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Measurement and Repair Techniques of Corroded Underwater Piles: An Overview

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ABSTRACT
The subsea infrastructure surrounded through water such as piles, are important for the today's civilization and plays a dynamic role. Piles largely support all the underwater structure and counted as one of the necessary elements for underwater structures. Piles in seawater are continuously attacked by the aggressive environment and suffers from the corrosion of reinforcement. Corrosion is the major cause of the piles destruction in marine environment. The failure of even one pile can cause loss of life and product, thus the goal of this study is to examine the marine corrosion repairs of underwater piles. This study presents several repair and measurement methods of corroded underwater piles.
Keywords: Cathodic protection, corrosion, fibre reinforced polymers, piles, repair, underwater structure

I. INTRODUCTION

The offshore and coastal structure plays a dynamic role and their construction increases day by day. Coastal and marine structure or commonly speaking any construction surrounded through water is important for the today's civilization**.** Many industries have built a large number of underwater structures worldwide for example piers, retaining walls, piles, and docks, communication cables**,** pipelines, deep-water storage, shore facilities, sea wind farms etc. that are constructed for diverse utility wherein piles are considered as one of the crucial key element because these largely supports all the underwater structure [1-3].

Nowadays, Corrosion of piles is a primary reason for the deterioration of the underwater structure and significant attention has been received by the topic of marine corrosion [4-5]. Corrosion is a natural process that is well defined as the electrochemical reaction between a metal and its environment. It changes the properties of the metal and may lead to loss of the metal and its mechanical properties such as strength, ductility and impact strength [6-7]. Worldwide, the annual cost of corrosion is around 1.8 trillion US Dollars (3% of the world's gross domestic product) which is estimated by the world corrosion organization. Francis [8], Frankel [9] reported that the underground and underwater metals are most susceptible from corrosion. It is most hazardous as a result of chlorides, moisture, oxygen and alternative marine factors continuously attacks on pile [3, 10-11].

The rate of incident is highest as a result of deterioration of the underwater structure [12]. The economy, the environment, and the human beings will seriously affect and also an interruption of working as a result of the collapse of even one pile [13-15]. Rizzo [2] reported that the expected design life of the underwater structure is often 25-30 years, but Corrosion crisis must be taken into account throughout the construction of the underwater structure [16].

Usually, the "chip and patch" method (whereby all loose material is removed and the section re-formed with new material to cover the affected areas) is used for repairing corrosion damage pile but due to its negative efficiency, there has been alternative methods such as cathodic protection, fiber reinforced polymer (FRP) wraps and fiber reinforced polymer incorporating cathodic protection are used for corrosion repair of piles [17-18]. Mullins *et al.* [19] described a demonstration study in which underwater repair of the corroding pre-stressed piles of Allen Creek Bridge using fiber reinforced polymer wrap and the results of this study indicated that the efficiency of the wrapped piles were consistently better than the unwrapped control piles. Sen and Mullins [20] demonstrated the protection of corroding piles supporting the Friendship Trail Bride in Tampa bay at the north coast of Florida using fiber reinforced polymer incorporating cathodic protection (FRP-CP) and results of this study indicated that the FRP-CP system can prevent and extend the life of piles in a corrosive marine environment.

The costly repair and maintenance works might have additionally to be undertaken if timely remedial action is not taken [4]. Hence, finally the repair of corrosion pile and cyclic inspection is essential before the collapse of the structure because demolition is intolerable and replacement is unfeasible [21-22].

II. CORROSION MEASURING METHODS

2.1 Overview

Corrosion measurement is necessary to assess the severity or rate of corrosion. It is required for durability, safety of structure, and confirming repair or maintenance methods [21, 23]. The methods can also be used for checking the efficiency of corrosion methods i.e. to check whether the adequate corrosion control has been achieved or not by the corrosion methods. The corrosion can be measure using any one of the following technique:

2.1.1 Half-cell potential test

This test was developed in the 1960s for corrosion measurement and comprised by ASTM standard C876 [23]. It is an electrochemical technique used to evaluate the rate of corrosion and classify the chloride infected boundaries [24]. This test comprises high impedance voltmeter and a standard reference electrode such as copper-copper sulfate electrode [25].

The reference electrode is placed by drilling a hole into the structure. The holes should be cleaned with fresh water and compressed air for removing the deleterious substance. Before placing reference electrode, holes should prefill with low resistivity grout then after reference electrode inserted in holes. The reference electrode is connected to the copper wire and the wire will fix into the grooves made in concrete and covered with grout. These copper wire for reference electrode was routed into the junction box where they were connected to the reinforcement and protected from the environment [19-20]. The test is conducted by connecting the negative and positive end of the voltmeter to the reference electrode and steel bars respectively.

