Corrosion monitoring of post-tensioned strands at the Piedra del Aguila spillway

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The Piedra del Aguila project in Argentina is a concrete gravity dam constructed in the 1980s, on the Limay river. The dam includes a spillway channel controlled by four gates. The spillway structure includes several post-tensioned systems installed in the concrete piers. These systems do not meet the cable protection standards of modern methods, which provide two barriers against corrosion and can be monitored. In 2004, several leaks were detected that could have reached the steel tendons. Because of this, an innovative programme was developed to ascertain the integrity and remaining life of the steel strands. This paper presents a summary of the activities performed and the instrumentation installed at Piedra del Aguila to assist with the long-term monitoring of the dam.

In 2004, several leaks were detected at the lateral walls of the spillway piers of Piedra del Aguila dam in southern Argentina. Most of these leaks were located at pier number 3, near to the trunnion and below the level of the strands, coinciding with carbonation surface marks. Concern arose about the integrity of the system supporting the gates on the top of the spillway, which comprised a set of post tensioned tendons embedded in the concrete piers. It was thought that they could have been dampened by the leaking water, so the onset of steel corrosion was quite likely.

As a result, there was a need to establish whether or not the steel strands were being corroded. In case corrosion was detected, an estimate of the amount of damage (by measuring the corrosion rate of the steel) was required to assess the remaining cross section of the tendons and the impact on the integrity and safety of the support system, for the spillway gates.

In agreement with the regulatory authorities of Argentina, ORSEP (Organismo Regulador de Seguridad de Presas), a permanent safety evaluation programme to evaluate and monitor the tendon corrosion, was implemented by the operator. It consisted of three activities, which would allow for a complete assessment of the significance of the problem. The activities were:

• In-situ water sampling in several locations at the dam. The samples were chosen to represent the variety of water compositions encountered and were analysed for composition and the overall corrosion risk in accordance with DIN 50 929 Part 3 Standard. Also, a metallurgical examination of the steel strands was performed.
• Laboratory tests, carried out to simulate potential corrosion rates using actual water samples collected.
• The installation of sensors for continuous monitoring of several parameters related to the corrosion susceptibility of the grouted steel.

This work programme began in 2005 and is still running, managed by the Auscultation and Maintenance Division (A&MD) of Piedra del Aguila Company and carried out by the Corrosion Department of the National Atomic Energy Commission of Argentina (CNEA). Only a few references were found in literature concerning this type of task [Herweynen and Hughes, 2002[1]; Powers, 1999[2]; Powers *et al*., 2001[3]].

1. Features of the Piedra del Aguila dam

The Piedra del Aguila project is a 1400 MW hydropower plant located in the province of Neuquén in the northern part of Argentinean Patagonia. As with the other four dams built along the Limay river by the state enterprise Hidronor, it was constructed in the 1980s. The Hidroeléctrica Piedra del Aguila SA Company (HPDASA) is currently the operator. As HPDASA started operating the utility in 1993 an Auscultation and Maintenance Division (A&MD) was created to work on the safety requirements imposed on the dam by ORSEP.

(a) General view of the Piedra del Aguila dam.

(b) View of the spillway and floodgates.

From left: (c) View of one of the piers studied. (d) Network of the fully grouted post-tensioned strands. (e) Detail of a strand.

Piedra del Aguila is a gravity dam with a maximum height of 170 m and an 820 m-long concrete wall forming a 292 km^2 reservoir with a water level varying between 586 and 592 m. The four-gate spillway channel is at the left side of the dam with a ski jump type deflector at the end. The spillway crest is located at el. 574 m and can be seen in photo (a).

Each of the four radial floodgates has two V-shaped 'arms' between els. 574.4 and 586.4, which are supported by the trunnions of the two concrete piers (see photo (b).

The integrity of the spillway's piers, and especially the trunnions, is assured by a network of 21 fully grouted post-tensioned tendons (strands) placed longitudinally along the pier wall, between the dam wall and the trunnions, distributed in an area of 1 m^2, see photo (c).

Each strand comprises seven wires, 5 mm in diameter, six of them twisted around the straight one in the centre. According to the technological knowledge at the time the dam was built, the tendons were protected against corrosion by the filling grout exclusively. Therefore, they do not have the cable protection of modern methods, which provide two barriers. They are, in terms of the current standards [American Concrete Institute, 2001[4]], uncoated Class II tendons (strands) with just one corrosion barrier.

