

Reliability of UT for the grouting inspection in PT bridges: A case study

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ABSTRACT: The inspection of the condition of prestressing steel in post-tensioned structures is a challenging issue because of the potential presence of corrosion in the tendons not warned by any other visible degradation condition. The economic unfeasibility and technical difficulty of performing a large number of semi-destructive tests (endoscopies) require the identification and practical application feasibility of non-destructive testing techniques to optimize the inspection procedure and enhance its accuracy. Many real-world examples have evidenced that ineffective grouting, or even the lack of it, triggers the corrosion mechanism that, if not detected early, can lead to the brittle failure of the bridge. Therefore, failure of post-tensioned structures is normally associated with ineffective grouting. For this reason, it becomes of interest to localize and quantify grouting defects and voids in the tendons. Some non-destructive techniques are currently available; one of these being the Ultrasonic Tomography.

This paper presents the results of the combined application of Ultrasonic Tomography and endoscopies in the detection of un-grouted regions in a real bridge. The reliability of the Ultrasonic Tomography results is then obtained through the Probability of Detection (PoD) curves which are checked against the results given by the endoscopic testing campaign.

1 INTRODUCTION

Prestressed concrete bridges with bonded internal post-tensioning, in the following PT bridges, are difficult to investigate and assess. The high-strength steel cables are protected from dangerous conditions triggering corrosion by the grout, the metallic or plastic sheet of the ducts, and the concrete cover. Many protective layers are, therefore, provided, and for this reason, especially for the first constructions, there were no worries about their durability (Godart 2001). One of the serious and sudden events occurred in the UK in 1985 when a single-span PT bridge collapsed without any warning (Woodward 2001; Woodward and Williams 1988). The events led to the Department of Transport's (DoT) decision to ban the PT bridges with internal tendons until the design and construction standard could be reviewed, in September 1992. At the same time, DoT announced that all the PT Trunk bridges would be systematically inspected over a five years period. The moratorium was lifted for cast-in-place posttensioned concrete bridges in 1996 since the results of the Special Inspections revealed that the majority of structures have a good record of durability. Anyway, this fact focused the

attention on the methodologies to apply to inspect these structures, in particular in identifying not visible defects.

Regarding Italy, the triggering event was the collapse of the Polcevera viaduct, in August 2018. After that, many efforts were made to organize and standardize the inspection and assessment of bridges and viaducts of any typology. The publication of the Guidelines for Risk Classification and Management, Safety Assessment and Monitoring of Existing Bridges (MIT CSLP 2020) in 2020 stated a set of actions to be completed to inspect the structures depending on the level of knowledge to reach. In this context, PT bridges are presented as a “particular case”, to be dealt with by executing the so-called Special Inspection. The main problem is that, even if some indications are given, there is a gap regarding the testing methodologies to apply and the definition of the number of samples. Some proposals have been made during the very last years to cover this lack (Mazzatura, Caprili, et al. 2023; Mazzatura, Salvatore, et al. 2023), and the research here presented is part of these wider topics.

The focus is on the possible non-destructive methodologies to apply in searching for defects in PT tendons. Since searching for corrosion is difficult, and since corrosion is often associated with the lack of grouting (i.e. voids within the ducts), a way to search for defects can be searching for voids. The underlying and main assumption is that the void sections are associated with the defective ones. Even if this assumption is conservative, detecting voids is easier through Non-Destructive Technologies (NDTs). Many NDTs are proposed in the state of the arts. In the present research, the choice is to apply the proposed method to a real bridge and investigate the reliability of the result provided by UT.

