Marine Corrosion Protection: Current Status and Future (Postprint)

Authors: Hou Baorong, Zhang Dun, Wang Peng

Date: 2016-12-26T00:00:00+00:00

Abstract

The marine environment is the most severe natural corrosive environment; marine corrosion issues constitute a major threat to the safe service of marine engineering and also cause tremendous losses to the national economy. As humanity continues to expand the depth and breadth of marine development in the future, it will also face challenges from continuously emerging new corrosion problems. This article, combining the current status of marine development research and future development trends, introduces the characteristics of the marine corrosive environment, analyzes the current status and requirements of marine corrosion protection in China, and proposes recommendations for marine corrosion protection research and the formulation of relevant policies and regulations.

Full Text

Marine Corrosion and Protection: Current Status and Future Prospects

Hou Baorong, Zhang Dun, Wang Peng
Institute of Oceanology, Chinese Academy of Sciences, Qingdao 266071, China

Abstract

The marine environment represents the most aggressive natural corrosion setting. Marine corrosion poses a primary threat to the safe service of marine engineering structures and inflicts substantial economic losses on national economies. As human exploitation of the ocean continues to expand in both depth and scope, new corrosion challenges will inevitably emerge. This paper examines the characteristics of marine corrosion environments in the context of current marine development research and future trends, analyzes the present status and requirements of marine corrosion protection in China, and proposes recommendations for future research and policy formulation in marine corrosion prevention.

Keywords: marine environment, corrosion and protection, planning proposals

Introduction

The ocean harbors abundant resources with potentially enormous economic benefits and strategic defense significance. The level of marine industry development reflects a nation' s comprehensive scientific and technological strength, as well as its economic development and international standing. Marine corrosion represents one of the critical threats encountered during ocean development, with numerous catastrophic accidents causing immense losses. In 1980, the "Alexander Kielland" drilling platform in the North Sea collapsed when seawater corrosion of weld joints on its legs led to crack propagation under repeated wave loading, claiming 123 lives. On April 20, 2010, a subsea valve failure on BP' s "Deepwater Horizon" drilling platform in the Gulf of Mexico caused an explosion that killed 11 people. Over the subsequent three months, more than 4 million barrels of crude oil gushed from the seafloor, creating the most severe environmental disaster in U.S. maritime history. Due to the complexity of the 3,000-meter deepwater environment, it took over three months and nearly all available resources to finally seal the leak. On November 22, 2013, an explosion in a drainage culvert in Qingdao' s economic development zone killed 62 people and caused direct economic losses exceeding 750 million yuan. The State Council' s special investigation report identified the direct cause as pipeline corrosion thinning at the intersection of an oil pipeline and drainage culvert, leading to rupture and oil leakage.

Beyond safety concerns, marine corrosion generates enormous economic losses. A global corrosion survey from March 2016 indicated that worldwide corrosion losses average approximately 3.4% of Gross National Product (GNP). Marine corrosion is generally estimated to account for about one-third of total corrosion losses, making its impact staggering. Based on domestic and international experience, 25–40% of these losses could be avoided through effective protective measures.

In summary, marine corrosion causes structural damage to facilities and equipment, reduces service life, and represents a critical issue affecting national welfare and people' s livelihoods. Severe corrosion can also trigger catastrophic accidents, pollute the environment, and endanger lives and property.

1. Characteristics of Marine Environment Corrosion

The marine environment constitutes the most corrosive natural setting. Seawater is a highly corrosive electrolyte solution containing substantial salts, including sodium chloride and salts containing potassium, bromine, and iodine. Dissolved gases such as oxygen, nitrogen, and carbon dioxide are present, with oxygen being a crucial factor in the corrosion of carbon steel and low-alloy steel structures in seawater. Surface seawater is saturated with oxygen at approximately 8 mg/L, making it particularly corrosive. Seawater temperature undergoes periodic changes, and generally, the corrosion rate of steel increases with rising temperature. Additionally, seawater contains abundant trace elements and nutrients that provide essential conditions for marine organisms, whose presence subsequently influences the corrosion behavior and mechanisms of metallic materials.

From a corrosion perspective, the marine environment is typically divided into five distinct zones: marine atmospheric zone, splash zone, tidal zone, full immersion zone, and seabed mud zone (Table 1)[1].