Drainage of water saturated with carbonates, as indicated by the white spots that had been deposited, was detected at several of the trunnions' front faces downstream of the dam wall, as can be seen in picture (f). This indicates that the reservoir water was able to diffuse through the concrete voids from the reservoir to the spillway pier's trunnion so there was a high probability that water had come in contact with the embedded steel tendons.

Carbonation (leaching compounds) residue was detected on some of the trunnion front faces downstream, as can be seen in picture (f). It was probably then that small defects in the concrete upstream face of the dam caused leakage and water subsequently reached the trunnions.

This was confirmed by injecting water and air under pressure at a drainage hole in the dam galleries at el. 560. During this test, water and air drained out to the reservoir in front of the spillway's concrete wall, bubbling in the water, as observed by a scuba diver. Water draining from the trunnion was also observed. This test confirmed the connection between the reservoir water and the strands, or at least with its PVC tube. The uncoated steel tendons would develop corrosion processes if they came into contact with the water, oxygen and aggressive ions filtered through the concrete.

(f) White spots of leaching material on the surface of the walls.

2. Development of the evaluation programme

The laboratory corrosion study and the various activities performed to carry out the corrosion monitoring measurements were started simultaneously. A description of these activities and the results are presented next.

3. Water sampling and metallographic studies of the steel strands

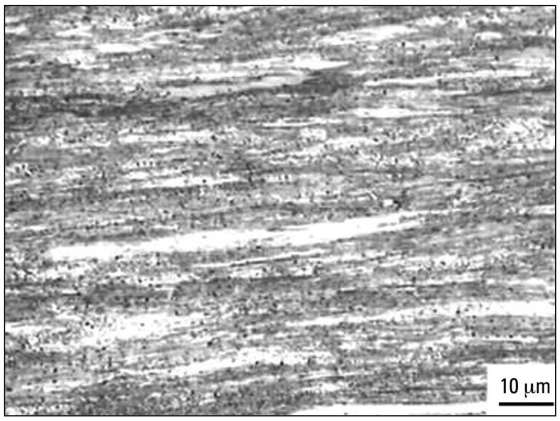
To study the whole system, a metallographic and chemical characterization of the steel was performed. A chemical analysis of water samples, taken from two locations where the water could wet the tendons, were also done. The chemical composition of the steel, according to the ASTM E 1024-97 standard procedure [American Society of Testing and Materials, 2004[5]] and expressed as per cent weight/weight is shown in Table 1.

This composition fits the requirements of an SAE 1070 high strength steel. From the metallographic analysis, photo (g) shows that the steel strands have a highly deformed cold drawn banded ferritic-pearlitic microstructure.

Two water samples selected as representative were called 'drainage water' and 'pumped water'. The first is the water diffusing through the concrete dam's walls that drains to the different leakage sites in the dam's

Table 1. Chemical composition of the steel strands

C	Si	Mn	P	S	Cr	Ni	Mo
0.75	0.25	0.78	0.012	0.009	0.05	0.03	0.01



(g) A longitudinal metallographic section of the steel strand.

galleries; and, the second one is the water that drains out of the existing concrete cracks in the pier walls. The pumped water was lake water, pumped at high pressure through the concrete to assess the origin and length of the cracks. Samples of this water were taken when draining from the cracks on the pier concrete faces and submitted for chemical analysis. The two water samples, and a reservoir water sample, were used for the corrosion tests. Table 2 summarizes the origin and features of the water samples. The composition of the samples is shown in Table 3.

As can be seen, the reservoir water composition corresponds to typical thaw water. The drainage water shows slightly higher ion concentration values and a higher pH value. The pumped water has a much higher ion content because of the leaching effect of the water on the concrete. The pH value is higher as well, indicating the higher alkalinity of this water sample.

The awareness of the water composition led to the application of standards to predict the water aggressiveness against the steel strands. The overall corrosion risk assessment, in accordance with DIN 50 929 Part 3 [1985[6]], 'Probability of corrosion of metallic materials when subject to corrosion from the outside' reveals that the predicted uniform corrosion rate is about 10 μm/year, with a maximum penetration of 50 μm/year, and a tendency to decrease with time.

Table 2. Different types of water analyzed.

Sample	Origin	Features
A-1	Draining water, pier no. 3 trunnion	Injected water
A-2	Lake, water level 564 m pier no. 3	Lake water
A-3	Drainage from pier no. 3, water level 560 m	Drainage water

Table 3. Chemical composition of the different water samples studied.

