ce/papers Proceedings in civil engineering

Ernst & Sohn
A Wiley Brand

EUROSTRUCT

ORIGINAL ARTICLE

Assessment of bridge Post-Tensioning systems using non-destructive (ND) inspection methods

Virginio Quaglini[1] | Carlo Pettorruso[1] | Sara Cattaneo[1] | Dalila Rossi[1]

Correspondence

Prof. Virginio Quaglini
Politecnico di Milano
Department of Architecture, Built environment and Construction Engineering
Piazza Leonardo da Vinci 32
20133 Milan, Italy
Email: virginio.quaglini@polimi.it

[1] Polytechnic di Milano, Department of Architecture, Built environment and Construction Engineering, Milan, Italy

Abstract

Reinforced concrete bridges with post-tensioned cables are particularly critical structures, as the degradation of the tendons is not fully detectable through conventional investigation methods and/or through visual inspections, due to the intrinsic nature of the structural typology. After shortly reviewing the main applications of current non-destructive (ND) methods available for investigating the deterioration of tendons and grout, the paper presents a simple procedure to rank these methods through a series of metrics formulated to evaluate the various technologies under four different aspects: accuracy of measurement, ease of use, cost, impact on the operation of the bridge. The procedure has the aim of providing bridge owners with a decision tool which can assist in the selection of the optimal ND technology available to detect a particular strand or grout defect.

Keywords

Prestressed concrete bridges, Post-tensioned cables, Non-destructive methods, Special inspections, Evaluation metrics, Grout defects, Strand defects.

1 Introduction

Post-tensioning (PT) is a popular technique used to improve the performances of reinforced concrete bridges. This technology consists in introducing into a concrete element a prestress (by means of post-tensioned steel tendons) which counteracts tensile stresses due to external loading, resulting in reduced deformation and cracking of concrete. Among the advantages of post-tensioned structures there are the possibility of achieving long beam lengths with reduced deflections and high span/depth ratios, the increase in durability achieved by reducing or eliminating cracking, and a more efficient utilization of steel and concrete materials. Since the ‘50s of the last century, post-tensioning has permitted to extend the application of concrete bridges for larger spans, and enabled for new construction methods, making them simpler and faster. Post-tensioning tendons are encased in a duct, which can be made either of steel or a non-metallic material such as HDPE. Two different kinds of PT ducts are used in bridges: internal and external ducts, depending on whether tendons lie within the cross-section of the structure, or are placed outside of the section being stressed, and the forces are only transferred to the anchorage blocks or deviators. Subsequent to stressing the strands, the duct is filled with a cementitious grout aimed at protecting the tendons from corrosion by preventing the ingress into the duct of water, oxygen, chlorides and other aggressive elements. However, in spite of these protective measures, field observations have shown that prestressed concrete members may be very susceptible to reinforcement corrosion. In particular, concentration of tendons into several large cables makes bridges vulnerable to localized corrosion. Moreover, poor workmanship in grouting activities, especially using spacers within the ducts and with untrained staff, poor detailing, scarce quality of joints on segmental construction, fragile vent pipe details, poor supervision and bad structural waterproofing impact on the quality and soundness of the grout increasing the risk of corrosion. Deterioration conditions of PT systems are broadly categorized into strand defects and grout defects. Possible strand deterioration may include: corrosion, section loss and breakage of the metal strands. Deterioration of grout may include: voids, water infiltration, and compromised grout (e.g., segregated grout, non-hydrated grout or gassed grout). The deteriorated conditions of PT systems usually lead to a loss of prestressing force, with impacts on the bridge management in the form of reduced load capacity and structural safety, need for expensive rehabilitation interventions, and traffic disruption. Serviceability and safety impairments are in fact associated to the loss of prestressing force due to long-term effects, to the increase of tensile stresses in concrete and to the arise of possible cracking phenomena, with consequent effects on the exposure of reinforcement, and lastly leading to potential structural failure. The failure of the principal tensile load-carrying components may have catastrophic consequences, especially in case of a lack of redundancy within the structure, leading to a possible brittle collapse. Notable

https://doi.org/10.1002/cepa.2065

failures of post-tensioned bridges [1-5] have indeed highlighted their vulnerability to hidden defects. Therefore, the assessment of the conditions of PT systems is critical for maintaining public safety, as well as to allow undertaking timely, proactive actions to mitigate or prevent further deterioration and unanticipated failure of post-tensioned structures.

To give bridge owners confidence that their post-tensioned bridge stock is in a good and safe condition it is essential to implement effective inspection and monitoring regimes. Visual inspections alone may not give warning of imminent collapse, but, on the other hand, can be useful to identify defects relevant to the PT system [6], which provide symptom regarding the system itself. Starting from the data collected, visual inspections must be associated with other techniques because tendon ducts and grout, which are intended to provide corrosion protection to strands, hide them making it impossible to evaluate their condition by visual inspection alone. In particular, internal ducts are embedded within the structure, which makes them difficult to access and inspect, while, on the other hand, external ducts are not embedded in the concrete, allowing for easier and less intrusive inspections. Modern inspection guidelines [6] have identified non-destructive (ND) methods suitable for evaluating the conditions of the tendons and the grout. Moreover, ND technologies used in other industries may have potential for PT bridge assessments. A brief compilation of the main ND methods for inspection of PT systems will be reported in section 2 of this paper. In particular, NCHRP Research Report 848 [7] presented a procedure to rank ND techniques through a series of metrics formulated to evaluate the various technologies under different aspects (precision, accuracy, ease of use, cost, requirements for inspection), with the aim of helping end users to choose the most appropriate ND method to evaluate specific deterioration conditions. Moving from such findings, this contribution presents a refinement of the scoring procedure, calibrated based on suggestions and advises from end-users operating in the Italian context.