1.1 Corrosion Characteristics in Marine Atmospheric Zone Atmosphere is the environmental medium most frequently in contact with metallic materials, with approximately 80% of metal components used in atmospheric conditions. China has over 18,000 kilometers of coastline, exposing numerous metallic materials to marine atmospheric environments. The marine atmosphere contains abundant salt particles that are highly corrosive to metals. Atmospheric corrosion of metallic materials proceeds through electrochemical mechanisms. When exposed to atmospheric environments, metals absorb moisture, forming a thin electrolyte film on their surfaces that enables electrochemical reactions. The amount of water absorbed on metal surfaces correlates with relative humidity. At 75% relative humidity, the adsorbed water molecular layer is about five molecules thick. Generally, when the water film exceeds five molecular layers, the electrochemical corrosion process can proceed. Atmospheric pollutant gases and suspended particles settle in this thin liquid layer on metal surfaces, influencing and participating in the atmospheric corrosion process.

1.2 Corrosion Characteristics in Splash Zone The splash zone refers to areas in marine environments where seawater spray can reach the surface but which are not submerged during high tide. In this zone, materials experience prolonged wet-dry cycling with abundant oxygen supply. Seawater spray directly impacts metal surfaces, causing extremely severe corrosion—typically 5-10 times greater than in fully immersed zones—making it a particularly aggressive corrosion area in marine environments. The Key Laboratory of Marine Environmental Corrosion and Biofouling at the Institute of Oceanology, Chinese Academy of Sciences, has conducted continuous research on corrosion mechanisms and protection technologies in marine splash zones, successfully developing mineral coating protection technology that addresses splash zone corrosion issues. Additionally, anti-corrosion and repair technologies for reinforced concrete structures have been developed and widely applied in marine engineering structure protection.

1.3 Corrosion Characteristics in Tidal Zone The tidal zone lies between the mean high and low tide lines. This area receives protection as the cathodic region of oxygen concentration cells, resulting in relatively low corrosion rates. However, marine biological fouling and aerobic bacterial attachment corrosion occur in this zone. Corrosive organisms accelerate metal substrate corrosion through oxygen concentration cells and other mechanisms, inducing localized corrosion damage. Reportedly, microbiologically influenced corrosion accounts for approximately 20% of total corrosion losses[2].

1.4 Corrosion Characteristics in Full Immersion Zone In the full immersion zone, corrosion rates decrease with depth due to the close relationship between corrosion and oxygen content. However, this extensive zone exhibits significant variations in seawater pressure, pH, salinity, marine organisms, and oxygen content with increasing depth. While uniform corrosion rates decrease, localized corrosion such as galvanic corrosion, crevice corrosion, and pitting intensifies. Furthermore, corrosion in this zone features multi-factor interactions, with significant changes in the mechanisms of hydrogen-induced cracking, stress corrosion, and corrosion fatigue, making materials more susceptible to environmentally sensitive fracture in marine environments.

1.5 Corrosion Characteristics in Seabed Mud Zone In seabed mud zones, corrosion rates are generally low due to limited oxygen concentration. However, the presence of corrosive microorganisms and their metabolic activities can accelerate metal corrosion and alter corrosion mechanisms. The Institute of Oceanology, Chinese Academy of Sciences, has accumulated substantial research achievements in microbiologically influenced corrosion, investigating marine microbial corrosion mechanisms[3,4], developing rapid detection sensor technologies for corrosive microorganisms[5,6], and creating new material technologies for marine microbial corrosion protection[7,8].

2. Current Status of Marine Corrosion and Protection in China

2.1 Current Status of Marine Corrosion in China To comprehensively understand China' s current corrosion situation, the Chinese Academy of Engineering established the major consulting project "Investigation and Strategic Study on Corrosion Status and Control in China." The project organized 200 scientists and engineers, including nearly 30 academicians, to investigate corrosion costs and protection strategies across more than 30 key industries in five major sectors: infrastructure, water environment, energy, transportation, and manufacturing. These industries include railways, airports, highway bridges, port terminals, hydraulic engineering, ships, aircraft, trains, coal industry, power systems, urban water supply, mariculture, cultural relics/monuments, seawater desalination, offshore platforms and equipment, subsea pipelines, offshore oil equipment, construction, automobiles, oil and gas industry, metallurgy, electronics, papermaking, chemical industry, telecommunications, home appliances, pharmaceuticals, mining, food processing, medical devices, and agriculture. Using mathematical and economic theories and methods, the project calculated China's corrosion costs. Through systematic work including questionnaires, field investigations, case studies, conferences, seminars, online searches, simulations, and statistical analysis, the results indicated that in 2014, China' s corrosion costs reached approximately 2,127.82 billion yuan, accounting for 3.34% of GDP, with per capita corrosion costs exceeding 1,555 yuan. Compared with developed countries, China started corrosion investigations later with lower priority. This corrosion cost survey is significant for raising awareness about corrosion hazards and improving anti-corrosion consciousness.

