CORROSION RATE MEASUREMENT OF SHEET PILE WALL IN THE PORT OF DURBAN

by

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DECLARATION

I, Mncedisi Mangaliso Nyawo, declare that this dissertation is my original work, unless otherwise indicated in the text. It has not been submitted, in whole or in part, to any other university or university of technology, and its only prior publication is as a journal article listed in **Appendix A**.

This research investigates the corrosion rate of steel sheet piles exposed to marine environments at the Port of Durban, South Africa, and was conducted under the supervision of Professor Dhiren Allopi at the Durban University of Technology.

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ABSTRACT

Ports and harbours are typically located along coastal and inland waterways. Harbours refer to water bodies adjacent to the shore that shelter watercrafts from stormy weather and provide anchorage for ships. Ports, on the other hand, denote infrastructure designed for docking vessels that transport passengers and cargo to and from land. In essence, harbours become ports when they are utilised for commercial activities, such as loading and unloading cargo, embarking passengers, or any other revenue-generating operations. At the Port of Durban, steel sheet piles were installed beneath the quay walls to protect against rising sea levels, prevent soil erosion, and support the riprap beneath the deck of the pile quay wall. However, these steel sheet piles have reached the end of their design life. Furthermore, the thickness of the steel sheet piles at several berths has decreased due to corrosion.

The aim of this study was to determine the corrosion rate (mm/year) and estimate the remaining thickness of steel sheet pile walls at Island View Berth 3 and Maydon Wharf Berth 12 in the Port of Durban. This investigation provided an estimation of the quay wall's functionality and determine whether maintenance, reinforcement, or replacement is necessary. Additionally, the determined corrosion rate will inform future designs of steel sheet piles.

Island View Berth 3 was constructed in 1993 using the ARBED BZ 7 sheet pile type, while Maydon Wharf Berth 12 Berth was rebuilt in 2012 with the new HZM/AZ combined sheet pile wall system. The latter utilised over 2 800 tonnes of HZ 1180M A-24 king piles and 440 tonnes of AZ 18-700 sheet pile pairs as intermediate piles. A significant challenge at the Port of Durban was the development of excessive sinkholes behind berths, believed to result from erosion caused by deteriorating sheet pile structures. Currently, the Port lacks mechanisms to measure the remaining thickness of the steel sheet piles or perform underwater maintenance of these structures. Furthermore, no system is in place to monitor or track the condition of the sheet piles, making it difficult to determine when replacement or maintenance is necessary.

During the inspections, 42 points were examined: 22 in Island View Berth 3 and 20 in Maydon Wharf Berth 12. Island View Berth 3 was inspected over two days in January 2020, while Maydon Wharf Berth 12 was inspected over 14 days. Prior to measurements, divers cleaned 200 mm x 200 mm patches of the steel sheet pile wall. Marine growths were manually removed using a steel scraper, hammer, and wire brush. The outer flanges surface of the steel sheet pile was cleaned from top of pile to the bottom of sheet pile.

An ultrasonic thickness (UT) gauge was employed to assess the remaining thickness of steel sheet piles at both berths. This device emits high-frequency sound pulses through a hand-held probe in contact with the metal, measuring the time taken sound waves to travel through the material, reflect off the back wall, and return to the probe. The remaining thickness was determined by calculating the sound speed in steel and using half the total travel time. Corrosion rates were calculated using the formula icorr $=(T_o-T_a)/t$, where T_o is the original thickness, T_a is the actual thickness, and t is the exposure time in years. This data can inform the design of new steel sheet pile structures for ports.

At Island View Berth 3, the average corrosion rate 28 years after installation was 0.0516 mm/year. Maydon Wharf Berth 12 showed varying corrosion rates by zone: 0.0545 mm/year (splash zone), 0.0485 mm/year (tidal zone), 0.0345 mm/year (low-water zone), and 0.0290 mm/year (immersion zone), with an overall corrosion rate of 0.0466 mm/year. This study highlights significant corrosion variability across studied zones and emphasises the need for a comprehensive maintenance plan. These findings provide essential insights for future design and preservation strategies of marine structures at the Port of Durban.

ACKNOWLEDGEMENTS

First, I want to express my gratitude to the Lord Jesus Christ for giving me the strength and wisdom to embark on the journey of pursuing and completing this dissertation.

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ABBREVIATIONS

pH	Potential Hydrogen
yr	Year
UTG	Ultrasonic Thickness Guage
TNPA	Transnet National Port Authority
TEU	Twenty Foot Equivalent Unit
PRDW	Prestedge Retief Dresner Wijnberg,
CD	Chart Datum
MLW	Mean Low Water
EIS	Electrochemical Impedance Spectroscopy
LWZ	Low water zone
PIZ	Permanent immersion zone
NDT	Non-Destructive Techniques
CP	Cathodic protection

LIST OF EQUATIONS

LIST OF SYMBOLS

m - Meters

mm - Millimetres

US$ - United States Dollars

cm^2 - Square Centimetre

cm – Centimetre

kg – Kilogrammes

m^2 - Square Metre

mg – Milligram

L – Litre

CHAPTER 1

INTRODUCTION

1.1. Background of the Study

Corrosion of steel sheet piles is a major issue in marine environments, affecting port infrastructure. This study observes corrosion at Island View Berth 3 and Maydon Wharf Berth 12 in the Port of Durban. Island View Berth 3 and Maydon Wharf Berth 12, are used for dry bulk and general cargo, and are affected by tidal exposure and mechanical wear.

The key factors contributing to corrosion include electrochemical reactions, chloride exposure, microbial-induced corrosion (MIC), and physical impact. If corrosion is not properly managed, structural stability might be compromised, increase maintenance expenses, and disrupt operations. This study aims to assess the extent of corrosion and recommend effective mitigation strategies, such as cathodic protection and protective coatings, to enhance the durability of port infrastructure.

1.2. Natural and artificially created harbours

As opposed to natural ports, harbours can be created either naturally or artificially. Some of the world's most recognisable natural harbours include the Port of Durban (also called Durban Harbour) and Saldanha Bay (South Africa), Harbour of Rio de Janeiro (Brazil), Sydney Harbour (Australia), San Francisco Bay (United States), Port of Trincomalee (Sri Lanka), Mormugao Port (India), Victoria Harbour (Hong Kong), Poole Harbour (United Kingdom) and Guantánamo Bay (Cuba). Although, Poole Harbour is the largest natural harbour in the world, Saldanha Bay is the largest and deepest natural port in the Southern Hemisphere. Despite their natural formation, many of these harbours have been modified for commercial or strategic reasons.

Since natural harbours do not always meet human needs, artificial harbours were created to develop and improve trade. To this end, some of the hallmarks of artificial harbours include concrete sea walls, breakwaters and other forms of barriers that reduce the tidal range (also called tidal amplitude) and protect the harbour from currents, waves and storm surges. Anecdotal evidence also indicated that artificial barriers can stabilise the seabed in artificial harbours more than in natural harbours. Jebel Ali (United Arab Emirates) is the largest man-made harbour in the world. Other large artificially created harbours include the Port of Rotterdam (Netherlands), Long Beach Harbour (United States), Chennai Port (India), and Port of Casablanca (Morocco).

Harbours and ports are vital for global trade because they enable the movement of cargo between different countries. Efficient ports contribute to international trade expansion, providing access to various goods from around the world and boosting a country's exports (Marggraff, et al. 2024). Whether natural or artificially created, harbours are an integral part of supply and distribution chains worldwide, serve as gateways for imports and exports, facilitate the exchange of products and resources necessary for economic development and serve as arrival points for passenger tourists. Apart from their commercial importance, many natural harbours are also used for military purposes.

1.3. Hierarchy of ports' commercial operations

A common trait shared by many harbours is that they have ports or seaports, which are essentially trade or shipping handling areas within a harbour. A port is typically dedicated to the loading and unloading of cargo and/or passengers, service handling, or any other commercial activity within a harbour. Although a port is, by definition, positioned within a harbour, the entire harbour is referred to as a port.

Each port has terminals designed to handle different types of cargo, including car cargo, oil and gas, bulk cargo, multipurpose, container, and cruise and ferry (passenger) terminals. Each terminal has one or more berths or quays, allowing for the simultaneous handling of multiple ships. All commercial activities take place in berths and quays. A berth, which refers to the area where a vessel is moored or anchored, has the requisite infrastructure, equipment and facilities for the vessel to dock; load, discharge and store cargo; and receive services such as maintenance and refuelling. According to Sinay (2023), the land adjacent to a berth or structures built along the shoreline of a harbour or port is referred to as a quay, wharf, or waterfront. Quays usually have a solid and elevated surface for transferring cargo and passengers between ships and the shore. However, in today's global economy, where reliability is critical, cargo-handling operations at any terminal or port are supported by ship-to-shore quay cranes, storage facilities, and other cargo tools.

The steel sheet piles, which have been installed under the quay walls at the Port of Durban to protect the quay against rising sea levels are closer to end-of-design life. In addition, the thickness of the steel sheet piles forming part of several ports has been reduced due to corrosion. Therefore, a need existed to determine the corrosion rate (mm/year) of steel sheet piles exposed to the marine environment at the Port of Durban. Such an investigation will allow the remaining life of the existing sheet pile to be established (Wall & Wadsö, 2013). Information about corrosion rates will also be useful for designing new sheet-piled quay wall structures at the Port of Durban and other South African ports.

1.4. Problem statement

Corrosion of steel sheet piles in marine environments poses a significant challenge to port infrastructure, leading to structural deterioration, increased maintenance costs, and potential safety risks. At the Port of Durban, Island View Berth 3 and Maydon Wharf Berth 12 are experiencing corrosion due to prolonged exposure to seawater, chemical pollutants, tidal fluctuations, and mechanical wear.

Currently, the Port of Durban lacks a structured methodology for underwater maintenance, monitoring, and tracking of steel sheet pile conditions. Without a system in place, there is no accurate method to determine when the structures require maintenance, reinforcement, or replacement. The absence of a proactive corrosion management plan also means that the long-term integrity of quay walls cannot be effectively assessed, potentially shortening their service life.

This study aimed to investigate the extent, causes, and corrosion rate affecting the sheet piles at these berths, identify contributing environmental and operational factors, and evaluate effective corrosion control strategies. Additionally, this study seeks to recommend a systematic monitoring and maintenance framework that will not only estimate the corrosion rate of existing structures but also influence the future design and lifecycle management of steel sheet piles.

Corrosion significantly compromises the structural integrity and longevity of marine structures, particularly in high-salinity environments (Xia et al. 2024). Sheet-pile walls are essential for the operational safety of the Port of Durban. Understanding the corrosion rates of these structures is vital for developing effective maintenance strategies.

1.5. Aim and objectives of the study

The aim of this study is to assess the extent, causes, and impact of steel sheet pile corrosion at Island View Berth 3 and Maydon Wharf Berth 12 in the Port of Durban and to develop an effective monitoring and maintenance framework. The study seeks to propose strategies for mitigating corrosion, preventing structural failures, and extending the service life of port infrastructure.

To achieve the aim of this study, the following objectives were established:

- Evaluating the extent and severity of corrosion in the steel sheet piles at Island View Berth 3 and Maydon Wharf Berth 12.
- Analyse the environmental, chemical, and operational factors contributing to the deterioration of the sheet piles.
- Assessing how corrosion-related damage, including sinkhole formation and soil erosion, affects berth stability and operational efficiency.
- Examine the current port maintenance strategies and identify gaps in underwater inspection and tracking of steel sheet pile conditions.
- Propose a systematic methodology for tracking corrosion rates, scheduling maintenance, and determining when reinforcement or replacement is necessary.
- Recommend appropriate protection techniques, such as cathodic protection and coatings, to improve the longevity of steel sheet piles.
- Using the findings to provide recommendations for the design and construction of more durable steel sheet piles in future port developments.

These objectives aimed to provide a comprehensive understanding of the factors that affect the durability of steel sheet piles in a marine environment, ultimately contributing to better management and maintenance strategies for infrastructure in port areas.

1.6. Research questions

The research questions were identified as follows:

1.6.1. Main research question

The main research question is as follows:

> *What is the corrosion rate of steel sheet piles in the Port of Durban?*

To effectively address the question of corrosion in seawater, several critical factors must be considered. Chloride ions are of primary concern because they significantly enhance electrical conductivity and accelerate corrosion currents in steel sheet piles and other metals. Additionally, the corrosion rate is influenced by various environmental conditions, including pH, wind exposure, pollution, salinity, and rainfall. Each of these elements plays a role in determining the severity of corrosion, necessitating a comprehensive understanding to mitigate its effects on marine structures.

Furthermore, the corrosion of steel sheet piles depends on the following conditions:

- Applications and elementary design issues
- Environmental impact
- Under water-induced steel sheet pile maintenance

1.6.2. Sub-research question 1: Elementary design and applications

> *How does the design and application of steel sheet piles contribute to rapid corrosion?*

This query addresses the steel sheet pile application and design parameters to be considered when designing steel sheet piles.

It is important to understand an approach for calculating the section of steel loss of sheet piles due to corrosion and knowing the applicable design methods and standard codes that should be used. Sub-question 1 can be broken down into the following:

- What types of steel sheet piles are used in the Port of Durban?
- What was the design life of the steel sheet piles at Island View Berth 3 and Maydon Warf Berth 12?
- How are the steel sheet piles installed?

1.6.3. Sub-research question 2: Environmental Impact.

What is the environmental impact on steel sheet piles under seawater?

The aim of this question is to understand the different environments to which steel sheet piles are exposed in harbours, as well as how steel sheet piles react under different environmental conditions. Understand the environmental factors that contribute to the deterioration of steel sheet piles under seawater is crucial.

The following factors contribute to the corrosion of steel sheet piles:

- Chlorides
- pH value
- Pollution

1.6.4. Sub-research question 3: Under water steel sheet pile maintenance

How can maintenance of steel sheet pile structures be constructed under water?

One of the aims of this study is to propose strategies for mitigating corrosion, preventing structural failures, and extending the service life of port infrastructure. Steel sheet piles subjected to corrosion over the years, and it is important to identify maintenance plans that can increase the longevity of the structure.

1.7. The expected outcomes based on the research questions

The research determined the average corrosion rate (mm/yr) for the Port of Durban and provide maintenance plans for under-water steel sheet piles. It is crucial to know the corrosion rate of steel sheet piles exposed under seawater to be able to predict their life span. Knowing the corrosion rate of steel sheet piles assisted in designing future steel sheet piles for the Port of Durban.

This research also outlines processes and procedures for maintaining underwater steel sheet piles.

1.8. Methodology

This study investigated the corrosion of steel sheet pile walls at Island View Berth 3 and Maydon Wharf Berth 12 in the Port of Durban. Utilising a quantitative research approach, the study involved underwater inspections by divers to measure the remaining thickness of the steel piles and assess their condition. Key methodologies for evaluating the environmental impacts on corrosion rates included ultrasonic thickness measurements, chloride sampling, and pH testing.

Data collection focused on specific corrosion zones within Island View Berth 3 and Maydon Wharf Berth 12. This study aims to measure the extent, causes, and impact of steel sheet pile corrosion under seawater. Overall, the study provides a comprehensive assessment of the effects of marine environments on steel sheet piles.

1.9. Limitations of the study

Despite the comprehensive approach, this study has several limitations that impacted the scope and applicability of its findings:

- **Limited Historical Data on Corrosion Rates** – The study relied on current assessments, due to limited historical corrosion data for the sheet piles at Island View Berth 3 and Maydon Wharf Berth 12, making it difficult to establish long-term deterioration trends.

- **Challenges in Underwater Inspection** – Conducting detailed underwater inspections was complex due to poor visibility. This has affected the accuracy of corrosion assessments.
- **Variability in Environmental Conditions** – Corrosion rates are influenced by changing environmental factors such as salinity, temperature, water pH, and pollutant levels. The study was limited to observations within a specific timeframe and did not fully capture seasonal variations or long-term environmental changes.
- **Limited Testing and Laboratory Analysis** – The study relied on non-destructive testing (NDT) techniques rather than laboratory-based material analysis. This limited the ability to precisely determine corrosion mechanisms, such as specific chemical interactions.
- **Site-Specific Findings** – The study focused on Island View Berth 3 and Maydon Wharf Berth 12, and while the findings provided insights applicable to other areas of the port. This did not fully represent conditions at all berths with different operational factors.

Despite these limitations, the study provides valuable insights into the corrosion challenges at the Port of Durban and offers a foundation for developing a structured maintenance and monitoring framework. Future research and continuous data collection will help refine the findings and improve corrosion management strategies.

1.10. Analysis, discussion, and findings

After physical assessment, steel thickness was measured, and samples were collected for further analysis. This data was used to calculate the corrosion rate and to understand how various environmental factors contribute to the corrosion of steel sheet piles. The results also revealed varying corrosion rates across the different tidal zones.

1.11. Recommendations and conclusions

All final recommendations from the study are discussed and the proposed future scope level presented. Other potential future studies are also highlighted.

1.12. Dissertation layout

This dissertation consists of five chapters, which are outlined below:

Chapter 1: Introduction: This chapter provides a brief background of the research topic, followed by an outline of the problem statement and the aim and objectives of the research topic. Brief information relating to the methodology, sampling, and corrosion rate calculation is also provided before outlining the structure of the dissertation.

Chapter 2: Literature Review: Chapter 2 provides a review of the existing literature on the installation of underwater steel sheet piles, corrosion, corrosion rate measurement, testing, and maintenance. Previous studies conducted in the world on harbours and steel sheet piles are also included.

Chapter 3: Materials, equipment, and methodology: This chapter outlines our methodological approach for conducting this study. Furthermore, this chapter provides information related to the equipment used, the processes followed, and how the results are evaluated following sampling measurements.

Chapter 4: Discussions: The Island View Berth 3 and Maydon Wharf Berth 12 steel sheet pile samples were taken underwater, and the measurements taken by divers as well as data collected from the sheet pile manufactures is analysed and discussed. Corrosion rate measurements were also calculated and analysed.

Chapter 5: Recommendations: This last chapter derives conclusions from the results of the study, and n makes recommendations regarding the maintenance of steel sheet piles.

1.13. Chapter conclusion

This chapter provides background information on the research topic. In addition, the importance of harbours and ports and the strategic role played by the Port of Durban in the economic value chain of South Africa and the region were highlighted. After outlining the key role played by steel sheet piles in the overall structure of the quay walls, potential threats to the quay wall structures, such as corrosion and degradation, were highlighted in the problem statement section. Once a strategy on how these threats can be addressed was proposed (aim and objectives), a methodological approach to addressing the problem was developed. The chapter concludes with an outline of the dissertation. The next chapter reviews relevant literature on the topic under discussion.

CHAPTER 2

LITERATURE REVIEW

2.1. Introduction

The Transnet National Ports Authority (TNPA) was established under the National Ports Act, No. 12 of 2005, to serve as a landlord port. It is responsible for ensuring the safe, efficient, effective, and economical operation of the national ports system, which it manages, controls, and administers on behalf of the State (Transnet National Ports Authority, 2019).

TNPA plays a strategic role in the country's transport logistics chain by managing South Africa's eight commercial seaports: Saldanha, Cape Town, Mossel Bay, Port Elizabeth, Ngqura, East London, Durban, and Richards Bay. Port Nolloth, the ninth port, does not handle commercial cargo and is fully leased to De Beers Consolidated Diamond Mines (Transnet National Ports Authority, 2019). **Figure 2.1** shows the South African ports.

Figure 2.1: Southern African ports.

Source: Maritime South Africa, 2015.

2.2. Port of Durban, South Africa

Owing to regional economic growth in tandem with infrastructure development in neighbouring countries, South Africa has substantial potential in maritime trade and logistics (Lee, 2015; Ng, 2018). The Port of Durban (**Figure 2.2**) is the largest and busiest shipping terminal in sub-Saharan Africa handling up to 31.4 million tonnes of cargo annually (Dormac, n.d.). Being also the fourth largest container terminal in the Southern Hemisphere, the import and export volumes for the Port of Durban were forecast to grow to approximately 2.5 million TEU and 1.0 million TEU, respectively, in 2020 (Kim et al., 2018).

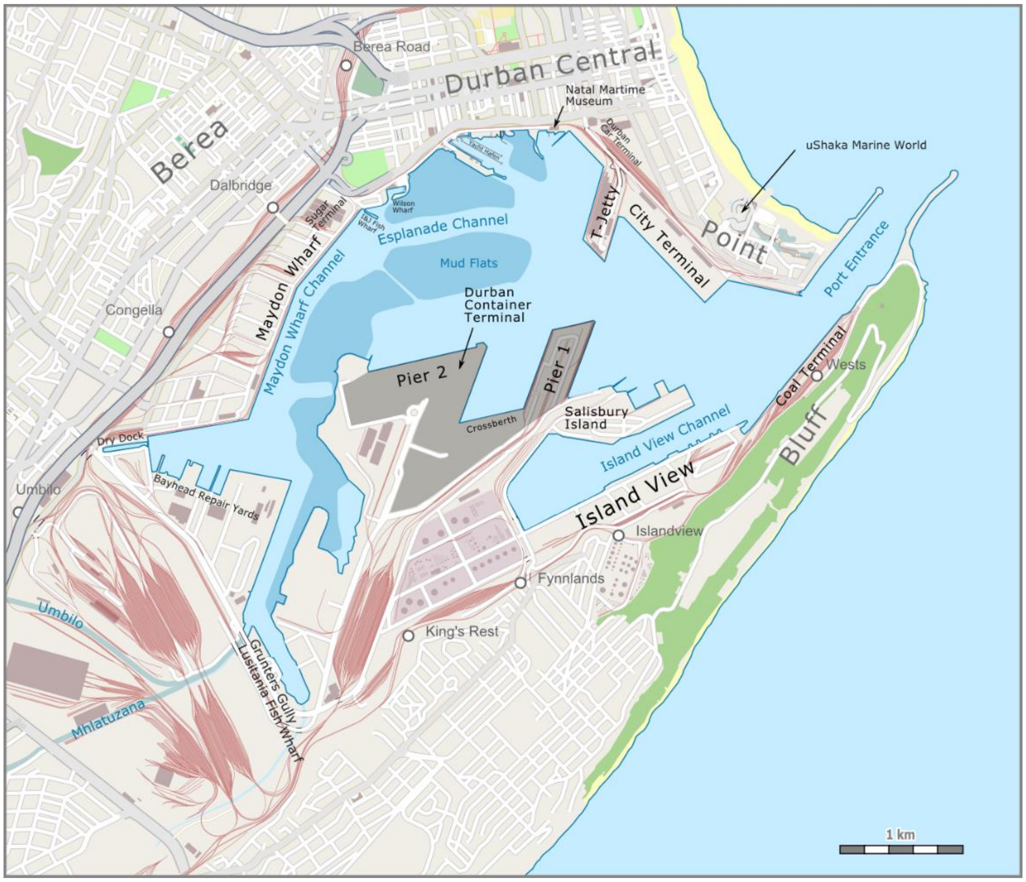

Figure 2.2: An illustration of the Port of Durban

Source: OpenStreetMap, 2015.

Apart from handling approximately 60% of South Africa's container traffic, the Port of Durban is also regarded as the busiest cargo port in Africa, with 59 berths used for safe and secure mooring while facilitating the loading and unloading of cargo or people from vessels (Wikipedia, 2025). The Port of Durban serves the south-eastern province of KwaZulu-Natal, the economic hub of the country (i.e. the Gauteng region), and a large portion of inland Southern Africa. Most importantly, it is ideally situated on major shipping routes. Owing to its excellent rail and road links, the Port of Durban is strategically located along international shipping routes and thus plays an integral role in South Africa’s economy. At the time this dissertation was compiled, the Transnet National Ports Authority (TNPA), a state entity responsible for managing South African ports, issued a Request for Proposals for a contractor to upgrade the Port of Durban. The goal is to enhance its role as an international container hub by increasing its container volume capacity from 2.9 million twenty-foot equivalent units (TEUs) to 11.4 million TEUs. (TNPA, 2023).

