AN INSIGHT INTO CATHODIC PROTECTION SYSTEMS FOR REINFORCED CONCRETE STRUCTURE

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ABSTRACT

Corrosion-induced concrete damages to concrete structures results in not only affecting the structural safety but also heavily financial burdening to the structure owners. An electrochemical method, cathodic protection (CP), for controlling corrosion of reinforcing steel in concrete involve techniques that interfere with the electrochemical reactions occurring on the embedded steel surface. When CP is selected as a rehabilitation method, there are many factors that can influence the effectiveness, durability and the cost of the CP system. To install durable and long term effective CP systems, the causes of the failures happened in the past are important information.

Key Words
Impressed cathodic protection, galvanic anode, concrete, corrosion,

INTRODUCTION

It is well known that cathodic protection (CP) is a powerful method for controlling corrosion of reinforcing steel in chloride contaminated concrete. Various types of CP systems have been developed after the first conductive asphalt system was installed in California in 1973. Unfortunately, many CP systems which had been developed failed. The reasons of the failures were obvious to some systems, but not clear to others because durable CP systems require the following factors:

1. Proper engineering design
2. Selection of durable anode
3. Proper installation and testing
4. Proper commissioning
5. Proper maintenance

If any one of these factors misses, durable CP systems cannot only be installed, but also may result in substandard performance, incompletely ineffectiveness, or a premature failure. These results are directly related to problems associated with insufficient track record, product durability, ambiguous technical specifications, poor engineering experiences and incapability of the maintenance of the systems. .

Now, after 30-years of practical experience in the US and some countries, concrete CP professionals have a better understanding of how cathodic protection works and how it can be used to effectively control corrosion of steel in concrete.

The purpose of this paper is to provide the guidelines to structure owners based on the author's numerous experiences and various projects in many countries.

FACTORS CAUSING FAILURES

The intent of use of CP is to provide long-term, effective corrosion protection to structures for the structure owners. However, many premature failures or ineffective CP systems have been installed in the past. The causes of these problems vary and some examples are:

1. Poor engineering capability and insufficient knowledge and experiences by CP professionals.
2. Selections of nondurable CP materials.
3. Selection of unsuitable CP system for a particular structure component and an environment.
4. Improper CP installation and lack of proper testing.
5. Lack of maintenance capability by the owners or contracted professionals.

When any one of the items listed above is involved, the CP system may not be durable or effective, as intended, and sometimes cause premature failures. To install effective and durable CP systems, various factors must be addressed.

Poor Engineering Capability and Insufficient Knowledge and Experiences by CP Professionals.

Both proper design capabilities and sufficient field experiences by the CP designers are one of the essential factors to install effective and durable CP systems. Increasing the popularity of CP for concrete structures in many countries naturally brings inexperienced engineers to CP projects. This unique technology has been mostly established based on the CP and concrete engineering experiences obtained from actual field projects, so that the CP designers must understand how to properly install each component of the system with proper testing and the characteristics of all CP components and associated materials used in their design rather than the theory of CP. Therefore, insufficient experiences on the materials and field works by the CP designers often result in ineffective or poor durable CP systems. Since this technology was developed 30 years ago, a number of premature failures occurred. However, many new CP designers are still repeating the same or similar mistakes which occurred in the past.

Many specifications and design drawings have been developed by various CP professionals in the past. The contents of the specifications and the design vary based on its conditions, including:

1. Structure exposing to a marine or de-icing salt environment.

2. Structure in a tropical, semi-tropical or cold environment.
3. CP for one component or multiple components of the structure.
4. Existing or new structure.
5. The concrete or structural damaging conditions for the existing structure.
6. Structure component experiencing wet-and dry conditions or constantly wet or dry environment.
7. Structure component containing complex or simple rebar configurations.
8. Structure located in a local or remote area.