2.2 Current Requirements for Marine Corrosion Protection in China

Marine economic and technological development has been elevated to an unprecedented strategic height in China. Strategic emerging marine industries such as coastal engineering, marine exploitation, and underwater engineering are rapidly emerging. Developing and constructing various new high-level deepwater drilling equipment, naval vessels, submersibles, and ocean space stations constitutes the fundamental material guarantee for marine resource development and national defense security. Additionally, China has an extensive coastline, and rapid economic growth in recent years has led to massive expansion in coastal engineering, port terminals, and sea-crossing bridge construction, utilizing large quantities of structural materials. China is developing a chain of economic zones including the Bohai Rim Economic Zone, Yellow River Delta Economic Zone, Shandong Peninsula Blue Economic Zone, Jiangsu Coastal Economic Zone, Yangtze River Delta Economic Zone, Pearl River Delta Economic Zone, and West Coast of the Taiwan Strait Economic Zone. While developing nearshore marine engineering, offshore facilities are continuously expanding into distant and deep waters. Currently, China has built and is building numerous marine steel and reinforced concrete structures for offshore oil and gas field development, port construction, sea-crossing bridges, subsea pipelines, ship engineering, and deepwater exploration. These facilities are widely distributed along China' s coastal frontlines and in key maritime areas such as the South China Sea and East China Sea, spanning different marine corrosion zones including atmospheric, splash, tidal, full immersion, and seabed mud zones, and suffering severe corrosion damage. Marine corrosion and biofouling seriously threaten the safe operation of these major engineering facilities. However, most marine engineering structures currently remain bare or under-protected, raising serious safety concerns and causing enormous corrosion losses. Ensuring the durability and safety of various marine engineering facilities, reducing catastrophic accidents, and extending service life are critical and common issues urgently needing resolution in China' s economic development.

Over the past decade, China' s harbor, bridge, tunnel, and coastal engineering construction has flourished, with rapid growth in steel and reinforced concrete structures in coastal areas. In sea-crossing bridge construction, recently completed and ongoing projects include the Donghai Bridge, Hangzhou Bay Bridge, Xiamen Haicang Bridge, Zhoushan Mainland-Link Island Project, Shanghai Yangtze River Bridge, and Qingdao Bay Bridge. Offshore oil development represents a key focus of China' s marine exploitation, with nearly 200 marine steel oil platforms already constructed. In port construction, major facilities such as the Caofeidian Terminal are under construction. Major marine engineering facilities are typically designed for service lives of 50 years or more. However, under synergistic effects of multiple marine corrosion environmental factors, investigations show that some Chinese harbor facilities have experienced steel reinforcement corrosion within 10–20 years of construction. Estimated annual corrosion losses for reinforced concrete exceed 100 billion yuan. Numerous existing coastal facilities in China are entering a high-risk period for corrosion damage, seriously threatening normal operations and inevitably causing severe economic and social losses. These facilities urgently require scientific corrosion control and repair. This is no longer merely a technical issue but an important matter concerning national development and social progress.

3. Recommendations for Future Development of Marine Corrosion Protection in China

In today' s climate of intense international competition for marine resources, it is necessary to address China' s major needs for corrosion and fouling protection of marine engineering facilities by conducting research on marine corrosion and bio-corrosion mechanisms and protection technologies. This will solve common and critical issues in marine engineering corrosion protection while integrating marine engineering facility corrosion protection into national strategy, raising the priority of marine corrosion protection and promoting the development of China' s marine anti-corrosion industry at the national level.

(1) **Research on processes and mechanisms of marine environmental factors affecting corrosion.** Research should focus on the mechanisms by which marine environmental corrosion factors affect the corrosion processes of commonly used engineering materials. Studies should examine how wet-dry cycling, alloying elements, protective coatings, light exposure, and corrosion product structure influence the corrosion mechanisms of steel and reinforced concrete structures. This research should reveal the corrosion mechanisms induced by the five marine corrosion zones (marine atmospheric, splash, tidal, full immersion, and seabed mud zones) and identify core elements of corrosion protection to provide scientific basis and countermeasures for the design and anti-corrosion of offshore oil platforms and subsea pipelines.