2.3. Quay walls

Quay walls can be described as earth-retaining structures built in a water body where ships and other vessels are moored (anchored) and berthed to allow the loading or uploading of ship cargo (Thoresen, 2014). Quay walls are more than just walls in the water; they are a critical component of port infrastructure. Efficient transfer at the quay wall interface plays a pivotal role in the commercial and operational success of any port. Furthermore, quay walls ensure the safety and functioning of ports and their surrounding areas. For this reason, they must endure loads from harsh marine and soil as well as external loads from ships and the loading and uploading of cargo over the quays over long periods of time.

Many of today's quay walls, such as those found at the Port of Durban, are old and have lasted for decades or even centuries (Zikhali & Setaka, 2019). The ever-increasing global trade and the concomitant increase in cargo volumes coupled with increasing new-age vessel sizes have imposed increasing demands on these quay walls. Moreover, quay walls and infrastructures are typically exposed to corrosion, degradation, subsidence, sea-level rise, and extreme weather over their lifetimes. Therefore, to ensure that people and other vulnerable areas surrounding the ports are protected, it is important that existing quay walls remain and continue to function.

Quay walls can be constructed from mass concrete, steel sheet, or timber piles; however, steel and concrete are the most common materials used in quay wall structures. Although the main structural component of the quay wall consists of steel sheet pile, reinforced concrete still plays an important role in the structure of the wall.

2.4. Steel sheet piles

As illustrated in **Figure 2.3**, standard sheet pile walls are used in the quay walls designed for small- to medium-sized drafts. Steel sheet piles have been used extensively all over the world to build reliable quay-wall structures in commercial ports and marinas. They are prone to corrosion and degradation, thus compromising the structure of the quay walls.

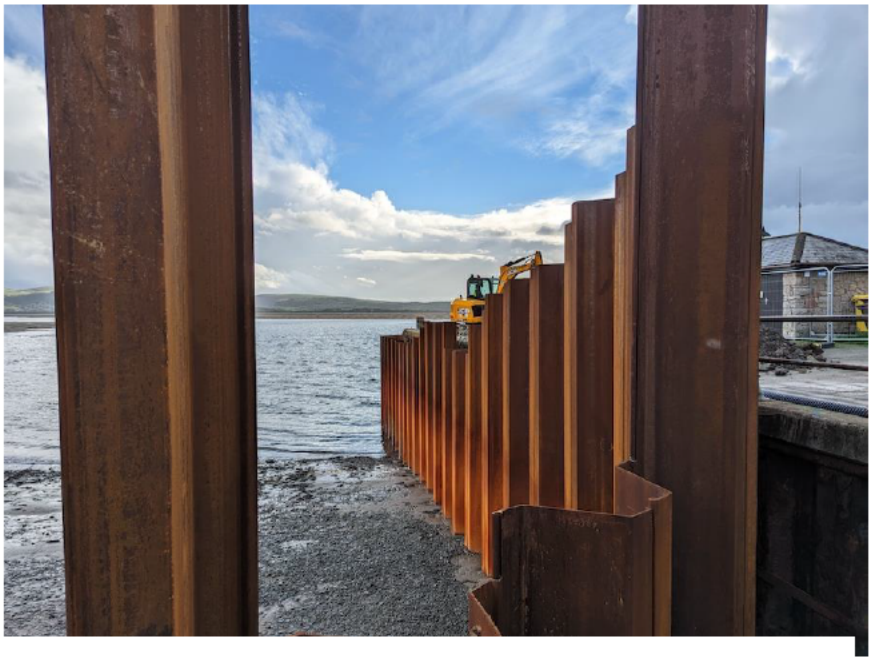

Figure 2.3: Construction of the sheet pile
Source: Pile Buck, 2023

Figure 2.4 illustrates the interlocking of the Z-sheet piles as they are driven into the ground to strengthen the quay wall. According to Sheet Piling (UK) Ltd. (2024), Z Section Sheet Piles are noted for their optimised section profile and high bending moment resistance.

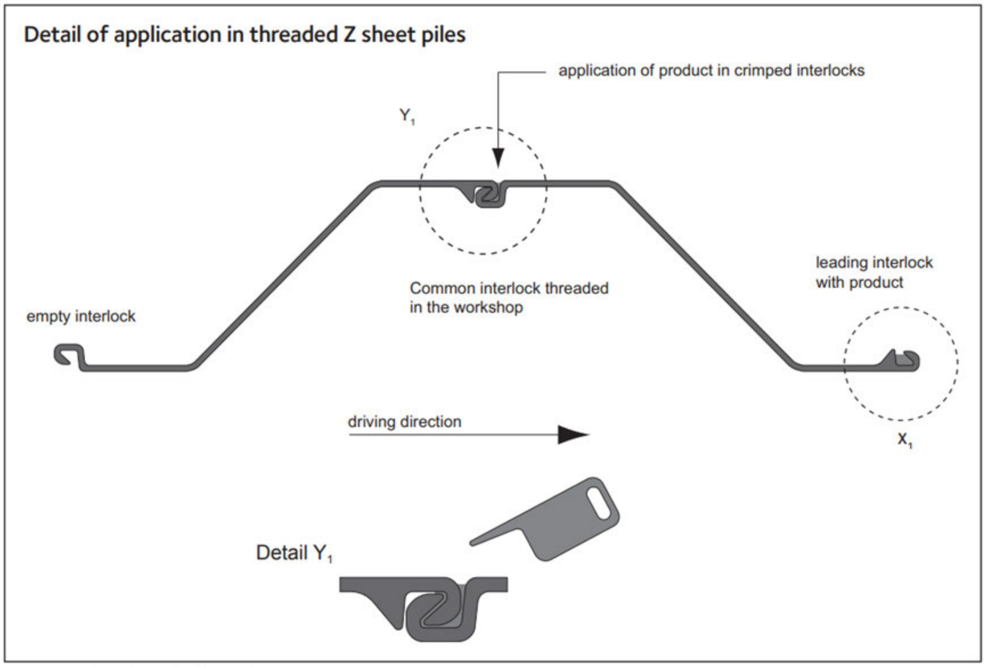

Figure 2.4: Detail of Z Sheet Pile

Source: ArcelorMittal 2019

Quay walls, dolphins and jetties are the primary interfaces between land and water. The important role of quay walls, jetties, and dolphins is to support the transfer of cargo between vessels and landside facilities, the berthing of vessels, and the loading/unloading equipment. These important structures must be available on request for the port to function efficiently (Transnet National Ports Authority 2016).

The type of structure used at the berth is primarily dependent on the soil conditions, a type of cargo being handled, or vessel requirements. In South Africa, quay walls generally consist of caisson walls, block walls, steel sheet pile walls, decked pile walls, and counter-fort walls. Jetties are usually constructed as decked pile structures that are perpendicular to the land. The dolphins are comprised of caissons, blockwork, and concrete decks on piles (Transnet National Ports Authority 2016).

Island View Berth 3 is a berth mainly used for dry bulk such as chrome ore, minerals, maize, rice, wheat and sunflower seeds, which are imported and exported (Diamond Shipping Services, South Africa, 2017).

The cross-section of Island View Berth 3 is illustrated in **Figure 2.5**.

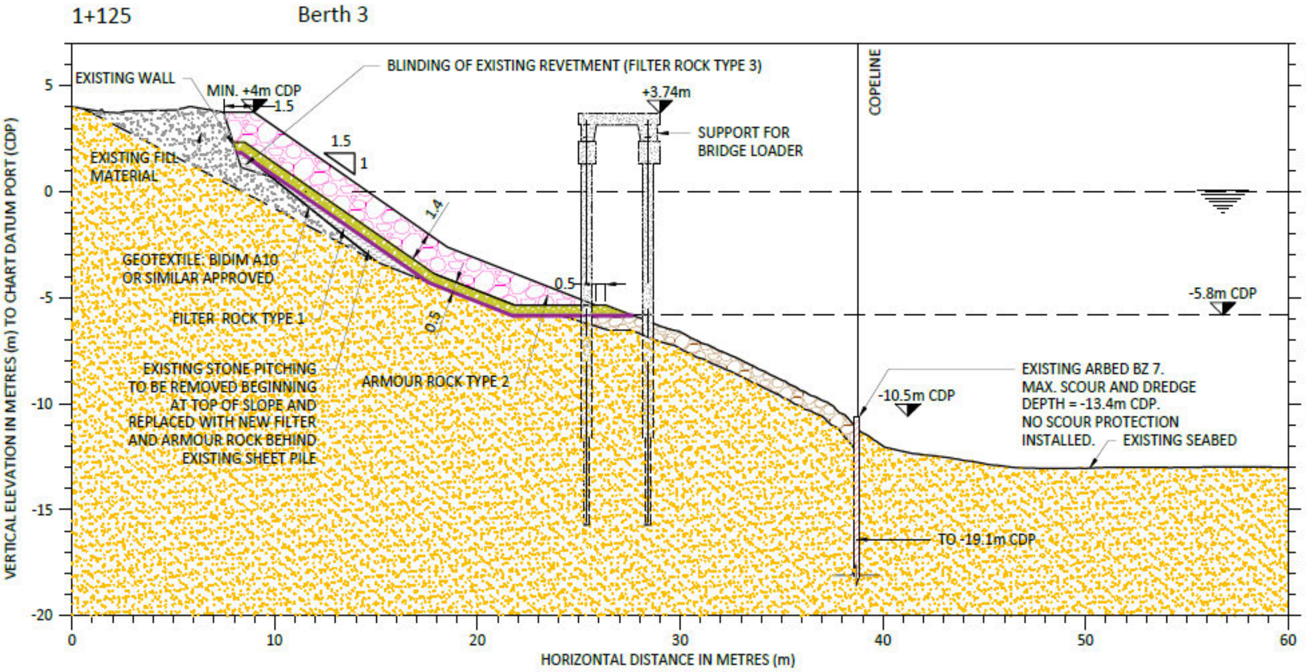

Figure 2.5: Island View Berth 3

Source: Prestedge, Retief, Dresner Wijnberg (PRDW) Consulting, 2018.

PRDW Consulting (2018) stated that the Island View Berth 3 revetment requires an upgrade and that the existing sheet pile wall in front of the berth will support the new proposed revetment. Nevertheless, a detailed assessment and measurement of the existing sheet pile wall was conducted to determine whether the existing piles could resist the imposed load of the new revetment. Further studies were conducted during this research in which measurements and tests were conducted to determine the corrosion rate of the Island View Berth 3 and Maydon Wharf steel sheet piles.

PRDW Consulting (2018) reported that the original thickness of the sheet pile wall was 8 mm. Based on the British Standards (BS) 6349-1:2000, it was assumed that the remaining wall thickness of the sheet piles of 7.4 mm below the -13.0m Chart Datum (CD) in 2018. A thickness of 5.2 mm was assumed to be above -13.0m CD, which is a result of the sheet pile wall section being exposed to sea water (PRDW Consulting 2018). This study was conducted to determine the corrosion rate of sheet pile walls in the Port of Durban.

The British Standard (BS) 6349-1 is a comprehensive code of practice providing guidance on general criteria for maritime structures, serving as an important reference for engineers working on coastal and port infrastructure projects. Therefore, based on the British Standard 6349 (1:2000), it was assumed that in 2019, the existing thickness of the sheet pile wall at the maximum corrosion rate per side/year for any type of sea water was as follows:

- Continuous seawater immersion zone: 4.49 mm (56% remaining)
- Below seabed level or in contact with soil: 7.6 mm (95% remaining)

The Maydon Wharf Berth 12 quay wall was re-built in 2012 with the new HZM/AZ combined sheet pile wall system as shown in (**Figure 2.6**): over 2 800 tonnes of HZ 1180M A-24 king piles and 440 tonnes of AZ 18-700 sheet pile pairs as intermediate piles. A high-strength steel grade S 430 GP (430 MPa yield strength) was chosen by the design engineer to optimise the steel quantity needed (ArcelorMittal, 2019). The cross-section of the Maydon Wharf Berth 12 (**Figure 2.7**) shows how the quay wall was constructed.

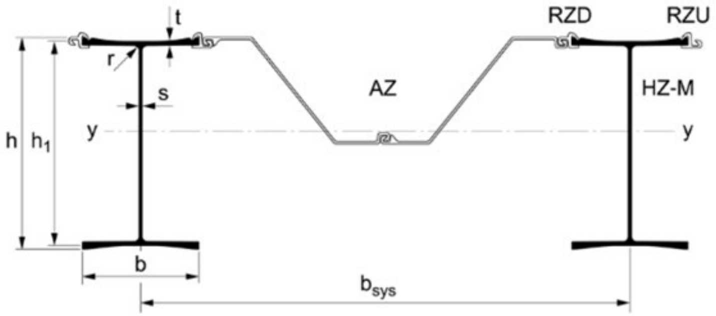

Figure 2.6: Combination of HZ and AZ sheet flakes

Source: ArcelorMittal. 2019

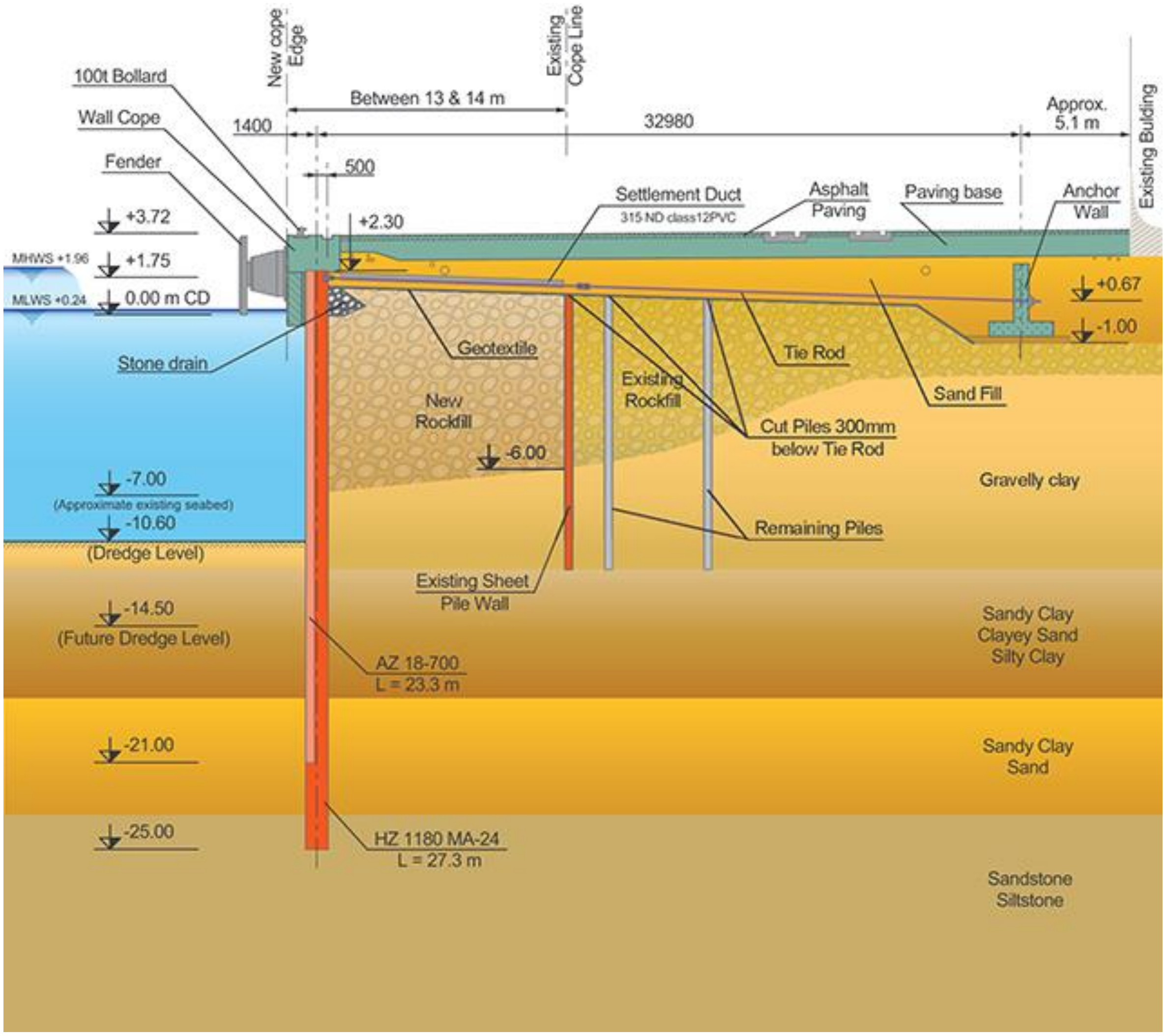

Figure 2.7: Rehabilitation of Maydon Wharf Berth 12

Source: ArcelorMittal 2019

2.5. Existing steel sheet piles

The sheet piles used at Island View Berth 3 were type ARBED BZ 7 and were designed to have interlocks situated in the outmost side of the section to ensure that when the sheet pile was experiences bending due to soil pressure or horizontal loads, a significant bending shear force is generated in the interlocks of the sheet piles (Nippon Steel, 2019).

ARBED Z-shaped sheet pile consist of a section modulus of 4200 cm^3 per running metre of wall but a mass of 271 kg/m^2 and hence a less favourable specific section modulus of 15.5 $(cm^3/m)/(kg/m^2)$. This sheet pile features gripping elements of the BELVAL type, with a web that forms an acute angle of approximately 83.5° and a plane parallel to the flanges (Bourdouxhe 2000).

The ARBED BZ 7 series features outstanding characteristics, coupled with the proven reliability of the Larssen interlock. It offers several key advantages, including an extremely competitive section module-to-mass ratio; increased inertia for reduced deflection; and a wide profile that ensures exceptional installation performance. (ArcelorMittal Sheet Piling 2019).

The sheet piles used in Island View Berth 3 and Maydon Wharf Berth 12 are also used in other berths at the Port of Durban and in various ports around the world. As stated by ArcelorMittal (2016), steel sheet piling is a reliable and proven material for quickly and cost-effectively constructing quay walls. These steel sheet piles can be designed to handle heavy vertical loads and substantial bending moments.

2.6. Corrosion of steel sheet piles

Corrosion is a natural electrochemical reaction that affects all steel to some extent. It occurs in a manner similar to a battery, where an electric current flows between a positive electrode (anode) and a negative electrode (cathode) in the presence of an electrolyte, typically wate. As the current flows from the anode to the cathode, the anode (the steel) corrodes, leading to rust formation. When corrosion affect the steel, it results in a loss of thickness. Corrosion of steel sheet piles becomes a design concern if the anticipated loss of steel thickness over the structure's design life compromises the sheet piling's structural capacity (North American Steel Sheet Piling Association n.d.).

As noted by the ESC Group (2022), rust is the result of corroding steel particles upon exposure to oxygen and moisture.

According to Pile Buck (2017), there are different types of corrosion on steel sheet piles in marine environments, and these are listed below:

- **Pitting Corrosion**: when the corrosion rate is higher in exposed areas, leading to the formation of narrow, deep holes, particularly in environments with saltwater immersion. This type of corrosion can cause heavy pitting, which can reduce the cross-sectional area and failure.

- **Uniform Corrosion**: This type of corrosion is characterized by a uniform loss of metal across the surface, leading to a reduction in the structural strength of the material and an increased risk of failure due to overstressing. Corrosion resulting from exposure to atmospheric conditions and freshwater immersion is generally uniform in nature.
- **Galvanic Action**: This stage accelerates metal corrosion due to electrical contact with more passive metals. When different types of metal are coupled together in a seawater structure, galvanic corrosion will occur on the anodic member, with the cathodic member rendered inactive.
- **Stray Current Corrosion**: Occurs when direct currents from improperly grounded sources such as cathodic protection systems, ship service systems, welding generators and electric railway systems can cause stray current corrosion damage to ungrounded structures in harbour areas. One ampere of direct current passing from a structure to seawater can remove approximately 9 kg of steel over the course of one year.
- **Fatigue Corrosion**: This type of corrosion refers to accelerated failure of a metal due to the combined effects of corrosion and repeated or cyclical stress.
- **Bacteria and Fouling**: A broken sewer line or illegal discharge can release anaerobic bacteria, which can accelerate corrosion at or near the mudline. Additionally, fouling occurs when marine organisms such as barnacles, worms, and other biological entities attach themselves to the surfaces of marine structures, further contributing to degradation and corrosion.

Corrosion of steel sheet piles is primarily driven by moisture, oxygen, and chlorides (salt from seawater). Moisture acts as an electrolyte, facilitating electron movement between the anode and cathode, which is crucial for corrosion. Steel piles exposed to air generally corrode at slower rates than those in wetter environments. Oxygen accelerates corrosion by promoting the cathodic reaction when moisture is present. In marine environments, chlorides increase water's electrical conductivity, speeding up corrosion and making it progress more quickly. (North American Steel Sheet Piling Association .n.d).

According to ArcelorMittal Sheet Piling (2016), Corrosion is a natural electrochemical process where iron atoms in steel react with environmental elements like oxygen and moisture, forming iron oxide, or rust. This reaction gradually deteriorates the metal, weakening its structure and compromising its integrity over time. The following **Eq. 1** shows how corrosion is formed:

$$4Fe + 3O_2 + 6H_2O \rightarrow 4Fe_2OH_3 \qquad \textbf{Eq. 1}$$

Therefore, the coating layer in the steel sheet pile prevents the above chemical reactions by splitting the steel surface from the electrolyte (water) by forming a barrier that reduces the transfer of reactions between the steel and water. (ArcelorMittal Sheet Piling 2016)

Alcántara *et al.* (2017) stated that the anodic reaction, consisting of the oxidation of the metal, can be given in **Eq. 2** as

$$Fe \rightarrow Fe^{2+} + 2e^- \qquad \textbf{Eq. 2}$$

Oxygen (O_2), which is highly soluble in aqueous layers, is a possible electron acceptor. Oxygen reduction in neutral or basic media occurs according to the reaction shown in **Eq. 3**.

$$O_2 + 2H_2O + 4e \rightarrow 4OH^- \qquad \textbf{Eq. 3}$$

During corrosion, hydroxide ions move to the anodic areas, where they react with iron to form ferrous hydroxide [$Fe(OH)_2$], the initial corrosion product. The corrosion rate is largely influenced by oxygen diffusion through the aqueous adlayer, a thin layer of water on the metal surface. The corrosion rate is highest when the adlayer has an intermediate thickness, as this allows for optimal oxygen diffusion. If the adlayer is too thin or too thick, oxygen diffusion is less efficient, leading to a slower corrosion rate. (Alcántara *et al.* 2017).

The corrosion of marine environments is usually influenced by temperature and chlorides. An increase in temperature leads to an increase in the rate of chemical reactions and then to an increase in the corrosion rate. Seawater contains chlorides, mainly sodium chloride (more than 90% of the salt), accompanied by calcium and magnesium chlorides, which lead to increased corrosion rates. (Hilti Corporation 2015).

The life span of a steel sheet piling structure depends on the natural process of corrosion. Corrosion is the reaction of steel with oxygen and the associated formation of iron oxide. Therefore, continuous weakening of the sheet-pling cross-section, which is necessary for the stability of the wall, occurs over several years. This weakening must be considered when analysing the serviceability and the ultimate load capacity (Grabe.2008).

According to Vashi (2009), the corrosiveness of a marine environment depends on the topography of the shore, wave action at the surf line, prevailing winds, and relative humidity. The corrosiveness decreased rapidly with increasing distance from the shore.

