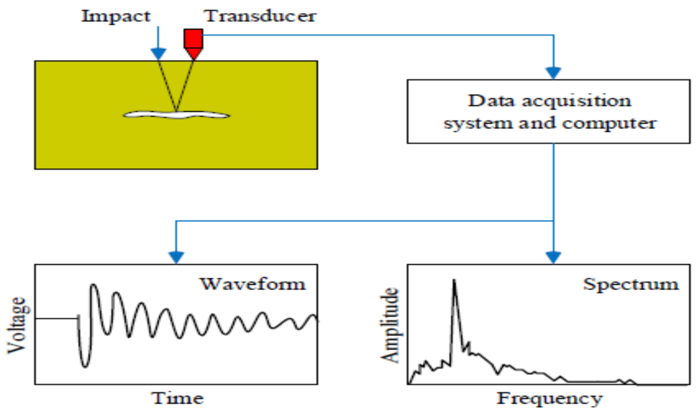

Figure 4.1 Simplified diagram of the IE-method (from www.ndt.net)

Dominant frequencies are assigned to depth values by applying the so-called IE formula, whereby the wave speed must be determined for each concrete through calibration at a position of known thickness or by measuring on a core.

$$T = \frac{C_p}{2f}$$

where Cp is the P-wave velocity and f is the measured frequency.

Minimum detectable target size varies according to the depth of the target. It is a very effective test method for a depth from 0.1 m up to about 1.2 m. This method is typically used for thickness determination, localisation of delamination, voids, inhomogeneity's, as well as voids in tendon ducts.

4.2 Capabilities and limitations of the IE technique

Capabilities:

- IE can locate voids and grout in internal ducts with moderate accuracy. It can also identify tendons.
- Can be used on both internal and external ducts, metal and non-metal.
- Good penetration, however, thick concrete attenuates the impact echo signal and may lead to difficulties during measurements.
- IE demands only a small accessible area.

Limitations:

- IE cannot locate strand defects in ducts nor defects of the anchoring.
- Layered ducts obstruct measurements.
- Steel reinforcements obstruct measurements.
- No possibility to detect corrosion.

5 Intrusive methods

5.1 Specification

Endoscope (ES)
This technique, borrowed from medical applications, is a slightly destructive method. Holes (approximately 25 mm in diameter) are drilled. After meticulous cleaning of the hole from dust and loose material, the endoscope is introduced into the hole. The core of the endoscope, consisting of optical fibres, allows for direct observation of the walls of the hole. In addition, pictures can be taken at any depth of the hole.

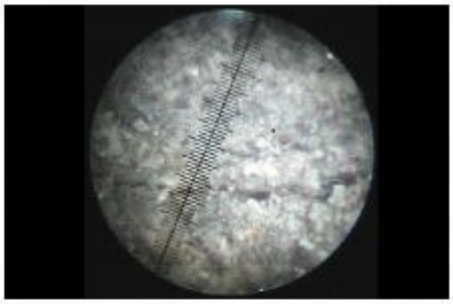

Figure 5.1 Use of endoscope, from (http:// www.nishimatsu.co.jp)

The endoscopes can be rigid (endoscope with metallic pole of variable length) or flexible. The endoscope enables the connection to video and/or photographic devices. A variant of this system is the endoscopic video made through a miniaturised camera directly connected to a device recording images.

5.2 Capabilities and limitations of the ES technology

Capabilities:

- ES can be used to verify possible voids and corrosion.
- ES is easy to use, it can often be used as a complementary to other methods.

Limitations:

- Drilling is required for use of ES

6 Application scope for methods

Application scope	Methods					
	VI	CM	GPR	UPE	IE[4]	ES
Surface deviancies	X	-	-	-	-	-
Locating reinforcement **(L=location, Ø = diameter)**	-	X (L/Ø)	X (L)	X (L)	-	-
Locating ducts **(P= plastic, S=steel)**	-	X (S)	X (P/S)	X (P/S)	-	-
Voids in concrete	-	-	X	X	X	-
Voids in duct **(M=medium accuracy, H=high accuracy, P=partially grouted ducts)**	-	-	-	X (M/H, P[3])	X (M/H, P)	X[1] (H, P)
Corrosion tendon/rebar	-	-	-	-	-	X[1]
Layered ducts	-	No	No	No	No	-
Measuring depth (mm)	-	≤80	600-800	≤1500	[5]	-
Complexity / user friendliness [2]**(E) =easy, (M) = medium, (A) = advanced**	A	E	M	M/A	A	E
Speed (area coverage)	High	High	High	Medium	Low	Low
Accuracy	-	High	High	High	High	-

Table 6.1 Application scope for selected methods

1) by intrusive drilling

2) (E) =easy, no prior experience needed, (M) = medium difficulty, some prior training and experience needed, (A) = advanced, extensive prior training and experience needed.

3) When prior similar measurements have been confirmed through IE and ES.

4) Only as supplement to UPE.

5) For $d/T < 1/4$, the flaw cannot be detected. For $1/4 < d/T < 1/3$, the flaw can be detected, but it`s depth cannot be determined. For $d/T > 1/3$, flaw depth can be determined; and for $d/T > 1.5$, the behaviour is that of a plate with thickness equal to the flaw depth. d = flaw size, T = flaw depth. (Impact-Echo - The Fundamentals, Carino 2015)

Statens vegvesen
Pb. 1010 Nordre Ål
2605 Lillehammer

Tlf: (+47)22073000
firmapost@vegvesen.no

ISSN: 1893-1162