The specification for each condition listed above should be somehow different when the CP designer considers these factors. However, some CP designers cannot distinguish the differences and copy the specifications or the design used for other structures. As a result, improper or misfit CP system is installed. Even though the CP system may initially be effective, it would last a short period of time.

Figure 1 shows the example of wrong application of discrete anodes to the prestressed concrete beams which were exposed to a marine atmosphere. The reinforcing steel in the lower portion of the beams were experiencing corrosion. To reduce the cost of the CP system, the designer installed only two discrete anodes from the top portion of the beam. However, the beam contains many steel components, including rebars, post-tensioned ducts. One of the advantages of discrete anodes is good current distribution when the anode is located in a proper position in the concrete component. However, the position of the discrete anodes was wrong because the internal steel components were too close to the anodes. Figure 2 shows the results of the CP performance after 3 years. To prove the ineffectiveness of the CP system, the current distribution from the anode to the surrounding steel components was analyzed using the finite element method, as shown in Figure 3.

In many cases, the result of the ineffectiveness of the CP system installed on a repaired concrete structure will not show in a short period of time, as indicative of concrete damages by the continuous corrosion of the reinforcement. Therefore, it is difficult for the owner to point out the problem immediately. In other words, after the concrete structure is repaired, the owner will not visually observe the CP effectiveness until a few years later. Therefore, it is important to select the qualified and experienced professionals for projects to minimize such risks. .

The owner of many ferry terminals in Hong Kong recently developed a training program for their in-house engineers using the actual CP projects. After 3 to 4 years of intensive training of their engineers by an experienced CP professional, they understand the technology to some extent how to use proper anode systems. The most important things by the owner is that they can understand the meanings of the field data collected during the installation, so that they can point to the contractor to correct the problems, if occur, before the system installation is completed. In addition, the owner always involves a high qualified CP professionals in their CP projects, as follows::

> The Contractor shall provide a Cathodic Protection Specialist for the works. The CP Specialist shall be independent of the Contractor and have at least 15 years of experience in the design and installation of ICCP systems to atmospherically exposed reinforced concrete structures in marine environments. The CP Specialist shall endorse all the test and inspection reports carried out for the work before submission to the Engineer.

Their knowledge obtained during their training minimizes the risks and increases the chances of successful CP projects in the future.

Selections of Nondurable CP Materials

The anode is the most important and expensive component of the CP system, and several options may exist. The selection of the anode type depends on the following factors:

1. Remaining service life of the structure.
2. CP current requirement to stop or prevent corrosion of embedded steel.
3. Durability of the anode and related components.

Remaining service life of the structure

If the structure's remaining life is e.g., 15 to 20 years, the use of a 75-year life anode may not be cost effective in some situation. Selecting a shorter life anode may reduce the cost of the CP system to some extent.

CP current requirement to stop or prevent corrosion of embedded steel

Steel embedded in higher chloride contaminated concrete requires greater amount of CP current. The structures exposed to higher temperatures also require greater amount of CP current to stop the corrosion. According to the European Standard, the CP current requirement for chloride contaminated concrete structures is 2 to 20 mA/m^2 on steel, and the steel embedded in chloride free concrete requires 0.2 to 2 mA/m^2 on steel to prevent the future corrosion.

To stop the corrosion in carbonated concrete, much smaller CP current is required than steel in chloride contaminated concrete. After the CP current is applied to the steel for a period of time, the pH at the steel-concrete interface increases significantly by the cathodic reactions on the steel/concrete interface. As a result, the new passive protective film develops. Once the film is re-established, small amount of CP current is required to maintain the high pH.

When the designer selects the anode material or anode size, these factors must be considered to reduce the cost of the CP system.

Durability of the anode and related components

The durability of the anode is the most important cost factor. Even though the CP system is initially effective, premature failure of the anode, if occurs, will cost additional money to the owner to maintain the structure. Figure 4 shows an example of the premature failure of the zinc anode.

