

Appendix-4: Corrosion Protection of Port Concrete Structures by Cathodic Protection Methods

1. Overview of Cathodic Protection Method

1.1 Introduction

In marine environments, steel materials are highly susceptible to corrosion due to chlorides supplied from seawater. Even in reinforced concrete structures, reinforcing steel embedded inside the concrete becomes far more prone to corrosion than in ordinary environments as a result of the ingress of external chlorides.

Photos 1 and 2 show the deterioration of concrete beams and slabs in the superstructure of a pier. When corrosion of the internal reinforcing steel progresses due to chloride ingress, the concrete cover eventually spalls off. Furthermore, as the cross-sectional area of the reinforcing steel is reduced by corrosion, the load-bearing capacity of the member decreases, leading to a loss of structural safety. One of the countermeasures against chloride-induced deterioration of concrete structures is the application of cathodic protection. In recent years, the number of applications has increased due to its high corrosion protection performance. This section outlines the cathodic protection methods for concrete structures.¹⁾



Photo 1 Deterioration condition of the pier superstructure (beam)



Photo 2 Deterioration condition of the pier superstructure (underside of slab)

1.2 Principle and Characteristics of Cathodic Protection²⁾

Figure 1(a) illustrates the condition in which reinforcing steel inside concrete is corroding due to the ingress of chloride ions (Cl^-). In this state, a corrosion current flows as a result of the potential difference generated between the corroding region (anodic area) and the non-corroding region (cathodic area).

Figure 1(b) shows a condition in which a direct current is applied from an anode installed on the concrete surface toward the internal reinforcing steel that is electrically connected to it. Because the current preferentially flows to the cathodic area, which has a more noble (+) potential, the potential of the cathodic area shifts in the more active (-) direction. As the applied current increases, the potential difference between the anodic and cathodic areas is eliminated, and the corrosion current ceases to flow. This is the fundamental principle of cathodic protection.

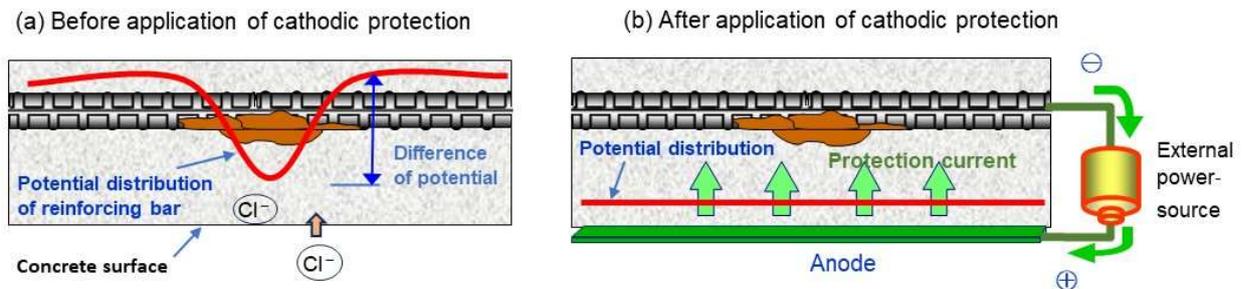


Figure 1 Principle of Cathodic Protection

As described above, the cathodic protection method is a highly reliable and rational corrosion protection technique because it controls the corrosion reaction itself through electrochemical action. In addition, the cathodic protection method has the following advantages:

Even when a large amount of chloride ions has already penetrated into the concrete, it is not necessary to remove the chloride-contaminated concrete. Although simple surface treatment or partial repair may be required in some cases, cathodic protection can be applied while maintaining the existing condition.

When cathodic protection is applied to members where the concrete cover has partially spalled, section repair must be carried out after cleaning the reinforcing steel. If the countermeasure consists only of conventional section repair, the reinforcing steel must be sufficiently exposed and carefully treated with anti-corrosion measures to prevent re-corrosion. In contrast, with the cathodic protection method, it is sufficient to remove rust from the exposed reinforcing steel, and anti-corrosion treatment is not required, which makes construction easier.

After completion of cathodic protection installation, the condition of the internal steel (e.g., potential) is generally monitored continuously. This makes it possible to quantitatively confirm the corrosion protection effect and to respond promptly even if any abnormality occurs.

2. Types of cathodic protection methods

2.1 Methods of Supplying Protective Current

Cathodic protection methods are classified into the impressed current system and the galvanic (sacrificial anode) system, depending on the method of supplying protective current.