(2) **Key processes, mechanisms, and protection technologies for marine biofouling corrosion.** Research should address microbiologically influenced corrosion and biofouling in marine environments by investigating microbial corrosion mechanisms in different sea areas. The focus should include analyzing the composition and structural evolution of biofilms on material surfaces, proposing corrosion mechanisms by which microorganisms induce corrosion in typical marine engineering metallic materials, and examining the mutual promotion and inhibition processes between calcareous deposits formed on steel surfaces under cathodic protection

and fouling biological communities. This research should reveal the mechanisms by which microbial activities affect localized corrosion of metallic materials and elucidate at the molecular level how material types, surface physicochemical properties, and bioactive molecules influence biological attachment processes to enable control of biofouling. Based on this theoretical research, marine biological corrosion and antifouling technologies should be developed based on material surface physicochemical properties, surface microstructure, and photocatalytic characteristics.

(3) **Development and application of marine corrosion protection and monitoring technologies.** Integrated marine environmental corrosion protection technologies should be developed to meet marine corrosion protection needs, including steel structure splash zone corrosion protection, marine reinforced concrete structure corrosion protection and repair/strengthening technologies, marine corrosion monitoring technologies, and corrosion detection and early warning systems. Technical performance testing specifications, field construction quality specifications, and field quality inspection specifications should be established to form an advanced anti-corrosion design standard and quality management system. Based on this foundation, nearshore corrosion monitoring experimental stations and corrosion protection technology demonstration bases should be established to accelerate technology promotion and transformation.

(4) **Standards and awareness in marine corrosion protection.** Building upon marine anti-corrosion and antifouling technology research, it is necessary to accelerate the establishment of enterprise, local, and national standards for marine corrosion protection technologies to guide the healthy development of the corrosion industry and ensure safe operation of marine engineering facilities while reducing economic losses. Simultaneously, marine corrosion education and popular science outreach should be strengthened to enhance professionals' awareness of marine corrosion protection through specialized technical training and to improve public corrosion protection consciousness through media campaigns.

References

[1] Hou Baorong. *Marine Corrosion Environment Theory and Its Application*. Beijing: Science Press, 1999.

[2] Jia R, Tan J, Jin P, et al. Effects of environmental parameters on marine corrosion behavior of Q235 steel in aerobic conditions. *Electrochimica Acta*, 2010, 55(5): 1528-1834.

[3] Wu J, Zhang D, Wang P, et al. The influence of *Desulfovibrio* sp. and *Pseudoalteromonas* sp. on the corrosion of Q235 carbon steel in natural seawater. *Corrosion Science*, 2016, 112: 552-562.

[4] Zhang D, Li H, Lin Z, et al. A study of the microbiologically influenced

corrosion of 304 stainless steel by the *Desulfovibrio vulgaris* biofilm. *Bioelectrochemistry*, 2015, 101: 14-21.

[5] Qi P, Wan Y, Zhang D. Impedimetric biosensor based on cell-mediated bioimprinted films for bacterial detection. *Biosensors and Bioelectronics*, 2013, 39(1): 282-288.

[6] Wan Y, Lin Z, Zhang D, et al. Impedimetric immunosensor doped with reduced graphene sheets fabricated by controllable electrodeposition for the non-labelled detection of bacteria. *Biosensors and Bioelectronics*, 2011, 26(5): 1959-1964.

[7] Wang P, Zhang D, Lu Z, et al. Fabrication of slippery lubricant-infused porous surface for inhibition of microbially influenced corrosion. *ACS Applied Materials & Interfaces*, 2016, 8(2): 1120-1127.

[8] Zhang D, Li H, Chen Y. *Ag@TiO2* phototoxicity for bacteria. *Journal of Hazardous Materials*, 2011, 186(1): 306-312.

Author Biographies

Hou Baorong is an Academician of the Chinese Academy of Engineering, Professor at the Institute of Oceanology, Chinese Academy of Sciences, and Director of the National Research Center for Marine Corrosion Protection Engineering Technology. For nearly 40 years, he has dedicated his career to marine corrosion protection technology research, leading investigations of China' s offshore corrosion environment and establishing the theoretical system for marine corrosion environments. E-mail: baoronghou@163.com

Zhang Dun is a Professor at the Institute of Oceanology, Chinese Academy of Sciences, awardee of the CAS Hundred Talents Program, and Director of the CAS Key Laboratory of Marine Environmental Corrosion and Biofouling. She also serves as Vice President of the Chinese Society for Corrosion and Protection and Director of the Marine Corrosion and Biofouling Committee of the Chinese Society for Oceanology and Limnology. Her research focuses on marine environmental corrosion and biofouling. E-mail: zhangdun@qdio.ac.cn

Note: Figure translations are in progress. See original paper for figures.