The condition of the prestressing tendons within the oldest post-tensioned concrete bridges in Slovakia

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Summary

The article presents the results of diagnostics of prestressing tendons within the oldest post-tensioned bridges in Slovakia. Selected details that led to a shortened service life of post-tensioned bridges are described, and the overall problems of the first generation of post-tensioned bridges are shown. Examples include also bridges which have collapsed in recent years due to corrosion of post-tensioning tendons in Slovakia. At the end of the article, findings from in-situ surveys are summarised, and possibilities for reconstruction or monitoring of high-risk bridges are discussed.

1 INTRODUCTION

During 2019 and 2020, several segmental post-tensioned bridges or footbridges collapsed in the Slovak Republic. Many other bridges showed severe deterioration; some had to be closed for traffic. This situation led to an inspection of a large number of segmental post-tensioned structures in order to determine their condition and their risk rating. The findings obtained from the targeted bridge diagnostics carried out by the Department of Concrete Structures and Bridges of the Slovak University of Technology in Bratislava show, that more than half of the inspected old post-tensioned bridges (built in the 1960s, 70s and 80s) have some percentage of tendons, which are only partially or, in some cases, completely ungrouted. Due to the deterioration of the prestressing cables it was necessary to reduce the maximum permitted load of vehicles on some bridge. The absence of cable grouting is evident on the surface of concrete structural elements before the late stage of corrosion. The symptoms of prestress degradation vary depending on the stage of corrosion and the extent of grouting and are most often manifested in the form of cracks that follow the trajectory of the cable ducts or at the joints of individual girder segments.

2 TECHNICAL CONDITION OF BRIDGES IN SLOVAKIA

According to statistical data from the Slovak Road Administration (SSC) [1], there are 2358 prestressed bridges in Slovakia, 507 of which are prestressed monolithic bridges. This statistic only includes bridges within road infrastructure and pedestrian bridges are not included, thus the number of precast PT bridge is significantly greater. The evaluation of the condition of bridges in Slovakia is based on the mandatory regulation: "Bridge Management System" [2] and is divided into seven categories according to the structural technical condition (denoted as STC). According to Fig. 1 it is possible to observe a significant decrease in the STC of bridges in Category III and a sharp simultaneous increase in bridges in Categories IV and V since approximately 2013. This phenomenon occurred at a time when many bridges within the road infrastructure reached a service life of approximately 60 years.

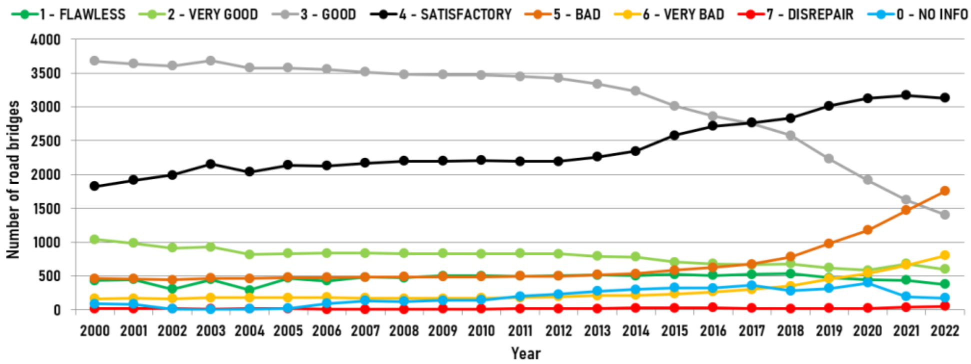


Fig. 1 Evolution of the STC of bridges over the years [1]