In the impressed current system, as shown in Figure 2(a), an anode system installed on or near the concrete surface is connected to the positive (+) terminal of a DC power supply, while the steel to be protected is connected to the negative (-) terminal. Cathodic protection is achieved by supplying protective current between the two using the DC power supply.

In contrast, in the galvanic anode system, as shown in Figure 2(b), an anode system made of a metal that is electrochemically less noble than the steel embedded in concrete is installed on or near the concrete surface and electrically connected to the steel. By utilizing the potential difference between the two, protective current flows and cathodic protection is achieved. This system has the advantage that no external power supply is required; however, its service life is shorter than that of the impressed current system.

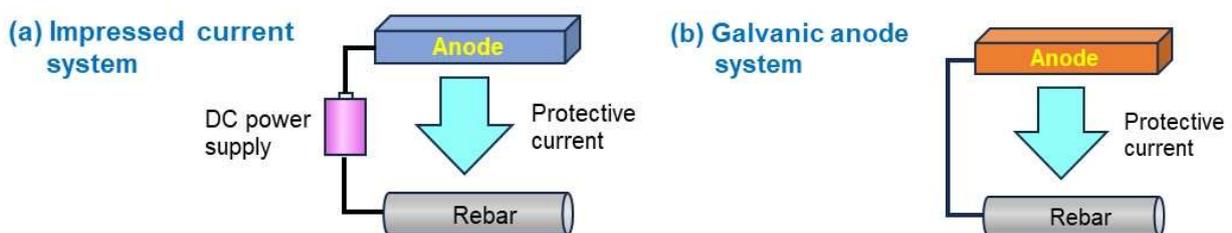


Figure 2 Differences in Protective Current Supply Methods

Cathodic protection suppresses the corrosion reaction in which iron is ionized by supplying protective current; therefore, steel corrosion is inhibited as long as the current is supplied. When applying cathodic protection, the following points should be confirmed:

- i) Environmental conditions, installation costs, and the service life of cathodic protection equipment should be examined.
- ii) Anode materials that can withstand continuous current application should be selected, and it should be confirmed after installation that the protective current is flowing appropriately.

In addition to initial costs such as equipment expenses, the impressed current system requires running costs, including current management, replacement of external electrodes, and electricity charges. When adopting this method, it is necessary to consider the purpose and importance of the repair of the structure and to evaluate the service life of the structure and its life-cycle cost.

2.2 Types and Shapes of Anodes

Depending on their shape, anodes are classified into surface-type, linear-type, and point-type, as shown in Figure 3.

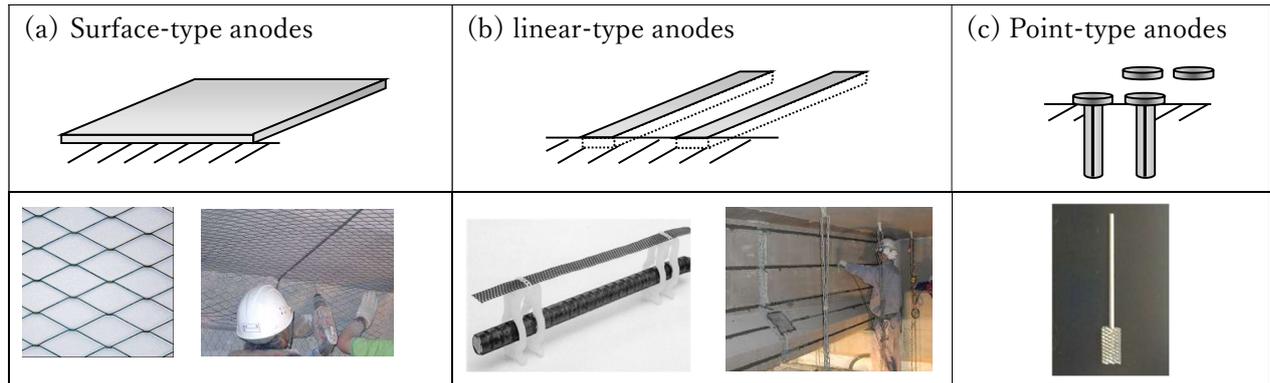


Figure 3 Types and Shapes of Anodes

Surface-type anodes are suitable for cases where a wide protection area is required and provide excellent uniformity of protective current. However, the area of overlay covering the anodes becomes large, resulting in a greater amount of construction work and higher costs.

