Life-Cycle of Structures and Infrastructure Systems – Biondini & Frangopol (Eds)

A multi-phase survey approach for post-tensioned prestressed concrete bridge decks

Isabella Mazzatura, Silvia Caprili & Walter Salvatore
Department of Civil and Industrial Engineering (DICI), University of Pisa, Pisa, Italy

Alessio Lupoi
Department of Structural and Geotechnical Engineering, La Sapienza, Roma, Italy

Alessio Ficociello
SPERI, Engineering Design Firm, Roma, Italy

ABSTRACT: The assessment of existing structures is a crucial task upon which rely an efficient retrofit design. Bridges are 'key elements' of the infrastructural network, and ensuring their good serviceability is of paramount importance. In 2020, in Italy were enacted the '*Guidelines for the classification, risk management, safety evaluation and monitoring of existing bridges'*: the underlying philosophy is to deepen the analysis only on those bridges showing poor maintenance conditions. Prestressed concrete bridges with post-tensioned cables are one of the bridge typologies mostly affected by relevant structural issues and whose assessment is more complicated. In this research, a multiphase methodology is proposed, specifically to be applied to PT bridges. The method is organized in progressive levels of knowledges. The aim is to provide an answer about how to perform the safety assessment of these structures and how deep shall be the preliminary knowledge campaign to consider the PT bridge completely investigated.

1 INTRODUCTION

Bridges are crucial points in the infrastructural system, as their suboptimal functionality strongly affects the economic and social life of the community. The need to optimize the inspection and intervention procedures is, nowadays, a central issue especially in countries like Italy where several catastrophic events have occurred in recent decades. Since the Polcevera viaduct collapse (2018), both the professional and academic communities have been working on shared methodologies to optimize census and assessment; the overall effort led to the adoption of the *'Guidelines for the classification, risk management, safety assessment and monitoring of existing bridges'* in 2020 (MIT CSLP 2020). The Italian Guidelines are organized into six deepening levels for the assessment. This multilevel approach allows to save resources and to optimize both inspections and interventions, since a lower risk level requires less analysis and a lower level of knowledge achieved for the infrastructure.

The first three assessment levels are required for all the structures: through Level 0 it is possible to carry out the census, Level 1 is devoted to the execution of in-situ visual inspections allowing to classify the infrastructures according to indications of Level 2. The Level 2 classification is the results of four different risks: the structural and geotechnical risk, the hydraulic risk, the seismic risk and the landslide risk. The so-derived 'Attention Class' allows the definition of a priority order of interventions and/or monitoring for considered infrastructures. All these evaluations can be performed by collecting data from the original documentation and

DOI: 10.1201/9781003323020-487

through only visual inspections. However, there are some situations where visual inspections only are not sufficient: this is the case of precast concrete bridges with post-tensioned cables (namely PT bridges).

PT bridges represent a consistent portion of the infrastructural system, especially of the highways' one. Their large number is due to the inherent advantages that this technology offered in comparison to the Reinforced Concrete (RC) one, as the possibility to gain longer spans using less materials, the easiness of construction phase thanks to the partial prefabrication and the repeatability of the static schemes. However, as the decades passes, the materials physiologically degrade, and the issue of inspection and evaluation becomes more and more urgent. The evaluation of the maintenance condition of a RC structure is relatively easy since the defectiveness is usually visible: the strong corrosion of rebars is often joined to the loss of the concrete cover or to a very serious degradation of it. On the other hand, PT structures may be affected by defects difficult to detect: for instance, since the steel cables are inside a duct, and the duct is inside the concrete section, with a cover usually thicker than that for ordinary reinforcement, it may be difficult to find corrosion defects on the cables. These situations may be defined as "*hidden defectiveness*" and in these cases a visual inspection cannot be sufficient to assess, even if in a preliminary evaluation, a PT bridge. The issue is complex being the hidden defects completely unknown and the critical questions are mainly two: how and where to perform inspections, i.e. which investigation technique shall be used and how many samples shall be analysed. The present research tries to give a general methodology to evaluate PT structures, from the preliminary to the accurate assessment.

2 THE MULTI-PHASE METHODOLOGY

The proposed methodology has been conceived referring to the Guidelines of the Federal HighWay Administration (FHWA 2013), to the directions given by the Highways England in *CS 465 – Management of post-tensioned concrete bridges* (Highways England, 2020) and to the Italian Guidelines (MIT CSLP 2020).

