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Permanent strand anchors: investigation on existing works

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ABSTRACT: Permanent strand anchors are versatile and efficient geotechnical systems for transferring tensile loads to the ground. For this reason, they have been widely used in infrastructural works, such as bulkheads, quays, dry docks, dams, etc. The use of strands as tendons for geotechnical applications has revealed over time some critical issues related to the care in the execution of some construction details which can greatly shorten the service life of the system or drastically reduce its ultimate capacity. Since ground anchors are often essential elements for the stability of geotechnical works, it is important to define control methods that allow revealing degradation problems that could reduce the development of the full resistance of the system. Based on recent investigation experiences on strand anchors of existing port quays, the paper intends to examine the relevant aspects for the control of these structural systems and describe a new investigation procedure, partially destructive and innovative, which has been tested in a real case study.

KEYWORDS: Ground anchor; Investigation test; Existing work; Corrosion; Failure.

1 INTRODUCTION

In recent years, the need for inspection, monitoring, and safety assessment of existing infrastructures has become increasingly important, primarily due to the aging of many structures, which are now reaching the end of their nominal service life, and to some structural failures that have significantly impacted public opinion (Pinho et al., 2023).

Within this context, the development of reliable testing methods for special geotechnical works, such as existing grouted anchors, has become increasingly relevant for the safety assessment of several infrastructures.

In geotechnical engineering, grouted (or ground) anchors are systems designed to transfer applied tensile load to a suitable bearing stratum. These systems consist of three main components: the anchor head, the free length, and the fixed (or bonded) length. Grouted anchors can vary in terms of the type of tendon used as reinforcement (e.g. strands, solid or hollow bars), the head locking device and the method of installation.

One of the most widely adopted reinforcement solution consists of high-strength steel strands, each made up of seven wires with a nominal diameter of 5 mm. In this case, the head locking system consists of barrel-wedge devices. Since the main components are made of steel, they are susceptible to corrosion and therefore must be adequately protected.

Corrosion problems affecting grouted anchors have been known for a long time and today strict standards, such as EN 1537:2013, are mandatory for the design and execution of these systems, particularly when strands are used as reinforcements. However, permanent strand anchors installed decades ago may have been designed with corrosion protection measures that are now considered inadequate by current standards. Moreover, environmental conditions and initial construction defects may have contributed to the degradation of these systems over time.

For these reasons, the identification of reliable testing methods that allow the detection of degradation problems that could reduce the development of the full resistance of permanent strand anchors appears particularly relevant.

This study, after a brief overview of potential causes of anchor failure, analyzes the functioning of the barrel-wedge locking system and presents an innovative laboratory testing procedure, carried out on barrel-wedge-strand assemblies taken from existing anchors.

2 IN-SERVICE FAILURES OF GROUTED ANCHORS

Apart from problems occurring during the construction phase and usually identified during acceptance testing, in-service failures of grouted anchors are mainly associated with situations where the tensile load acting on the anchor exceeds the system's effective capacity.

Depending on whether the failure mechanism originates in the soil or within a structural component, two primary failure modes can be identified:

- Geotechnical failure, which occurs when the resistance at the soil–foundation interface is exceeded, resulting in anchor pull-out.
- Structural failure, which takes place when one of the system components exceeds its load-bearing capacity, such as the strands, the bearing plate, the locking devices, or the foundation-reinforcement interface.

Structural failure also includes all situations where, despite no increase in applied loads, a reduction in structural capacity of one or more elements constituting the system leads to collapse. This is the typical case of degradation caused by corrosion of the metallic elements. Corrosion can affect all the metallic components of the anchor; however, the most critical issues arise when the strands or the locking system are compromised.

Strands are particularly vulnerable to corrosion because they are made of high-strength steel (i.e. harmonic steel with a tensile strength of 1,860 MPa) but are susceptible to pitting corrosion, a dangerous form of localized corrosion that cause cavities in the metal and can rapidly lead to wire failure.

Barrel-wedge device is also highly sensitive to corrosion as it alters the friction angle at the interfaces between its components (i.e. barrel, wedge and strand) leading to a reduced gripping capacity on the strand and compromising the locking mechanism, especially under increasing load conditions.