According to Yáñez-Godoy *et al.* (2018), Corrosion gradually reduces the geometric properties of steel sheet piles, making the material more flexible. This results in a decrease in the bending moment, especially on the seaside of the wall. After 50 years of exposure in a marine environment, the reduction in bending moment can be as much as 15%, weakening the structural integrity of the wall and potentially compromising its overall performance.

The modelling performed by Yáñez-Godoy *et al.* (2018) revealed that the long-term corrosion of steel structures in marine environments poses a significant challenge for assessing safety and optimizing maintenance strategies. The corrosion process is complex, influenced by factors like the environment, material properties, and the type and use of the structure. To accurately perform structural analyses, these factors must be carefully characterized and modelled, particularly to account for the gradual loss of steel thickness over time.

Yáñez-Godoy *et al.* (2018) used a gamma probability distribution to model corrosion variability. The authors also revealed that this corrosion probabilistic modelling provides the best estimation of real-life situations. According to Yáñez-Godoy *et al.* (2018), A statistical analysis of empirical data for each exposure zone enabled the adjustment of the evolution of mean thickness loss and standard deviation using the least squares method **(Figures 2.8 – 2.9).** Consistent with existing literature, the average thickness loss is highest in the low seawater level zone due to differential aeration, where the tidal zone is well oxygenated, while the immersion zone experiences less oxygen. The corrosion model's distribution of thickness loss after 25 years of exposure is shown in **Figure 2.10**.

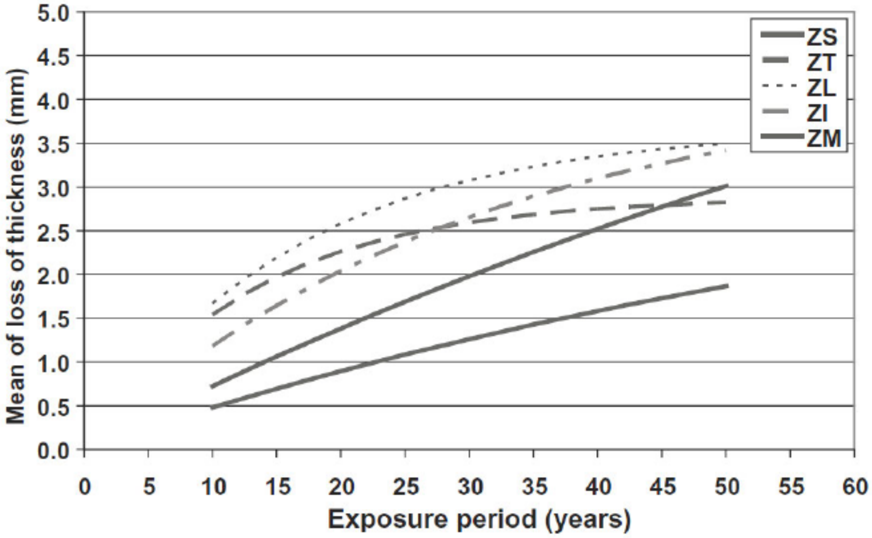

Figure 2.8: Temporal evolution of mean loss of thickness.

Source: Yáñez-Godoy *et al.*, 2018

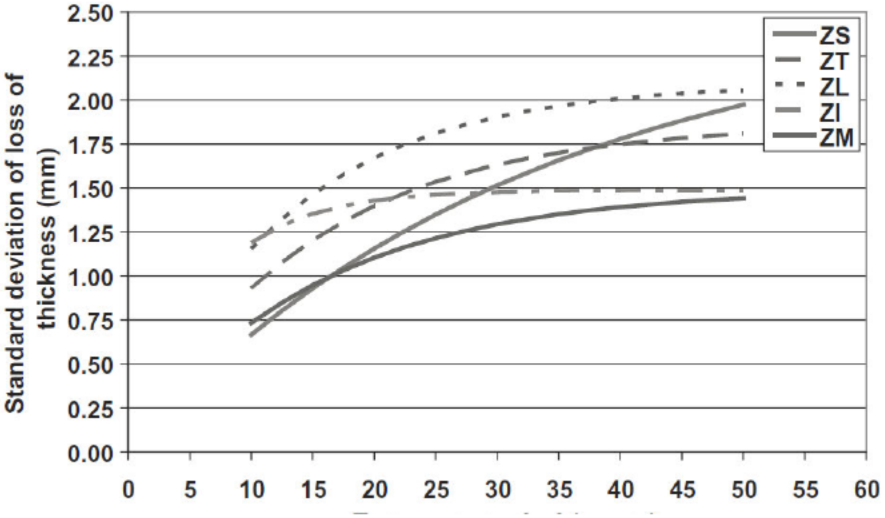

Figure 2.9: Temporal evolution of the standard deviation of the loss of thickness.

Source: Yáñez-Godoy *et al.*, 2018

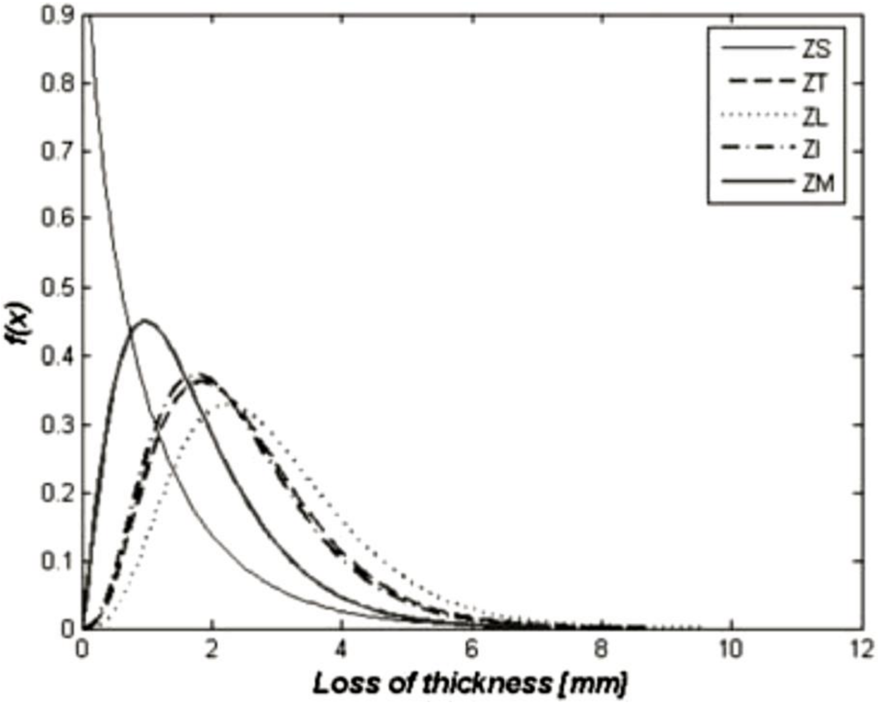

Figure 2.10: Gamma distributions of loss of thickness over several exposure zones for t = 25 years. *(Legend: ZS = Splash zone; ZT = tide zone; ZL = Low seawater level zone; ZI = Immersion zone; ZM = Mud zone)*

Source:Yáñez-Godoy *et al.*, 2018

According to Brouillette and Hanna (1960), the highest corrosion of steel sheet piles occurs at the splash zone, approximately 0.6 meters below the mean low water (MLW) level. Most of the corrosion also occurred on steel sheet pile structures that did not have protective coatings. Coating a steel sheet pile fully before installation increases the life span.

Steel sheet pile-wall corrosion in soils and water is a complex phenomenon. The deterioration of these structures is costly and very difficult to predict. Care should be taken to ensure that maximum bending moments do not occur at the same level as in the main corrosion zones (Benamar & Habib .2018).

2.7. Corrosion rate measurement

Wu *et al*. (2016) developed a marine corrosion simulation and acceleration test device to study the corrosion behavior of Q235 carbon steel in various marine zones, comparing indoor corrosion performance with outdoor exposure tests. The results from the 10-day simulation and acceleration tests revealed the following corrosion rates for Q235 carbon steel in different marine zones: immersion zone = 0.21 mm/a, tidal zone = 0.24 mm/a, splash zone = 0.28 mm/a, and atmospheric zone = 0.025 mm/a. The primary corrosion products identified were α-FeOOH, γ-FeOOH, Fe_3O_4, $Fe(OH)_3$, $Fe_8(OOH)_{16}Cl_{1.3}$, and Fe_2O_3. Among all the marine zones, the splash zone samples exhibited the highest corrosion rate, as indicated by weight loss, polarization curves, and the lowest charge-transfer resistance in electrochemical impedance spectroscopy (EIS) measurements.

Furthermore, after the tests were conducted, results were analysed and the graphs (**Figure 2.11 and Figure 2.12**) were developed. It is shown that most corrosion occurs in the splash zone.

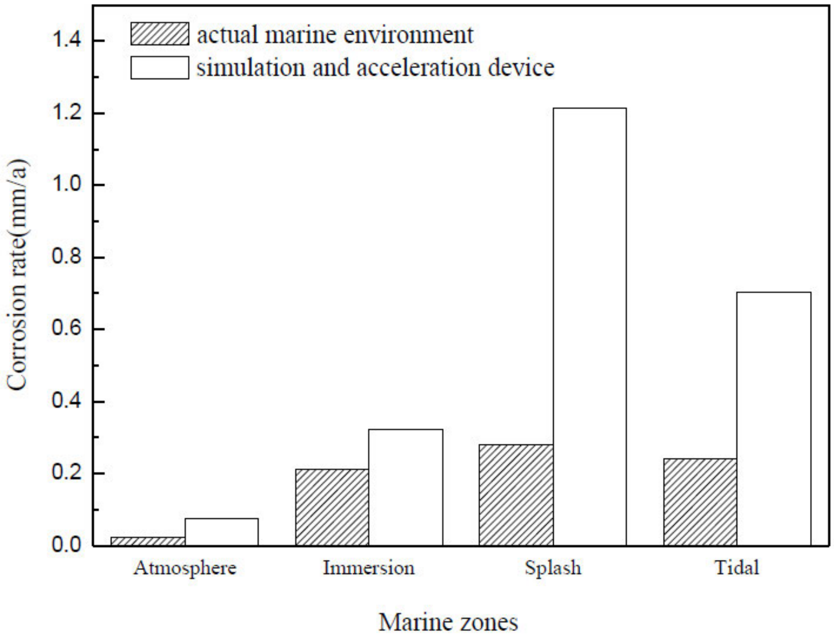

Figure 2.11: Corrosion rates of the specimens in the actual marine environment of Qingdao and in the simulation and acceleration devices

Source: Wu et *al*. 2016

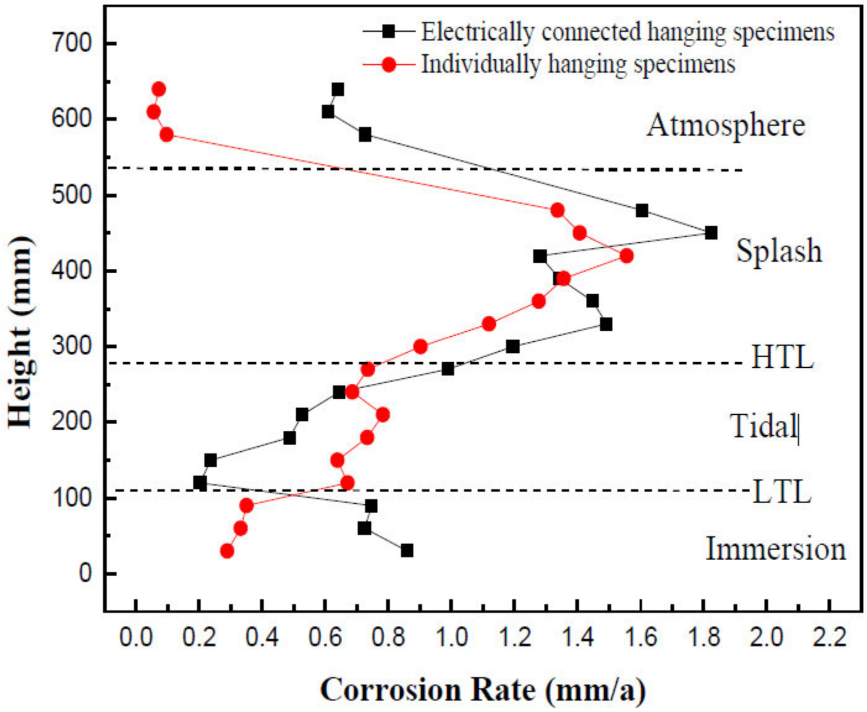

Figure 2.12: Corrosion rate curves of Q235 carbon steel exposed in the simulation and acceleration test device for 10 days

Source: Wu et al. 2016

As far as Bethencourt *et al.* (2007) are concerned, in marine environments, steel structures are susceptible to six main types of deterioration: corrosion, abrasion, loosening of structural connections, fatigue, overloading, and loss of original material. Among these, corrosion is the primary cause of degradation, significantly affecting the durability and performance of steel structures exposed to seawater and harsh environmental conditions.

Furthermore, Dantas et al. (2024) stated that marine environments involve several exposed zones with different aggressiveness, and the corrosion performance of marine steel sheet pile structures in each zone requires separate attention. Therefore, the corrosion rate of the steel sheet pile surface is typically different for each zone. The average corrosion rate profiles of steel sheet piles in most marine environments are shown in **Figure 2.13**.

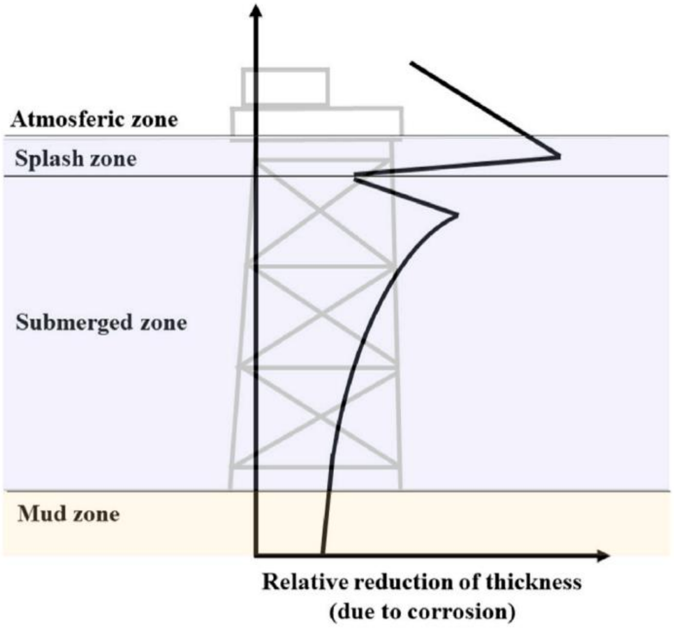

Figure 2.13: Marine environment zones and variations in corrosion attack between zones

Source: Dantas et al. (2024)

ArcelorMittal (2016) stated that durability has been a challenge that manufacturers have been addressing for some time. They achieved this by conducting surveys at various ports through official agencies and publishing the corrosion rate data.

Furthermore, ArcelorMittal (2016) stated that the main challenge was to develop a micro-alloyed steel that could perform better in the different areas typically exposed to harsh conditions on maritime quay walls. Over an extended period, a wide range of steel grades were tested across various ports. Numerous laboratory experiments were carried out to assess the impact of different parameters. In parallel, trials with steel plates and rolling mills were conducted to refine the production process for this specialized steel. These efforts led to the development of the low-coarse steel grade AMLoCor. In-situ tests demonstrated that AMLoCor experienced a reduction in steel thickness loss by a factor of 3 to 5, depending on the exposure zone.

Figure 2.14 compares the corrosion rates in seawater between carbon steel and AMLoCor. It shows that there is a huge difference between the low water zone and

Permanent immersion zone. From the tidal zone to the atmospheric zone, there is a slight difference between the two types of steel.

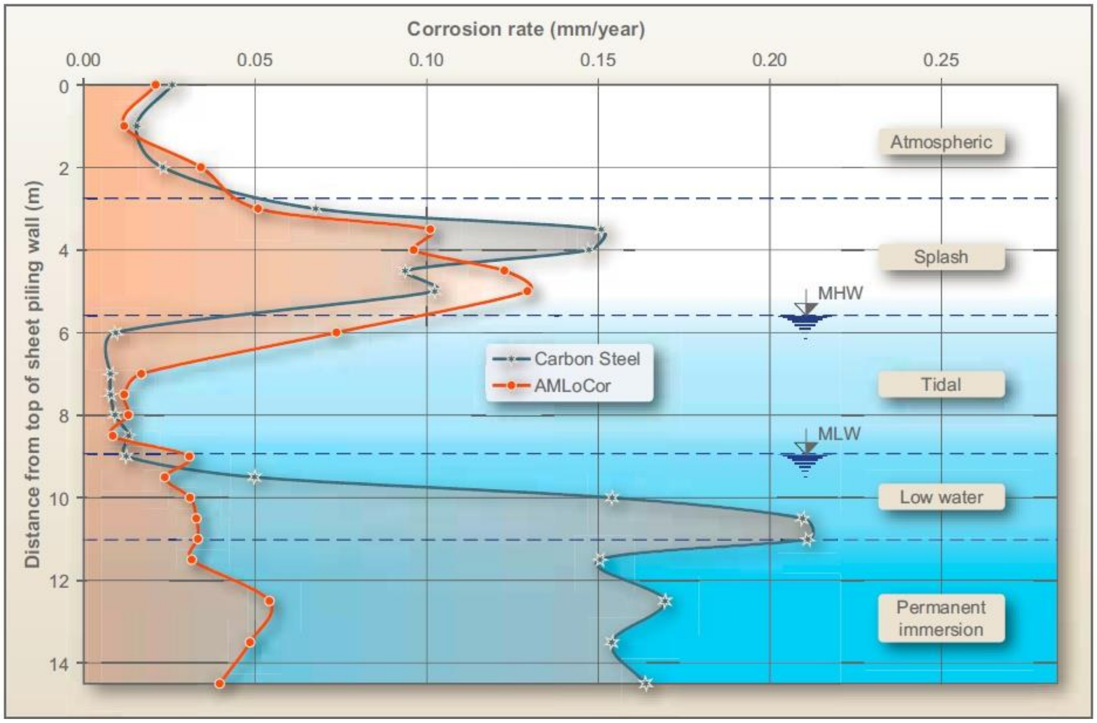

Figure 2.14: Corrosion rate measurement in northern European ports.

Source: ArcelorMittal, 2016.

ArcelorMittal (2019) stated that the primary benefit of AMLoCor is its substantial reduction in corrosion rates in both the Low Water Zone (LWZ) and the Permanent Immersion Zone (PIZ). These zones are typically where bending moments occur, resulting in the highest steel stresses. The steel grade offers a solution to the key challenges faced by designers and port authorities, particularly concerning the longevity of marine structures like quay walls, breakwaters, and jetties.

Figure 2.15 Illustrates a cross-sectional view of a steel sheet pile in a marine environment, proving the comparisons of AMLoCor and carbon steel as well as the location where the maximum bending moment occurs.

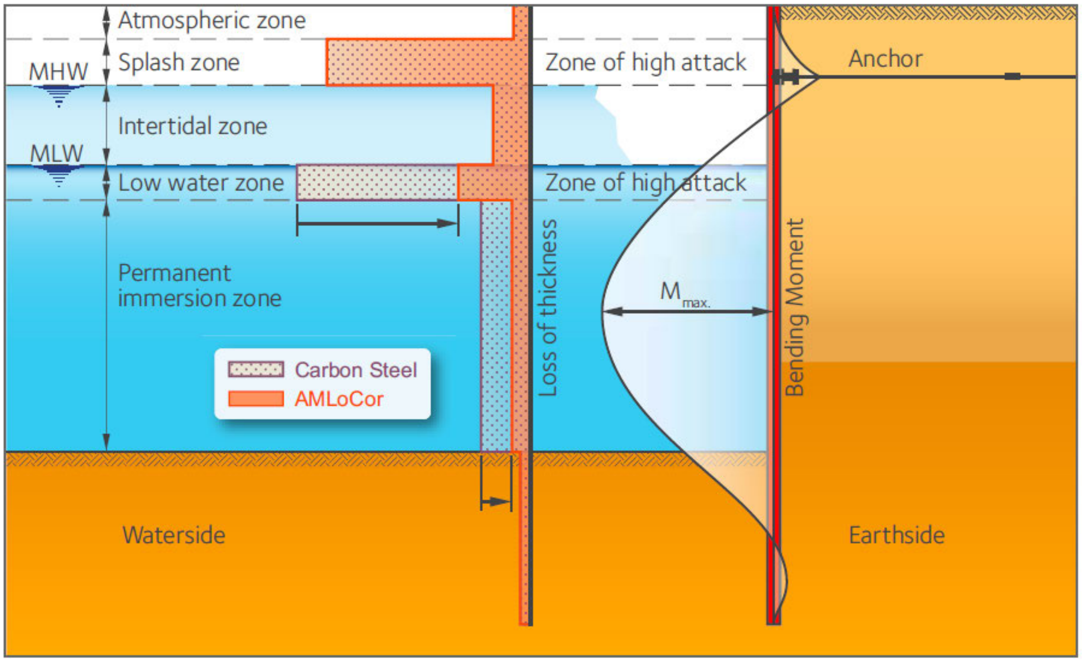

Figure 2.15: Corrosion rate measurement in northern European ports.

Source: ArcelorMittal. 2019

Wall and Wadsö (2013) stated that understanding the corrosion rate is essential for assessing the remaining load-bearing capacity and predicting the service life of existing structures. One approach to determining the corrosion rate at a specific site is by measuring the remaining thickness of materials on the structures. By knowing the original dimensions of the sheet piles and their installation year, the average corrosion rate can be calculated. Understanding this rate in individual harbours provides both economic and environmental benefits, as it enables the optimization of structural maintenance based on the actual material loss.

Wall and Wadsö (2013) also stated that when examining existing steel sheet structures, the corrosion rate is typically measured uniformly over a specific area. However, this approach oversimplifies the actual corrosion process, as localized pit corrosion often occurs in small, concentrated areas. Pit corrosion can lead to inaccurate measurements when using standard ultrasonic gauges to assess steel thickness. Protective measures such as concrete encasement and cathodic protection are common strategies for combating corrosion (RPI Construction Equipment 2022).

Bethencourt *et al.* (2007) mentioned that in ultrasonic inspection, thickness measurements are taken because certain ultrasonic waves travel at a constant speed through a material in straight lines. When these waves encounter an interface, a portion of the wave is reflected back. The time difference between the detection of echoes from the front and back surfaces is used to calculate the thickness of the material. This method relies on accurately measuring the travel time of the waves to assess material thickness. In this work, a Handheld Multiple Echo Ultrasonic Thickness Gauge Cygnus 1 Underwater has been employed, **Figure 2.15**. This is a digital ultrasonic thickness gauge designed for underwater use, capable of measuring the thickness of metals to assess corrosion or material loss, all without the need to remove surface coatings.

The data required was collected by utilising the Patent System, shown in **Figure 2.16**. This system comprises housing stems manufactured from stainless steel (AISI 316) and designed to operate underwater up to one hundred metres. Such a system is permitted to visualise the values of the measurements (pH electrode of flat surface model HI 1001 of Hanna Instruments, connected to a field pH mete, model HI 9025 of Hanna, and specific reference electrode Ag/AgCl (+0.262 V vs. SHE) for the determination of potentials in seawater, connected to a high impedance digital multi-meter Mastech 890G) (Bethencourt *et al.* 2007).

Figure 2.16: Monitoring the corrosion of steel-sheet piles using ultrasound and corrosion potential measurements

Source: Bethencourt et al. (2007).

