Non-destructive testing of a post-tensioned concrete road bridge in Norway

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Abstract. The Herøysunds bridge on the west-coast in Nordland Fylke in Norway had undergone concrete repair works with focus on reinforcement corrosion. During these actions, it was discovered that the tendon ducts had loss of injection.

To ensure the safety of the bridge it was decided to map voids and defects in the ducts. Several risk areas were pointed out by the contractor and a non-destructive test (NDT) was carried out. The scope of the NDT inspection was to determine voids in the cable ducts at the areas which had been pointed out by the designer. In the project we followed a strict procedure. Based on this we used a combination of different methods such as GPR (Ground Penetrating Radar), UPE (Ultra Pulse Echo) and IE (Impact Echo). It should be mentioned that considerable experience is needed when these methods are combined to investigate voids and defects in tendon ducts. In addition, it is difficult to determine the degree of grouting in the duct and the NDT methods often need to be combined with partly destructive testing, i.e. a hole needs to be drilled into the duct and closer investigation with for example endoscope might be needed. The results from the NDT investigate shows that the suggested approach was successful and it was possible with high accuracy to detect voids in the ducts. The methodology forms a basis for the procedure recommended by the Norwegian Public Roads Administration.

Keywords: Concrete, Bridge, Post tensioned, NDT, GPR, UPE, IE

1 Background

Herøysundet Bridge is a beam bridge, constructed on-site with varying height. The bridge has 6 spans consisting of 5 pillars and two abutments. The total length of the bridge is 154 meters, it has one traffic lane, as well as sidewalks on both sides, and the largest overall width is 5.30 meters. The largest span, which is the navigational channel, is located in span 4 and has a length of 60 meters. Pillars and abutments are founded on rock.

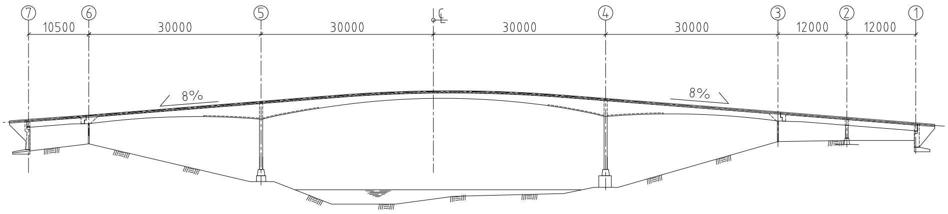


Fig. 1. Herøysund Bridge – elevation

The Herøysund Bridge, situated in Nordland County, Norway, is a post-tensioned bridge. Recent inspections have revealed corrosion in the tendons of its post-tension system. Plans are in place for the replacement of the bridge, followed by the demolition of the old structure. This scenario serves as an excellent case study[1] to enhance current engineering practices in the assessment of existing structures by incorporating the latest scientific advancements. Nordland County, in collaboration with the Norwegian Public Roads Administration (Statens Vegvesen), believes that conducting a thorough evaluation of this bridge can contribute valuable insights, offering a better understanding of the structure's condition, deterioration mechanisms, and overall structural safety[2]. This paper presents the planning and implementation of nondestructive testing for the Heroy Bridge, encompassing the assessment and recommendation of testing methodologies to detect voids in the ducts. Detecting defects and deterioration of the prestressed tendons is a complex task due to inaccessibility. Exploratory openings (e.g. coring) would offer limited results to localized areas. Non-destructive methods should be preferred for minimum disturbance to the structure – i.e. coring done for validation only. In non-destructive testing (NDT), the planning of the inspection is an important part for a successful end result. During the planning, a testing procedure was established where the overall problems of the construction are first mapped and then suitable NDT methods are selected, in which order they should be carried out and which areas should be prioritized in the investigation. When establishing the testing procedure, drawings, previous inspection reports and photos are reviewed – process known as desk study. With this as a basis, the inspection can be placed on the construction parts that are most relevant and where the greatest risk of serious damage exists[3,4].