In addition, the selection of the materials associated with the anode is also important. For example, the cementitious grout material embedding the titanium anode must be durable. When precious metal oxide coated titanium anode is used, it must make sure that the grout material does not react with the activated titanium anode. However, the lack of the track record or testing of cementitious grout sometimes causes some kinds of reactions (Figures 5 and 6), resulting in increasing the anode-concrete resistance. If the resistance increases above the maximum voltage of the rectifier, the anode cannot maintain the proper CP current any more. There are a number of concrete CP Standards; however, none of the standards do not indicate this important factor because this fact has not been known by many CP designers. As a result, the CP system fails in a short period of time even thought the anode is still in tact.

Selection of Unsuitable CP System for Particular Structure Component and Environment

In theory, given that all other parameters are defined, the anode is the primary electrode that is used to discharge CP current into the concrete electrolyte and achieve cathodic protection of the embedded steel.[1] In reality, however, different anode systems are more suitable for certain applications. It should be mentioned that one anode cannot be used every environments or structures. The examples are shown in Table 1.,

There are a few different geometries of anodes for concrete structures, ribbon mesh, expanded mesh, discrete anodes, and surface applied anodes. Each type of the anode has advantages and disadvantages, as shown in Table 2. It is important for CP designers to understand which anode system is the most-cost effective and durable.

Improper CP Installation and Lack of Proper Testing

Since CP becomes more popular to rehabilitate corroding concrete structures, many new contractors are involved in the installation. However, inexperienced CP contractors are not familiar with the detailed works involving the CP system installation and required testing. As a result, the system may not function properly, or the durability of the system may be compromised. To overcome this problem, some contractor includes training program to their workers. Figure 7 shows some examples that by identifying various CP parts to their inexperienced workers, the contractor tries to minimize mistakes.

There are several important factors to install effective CP systems:

1. Electrical continuity of the steel reinforcement and other components
2. Installation of uniform current distributing anode systems
3. Proper installation of CP components

<u>Continuity</u>

Electrical continuity of the steel embedded in concrete is one of the most important factors for CP to effectively protect the structure. When any steel component is not electrically continuous to the system ground of the CP system, the discontinuous steel will not be protected from corrosion. However, some technicians or engineers may not properly test to determine the continuity. For example, rust or passive-film existing on a steel surface is not electronically conductive, However, they are ionically conductive. Therefore, the technician or engineer must understand when they conduct the continuity test the differences. Otherwise, the test results will be misled. In addition, some technicians or engineers use a fix ground for the continuity test which is not electronically continuous to majority of the rebars. These results obtained by an inexperienced contractor will add the cost to the CP system even though the continuity is not a problem.

Another mistake by an inexperienced contractor is that the continuity results are misled by the scaffolding attached to the structure. In many case, the scaffolding is electrically shorted to the reinforcing steel. If so, discontinuous steel components in the concrete become continuous by the scaffolding. After the scaffolding is removed at the completion of CP system, many discontinuous steel components result in ineffective CP or interference the CP current.

Installation of uneven current distributing anode systems

Another important factor for CP systems to properly function is the current distribution to the steel embedded in concrete. Uneven CP current distribution is caused by a high voltage-drop in the anode system and/or near-short circuits between the anode and the reinforcing steel. Many CP engineers are reasonably familiar with the voltage-drop and short circuit. However, the near-short circuit is more common to cause a problem to a CP system. The definition of the near short circuit is somehow difficult because the level of problem by the near short circuit varies for type of anode, the circuit resistance of the anodic zone, location of the near circuit, etc. Near-short circuit is the concentration of the CP current discharge at local area(s) of the anode system to the embedded steel. The condition of each near-short circuit is different, and in some cases it is detrimental to the CP system performance. Figure 8 shows an example. Since the detection of near-short circuits is difficult during the CP system installation, many CP engineers cannot find out until the system is commissioned.