Several case studies documented in the technical literature report failures due to corrosion of ground anchors, particularly in retaining walls where anchors play a critical role in ensuring global stability. Among others, Barley (1997) described the collapse of a twenty-one-year-old anchored sheet pile quay wall on the Thames River, which occurred in 1990. Barley et al. (2007) investigated the failure of permanent anchors in a sheet pile wall constructed to protect a densely populated area from flooding. More recently, Li et al. (2023) reported a landslide in Taiwan along Freeway No.3, resulting from corrosion of the grouted anchors supporting the slope.

It is interesting to note that, in the analyzed failure cases, a significant amount of the anchor corrosion that led to failure was concentrated near the anchor head, sometimes resulting in strand rupture and in other cases affecting the barrel-wedge devices. Notably, Barley et al. (2007) observed that several wedges were "corrosion-welded" into the barrels, rendering them virtually immovable and thereby preventing the proper functioning of the gripping mechanism.

A case of quay wall collapse caused by strands pull-out from the barrel-wedge devices is presented in Ruggeri et al. (2013). The investigation revealed that structural instability was triggered by the failure of the anchors, primarily due to the corrosive attack on the barrel-wedge locking devices and the infiltration of sealing grout between the wedge segments, which prevented their movement.

The criticality of the zone beneath the anchor head plate is related to the tensioning process using the barrel-wedge device, which requires the removal of the protective sheath to expose a portion of the strand. As a result, a segment of the strand remains unprotected, without its plastic sheath, even for several centimeters below the barrel and the bearing plate.

Corrosion becomes a critical issue particularly in aggressive environments, such as marine areas, where the presence of chloride ions can depassivate steel and trigger electrochemical corrosion. For this reason, both national (e.g., *"Ancoraggi nei terreni e nelle rocce,"* AGI-AICAP, 2012) and international standards (e.g., *EN 1537 "Execution of special geotechnical works – Ground anchors"*) devote considerable attention to the protective measures required to prevent the onset of such phenomena. These include the use of double corrosion protection for permanent anchors, protective wedge caps for locking devices, the recommendation of cement grouting (or anticorrosive saturating agents) beneath the anchor head plate, and the use of protective caps covering the entire anchor head.

Although protective measures against corrosion have long been specified for ground anchors, in Italy significant attention to their practical application has only emerged in the past two decades. In earlier installations, the anchor head area was typically protected solely by sealing with cement grout, while the use of protective wedge caps and head enclosures became common only more recently. Grout injection beneath the bearing plate following tensioning was also not consistently implemented in the past. The consequences of omitting such injection, despite the presence of a sealed recess, are clear in Figure 1, which shows the anchor head of a grouted anchor removed from a quay wall after approximately 35 years of service. While the locking devices on the front side, though infiltrated by grout, exhibited no significant corrosion, the strands beneath the bearing plate were severely corroded.

Figure 1. Photos showing the front and rear sides of the same anchor head, removed from a quay wall after 35 years of service.

3 THE BARREL-WEDGE LOCKING DEVICE

The barrel-wedge locking device, invented by Eugène Freyssinet and patented in 1947, is the core component of the post-tensioning system (Xercavins et al., 2010). Initially introduced to the European market in 1951 for prestressed concrete construction, the system has been widely adopted in geotechnical engineering since the 1970s.

The barrel-wedge locking device for strands, schematically illustrated in Figure 2, essentially consists of two steel components: the barrel and the wedge. The barrel, with a conical shape, houses the wedge, which is typically divided into two or three parts. The wedge has a smooth outer surface, in contact with the barrel, and a toothed inner surface. The wedge is made of high-hardness steel, typically carburized, so that the teeth can effectively grip the strand, which - although made of high-strength steel - has slightly lower hardness than the wedge.

The functioning of the barrel-wedge retention system is essentially friction-based: as the wedge slides along the conical surface of the barrel, it generates an increasing clamping force on the strand, preventing any relative slippage between wedge and strand as the applied tensile load increases. The mechanical behavior of the barrel–wedge system can be understood by analyzing the interaction forces between its components (see Figure 2). If T is the applied tensile load, balanced by a reaction force R between the bearing plate and the barrel, then the internal forces between the system components can be determined using basic equilibrium equations. These depend mainly on the geometry of the elements and two friction angles: the barrel–wedge friction angle and the wedge–strand friction angle.