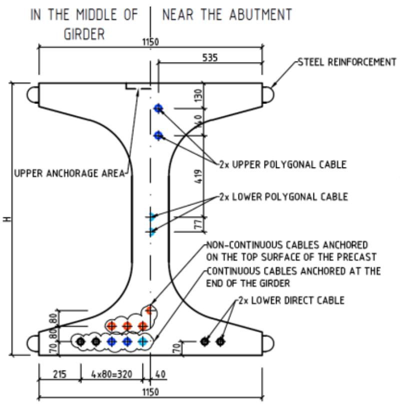
3 POST-TENSIONED BRIDGES IN SLOVAKIA

The beginning of the construction of PT bridges in Slovakia dates back to 1956 when the first precast post-tensioned girders were developed for road infrastructure (inverted 'U' girder Vloššák). Girders were produced as a single piece with a maximum length of up to 18 m or as PT segmental with various lengths of up to 40 m [3]. The girders were mainly used to form simply supported spans. The cables were made of patented (P) 4.5mm diameter smooth wires and were mainly routed in thin-walled corrugated metal ducts. At the joint between the segments, which was usually about 20-30 mm wide, the thin-walled corrugated metal ducts were connected by a short, thick-walled metal pipe (plastic couplers were rarely used). Thin-walled corrugated metal ducts are still commonly used in the construction of prestressed bridges in Slovakia, unlike some countries where their use is prohibited (e.g., Florida, USA) [4]. The 20-30 mm wide joints between the segments were filled with mortar, and later, when match casting was developed, the joints between the segments were provided with epoxy compounds (approx. 1 mm thick). In some cases, if the couplers of the cable ducts were missing or damaged, the mortar or epoxy compound would leak into the cable duct, making it impossible to insert the cables into the cable duct. The first generation of post-tensioned precast elements were also prestressed in the transverse direction to create the orthotropic deck, and there was no need for monolithic distribution slabs. The joints between the girders in the cross direction were usually reinforced and filled with concrete. During construction, manufacturing inaccuracies often occurred and the transverse ducts of adjacent girders did not align, making it impossible to insert the cable. In such cases, the load distribution was negatively affected by missing tendons in the transverse direction.

Most of the older segmental PT bridges in Slovakia fall into the category of bridges with internal PT systems with bonded tendons. Until 1990, external tendons were used only for additional bridge strengthening. The internal PT system with bonded tendons is characterised by the fact that the prestressing cables are placed inside the concrete of the structural element, and the bond of the prestressing tendons with the surrounding concrete is ensured by filling the duct with grouting material. The grout ensures the bond of the tendon to the structure and acts as a corrosion protection [4–7]. Any voids created by improper cable duct grouting can cause discontinuities in the stresses of individual precast segments [4,7]. In cases where all ducts are ungrouted, most often due to gross manufacturing error, the structure falls into the category of bridges with internal PT systems with unbonded tendons. This structure is automatically classified as a hazardous structure because if local failure occurs within the ungrouted tendon (most often caused by chloride-induced local pitting corrosion of the prestressing wires [5,8]), the structure loses the entire prestressing force along the entire length of the ungrouted cable duct [4,9]. These two categories of bridges also need an entirely different approach to inspection and maintenance. In the case of a PT system with bonded tendons, even if a local breakage of the prestressing tendon occurs, the prestressing wires are able to re-anchor by friction, and the cable performs its load-bearing function along its full length, except the small portion around the failure zone [10]. The structural element is locally weakened at some distance before and after the rupture point [11].

In the first decades of the application of prestressing technology in bridge construction in Slovakia, design and construction techniques were imperfect due to limited knowledge, technical possibilities, and insufficient supervision at construction sites. Many errors were made, such as leaving ungrouted cable ducts, use of improper grout materials and improper fixation of the cable ducts, resulting in insufficient cover of the cable ducts, which are often even visible at the surface of the concrete structure. Other errors are associated with the use of hand pumps to pump grout into the cable duct and the use of an inappropriate grout compound that frequently segregated and bled the water, resulting in cavities in the grouted cable ducts. Also, leaks between couplings and corrugated metal ducts were causing many problems, often leading to the impossibility of grouting a part of the cable. As a result, these defects are mainly affecting the durability, increase maintenance costs, and increase the possibility of brittle failure.

Most PT bridges in Slovakia are made of precast girders with various cross sections such as T, I (Fig. 2), inverted U ("Vloššák" - Fig. 3), or box girder shapes such as KA type (Fig. 4). All these types were widespread throughout Czechoslovakia, and most of them were built between 1956 and 1990. After the designation of the type of precast girders, a number is given to indicate the year in which the production of that type of bridge girder began. The difference between the same type of girders produced in various years is mainly only in the number of cables used.



