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Repair of Corrosion Damages and Protection of Cooling Water Intake/Circulation Structures

Réparation de dommages par corrosion et protection des installations d'eau réfrigérante

Reparatur von Korrosionsschäden und Schutz bei Kühlwasserbauwerken

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SUMMARY

Once corrosion reaches the initial corrosion phase, effective remedial measures must be taken so as to minimise the potential damage and economic loss. A holistic approach with multiple remedial repair/protection measures is essential in arresting corrosion in complex structures. The implementation of those measures in the sea water intakes, pump houses and circulating water conduits of a large power plant requires a comprehensive, long-term program covering surveillance, testing, repair, and maintenance. This paper discusses the implementation of such a program at a power plant as a successful example.

RÉSUMÉ

Il faut intervenir au stade initial de la corrosion des ouvrages par des contremesures efficaces, afin de minimiser les dommages potentiels et les pertes financières. Une approche exhaustive, comportant de multiples mesures de rénovation et de protection, s'avère indispensable pour stopper les effets corrosifs dans les structures complexes. La mise en oeuvre de ces moyens d'intervention dans le circuit de réfrigération d'eau de mer d'une grande centrale électrique (ouvrage d'entrée, station de pompage et tuyauteries de circulation) implique une conception globale et à long terme, incluant surveillance, essais, réparation et entretien. La communication traite de l'application réussie d'un tel programme dans une centrale électrique.

ZUSAMMENFASSUNG

Bereits im Anfangsstadium von Korrosion müssen wirksame Gegenmassnahmen getroffen werden, um mögliche Schäden und wirtschaftlichen Verlust zu minimieren. Bei komplexen Bauwerken braucht es dazu einen ganzheitlichen Ansatz mit mehreren Reparatur- und Schutzmassnahmen. Die Umsetzung solcher Massnahmen im Seewasserkühlkreislauf eines Grosskraftwerkes (Einlaufbauwerk, Pumpenhaus und Umlaufleitungen) benötigt ein umfassendes, langfristiges Vorgehen mit Ueberwachung, Tests, Reparatur und Unterhalt. Der Beitrag berichtet von einer erfolgreichen Durchführung eines solchen Programms.

1. INTRODUCTION

Cooling water intake/circulation structures in power plants located on a seacoast region typically consist of the pump house structures, water delivery conduits, discharge structures and discharge conduits. These structures have frequently experienced accelerated deterioration due to reinforcing steel corrosion, resulting from chloride intrusion. As an increasing amount of effort is being spent on maintenance and repair of these facilities, the industry has been going through a learning curve to achieve cost-effective repair methods. This paper presents a holistic approach to maintenance and protection of cooling water structures against steel corrosion and discusses the implementation of a comprehensive repair/maintenance program at a coastal power plant as a successful example. It is believed that this approach is generally applicable to other marine structures.

2. CORROSION PROBLEMS IN THE SEAWATER INTAKE/CIRCULATION STRUCTURES

The fundamental cause of steel corrosion is electrical potential differences of the steel, in which corrosion (oxidation) of steel occurs at the anodic area and reduction of oxygen occurs at the cathodic area. Oxygen and water are key ingredients for the cathodic reactions, while chloride ions depassivate the anodic regions. Steel corrosion may involve various physical and chemical reactions, depending on the environments. In general, elements of the cooling water structures are subjected to a variety of exposures, ranging from salt water leakage from screen wash stations and glands of pumps to full immersion in seawater. A complete coverage of these conditions is beyond the scope of this paper. Only an introductory discussion is presented to illustrate the complex nature of the problem.

Circulating water conduits contain full head seawater, flowing at moderately high velocity under pressure. It has been recently realized that corrosion of these immersed structures exhibits many characteristics different from the more common corrosion observed in structures continuously exposed to air. Steel corrosion in such an environment is predominantly controlled by the rate of cathodic reaction, due to the limited access of oxygen. Although past experience has shown that marine structures fully immersed in seawater can withstand the severe seawater attack for many years, the circulating water conduits are very vulnerable to corrosion attack due to periodical dewatering of the conduits for cleaning and inspection. During even very short periods of dewatering, oxygen can quickly diffuse through the concrete cover and refuel cathodic reactions. As a result, it is not uncommon to see delaminations and spalling in these conduits, even though they have been in service for merely ten to twenty years.