The FHWA guidelines provide a method based on the adoption of destructive testing, which aims to assess the risk of PT bridges, and thus prioritize interventions and define a probable level of defectiveness. The determination of the number of samples to investigate is performed by assuming that the tests' results can be described with a hypergeometric distribution. The CS 465, on the other side, proposes a methodology for the management of inspections, monitoring and interventions on PT bridges carried out through a process including risk review, risk assessment and risk management. Suggestions are given about how to perform the tests, their best location and the most critical defects to be considered.

For PT systems, the Italian Guidelines 2020 proposes the so-called 'Special Inspections' (SI), giving indications about the mandatory information to collect, i.e. the individuation of the cables' trace, the localization of defects and their quantification and qualification, and how to perform the tests. Being the assessment of PT structures a relatively recent issue and lacking the knowledge about the technologies to employ and the way to perform an inspection campaign, more indications are needed.

A multi-phase methodology, following the approach of the Italian Guidelines and comprehensive of the suggestions given by FHWA and the Highways England, is then proposed (Figure 1). It works at subsequent levels of analysis: the more likely the presence of serious defectiveness, the more accurate the investigations. It means that it is not necessary to go through each phase for all the bridges, but only the most degraded ones need to be deeply assessed. The first two phases are mandatory for all the bridges: *phase 0* provides the knowledge of the structure and indications about the number of samples to investigate, *phase 1* provides for the overall assessment conditions through both non-destructive (ND) and semi-destructive (SD) testing, *Phase 2* consists in the deep analysis of the defectiveness individuated at the end of the phase 1 and, finally, *phase 3* is optional and contains suggestions for the global analysis of the bridge.

Two are the possible overall outcomes of the proposed procedure: (a) the classification of the bridge according to the LG as for all other bridge typologies or (b) the need for its accurate assessment. The classification shall be performed according to the Italian Guidelines, considering that the present methodology gives information only about the defectiveness level of the bridge. The accurate assessment is required only if the structure presents worrying defects. In the following, each phase will be discussed and deepened.

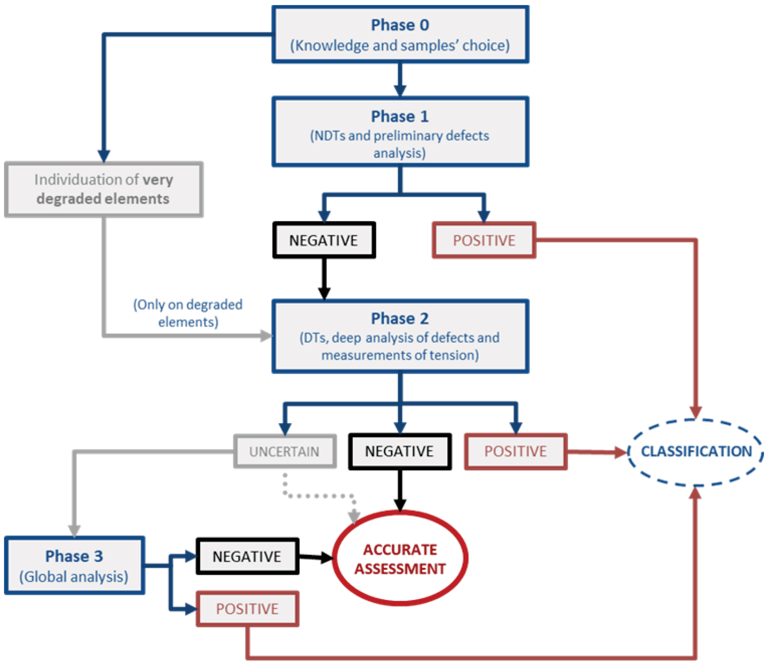


Figure 1. Logical flow of the proposed multi-phase methodology.

2.1 *Phase 0: The knowledge*

Phase 0 is devoted to the knowledge of the structure and can be divided into two main parts: (0a) the historical-critical analysis of the available documentation and (0b) the assessment of the conservation conditions through visual inspections. By completing these operations, all the required data to define the number of samples to investigate in the following steps, according to a method deriving from FHWA, are achieved. Besides, portions affected by high degradation - namely strong oxidation, or corrosion of the PT cables, if present - can be determined.

The historical-critical analysis (0a) is necessary to collect information about the type, the number and the trace of PT cables and relevant intervention/modifications after construction. In case of lack of original documents, on-site operations (geometrical surveys, non-destructive and/or destructive testing) shall be carried out: of course, the more unknowns, the more invasive will be the impact on the structure. Defectiveness (0b) shall be assessed according to Level 2 of the Italian Guidelines (MIT CSLP 2020), considering only beams and crossbeams belonging to the PT system, resulting in an overall defectiveness level strictly related to the one of each accounted component.