Sample/content	A-1* injected water	A-2 reservoir water	A-3 pier Nº3 drainage water
Chloride (mg/l)	--	≤ 1	≤ 1
Sulfate (mg/l)	--	≤ 3	8
Total (mg $CaCO_3$/l)	--	27	34
Carbonates alcalinity (mg $CaCO_3$/l)	--	ND	16
Bicarbonate alcalinity (mg $CaCO_3$/l)	--	27	18
Hidroxide alcalinity (mg $CaCO_3$/l)	--	ND	ND
Conductivity (microS/cm)	10.000	49	69
pH	12	7.6	8.3
ND = not detectable			
*Not sufficient amount for chemical analysis.			

4. Laboratory corrosion tests

The laboratory corrosion rate measurements were carried out by two electrochemical methods: polarization curves to obtain corrosion rate mean values; and, the linear polarization resistance technique (LPR) for instantaneous corrosion rate data [Jones, 1996[7]]. Working electrodes were prepared from the straight wire of the strands. Several of these electrodes were set into a standard cement grout with coverage of less than 1.2 cm wide. Tests were performed in three conditions: ungrouted electrodes (bare steel) in the water samples; grouted electrodes in the water samples; and, 'coupled electrodes', where grouted and ungrouted electrodes were connected using a zero resistance ammeter, to determine the extent of any acceleration. The coupled electrode test was designed to show the effect of the galvanic coupling that occurs when the cracked grout allows direct contact of a part of the strand metal with water at a limited location. All measurements were performed in the three water samples mentioned previously (lake, drainage and injected water).

As established in the ASTM C876 standard [American Society of Testing and Materials, 1987[8]], potentials more positive than -0.100 V_{SCSE} (copper-saturated copper sulphate electrode) indicate a passive condition, or non-corroding steel. Potentials more negative than -0.300 V_{SCSE} indicate active corrosion. Between the values of -0.100 and -0.300 V_{SCSE}, there is an equal likelihood of passive and active conditions. Table 4 summarizes the practical meaning of the corrosion potential.

Table 5 shows the results of laboratory and on-site corrosion potential measurements (performed in four different strands). On-site potentials are generally more positive than laboratory values, showing a better condition in the three places tested. Laboratory data showed that only grouted steel in drainage and injected water are in the protected zone (according to ASTM C876 Standard [American Society of Testing and Materials, 1987[8]]), while bare and coupled steel are in the active corrosion zone. These data also show that the laboratory measurements represent extreme conditions, unlikely to be reached by the actual strand steel (a so-called 'worst case scenario'). It can also be seen that in cases where the water has passed through the concrete, the corrosion potential of wet steel is higher, probably because of the presence of carbonate anions leached from the

Table 4. Meaning of the corrosion potentials according to ASTM C876 standard [Jones, 1996[7]].

Potential (V_{SCSE})	Meaning
> -0.200	No corrosion. 90 per cent probability of grouted steel in a passive state.
-0.350< E <-0.200	No certainty about the steels condition.
< -0.350	Corrosion. 90 per cent probability of grouted steel in an active corrosion state.

concrete that raise the pH value of the water solution allowing the formation of a protective oxide film on the steel surface.

The polarization curves of steel in the three water samples were carried out in aerated and non-aerated conditions. The corrosion current of the iron dissolution reaction in each solution was graphically calculated from the intersection of the slope line of the anodic branch of the polarization curve with the corrosion potential value, as can be seen in Fig. 1. In this case, the corrosion current density (I_{corr}) is calculated as $I_{corr} = B/R_p$ where B is a constant depending on the active or passive state of the steel [Andrade and Alonso, 1996[9]]. The corrosion rate (CR) in μm/year is obtained with the equation CR = I_{corr}.1.16 × 10^7, with I_{corr} expressed in A/cm^2 [Andrade and Alonso, 1996[9]]. Table 6 summarizes the results obtained in both aerated and non-aerated water samples. It is worth mentioning that all electrochemical tests were performed in triplicate, and the average values are reported here.

It can be seen clearly that in aerated water at neutral or slightly alkaline pH values, the steel rapidly develops a passive oxide film leading to lower values of the measured corrosion rates.