BASIC LENGTH [m]	BASIC DIMENSIONS [m]				WEIGHT [t]
	CLEAR SPAN	MANUFACTURING LENGTH	SPAN	HEIGHT	
21	19,0	20,96	20,0	1,00	30,58
24	22,0	23,96	23,0	1,10	35,97
27	25,0	26,96	26,0	1,25	42,47
30	28,0	29,96	29,0	1,40	49,61

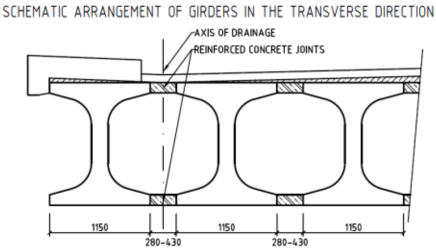
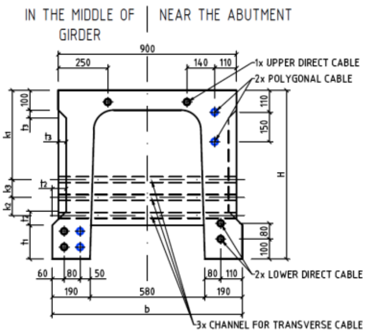


Fig. 2 Prestressed precast bridge girder type I-67 - beginning of production 1967.



BASIC CLEARANCE [m]	BASIC DIMENSIONS [m]								CLEAR SPAN [m]	LENGTH L [m]	SPAN [m]	WEIGHT [t]	NUMBER OF TRANSVERSE CABLES	MAXIMUM BENDING MOMENT [kNm]
	H	t_1	t_2	t_3	k_1	k_2	k_3	b						
12	0,63	0,10	0,09	0,06	0,40	0,09	0,09	0,96	10	11,3	11	8,9	3x12	439
									11	12,3	12	9,6	3x13	476
									12	13,3	13	10,9	3x14	514
15	0,70	0,17	0,07	0,04	0,45	0,16	0,08	0,96	13	14,4	13,8	12,5	3x15	572
									14	15,4	14,8	13,3	3x16	639
									15	16,4	15,6	14,1	3x17	707
18	0,85	0,17	0,07	0,04	0,45	0,09	0,09	0,96	16	17,4	16,8	17,4	3x18	831
									17	18,4	17,8	18,3	3x19	900
									18	19,4	18,8	19,3	3x20	964

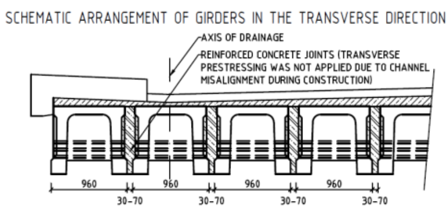
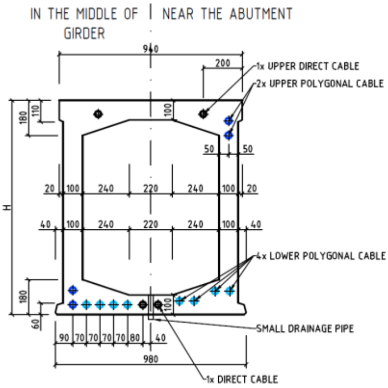


Fig. 3 Prestressed precast bridge girder type Vloššák - beginning of production 1956.



BASIC LENGTH [m]	BASIC DIMENSIONS [m]				WEIGHT [t]
	CLEAR SPAN	MANUFACTURING LENGTH	SPAN	HEIGHT	
11	9,0	10,6	10,0	0,45	7,67
14	12,0	13,6	13,0	0,60	10,95
17	15,0	16,6	16,0	0,70	14,2
20	18,0	19,6	19,0	0,80	18,28
22	21,0	22,0	22,0	1,10	24,02

SCHEMATIC ARRANGEMENT OF GIRDERS IN THE TRANSVERSE DIRECTION

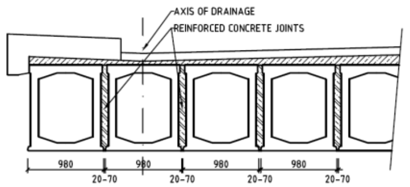


Fig. 4 Prestressed precast bridge girder type KA-61 - beginning of production 1961.

4 COLLAPSED SEGMENTAL BRIDGES IN SLOVAKIA

Collapse of the PT segmental concrete bridge collapse in Kysak - eastern Slovakia

The road bridge superstructure consisted of precast PT girders (I-type shown in Fig. 2), consisting of three segments with the total length of the superstructure approximately 50 m. The girders were simply supported and formed two spans with a length of approximately 25 m. The bridge was partially reconstructed due to extensive leakage, but the reconstruction did not consider the condition of the prestressing tendons, which were not inspected during the diagnostics. In August 2020, after a major bridge inspection, it was discovered that the joints between the precast segments had opened. The bridge was immediately classified as STC level VII and closed. In October of the same year, one of the two spans of the bridge suddenly collapsed under its own weight (Fig. 5). The reason for the collapse was the gradual corrosion of defectively grouted or completely ungrouted tendons routed in corrugated metal ducts. Due to waterproofing leakage, water containing deicing salts was ingressed into the cable ducts. Chlorides accelerated the corrosion of individual wires and caused localised pitting corrosion, which led to the breakage of some ungrouted tendons and progressively led to the collapse of a span of the bridge.