Proper installation of the CP components

Proper selections of the CP materials is not only important but also the method of the installation is but also important. Typical installation of CP components includes:

1. Reference electrodes (RE) and its ground
2. System negative connections
3. Anode
4. Current feeding connection
5. Overlay or grouting
6. conduit and junction boxes
7. wiring and splicing of the wires
8. Transformer rectifier

Installation of each component with proper testing is important for the CP system to function effectively. Since this paper is not the installation manual, some examples are simply discussed here.

Reference Electrodes (RE)

In most industrial standards, the RE should be installed in the areas showing active corrosion without exposing the steel for an existing structure. However, when a structure or a structure component contains dense reinforcing steel, it is not possible to excavate the concrete without exposing the steel. When the RE is installed with chloride free concrete patch material, the exposed reinforcing steel will passivate. As a result, the RE will monitor the non-corroding steel. As mentioned before, the CP current density for non-corroding steel is about 10 percent of that for corroding steel. Since the CP engineer will determine the amount of the CP current required to stop the active corrosion based on the polarization of the steel at the RE location, this will mislead the results. If so, the CP current the engineer selected based on the non-corroding rebar will not stop the corrosion in other actively corroding areas.

Cemetitious Grouting

When a slotted CP system is designed and installed, the slots must be filled with cementitious grout material. Since the slots are deep and narrow, the filling method of the grout is important. After the grouting operation is completed, concrete cores must be taken to inspect the grout filling condition in the slots as shown in Figure 9. Figure 10 shows the poor grouting conditions. When approximately a half of the titanium ribbon mesh anode is not embedded in the cementitious material, this causes much higher anode current density discharging form the anode, and it may result in acid generation at the anode/concrete interface. If so, the anodes where are not completely encapsulated may fail in a short period of time.

Lack of Maintenance Capability by Owners or Contracted Professionals

Long term effective CP systems can be achieved by minimizing the maintenance of the CP system. This can be achieved by designing and installing a simple and durable CP system. Since CP is an active system, the maintenance of all hardware is required during the life of the system.

Some CP designers specify unnecessary accessories or components for the CP system without understanding the consequence or their purposes. This may be happened when the designer copies the specifications from other projects. This will add not only the cost of the CP system but also add significant amount of efforts to maintain such accessories or components.

To reduce the cost of the maintenance, the CP designer must design durable CP systems and minimize unimportant accessories or function of the TR.

1. Structure exposing to a marine or de-icing salt environment

Structure exposing to a marine environment generally requires higher amount of CP current to stop the corrosion compared with the structure exposing de-icing salts. Therefore, the high current rated anode must be selected. If the anode fails prematurely or consumed at a faster rate than expected, the cost of the anode replacement is very high. On the other hand, if the structure does not require high CP current and/or a short time protection, the CP designer may use a lower cost anode or galvanic anode. In particular, the galvanic anode CP system is virtually maintenance free, so that the maintenance cost is minimal during the life of the anode.

Furthermore, for the impressed current CP system installed on the structures being exposed to de-icing salt, the constant voltage control or manual type transformer-rectifier (TR) is generally sufficient to control the corrosion because the exposing environment is not so varies compared with marine structures. Since the constant voltage control TR is simple and durable, the maintenance cost is minimal. However, the structure which is exposed to a marine environment is more dynamic, so that the constant current control TR is preferred to avoid over current discharges from the anode during high tide periods and storms. If the CP system installed in a tidal zone, the TR should require the constant current control with the voltage limit to avoid the anode/concrete damages due to over current discharging conditions.

2. Structure located in local or remote area

Some CP designers prefer to use a remote monitoring system (RMS) for a structure. It appears that RMS is cost-effective to access the status of the TR condition without travelling to the remote site. However, the cost-effectiveness is only when the RMS is functioning. If the RMS is not durable enough, the cost of the maintenance and troubleshooting may not be low. Therefore, selecting durable RMS is important. Remember that the RMS requires the computer software and the communication system. The software and the communication system may need to be upgraded when new computer operating software comes out. Therefore, if the structure is located in the local area, it is not recommended using a RMS to reduce the maintenance cost.