Assuming a typical literature value of 45° for the wedge–strand friction angle and considering the most common barrel cone angle of 7°, the device can retain the strand if the barrel–wedge friction angle is lower than 38°; otherwise, the strand may slip. Experimental studies on the barrel–wedge friction angle indicate values ranging from 6° to 10° for new and well-lubricated components, 15° to 20° for new but unlubricated components, and 30° to 40° for corroded or rusty elements (Thompson, 2004; Ruggeri et al., 2013).

Importantly, due to the geometry of the barrel-wedge locking device and the friction between strand, barrel and wedges, the clamping force on the strand is preserved even after the tensile load (T) is released.

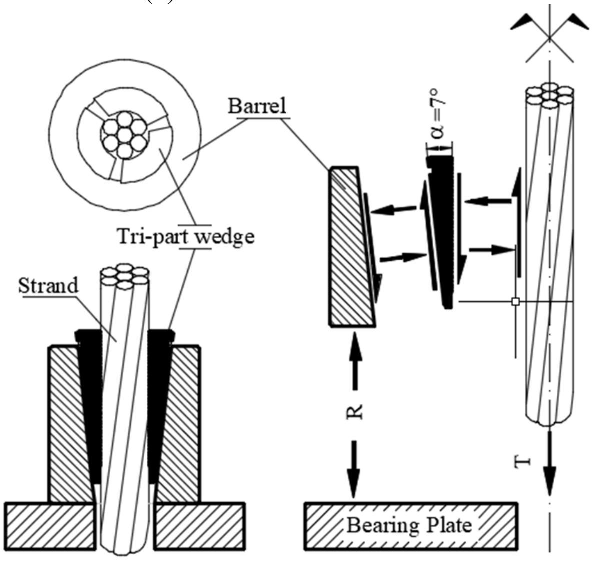

Figure 2. Schematic of a barrel-wedge locking device and the component forces acting between bearing plate, barrel, wedge and strand.

4 INSPECTION AND MAINTENANCE TESTING ON GROUTED ANCHORS

Inspection of the condition of grouted anchors and evaluation of their efficiency are critical aspects in the structural safety assessment of existing infrastructure, due to the essential role these components play in the overall stability of the system. A reliable assessment of the load-bearing capacity and structural integrity of old anchors is also crucial when making informed technical and economic decisions regarding the strengthening or upgrading of existing structures.

Despite the importance of such knowledge in the engineering assessments of existing structures, there are currently no well-established procedures for evaluating the condition of grouted anchors. Technical literature generally distinguishes between qualitative inspections, aimed at assessing the overall state of the anchor components, and quantitative maintenance testing, focused on determining the in-service stress state of the anchor.

In both cases, access to the anchor head is required, usually involving the removal of the grout used to seal the recess. Once this protective cover is removed, the barrel-wedge devices, bearing plate and terminal portion of the strands can be visually inspected. From the anchor head inspection, it is possible to determine:

- The number of strands.
- The type of anchor head used (whether with individual locking devices for each strand or a single head featuring conical recesses for the wedges).
- Signs of corrosion on the metallic components.
- The presence of protective elements (such as plastic wedge caps), or, if these are missing, the presence of grout infiltrated between the wedge parts.

Three anchor heads exposed during inspection are shown in Figure 3. From the photos, the condition of the metallic components and the presence (or absence) of plastic caps on the locking devices can be observed. Notably, as shown in Figure 3c, severe corrosion of the strands has led to the detachment of three locking devices from the bearing plate, a highly alarming indication of the compromised structural integrity of the anchor.

Operating from the anchor head, several non-destructive testing methods can be carried out to determine:

- Electrical isolation measurements and corrosion potential measurements.
- Endoscopic investigations to assess grout filling behind the bearing plate or to inspect the condition of the strands in case of voids beneath the plate (Liao, 2018).
- Impact-echo tests from the strand ends (Kim et al., 2012).

These investigations allow for the identification of the main “pathologies” affecting the anchor, but they do not provide information regarding the existing tensile state, nor do they enable reliable evaluations of the structural components’ capacity under increased loading conditions.

Regarding the evaluation of the tensile stress in the strands, two partially destructive tests can be adopted:

- Strand-cutting test: the strain release after cutting one of the strands of the anchor is measured.
- Release test on a single wire of a strand: the strain release produced by cutting one of the seven wires composing a strand is measured.