Fig. 5 PT segmental bridge in Kysak – collapse of one of the two bridge spans.

Partial collapse of a PT concrete bridge in Strážske - eastern Slovakia

The superstructure of the road bridge consisted of precast PT Vloššák girders (Fig. 3) with a total length of superstructure of approximately 65 m. The girders were simply supported and formed three spans. These girders have very thin walls and the cover of the cable ducts is only about 30mm. The bridge was inspected in April 2019 and classified as STC level IV. In October of the same year, a sudden collapse of the outermost precast girders occurred from their own weight (Fig. 6). The cause of the collapse was corrosion of the ungrouted tendons of the outermost precast girders, where stains caused by extensive leakage of waterproofing were reported. The interaction of the individual girders in the transverse direction was meant to be ensured by transverse prestressing. However, transverse prestressing was not implemented on the construction site due to manufacturing inaccuracies (misalignment of transverse cable ducts in adjacent girders), resulting in limited load redistribution to adjacent girders after the tendons of the outermost girders corroded.

Fig. 6 Side view of the bridge

Collapse of a pedestrian segmental PT concrete bridge in Spišská Nová Ves - eastern Slovakia

The pedestrian bridge consisted of a pair of precast PT segmental I-girders (Fig. 2), each consisting of three segments. The girders were simply supported with a length of 30 meters. In July 2020, the bridge suddenly collapsed during service without considerable overload (no fatalities, one injury). The cause was corrosion of ungrouted tendons. The last bridge inspection, which was done more than 4 years before the collapse, found no severe visible defects. After the collapse, longitudinal cracks along the tendons were discovered, indicating possible corrosion of the prestressing wires. Wider cracks probably formed only in the last phase of tendon corrosion because, in the case of ungrouted cable ducts, corrosive products have sufficient space to expand until they fill the duct and begin to exert pressure on the concrete.

Fig. 7 View of the collapsed pedestrian footbridge in Spišská Nová Ves – marking the cracks along a polygonal tendon.

5 RESULTS OF IN SITU SURVEY OF PT BRIDGES

An updated report documenting the number of road bridges inspected is provided in Table 1, which gives a basic overview of the complete or partial absence of grouting (denoted "CPAG" herein) of the tendons. Based on the study, more than 50% of the bridges inspected exhibit some percentage of CPAG of the tendons. In the worst case, the percentage of CPAG is 50%, exceeding any safety limits accepted in Slovakia. The CPAG limit is set at 30% and decides the classification in the high-risk category. Since then, more attention has been paid to the bridge due to the increasing likelihood of brittle failure. Above the 30% threshold, there is a high risk of damage accumulation due to corrosion of the tendons to such an extent that the structural integrity of the girders assembled from the individual segments may be compromised during regular bridge operation. In this case, the bridge is allowed to temporarily operate if the structure is equipped with an online monitoring system, which controls the opening of the joints.

Table 1: List of road bridges checked by targeted diagnostics of prestressed tendons.

Bridge	Number of drilled cable ducts	Number of partially grouted tendons	Number of completely ungrouted tendons	Precast	CPAG of cable ducts [%]
M2717	45	1	1	I-type	4,4
M2191	11	3	0	KA	27,3
M2775	9	0	0	I-type	0
M3316	17	1	1	I-type	11,8
M6583	12	0	0	KA	0
M665	33	1	1	KA	6,1
M1642	17	0	0	KA	0
M1782	19	2	2	KA	21,1
M7507	26	1	1	KA	7,7
M4240	15	0	0	I-type	0
M7764	18	3	2	KA	27,8
M1734	7	0	0	KA	0
M2798	6	0	0	KA	0
M2907	23	1	1	I-type	8,7
M7109	16	0	0	I-type	0
M7488	19	1	1	I-type	10,5
M221	7	0	0	KA	0
M4006	8	0	0	I-type	0
M4874	13	0	1	I-type	7,7
M4912	6	0	0	KA	0
M6067	14	0	0	I-type	0
M2465	117	11	30	Vloššák	35,0
M-S01	16	5	3	I-type	50,0
M181	45	2	9	I-type	24,4
TOTAL	**519**	**32**	**53**	**-**	**16,0**