Once all the previous data are known, it is possible to proceed with the risk assessment, a necessary step to estimate the minimum number of samples to investigate. These two operations are based on the same hypothesis and follow the methodology proposed by the FHWA, with few integrations and adjustments required to match the Italian Guidelines.

To perform the risk assessment and therefore define the number of samples to investigate, it is necessary, as the FHWA proposes, to make some assumptions about the expected distribution of the defectiveness within the structure. The worst defect considered in this field is the one that may determine the corrosion of the cables; since the corrosion is most probable to occur in areas where the grouting is not complete, the investigations are focused on finding grouted/ungrouted areas. Being these two outputs the only two possibilities and being the single investigation not able to provide the re-entry of the single test in the sample, the distribution can be described as hypergeometric.

The probability mass function of the hypergeometric distribution is then defined according to (1), being the main parameters n - the number of cables to be investigated, N - the total number of cables belonging to the same homogeneous group, k - the number of times in which the cables are ungrouted and $m = n/N \cdot 100$. By considering a homogeneous group of cables, in terms of geometrical and typological characteristics, the width N can be defined; by supposing a certain percentage of defective cables m (as described in the following) and by relating the probability of finding at least one defective cable ($k = 1$) to the concept of confidence in the outcome of the investigations and, therefore, establishing a confidence level, it is possible to determine the amplitude n of the sample to investigate.

The FHWA proposes to establish a probability/confidence level of 75%; being the planned investigations for Phase 2 'preliminary', the same percentage is suggested to be adopted.

$$P(X = k) = \frac{\binom{m}{k}\binom{N-m}{n-k}}{\binom{N}{n}} \tag{1}$$

where m = defects present; n = number of cables to be investigated; N = total number of cables; k = times in which the cable is defective.

The assumed level m of defective elements depends on the risk level associated to the structure and on the structural impact associated to the tests to be performed. Three risk levels and three structural impact levels are then provided: *high*, *medium* and *low*. As showed in Figure 2, the risk level must be defined through the calculation of a probability index and of a confidence index, with values in the range 1÷5. The probability index depends on the presence of technical documentation, the length and type of PT cables and the actual defectiveness level of the structure, this last one defined as previously explained. The consequence index depends on the cost for restoring, the redundancy of the structure and its importance level, representing therefore a sort of exposure indicator.

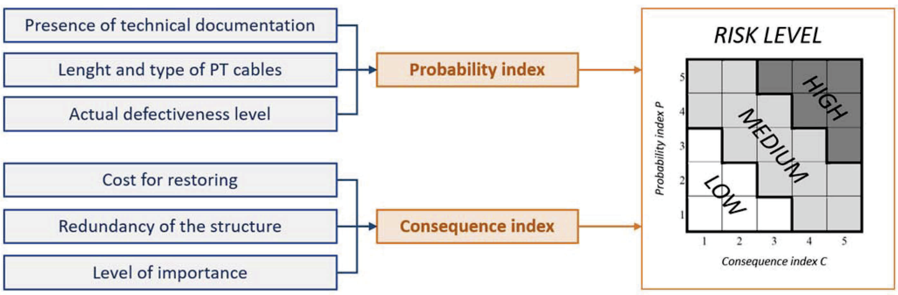


Figure 2. Definition of the risk level.

The number of samples deriving from the previous consideration must not include all the cables that present evident corrosion defects after a visual inspection. These samples must be deeply investigated directly by the analysis provided in the *Phase 2*.

In this context, one sample means one cable. A cable can be considered fully inspected if all the critical areas for the injection and therefore all the areas where the presence of defective grouting is most probable (Trejo et al. 2009), are investigated. Figure 3 shows the riskiest zone of a cable belonging to a simply supported post-tensioned beam: the anchorage zones, the midspan region and the zones in which there is a change in curvature. Finally, it is necessary to choose which sample to investigate. The suggestion is to investigate at most two cables for beam, to obtain a statistically significant result, and choosing the most defective beams belonging to the most defective spans.