2 METHODOLOGY

A 14-span viaduct located on a Highway in the North of Italy was investigated. The followed methodology was the one explained in (Mazzatura, Caprili, et al. 2023). Even if the present paper will focus only on the individuation of ungrouted areas within the PT ducts, a few words will be spent in the following to explain the determination and the location of the samples to investigate. Starting from the consideration given by the Italian Guidelines (MIT CSLP 2020), and by the study of the available state of the art (in particular of (FHWA 2013; Highways England 2020)), a multiphase methodology is proposed. It works on subsequent levels of analysis, meaning that only for the most degraded structures is necessary to go through all the phases. The first two phases are mandatory for all the bridges: *phase 0* provides the knowledge of the structure and the determination of the number of samples to investigate, *phase 1* provides the overall assessment conditions through both non-destructive (ND) and semi-destructive (SD) technologies, *phase 2* consists in the deep analysis of the defectiveness individuated at the end of the previous one, and *phase 3* is optional and contains suggestions for the global analysis of the bridge. For the present structure, the first two phases are executed.

Once the number of samples was determined, the choice was to employ as NDT the Ultrasonic Tomography. On the basis of a laboratory testing campaign previously executed and presented both in (Mazzatura, Salvatore, et al. 2023), and in (Mazzatura et al. n.d.), the way of employing the instrumentation and some considerations useful for the critical elaboration of data had been determined. In particular, the main results are about the reliability of the NDT given in terms of Probability of Detection (PoD). The PoD model is an evaluation often carried out for Non-Destructive methodologies, widely employed in the context of aerospace and nuclear engineering, and standardized by ASTM (ASTM International 2015, 2018). Stated a certain confidence and for a given probability, by the PoD curve it is possible to determine the largest flaw that a system can miss.

The tests' campaign will be described, and the focus will be on the tests for the location of the grouting defects. Finally, a critical analysis of the results is given, considering the main outputs deriving from the PoD analysis.

3 EXPERIMENTAL CAMPAIGN

3.1 Description of the structure

The studied viaduct is located on a highway in the North of Italy. It has 14 spans of variable length for a total length of 600 m. Each span is either 45, 40, or 34 m; but the very large part (11) is 45 m. The deck has 4 posttensioned beams and 4 reinforced concrete cross members. The subject of the investigation campaign were the beams belonging to the large population, i.e. the ones of 45 m.

From the design documentation, it is known that each beam is posttensioned by 6 cables (Figure 1), each composed of 42 wires of 7 mm diameter. The longitudinal design layout of the cables is known as well (Figure 1), and also the design mechanical characteristics of both the concrete and the high-strength steel. The initial prestress is not known. The main information about the viaduct is summarized in Table 1.

Table 1. Main information.

Year	N_{spans}	L (m)	L_s (m)	$N_{\text{beams}}/\text{span}$	$N_{\text{cables}}/\text{beam}$	Cables' typology	f_t (MPa)	Initial prestress
1976	14	600	34-40-45	4	4-5-6	Parallel wires	1'600	Unknown

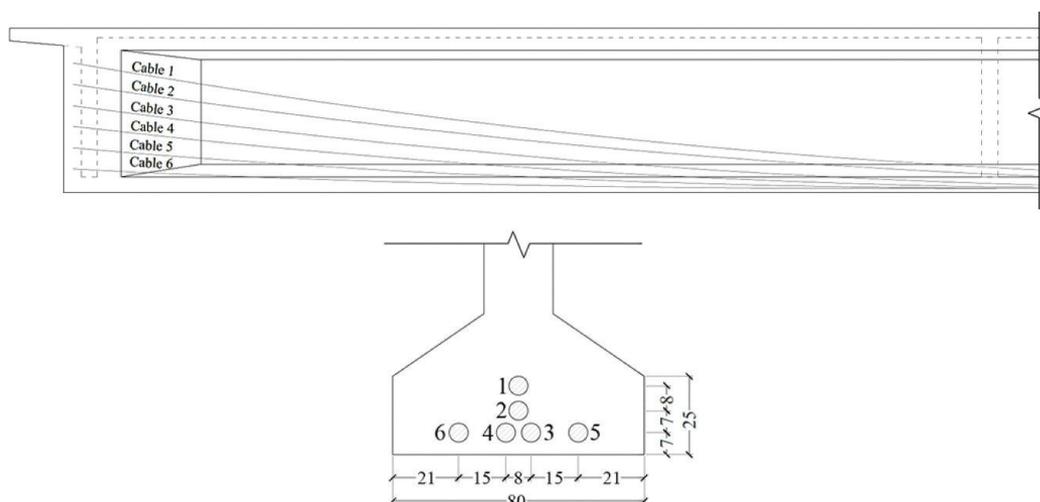


Figure 1. The upper figure shows the cables' trace, the lower one the middle-span cross-section.