Shen et al. (2023) maintains that several techniques, such as electrochemical sensing technology, visual inspection, and weight loss measurement, have been employed to measure corrosion rates in marine environments. While straightforward, these techniques may lack precision and can be labour intensive. The obtained results were used to calculate corrosion rate using **Eq. 4**.

$$i_{corr} = (T_o - T_a)/t \qquad \textbf{Eq. 4}$$

where (T_o) is the original thickness, (T_a) is the current thickness, and (t) is the exposure time in years (yr).

UT necessitates the removal of concretions and significant surface preparation of the steel sheet pile hull, including cleaning and grinding the steel to achieve the smoothest possible surface before taking measurements. However, when preparing the steel surface, there may be areas where UT readings are unreliable due to unevenness caused by corrosion on the steel surface (Russell *et al*. 2006).

Solorzano (2018) described another mechanism to clean the sheet pile surface measurement point where an air needle powered by a compressor was used to remove marine growth and corrosion at each measurement point. Such cleaning was performed in circles not more than 100 mm in diameter, as indicated in **Figures 2.17** and **2.18**, respectively.

Therefore, the thickness of steel sheet piles was measured using ultrasonic equipment (UT) with a nominal frequency of 5 MHz and a straight ½ in. diameter underwater transducer with a 15m cable so that the measuring device could be located at the upper part of the cell all the time. **Figure 2.19** shows how the measurements were conducted using the underwater ultrasonic equipment.

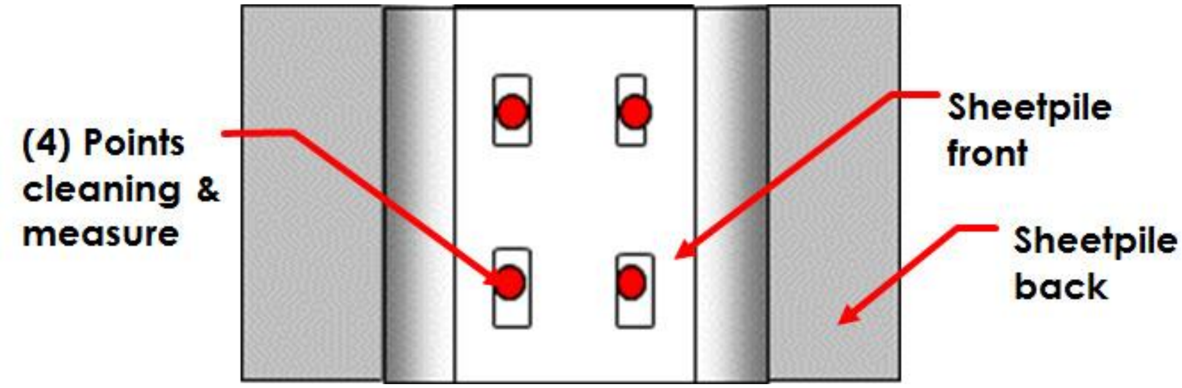

Figure 2.17: Scheme of point measurements at each elevation

Source: Solorzano (2018)

Figure 2.18: Underwater cleaning at the measurement points
Source: Solorzano (2018)

Figure 2.19: Underwater thickness measurement with an ultrasonic sensor
Source: Solorzano (2018)

Wey (n.d.) stated that the corrosion rate was uniform throughout the entire length of the sheet pile, and a 10% additional allowance of steel in the section of the member could provide an expected life span of approximately 40 to 50 years. In many areas, the 10 percent has been increased to 20%. Therefore, all types of steel piles exhibited the same corrosion rate and the same corrosion.

Therefore, when designing steel sheet piles, corrosion rates should be considered. The thickness loss was measured at 0.02 mm per year at locations where marine conditions could impact the structure's performance. For a sheet pile in seawater with a design life of 50 years, the recommended corrosion thickness loss values are as follows: 3.75 mm for areas exposed to seawater in the low water and splash zones, and 1.75 mm for areas in permanent immersion or the intertidal zone (European Standard EN1993-5 7. 2007).

2.8. Steel-sheet-pile corrosion protection

Corrosion protection of steel sheet piles differs depending on the exposed environment and other influencing factors. Methods of corrosion protection include the application of inhibitors, surface treatments, coatings, and sealants, as well as cathodic protection and anode protection (Malu n.d.)

According to Alocit systems (2014), coating layers on steel sheet piles increase the life span of a sheet pile by +/- 10 years. Since the maintenance of steel sheet pile structures is costly and is not easy to perform underwater, the application of a protective coating layer can be performed underwater as part of maintenance to increase the life of the sheet pile structures. Before the protective coating is applied to an underwater steel sheet pile, the rust must be removed by hydroblasting. Once the surface is free of rust, the coating can be applied using a power brush or hand brush.

Genin (2023) explained that protecting steel structures in marine environments involves a range of measures, such as (organic) coatings, corrosion allowances to reduce corrosion loss, and cathodic protection systems, such as galvanic anode cathodic protection (GACP) and impressed current cathodic protection (ICCP). Furthermore, cathodic protection mitigates the high cost of steel and other alloys corroded in seawater (Googan 2022).

Malu n.d. (2020) explained the types of coatings used for underwater piles as follows:

- **Inorganic Zinc Silicate Primers:** This coating serves as an anodic layer for steel structures submerged in seawater, helping halt rust progression. It offers high heat resistance and protection against chemical spills.
- **Epoxy Coatings (High Build):** Compared with primers and topcoats, epoxy coatings provide superior chemical and abrasion resistance. They protect not only the substrate but also the zinc primer from various harmful factors. However, these coatings have limited resistance to UV rays, which can lead to erosion and reduce the protective barrier.
- **Epoxy Primers (Zinc Rich):** Zinc-modified epoxy anti-corrosives offer excellent performance and are resistant to various weather conditions, making them effective in preserving damaged areas.
- **Aliphatic Polyurethane Topcoats:** These coatings provide excellent UV resistance, flexibility, and chemical durability. They maintain a high level of gloss and colour retention and are easy to clean. Although they do not offer significant anticorrosive or barrier protection, they greatly enhance the overall integrity of coating systems.
- **Non-Skid Deck Coating:** Designed to have anti-slip properties, these coatings incorporate coarse aggregates and are typically applied in thick layers, often without a zinc-rich primer.
- **Cathodic Protection (CP):** This technique is widely used to reduce marine corrosion by electrochemical reactions to protect steel structures. A protective circuit is created between the anode, steel (cathode), seawater (electrolyte), and power supply.

Concentrated corrosion and salt-induced corrosion are common occurrences in marine environments around the world. To prevent concentrated corrosion, cathodic protection is essential, while both coatings and cathodic protection are required to safeguard against salt-induced corrosion (Zen. 2005).

2.9. Maintenance of the underwater steel sheet pile (Asset)

Asset maintenance management is a key function of the TNPA, with accountability resting with the Port Engineering Department. This responsibility includes overseeing the budget for the maintenance of port infrastructure assets (Transnet National Ports Authority.2010).

All asset categories should be assessed regularly based on established criteria to determine their overall condition. These criteria should address factors such as safety and legal compliance, the asset's strategic importance to the business, its value, operational impact, and the time required for repairs. Each asset should be evaluated to define what constitutes "Satisfactory Condition" for that specific asset, ensuring it is maintained at an optimal level for the business neither over-maintained nor under-maintained (Transnet National Ports Authority.2010)

Pellny (1936) also stated that the maintenance of underwater steel sheet piles is very costly and difficult. It is recommended to over design or use thicker sections of the sheet pile to delay the service life of the structure as long as possible.

To prevent the need for large-scale rehabilitation due to neglecting periodic maintenance, systematic planning and budgeting of maintenance activities are essential. Lifecycle management (LCM), along with whole life costing (WLC), provides a realistic framework for developing maintenance policies (Zen. 2005).

2.10. Chapter conclusion

This chapter provided an overview of the Port of Durban and its existing infrastructure. The chapter also included previous studies conducted on steel sheet pile walls around the world and the methodologies used to conduct these studies. For the Port of Durban to be able to manage the underwater steel infrastructure, it is recommended that a study on the corrosion rate be conducted.

CHAPTER 3

MATERIALS, EQUIPMENT AND METHODOLOGY

3.1. Introduction

This chapter describes the materials and equipment used in the study, as well as the methodology employed to investigate corrosion in existing steel sheet piles. It covers both the theoretical and practical approaches used during the investigations.

The investigation was carried out in Island View Berth 3 and Maydon Wharf Berth 12 situated in different precincts in the Port of Durban. The two Berths were examined to assess the remaining steel thickness of the sheet pile walls submerged in seawater. Island View Berth 3 accommodates vessels transporting dry bulk products, primarily mainly agricultural goods, while the Maydon Wharf Berth 12 handles a variety of containerised, break-bulk, and bulk cargo, specialising in specific commodities (ArcelorMittal, 2019).

Island View Berth 3 was built in 1993 with two dolphins supported by concrete piles. Underneath the quay wall, a BZ-7 steel sheet pile wall serves as a support structure against soil erosion. The original thickness of the existing steel sheet pile was 8 mm.

Maydon Wharf Berth 12 reconstructed in 2012 incorporate a combination of HZ and AZ18-700 steel sheet pile walls with an original thickness of 9 mm, excluding any protective steel coating (PRDW 2012). Divers conducted underwater inspections to confirm the sheet pile types and obtain steel thickness readings.

Figures 3.1 and **3.2** show the layout plans of both Island View Berth 3 and Maydon Wharf Berth 12, respectively, where the steel thickness of the existing sheet piles was measured to assess the corrosion rate.

Figure 3.1: Island View Berth 3 Layout Plan

Source: Port of Durban Aerial Photo (2020)

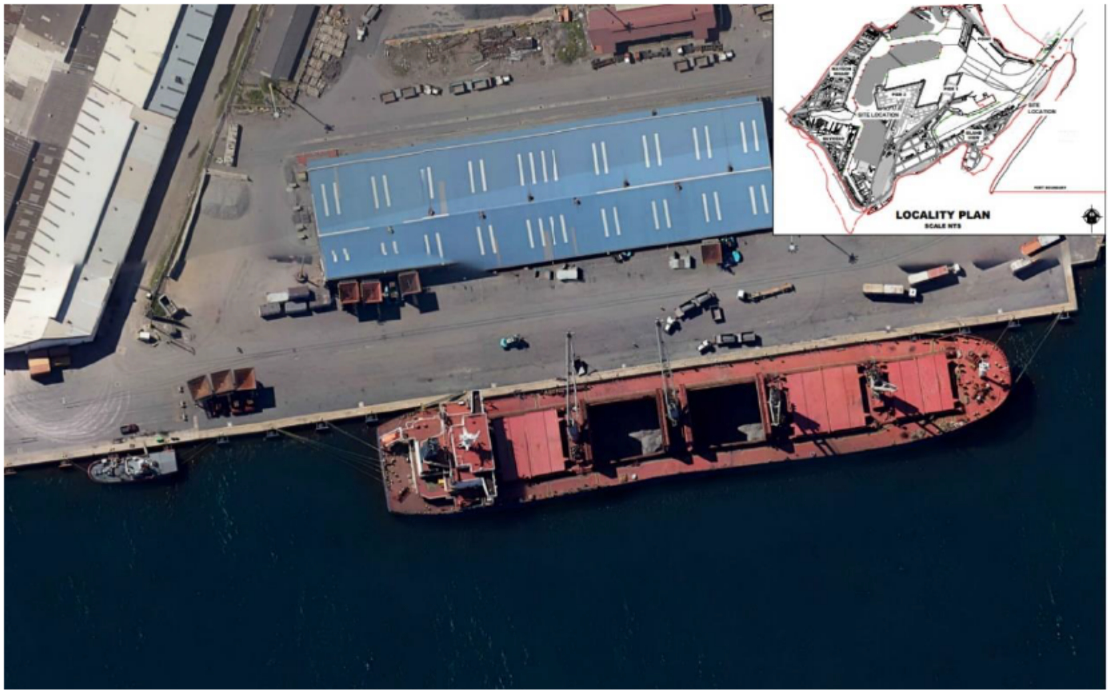

Figure 3.2: Maydon Wharf Berth 12 site layout plan

Source: Port of Durban Aerial Photo (2020)

3.2. Research design

The research approach adopted is quantitative, where the collection and analysis of data for the research involved visual assessment, sampling, and physical measurement of steel sheet pile thickness. The phases of the study are as follows:

- Data Collection
- Calculations and Simulations
- Analysis, discussion, and findings
- Recommendations and conclusions

To achieve the objective of the study, the following methodological approach was adopted:

- Measurement of the remaining thickness of the steel sheet pile
- Testing of the chlorine level
- Calculation of the corrosion rate of the steel sheet pile

3.3. Corrosion rate data collection

3.3.1 Steel sheet pile measurements

The divers were deployed under sea water to take samples or record the condition of the existing sheet pile wall and to measure the remaining thickness of the sheet pile wall. Prior to measuring the dimensions of the existing sheet piles with a tape measure, the divers conducted inspections to identify and record all visible defects on the steel sheet piles. The measurements taken were to determine the depth and width of the existing sheet pile wall in both Island View Berth 3 and Maydon Wharf Berth 12.

Prior to measuring the steel thickness of the sheet piles, an investigation was conducted to determine whether both berths exhibited all five corrosion zones: atmospheric zone, splash zone, tidal zone, low water zone, and permanent immersion zone. **Figure 3.3** shows these marine zones.

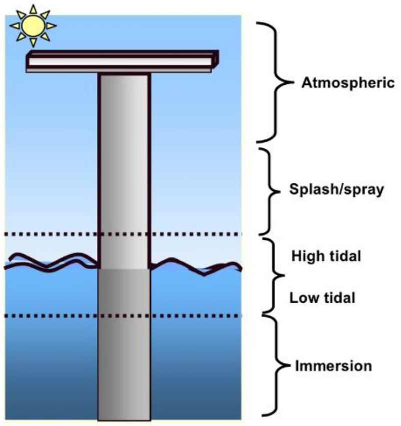

Figure 3.3: Marine zones around the metallic pile in the harbour structure

Source: Farro et al (2009)

During the preparation of measuring the steel thickness, 20 inspection positions were cleaned using chipping hammers and wire brushes over the 273 m X 8.5 m surface area of the sheet pile at Island View Berth 3. A surface area of 200 mm X 200 mm per position was cleaned from marine growth and prepared for inspection and measurements. Cathodic protection was also inspected on the existing underwater steel sheet piles. **Figure 3.4** detail the cross section of Island View Berth 3, showing the position of steel sheet pile wall.

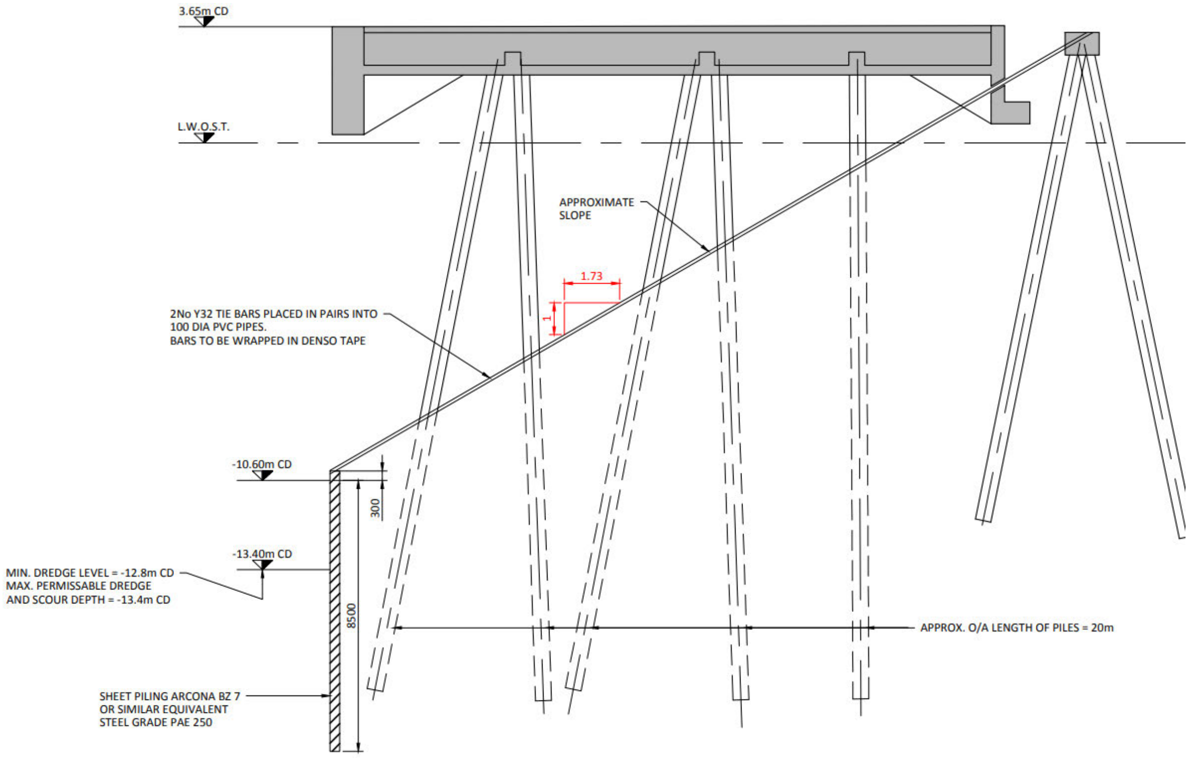

Figure 3.4: Cross section of the Island View Berth 3

Source: PRDW (2018)

Maydon Wharf Berth 12 is 230 m long with a design draft of 10.6 m below the CD. Twenty horizontal inspection points, each measuring 200 mm x 200 mm, were cleaned using chipping hammers and wire brushes along a 230 m length. The inspection points were 10 m apart, with five inspection points in each of the four zone: atmospheric zone, splash zone, tidal zone, and low water zone). An ultrasonic thickness (UT) gauge was used to measure the steel thickness of the sheet piles underwater in various zones, in order to determine the remaining steel on the existing structure (Kelly1999). The ultrasonic thickness gauge, shown in **Figures 3.5a** and **b**, were used to measure the thickness of the existing steel sheet piles.

Figure 3.5 a & b: Underwater Ultrasonic Thickness Gauge

Source: Tritex Sale (2013)

According to 3H Consulting (2016), the ultrasonic thickness gauge emits short pulses of high-frequency sound waves from a handheld probe in contact with the metal. It measures the time it takes for each sound pulse to travel through the material, reflect off the back wall of the material, and return to the probe.

Data obtained during inspection and measurements of the existing underwater sheet pile were recorded and analysed to determine the corrosion rates of the Island View Berth 3 and Maydon Wharf Berth 12 steel sheet piles.

3.3.2 Chloride sampling

Pile Buck (2023) asserts that saltwater is highly corrosive to steel, primarily due to the dissolved salts, particularly chloride ions. These ions can actively accelerate the corrosion of steel structures, speeding up the oxidation process that leads to rust. In marine environments, this can weaken steel sheet pilings, reducing their load-bearing capacity and shortening their lifespan.

The data was collected by sending divers to obtain water samples from both Island View Berth 3 and Maydon Wharf Berth 12. Two empty bottles were used to collect the water samples, which were then taken to the laboratory for chloride and pH testing. **Figure 3.6** shows the bottles containing seawater samples collected at the Port of Durban.

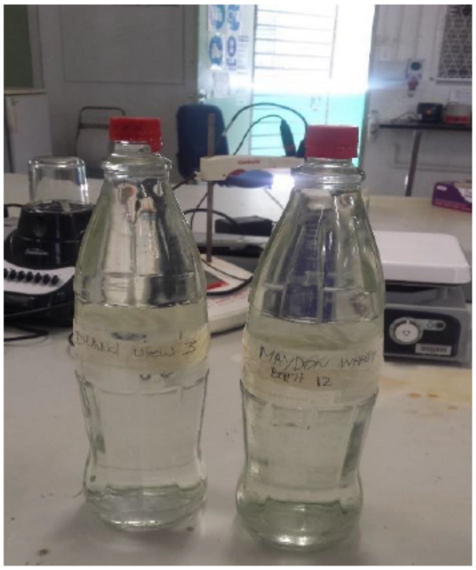

Figure 3.6: Seawater samples

Source: Image by the Researcher

These seawater samples were transported to a laboratory where their chloride content was measured using a Chloride Chequer® HC HI753, a handheld colorimeter. The chloride colorimeter (**Figure 3.7**) provides quick and accurate results.

Figure 3.7: Chloride Colorimeter

Source: Image by the Researcher

To determine the chloride content,1.0 mL of HI93755-01 chloride reagent (shown in **Figure 3.8**) was added to the seawater sample. After the reaction took place, a compatible photometer was used to determine the concentration based on the colour produced. The results were displayed in mg/L (ppm) of alkalinity, expressed as calcium carbonate (CaCO3).

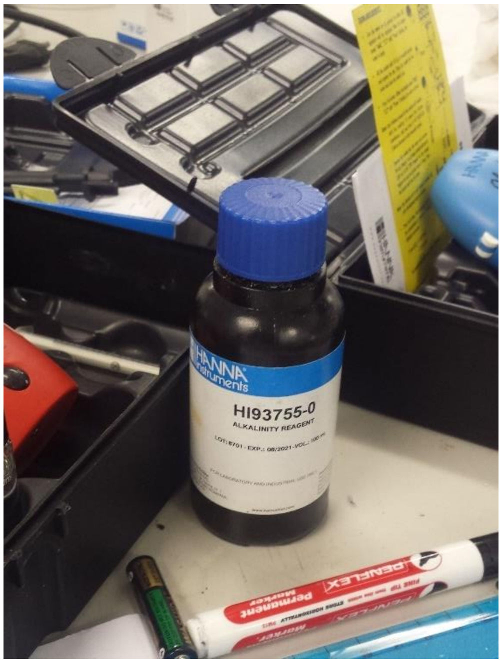

Figure 3.8: The HI93755-01 alkalinity reagent.

Source: Image by the Researcher

3.3.3 Measurements of pH

A Hanna HI 98129 pH Meter Instrument (**Figure 3.9**) was used to measure the hydrogen-ion levels in the seawater samples taken from Island View Berth 3 and Maydon Wharf Berth 12. The pH meter measures the acidity and alkalinity of seawater by measuring the voltage between two electrodes.

Figure 3.9: Hanna HI 98129 pH Instrument

Source: Image by the Researcher

Data obtained from chloride sampling and pH measurements were recorded and analysed to determine how chloride content and pH values contribute to the corrosion rate of the stee-sheet piles at Island View Berth 3 and Maydon Wharf Berth 12.

3.3.4 Calculation of corrosion rates

After collecting the required data, the corrosion rate (mm/year) was calculated using the following formula:

Metal loss = $T_o - T_a$, where (T_o is original thickness and T_a is actual thickness). The corrosion rate (icorr) is defined as the metal loss per unit of time: i_{corr} $(T_o – T_a)/t$ (Russell et al. 2006).

Once the speed of sound in the tested material was known, the remaining thickness of the sheet pile was calculated by multiplying the speed by half the total travel time. According to the British Standard 6349 (1:2000), there is a standard or assumed loss of steel thickness on sheet piles exposed in different zones in marine environments. **Table 3.1** lists the estimated minimum and maximum corrosion rates per corrosion zone.