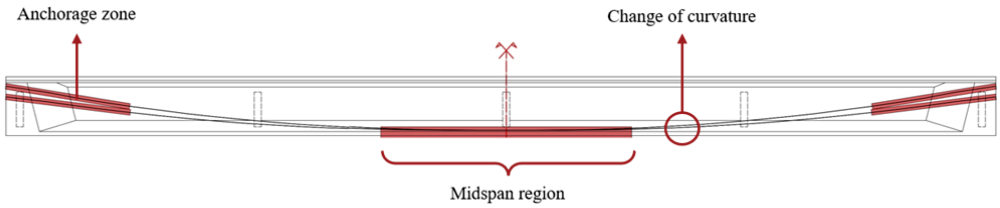


Figure 3. Areas to investigate in order to consider a sample (a cable) fully inspected.

2.2 *Phase 1: Preliminary analysis*

Phase 1 is devoted to the (1a) preliminary analysis of the defects through non-destructive (NDTs) or semi-destructive (SDTs) techniques and (1b) the definition of the corrosion probability of the concrete matrix.

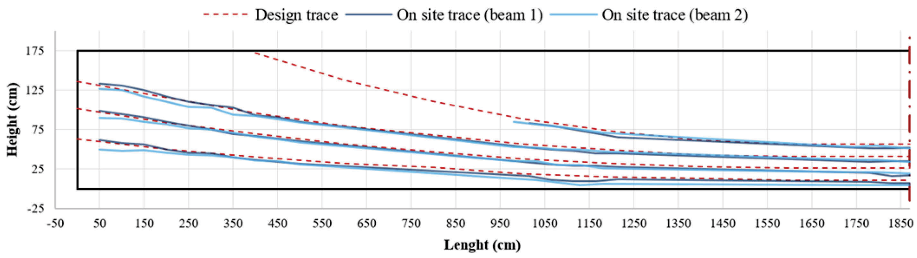


Figure 4. Individuation of cables' layout by using GPR technology (on site trace VS design trace).

The preliminary analysis of the defects (1a) aims to locate eventual deficiencies in the grouting. The definition of the cables' layout is then the preliminary necessary step and can be performed, for instance, through the Ground Penetrating Radar (GPR) technique (see Figure 4), strongly promoted and used by many researches (Terzioglu et al. 2018; Sławski, Kosno, and Świt 2016; Wai-Lok Lai, Dérobert, and Annan 2018). Of course, other possibilities can be explored if able to provide adequate and reliable results.

The individuation of defective grouting can be carried out by any test methodology of proven validity. In (Highways England 2020a) many proposals are given, such as the Impact Echo (IE), the Ultrasonic Echo (UE), the Ultrasonic Tomography (UT) and the X-rays scans. Even if in the academic and scientific world these technologies are well-known and widely tested (Giannopoulos et al. 2002; Sławski, Kosno, and Świt 2016; Terzioglu et al. 2018; Wai-Lok Lai, Dérobert, and Annan 2018), in the common practice there are still no consolidated procedures and protocols since the results of their application are often difficult to be interpreted and applied on-site. Keeping in mind the need for determining objective procedures and protocols for in-situ NDTs, the application of even more than one ND technique can be promoted (Terzioglu et al., 2018), or in combination with semi-destructive tests (e.g. endoscopic investigations) more or less widely applied. Alternatively, it can be possible to apply only semi-destructive tests, but widely spreading them through the samples.

The definition of the corrosion probability (1b) can be performed preliminarily on the concrete matrix to evaluate the likelihood of occurrence of corrosive phenomena in the ordinary steel and in the metallic ducts. A high corrosion probability on these elements does not necessarily imply corrosion of the PT cables, as the opposite situation, but a low corrosion probability, together with the lack of ungrouted region, may indicates the good condition of the PT system. As suggested in (Highways England 2020b) the main factors to investigate, in this case, are: the width of the concrete cover, the depth of carbonatation, the concrete resistivity, the half-cell potential, the chloride, sulphate and alkali contents.

According to Figure 1, Phase 1 can give either 'positive' or 'negative' results. By adopting the classification of voids proposed by (Highways England 2020b) and reported in Table 1, a positive result means no voids or only small voids determined: namely, it is possible to consider that the structure, with the probability defined before, has no defects. On the other hand, if even one large void is found, or several medium voids and a high probability of corrosion is stated, it is not possible to consider the structure without defects and *Phase 2* becomes therefore necessary.

Table 1. Classification of voids according to (Highways England, 2020b).