3.2 Number of samples and localization

Many tests were performed on the structure. In the following, the focus will be only on the ones necessary to investigate the grouting defects within the ducts. First, a revision of the design documentation and the execution of a visual inspection is completed. This allows reaching a satisfying level of knowledge for the definition of the number of samples.

The basic assumption is that a sample corresponds to a cable and that a cable can be considered fully investigated if all the sites where voids are most likely to occur are tested. For more details, please refer to (Mazzatura, Caprili, et al. 2023).

In the present case, 14 samples resulted, therefore, 14 cables were chosen. A maximum of two tendons per beam are selected, to reasonably spread the testing campaign. Thus, 7 beams are chosen belonging to 3 different spans. The NDTs for the preliminary investigation aiming to define the layout of the cables (i.e. Ground Penetrating Radar), and the ones for the localization of voids (i.e. Ultrasonic Tomography), can be executed only in the areas shown in Figure 1, which corresponds to the ones in which the cables lie in the web of the beam and not in the lower part. The other locations (mainly the mid-span regions) were investigated through SDTs, i.e. endoscopies.

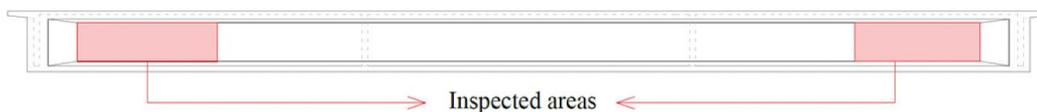


Figure 2. Inspected areas by GPR and UTs.

Endoscopies were also executed on the cables' trace in the web of the beam, both in areas warned by the Ultrasonic Tomography and in random areas.

3.3 Preliminary investigation

Before performing the investigations to locate grouting defects, it is necessary to collect some pieces of information about the structure. A revision of the design documentation was carried out, to identify potential conditions promoting damage, such as inadequate waterproofing and drainage system. The visual inspection is also fundamental to preliminary state the conservation status of the structure and to identify defects that can warn of possible deficiencies in the PT system. Particular attention must be given to cracks, whose presence could mean excessive losses in the precompression, and to defects showing the penetration of water/moisture inside the concrete section. Anyway, no worrying conditions were identified.

Once the overall condition of the structure is stated, and the number of samples to investigate is computed, it is possible to proceed with the preliminary in situ tests, mainly devoted to the location of the cables' layout. All the subsequent tests are concentrated on the cables, then it is important to exactly know their trace. In the present research, the Ground Penetrating Radar (GPR) was employed to locate the ducts.

GPR is a radar imaging technique using electromagnetic pulses transmitted to the element at very high frequencies. It was widely used (Terzioglu et al. 2018a) for achieving information about reinforcements' layout (Beben, Mordak, and Anigacz 2012; Kohl and Streicher 2006; Pasculli et al. 2018; dos Santos et al. 2014; Shaw et al. 2005; Soldovieri et al. 2006), the position of prestressing strands and metallic ducts (Clem, Schumacher, and Deshon 2015; Kohl and Streicher 2006; dos Santos et al. 2014; Terzioglu et al. 2018b), and the presence of voids in the concrete. From a practical perspective, the tests were executed by doing vertical scans (i.e. the 0, 1, ... 10 sections in Figure 2) on the beam web each 100 cm. In each section, the location of each cable is identified. Finally, the single locations are joined to obtain the actual trace. As previously mentioned, the GPR test was executed in the areas of the beam where the cables lie in the web. These areas correspond to around the first 10 m from the beam heads. Indeed, it is not possible to execute the tests in other areas, such as the bulb of the beam, because the investigation surface is inclined. The trace of the cable represents the fundamental base for the execution of posterior tests.