2 ND techniques for evaluation of PT systems

Current ND techniques for the evaluation of PT systems in post-tensioned concrete bridges include:

- electromagnetic methods: Ground Penetrating Radar (GPR), Infrared Thermography (IRT), Electrical Capacitance Tomography (ECT);
- magnetic methods: Magnetic Flux Leakage (MFL), Magneto Motive Force Method with permanent magnet (MMFM-Permanent) and with solenoid (MMFM-Solenoid);
- mechanical wave and vibration methods: Impact Echo (IE), Ultrasonic Tomography (UST), Ultrasonic Echo (USE), Sonic-Ultrasonic Pulse Velocity (SPV-UPV), Low Frequency Ultrasound (LFUT), sounding;
- visual methods: Visual inspection (VT), borescope (Bor);
- electrochemical methods: Electrochemical Impedance Spectroscopy (EIS);
- radiographic methods: X-Ray Radiography (XRR);
- diffractometric methods: X-ray Diffractometry(XRD);
- stress measurement methods: stress release on wire and on concrete.

Table 1 lists, for each possible deterioration condition of the PT system, the applicable ND techniques, distinguishing between internal and external tendons, and duct materials (either metallic or non-metallic). Methods for evaluating the loss of prestressing force are considered as well. A short description of the main techniques and their limitations is also provided in the following paragraphs.

Table 1 ND technologies and relevant applications for the evaluation of PT systems depending on the deterioration condition to be investigated

deterioration condition	internal tendons		external tendons	
	metal ducts	nonmetal ducts	metal ducts	nonmetal ducts
compromised grout	USE, XRR	IE, UST, USE, XRR	sounding, XRR	GPR, IRT, ECT, IE, LFUT, sounding, XRR
voids	IE, USE, XRR	USE, XRR	IE, sounding, XRR	GPR, IRT, ECT, IE, LFUT, sounding, XRR
water infiltration	IE, USE	IE, USE	sounding	GPR, IRT, ECT, IE, LFUT, sounding
strand corrosion	VT, Bor	VT, Bor	MFL, MMFM-Permanent, MMFM Solenoid, EIS	MFL, MMFM-Permanent, MMFM Solenoid, EIS
loss of section	VT, Bor	VT, Bor	MFL, MMFM-Permanent, MMFM Solenoid, EIS	MFL, MMFM-Permanent, MMFM Solenoid, EIS
strand breakage	VT, Bor, XRR	VT, Bor, XRR	MFL, MMFM Solenoid, XRR	MFL, MMFM-Permanent, MMFM Solenoid, XRR
loss of post-tensioning	stress release, XRD	stress release, XRD	stress release, XRD	stress release, XRD

2.1 Ground Penetrating Radar

Ground-penetrating radar (GPR) is a geophysical method that uses radar pulses to image the subsurface. Electromagnetic radiation in the microwave band (UHF/VHF frequencies) of the radio spectrum is sent within the structure, and the reflected signals from subsurface structures are captured by a receiver. These reflections are a result of changes in the materials electrical conductivity [8,9]. Since the changes in surface dielectric are highly influenced by the presence of water, the method has capabilities of detecting locations of moisture-related deterioration. GPR is not effective for detecting grout or strand defects in internal ducts made either of metal or HDPE. However, it is effective in detecting the location of these ducts, providing useful information for performing other methods such as impact echo and ultrasonic tomography. In this respect, the method is more advanced than some of the other methods and can be performed quickly. GPR can detect water infiltrations, compromised grout and void defects in external HDPE ducts with low accuracy, but is unable to detect corrosion and cable breaks. Due to the sensitivity to metallic materials, it is not able to detect any strand breakages or grout defects within metal ducts or in the anchorage zone. GPR is a medium cost and non invasive technique, but interpretation of GPR radargrams may require a high level of experience.

2.2 Infrared Thermography

Infrared Thermography (IRT) is an imaging technique that translates thermal energy emissions to a temperature map. There are two types of IRT: Passive and Active. Passive IRT relies on the heating and cooling of the sun at different times of the day, whereas Active IRT uses a controlled heat source [8] [9]. One limitation of IRT is its dependency on the ambient temperature, hence optimal results are obtained during the day when the temperature changes rapidly compared to overnight. IRT is effective in detecting water infiltrations, voids and compromised grout within external nonmetal ducts by recognizing the differences in the heat map provided by the camera's image of the duct with areas of less heat indicating a void, based on the principle that air will not conduct heat through the duct wall as well as a filler material would. By means of this technique it is also possible to make rough estimates on the size of the void and water infiltration defects, although IRT is not able to differentiate between these defects. The method only works on external tendons. While IRT cannot be used to locate defects within the ducts embedded in the anchorage zones, it can detect the void and water infiltration defects in the end caps of the anchorage regions with moderate to high accuracy. IRT is quickly becoming a popular ND method as it is relatively cheap and does not require extensive knowledge to detect voids within the ducts. This method can be effectively used as a simple first pass inspection method that will require more advanced ND techniques to pinpoint the issues in the areas flagged by IRT.