After arrangement, half-cell potential readings are taken and can be plotted on equipotential contour map [25]. Potential recorded in the half-cell potential test is used to an interpretation of corrosion reading as summarized in Table 1. For illustration, the more positive reading of potential is generally indicates the less corrosion.

Table 1 Half-cell potential readings [25]

S.no.	**Half-cell potential readings (in volts)**	**Corrosion probability**
1	Less than -0.200	90% probability of no corrosion
2	-0.200 to -0.350	Uncertain
3	More than -0.350	90% probability of corrosion

2.1.2 Linear polarization test

Linear polarization is the best method for measuring the corrosion rate of metal embedded in concrete and also known as polarization resistance. The PR-Monitor (Cortest Columbus tech.), the NSC Device (Nippon steel corp.), the Gecor Device, and the 3LP Device etc. are used to measure the corrosion rate [26]. Linear polarization relies on the linear relationship between the corrosion current and its potential when the equilibrium potential is disturbed by the application of an incremental current or incremental voltage [19, 23].

The slope of linear polarization curve as follows:

$$R_p = \frac{\Delta E}{\Delta i_{app}} = \frac{11 \times 10^6 \times B}{X \times A} \qquad \text{(i)}$$

Where
R_p= Polarization resistance in ohm (volts/amperes)
B = Tafel constants, for concrete vary typically from 26 to 52 mV depending on the passive or active condition of the steel
A= Surface area of the steel measured
X= Corrosion rate in micro meter per year (µm/year) or mils per year (m/year)
Equation (i) can be used to calculate the corrosion rate of the system.
The measurement of the corrosion rate requires [19]:

- A working electrode, the element whose corrosion rate is to be determined.
- A reference electrode, to measure the electrical potential of the working electrode.
- An auxiliary or counter electrode, to apply a current and complete the circuit.

The setup for linear polarization measurement technique is shown in Fig. 1

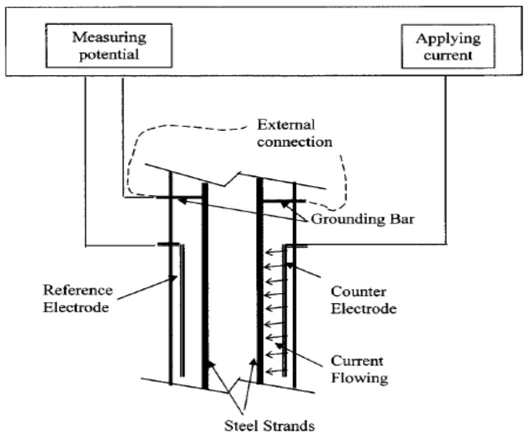

Fig. 1 Setup for linear polarization measurements [19]

The reference electrode and counter electrode embedded in concrete and connected to the PR-monitor. The reading is taken by varying the voltage in steps from zero to 15 mV, with the current adjusted accordingly. The slope of the change in potential and applied current gives the polarization resistance, Rp [19]. After finding Rp, the corrosion rate is calculated by equation (i). Interpretations of values for i_{corr} are summarized in Tables 2 and 3.

Table 2 Interpretation of Linear Polarization Results [26]

S.no.	i_{corr} (μA/cm^2)	Corrosion level
1	< 0.1	Low corrosion
2	0.1 to 0.5	Low to moderate corrosion
3	0.5 to 1	Moderate to high corrosion
4	> 1	High corrosion

Table 3 Correlation of corrosion rates to section loss [26]

S.no.	i_{corr} (μA/cm^2)	Section loss (mils/year)
1	0.1	0.04
2	0.5	0.22
3	1	0.45
4	10	4.49

2.1.2.1 Advantage

- This technique may be used for accurately measuring the very low corrosion rate i.e. less than 0.1 mils per year [27].
- This technique may also be used for rapid corrosion rate measurement [27].

2.1.2.2 Disadvantage

- This test cause error up to 50% because the approximation comprises by this method in the calculation [27].
- Another disadvantage is that the test is sensitive to factors such as humidity and temperature. Corrosion rate measurements will increase in warm conditions. Since the resistivity of concrete decreases when the concrete is wet, corrosion rate measurements increase in wet conditions [28].

2.1.3 Polarization decay test

The performance and monitoring of the cathodic protection system are given by the polarization decay test. This test is also known as an instant-off test [29] as it conducted only in two days.