Classification	Description
No void	Fully grouted
Small void	<50 mm length
Medium void	50-300 mm length
Large void	>300 mm length
Ungrouted	No evidence of grout

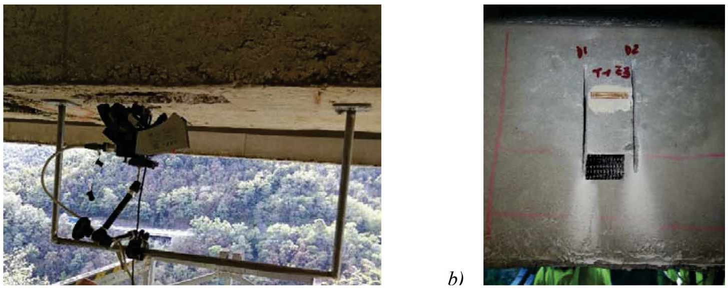
2.3 *Phase 2: Deep analysis*

Deep analysis of *Phase 2* is necessary when, from *Phase 1*, it is not possible to conclude that the structure has no deficiencies in the grouting, and/or when, from *Phase 0*, the presence of defects of oxidation/corrosion on the PT system is assessed by visual inspection. In-depth investigations must be then located in those areas emerged as defective from *Phase 1*, and/or on the degraded portions determined in *Phase 0*.

The primary objective is the damage evaluation in terms of cross-section reduction; therefore, samples through concrete excavation are required. If no corrosion/oxidation is stated after these operations, it is suggested to evaluate the corrosion probability of the grout by defining the cement content, the chloride ion concentration, the sulfate ion concentration, the alkalinity and the moisture content (Highways England 2020b). In addition, it is possible to evaluate the stress acting through the steel cable and/or the tensional state of the concrete cross-section, to indirectly assess the efficiency of the PT system and therefore exclude the presence of strong corrosion phenomena.

These evaluations can be performed in any way deemed effective by the current scientific literature. Some test methodologies can be suggested: for instance, to assess the stress acting through the wire/strand it is possible to perform the X-ray diffraction investigations, NDT usually adopted in the quality check of the manufacturing processes by the measure of residual stresses. Many researchers in last years confirm the reliability of this NDT (Carfagno et al. 1995; Morelli et al. 2021; Zanini, Faleschini, and Pellegrino 2022). The measure can be indirectly performed on the concrete section through the saw-cut method, which is basically a SDT relating the "released" deformation of the test area with the pre-existing tensional state; this methodology has been employed both on-site (Bagge, Nilimaa, and Elfgren 2017;

Jakub Kraľovanec, Moravčík, et al. 2021) and in laboratory (J Kraľovanec and Moravčík 2021; Jakub Kraľovanec, Bahleda, et al. 2021).



a) b)

Figure 5. The picture in a) shows X-ray diffraction measurements on-site, while the picture b) shows the saw-cut method.

As well as for *Phase 1*, *Phase 2* can give either 'positive' or 'negative' results, but also the 'uncertain' condition is admitted. If no corrosion phenomena are detected and the probability of grout corrosion is negligible, it is possible to consider the structure, with the probability previously defined, not defective therefore going on with the classification according to Italian Guidelines. If corrosion phenomena are detected, or if large voids associated with a high corrosion probability are found, the accurate assessment of the structure is required. When the results of the investigations are difficult to interpret, or in any case, when the designer thinks that could be necessary, it is possible to go through the global analysis of the structure.

2.4 *Phase 3: Global analysis*

If the expert judgment is not able to completely exclude the presence of conditions that could compromise the safety of the whole structure or a part of it, or if there is the will of assessing the influence of certain detected damage on global behavior, it is possible to perform dynamic tests or static load tests. For this Phase too the final outputs can be positive or negative. Being these evaluations complex, it is not possible to generalize the cases in which it results a positive judgment instead of a negative one. The designer must have the responsibility in the assessment of the structure deriving from global analysis.

3 CONCLUSIONS

The present research aims to define a methodology for the design and execution of the in-situ inspection on precast concrete bridges with post-tensioned cables. This structural system is very complex to investigate as a consequence of the potential presence of hidden defectiveness: therefore, a multi-phase procedure organized into four different steps is proposed.

The procedure follows the same philosophy adopted by the Italian Guidelines, with the aim of optimizing time and economic resources for the inspection and the assessment of bridges: the higher the defectiveness, the deeper the evaluation and the more complex and reliable the tests' methodologies required. For the methodology elaboration, reference has been also made to the indications provided by English and American Standards; in particular, the assumption for the determination of the number of samples to investigate is the same as the ones proposed by the FHWA. Many experimental campaigns are going to be planned and performed on existing case studies with the aim of validating the proposed procedure and providing in-depth indications about how to perform the accurate assessment of PT bridges.