2.3 Electrical Capacitance Tomography

Electrical Capacitance Tomography (ECT) works by measuring the capacitance of the object below the sensor head, which through iterative scans make a composite image showing the zones of different capacitance. ECT has been primarily used and tested in the oil industry where it has been used to analyse the flow of crude oil through pipelines, mainly detecting air pockets/voids in the flow. Due to this method being effective in determining voids in pipelines, ECT seems to be a promising method in locating grout defects, voids and water infiltration in external nonmetal ducts; however, with current technology, accuracy is still low [10].

2.4 Magnetic Flux Leakage

Magnetic Flux Leakage (MFL) uses the interaction between magnetic fields and matter to inspect distress in ferrous materials. There are two kinds of MFL: Active and Residual. Active involves subjecting a ferrous material to a strong magnetic field produced by a portable magnet which induces flux paths in the material. In locations that experience section loss, there is a "leak" in the magnetic field. This leak is then measured by a magnetic field detector and can determine the location of section loss. In Residual MFL, the ferrous material is brought to full magnetic saturation (to erase magnetic history), then the magnet is removed, and the sensors are passed over to detect the residual magnetic field [10-12]. MFL is a promising method in locating steel section loss due to corrosion, strand/wire pitting or breakage when inspecting external tendons, but additional factors such as other ferromagnetic sources (mild reinforcement and steel ducts) and masking effects lead to complicated signals that are difficult to decipher. Investigations on beams with controlled strand defects pointed out that the method can have a fair accuracy in estimating small to moderate decrease in wire section due to corrosion, whereas the accuracy falls in detecting wire rupture [11].

2.5 Impact Echo

Impact Echo (IE) involves hitting the concrete surface with a small impactor/impulse hammer and analysing the reflected wave energy with a displacement or accelerometer receiver mounted on the surface near the impact point [9,10]. A fully grouted duct will emit a current passing straight through the duct, while a voided duct will behave differently and veer off. Because the impact generates a high energy pulse and can penetrate deep into the concrete, IE is particularly promising for detecting defects in concrete structures, where it produces a better signal to noise ratio than other ultrasonic techniques because of its low attenuation in composite materials such as concrete. IE is not effective in the anchorage regions due to the small cover depth; moreover, it is more effective in metal ducts rather than in nonmetal ducts. The method can locate voids and water infiltrations in internal metal ducts with moderate accuracy, and compromised grout and water infiltration in internal nonmetal ducts with low to moderate accuracy. IE can also detect compromised grout, voids, and water infiltration in external HDPE ducts with moderate accuracy. In general, the estimates provided on the size of the defects are rough.

2.6 Ultrasonic Tomography

Ultrasonic Tomography (UST) uses acoustic waves over 20 kHz. The principle of operation is the same regardless of the type of UST system: a sensor or group of sensors emits a stress pulse (typically a P- or S-wave) into the structure. As the waves propagate, areas with changes of impedance reflect portions of the wave, and these reflections are captured by sensors. Through time-of-flight measurements and frequency/amplitude characteristics, defects and/or discontinuities can be determined. UST is not able to detect strand or grout defects in internal metal or nonmetal ducts or in the anchorage regions. However ultrasonic techniques are suitable for detecting and locating internal ducts, and have shown to be more effective when used upon nonmetal ducts, with difficulties when inspecting metal ducts [9,10]. Because of the configuration of the equipment, the method is not suitable for detecting defects in external ducts.

2.7 Ultrasonic Echo

Ultrasonic Echo (USE) relies on a group of sensors emitting a stress pulse into the structure which travels along the beam. As these waves propagate through, the area of varying impedance is reflected upon the waves. These waves are then captured by the group of sensors [10]. In USE testing, the concrete element is excited by a pulse in an inaudible ultrasonic range, and the reflected portions of the pulse are then evaluated. These reflections occur when the pulse interfaces with metal (such as mild reinforcement, or metal ducts) and with air (voids). When using USE, multiple measurements along the specimen are required to gain the full picture of where the reinforcement is located. USE can detect and locate grout defects in internal (both metal and nonmetal) ducts with low to moderate accuracy, but it has low accuracy in detecting voids and water infiltration in anchorage regions. Nevertheless, it is still promising in locating reinforcement/duct locations. The method requires calibration based on the duct material.

2.8 Sonic/Ultrasonic Pulse Velocity

Sonic/Ultrasonic Pulse Velocity (SPV-UPV) is another ultrasonic method similar to USE and UST. The underlying principle consists of measuring the time-of-arrival of compressional waves, which are generated by sources with resonant frequencies ranging from 50 to 150 kHz. The method consists of impacting one side of the specimen with an instrumented hammer while recording the signal on the other side. By evaluating the time of arrival of this signal, the material velocity can then be calculated [9,10]. However, to date there is not conclusive data available on whether this method would be effective to detect deteriorated grout or voids. Moreover, the method is not effective in the anchorage region. The results may be not conclusive when large amount of reinforcement is present, as it may shield the presence of voids. Other limitations of the method include the inability to investigate regions that have not access on both sides, and depth limitations associated with the scanning frequency. Interpretation of UPV scans may require a high level of experience.