For linear-type anodes, methods include embedding the anodes in grooves formed on the concrete surface or bonding them directly to the concrete surface. Compared with surface-type anodes, these methods are easier to construct and more cost-effective.

Point-type anodes are installed by drilling holes in the concrete surface and inserting rod-shaped anodes. They are suitable for localized cathodic protection.

3. Construction and Management of Cathodic Protection Works

3.1 Construction Procedure

A typical construction procedure is shown in Figure 4.

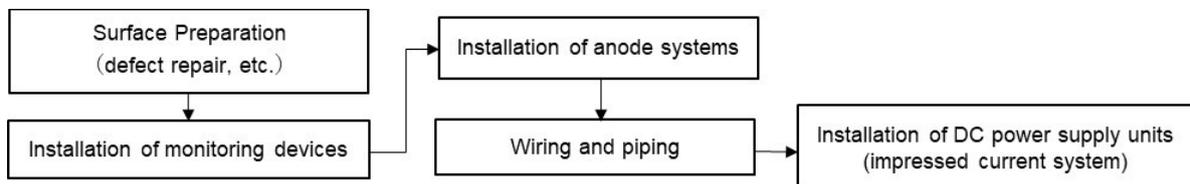


Figure 4 Typical construction procedure

3.2 Surface Preparation

As surface preparation, the area to be protected by cathodic protection is cleaned by blasting. In addition, repairs are carried out at locations where the concrete section has delaminated or spalled, and exposed metal fragments on the surface are removed. When the concrete cover has extensively delaminated, it is necessary to remove the concrete in that area to expose the reinforcing steel. The exposed reinforcing steel is cleaned to remove rust;

however, if the reinforcing steel has been lost due to corrosion, additional reinforcing bars must be installed.



Photo 3 Surface Preparation

3.3 Installation of Monitoring Devices

To install monitoring devices such as reference electrodes and drain terminals for electrically connecting the anodes and the internal steel, part of the concrete is chipped away to expose the reinforcing steel, and these devices are then installed.

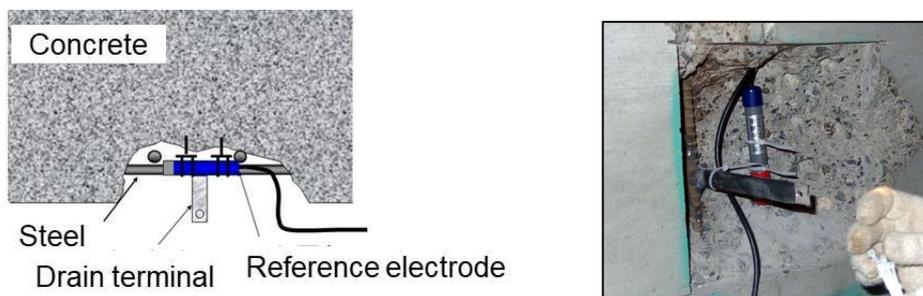


Figure 5 Installation of Monitoring Devices

3.4 Installation of Anode Systems

3.4.1 Installation of Surface-Type Anodes

After completion of surface preparation of the concrete, the anodes are attached to the concrete surface using plastic nails. Segmented anodes are electrically connected to each other via distributors. To protect the anodes and to ensure uniform distribution of the protective current, an inorganic overlay mortar is applied over the anodes by troweling or spraying. When the application area is large, spraying is an appropriate method.

When applying the mortar covering the anodes, dust, debris, and other contaminants on the concrete surface should be removed in advance. To ensure reliable adhesion between the mortar and the concrete, the concrete surface must be washed with water and kept in a moist condition.



Photo 4 Installation of Surface-type Anodes

3.4.2 Installation of Linear-Type Anodes

Grooves are formed on the concrete surface to embed the linear-type anodes. The linear anodes are inserted into the grooves, and the grooves are then backfilled with mortar. As with surface-type anodes, the linear anodes are electrically connected to each other via distributors.