In the pump houses and discharge structures, there are pumps and valves which are susceptible to salt water leakage due to ineffective seals and pump packing problem, as well as traveling screen wash stations, all of which cause periodical spray, ponding and wetting of the concrete surface. During a drying period, water evaporates from the concrete surface, leaving salt inside the concrete pores. During a wetting period, seawater is quickly absorbed into the concrete, due to capillary "wick" action. Consequently, the concrete components develop chloride concentrations many times greater than that required to initiate corrosion. Furthermore, the chloride content is nonuniform which leads to a substantial potential difference on the steel surfaces and creates a very severe corrosive environment. Multiple pumps, piping and electrically powered equipment inside these structures may induce stray currents, frequently transient in nature, adding additional complexity to the situation.

Different exposure conditions often act synergistically to impose an increasingly aggressive attack on the reinforcing steel. Reference (1) discussed a number of case histories with the interaction of several degradation phenomena. Due to the complex nature of the problem, the authors believe that simple solutions and a single repair/maintenance measure are rarely adequate. A holistic approach to the problem is essential. Multiple repair/protection/maintenance measures need to be systematically combined to arrest several interrelated degradation phenomena. This is the basis of the repair/maintenance program discussed below.

3. CORROSION DAMAGE PROTECTION STRATEGY

The electrochemical corrosion of reinforcing steel involves complex physical and chemical processes. At present, these corrosion mechanisms are still not fully understood. A methodology to provide a quantitative measure of the service life and performance of a corrosion-damaged structure does not exist. In the opinion of the authors, a reliable durability assessment and service life prediction must be based on the field observations and past experience with actual structures and environments. The authors' field experience shows that, under most actual circumstances, corrosion in marine structures propagates at a nonlinear and accelerating rate. For practical purposes, the progression of steel corrosion can be described in three stages: (1) initiation phase; (2) initial corrosion phase; and (3) free corrosion phase. The initiation phase covers the period between the construction of a structure and depassivation of the reinforcing steel. The initial corrosion phase starts with the initiation of corrosion. The free corrosion phase is associated with formation of substantial delamination and cracking. Such delaminations and cracks provide easy access of chlorides, oxygen and water to the reinforcing steel, causing accelerated propagation of corrosion.

In practice, we find that the time for visible corrosion to appear varies in a wide range, depending on many factors such as the concrete quality, concrete cover, construction quality, and severity of the exposure environment. In many seawater intake/circulation systems, considerable corrosion damages were observed in ten to twenty years after the construction. A long delay in repairs may allow the condition to develop into the free corrosion phase, which imposes risk of structural failure and personnel safety and rapidly increase repair/maintenance costs.

Application of the Present Value concept indicates that prompt action to arrest and repair corrosion damage is fully justified, since corrosion damage generally increases more rapidly than the effective rate of interest. Further, the increased interference and impact on the plant operations must be added to the cost of money. Experience demonstrates that the most cost-effective repair strategy is to take remedial measures before the corrosion reaches the free corrosion phase so as to minimize the potential damage and economic loss. Furthermore, a persistent and continuing effort of maintenance and protection of such structures must be exercised in order to maximize the benefits of repair work and, thereby extend the service life of the plants.

4. CORROSION DAMAGE PROTECTION PROGRAM

In the past, general maintenance practices in the power plants usually focused on the plant operation activities with little regard for the progressive detrimental effects of the long-term exposure of seawater on structures. Concrete deterioration and local damage showed that "sustained" maintenance/repair practices would be essential to preserve structural integrity, prevent disruption to plant operations and extend the service life. A comprehensive refurbishment program is being successfully implemented at a nuclear power plant on the Pacific coast. Over four years of consistent efforts in carrying out this program have resulted in stabilization of the degradation trend, thereby improving service performance and minimizing the risk to operations. As a result, the service life of the plant is expected to extend for at least another 40 years with the continuation of the program. This program is discussed in detail below.

