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# CATHODIC PREVENTION AND CATHODIC PROTECTION OF NEW AND EXISTING CONCRETE ELEMENTS AT THE SYDNEY OPERA HOUSE

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## ABSTRACT

As a part of a major rehabilitation programme of the Sydney Opera House (photo1), cathodic prevention and cathodic protection systems were installed to protect new precast elements, the soffit and piers under the western broadwalk. The CP installation was carried out using a grid anode installed in the new precast elements, before concrete casting or put in concrete slots cut into the soffit and piers. The system was energised in May 1996. This paper describes the design criteria, installation and system performance after energizing the system.

**Keywords:** cathodic prevention, cathodic protection, corrosion in concrete, monitoring, potential.

## INTRODUCTION

Chloride induced corrosion of steel in concrete is a major cause of deterioration of reinforced concrete structures located in the coastal regions of Australia. Chloride induced corrosion of reinforcement had caused deterioration problems to some of the elements of the substructure of the Sydney Opera House western under broadwalk. A major rehabilitation programme was established by the NSW Departement of Public Works and Services for this structure. As a part of this programme cathodic protection and prevention systems were installed in order to stop corrosion in the existing elements of the structure (piers and soffit) and to improve the corrosion resistance of the reinforcement of the new precast elements which are expected to become chloride contaminated. The design concept, installation and monitoring of these installations are discussed.

## DESIGN CONCEPT

The principle of applying cathodic protection and cathodic prevention are well documented and need not to be repeated here (1-7). However the understanding of the individual requirements for each structure and each CP system cannot be over emphasised. This understanding is necessary to satisfy specific conditions related to the selection of anode material, zoning of the CP system and type of monitoring needed for the system.

### Anode material

Various anode materials were considered for this installation. Titanium expanded mesh with mixed metal oxide coating was considered inappropriate due to possible problems associated with the application of a concrete overlay over the mesh. Some previous repair areas had been coated with epoxy and removal of the existing coating was considered inappropriate. Other materials such as conductive coatings were also considered inappropriate due to the harsh environment of the structure and the life requirements of the CP system.

Mesh ribbon anode LIDA® Grid [1] was considered the most appropriate anode material in this installation due to its flexibility of application i.e. installation with different spacing to satisfy variations in current requirements.
The specifications of the mesh ribbon anode grid are the following:

- width 20 mm
- thickness 0,5 mm
- current output 5,5 mA/m

For the existing elements the mesh ribbon anode grid was placed in slots and backfilled with cementitious material while for the new precast elements the mesh ribbon anode grid was attached onto the reinforcing cage with specially designed insulating cementitious materials prior to pouring. The effectiveness of this innovative concept has been previously tested on a laboratory scale (6).
In practice the anode grid assembly for the new precast elements is made of an array of parallel mesh ribbon anode grids supported by the composite cementitious spacer above which the anode elements are secured by means of plastic fixings. The assembly is positioned on the reinforcing steel and fixed by using plastic ties (photo 2,3,4).

Once positioned, the anode strips are connected together by means of titanium bus bars welded to them or connected to insulated copper wires. The main characteristics of this assembly is that by varying the degree of expansion , the width and the spacing between the parallel strips, the current output of the anode assembly can be easily varied to match the variations of the steel density of the concrete structure. For example strips having a fixed degree of expansion and width (that is to say a fixed current capacity) can be less (more) spaced where more (less) current is required; if the spacing between the strips is fixed, then the anode current capacity can be varied changing the expansion degree (and width).For the protection of reinforced concrete elements below water level titanium anode rods with a mixed metal oxide (MMO) coating were used as water anodes.

[1] LIDA ® Grid is a tradename of Oronzio De Nora S.p.A. - Lugano - Switzerland.

Zones of CP system

Creating the proper electrical zones was one of the major issues of the system design. The following considerations were taken into account.

1) The different environmental conditions of the elements to be protected such as tidal, submerged and atmospheric zones.
2) Different corroding conditions of existing elements.
3) Different concrete resistivity of existing elements.
4) Size of power supply units.
5) Geometry of the structure.

A total of 68 separate electrical zones were created in order to satisfy the above considerations. The large number of zoning for this installation was essential to ensure even current distribution, prevent current dumping and ensure that any short circuit problems during construction could be easily found and rectified.