The strand-cutting test is a traditional method developed for assessing residual prestress in existing concrete bridges (Bagge et al., 2017).

A more recent variation involves cutting only one wire of the strand, aiming to gather useful information while minimizing damage to the structural integrity. However, this method is typically applied to bonded strands and may produce unreliable results when used on unbonded strands, as is the case along the free length of grouted anchors.

Significant efforts are still ongoing to develop non-destructive testing methods for measuring tensile stress in strands. Drawing on industrial technique used to assess residual stress in metallic components, Morelli et al. (2021) investigated the use of X-ray diffraction to evaluate the tensile force in pre-stressing wires and strands. The results appear promising, however, the current application is limited by the surface condition of the strands, which can vary significantly from one site to another.

In all the cases, the evaluation of tensile stress requires access to the strand along a loaded section and cannot be carried out from the anchor head. Moreover, all the mentioned tests can, at best, provide a picture of the current condition but do not offer direct insight into the behaviour of the anchor under increasing loads.

Liao (2018) describe a lift-off test in which the tensile force is measured by applying a strand jack to the locking devices. This method may allow for testing the anchor even under higher loads. However, the limited available space, the difficulty in gripping the locking devices and the short length of strand protruding beyond the wedges typically make this operation rarely feasible in many real-world conditions.

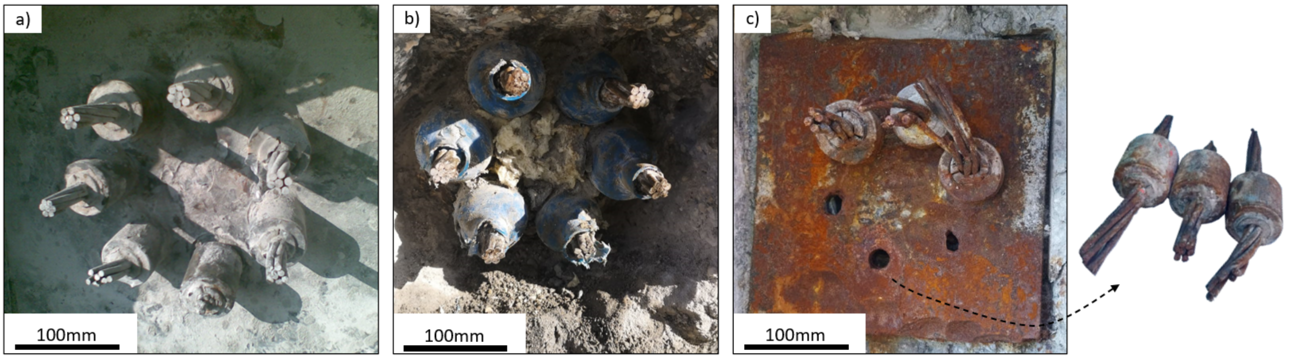

Figure 3. Photos of the anchor head recess after grout removal: a) locking devices without plastic caps, showing no significant signs of corrosion; b) locking devices with plastic caps; c) clear evidence of corrosion on the metallic components, with three out of six locking devices holding strands that are completely corroded beneath the bearing plate.

5 LABORATORY TESTING ON THE BARREL-WEDGE-STRAND ASSEMBLY

Inspecting the strands at their critical section beneath the anchor plate, as well as evaluating the capacity of the barrel-wedge assembly to retain the strand under increased tensile load, is not straightforward.

To address these issues, an innovative methodology has been proposed and tested to assess the degradation level and residual capacity of existing anchors near the anchor head. The method was applied during recent strengthening works on a quay wall constructed with an anchored sheet pile system.

The proposed methodology involves performing an on-site “release test” followed by a laboratory “tensile test” on a barrel-wedge-strand assembly extracted from the anchor head.

The method allows to:

- Estimate the tensile load in a strand.
- Inspect the integrity of the initial strand segment, including the area beneath the anchor plate.
- Verify the ultimate capacity of the barrel-wedge-strand assembly.