2 Condition assessment of post-tensioned concrete bridges

2.1 General

In any condition survey, there are two main categories of potential performance failure within an existing structure: defects and deterioration. A defect, is a nonconformity with a standard or specified performance of a structural component from an existing structure. Defects are usually introduced during design and/or construction before the structure begins its service life. Deterioration is a gradual loss in performance (e.g. loss of material properties) over time. Defects may influence the rate of deteriorations or may initiate premature deterioration for materials; thus, the two are often involved in a cause-and-effect relationship. For post-tensioned concrete bridges one defect may be the incomplete grouting of the tendons which over time might lead to deterioration of the prestressed tendons, i.e. corrosion with loss of prestress force. Identifying such defects are critical in extending the service life of existing pre-stressed concrete bridges. Without detection through condition assessments and subsequent repairs, defects and deterioration of the prestressed tendons may lead to failure.

Previous research shows that the technology of prestressed concrete shows excellent durability. However, in some cases corrosion of post-tensioning tendons being mentioned as one of the deficiencies found in previous studies[2].

3 Test Locations

The testing sites for the Herøysund Bridge have been prearranged in consultation with the Norwegian Road Administration and Nordland County. The objective is to conduct Non-Destructive Testing (NDT) on all girders where access to tendons was feasible. It should be noted that tendons situated in the concrete deck have not undergone inspection All test locations are illustrated in figure 2 together with a more detailed description of section A in figure 3. Also, the original section is presented in this figure. However, in this paper only location A, and only the North beam is going to be discussed. The approach is then similar for all other locations. In the next section the NDT (Non-Destructive-Test) approach is presented.

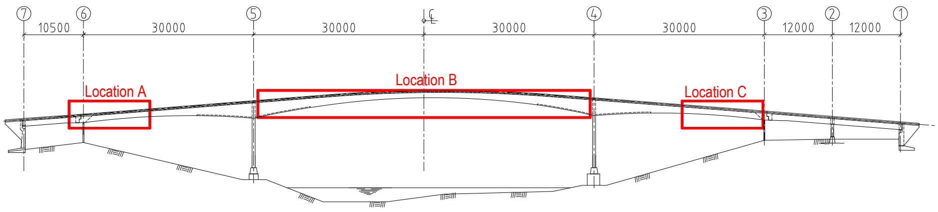
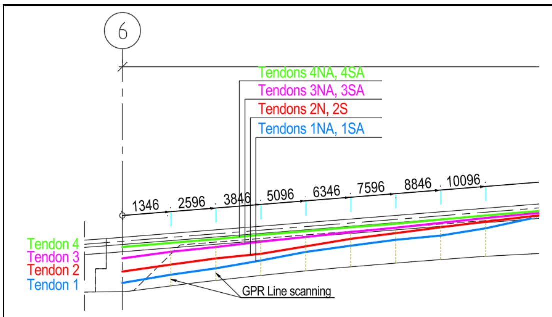


Fig. 2. Testing locations



South girder (tendon ducts and length inspected)
- *Tendon 1SA – 10.0 m long*
- *Tendon 2SA – 7.0 m long*
- *Tendon 3SA – 5.0 m long*

North girder (tendon ducts and length inspected)
- *Tendon 1NA – 8.0 m long*
- *Tendon 2NA – 7.0 m long*
- *Tendon 3NA– 5.0 m long*