2.9 Low Frequency Ultrasound

Low Frequency Ultrasound (LFUT) is another ultrasonic ND method available. This method is different from the others, as it is designed to generate and receive low frequency ultrasonic waves, which propagates through the duct, in a pitch-catch fashion. By analysing these waves, grout defects such as voids and water infiltration can be detected [10] with low to moderate accuracy; an estimate for the size of the grout defects is not provided. LFUT is an effective method in evaluating external nonmetal ducts, but not internal. The method is also not effective on metal ducts, either internal or external. A further limitation of this method is that while it can detect air voids, it is unable to decipher between the severity of these voids. Therefore, further ND methods would be required to determine more thorough results regarding how severe these defects are. For the investigation of external ducts, LFUT needs physical access for the placement of transducers on the ducts.

2.10 Sounding

Mechanical sounding is used in combination with visual inspections: if an abnormality is visually apparent to the inspector, he will then conduct this method. Sounding is only effective for external tendons and consists of the inspector tapping along various points on the duct and listening for sound differences. An experienced inspector is trained to hear the dull/hollow sound that indicates the presence of voids or water infiltration, though he will not be able to differentiate between them. Sounding can also be used to detect voids, compromised grout, and water infiltration defects within the end caps of the anchorage [13-15]. One downfall of this method is that it is not always accurate and is a loose indication of voids within the tendons. Moreover, the application of sounding inspection on metal ducts could be more challenging compared to nonmetal ducts. If an inspector suspects voids from performing this method, he will then be prompted to perform a more in-depth inspection. This method is also unable to detect soft grout or small voids/defects. As reported in literature [10] the method was found to be consistent for different trials and inspectors when conducted on nonmetal ducts.

2.11 Visual Testing

Visual testing (VT) consists of opening the duct or end cap in areas that are a cause for concern and looking inside to determine the state of the strands [15]. This method is effective in detecting grout defects, corrosion, or any kind of deterioration that could negatively affect the structure. Visual testing is effective for internal and external tendons, however internal tendons pose more difficulties of accessibility to the tendon resulting in VT being less common in these scenarios. In terms of external ducts, visual testing is one of the more common methods utilized to detect abnormalities. VT is also very effective in investigating the end caps of the anchorage regions, provided the end caps can be removed. However, VT is usually limited by the lack of accessibility to the inspection area. A downside of this method is that it is more invasive than the other methods while also being more time consuming. It is not feasible to perform this method on a large number of ducts/caps throughout the bridge, as it cannot detect the specific location of a defect until the later stages of deterioration when there are more apparent visual indicators on the outside of the duct. VT is not effective in detecting early stages of grout/strand deterioration which is why it is always coupled with another ND technique. Therefore, the method is often combined to mechanical sounding, which is used to decide the location of VT.

2.12 Borescope

Another tool that is utilized by bridge inspectors is the Borescope (Bor). Bor is more invasive than most of the other ND techniques, so it is sometimes referred to as a semi-destructive method, as it requires creating an access port for the borescope to enter through [15], which however can be promptly repaired with no long-term effects on the overall structure. This method is used once sounding or visual testing has been performed and degradation of the grout or strands has been detected. The method allows the inspector to observe the corrosion or voids within the duct by running the borescope inside the system. It provides an accurate representation of what is occurring within the ducts, which allows the inspectors to see the state of the tendons and decide on how, where, and if repairs are necessary to keep the structural integrity of the bridge. Limitations of this method include the inability to identify the amount of voided area between congested strands. The borescope requires a void to enter the duct/anchorages, and the sight is limited to where the main voids are located.

2.13 Electrochemical Impedance Spectroscopy

Electrochemical Impedance Spectroscopy (EIS) is an impedance technique that consists in applying a low-amplitude voltage under multiple frequencies to obtain the transfer function for an electrochemical system. The impedance of the grout-steel interface can then be calculated by measuring the changes in phase shift and signal amplitude between the input (voltage) and the output (current), therefore gaining information on the possible corrosion [16-20]. EIS is applicable to external nonmetal ducts, where it can identify strand corrosion with moderate accuracy. One limitation with this method is that it requires highly qualified operators and advanced processing of the data to evaluate the results. EIS has been reported to be effective in determining the location of grout defects, such as deteriorated grout and water, but similar to other methods it is not able to detect the severity of the damage [7]. EIS requires physical access to the duct being inspected, and the ability to drill small holes into the external duct.