SUMMERY

1. The intent of cathodic protection is to provide a long-term, effective corrosion control system that is technically acceptable to the structure and cost-effective to the owner. To achieve this, the experiences from the past are greatly important. Otherwise, the mistakes may be repeated by inexperienced CP engineers and contractors

2. The factors which cause the ineffectiveness and/or nondurable CP systems are generally contributed by:

   - Poor engineering capability and insufficient knowledge and experiences by CP professionals.
   - Selections of nondurable CP materials.
   - Selection of unsuitable CP system for a particular structure component and an environment.
   - Improper CP installation and lack of proper testing.
   - When the sophisticated CP systems are built, the poor maintenance capability by the owners or the lack of engineering abilities by the contracted professionals may have problems to maintain the function of the system..

   When any factors listed above are missed, the structure owner’s interest, the effectiveness and the durability of CP systems may be compromised.

3. It is important for CP professionals not to repeat the same mistakes happened in the past.

REFERENCES

Callon, R., Daily. F. S. and Funahashi, M., 2004, Selection Guidelines for Using Cathodic Protection Systems on Reinforced and Prestressed Concrete Structures, NACE International, Corrosion 2004, Paper No. 4325

Table 1. Applications of various types of anodes

Type of Anode	Suitable	Not Suitable
Carbon based anodes	• Dry environment • Low CP current requirement • Short remaining service life	• Cyclical wet and dry conditions • Exposed to excessive moisture • Medium to high CP current requirement
Titanium based anodes	• Cyclical wet and dry conditions • Low to high CP current requirement • Medium to long remaining service life	• Drier environment
Thermally sprayed metallic anodes	• Complex geometry shaped structure • Exposed to high to medium relative humidity environment	• Long remaining service life • Not exposed to direct moisture • Not on riding surface

Table 2. Advantages and disadvantages of various types of anodes

Type of Anode	Advantages	Disadvantages
Ribbon mesh	• In-expensive • No requirement of concrete overlay • Long track record • Suitable for slots or new structures	• Less uniform CP Current distribution • Requires sufficient concrete cover (Min. 20 mm) • Expensive if used with concrete slots
Expanded Mesh	• Uniform CP current distribution • Excellent redundancy • Long track record	• Required cementitious overlay • Overlay adds additional dead load • Risk of overlay disbondment
Discrete Anodes	• Uniform CP current distribution if the anodes are spaced properly and positioned sufficiently remote from the rebars. • No requirement of concrete overlay • Inexpensive installation cost	• Cannot be used for the components which have many layers of rebar cages or inner rebars • Detection of shallow steel in drilled holes may be difficult. It may cause near short circuit condition.
Surface Applied Anodes	• In-expensive in installation • Local wet conditions may cause premature failure	• May cause near or dead short circuits when applied to metal exposed concrete surface. • Local wet conditions may cause premature failure • Poor durability on riding surface

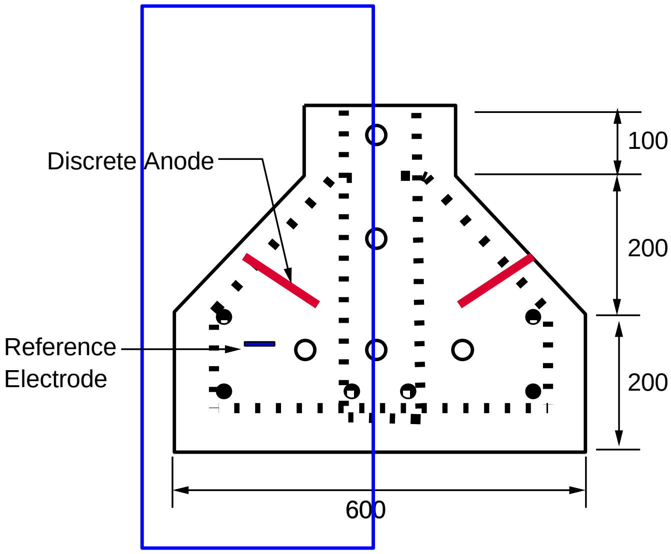


Figure 1. Configuration of discrete anode position in prestressed concrete beam

Figure 2. Concrete spalls after the discrete anode CP system was installed.