4.1 Site Condition Survey

In developing a program for future repair and maintenance, it is necessary to determine the rate at which corrosion will proceed and its effects on the safety of the structures. While corrosion rates depend on complex actions and interactions of many factors and, hence, cannot be accurately quantified, their trends can be clearly bracketed with sufficient accuracy to form a basis for decisions. The condition survey was implemented in two phases.

Phase 1 - Detailed inspection/testing: The objective of the initial inspection and testing was to establish the baseline data regarding the extent of deterioration and to serve as a basis for future monitoring and for service life prediction. Extensive testing was carried out during the initiation stage, which includes visual inspection, hammer sounding to determine delaminations, rapid chloride test to determine the soluble chloride content, half-cell potential test to detect corrosion activities, impact echo test to detect concrete defects like internal/remote cracks, polarization resistance test to estimate corrosion rates and many other tests. In practice, the hammer sounding test has proven to be the most cost-effective and reliable way of finding delaminated and corrosion-damaged areas.

Phase 2 - General monitoring plan: The initial inspection and testing showed that chlorides had penetrated into the concrete in high concentrations, well above the threshold value to initiate corrosion. Although systematic repairs of the severely corroded areas have been undertaken, it is expected that many other areas which have not shown problems to date may develop delamination and/or cracks in the future. A monitoring program was therefore implemented to keep track of the general condition of the intake/circulation system. The monitoring has been carried out periodically, such as during every plant outage. The extent of the monitoring is generally limited to visual inspection and hammer sounding, supplemented by other tests as deemed necessary, especially in local areas. The degraded areas of delaminations, cracks, spalls are charted in a consistent manner to graphically display the inspection results. The main objective of the general monitoring plan is to confirm the trend and progression of the corrosion problem at the plant and detect severely damaged area as early as possible and to develop guideline for planning and prioritizing future repairs.

4.2 Engineering Assessment

From a technical point of view, delaminated and spalled areas should be repaired as soon as practicable, because a long delay in repairs accelerates corrosion and ultimately repair costs. Due to manpower, economic and plant schedule constraints, the amount of repair work may be limited in a given time period. Therefore, the repair work should be prioritized in a systematic way so as to minimize overall costs. A structural assessment should be performed to evaluate the corrosion deterioration effects on the structural integrity. It involves (1) identification of structurally critical areas, (2) evaluation of reductions in safety margins in the degraded areas, and (3) categorization of damaged areas for repair prioritization. The structural components may be divided into four main categories as follows:

- (1) Critical areas in terms of structural adequacy and safety, such as structurally sensitive areas and occupational safety-hazard areas,
- (2) Critical areas in terms of rapid corrosion growth and high economic impact areas where delayed repairs will cause substantially higher costs,
- (3) Non-critical areas showing corrosion damage,
- (4) Non-critical areas with no present corrosion damage.

According to the priority criteria, the areas falling under Categories (1) and (2) are the critical areas in terms of structural adequacy and safety, and rapidly increasing cost of delayed repairs. Corrosion damage in these areas should be repaired as soon as practicable. The areas under category (3) do not require immediate attention and may be scheduled for repair in subsequent years to suit economic options. The areas under category (4) should be monitored.

4.3 Repair/Maintenance Measures

Patching repair is the basic method employed to restore structural integrity of local areas in a corrosion-damaged structure. However, in a typical seawater intake structure, the chloride permeation may progress globally to contaminate extensive portions of the structure, resulting in a general deterioration due to steel corrosion. The patching repair method alone cannot arrest this general deterioration. The effective measures to control such deteriorations include: (1) keeping the pump house structure dry so as to maintain concrete resistivity at a level higher than that associated with steel corrosion, (2) choking off the oxygen supply to cathodic areas, e.g., use of epoxy coating over the concrete surface, and (3) cathodic protection of reinforcing steel in appropriate areas. Proper implementations of these measures are discussed as follows.