Table 3.1: Typical rates of corrosion in structural steel (BS 6349-1:2000)

Exposure zone	Corrosion rate mm/side/year	
	Mean[a]	Upper limit[b]
Atmospheric zone: - above splash zone and where direct wave or spray impingement is uncommon	0.04	0.10
Splash zone: - above mean high water to a height depending on the mean wave height and exposure to wind	0.08	0.17
Tidal zone: - between mean high-water and mean low-water spring levels	0.04	0.10
Intertidal low-water zone: - between low-water spring and 0.5 m below the LAT	0.08	0.17
Continuous seawater immersion zones: - from 0.5 m below the LAT to seabed level	0.04	0.13
Below seabed level or in contact with soil		0.015 max
a) The rate for each face exposed to the environment of the zone. b) The upper limit figures are the 95 % probability values.		

To evaluate the corrosion rate of sheet piles in the Port of Durban, **Table 3.1** was used as a reference for comparing the calculated results.

3.4. Underwater assessment and measurements

3.4.1 Island View Berth 3

During the underwater investigations, divers located sheet piles in front of bollards 1, 2, 3, and 4 in both dolphins. No sheet piles were observed protruding above the water level. This was evidenced by underwater images taken at Island View Berth 3 (**Figure 3.10**), which showed sheet piles covered with marine growth.

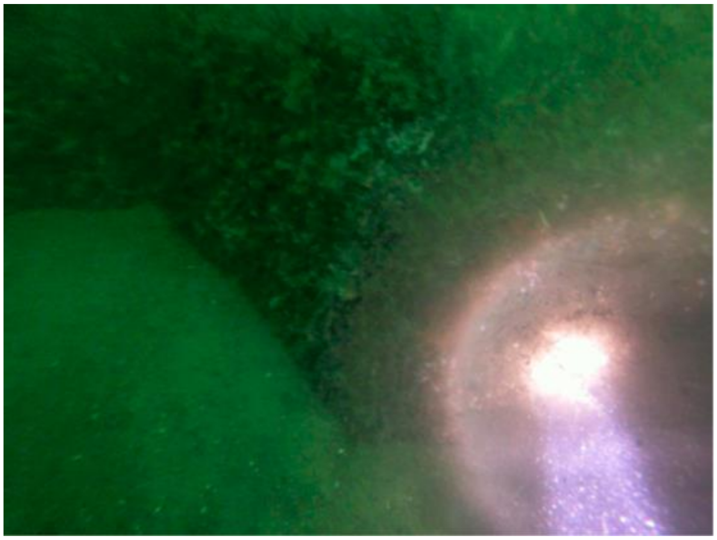

Figure 3.10: Images of a steel-sheet pile covered by marine growth

Source: Image by the Researcher

No mechanical damage or visible cracks were observed on the sheet pile walls. Upon inspection of the stee-sheet piles, no visible protective coating was detected.

The depth of the sheet piles was measured using measuring tape. Sheet piles were measured to be 0.8–1 m in height from the seabed to the top of the pile. This means that approximately 90% of the sheet piles were below seabed and approximately 10% were in the permanent immersion zones.

According to Bariler (1991), the existing steel sheet piles at Island View Berth 3 are ARBED BZ-7, installed in 1993 with an original steel thickness of 8 mm. **Figure3.11** shows a cross-section of the Berth and the position of the sheet pile that is completely underwater. The sheet piles are the major support for the quay wall as they serve as a wall behind the revetment and as a support to the concrete pile holding the quay wall infrastructure.

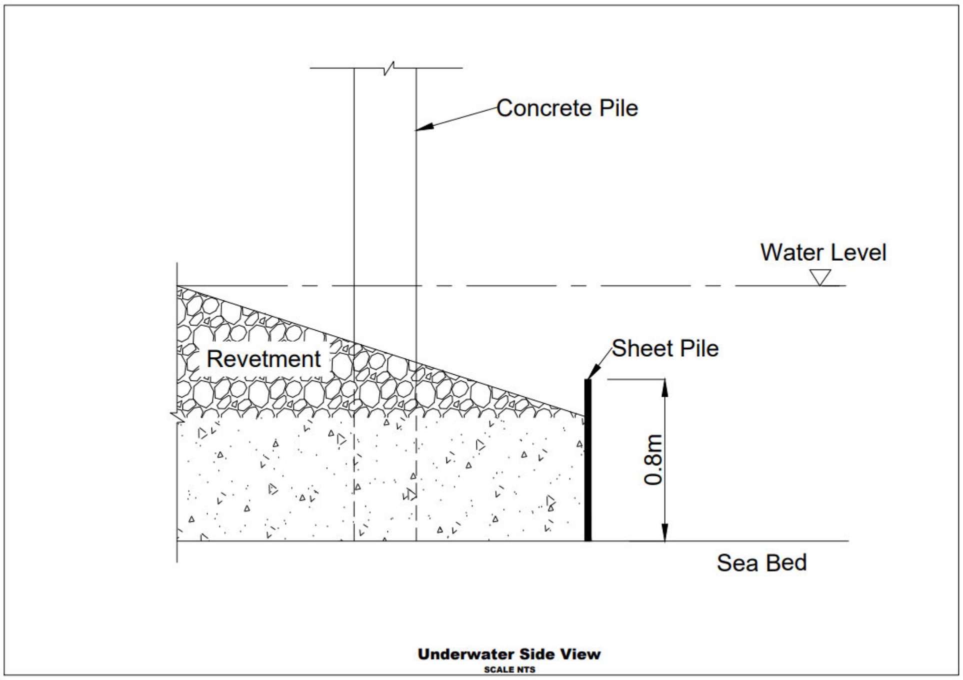

Figure 3.11: Cross-section of Island View Berth 3

Source: AutoCAD drawing by Researcher

3.4.2 Maydon Wharf Berth 12

Inspections were conducted in Maydon Wharf Berth 12, and sheet piles are located underwater, starting from bollard 119 to bollard 138. At Maydon Wharf Berth 12, measurements were taken on the sheet pile walls at depths of 4.5, 5.8, 8.5, and 10.5 m, starting from the water level and progressing towards the seabed. The cope beam served as a reference point for depth measurements, which were taken using measuring tape. The tape was lowered from the top of the quay to the seabed to mark the inspection points. **Figure 3.12** illustrate the top and front views of the sheet pile wall, showing the positions of these inspection points.

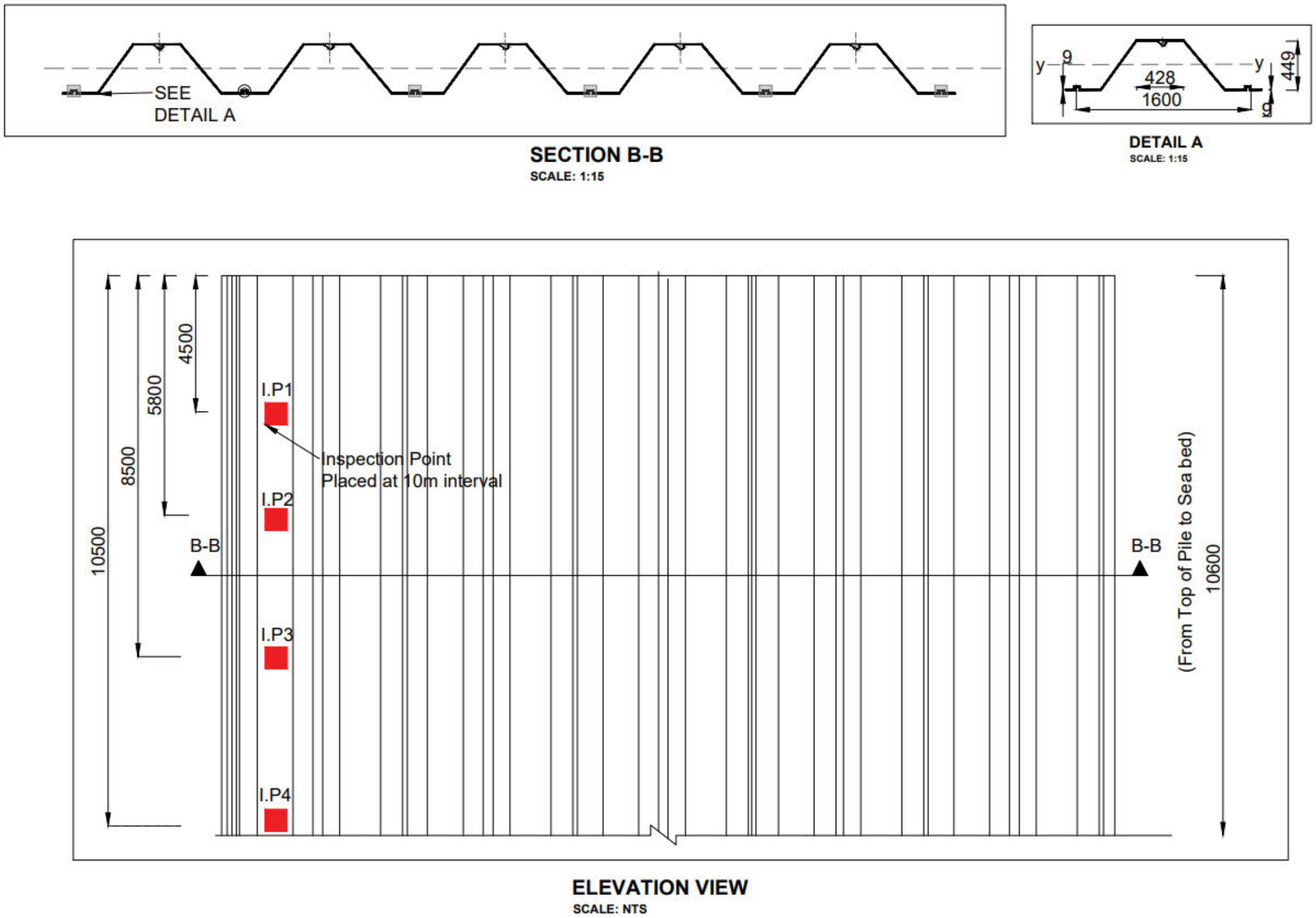

Figure 3.12: Inspection points on sheet liners

Source: AutoCAD Drawing by Researcher

3.5. Underwater Inspection and Cleaning of Sheet Pile Walls

During the inspections, a total of 42 points were examined: 22 at Island View Berth 3 and 20 at Maydon Wharf Berth 12. The inspection of Island View Berth 3 as conducted over a two-day period in January 2020, while Maydon Wharf Berth 12 was inspected over 14 days in November 2022. Water visibility was poor due to contaminated discharged from canals flowing into the harbour. Notably, inspections at Maydon Wharf Berth 12 were interrupted for over a year due to the suspension of diving activities at the Port of Durban, caused by sewer spillage from the city into the harbour.

Prior to taking measurements, divers cleaned sections of the sheet pile wall in 200mm x 200mm patches. Marine growth was manually removed using a combination of steel scrapers, hammers, and wire brushes. The cleaning process covered the area from the water's surface to the bottom of the sheet pile, with a particular focus on the outer flanges.

3.6. Chapter conclusion

This chapter outlined the methodology used in gathering data for the study, including the equipment used. The types of samples collected on site underwater and the samples tested in the laboratory were discussed. Furthermore, the chapter covered the sites from which the samples were collected and describes the formula used to calculate the corrosion rate of the existing steel sheet piles at the Port of Durban.

CHAPTER 4

DATA ANALYSIS AND FINDINGS

4.1. Introduction

This chapter presents the test results for steel sheet piles and water samples collected from the Port of Durban. It discusses and interprets the measurements of remaining steel thickness in the sheet piles, as well as the laboratory findings on chloride content and pH levels. All data were obtained through underwater measurement and laboratory experiments. The data collected for each berth is presented in the tables and figures, followed by an analysis of the corresponding information. Tables and figures display the collected data for each berth, followed by a comprehensive analysis of the results.

Tables 4.1, 4.2 and **4.3** present the inspection results, detailing the corrosion rates in mm/yr, based on the known ages of the inspected steel sheet piles. The figures display the average corrosion rates for each berth at the Port of Durban.

4.2. Environmental impact

4.2.1 Chloride content

The chloride content analysis, conducted using a Chloride Checker® HC HI753 colorimeter on water samples collected from both berths on the same day, revealed a chloride concentration of 13.8 mg/L at Island View Berth 3 and 7.1 mg/L at Maydon Wharf Berth 12, indicating a higher chloride presence at Island View Berth 3, which may contribute to an increased corrosion rate in that area.

4.2.2 Measurement of pH values

The pH analysis, conducted using a Hanna HI 98129 pH meter, indicated values of 6.75 for Island View Berth 3 and 7.34 for Maydon Wharf Berth 12, suggesting that the water at Island View Berth 3 is slightly more acidic, which could potentially influence the corrosion rate of steel sheet piles in that area.

4.2.3 Pollution

Steel pilings in the Port of Durban face physical challenges from floating debris originating from intersecting canals and surrounding streams or rivers. This debris, carried by currents, is more prevalent during stormy weather. At low tide, debris collides with sheet piles, causing physical damages and scratches. During the inspection of Island View Berth 3, areas were identified where corrosion had accelerated more rapidly due to physical impacts.

4.3. Data analysis and results

4.3.1. Measurements at Maydon Wharf Berth 12

Corrosion rates were measured 20 points accross four different heights (4.5 m, 5.8 m, 8.5 m, and 10.5 m) from the top of the pile to the seabed level. The scatter plots below illustrates the corrosion rates at each depth:

- At 4.5 m depth, the corrosion rate decreased with distance (slope = -1.94×10^{-3}) (**Figure 4.1**)
- At 5.8 m depth, the corrosion rate increased with distance (slope = 1.2×10^{-3}) (**Figure 4.2)**
- At 8.5 m depth, the corrosion rate decreased with distance (slope = -1.74×10^{-3}) (**Figure 4.3**)
- At 10.5 m depth, the corrosion rate decreased with distance (slope = -1.28×10^{-3}) (**Figure 4.4**).

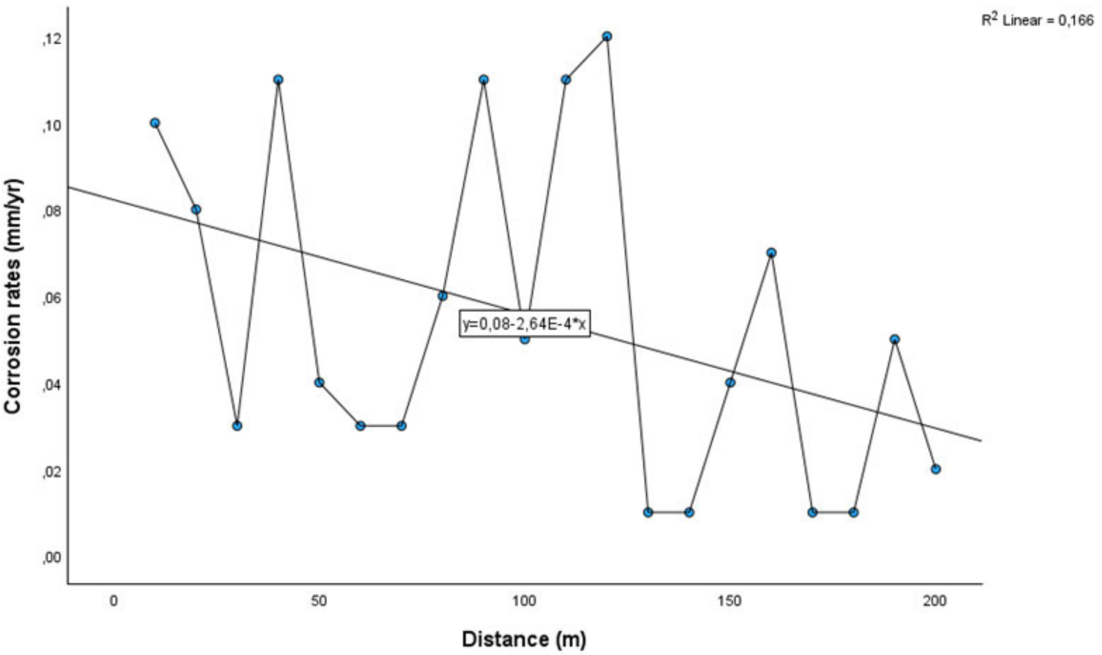

Figure 4.1: Corrosion rate measured horizontally at 4.5-m depth from the top of the pile.

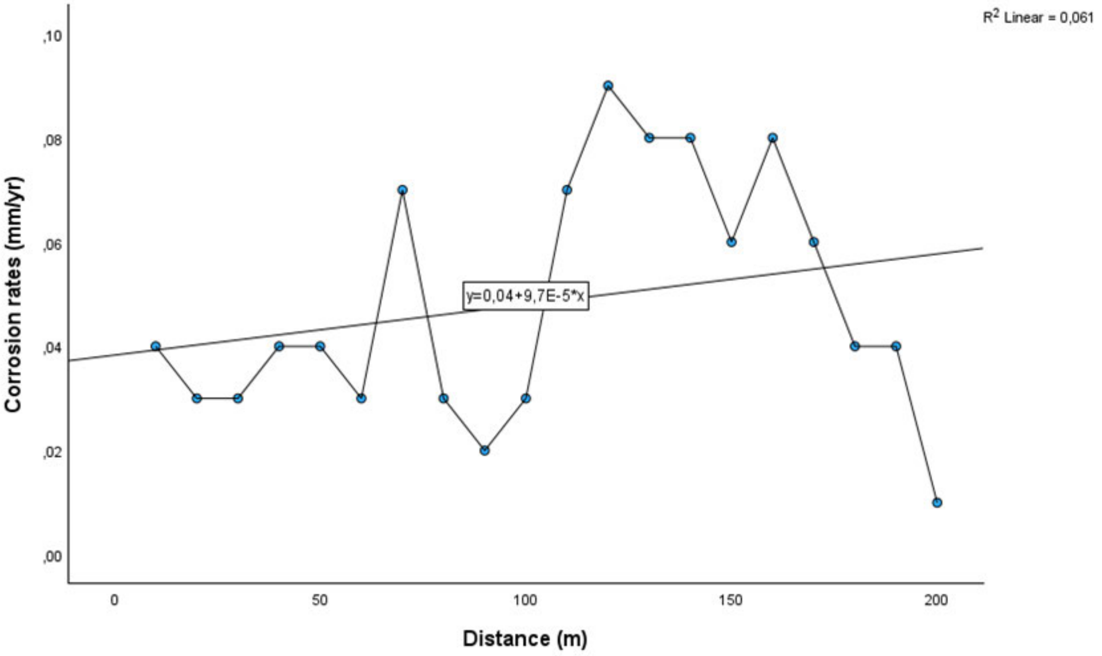

Figure 4.2: Corrosion rate measured horizontally at a depth of 5.8 m from the top of the pile.

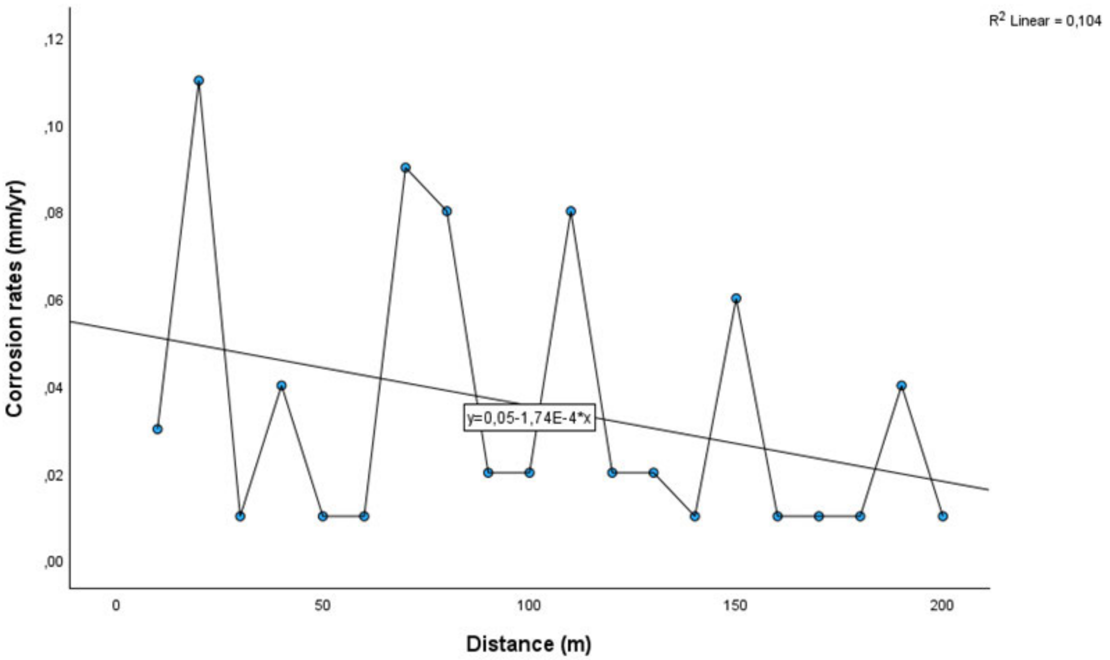

Figure 4.3: Corrosion rate measured horizontally at an 8.5-m depth from the top of the pile.

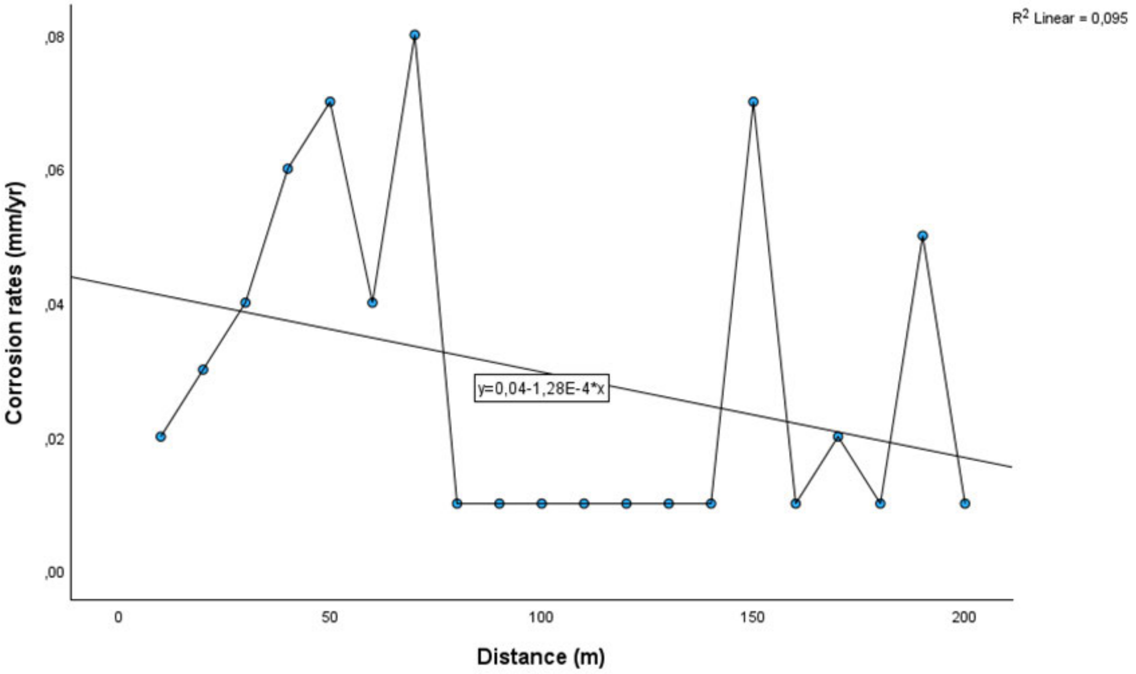

Figure 4.4: Corrosion rate measured horizontally at 10.5-m depth from the top of the pile.

4.3.1.1. Mean corrosion rate

Table 4.1 illustrate the mean corrosion rates at depths of 4.5, 5.8, 8.5, and 10.5 m from the top of the sheet pile to the seabed. The highest mean corrosion rate was observed at 4.5 m (0.0545 mm/yr), followed by 5.8 m (0.0485 mm/yr), 8.5 m (0.0345 mm/yr), and 10.5 m (0.0290 mm/yr). The overall mean corrosion rate across all depths was 0.0416 mm/yr.