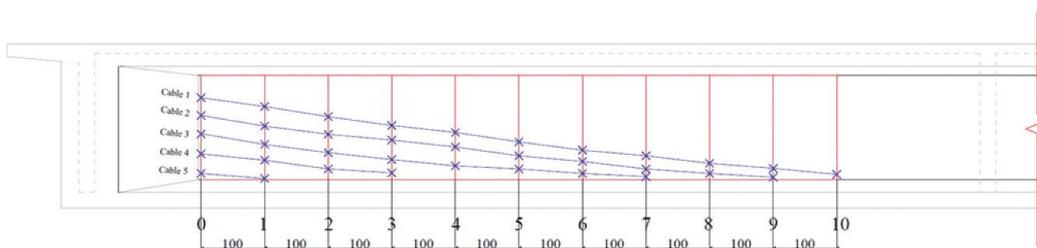


Figure 3. Operating modality for tracing cables.

3.4 Investigations for the localization of voids

The localization of voids was performed through Ultrasonic Tomography and endoscopies. Two cables per beam were inspected, and in detail cables 3 and 4. These are the cables that present largest areas on the web for feasible investigation. For instance, cable 1 and cable 2 are more visible in correspondence of the web, being the higher ones, but it is not possible to investigate them in the midspan region because they are located in the second order of PT reinforcements, having both a very large concrete cover, and the cables from 3 to 6 and the

ordinary reinforcements in the first order, making difficult the execution of any other kind of test (endoscopies and UTs), considering to execute them on the intrados of the beam (Figure 1 in the lower part shows the mid-span cross-section of the beam).

UTs were performed in all areas of the cables that could be tested, while endoscopies were performed in areas in which UTs gave no information (i.e. midspan region), in random areas (i.e. locations investigated but not warned by UT), and in critical areas (i.e. locations warned by UTs).

3.4.1 Ultrasonic tomography

UT was selected because of its quick and easy in-situ application. The in-situ conditions are often very adverse, mainly because of the height of the bridge, and therefore the uncomfortable work areas, and of the limited time available to complete the tests (it is often necessary to stop the traffic, or at least to limit it).

UT is reliable in estimating the thickness of elements/layers and in locating voids in PT ducts, especially when coupled with other testing methodologies (Martin et al. 2001; Muldoon et al. 2007). In the present campaign, the MIRA A10403d instrument, employing shear waves and dry point contact sensors was used. A stress pulse is generated through a mechanical impact of the sensors, even working as receivers. Part of the pulse propagates through the body, and part is reflected. Changes in the acoustic impedance are then captured. Through time-of-flight measurements, it is possible to locate discontinuities and therefore reinforcements, tendons, voids (cracks, honeycomb, delamination), or water defects (Muldoon et al. 2007). The testing apparatus gives images as results, elaborated through the SAFT algorithm (Schickert, Krause, and Müller 2003; Stepinski and Lingvall 2010). Figure 4 shows the elaborated results of the UTs on one of the beams.

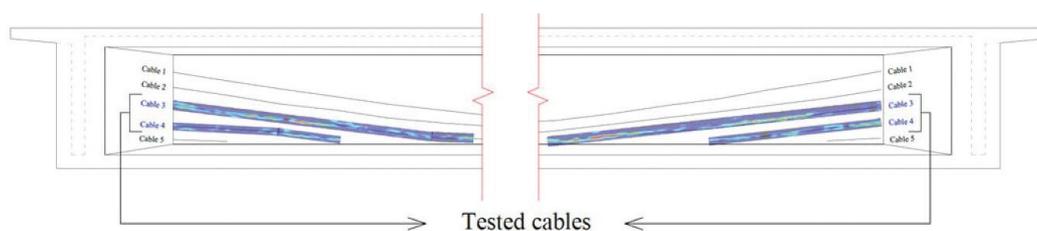


Figure 4. Results from UTs after postprocessing.