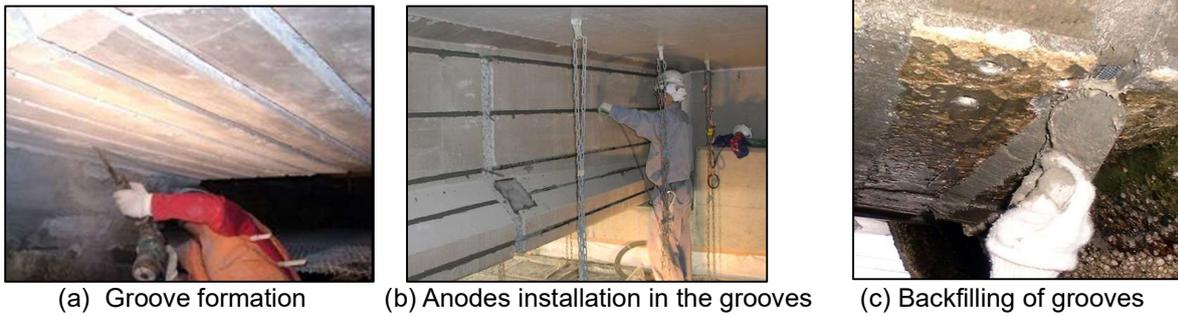


Photo 5 Installation of Linear-Type Anodes

3.5 Wiring and Piping

When installing wiring and piping to connect the anodes and reinforcing steel to external power supplies and monitoring devices, the following points should be noted:

- (1) When installing conduits or similar components, care must be taken not to damage the anodes themselves or reference electrodes embedded in the concrete by concrete drills, fixing anchors, or other tools.
- (2) Electrical connections shall be made inside junction boxes, and the connection points shall be completely waterproofed using insulating materials.
- (3) For cable connections, wiring shall be carried out accurately using a wiring termination table (the Wiring Termination Table) or similar documents to avoid any wiring errors.

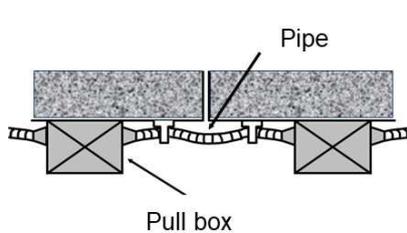


Figure 6 Wiring and Piping



Photo 6 Completion status

3.6 Installation of DC Power Supply Units

For DC power supply units, in addition to those using commercial power sources, systems using battery power or solar-powered DC supplies are also employed. The following points should be considered for DC power supply units:

- (1) They shall have the capability to supply current stably throughout the entire protection period.
- (2) All components used shall satisfy the applicable standards and be easy to replace or renew.
- (3) In regions with frequent lightning, the units shall be equipped with functions to protect the equipment from lightning strikes.

Depending on the method of controlling the protective current, power supply systems are classified into constant-

current control systems and constant-voltage control systems. The constant-current control system is the most widely adopted because it allows direct control of the magnitude of the protective current. On the other hand, the constant-voltage control system is suitable in environments where conditions such as temperature and humidity vary significantly.

When the power supply unit is of small capacity or has a limited number of circuits, it is often fixed to the wall of the structure or installed on a nearby utility pole. In contrast, when the unit is of large capacity, has many circuits, and requires a large enclosure, it is fixed on the structure itself or on newly constructed concrete foundations.



Photo 7 Installation of DC Power Supply Units

3.7 Construction Management

To prevent deterioration of concrete structures, it is necessary to continuously apply protective current over a long period by adopting cathodic protection. For this purpose, careful execution at each construction step and appropriate quality control are required.

3.7.1 Protection Control Criteria

To protect steel embedded in concrete, it is necessary to shift the steel potential in the negative direction by applying current. The target amount of potential shift is referred to as the protection criterion. In Japan, based on past experience and safety considerations, cathodic protection is regarded as being achieved when the potential shift of the steel, measured before and after current application, is 100 mV or more, and this is adopted as the protection criterion.

If an excessive protective current flows into the steel and the potential shift in the negative direction becomes too large, this condition is referred to as overprotection. In the case of prestressed concrete PC steel, overprotection may cause embrittlement due to hydrogen generated on the surface of the PC steel. Therefore, for PC steel, the steel potential shall not be shifted more negative than -1000 mV (vs. saturated copper sulfate electrode).

3.7.2 Quality Control

To prevent corrosion of steel embedded in concrete, it is necessary that the protective current continuously flows from the anodes to the steel in the concrete. Therefore, quality control during construction is essential. Among quality control measures, the following management tests are particularly important to ensure continuous and stable current application.