5.1 *Sample extraction and release test*

The operative sequence required to extract a sample, including the strand and the barrel-wedge locking device, and to perform the release test illustrated in Figure 4. In particular:

- Opening of the anchor head recess by removing the grout seal, allowing inspection of the barrel-wedge locking devices (Phase 1).
- Excavation behind the top beam to expose the free length of the anchor (Phase 2).
- Removal of the strand sheath (Phase 3).
- Installation of miniaturised strain-gages on one wire of the strand using cyanoacrylate glue applied to a clean and degreased surface (Phase 4).
- Cutting of the instrumented wire using a mini-grinder tool and measurements of the strain release (Phase 5).
- Extraction of the strand along with its locking device from the anchor head (Phase 6).
- Restoration of the strand using a coupler to join a new strand segment, installation of a new locking device and re-tensioning using a strand jack (Phase 7).

Note that in the case study considered, grout injection beneath the bearing plate after tensioning was absent, and the greased sheath adopted in the free length enabled the extraction of the strand from the anchor head after cutting by simply using a hand hammer. According to the authors’ experience, this is the typical situation for existing grouted anchors, even those constructed in the ’70s when double protection was not yet adopted, making the proposed method broadly applicable.

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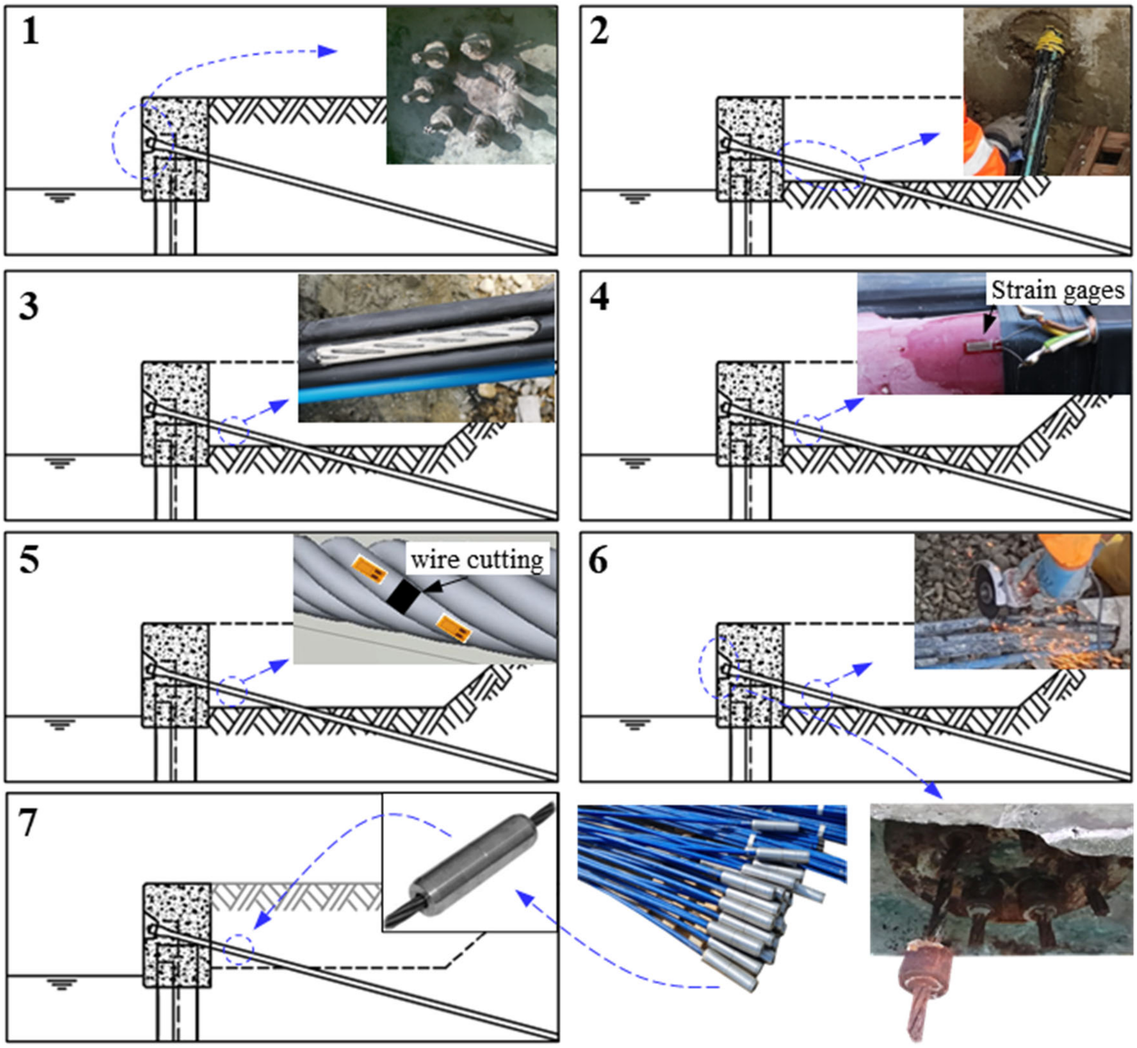

Figure 4. Operative sequence proposed for the extraction of a barre-wedge-strand assembly from an existing grouted anchor.