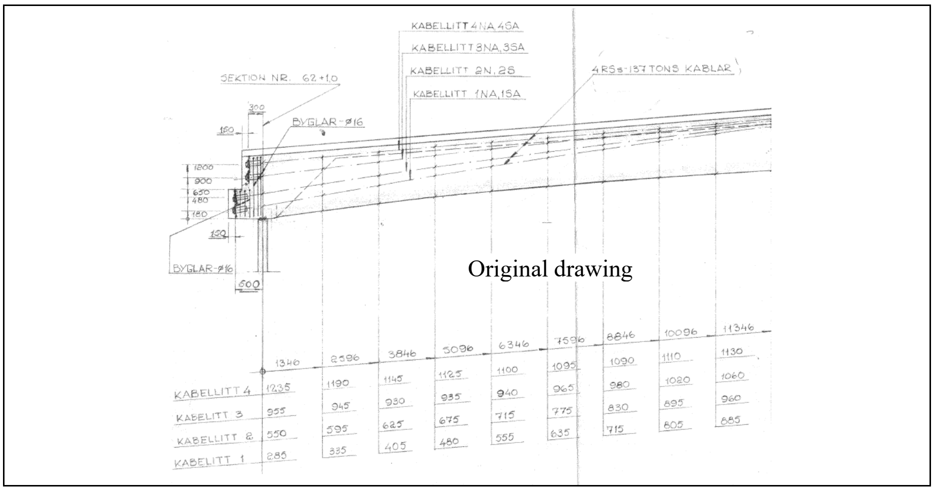


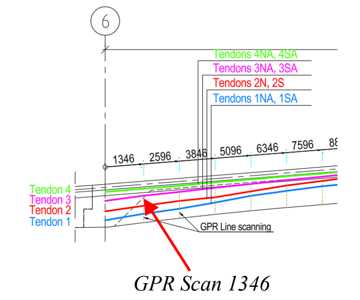
Fig. 3. Inspection of ducts in the north/south girder, Location A

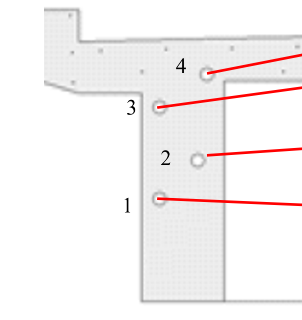
4 Non-destructive testing approach

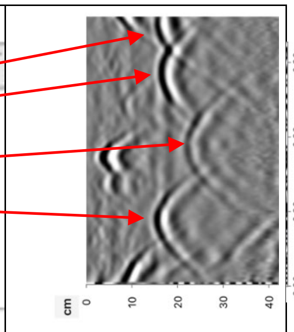
The inspection task was carried out by using the following NDT systems: Cover meter, Ground penetrating radar (GPR), MIRA ultrasound 3D (UPE), Impact echo and Videoscope. In addition, coring was done at select locations to provide access to the tendon ducts followed by drilling to provide ground truth information and validation. The inspection process included the following actions: 1) Desk study where potential focus areas were defined, 2) Locate the areas to be inspected based on the original planning and adapt based on local conditions. Deviations may exist due to local unevenness of the concrete surface making the data collection difficult, 3) On the areas marked in step 2, use ground penetrating radar to locate the ordinary reinforcement and prestressed reinforcement, 4) Mark the position of the prestressed reinforcement directly on the concrete surface and divide the profile line in 10 cm segments, 5) Use MIRA instrument to capture 2D slices at every 10 cm segment defined in step 3, 6) Combine the 2D slices within a 3D image that can be used for interpretation of the results, 7) Any detected flows on the 3D image based on MIRA measurements are further investigated using Impact echo instrument and 8) Coring/drilling is carried out in areas with potential voids inside the tendon ducts.

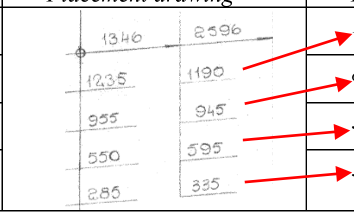
5 Results

The main purpose of the investigation conducted at Herøy Bridge was to verify the integrity of the grouting along the post tensioned tendons. Non-destructive test methods have been used to be able to check for defects. The measurements were repeated as vertical scans in the same locations as the original drawing, with this approach, the placements could be compared for the north beam in location 6, see figure 4. MIRA equipment has been used in all cases to evaluate the condition of grouted post-tensioning ducts in the webs. B-scans (2D images) were collected every 10 cm along the ducts, see figure 5. In total, around 3000 B-scans were collected throughout the bridge. The B-scans reflects the cross-section (perpendicular to the test surface) while the C-scans are obtained by combining multiple B-scans – thus, showing the reflecting interfaces on a plane parallel to the test surface. For example, tendons are shown as big dots on a B-scan together with their depth ("concrete cover") as well as the back-wall (thickness of the scanned element). On the C-scan the tendon ducts are shown as continuous lines. The lines may have a green-yellow color and indicates lower amplitude reflections from the steel tendons – meaning the duct is fully grouted. If the lines are displayed as red color, this indicates strong reflections from a discontinuity in material properties. Areas with strong interference that is characteristic of an air void will be further inspected with impact-echo instrument, se also figure 5.