Monitoring of the CP system

The system contained a total of 80 embedded reference electrodes. The type of electrodes used were silver/silver chloride and titanium electrodes in concrete and zinc electrodes in water. The 100mV decay criterion "protection or prevention conditions are reached when a potential decay of at least 100mV over a period of 4 to 24h from instant off potential is measured"(4) was adopted for the CP system in splash and atmospheric zone while the criterion adopted for the water anode system required that the potential of the reinforcing steel at the instant of switching off the system be more negative than -900mV limited to -1100mV versus Ag/AgCl reference electrode. A manual monitoring system was considered initially for this installation however the existence of pre-stressing bars in the precast elements made it necessary to consider the use of a computerised control system in order to avoid the possibility of overprotection conditions. The pre-stressed bars were located in the precast elements and subject on a daily basis to tidal, submerged and atmospheric conditions. In addition to the protection provided by the embedded grid system these elements were subject to additional protection provided by the water anode system while in submerged conditions. Avoidance of any overprotection conditions was achieved by adopting a special shielded detail for the construction of the pre-stressed bars. Reference electrodes were also embedded in the concrete during the construction in selected locations.

The computer control system supplied for this installation has the capability of limiting the the maximum current and voltage for each zone in addition to limiting the instant off potential of the embedded reference electrodes to a selected value and adjust current/voltage continuously to reach such potential without exceeding it. The computer system offers other various features which assist in proper and effective control of the performance of the installation. However the limit of the maximum potential to a predetermined value was an essential factor for the selection of the computerised system.

## INSTALLATION

The cathodic protection system was designed to protect 1015 m$^2$ of soffit area, 330 m$^2$ of piers area, 142 m$^2$ precast A-frames area (photo 2,3,4), 600 m$^2$ walkways area, stairs and additional beam 40 m$^2$. The overall area where cathodic protection is applied in existing concrete is 1385 m$^2$ corresponding to a 20 Amp design current output; total area for cathodic prevention (precast concrete elements) is $742m^2$ corresponding to a 10 Amp design current output.

Precast elements

Reinforcing bars had been welded to ensure that electrical continuity exists between rebars. An assembly of grid anode/cementitious spacers were delivered to site and were fixed to the rebar cage using plastic ties. Conductor bars were spot welded to strip anodes and anode and steel connections were established for each precast element. Reference electrodes were fixed to the steel cages by means of plastic ties. Continuity testing of steel bars and short circuit testing between rebar and anode was carried out prior, during and after concrete application. Each precast element was subject to steam curing for 12 hours and then delivered to site. As a part of the testing procedure of precast elements, fixed current was applied to the steel/anode circuit for each precast element. Change of steel potential with respect to embedded reference electrodes or external reference electrodes on the concrete surface were measured. For each type of precast element (walkway, A Frame and mid span tie), extensive potential mapping was undertaken in order to check current distribution and for design verification purposes. A total of 18 A Frames, 17 walkways and 17 mid span ties were cast and delivered to site for installation over a period of approximately 6 months. These new elements replaced the old elements which were cut out and removed from site due to excessive deterioration problems. All cablings from the precast elements were terminated to the 5 substations located along the western broadwalk.

Existing elements

The continuity of the steel in existing elements was very good. Spacing between strip anodes was determined based on steel density and the results of pre-installation site trials carried out for various elements of the installation. Slots were cut and the titanium anode grid was installed into the slots which were filled with cementitious materials. Anode and steel connections were established from each electrical zone and reference electrodes were installed in selected locations for monitoring purposes. All cabling from the existing elements were terminated in the 5 substations along the western broadwalk. Similar testing procedures that were applied to precast elements were undertaken for existing elements of the CP system to ensure proper operation of the system and to detect any defects during construction. 16 water anodes were installed along the western broadwalk for the protection of reinforced concrete elements below water level. Each anode was connected to a separate electrical zone. In addition 16 zinc reference electrodes were installed in the water in order to monitor the performance of the water anode system.

Monitoring system

A computerised monitoring system was selected for the monitoring and control of the CP installation. Some of the features of the system are:

- Hourly recording of power supply current and voltage
- Hourly recording of reference electrode instant off readings (table 1and table 2)
- 24h decay test once every month (table 3 and table 4)
- Adjustment of current/voltage of each power supply unit in accordance with the required set instant off potential of the reference electrodes in each zone

A specially designed interface with the client's monitoring system was provided as part of the monitoring system for an alarm function.

The system was energized in May 1996. The initial data shows that the system is performing very satisfactorily (table 1 and table 2). A 24 hour depolarisation decay test is being carried out for the system automatically on a monthly basis (table 3 and table 4). Maximum current, voltage and maximum potential for the reference electrodes has been set for each zone of the CP system.