4.3.1. Patching repair: In order to ensure successful use of the patching repair method, a guideline application procedure should be developed to address issues like material compatibility and substrate bonding. The guideline includes identifying repair priority, shoring needs, repair sequence as to maintain the structural safety margins, selection of patch materials, surface preparation and curing. To ensure durable repairs, zinc silicate primer and zinc ribbon attachments can be used at the perimeter of the patched areas so as to eliminate or mitigate the reversal of galvanic cells. Epoxy primer is applied to the substrate surface to minimize any adverse interaction between a patch and its substrate. Material selection is one of the critical factors, since improper use of patching materials has become the most common cause of patching repair failures. In the program, the criteria for material selection is based on exposure conditions, structural adequacy, durability, easy construction and cost-effective aspects. The field experience shows that well-constructed, dense concrete with proper addition of pozzolanic admixtures is a very satisfactory material for long lasting repairs. Proper curing and sealing of the perimeter of the patch is important.

4.3.2 Coating systems: Application of surface coatings and sealers proved to be an important protection measure against further ingress of chlorides, especially in the areas periodically exposed to salt water sprays. Selection of the coating system depends on the exposure conditions, effectiveness of the material as a barrier to chloride penetration, and ability of the material to allow vapor migration.

4.3.3 Leakage control: In the pump houses, the most cost effective way to control corrosion is to take adequate preventive measure to stop the leaks and to keep concrete as dry as possible. Simple and inexpensive measures, such as providing adequate seals for glands and valves, using pump spray shields, and the restoration or replacement of hatches and joint seals, are the key elements of the program. Other preventive measures such as providing proper drainage and maintaining floor drains clean and free of debris, should also be implemented,.

4.3.4 Communication: Corrosion awareness communication is an important part of the program. Routine walkdowns and frequent discussions among engineering, construction, maintenance and operation personnel can heighten the awareness of corrosion damage factors like salt water leaks, equipment sprays, plugged drains, water ponding on roofs and floors, rust streaks, cracks, and coating/sealers. This has been one of the key measures in keeping a pulse on the structure performance and has led to timely responses, and appropriate corrective actions.

4.3.5 Cathodic Protection: Cathodic protection has a long and successful history in application to marine structures. Although cathodic protection for above water structures is still in the developmental stage, use of sacrificial aluminum-alloy anodes in protecting reinforcing concrete immersed under seawater has proven to be relatively simple, economical and very efficient. This is primarily due to the high anode-to-ground resistance such that anode currents are able to distribute uniformly over a very large area. This sacrificial anode cathodic protection is especially appropriate for intake/discharge tunnels which are fully submerged in seawater during operational periods. A successful example of such application is the cathodic protection of Jubail seawater canals in Saudi Arabia during the mid-1980's (ref.(2)). Reported performance to date has been excellent. At the power plant, design and construction of similar cathodic protection systems are currently in progress for the circulating water conduits and auxiliary salt water piping.

4.3.6 New technologies: Many innovative proprietary corrosion repair procedures and methods are being developed which give promise of controlling the on-going corrosion and of reducing the cost of repairs. To verify their effectiveness in the exposure environments at the plant, an independent laboratory test is being carried out in conjunction with field testing to investigate several corrosion inhibitors. The test program is set up to simulate (1) the chloride contamination levels, (2) the concrete mix design, and (3) the drying/wetting exposure conditions at the plant.

5. CONCLUSION

Cooling water intake/circulation systems in coastal power plants are exposed to a very severe corrosive environment. The varying exposures often act synergistically to impose an increasingly aggressive attack on the reinforcing steel. Once the corrosion has caused substantial delaminations and cracks, the corrosion rate will increase in a nonlinear and accelerating rate. A long delay in repairs rapidly increases repair costs and ultimately imposes risks of structural failure. For effective results, a comprehensive refurbish program should include the following attributes:

- A sustained, long-term inspection/monitoring/repair plan,
- Thorough engineering assessment and prioritization of degraded areas for repair,
- A holistic approach to combine multiple repair/maintenance measures such as patching repair, coating treatment, control of water leakages and cathodic protection,
- A persistent maintenance effort
- Adaptation to effective new technologies

The experience shows that cathodic protection should be installed early in construction for seawater intake structures. More communication within the industry is needed to share the experiences and information. Various responsible agencies and private sectors should put the resources together in developing new, effective technologies of controlling the corrosion problem.

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