Duct number	*Placement drawing*	*Placement GPR scan*
4NA		*1050*
3NA		*850*
2NA		*540*
1NA		*300*

Fig. 4. Corroborating the GPR results with as-designed drawings showing the placement of tendon ducts in north girder and a comparison with the placement.

MIRA (UPE) *Impact Echo (IE)*

Fig. 5. Inspecting grouting conditions with MIRA and Impact Echo

Inspection of tendon ducts started at the anchors placed in axis 6 in both north (N) and south (S) girder. The most severe locations were found on the south girder in tendon 2SA and 3SA. In the south girder two of the ducts was completely empty and had severe corrosion on the tendons. In the north girder duct 1NA gave indications to be lacking grout, the verification showed no presence of voids. Figure 6 shows a simplified overview of the scans and the ultrasonic results is shown in Figure 7.

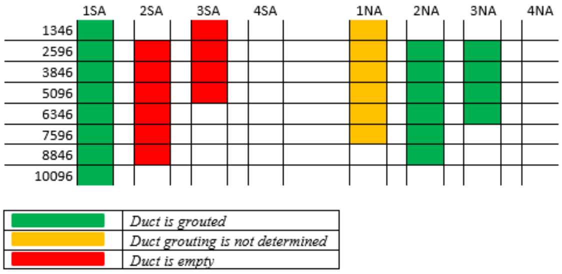


Fig. 6. Grouting status according to Ultrasonic results

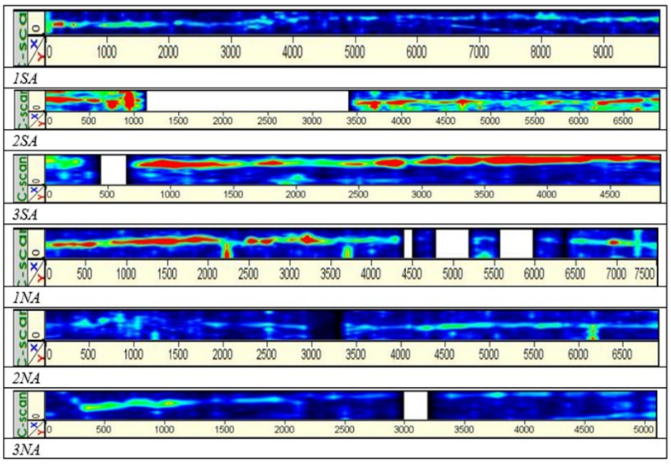


Fig. 7. Ultrasonic results in south and north girder

Impact echo was used in some locations to verify the results from ultrasonic scans. In order to detect ungrouted tendons two features in the frequency spectrum were of interest. First, a frequency peak in the spectrum that is associated with the thickness of, in this case, the girder needs to be calculated. The frequency peak for the backwall is calculated with the actual thickness measured at the girder, *T= 400 mm*, and the velocity measured with ultrasonic pulse, $C_p = 4140\ m/s$:

$$f = \frac{C_p}{2T} = 5.176kHz \tag{1}$$

The frequency peak we should look for is 5,176kHz and if we get a peak at this frequency Impact echo shows that no voids is presence in the inspected duct 2NA, see figure 8.

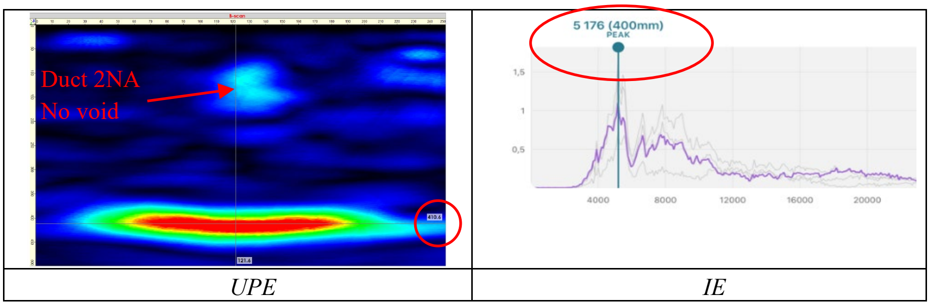


Fig. 8. Scan in 2NA scan 67 with no presence of voids. Backwall at 400 with both UPE & IE.