2.14 X-Ray Radiography

Radiography is a very useful ND method that allows inspectors to get a clear visual of what is happening within the ducts. Images of an object are assessed by projecting high energy beams of electromagnetic radiation (typically x-rays or gamma-rays). X-rays are typically produced by a linear accelerator, a cyclic particle accelerator, or an X-ray generator. When film is used to inspect the object, this technique is called X-ray Radiography (XRR). It is also common to use X-rays with multiple scan angles and combine the obtained pictures through reconstruction techniques to display two dimensional images of a three-dimensional object (computed tomography) [19-20]. This method is capable of detecting strand breakage, corrosion, compromised grout, and voided regions in internal and external ducts (both metallic and non-metallic). XRR is applicable for both internal and external ducts; however, concrete cover and surrounding reinforcement may severely limit penetration for internal ducts [20]. The method has some limitations, among which the expensive equipment and the need of having trained personnel that know how to use it; generally, it cannot be carried out with open traffic on the bridge to avoid radiation exposure. This method also requires access to two sides of the structure, making internal tendons more difficult to image.

2.15 Stress release methods

The evaluation of the residual prestress force in PT elements is considered one of the fundamental keys for understanding the actual health condition of the whole structure. Different deterioration phenomena may in fact accelerate the prestress loss, which are often linked to corrosion processes acting on the tendons. Stress release methods are generally based on the principle of estimating the current prestress force based on the stress released either in a concrete member or in a wire of the strand [21, 22]. These techniques can be considered partially non-destructive, as they typically induce a local damage on the structure (which can however be repaired to avoid long-term effects on the overall structure). Among these methods, the saw-cut method, the stress release coring (or drilling method), the strand-cutting method (or wire-cutting), and exposed strand methods must be cited [23]. The saw-cut method and the drilling method are based on measuring the change in strain in the area of concrete adjacent to a saw-cut isolated concrete block or a drilled hole. The results in terms of concrete stress obtained from this test can be, thus used to quantify the residual prestress force acting in the tendons, using, for example, finite element (FE) models, or more simply, Navier's formulation [24]. The second stress release method is the wire-cutting: one of the wires belonging to a tendon is exposed for a minimum length, then a strain gauge is installed and used to measure the strains that develop when the wire is cut. Then, corresponding prestress force in the wire can be easily determined [24]. Compared to other test methods, this approach is slightly destructive because one single wire is cut; however, the stresses can be redistributed in other wires of the tendons if the grout has sufficiently good quality. The cost is medium-high. It is also necessary to monitor the temperature where concrete or strand is cut, as strain changes due to stress release may be in the same order of those due to temperature variations [24].

2.16 X-Ray Diffractometry

X-ray diffraction (XRD) is a ND method originally adopted for the individuation of the different crystalline materials mixed in the form of a powder, and it is currently used in material science and mechanical field for the estimation of the stresses on steel elements and crystalline materials. The method is based on the Bragg equation relating the angle of scattering to an X-ray incident onto a crystal surface to the distance between the planes of the crystalline lattice. If the crystalline lattice is subject to a stress state, the interatomic distance modifies and this makes in turn a variation of the angle of scattering. By knowing the material composition (i.e., the steel type used for the strand realization) and its elastic properties it is possible to directly evaluate the stress present on the surface of the strand and hence assessing the prestressing force of tendons. However, as X-ray diffractometry supplies a local measure that is, inevitably, affected by the measuring conditions and by the specific point investigated, a reliable procedure is needed to estimate the total prestressing force from the local stress on the wire or strand [25]. Like stress release methods, XRD is an indirect method for assessing the prestressing force, and requires further post-processing of the data using FE models, or accurate calibration of the relationship between the local stress in the wire and the force of the strand. It should be noted that the results of the diffractometric measurements, investigating a thickness of a few microns, are influenced by the presence of residual stresses resulting from the manufacturing processes to which the wires are subjected. The tension detected by the instrument is therefore given by the sum of the residual tension deriving from the manufacturing process and the tension deriving from the tensile stress applied during the pulling phase to the prestressing reinforcement.

3 Evaluation metrics for ND techniques

Moving from the procedure presented in the NCHRP Research Report 848 [7] to rank ND techniques, a refined set of metrics has been formulated considering four criteria, that express the perception that end users have of the performance of the various ND techniques, and combining the scores assigned for each criterion according to a weighted sum.

3.1 Weighted sum model

In order to rank the methods, a weighted sum model (WSM) is used which provides a final score for each method, given its individual scores in chosen weighted categories. In other words, given a deterioration condition, for each one of the available ND techniques the procedure calculates an overall score by summing the individual scores under four performance criteria multiplied by the weight of the associated criterion. Mathematically, the score for method 1 (S_{A1}) can be expressed as

$$S_{A1} = \sum_{i=1}^{4} a_i \cdot w_i \quad (1)$$

where a_i is the individual score for performance criterion i and w_i is the weight for the ith criterion. Each one of the criteria is weighted to emphasize their desired influence among the various criteria, depending on a chosen evaluation scenario.

3.2 Performance categories

The criteria are linked to four performance categories perceived by end-users (structural engineers) or bridge owners to be most important in the ranking of ND technology: Accuracy, Ease of Use, Impact on Traffic, Cost. Each category can be further divided into subcategories which concur to define the overall performance in relation to the aspect under consideration. The four categories and the relevant score criteria are defined in the next subsections.

3.2.1 Accuracy

Accuracy is a measure of how closely the measured data match the real condition ("ground truth"). Accuracy is an extremely important category for structural engineering needs, but the required level of accuracy may vary depending on the application. Within the proposed approach, Accuracy is rated based on the ability of the ND method to detect the correct location of the defect and evaluate the severity of the damage according to the criterion defined in Table 2. It must be noted that, depending on the type of defect that is evaluated, in some cases either defect localization or damage severity estimation can be only possible. In case the method can both locate the defect and measure its severity, the two scores sum up.