The results indicated that corrosion rates decrease with depth, with the highest rate observed at 4.5 m (0.0545 mm/yr) and the lowest at 10.5 m (0.0290 mm/yr). This trend aligns with corrosion theories, which suggest that increased oxygen availability and environmental exposure at shallower depths accelerate the corrosion process. In contrast, lower oxygen levels at greater depths result in reduced corrosion rates. The overall mean corrosion rate of 0.0416 mm/yr is consistent with findings from previous studies, highlighting the influence of localized environmental factors on steel deterioration in marine conditions.

Table 4.1: Descriptive statistics

Distance from the top of the pile	N	Mean corrosion rate	Std. Deviation	95% Confidence Interval for Mean	
				Lower Bound	Upper Bound
4.5 m	20	0.0545	0.06680	0.0077	0.0703
5.8 m	20	0.0485	0.03242	0.0273	0.0577
8.5 m	20	0.0345	0.04175	0.0085	0.0475
10.5 m	20	0.0290	0.03784	0.0023	0.0377
Total	80	0.0416	0.04659	0.0220	0.0427

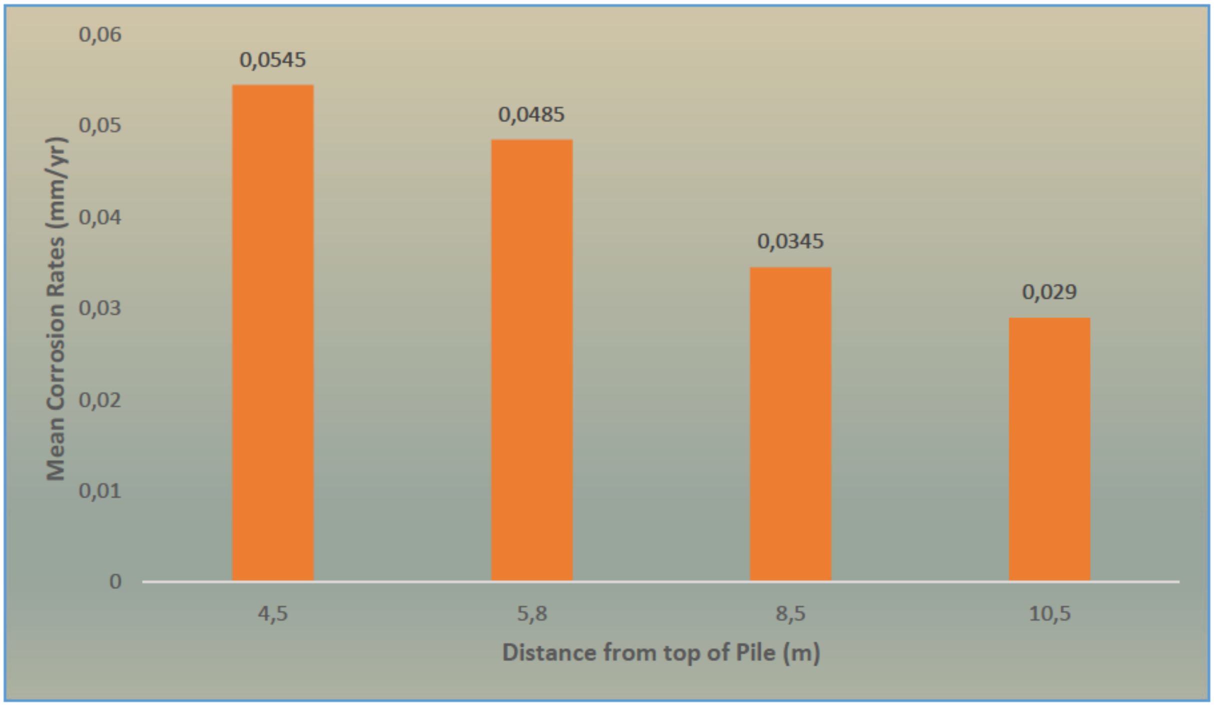

Figure 4.5: Average corrosion rate measured at different depths from the top of the pile to the seabed

4.3.1.2. Homogeneity of variances

The homogeneity of variances across the depths was assessed using Levene's test. The results, presented in **Table 4.2**, indicated that the variances were equal across all measured distances (Levene statistic = 0.754, p-value = 0.524).

Table 4.2: Tests of Homogeneity of Variances

		Levene Statistic	df1	df2	Sig.
Corrosion rates	Based on the Mean	0.754	3	76	0.524
	Based on the Median	0.754	3	76	0.523
	Based on median and adjusted df	0.754	3	47.052	0.526
	Based on the trimmed mean	0.800	3	76	0.498

4.3.1.3. Analysis of variance (ANOVA)

Analysis of Variance (ANOVA) was applied to the data to determine whether the mean corrosion rates between different distances were statistically significant or not. The ANOVA results presented in **Table 4.3** indicated that the mean corrosion rates were not statistically significant (F-value = 0.978, p-value = 0.408).

Table 4.3: ANOVA results

	Corrosion rates				
	Sum of Squares	**df**	**Mean Square**	**F**	**Sig.**
Between Groups	0.006	3	0.002	0.978	0.408
Within Groups	0.165	76	0.002		
Total	0.171	79			

4.3.2. Maydon Wharf Berth 12 observations

Based on the findings of this study, the following key observations regarding Maydon Wharf 12 were made:

1. The corrosion rate decreased as the distance from the pile top increased.
2. The highest mean corrosion rate was observed at 4.5 m depth (0.0545 mm/yr), suggesting that at this level the steel sheet piles may have been subjected to more aggressive corrosion factors.
3. The mean corrosion rates at the following depths demonstrated a declining trend as depth increased:
    - 5.8 m (0.0485 mm/yr)
    - 8.5 m (0.0345 mm/yr)
    - 10.5 m (0.0290 mm/yr)
4. The elevated corrosion rate at 4.5 m depth could be attributed to several factors, including increased exposure to seawater, heightened biological activity, and the specific environmental conditions such as temperature and salinity variations.

5. Understanding the corrosion rates at different depths is crucial for accurately predicting the longevity of sheet piles and determining appropriate maintenance required. Areas exhibiting high corrosion rates may necessitate more frequent inspections or additional protective measures.
6. The observed trend suggests that environmental conditions affecting corrosion become less severe with increasing depth, resulting in lower corrosion rates. This valuable information can inform the design of targeted interventions or the application of protective coatings, focusing on depths at which the sheet piles are most vulnerable with a view to enhance the overall durability of the structure.

4.3.3. Island View Berth 3 measurements

The corrosion rate was also measured horizontally at 10-along a 230-m stretch of Island View Berth 3. **Figure 4.6** summarises the recorded thickness revealing the significant variability in the remaining thickness of the sheet piles, ranging from 3.0 to 8.0 mm. **Figure 4.7** summarises the corrosion rate calculated based on the remaining steel thickness.

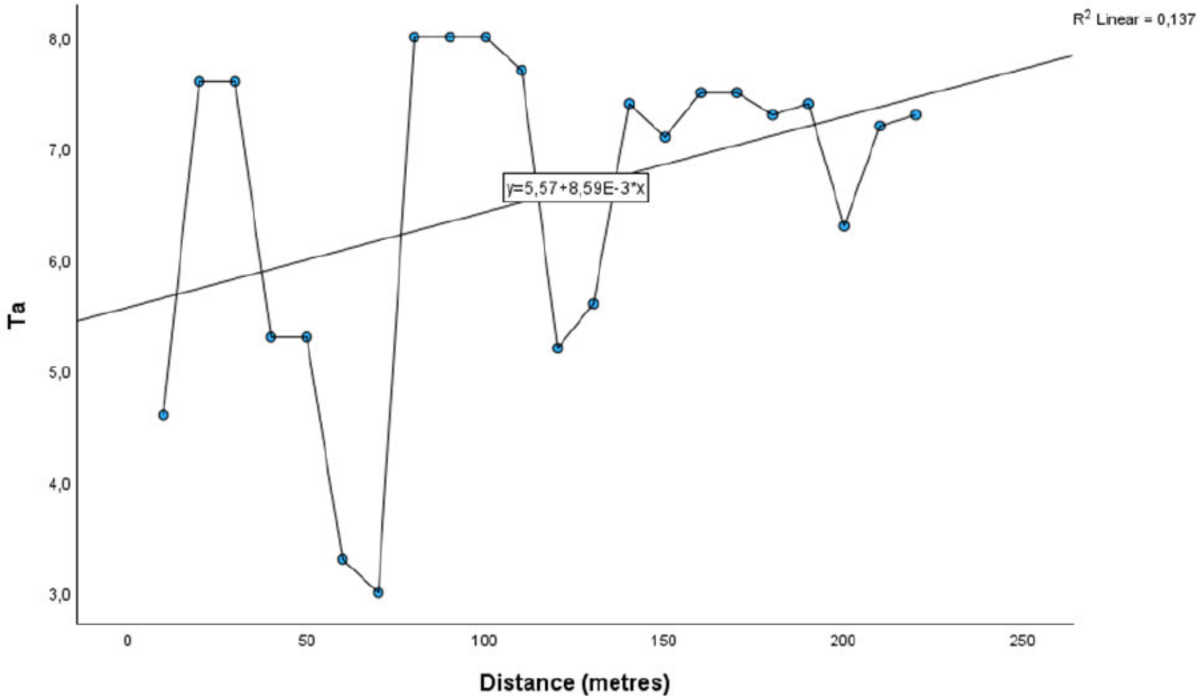

Figure 4.6: Measurements of sheet pile thickness at 10-m intervals

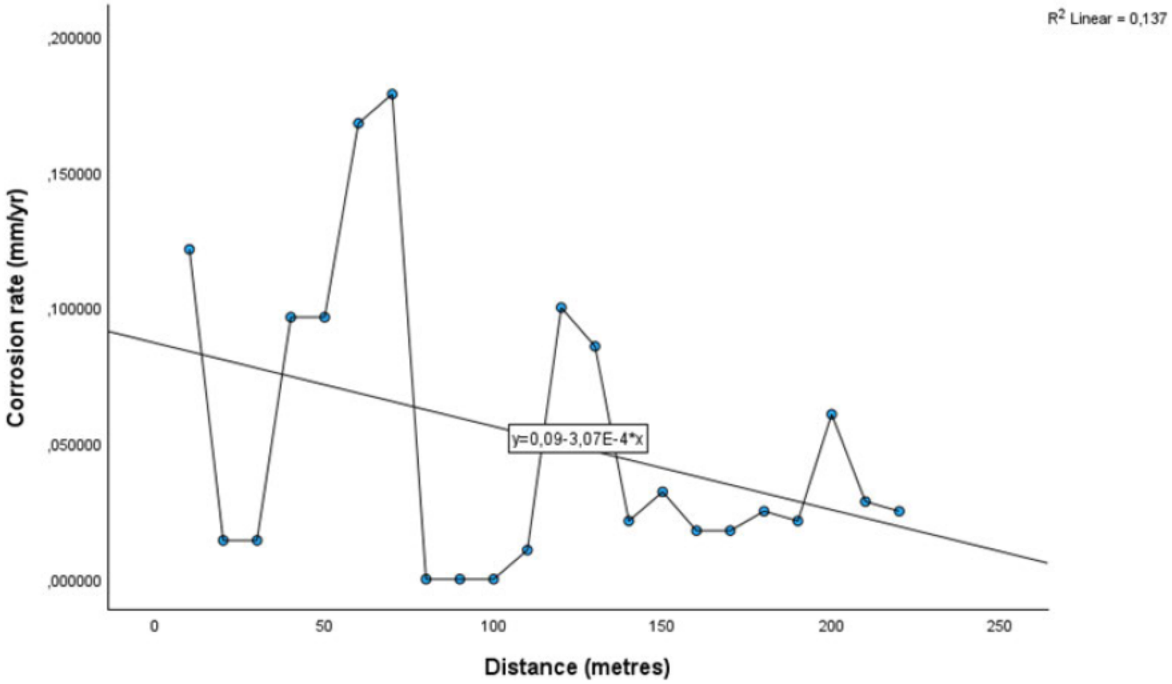

Figure 4.7: Corrosion rate measurements at 10-m intervals

4.3.4. Island View Berth 3 observations

Based on the findings of this study, the following key observations regarding Island View Berth 3 were made:

1. Corrosion rates peaked between depths of 60 m (0.1679 mm/yr) and 70m (0.1786 mm/yr), indicating significant risk in these areas and suggesting increased exposure to corrosive factors.
2. At depths of 80 m, 90 m, and 100 m, the corrosion rate was zero. This could indicate effective protective measures are in place, that environmental conditions at certain depths help prevent corrosion, or that the piles have been strategically positioned.
3. After reaching a peak at a distence of 70 m, corrosion rates decreased significantly. Corrosion rates at depths of 120 m (0.1000 mm/yr) and 130-m distance (0.0857 mm/yr) were relatively high but not as extreme as earlier measurements. The fluctuating corrosion rates without a clear linear trend suggest that local conditions likely played a crucial role in the corrosin process.

4.3.5. Chapter conclusion

The study found notable variability in the corrosion rates at both berths, reflecting the influence of environmental factors. At Island View Berth 3, the corrosion rates ranged from 0.0857 mm/yr to 0.1786 mm/yr, with the highest corrosion occurring at depths between 60m and 70m along the berth. For Maydon Wharf Berth 12, corrosion rates decreased with increasing depth, with the highest mean corrosion rate of 0.0545 mm/yr observed at 4.5m depth, and the lowest of 0.0290 mm/yr at 10.5m. These findings highlight the importance of depth and environmental exposure in the corrosion process.

The chloride content in the seawater significantly influenced the corrosion rate of the steel sheet piles. Water samples from both berths revealed chloride concentrations of 13.8 mg/L at Island View Berth 3 and 7.1 mg/L at Maydon Wharf Berth 12. According to Li and Du (2022), Higher chloride concentrations tend to accelerate the corrosion process, supporting the observed correlation between corrosion rates and water salinity. Additionally, the pH values, ranging from 6.75 at Island View Berth 3 to 7.34 at Maydon

Wharf Berth 12, further emphasized the role of the marine environment in the deterioration of steel.

Zones exhibiting higher corrosion rates may be influenced by factors such as exposure to pollutants and marine life. Understanding these factors can help in developing strategies to mitigate corrosion risks.

Zones exhibiting elevated corrosion rates, particularly those between 60 m to 70 m depths, should be prioritised for regular inspection and maintenance to prevent potential structural failures.

This analysis highlights the significant inconsistency in corrosion rates along Island View Berth 3 with specific areas requiring urgent attention. Understanding the factors affecting these rates is essential for maintaining the structural integrity of the Berth.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1. Introduction

The data collected to determine the corrosion rate of steel sheet piles at the Port of Durban berths has been presented in both graphical figures and tabular format to facilitate comprehensive analysis and interpretation. Following this, a detailed examination of the collected data was conducted in Chapter 4, where various factors influencing the corrosion process were assessed to provide a deeper understanding of the underlying mechanisms at play. In this chapter, an in-depth discussion is presented regarding the conclusions drawn from the data collection and subsequent analytical processes, highlighting key findings that contribute to the overall understanding of steel sheet pile degradation in a marine environment. Furthermore, this chapter does not only summarise the insights gained from the literature review undertaken as part of this research but also offer well-founded recommendations aimed at addressing the challenges associated with corrosion, ultimately providing guidance for future studies and practical applications in marine infrastructure maintenance and preservation.

5.2. Study conclusions

This study aimed to assess the corrosion rates of steel sheet piles at Island View Berth 3 and Maydon Wharf Berth 12 in the Port of Durban, contributing valuable data to the understanding of how marine environments impact the durability of steel structures. The research focused on the remaining steel thickness of the piles, chloride content in the surrounding seawater, and the pH levels, which are known to influence corrosion processes. This investigation was methodologically structured around a combination of underwater measurements, laboratory analyses, and corrosion rate calculations. This chapter summarises the key findings, discusses their implications for the longevity and maintenance of the sheet pile walls, and presents recommendations for future work.

5.2.1. Variation Across Different Zones

The corrosion rates exhibited distinct patterns across the different marine zones at each berth. In both locations, corrosion rates were highest in the splash and tidal zones, where the steel sheet piles are most exposed to seawater. The presence of marine life and physical damage from debris likely contributed to these elevated corrosion rates. In contrast, areas of the sheet piles submerged below the low water zone experienced lower rates of corrosion, suggesting more stable environmental conditions at these depths.

5.2.2. Implications

The results of this study provided valuable insights into the long-term durability of steel sheet piles in the Port of Durban. The observed corrosion rates indicated that while the steel sheet piles still possess substantial structural integrity, there are localized areas that exhibit accelerated corrosion, particularly in shallow regions and exposed zones. Given that corrosion is the leading cause of deterioration in marine structures, the findings underscore the need for targeted maintenance and monitoring in high-risk areas, particularly between 60m and 70m along Island View Berth 3.

The influence of chloride content and pH on corrosion emphasized the importance of regular environmental monitoring to anticipate and mitigate the risks posed by these factors. The differences in corrosion rates between Island View Berth 3 and Maydon Wharf Berth 12 also suggest that factors such as seawater circulation, tidal conditions, and the exposure of the sheet piles to various depths should be considered when planning maintenance schedules and determining the lifespan of the steel sheet piles.

5.2.3. Comparison of Results

The results obtained from the study of the corrosion rates at Island View Berth 3 and Maydon Wharf Berth 12 can be compared with the typical corrosion rates specified in the BS 6349-1:2000 standard:

5.2.3.1. Island View Berth 3:

The thickness was found to range between 3 mm and 8 mm for the steel sheet piles installed in 1993. According to the study, the mean corrosion rate across different inspection points was 0.1679 mm/yr at its highest.

When compared with BS 6349-1:2000 standard, the corrosion rates found (0.1679 mm/yr at its peak) are higher than the typical mean values for the Splash Zone (0.08 mm/yr) and Tidal Zone (0.04 mm/yr) given in the standard. This could indicate that environmental factors, such as biological growth, pollutants, or physical impacts from debris, may be accelerating corrosion more than expected.
At depths where corrosion rates are minimal (such as 0 mm/yr), this could align with the Continuous Seawater Immersion Zone (where corrosion rates are typically lower, around 0.04 mm/yr).

The fluctuations in the corrosion rate across the inspection points, particularly the high corrosion rates found at certain points, suggest local conditions or variations in the exposure to seawater and air, such as debris collisions, could explain the higher-than-expected corrosion rate in some areas. Therefore, the results at Island View Berth 3 indicated accelerated corrosion in certain sections of the sheet piles when compared to the BS 6349-1:2000 standard corrosion rate estimates for marine environments. The physical impacts from floating debris and potential exposure to pollutants may be contributing factors.

5.2.3.2. Maydon Wharf Berth 12:

Corrosion rates in the measurements taken at Maydon Wharf Berth 12 ranged from 0.029 mm/yr to 0.0545 mm/yr, with the highest corrosion rate observed at 4.5m depth.

The results were compared with BS 6349-1:2000 standard, where the highest corrosion rate of 0.0545 mm/yr falls within the upper limit of the Splash Zone (0.08 mm/yr) and Tidal Zone (0.10 mm/yr), which aligns with the expected range for areas exposed to high tidal fluctuations, spray, or biological activity.

The lowest corrosion rates (e.g., 0.0290 mm/yr at 10.5 m depth) are within the expected range for the Continuous Seawater Immersion Zone (0.04 mm/yr), indicating that these zones are performing within expected limits for this type of environment.

Therefore, the corrosion rates observed at Maydon Wharf Berth 12 fall within the expected range outlined in BS 6349-1:2000 standard, with higher corrosion rates observed in the shallower zones where the steel sheet piles are exposed to more aggressive marine conditions. The lower rates observed at deeper zones are in line with expectations for the Continuous Seawater Immersion Zone, which is subject to less atmospheric interaction.

5.3. Recommendations

Based on the findings from the corrosion rate study of steel sheet piles at Island View Berth 3 and Maydon Wharf Berth 12, the following recommendations can be made to help mitigate corrosion and ensure the long-term structural integrity of the sheet pile walls in the Port of Durban.

5.3.1. Monitoring and Inspection

Regular and Comprehensive Inspections: Given the varying corrosion rates across different depths and zones, it is recommended that more frequent inspections be conducted, especially in areas where corrosion rates are found to be higher (e.g., between 60m to 70m at Island View Berth 3). This can help detect corrosion early, identify areas of concern, and address them before they lead to structural failure. Inspections should utilize modern techniques, such as ultrasonic thickness measurements, to monitor the condition of the sheet piles accurately over time.

Advanced Non-Destructive Testing (NDT): Consider incorporating additional NDT techniques like corrosion mapping, electrochemical impedance spectroscopy, or robotic inspections to complement ultrasonic thickness testing. This can provide more detailed, localized data on the corrosion process and better inform maintenance schedules and decision-making.

Corrosion Hotspot Identification: The areas where corrosion rates were found to be the highest, particularly at shallow depths (4.5m at Maydon Wharf Berth 12), should be prioritized for intensive monitoring. Areas showing high variability in corrosion rates (as seen at Island View Berth 3) should also be given special attention to pinpoint specific conditions contributing to accelerated corrosion.

5.3.2. Corrosion Prevention Strategies

Cathodic Protection: The study indicated that corrosion can be a significant concern for sheet piles exposed to marine environments. As such, the port authority should assess the effectiveness of the current cathodic protection systems, particularly at areas with high corrosion rates. If necessary, upgrading or expanding cathodic protection systems could provide long-term prevention against further corrosion. Specifically, focusing on the tidal and splash zones where corrosion tends to be more aggressive could offer considerable benefits.

Protective Coatings: While no protective coatings were observed during the inspections, the application of protective coatings (such as epoxy or polyurethane-based coatings) can offer an additional layer of defence against corrosive elements. These coatings should be applied to sheet piles, especially in areas with high corrosion risk or where cathodic protection may not be as effective.

Corrosion-Resistant Materials: For future sheet pile installations or replacements, it may be worth considering the use of corrosion-resistant materials, such as stainless steel or coated steel sheet piles, particularly in areas with very aggressive marine conditions. These materials have longer lifespans and can reduce long-term maintenance costs.

5.3.3. Environmental Impact Considerations

Chloride Concentration Management: Given the high chloride content in the seawater samples, it is essential to monitor and mitigate factors contributing to chloride acceleration of corrosion. Strategies could include the monitoring of nearby industrial discharges and the implementation of measures to reduce seawater contamination by pollutants.

Marine Growth Control: The inspections revealed that marine growth was prevalent on the sheet piles, which can exacerbate corrosion. Regular cleaning and maintenance of sheet piles to remove marine growth is essential, as it not only facilitates easier inspections but also reduces localized corrosion caused by biofouling.

Pollution Management: Floating debris and contamination from surrounding canals were identified as contributing to the physical damage and accelerated corrosion of the sheet piles. It is recommended that the Port Authority implement strategies to reduce the inflow of pollutants and debris into the water, including improved waste management systems along the quayside and monitoring the discharge from nearby industrial areas and canals.

5.3.4. Data-Driven Maintenance and Planning

Predictive Maintenance Models: Given the variability of corrosion rates and the complexity of factors influencing the corrosion process, predictive maintenance models should be developed based on the data collected. These models would incorporate corrosion rate data, environmental conditions, and other relevant variables to predict when and where maintenance will be required. This would allow for a more proactive approach to managing the steel sheet piles and reduce the risk of unforeseen structural failure.