5.2 *Tensile tests*

The strand-barrel-wedge assembly extracted from the anchor is taken to the laboratory, measured and inspected to verify its dimensions and assess the extent of corrosion in the metallic components, with particular attention to the locking device and the segment of strand near the barrel base that was not visible prior to extraction.

The assembly is then subjected to a tensile test using the typical apparatus for reinforcing bar testing, with one end modified to accommodate the barrel as shown in Figure 5. Using such a setup makes it possible to reproduce the force transfer chain between the different components, as it occurs in real situations, when an increase in reaction force is required from the grouted anchor. Failure occurs when the weakest component reaches its capacity, allowing for the assessment of:

- The efficiency of the locking device in retaining the strand.
- The strength of the strand near the barrel base.
- The strength of the strand along the free length.

The test is considered successful when the locking device is able to retain the strand up to failure and the failure occurs at a load close to the nominal strength of the strand or to the strength measured on a segment of strand unaffected by corrosion.

The load-displacement curves from tensile tests carried out on 12 strand-barrel-wedge assemblies, extracted from grouted anchors of a quay wall, are shown in Figure 5.

The samples were taken after about 35 years of service in a marine environment. At the time of construction, the anchor head recesses on the top beam were sealed with grout, but the wedges were not protected with plastic caps. Additionally, an ungrouted void was found beneath the bearing plate, due to the absence of a dedicated sealing procedure to fill the spaces typically left after construction.

The load-displacement curves of all the assemblies exhibit a very similar elastic behaviour during the loading phase. However, the failure load reaches values close to the nominal strand strength of 260 kN in only 3 out of the 12 samples. Moreover, only one sample exhibited a yielding phase at the maximum load, while the other two failed in a brittle manner. In the remaining 9 cases, the failure occurred suddenly at loads between 100 and 150 kN, corresponding to only 40-60% of the expected capacity for an undamaged strand.

The analysis of the failure modes exhibited by the assemblies helps understand the load-displacement curves. Three distinct failure modes have been observed:

- Failure mode A: full development of the strand resistance; it is characterized by the simultaneous failure of the wires in the strand.
- Failure mode B: near-full development of the strand resistance. It is characterized by the progressive failure of the individual wires forming the strand.
- Failure mode C: very low resistance. It is characterized by slippage of the strand from the wedges.

6 ON THE RESULTS OF TENSILE TESTS

The failure modes observed in the tension tests are indicative of behaviour at failure that are known for strands. As pointed out in Caprili et al. (2024), the expected failure mode of an undamaged strand is characterized by the simultaneous rupture of all the wires, resulting in a "bird-cage" appearance of the strand after failure due to the partial loss of the helically wound pattern of the wires. Furthermore, they associate the "bird-cage" failure with a ductile performance of the strand, which aligns with the findings of the present investigation for Failure mode A.

In corroded strands, conversely, failure progresses wire by wire, initiating at loads below the nominal strength due to non-uniform stress distribution among the seven wires and the presence of localized corrosion, which accelerates crack propagation and shortens the yielding phase. This behaviour corresponds to Failure mode B, typically observed in slightly corroded strands. Regarding the relationship between the degree of strand corrosion and the corresponding reduction in resistance, the database recently compiled by Jeon et al. (2023) provides valuable insights. Specifically, they classify the extent of strand corrosion into five grades (A, B, C, D, E) ranging from "surface corrosion without sectional loss" to "dark reddish-brown rust covering entire steel wires" noting that when corrosion exceeds 5% of the cross-sectional area, tensile strength can decrease by up to 20% and elongation by up to 80%.