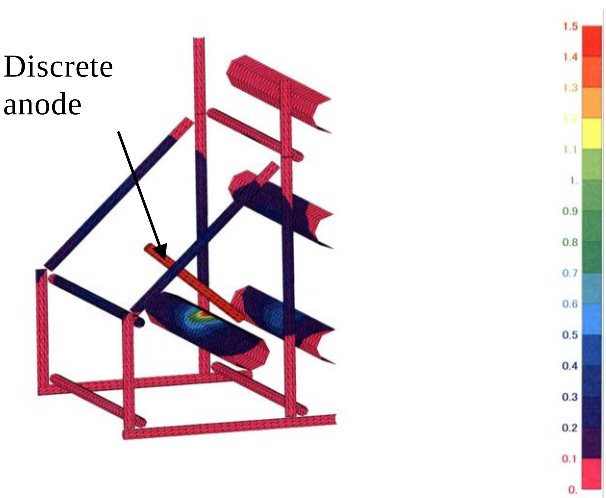
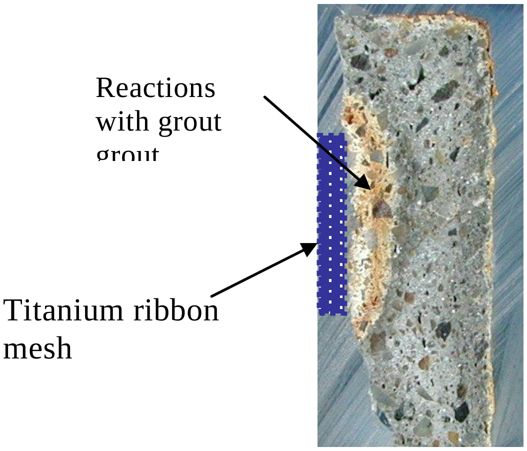


Figure 3. Current distribution from the discrete anode in he beam.

Figure 4. Zinc anode failure



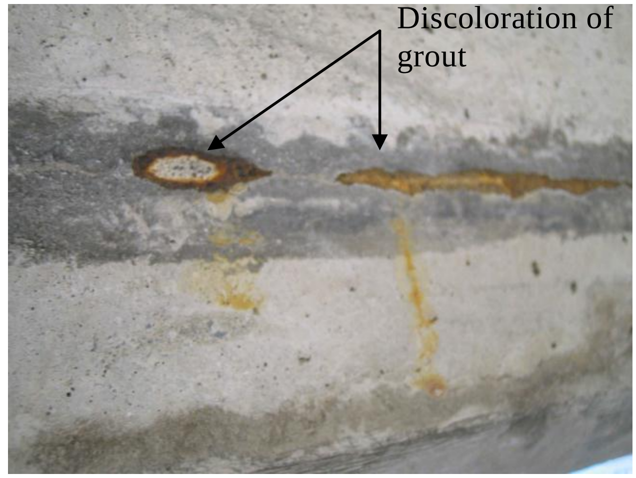


Figure 5. Discoloration of the grout surrounding The ribbon mesh in the slot

Figure 6. Discoloration of the grout by the reaction

Figure 7. Identifications of all CP components For training inexperienced works at a job site

Figure 8. The possible cause of near short circuit

Figure 9. Grouting conditions inspecting by cores

Figure 10. Poor grouting condition in slot