On the 1st day, an instant-off reading taken by temporarily cut off the connection between steel reinforcement and anode. This instant off readings shows the more negative or polarized potential against a reference electrode because taken immediately after the connection between anode and steel cut off i.e. system provides an electron to steel as a result, the steel becomes more negative [20, 22].

On the 2nd day i.e. after 24 hrs, once again the potential readings (i.e. stabilize readings) taken. This reading shows the less negative or depolarized potential against a reference electrode, because taken after 24 hrs i.e. temporarily cut off the connection between anode and steel, stops the supply of electron [20, 22].

The difference between these two readings shows the polarization decay. According to NACE SP0169 [30], when the polarization decay shows a minimum of 100mV potential with respect to a reference electrode, then the cathodic protection system shows full protection.

2.1.4 Galvanic current test

The performance and monitoring of the FRP system are given by the current density. Current density required the measured electric current and the surface area of protected steel. It maintains the protection level of steel and provides rapid polarization [30-32]. The data loggers are utilized to automatically record the electric current and recorded data is regularly downloaded from the site. The current density can be determined by dividing the measured electric current by the surface area of protected steel [20, 22]. The measured electric current is not constant but influenced by the water velocity and the concrete resistivity. Generally, dry concrete has a higher resistivity compared to the wet concrete [32].

The current density can be plotted on the graphs for a different element. On the comparison, the system has less current density shows the reduced corrosion rate [20, 22].

III. CORROSION REPAIR METHODS

3.1 Cathodic protection

Cathodic protection was invented by the Sir Humphrey Davy in the year 1824 [27]. Cathodic protection removes whole corrosion, while working. Cathodic protection is unique, steady process and always requires precise knowledge about the quality of corrosive medium [33-34].

The basic principle of cathodic protection is the continuous supply of electron to the steel by external sources i.e. to supply electric current to steel. If electrons are supplied to the steel by an external source, then the anodic reaction will be blocked. Due to blocking of anodic reaction, results lowering the potential of steel and there is no flow of electron between the anode and cathode, so corrosion will be stopped [35].

Prevention of corrosion in the cathodic protection process depends on the current density [31]. The current density is defined as the cathodic protection current per unit area of steel surface i.e. ampere per square meter that maintain the protection level of steel and provide rapid polarization [31-32]. Current densities are given in Table 4 for bare and coated steel in seawater. It is sometimes affected by oxygen and water velocity thus, these factors should be considered in cathodic protection process [32].

Table 4 Current Densities for marine structure [31]

S.no.	Cathodic protection system	Required current (mA/m^2)	
		Bare steel	Coated steel
1	Below mud line	22	11
2	In water	54	27
2	Water velocity up to 0.60 m/sec	110	-
3	Water velocity > 0.60 m/sec	220	-

For achieving the cathodic principle, it is essential to assemble the electrochemical cell with an auxiliary anode that can work properly in electrolyte and steel being the cathode [35]. There are two methods of achieving these requirements, one is galvanic anodes or sacrificial anode and second is immersed current and sometimes combination of both methods used for underwater structure, where there is sufficient conductivity to maintain the proper working of the cell [33-35]. The cathodic protection can be achieve any one of the following technique:

3.1.1 Galvanic anodes or sacrificial anode method

- In this method, cathodic protection can be achieved by attaching a less noble or more active anode to a structure, resulting in the new anode being corroded faster than the protected material [36].
- The driving electric current between anode and structure is provided directly by the potential difference between the materials i.e. generation of a galvanic cell between two metal with different potential [37].
- The new anode is corroded during the protection of steel thus, it is called as a sacrificial anode [27].
- The galvanic anode should be placed very close to or in contact with the protected structure by either welding or clamp [31].
- Zinc, magnesium, and aluminium are most widely used the material as a sacrificial anode for protecting the steel structure because they are more active than the steel [35]. Sacrificial anode doesn't require any maintenance except replacement at a suitable interval when to corrode [38].
- Generally it is very difficult and costly to replacing the anode on the stationary structure thus, galvanic anode system should be designed for 10 years or more [31, 38].

3.1.2 Impressed current method

- In this method, cathodic protection is achieved by application of a current from an external source such as DC transformer/rectifier, connected to an inert anode. The structure is cathodically polarized or lowered potential of steel, so protect the structure [35, 39].
- The negative terminal and positive terminal of the external source is connected to the structure and anode respectively, with the help of cable [31].
- The consumption rate or corrosion rate of immersed current anode is very low compared to a galvanic anode, even at high current densities because anodes are inactive [40].
- The impressed current anode should be placed well separated from the protected structure and if it is required to place very close to the structure, then dielectric shield should be provided between anode and structure [31].
- Impressed current system requires high maintenance cost and should be designed for 20 years or greater life [31, 33].
- This method is utilized for structure, where electric current is available [31].
- High silicon iron, platinized titanium, lead-silver alloy, graphite are most widely used as immersed current anode [31, 38].