## CONCLUSIONS:

The concept of cathodic prevention has been used for the first time in Australia to improve the corrosion resistance of new reinforced concrete elements. Electrochemical techniques for the repair and prevention of structures suffering from chloride induced corrosion is being widely recognised as an effective and relatively long term solution to stop deterioration in chloride contaminated structures in Australia. The experience gained from this project suggests that every installation should be designed, built and monitored according to its specific conditions. Proper design, attention to detail and extensive testing during construction are essential for the successful installation of any CP system.

## ACKNOWLEDGEMENT

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TABLE 1
SUBSTATION C - INSTANT-OFF POTENTIAL READINGS (Ti AND Ag/AgCl REF ELECTRODES)
(SYSTEM ENERGISED IN MAY 1996)

| Location | Sea Wall | | Walkway | | Pier C7 | | Pier C17 | | A Frame | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Reference electrode | Ti | Ti | Ti | Ti | Ti | Ag | Ti | Ag | Ti | Ag | Ti | Ag |
| | S11 | S22 | W81 | W82 | S41 | S42 | S51 | S52 | A61 | A62 | A71 | A72 |
| Natural potential (mV) | -133 | -288 | -76 | -126 | -14 | -269 | -296 | -387 | -6 | 18 | -43 | -377 |
| INSTANT OFF (02/06/96) | -650 | -430 | -210 | -500 | -470 | -380 | -690 | -840 | -480 | -280 | -330 | -690 |
| | Z1 | Z2 | Z3 | Z3 | Z4 | Z4 | Z5 | Z5 | Z6 | Z6 | Z7 | Z7 |
| (Ti = Titanium reference electrode, Ag = Ag/AgCl reference electrode) | | | | | | | | | | | | |

TABLE 2
SUBSTATION C - ZINC WATER ELECTRODES - INSTANT-OFF POTENTIAL READINGS
(SYSTEM ENERGISED IN MAY 1996)

| Location | Pier C 18 | Pier C14 | Pier C13 | Pier C17 |
|---|---|---|---|---|
| Reference electrode | ZN1 | ZN2 | ZN3 | ZN4 |
| Natural potential (mV) | 438 | 462 | 443 | 442 |
| INSTANT OFF ( mV) (02/06/96) | 180 | 180 | 140 | 150 |

TABLE 3
SUBSTATION C - INSTANT-OFF POTENTIAL READINGS AND 24 HOURS DEPOLARISATION
TEST ATER 3 MONTHS FROM ENERGISING

| Location | Sea Wall | | Walkway | | Pier C7 | | Pier C17 | | A Frame | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Reference electrode | Ti | Ti | Ti | Ti | Ti | Ag | Ti | Ag | Ti | Ag | Ti | Ag |
| | S11 | S22 | W81 | W82 | S41 | S42 | S51 | S52 | A61 | A62 | A71 | A72 |
| Instant OFF (mV) (01/09/96) | -770 | -350 | -560 | -620 | -460 | -360 | -690 | -810 | -450 | -240 | -210 | -690 |
| Potential after 24 hrs OFF (mV) | -270 | -180 | -170 | -270 | -140 | -160 | -430 | -540 | -80 | +10 | -20 | -540 |
| | Z1 | Z2 | Z3 | Z3 | Z4 | Z4 | Z5 | Z5 | Z6 | Z6 | Z7 | Z7 |
| (Ti = Titanium reference electrode, Ag = Ag/AgCl reference electrode) | | | | | | | | | | | | |

TABLE 4
SUBSTATION C - ZINC WATER ELECTRODES - INSTANT-OFF POTENTIAL READINGS AND 24 HOURS DEPOLARISATION TEST AFTER 3 MONTHS FROM ENERGISING

| Location | Pier C 18 | Pier C14 | Pier C13 | Pier C17 |
|---|---|---|---|---|
| Reference electrode | ZN1 | ZN2 | ZN3 | ZN4 |
| Instant OFF (mV) (01/09/96) | 160 | 170 | 160 | 170 |
| Potential after 24 hrs OFF (mV) | 370 | 380 | 390 | 400 |