At the same time, for all bridges that exhibited a certain percentage of CPAG, accompanying defects related to the quality of the grouting mortar were found. Most commonly, it was observed that the grouting mortar of the cable duct was crumbled and the prestressing wires were not completely covered by the grouting. This defect can directly impact the bond of the prestressing wires and affect the durability and service life of the bridge. In some cases, precast girders without any cable ducts were identified (straight cables only). The absence of cable ducts impacts the service life of the bridge, mainly if the concrete is contaminated by chlorides. Furthermore, grout settling was frequently observed, especially behind anchors or in inclined zones of cable ducts. Extensive cavities were observed at the highest points of the cable ducts, accompanied by cracks that formed along the polygonal cables.

6 OCCURRENCE OF CRACKS IN CONCRETE ALONG CABLE DUCTS

During the in situ study, a crack pattern was observed that followed the geometry of the tendons. Based on the observation and according to international research [12–16], the cracks were classified into three categories:

- Shrinkage cracks occurring as single cracks directly above the tendons with a width of up to 0.2 mm (constant crack thickness along its length), arising as a result of local weakening of thin-walled precast elements by cable ducts or due to the termal effects;
- A pair of relatively wide cracks that occur in the vicinity of the tendons – the crack pattern is similar to the mechanism of crack formation in reinforced concrete elements when the corrosion of rebar embedded in concrete occurs [12–16];
- Crack due to breakage and subsequent re-anchoring of prestressing wires at locations where the cable duct is grouted (the crack thickness is not constant along the length of the crack) – these cracks occur due to the absence of the reinforcement required to carry the stresses generated when the prestressing force is introduced into the concrete [17].

In almost all bridges, thin shrinkage cracks were observed above the cable ducts in the walls and in the precast girders' slabs and bottom webs. The condition of the tendons at the location of the cracks was verified by drilling into the cable duct, and in most cases the cable ducts were grouted or partially grouted. No significant corrosion of the prestressing cable wires was observed in the absence of moisture penetration from an external source into the interior of the cable duct according to scheme on the Fig. 8. In some cases, corrosion of the corrugated metal duct or local incrustations was observed due to penetration of water into the shrinkage cracks.

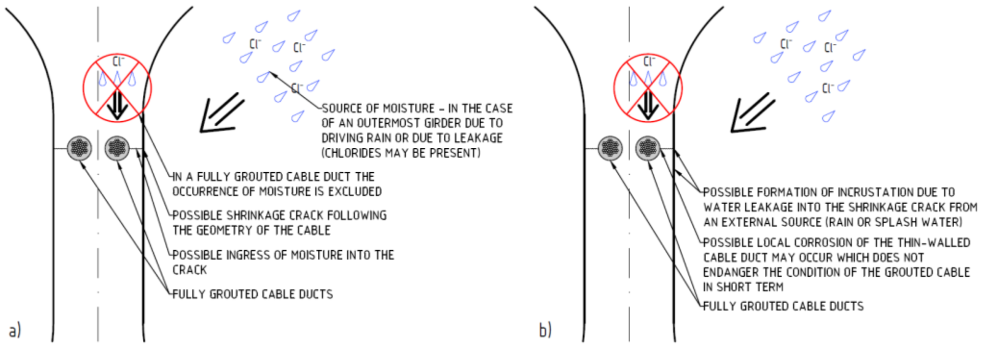


Fig. 8 Cross section through the wall of the girder - shrinkage cracks that copy the geometry of polygonal cable ducts.

On the bridges, where a pair of cracks were observed along the cable ducts, extensive corrosion damage and breakage occurred in most cases, particularly the tendon's outermost (perimeter) wires. The crack formation is described in Fig. 9 and is very similar to the corrosion of a single rebar embedded in concrete [16]. The main difference lies in the fact that the resulting ungrouted cavity is gradually filled with corrosion products in the first stages of corrosion, which causes late crack formation [4]. The entire corrosion process has three phases. Phase a), according to Fig. 9, is characterised by the initiation of corrosion of the thin-walled corrugated metal duct and the outermost wires of the cable due to moisture in the cable duct (most often due to anchor leakage). At this stage, the corrugated metal duct still acts to some extent as a diffusion barrier that prevents the penetration of moisture and oxygen, which is expressed by the graph in Fig. 9. Once the corrugated metal duct is completely corroded (phase b), acceleration of the corrosion of the prestressing wires occurs, according to Fig. 9. Crack development is delayed, occurring only at a late phase c), and at this stage could be noticed by bridge inspectors. However, the precast girder already suffers from a reduced load-bearing capacity.