Figure 9 shows a scan of a duct with a void, 1NC. In this example the duct is placed with a cover of $T=190\ mm$ and $C_p = 4140\ m/s$, a void in this duct should give a frequency peak according to the following calculation:

$$f = \frac{C_p}{2T} = 10.89 kHz \tag{2}$$

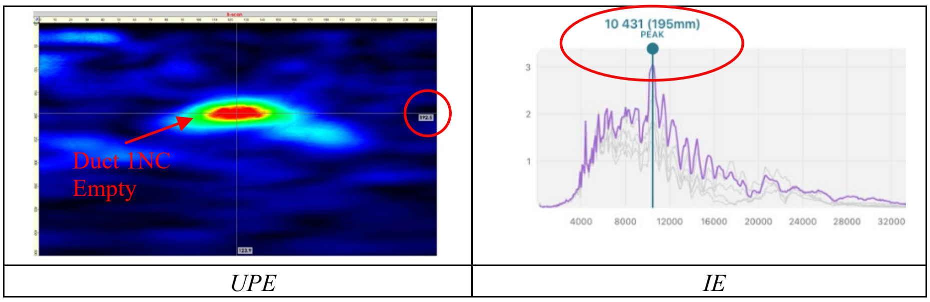


Fig. 9. Scan in 2NA scan 67 with no presence of voids. Backwall at 400 with both UPE & IE.

In figure 10 a longer grid scan with Impact echo from duct 3SC is shown, this duct is confirmed as empty in investigation made in 2020. No drilling was made during the inspection presented in this paper. The cover to the duct is around 160mm according to the GPR which means that the void could be somewhere between 160mm and 240mm. Red values shows the presence of voids and the depth to the void. The green values show the thickness peak for the backwall, and the orange values show a shift in the peak which indicates a void. It should be noted that only one scan in each location was made which could mean that the impact echo missed the duct, especially the last scans were the duct was placed above the marked line on the concrete surface. This could explain the green numbers in the end. Each measurement with impact echo was made along the duct with 10 cm between, the same grid that was made with UPE.

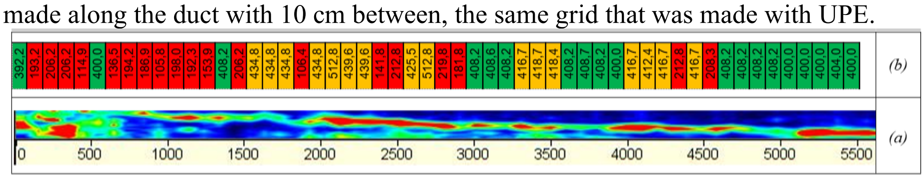


Fig. 10. Empty duct with results from UPE *(a)* and Impact Echo (IE) *(b)*.

6 Verification by coring

To verify the results from the measurement some of the tendon ducts were opened to investigate the status of the cables and to verify voids or no voids. One has to very careful when doing this, so the tendons are not damaged or even worse cut. The procedure is the following:

- Map placement of slack reinforcement – to avoid cutting reinforcement when drilling
- Map placement of ducts
- Use a hammer drill machine with f16 to verify the distance to the duct
- Mount and core with f80 – 100 mm depending on the depth to the duct
- Stop coring ca 15 mm outside the duct
- Carefully remove the concrete into the duct
- Open up the duct and inspect visually or in combination with videoscope
- After inspection repair the opening

The general process in photo format is shown in figure 11.

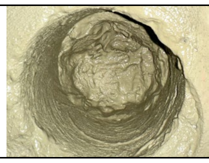
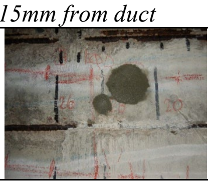
			
Core drilling Ø100mm aprox 10-15mm from duct	*Exposure of duct*	*Opening of duct and tendon inspection*	*Sealing with Mapei Redisit*
			
Repair with Mapei Redirep	*Location 3SA*	*Empty duct, corrosion*	*Humidity 99,8 in the duct*

Fig. 11. Opening in duct 3SA, 4 m from the anchor. Empty duct with corrosion.