3.4.2 Endoscopies

To execute endoscopic investigations is necessary to locate the cable. In fact, a tiny spot (usually no more than 20 mm in diameter) is investigated. The endoscopies were executed firstly by performing a hole of a bigger diameter (20 mm), and then proceeding with a smaller one (10 mm); this methodology avoids smashing the metallic sheet of the duct on the tendon (Figure 5a.) and thus avoids performing a non-informative test.

Understanding the conservation status of the tendons through endoscopic investigations could be challenging, but it is a balanced compromise between an NDT and a full destructive investigation (i.e. the removal of the concrete cover, the metallic duct, and the grout).



Figure 5. A. The mashed duct does not allow a correct evaluation; b. correct endoscopy with no evidence of grout.

4 RESULTS AND DISCUSSION

Starting from the results of a laboratory campaign for the definition of the Probability of Detection (PoD) curve for the UT investigating voids in PT metallic duct, the results of the in-situ testing campaign are elaborated. A critical discussion of the results is given with consideration about the overall observed state of conservation of the structure.

4.1 Probability of detection

The Probability of Detection is a methodology to evaluate the reliability of an NDT by furnishing as main information the largest flaw that the system can miss (given a certain probability and stated level of confidence). This piece of information is obtained by establishing a relationship between the probability of detecting a defect with its size, under representative application conditions. Since the main assumption is that the PoD depends only on the flaw size, it is very important to understand the other potential influencing parameters, that can be related to the geometry of the investigated body, environmental conditions, the testing set-up, and so on. Some details about the PoD construction are contained in (Mazzatura et al. n.d.); here the results of the PoD analysis are used to analyse the ones derived from the in-situ testing campaign.

The PoD useful for the present work is the one given in Figure 6, from (Mazzatura et al. n.d.). The displayed values are PoD(50%), i.e. the size of the void that the system can miss with a 50% probability and a 50% confidence level; PoD(90%), i.e. the size of the void that the system can miss with a 90% probability and a 50% confidence level; and PoD(90/95), i.e. the size of the void that the system can miss with a 90% probability and a 95% confidence level.

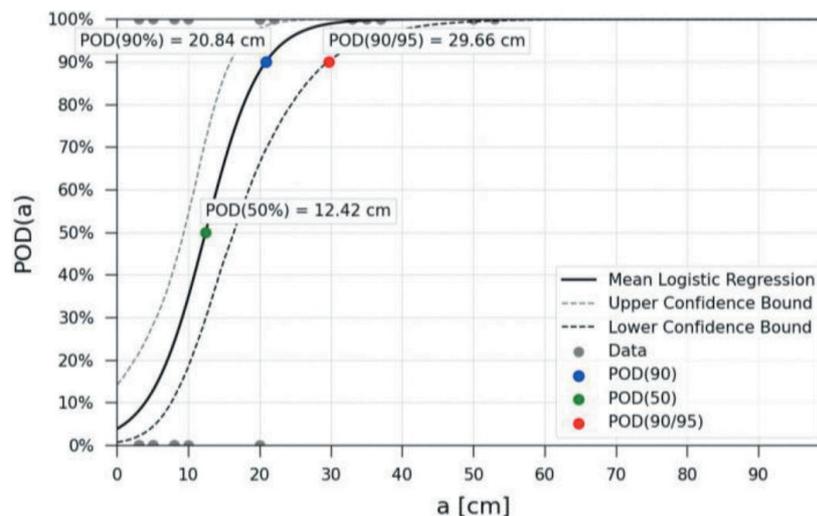


Figure 6. PoD curve for PT duct located at 15 cm from the investigation surface.