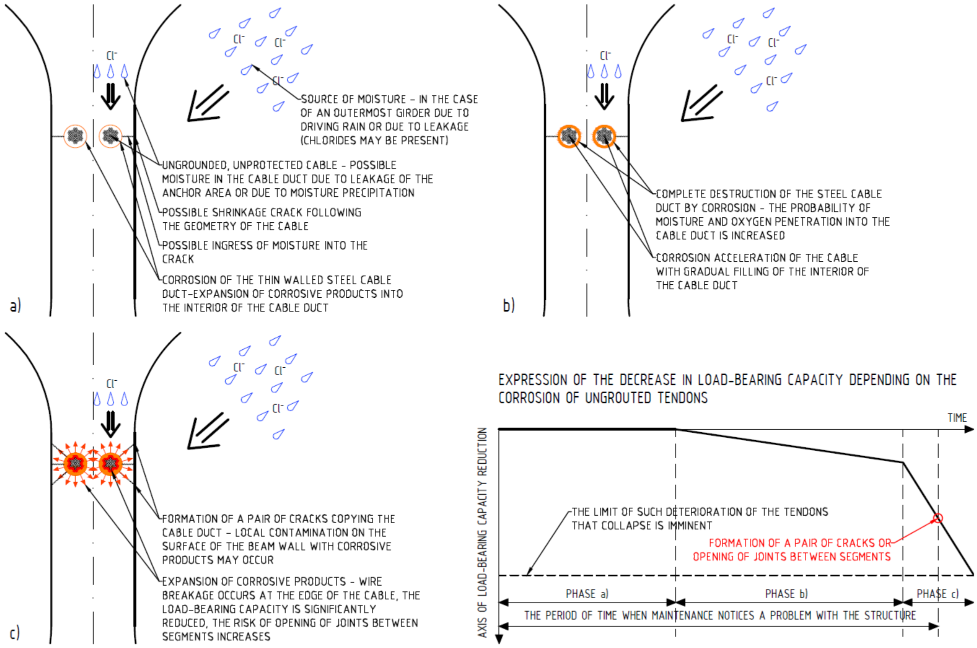


Fig. 9 Cross section through the wall of the girder – late formation of a pair of cracks due to the expansion of the corrosive products in the ungrouted tendon and a schematic graph showing the reduction of the load bearing capacity of the precast girder due to corrosion of the prestressing tendons.

Erro! Fonte de referência não encontrada. shows the case of a partially grouted cable duct and the visible signs observed on several bridges when tendons were damaged. In some cases, the outermost wires of the tendon were torn. Since the cable duct is partially grouted, the torn wires are reanchored, and a crack is formed above the cable duct due to the transverse tension, as seen in **Erro! Fonte de referência não encontrada.**.

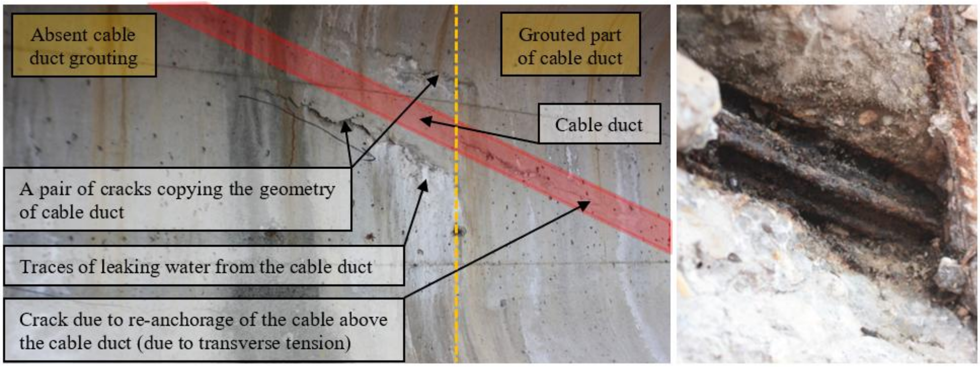


Fig. 10 A pair of longitudinal cracks parallel to the geometry of the polygonal cable duct; on the right, an access window for inspection of the cable duct shows extensive corrosion damage (the duct is full of corrosion products).