REFERENCES

Bagge, Niklas, Jonny Nilimaa, and Lennart Elfgren. 2017. "In-Situ Methods to Determine Residual Prestress Forces in Concrete Bridges." *Engineering Structures* 135 (March): 41–52. https://doi.org/10.1016/j.engstruct.2016.12.059.

Carfagno, Michael G, Faired S Noorai, Michael E Brauss, and James A Pineault. 1995. "Extending the Lifespan of Structures." *IABSE Reports*. Vol. 73. http://proceedings.spiedigitallibrary.org/.

FHWA. 2013. "Guidelines for Sampling, Assessing, and Restoring Defective Grout in Prestressed Concrete Bridge Post-Tensioning Ducts."

Giannopoulos, Antonios, Paul Macintyre, Scott Rodgers, and Mike C Forde. 2002. "GPR Detection of Voids in Post-Tensioned Concrete Bridge Beams."

Highways England. 2020a. "CS 464 - Non-Destructive Testing of Highways Structures."

Highways England. 2020b. "CS 465 - Management of Post-Tensioned Concrete Bridges."

Kral'ovanec, J, and M Moravčík. 2021. "Numerical Verification of the Saw-Cut Method." *IOP Conference Series: Materials Science and Engineering* 1015 (1): 012031. https://doi.org/10.1088/1757-899x/1015/1/012031.

Kral'ovanec, Jakub, František Bahleda, Jozef Prokop, Martin Moravčík, and Miroslav Neslušan. 2021. "Verification of Actual Prestressing in Existing Pre-Tensioned Members." *Applied Sciences (Switzerland)* 11 (13). https://doi.org/10.3390/app11135971.

Kral'ovanec, Jakub, Martin Moravčík, Petra Bujňáková, and Jozef Jošt. 2021. "Indirect Determination of Residual Prestressing Force in Post-Tensioned Concrete Beam." *Materials* 14 (6). https://doi.org/10.3390/ma14061338.

MIT CSLP. 2020. *Linee Guida per La Classificazione e Gestione Del Rischio, La Valutazione Della Sicurezza Ed Il Monitoraggio Dei Ponti Esistenti*.

Morelli, Francesco, Ivan Panzera, Andrea Piscini, Walter Salvatore, Francesco Chichi, Gian Paolo Marconi, Daniele Maestrini, Massimo Gammino, and Michele Mori. 2021. "X-Ray Measure of Tensile Force in Post-Tensioned Steel Cables." *Construction and Building Materials* 305 (October). https://doi.org/10.1016/j.conbuildmat.2021.124743.

Sławski, Lukasz, Lukasz Kosno, and Grzegorz Świt. 2016. "Evaluation of Precast Pre-Post-Tensioned Concrete Bridge Beams with the Use of GPR Method." In *Procedia Engineering*, 156:443–50. Elsevier Ltd. https://doi.org/10.1016/j.proeng.2016.08.319.

Terzioglu, Tevfik, Madhu M. Karthik, Stefan Hurlebaus, Mary Beth D. Hueste, Stefan Maack, Jens Woestmann, Herbert Wiggenhauser, Martin Krause, Patrick K. Miller, and Larry D. Olson. 2018. "Nondestructive Evaluation of Grout Defects in Internal Tendons of Post-Tensioned Girders." *NDT and E International* 99 (October): 23–35. https://doi.org/10.1016/j.ndteint.2018.05.013.

Trejo, David, Radhakrishna Pillai, Mary Beth, D Hueste, and Paolo Gardoni. 2009. "Parameters Influencing Corrosion and Tension Capacity of Post-Tensioning Strands." *ACI MAterials Journal* 106 (March): 144–53. https://www.researchgate.net/publication/289723918.

Wai-Lok Lai, Wallace, Xavier Dérobert, and Peter Annan. 2018. "A Review of Ground Penetrating Radar Application in Civil Engineering: A 30-Year Journey from Locating and Testing to Imaging and Diagnosis." *NDT and E International* 96 (June): 58–78. https://doi.org/10.1016/j.ndteint.2017.04.002.

Zanini, Mariano Angelo, Flora Faleschini, and Carlo Pellegrino. 2022. "New Trends in Assessing the Prestress Loss in Post-Tensioned Concrete Bridges." *Frontiers in Built Environment* 8 (November). https://doi.org/10.3389/fbuil.2022.956066.