Table 2 Definition of score for Accuracy (ε = deviation between measurement and ground truth)

score	accuracy for defect localization	accuracy for damage severity
0.2	$\varepsilon > 70\%$	$\varepsilon > 70\%$
0.5	$30\% \le \varepsilon < 70\%$	$30\% \le \varepsilon < 70\%$
1.0	$\varepsilon < 30\%$	$\varepsilon < 30\%$

3.2.2 Ease of use

Ease of use is a category that may directly influences the laboratory that has to set and perform the test; but indirectly, it influences both the end-user, who needs the data, as time and uncertainties grow, and the bridge owner or operator as the costs tend to increase. Ease of use of an ND technique is measured according to four criteria, namely power demand, personnel requirement, calibration requirement and data processing. Power demand and personnel requirement depend essentially on the characteristics of the instrumentation hardware. More specifically, power demand is ranked based on the power supply required by the instrumentation, as inspection equipment can require anywhere from long-life battery power to high voltage direct power. Personnel requirement accounts for both the size of the crew (different between e.g., small and light, or bulky and heavy equipment), necessary to transport and install the instrumentation, and the number of inspectors who are necessary on site for optimal testing. On the other hand, calibration requirement and data processing have a broader impact on the outcome of the inspection, as they may require different levels of experience and training of the operators, or complex post-processing procedures such as in the case of indirect methods. Calibration requirements are ranked based on the instrumentation needs, as some instruments need to be calibrated on-site by means of long and complex procedures or accounting for the actual properties of steel and concrete materials of the bridge, while other instruments may require a self-calibration only. Data processing is ranked depending on the complexity of the procedure and the skills required to the operator.

Table 3 Definition of scores for Ease of use: power demand and personnel requirement

score	power demand	personnel requirement
0.2	requires 220/240 V – 3 phase	≥ 5
0.5	requires 220/240 V	3 ÷ 4
1.0	no power required, or battery operated	≤ 2

Table 4 Definition of scores for Ease of use: calibration requirement and data processing

score	calibration requirement	data processing
0.2	requires specific calibration for bridge/duct/tendon material	high complexity, requires FE models and/or analytical calculations (indirect methods)
0.5	requires calibration to be performed on site	moderate complexity, requires bias correction
1.0	not required, or of short duration	fully automated, or low complexity

The scores for power demand and personnel requirement are listed in Table 3, while the relevant values for calibration requirement and data processing are given in Table 4. Eventually, a final score for Ease of use is calculated by averaging the individual scores of the equipment for each one of its subcategories. If required, weighting factors can be introduced depending on the specific application and scope of investigation to emphasize the importance of a specific subcategory.

3.2.3 *Impact on Traffic*

Impact on Traffic is a category that may more heavily influence the operator of the road network, as it quantifies how much the inspection impacts on the traffic on the bridge. The impact is measured by two subcategories: roadway occupancy and inspection duration. Roadway occupancy differentiates between ND techniques applied directly on the intrados of the bridge, with no or only moderate impact on road traffic (e.g., only the emergency lane is occupied), and ND techniques that require partial or total closure of the roadway. The total duration of inspection, including the setting up of the instrumentation and its dismantling, determines the severity of the (partial or total) roadway closure on the traffic management of the road network. The scores for roadway occupancy and inspection duration are listed in Table 5.

The importance of this category may vary depending on the importance of the bridge within the road network in terms of vehicles per day and possible road alternatives. Therefore, in order to account for the impact of traffic disruption during the inspection, the final score of the ND technique is obtained by averaging the scores for roadway occupancy and inspection duration and multiplying the result by a "traffic coefficient" C_T. An initial traffic class $C_{T,0}$ is assigned to the bridge based on the traffic data in terms of Average Daily Traffic (ADT), in accordance with Table 6.

Table 6 Initial traffic class $C_{T,0}$ based on Average Daily Traffic of the bridge

ADT (vehicles per day)	≥ 25000	10000 to 25000	≤ 10000
$C_{T,0}$	High	Moderate	Low

Partial or total closure of the bridge causes discomfort, which can be mitigated in presence of road alternatives where traffic flow can be diverted. The traffic class of the bridge assigned on ADT is therefore increased by one level in case there are no road alternatives, while it is maintained if road alternatives were available.

The last parameter to be considered is the strategic role of the bridge. A structure whose operation is fundamental for civil protection scopes in the aftermath of a critical event such as an earthquake is considered strategic and must have a higher traffic coefficient. Therefore, like for road alternatives, the traffic class is increased by one level for strategic bridges. The overall flow is illustrated in Figure 1, which also reports the traffic parameter associated to the bridge depending on the final traffic class.