As shown in **Erro! Fonte de referência não encontrada.**, there is a decrease in the shear capacity of the girder along the section between the anchorage and the point where the cable wires are reanchored. This condition directly endangers the shear capacity of precast concrete structures in which prestressing has an important contribution to the shear resistance. In this case, if the wires break in the inclined section of the tendon, brittle shear failure may occur [10]. Since most partially grouted tendons are located in locations subjected to high shear stresses (incline positions), the permitted load had to be restricted on several bridges in Slovakia.

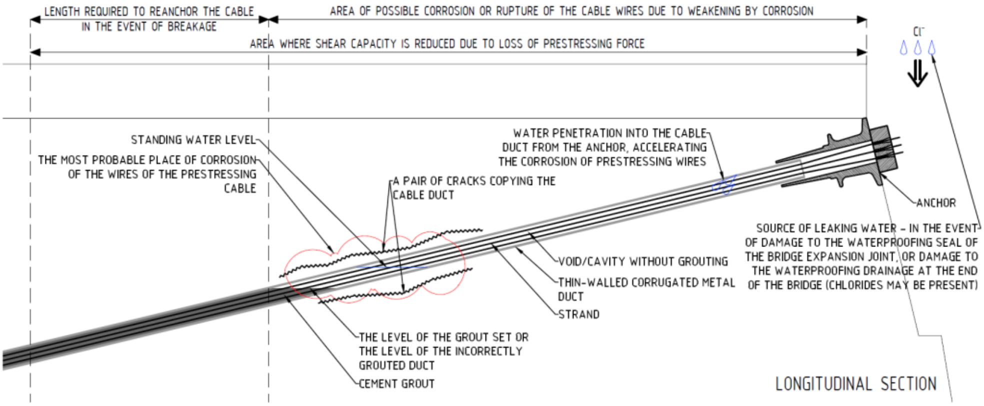


Fig. 11 Longitudinal section through a partially grouted polygonal cable duct.

7 CONCLUSIONS

Based on the information obtained, the following findings could be summarised.

- In the case of thin-walled PT precast concrete girders, thin cracks following the geometry of the cables were often – their formation was attributed to concrete shrinkage or termal efects. These cracks are most likely to occur as a result of local weakening of the beam walls/webs by the cable ducts; no significant effect of these cracks on the condition of the prestressing tendons has been observed, but locally, they slightly affect the condition of the corrugated metal ducts;
- Some of these shrinkage cracks were encrusted, which, at first glance, may indicate the presence of water in the cable duct. Their occurrence was attributed to rainwater, which leaked soluble hydration products from concrete. In any case, it is recommended to inspect the condition of the cable duct if there is a crack in the concrete in its vicinity;
- A pair of parallel nearby cracks, following the geometry of the tendon, may indicate the presence of progressive corrosion of the prestressing wires in the ungrouted cable ducts – on most bridges where these cracks have occurred, several prestressing wires have also ruptured;
- Despite corrosion damage to some of the tendons, the precast girders did not show loss of prestressing force by deflection visible by naked eye, flexural cracks or openings in the gaps between the segments;
- On all bridges, where ungrouted cable ducts were found, grouting defects were observed to occur most often in locations where the cable duct is in an inclined position, most often behind the anchorages or in the uppermost positions of the cable duct;
- Small cavities were observed locally in places where the cable duct has a horizontal geometry, probably due to the settling of the grout;
- During the study, it was found that the evaluation of cable duct grouting condition based on inspection of the anchor areas only (checking for the presence of grout around the vents/anchor cones) is insufficient, which was later confirmed during demolition work;
- Galvanic corrosion was not observed at the contact points of the thick-walled metal couplings and the thin-walled corrugated metal ducts;
- The dominant factor shortening the service life of segmental PT bridges is chloride-induced corrosion due to leakage of the waterproofment and subsequent penetration of water contaminated by chlorides into the interior of ungrouted cable ducts.

- In the case of segmental PT bridges, it is recommended to shorten the inspection time interval to half of the inspection intervals of conventional reinforced concrete bridges.

Acknowledgements

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