The comparison of both methods is given in Table 5:-

Table 5 Comparison of cathodic protection method for marine structures [33]

S.no.	Property	Galvanic anode method	Impressed current method
1.	Cost of installation	Medium	High
2.	Maintenance	Practically not	Yes
3.	Anode weight	High	Small
4.	Anode number	Large	Small
5.	Life	Limited	High
6.	Current output	Limited (self - regulating)	Controlled (manual or automatic)
7.	Current distribution	With many anodes good	Less good with few anode

8.	Damage	No	Yes
9.	Running cost	Favorable with small object	Favorable with large object
10.	Usual life	Over 10 year	Greater than 20 year

3.2 Fiber reinforced polymer (FRP) repair
3.2.1 Overview

The recent evaluation by the Florida Department of Transportation (FDOT) indicates that the cost of cathodic protection for pile repair was very high i.e. $1728/ft. (Aguilar, 2011). Due to the high cost of cathodic protection, Mullins *et al.* [19], Mullins et al. [41], and Sen *et al.* [42] explored the new technique such as fiber reinforced polymers (FRP) for lowering the cost of pile repair.

Fiber reinforced polymer is defined as a composite material containing the fibers and polymer where fibers floating in the polymer resins matrix [23]. Usually, glass fiber reinforced polymer (GFRP), carbon fiber reinforced polymer (CFRP), and aramid fiber reinforced polymer (AFRP) were used as FRP material. Glass fiber has the low elastic modulus and tensile strength as compared to carbon and aramid fiber. The fibers were selected to ensure that they provide adequate strength [19, 23, 43]. FRP can provide strength in any desired direction and can also be aligned as required. Repair of pile against corrosion become more versatile and cost effective by the application of FRP. FRP repair also useful where high speed and ease construction required such as underwater substructure element [22, 43]. FRP repair is a very emerging technology for structural repair of corrosion damaged pile due to the negative efficiency of the chip and patch method. Over the past decade, it has also made the ideal repair material for the reduction in corrosion rate due to the lightweight, high strength, and corrosion resistance of FRP [44]. FRP wrapped pile reduces the corrosion rate by preventing the entry of harmful materials similar to moisture, chlorides, and oxygen, but the efficiency of FRP is deepened on its bond with concrete [23, 43, 45].

3.2.2 Surface preparation

The surface of the pile should be clean so that proper bond can be achieved by the FRP over concrete. It can be done by the following operation removing the marine growth using scrapper, chipping the projection part of concrete using hammer and chisel, chamfering and smoothing of corner using underwater grinder, removing the dust and debris using clean water [11, 19, 43].

3.2.3 Access to the pile

Scaffolding, divers, boats may be used for the wrapping of FRP around pile [43, 46] as shown in Fig. 2.

Fig. 2 Fiber reinforced polymer wrap using divers [43]

3.2.4 FRP- Concrete bond

The bond between FRP and concrete can be improved by following methods:-

3.2.4.1 Pre peg system

It is water-activated urethane resin system that is used in combining with FRP fiber. FRP material must be saturated with resin in the factory and delivered to the site in air tight seal pouches because it is water-cured. For preventing premature curing from atmospheric moisture, it must be removed from pouches at the site just prior to the wrap. This system is useful for the dry region [22, 41, 43].

3.2.4.2 Wet layup system

Tyfo® SW-1 underwater epoxy is used for this system [47]. FRP material must be saturated with resin on the site just prior to the wrap as shown in Fig. 3. This system provides greater flexibility to the wrap but required precise preparation and take a large time to saturate the fabric. To overcome this problem, the FRP should be saturated with resin on site manually. This system is difficult to carry site because it is heavy. This system is useful for partially wet and submerged region [22, 43, 48].

Fig. 3 Mechanically saturation FRP on site [20]

Pre-peg and wet layup system are not useful where gravity effect comes into consideration such as vertical element (i.e. column and pile). To oppose the gravity effect, a uniform external pressure is required. The "pressure bagging" and "vacuum bagging" systems can be used to supply the uniform external pressure. This new system improves bond between FRP and concrete and it is simple, easy to use, cost-effective, and useful in both wet and dry system [49-50]. Before placing this system, FRP should be covered with plastic shrink material so that normal pressure can be given for necessary confinement to FRP wrap.