Table 1 Quality Control Tests Specific to Cathodic Protection Method ²⁾

Implementation Stage	Control Test	Description
After the installation of monitoring devices	Steel-to-steel continuity test	Confirm that the reinforcing steels within the protection area are electrically connected. A potential difference of 1 mV or less is acceptable.
	Reference electrode operation test	Confirm that the measured steel potential is stable.
After the installation of anodes	Anode-to-anode continuity test	Confirm that the anodes are electrically connected to each other. A potential difference of 1 mV or less is acceptable.
	Anode-steel insulation test	Confirm that the anodes and the steel are electrically insulated. A potential difference of 10 mV or more is acceptable.
After the completion of wiring and piping	Trial energization test	Confirm the operational condition of the entire circuit. Verify that the steel potential shifts in the negative direction when current is applied.
After the installation of the power supply unit	Energization test	Set the current level that satisfies the protection criteria.

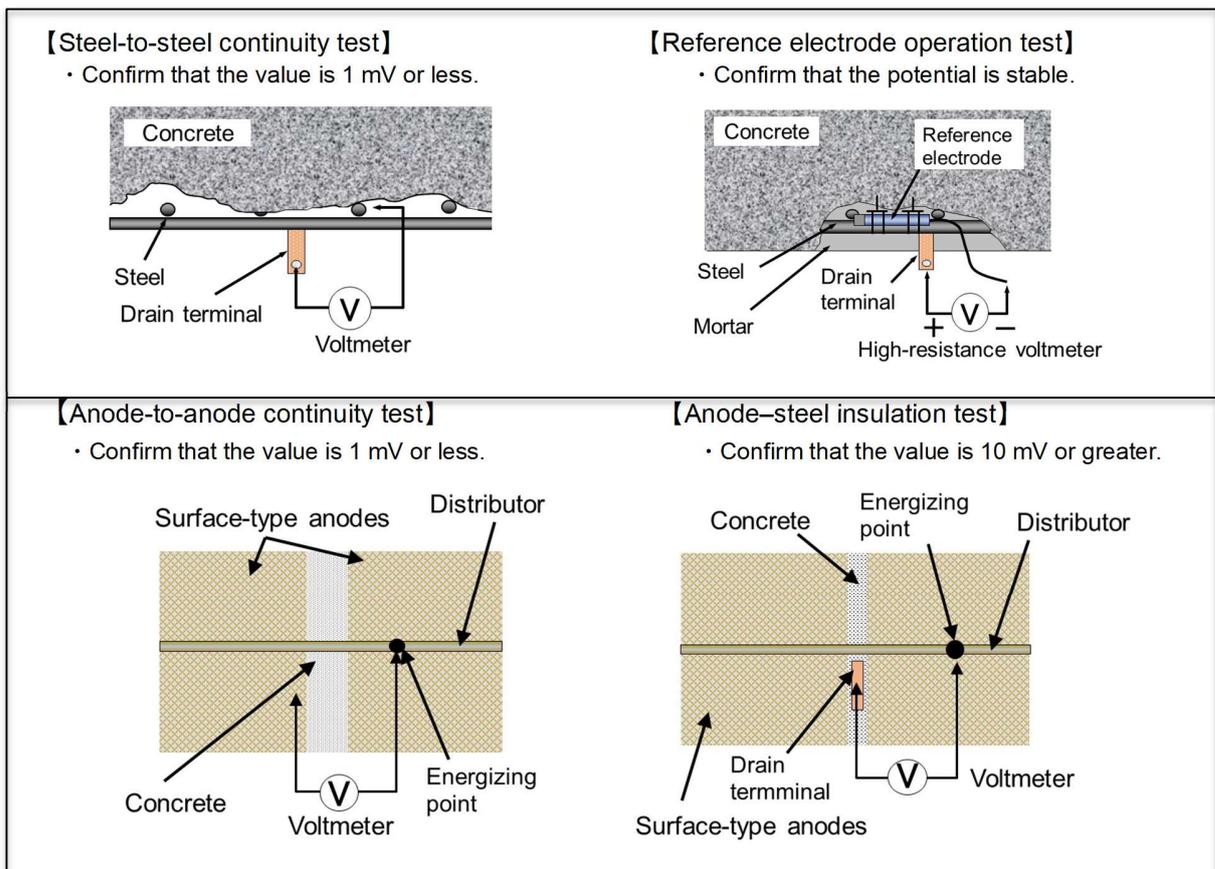


Figure 7 Method for conducting quality control tests

References

- 1)JSCE: Guidelines for Electrochemical Corrosion Control Methods, Concrete Library 157, October 2020 (https://www.jsce.or.jp/committee/concrete/e/web/pdf/LC157-common_part-.pdf)
- 2) Japan Elgard Association: <http://www.elgard.com>