Table 5 Definition of scores for Traffic impact: roadway occupancy and inspection duration

Score	roadway occupancy	inspection duration
0.2	the roadway needs to be closed	more than 2 days-
0.5	some carriageways must be closed, but at least one carriageway remains open	between 1 and 2 days
1.0	no traffic disruption during inspection	less than 1 day

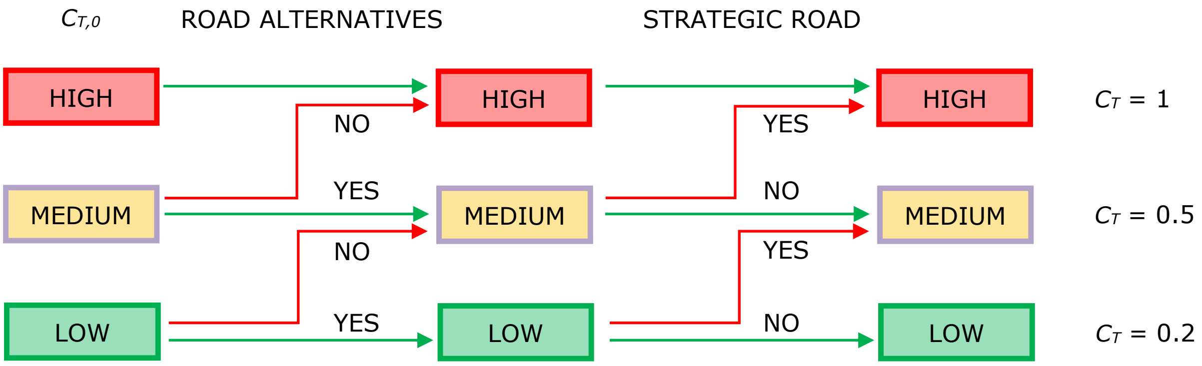

Figure 1 Flowchart for determining the traffic coefficient C_T

3.2.4 *Cost*

This criterion considers the final cost that is exposed by the laboratory to the bridge owner or operator. The category includes all costs associated with the employment of the ND technique, including the cost of the equipment and labour, and additional costs such as operator training, installation, etc. In order to have consistent scores, the cost is ranked by comparing the cost of the ND technology under consideration (C_i) to the average cost (C_{avg}) of all the technologies available to evaluate the same deterioration condition. The score for Cost is provided in Table 7.

Table 7 Definition of score for Cost

score	normalized cost C_i / C_{avg}
0.2	≥ 1.25
0.5	> 0.75 and < 1.25
1.0	≤ 0.75

3.3 Weight Factors

According to Equation (1), in combining the individual scores obtained for a given ND technique in relation to the four identified categories, weight factors are introduced to emphasize the importance of a specific criterion according to decision scenarios envisaged by the end-user. Table 8 provides the recommended weight factors for three scenarios believed to be most common in bridge inspections, namely the Accuracy-Driven Scenario, the Cost-Driven Scenario, and the Impact-Driven Scenario. The Accuracy-Driven Scenario emphasizes the category Accuracy, and is more indicated where accuracy of the evaluation is a primary deciding factor, such as when a single bridge is inspected in which possible areas of deterioration are already known or are expected to exist. On the other hand, the Cost-Driven Scenario is more indicated when cost is a primary deciding factor, such as in case of a large-scale bridge inspection program. Eventually, the Impact-Driven Scenario may be more indicated for road networks with a high traffic concentration, where there is a fundamental need of limiting discomfort due to traffic disruption.

4 Conclusions

Post-tensioned reinforced concrete bridges are particularly critical structures, as the degradation of the tendons is not fully detectable through conventional investigation methods, as the main load-bearing elements are typically embedded in massive concrete (internal tendons) or in ducts (external tendons). Several ND techniques have been either envisaged in inspection guidelines or have been proposed in research study for investigating the deterioration of tendons and grout. The paper presents a simple procedure to rank ND techniques through a series of metrics based on four performances criteria: Accuracy, Ease of use, Traffic impact and Cost, and their respective weight factors, which are used to emphasize the importance of a specific criterion depending on the assumed decision scenario. The goal is to provide decision-makers with a tool which can assist in the selection of the optimal ND technology available to detect a particular strand or grout defect accounting for different factors including the accuracy of measurement, the easy of use, the cost and the impact on the operation of the infrastructure.

Table 8 Categories and weighting factors for different scenarios

category	tag	weight factor	Accuracy-Driven Scenario	Cost-Driven Scenario	Impact-Driven Scenario
Accuracy	a_1	w_1	0.60	0.20	0.20
Ease of Use	a_2	w_2	0.15	0.10	0.10
Traffic Impact	a_3	w_3	0.15	0.10	0.60
Cost	a_4	w_4	0.10	0.60	0.10

References

[1] Carsana, M.; Bertolini, L. (2016) *Characterization of*

Segregated Grout Promoting Corrosion of Post-Tensioning Tendons. Journal of Materials in Civil Engineering, 28, article 04016009.

[2] Powers, R.G.; Sagues, A.A.; Virmani, Y.P. (2002) *Corrosion of Post-Tensioned Tendons in Florida Bridges*. Proc. 17th U.S.-Japan Bridge Engineering Workshop, Tsukuba: Japan Public Works Research Inst. Technical, pp. 579-594.

[3] Hartt, W.H.; Venugopalan, S. (2002) *Corrosion Evaluation of Post-Tensioned Tendons on the Mid-Bay Bridge in Destin, Florida*. Tallahassee, FL: Florida Department of Transportation.