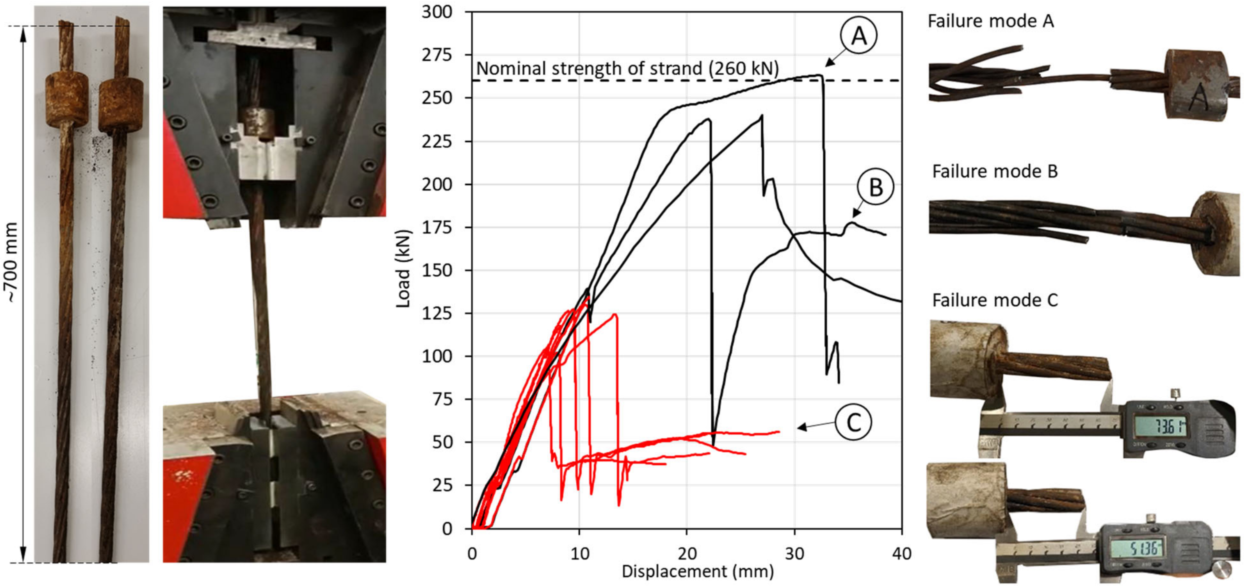

Figure 5. Tensile tests on barrel-wedge-strand system taken from existing anchors.

More critical than strand corrosion was Failure mode C, where the locking device failed to retain the strand up to its ultimate strength. This mode results from corrosion at the barrel–wedge interface, which raises the friction angle beyond the critical value of about 38°, above which the device loses its gripping capacity (Ruggeri et al., 2013). Failure mode C is typical in geotechnical applications because it is related to the low initial prestress (30–80 kN per strand) compared to the expected ultimate and service limit state loads. This low prestress is necessary to allow the soil to develop active pressure and to maintain strength reserves for variable loads, which are often as large as the permanent loads (e.g. seismic actions). Additionally, the application of a force on the locking devices at the end of the prestress phase (i.e. the "lock-off load") was often neglected in the past, resulting in an initial clamping force of the wedge insufficient to hold the strand under increased loads. When the locking device remains well lubricated, the clamping force can increase with the applied load to the necessary level. Conversely, corrosion or grout infiltration between wedge segments prevents the clamping force from increasing, causing inevitable strand slippage.

In summary, since inspection is ineffective at estimating the locking device's capacity to retain the strand, we believe that the proposed tensile test on the strand-barrel-wedge assembly represents a valuable tool for assessing the overall performance of the anchoring system.

7 CONCLUSION

Various maintenance tests are available for assessing the condition and reliability of in-service permanent strand anchors. However, effective methods to evaluate the residual capacity of strands and locking devices in the presence of corrosion are still lacking.

A new, partially destructive, tensile test on strand-barrel-wedge assemblies has been proposed to verify the residual capacity of existing grouted anchors. These assemblies can be extracted from the anchor head by cutting the strands upstream of the anchored structure. The method is applicable when single locking devices are used and when access to the free part of the anchor is possible via limited excavation.

The tensile tests presented in this paper, conducted on anchors that have been in service for about 35 years supporting a sheet pile quay wall, demonstrate clear and easily interpretable results, confirming that the proposed investigative method can be effectively applied in similar experimental contexts.

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