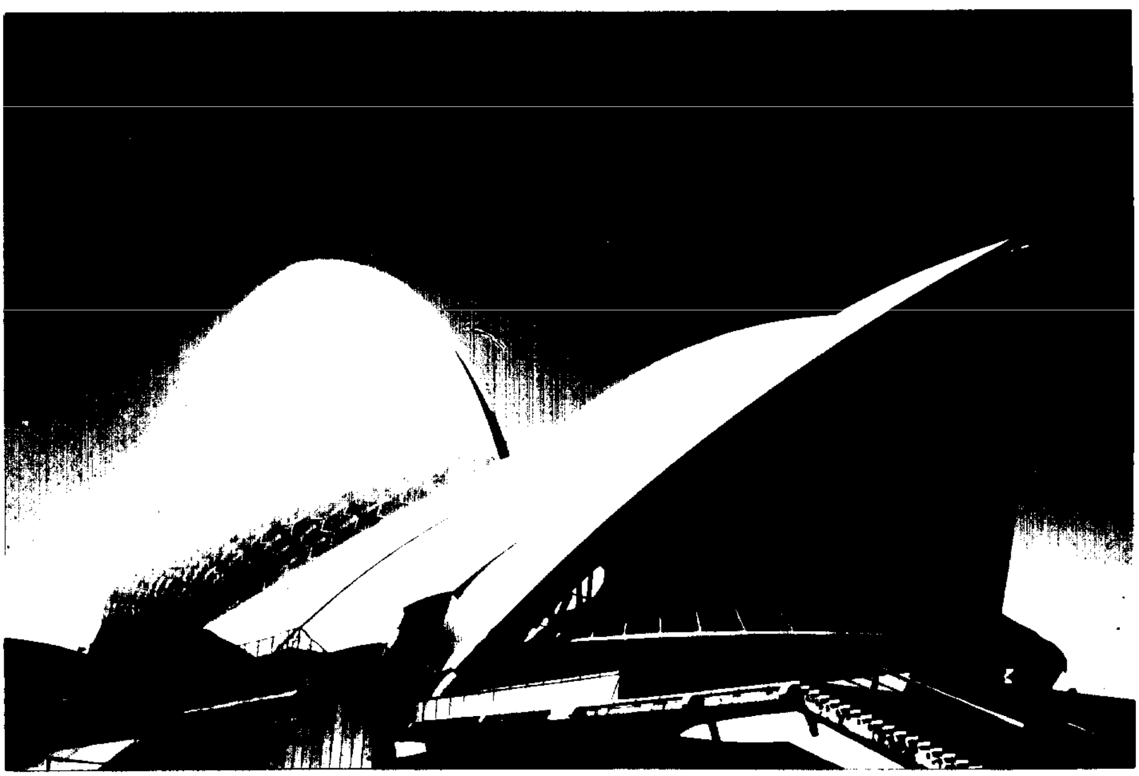

Photo n°1: Sydney Opera House.