[4] Woodward, R.J. (1988) *Collapse of a Segmental Post-Tensioned Concrete Bridge*. Transportation Research Record, 1211, pp. 38-59.

[5] Rymsza, J (2021) *Causes of the Collapse of the Polcevera Viaduct in Genoa, Italy*. Applied Sciences. 2021, 11, article 8098. https://doi.org/10.3390/app11178098.

[6] Highway Structures & Bridges Inspection & Assessment (2020) *CS 465 - Management of Post-Tensioned Concrete Bridges*. London: Highways England.

[7] 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.* Washington, DC: The National Academies Press.

[8] Pollock, D.;G. Dupuis, K.J.; Lacour, B.; Olsen, K.R. (2008). *Detection of Voids in Prestressed Concrete Bridges Using Thermal Imaging and Ground-Penetrating Radar*. Pullman WA: Washington State Transportation Center, Washington State University-

[9] Wimsatt, A.; White, J.; Leung, C.; Scullion, T.; Hurlebaus, S.; Zollinger, D.; Grasley, Z.; Nazarian, S.; Azari, H.; Yuan, D.; Shokouhi, P.; Saarenketo, T. (2014). *Mapping Voids, Debonding, Delaminations, Moisture, and Other Defects Behind or Within Tunnel Linings. SHRP 2 Final Report S2-R06(G)-RW, Strategic Highway Research Program 2*. Washington, D.C.: Transportation Research Board.

[10] Hurlebaus, S.; Hueste, M.; Karthik, M.; Terzioglu, T. (2016). *Condition Assessment of Bridge Post-Tensioning and Stay Cable Systems Using NDE Methods*. Washington, DC: The National Academies Press.

[11] Karthik, M.M.; Terzioglu, T.; Hurlebaus, S.; Hueste, M.B.; Weischedel, H.; Stamm, R. (2019) *Magnetic flux leakage technique to detect loss in metallic area in external post-tensioning systems*. Engineering Structures, 201, article 109765.

[12] DaSilva, M. Javidi, S.; Yakel, A.; Azizinamini, A. (2009) *Nondestructive Method to Detect Corrosion of Steel Elements in Concrete.* Lincoln, NE: Nebraska Department of Roads Research Reports.

[13] Im, S.B.; Hurlebaus, S. (2012) *Non-Destructive Testing Methods to Identify Voids in External Post-Tensioned Tendons*. KSCE Journal of Civil Engineering, 16(3), pp. 388-397.

[14] Im, S.B.; Hurlebaus, S. Trejo, D. (2010) *Inspection of Voids in External Post-Tensioned Tendons. Transportation Research Record.* Journal of the Transportation Research Board, 2172, pp. 115-122.

[15] Trejo, D.; Im, S.B.; Pillai, R.G.; Hueste, M.B.D.; Gardoni, P.; Hurlebaus, S.; Gamble, M. (2009) *Effect of Voids in Grouted Post-Tensioned Concrete Bridge Construction: Inspection and Repair Manual for External Tendons in Segmental, Post-Tensioned Bridges*. Report FHWA/TX-09/0-4588-2. https://rosap.ntl.bts.gov/view/dot/16988.

[16] Barsoukov, E.; and Macdonald, J.R. (2005). *Impedance Spectroscopy: Theory, Experiment, and Applications*. New York: John Wiley & Sons.

[17] Orazem, M.E.; Tribollet, B. (2008). *An Integrated Approach to Electrochemical Impedance Spectroscopy*. Electrochimica Acta, 53(25), pp. 7360-7366.

[18] Orazem, M.E.; Tribollet, B. (2011). *Electrochemical Impedance Spectroscopy*. New York: John Wiley & Sons.

[19] Azizinamini, A.; Gull, J. (2012). *Improved Inspection Techniques for Steel Prestressing/Post-tensioning Strand: Volume I*. Tallahassee, FL: Florida Department of Transportation.

[20] Harris, D. (2003) T*est and Assessment of NDT Methods for Post-Tensioning Systems in Segmental Balanced Cantilever Concrete Bridges*. Tallahassee, FL: Florida Department of Transportation.

[21] Kraľovanec, J.; Bahleda, F.; Prokop, J.; Moravčík, M.; Neslušan, M. (2021). *Verification of actual prestressing in existing pre-tensioned members*. Applied Sciences, 11(13), article 5971.

[22] Kraľovanec, J.; Moravčík, M.; Bujňáková, P.; Jošt, J. (2021). *Indirect determination of residual prestressing force in post-tensioned concrete beam*. Materials 14(6), article 1338.

[23] Kraľovanec, J.; Prokop, J. (2021). *Indirect methods for determining the state of prestressing.* Transportation Research Procedia, 55, pp. 1236–1243.

[24] Zanini, M.A.; Faleschini, F.; Pellegrino, C. (2022). *New trends in assessing the prestress loss in post-tensioned concrete bridges*. Frontiers in Built Environment, 8, paper 956066.

[25] Morelli, F.; Panzera, I.; Piscini, A.; Salvatore, W.; Chichi, F.; Marconi, G.P.; Maestrini, D.; Gammino, M.; Mori, M. (2021) *X-ray measure of tensile force in post-tensioned steel cables*. Construction and Building Materials, 305, article 124743.