7 Summary and Conclusions

The aim of the inspection was to evaluate the condition of the pretensioned tendons at Heröy Bridge. Specifically, voids in tendon ducts and consequently corrosion of the tendons has been the focus of the investigation. To achieve this, the condition of the grouting has been verified using non-destructive equipment MIRA, UPE, (shear-wave tomography) and DOCter (impact echo). Careful opening of tendon ducts by coring/drilling, and subsequent visual inspection with a videoscope was carried out in suspicious areas to validate the findings.

The inspection was done in several locations starting by locating the tendons using a GPR instrument. The placement of the tendon ducts was marked on the concrete surface. The next step was to check for voids using UPE. From all measurements performed suspicious areas were detected in Section A and B. These locations were further studied using DOCter impact echo – arguably a more refined NDT method. The findings were validated using core drilling.

In section C and especially section A where the core drilling took place, the results from the NDT corresponded with the verifications.

In section A, two out of six inspected ducts were found ungrouted and verified with core drilling, 2SA and 3SA, in these two ducts we also found corrosion on the strands. Duct 1NA was found grouted on the side that was opened, despite that the ultrasonic results showed voids. Most certain, there are voids present, but on the back of the duct. In table 2 a suggestion for probability grading is presented. The results from two girders is then summarized in table 3. Here only the verification from these inspections is shown. We know from earlier inspection that the results in section C is verified as well.

Table 2. Grading for probability of voids.

	No voids	Probability <50%
	Minor voids	Probability > 50 %
	Major voids	Probability >75%

Table 3. Suspicious areas from ultrasound investigation with coring verification and class in south and north girders

No.	South	UPE	Verif.	Grade	No.	North	UPE	Verif.	Grade
1	1SA				1	1NA			
2	2SA				2	2NA			
3	3SA				3	3NA			
4	1SB				4	1NB			
5	2SB				5	2NB			
6	3SB				6	3NB			
7	4SB				7	4NB			
8	1SC				8	1NC			
9	2SC				9	2NC			
10	3SC				10	3NC			

The results can be summarized: GPR was used to accurately locate ducts before inspecting them with MIRA and DOCter Impact echo. Ducts placed close to the reentrant corners were more difficult to locate. A smaller GPR was used for this purpose since easier access was possible. However, this required full contact with the concrete surface (rather than relying on wheels) which in some areas posed difficulties due to unevenness of the concrete surface.

The result from ultrasonic scanning shows that there where voids inside the ducts, this was confirmed with core drilling. In section A, south girder, 2 out of 3 ducts was completely empty, the tendons had severe corrosion and we also found a wire breakage in duct 2SA

The amount of grouting and corrosion differs a lot inside the same duct. Duct 3SA was completely empty 4,3m from the anchor point with and there where corrosion on all the strands. Closer towards the anchor the bottom half of the duct was grouted, and corrosion could only be found in the top half of the duct. In duct 2SA there was a big difference in corrosion degree only 20 cm between two openings. Therefore, it is important to trust the equipment and put some effort in the openings to make sure that the voids are located.

Although no defects to the grouting (i.e. voids) were found in 1NA when opening up the metallic ducts, it cannot be ruled-out the risk of voids on the other side of the duct or on the other side of the tendons in the duct. Change in material properties of the grouting mixture along the duct may also be an explanation for the suspicious areas obtained by MIRA. However, the effect of the grouting mixture has not been mentioned in the literature and probably additional research is needed.

Nevertheless, despite that it was sometime difficult to detect voids, the process developed has proven to work and that it can with certain probability detect voids in the ducts which then can be parameter for corrosion in the tendons.

Plans for future work is to develop an algorithm based on machine learning that can support decision making regarding voids in ducts, where raw data from different NDT technologies are combined. The machine learning training will be conducted on elements with known and unknown defects to the training procedure.

Acknowledgement

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