Long-Term Data Collection and Trend Analysis: It is recommended that long-term corrosion monitoring be implemented to track changes in the corrosion rate over time. Collecting data at regular intervals and comparing it with environmental conditions can help predict trends and allow for more informed decision-making when it comes to future repairs and replacements.

5.3.5. Structural and Design Modifications

Localized Reinforcements: For areas with higher corrosion rates, localized reinforcement or repair may be necessary. This could include the addition of sacrificial anodes or the application of further steel coatings to mitigate the effects of corrosion until a more permanent solution can be applied.

Design Considerations for Future Developments: For future infrastructure projects, it would be beneficial to incorporate corrosion-resistant designs. A holistic approach should be considered that accounts for local environmental conditions such as water salinity, tidal activity, and exposure to marine growth. For example, the use of steel alloys with higher corrosion resistance or the implementation of corrosion-inhibiting designs could improve the longevity of future sheet pile walls.

Use of Deep Soil Mixing: For areas with extremely high corrosion rates or weak soil conditions, deep soil mixing, or other ground improvement techniques could be explored as a way of enhancing the structural support provided by sheet piles and reducing their direct exposure to corrosive forces.

5.3.6. Conclusion

In conclusion, it is critical to continuously monitor, assess, and protect the steel sheet piles at both Island View Berth 3 and Maydon Wharf Berth 12 to extend their service life and ensure the long-term stability of the quay walls. By implementing a comprehensive corrosion management strategy that includes regular inspections, improved cathodic protection, environmental mitigation measures, and data-driven maintenance practices, the Port of Durban can significantly reduce the impact of corrosion on its infrastructure and improve the safety and efficiency of its operations.

These recommendations aim to ensure that the Port of Durban remains resilient against the challenges posed by marine corrosion, while also providing a sustainable and cost-effective approach to maintaining its quay wall infrastructure.

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APPENDICES

Appendix A: List of Publications

Nyawo M. M and Allopi D. 2024. Corrosion rate measurement of sheet pile wall in the Port of Durban. *Journal of Civil Engineering and Technology (JCIET), Volume 10, Issue 2, (July– December 2024*)

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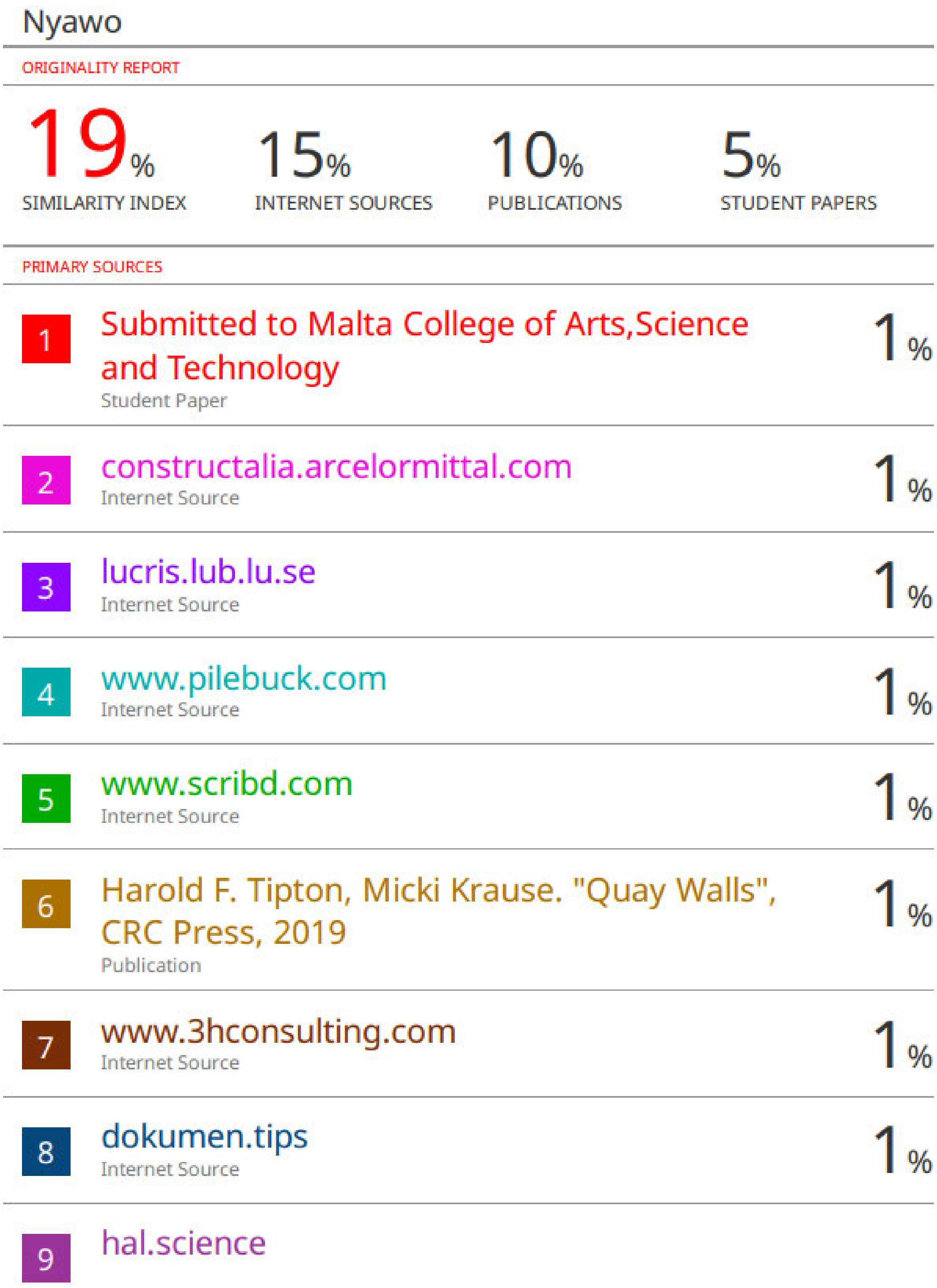

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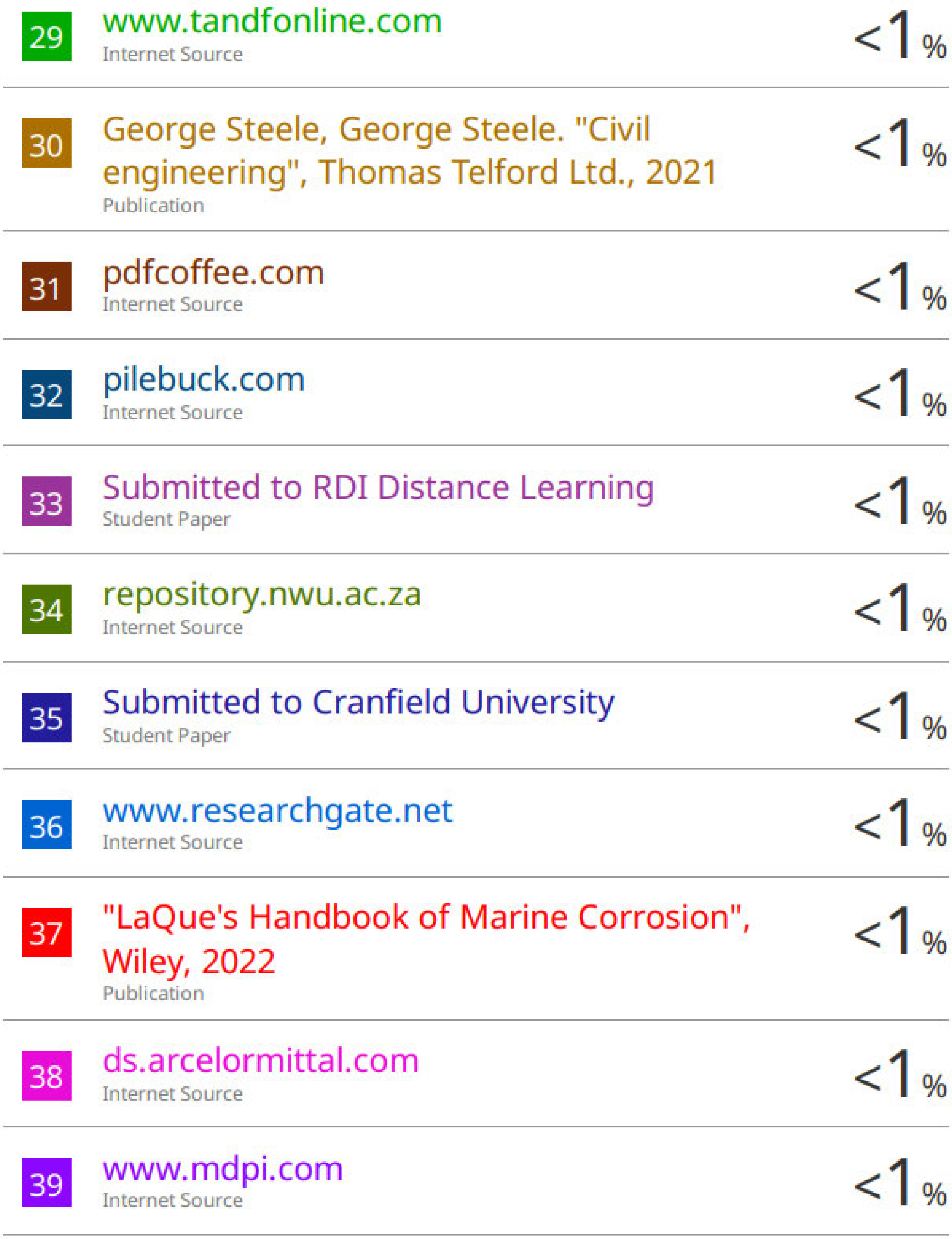

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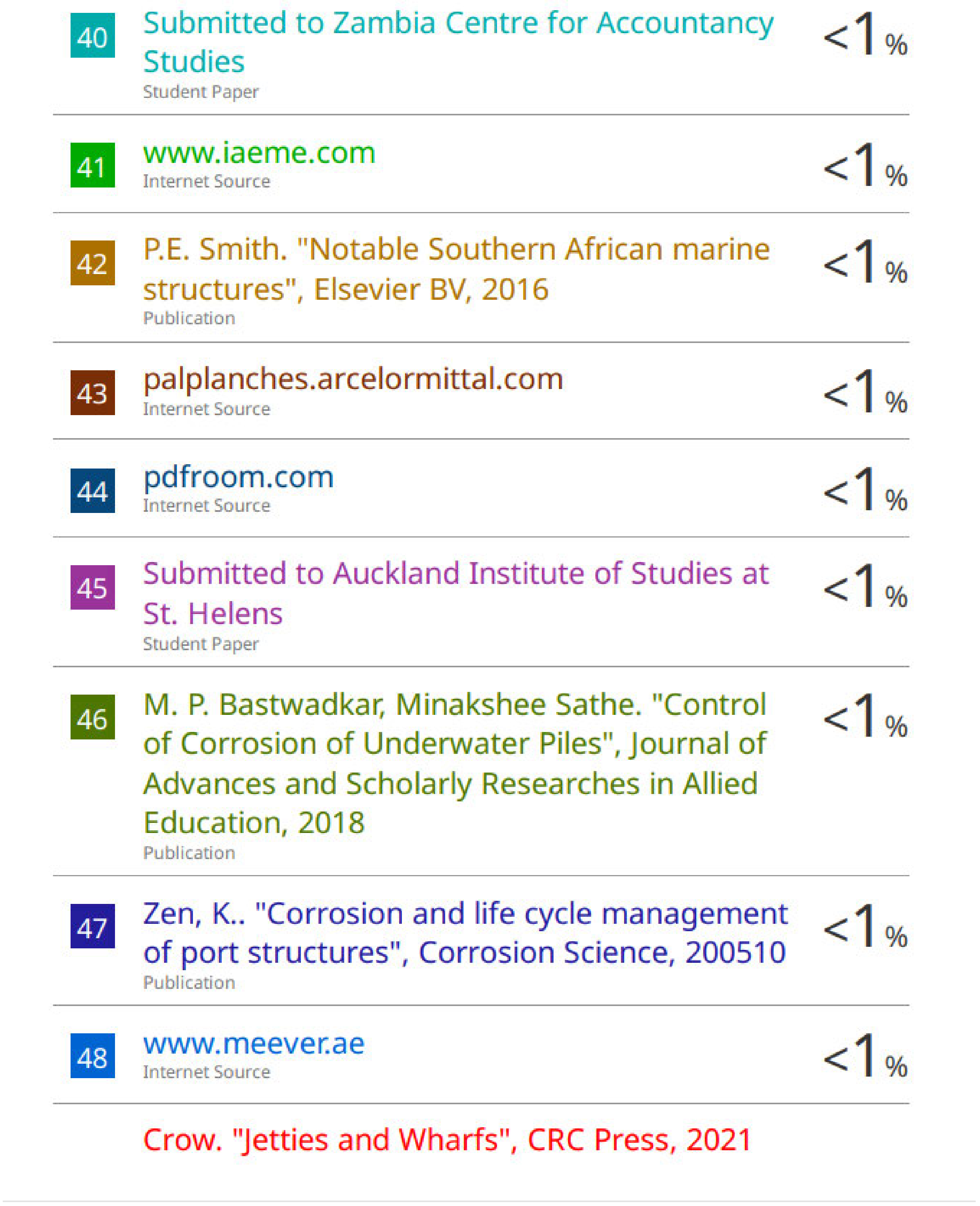

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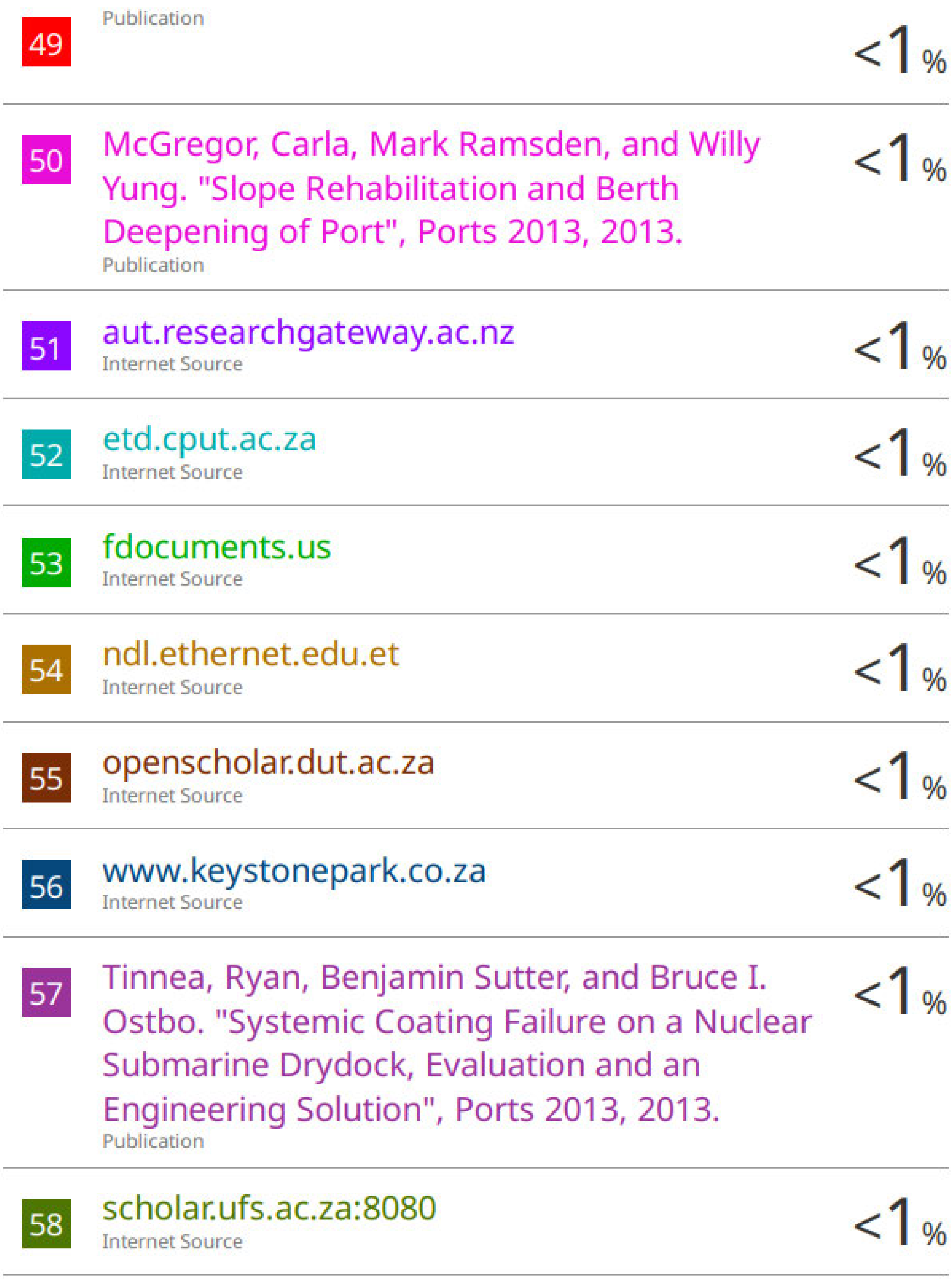

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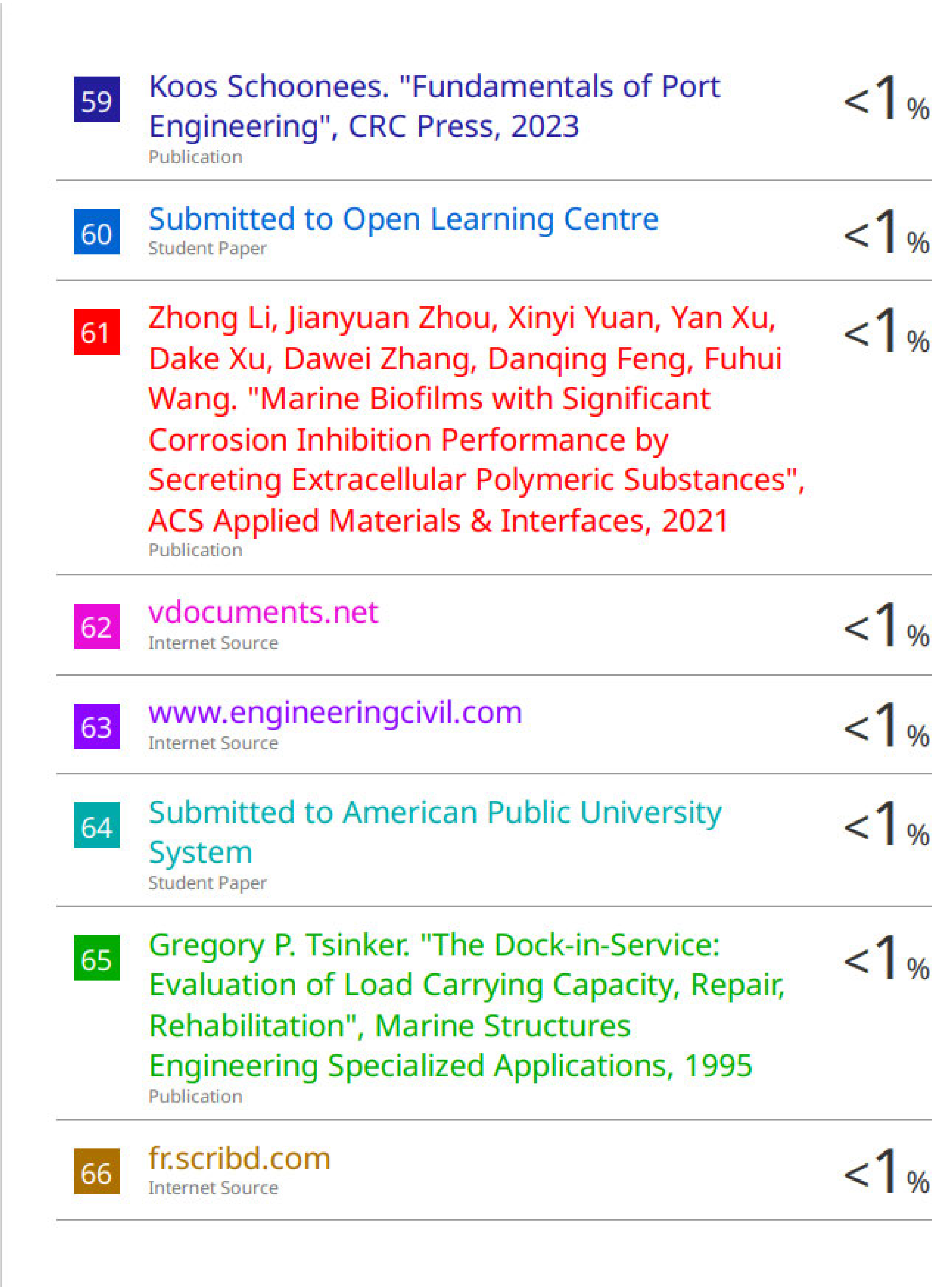

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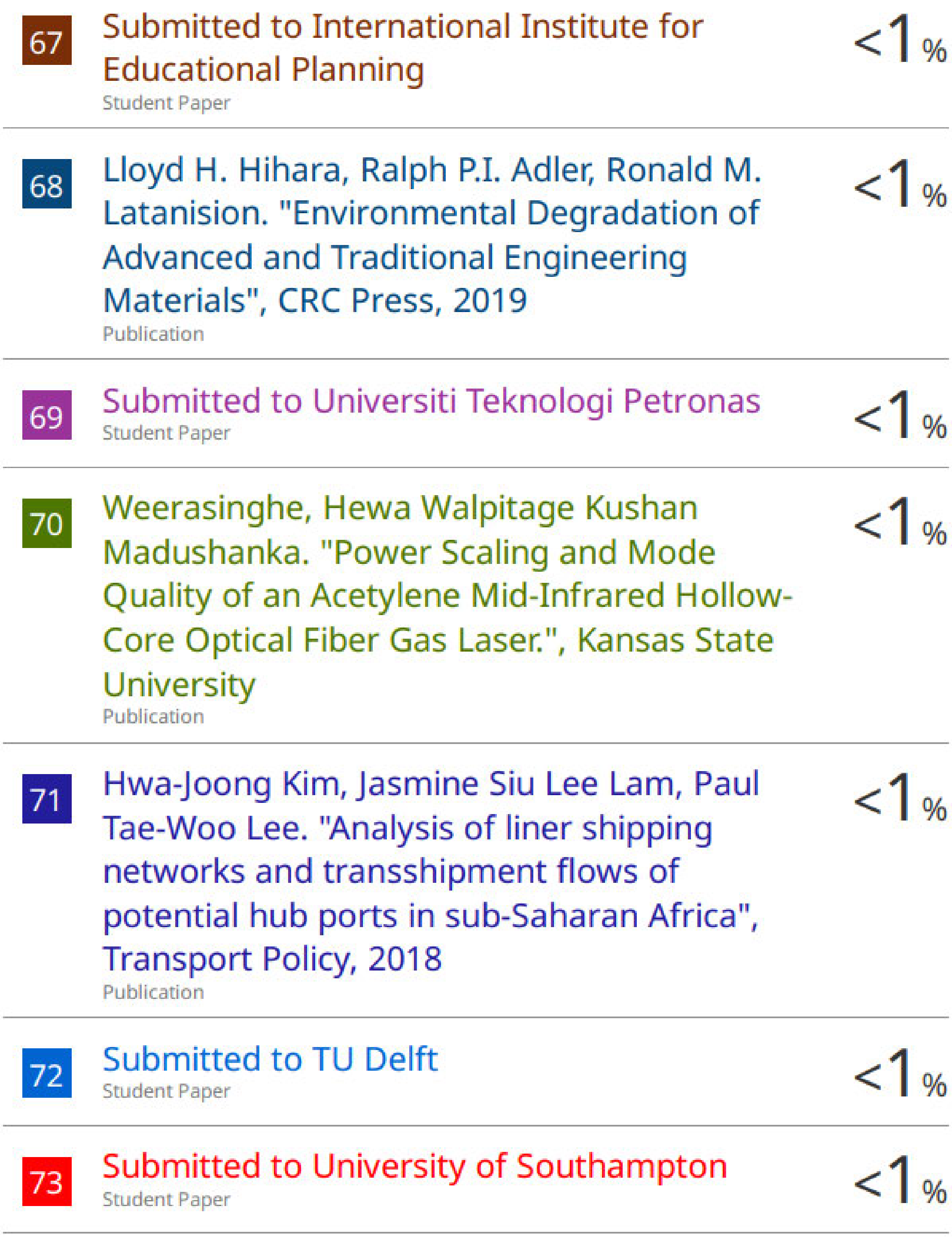