3.2.4.3 Pressure bagging

Pressure bagging is suitable for wet layup system. It is easier to use and gives better bond because it doesn't need a hermetic seal [51]. It is work on the same concept as blood pressure instrument used in medical. The component like air-tight bladder is required for this system which attaches inside the pressure bag and wrapped around the pile over FRP and plastic wrap. The uniform external pressure is given to inflating the bladder by compressed air and secured around pile by fastening. It doesn't remove until the resin has cured [20, 22].

3.2.4.4 Vacuum bagging

Vacuum bagging is suitable for pre-peg system. The external pressure is given by the provision of vacuum up to a maximum of 1 atmosphere (i.e. 760 mm of mercury). The component like an air-tight seal, vacuum bag, and vacuum pump for the application of the vacuum is required for this system. The maintenance of air-tight seal is very difficult, especially where concrete elements are cracked [20, 22]. The vacuum bagging system shown in Fig. 4.

Fig. 4 Vacuum bagged system [24]

FRP can slow down the corrosion rate but can't stop the corrosion of steel because the lower consumption of anode for FRP wrapped pile. The lower consumption of anode results in a higher life of anode due the reduction in current density [19, 24].

3.3 FRP-CP repair

3.3.1 Overview

Generally, CP stops corrosion but it can't be used alone because of its high cost. The FRP wrap also can't be used alone because it doesn't stop the corrosion only slow down the corrosion rate. Thus the development of new FRP-CP system which has to incorporate the CP system inside the FRP wraps. This system is versatile in which CP system stops corrosion and the FRP wrap slow down the corrosion rate and provide strengthening the pile while act as a barrier [20, 22]. The FRP-CP system has low-cost corrosion repair due to the low cost of fiber material.

3.3.2 Installation of CP system

In an embedded FRP-CP system, fiber reinforced polymer system wrap over the cathodic protection system. The installation of CP system requires the anode, reference electrode, and bulk anode. Reference electrodes are used to monitor the performance of the CP system. The bulk anode is used to provide protection below the water line. Holes drilled insufficient length for proper horizontal placement of long anodes. Holes should prefill with low resistivity grout then after anode inserted in holes. Before placing anode, the holes were cleaned with fresh water and compressed air for removing any deleterious substance. The placing of anode shown in Fig. 5.

Fig. 5 Anode being placed in grout filled hole [20].

The embedded anodes are connected by a single continuous copper wire and the wire fixed into the groove cut in concrete and covered with grout. The reference electrode is also placed in the same manner. The bulk anode is separately bolted to the pile and also electrically connected prior to wrapping with FRP [20, 22]. These copper wire for embedded anode, a bulk anode, and a reference electrode are routed into the junction box where they were connected to the reinforcement and protected from the environment. The junction box contained the switch for disconnect the anodes and data loggers for monitoring CP performance & recording anodic current [11].

After 1 to 2 months the installation of CP system, the FRP wrapping contained two glass or carbon fibre reinforced layers (GFRP) applies over the pile. The delay in FRP wrapping allows the CP system to stabilize. For improving the bond between FRP and concrete, the pressure bag or vacuum bag is applied over the FRP wrap and inflated by providing a uniform pressure.

IV. SUMMARY

Marine piles are located in a corrosive marine environment, such as salts, chloride, and oxygen, thus, corrosion of piles in underwater is one of the most expensive and risky problem. Corrosion of piles affect the durability of underwater structure and causes threatening of life and products. This report summarizes the corrosion measuring methods and their repair methods. This study presents an overview of the fiber reinforced polymer (FRP) and fiber reinforced polymer incorporating cathodic protection (FRP-CP) for repairing corrosion damaged piles.

This study presents the three field studies utilizing different corrosive prevention methods. Based on three field studies following conclusions are made:

- Wet-layup, Pre-peg, pressure bagging and vacuum bagging methods are used for improving the bond between FRP and pile.
- Cathodic protection is the best proven method for preventing corrosion in underwater piles but it can’t be used alone because of its high cost.
- Fiber reinforced polymer (FRP) is the best method for reducing the rates of corrosion due to its high resistance to corrosion property.
- Fiber reinforced polymer (FRP) is useful where high speed is required due to its light weight property.
- Fiber reinforced polymer incorporating cathodic protection (FRP-CP) is the best method for protecting the steel from corrosion.
- Fiber reinforced polymer incorporating cathodic protection (FRP-CP) system has low cost corrosion repair in which FRP slow down the corrosion rate and cathodic protection stop the corrosion.

Thus, overall CP, FRP, and FRP-CP systems can increase and preserve the life of marine piles in an aggressive environment.

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