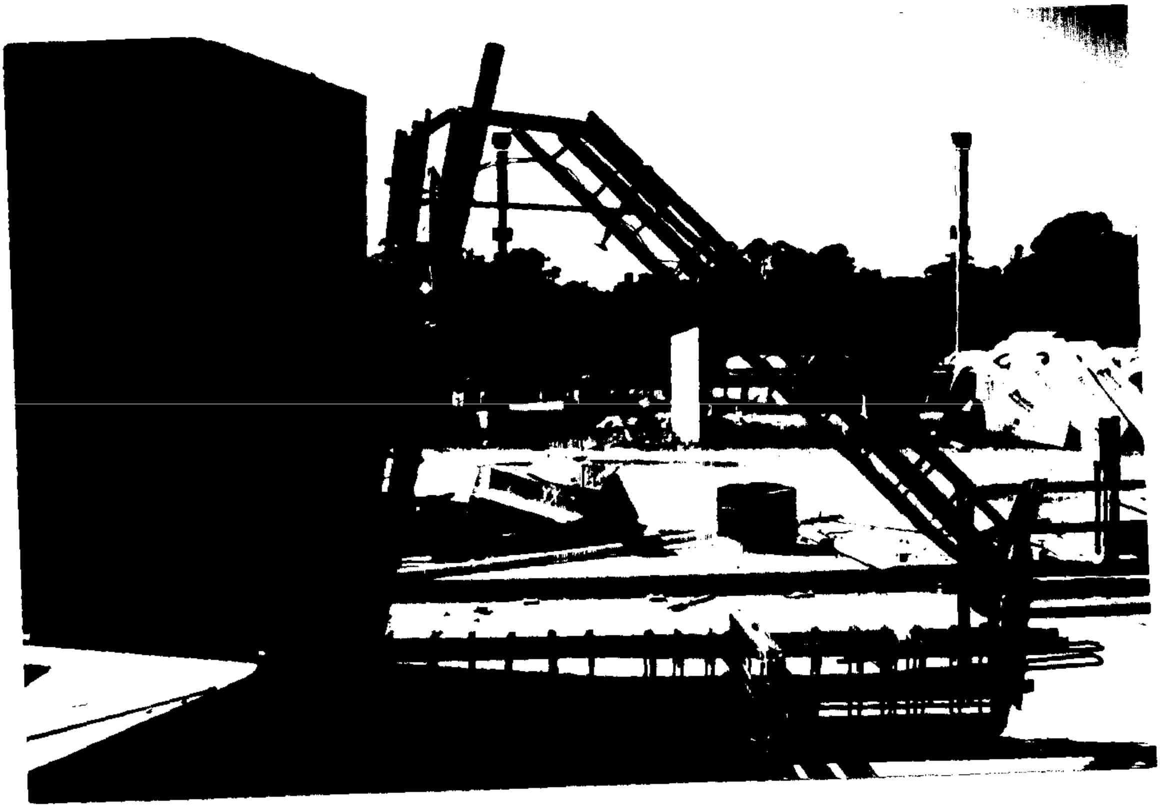

Photo n° 2: A frame with installed anode.

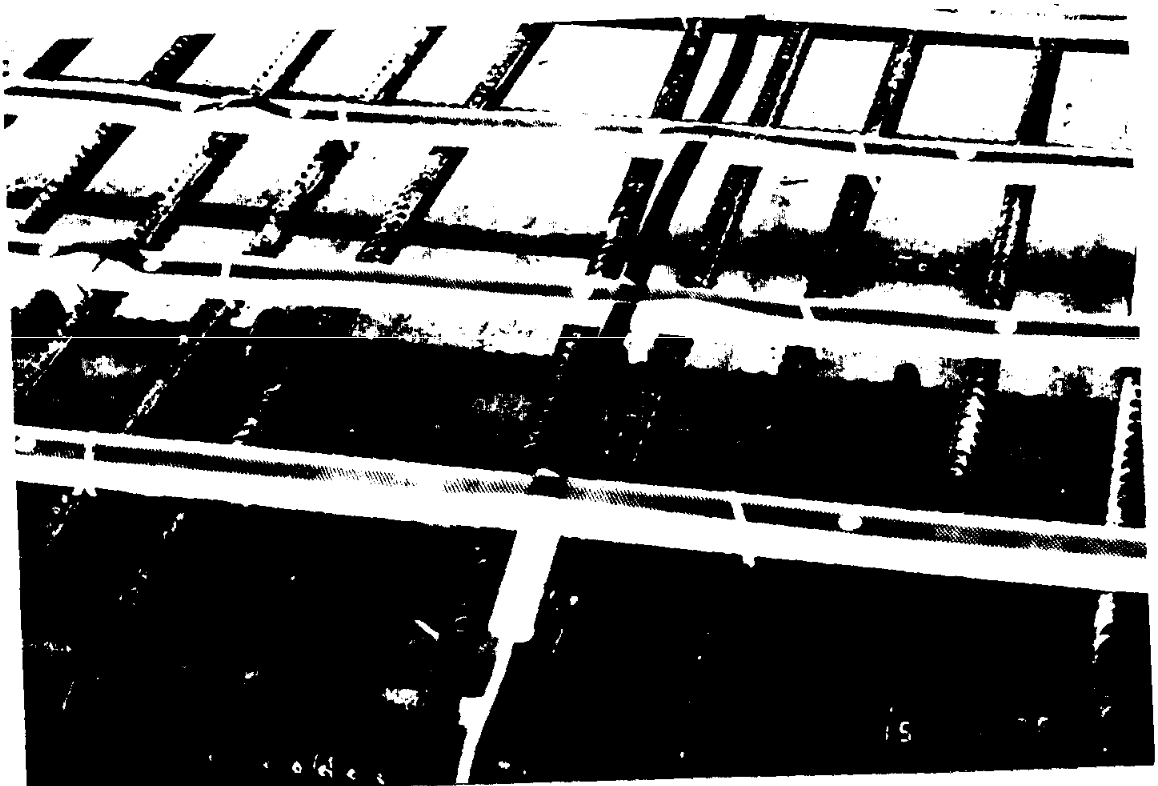

Photo n° 3: detail of walkway anode installation.

Photo n° 4: walkway anode installation.