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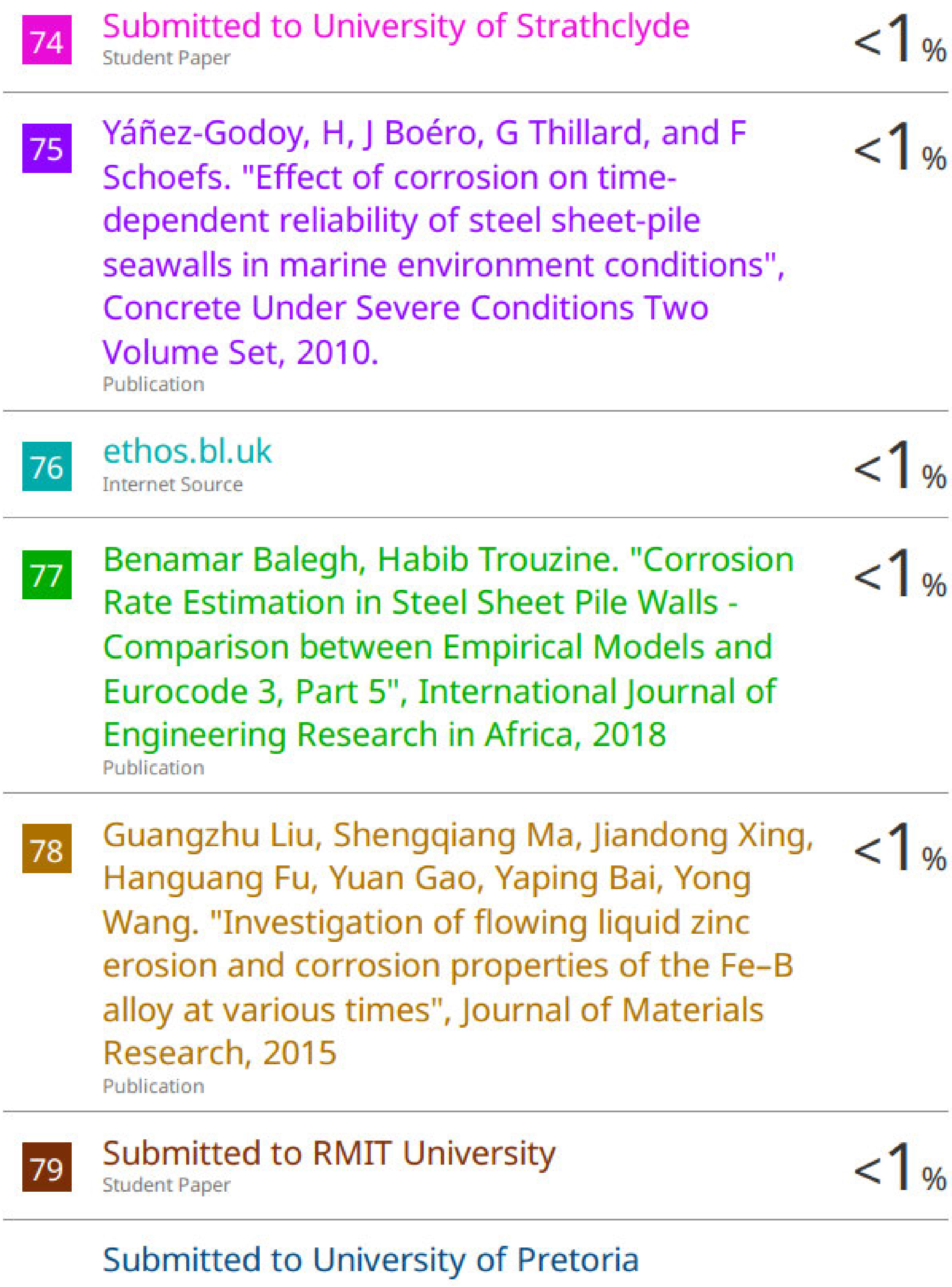

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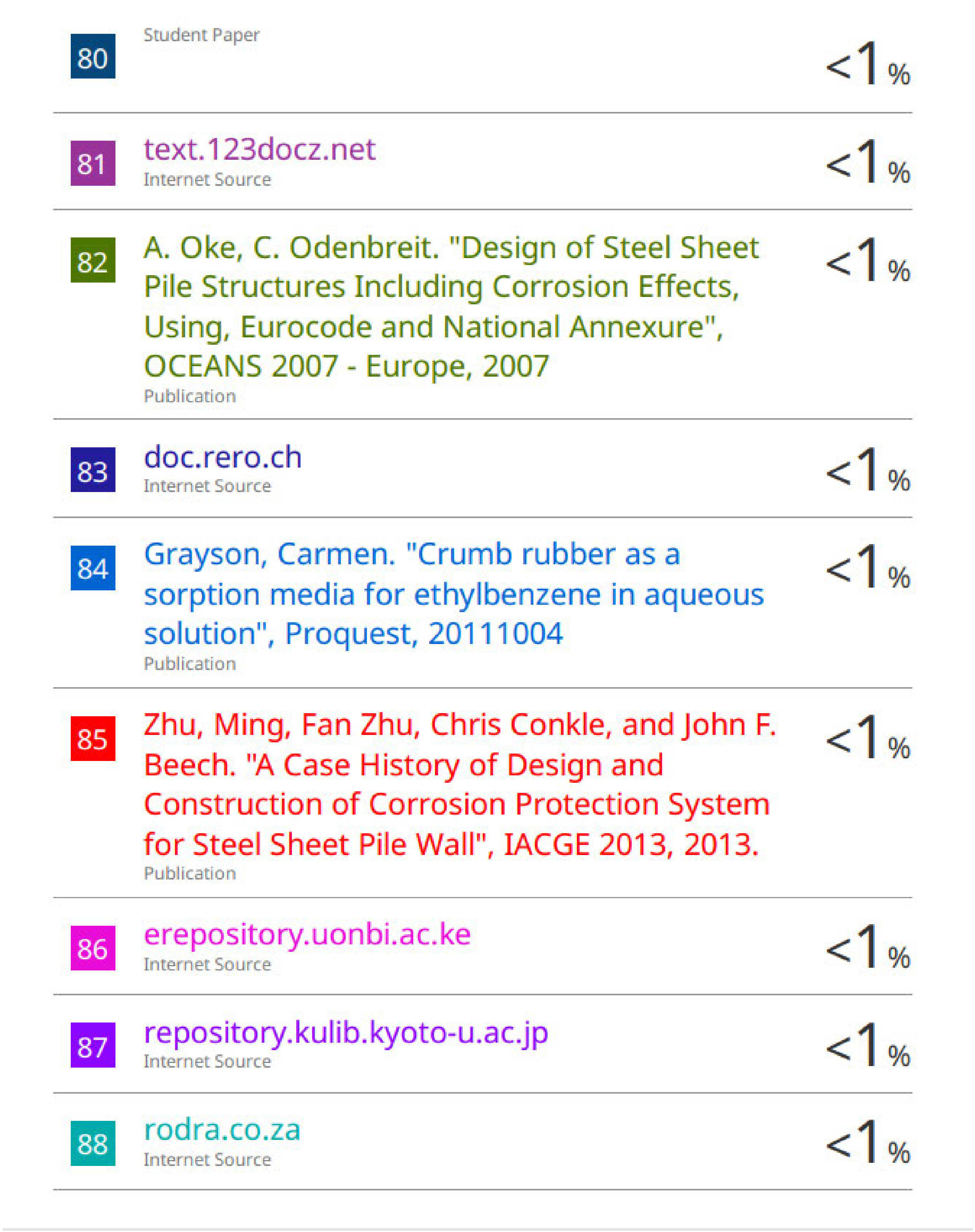

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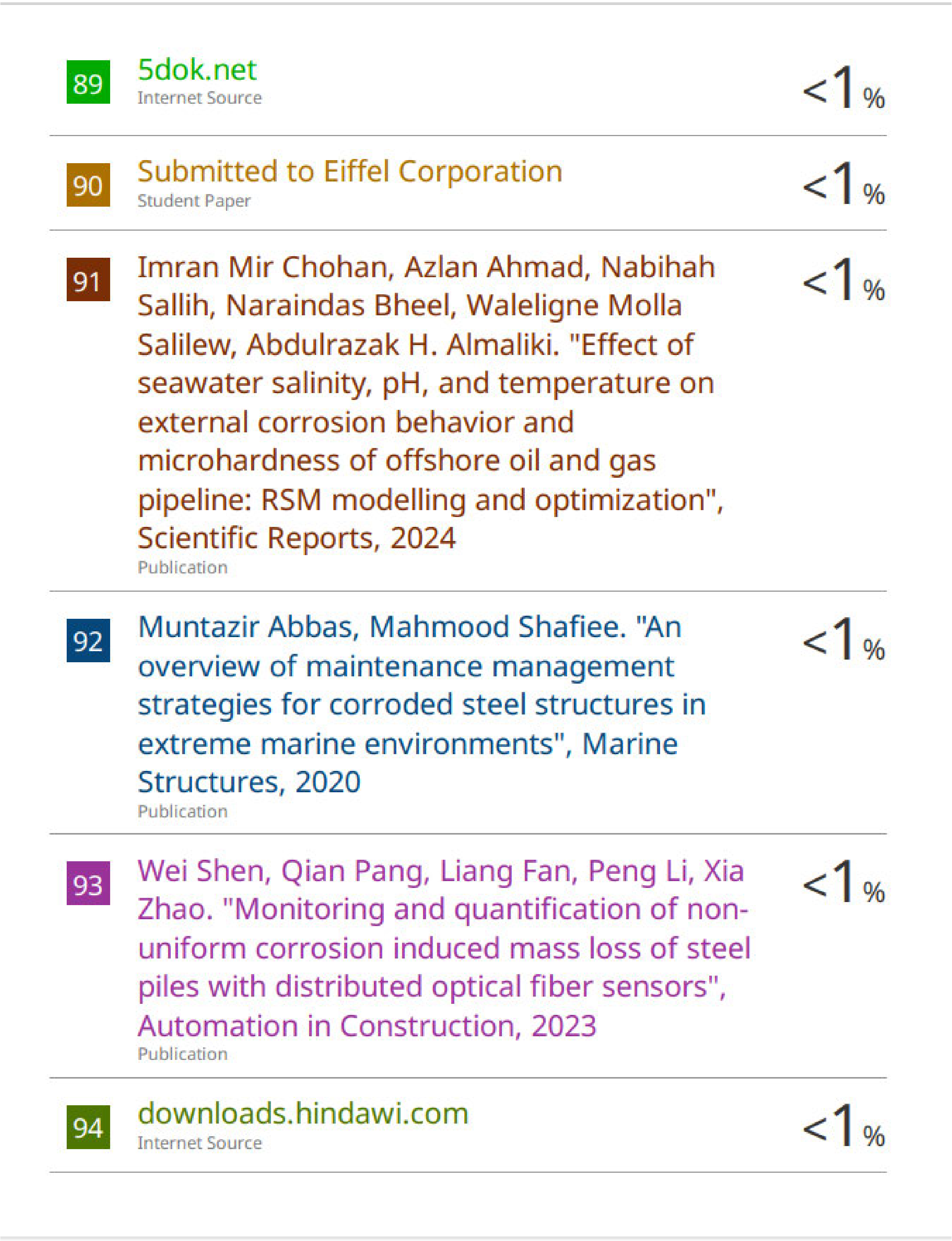

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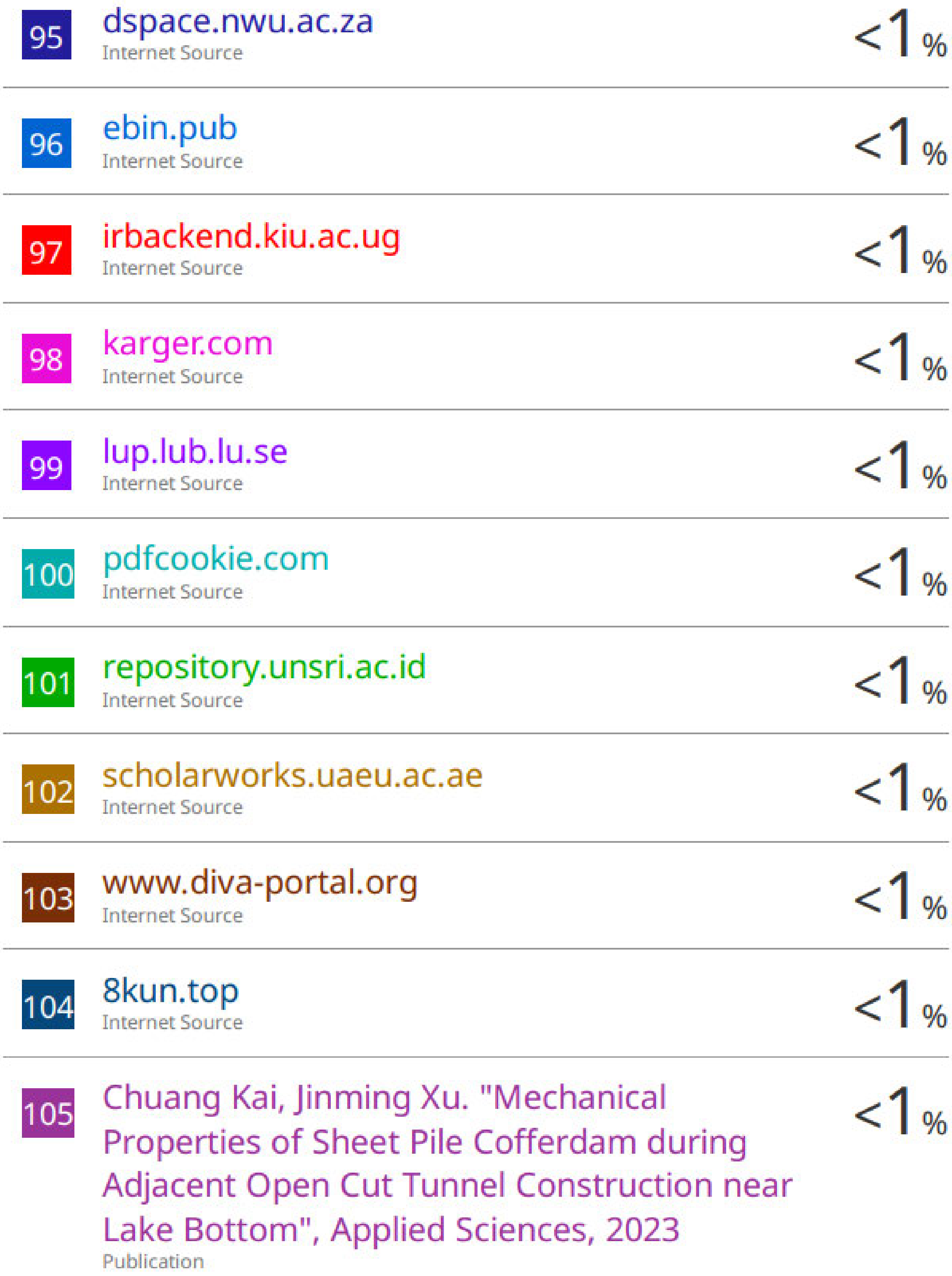

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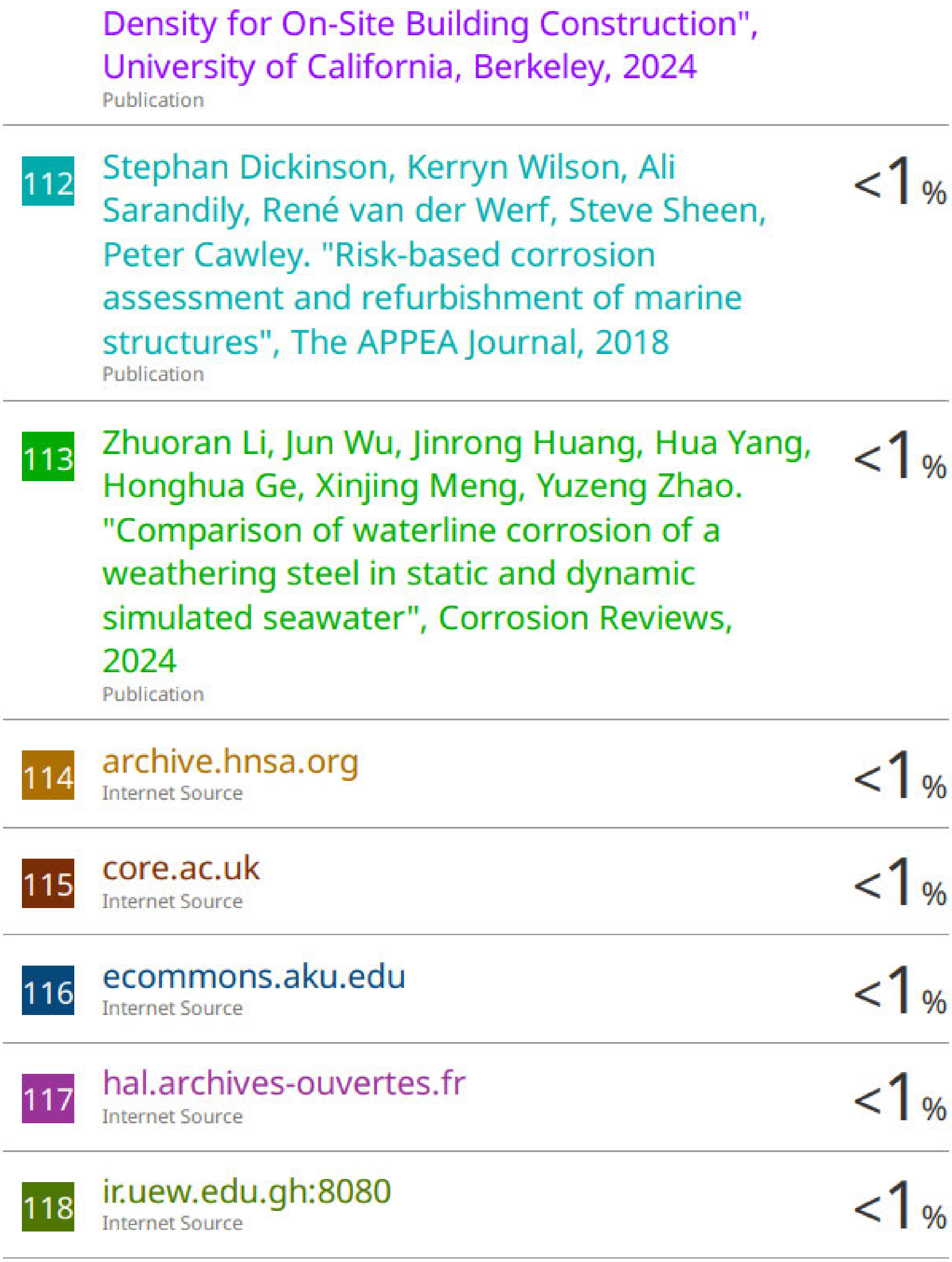

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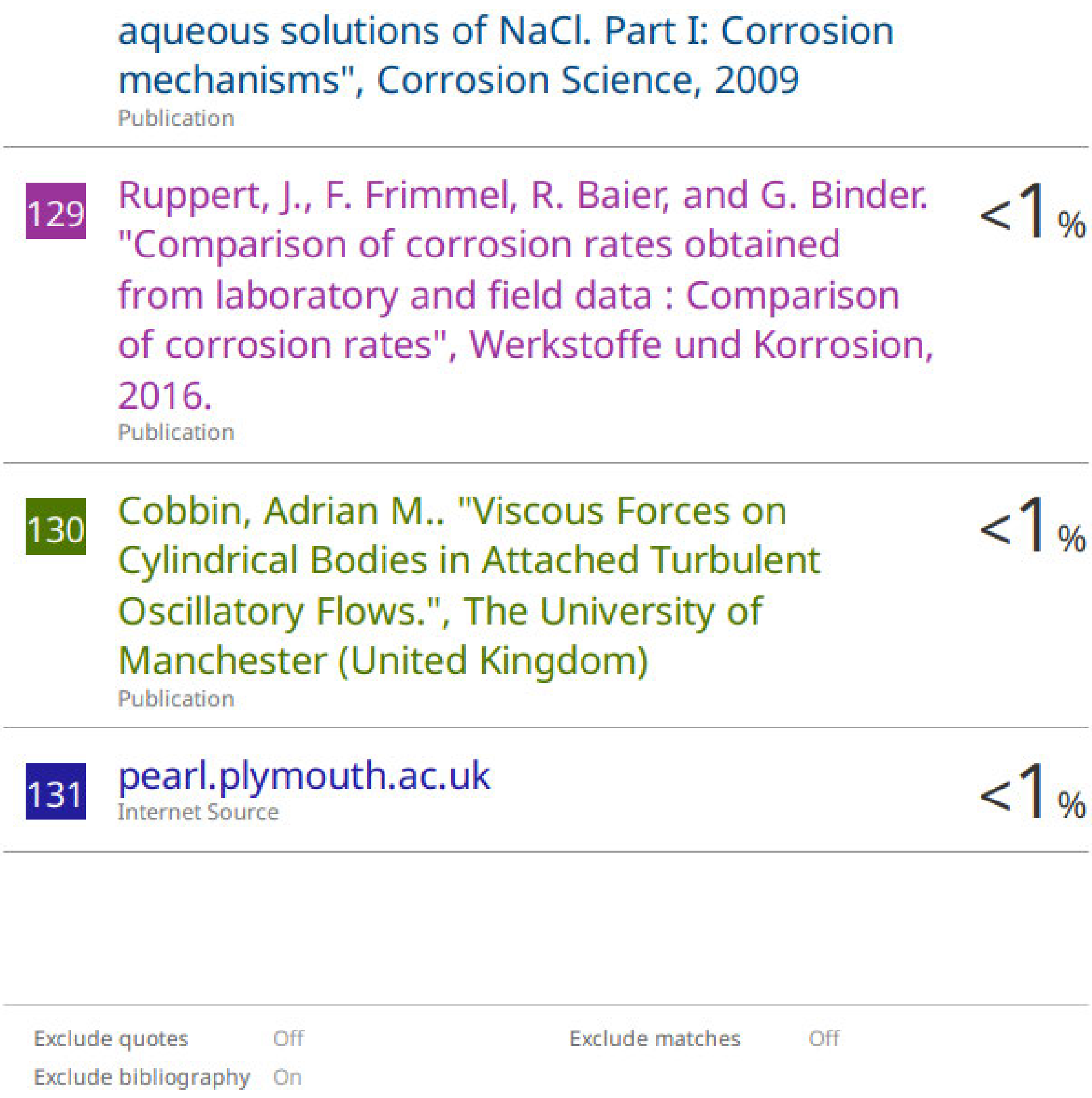

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