The last value, i.e. POD(90/95) is the interesting one, as the ASTM requires. The shown curve is obtained for defects located in cables lying 15 cm from the investigation surface and employing the same instrumentation calibration. This case represents the most similar one to the present testing campaign since the cables lie 11 cm from the concrete surface and all the tests were performed employing the same calibration.

4.2 Critical analysis

The results of the UTs and endoscopies were reported and compared as shown in Figure 7. Being the POD(90/95)= 25.66 cm (Figure 6), only the UTs showing a warn wider than 30 cm are considered as defective areas, i.e. voids inside ducts. In 4 out of 14 investigated cables, resulted in no defects at all.

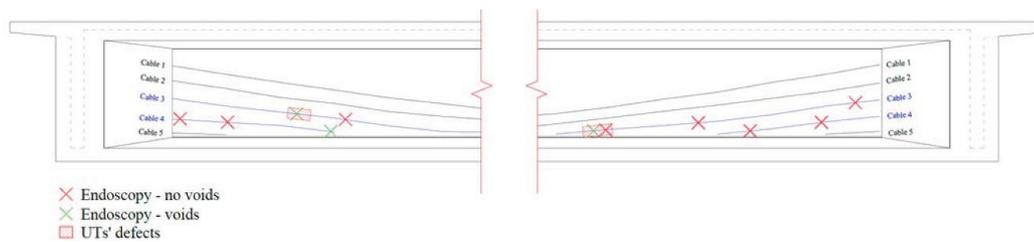


Figure 7. UTs defects and output of the endoscopic investigations.

In the other cables, some defects were signaled by the UTs. Table 2 gives a summary of the analysis. The last column represents the percentage of defective areas (L_{war} = warned length) on the total investigated length (L_{inv} = investigated length).

Table 2. Results of the UTs.

Span	Beam	Cable	UTs defective percentage ($L_{\text{war}}/L_{\text{inv}} \cdot 100$)
3	1	3	10%
3	1	4	30%
4	1	3	9%
6	1	3	8%
8	1	3	16%
8	1	4	43%
6	2	4	31%
8	2	4	6%
3	3	3	49%
3	3	4	55%

On a total of 56 endoscopies, 26 were executed in random areas of the cables and 30 in the areas warned by UTs. 63% of the tests in the warned areas reported the presence of voids; however, some of these voids are not located inside the duct but outside of it. The tests in random areas reported voids in 23% of the cases. No oxidized or corroded wires were found.

Table 3. Number of false positives and true positives.

	30 cm ≤ d < 50 cm	50 cm ≤ d < 100 cm	100 cm ≤ d < 150 cm
Number of false positives	4	3	2
Number of true positives	4	7	7

By combining the output of the endoscopies and the UTs, it is possible to obtain the results summarized in Table 3. The assumptions are that if endoscopies are executed in correspondence of areas warned by UTs, and no evidence of voids is found, then false positives are identified; otherwise, if the endoscopies are not executed, or if the endoscopies are executed and voids evidence is found, then true positives are identified. It can be observed that the quote of false positives decreases with the length of the defects.

5 CONCLUSIONS

The present research deals with the inspection of PT bridges, with particular attention to the execution of tests for the location of voids. The focus is on Ultrasonic Tomography, employed on a 14-span bridge located in the North of Italy to investigate the status of grouting of 14 cables. The results of the investigations are elaborated in view of the reliability evaluation of the technique obtained thanks to a previous laboratory testing campaign. Some endoscopic investigations were conducted to check the reliability of the detection technique.

This case study shows that the PoD curves obtained in laboratory under controlled conditions and where only the flaw size is the variable, may have to be considered cautiously when applied to real bridges under uncertainties not encountered in the laboratory, related to the inspectors' ability to work in difficult environments, the variability due to in situ conditions, and others. The number of false positives encountered in real conditions, even for large voids has to be taken into account in further applications to real bridges.

However, by considering both the results of the NDT and of the SDT, mainly since no evidence of corrosion was found in any case, it is possible to affirm that the structure is in a good state of conservation, even if some voids within the ducts were found.

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