The linear polarization resistance (LPR) technique determines the instantaneous corrosion rate of a metallic specimen by measuring the polarization resistance (R_p) at the corrosion potential (R_p is the slope $\Delta E/\Delta I$ close to the corrosion potential). By taking R_p values every hour during a 100 hours test, an R_p vs time curve can be drawn to obtain the corrosion rate mean value. Fig. 2 shows the R_p vs time evolution for steel in aerated and non-aerated drainage water and Table 7 shows the corrosion rate values obtained after integration of the R_p values. As expected, aerated water tests show higher R_p values, which means a lower corrosion rate. This is because of the poor steel passivation capacity in the absence of dissolved oxygen. It is important to highlight the low corrosion rate of steel in aerated alkaline pumped water (A1).

To determine the protecting effect of the grout coverage against steel corrosion, polarization curves with grouted specimens in aerated waters were also done. The corrosion rate values obtained (Table 8) are significantly lower than expected in the case of bare metal.

The unbounded length of the post-tensioned tendons are freely exposed to the atmosphere or barely covered with the grout. This could lead to the formation of a galvanic couple between grouted and bare or lightly grouted steel at the extreme end of the tendons. To reproduce this situation, polarization curves with coupled steel samples were done. The results can be seen in Table 9, which effectively show the increment in the corrosion rate compared with Table 8 values, produced in coupled steel samples in the three media tested.

5. Design, construction and installation of corrosion sensors

Corrosion sensors capable of measuring several parameters related to the corrosion susceptibility of the steel were already developed in the Corrosion Department of CNEA [Duffó *et al.*, 2007[10]; Duffó and Farina, 2009[11]]. In this case, these parameters describe thoroughly the conditions of the steel tendons in any place inside the concrete walls of the dam. The 'combined sensors' can measure on-site the corrosion potential and the corrosion rate of the steel specimen, the resistivity of the grout and, the oxygen flow through the grout's pores.

Table 5. Corrosion potentials measured on-site and in the laboratory.

Place no.	Corrosion potential on site (V_{SCSE})			Water sample	Bare steel	Corrosion potential in laboratory (VSCSE)	
	Coupled steel	Bare steel	Grouted steel			Grouted steel	Coupled steel
1	-0.18	--	--	A-1	-0.33	-0.15	-0.31
2	-0.14	--	--	A-2	-0.48	-0.28	-0.35
3	-0.166	--	--	A-3	-0.55	-0.18	-0.33
4	-0.4	--	--		--	--	--

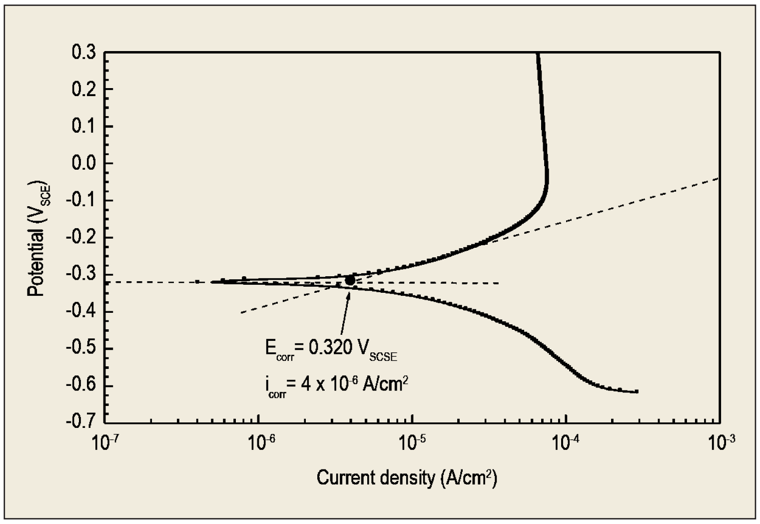


Fig. 1. Typical polarization curve of steel in an A-1 injected water sample, demonstrating how the corrosion current density (icorr) is obtained.

Table 6. Corrosion rates (CR) in aerated and non-aerated waters of different origins.

Water sample	Aerated		Non-aerated	
	I_{corr} (A/cm^2)	CR (μm/year)	I_{corr} (A/cm^2)	CR (μm/year)
A-1	4.9 × 10^{-6}	53	1.8 × 10^{-5}	209
A-2	2.4 × 10^{-6}	28	7 × 10^{-6}	81
A-3	6 × 10^{-6}	70	1.7 × 10^{-5}	197

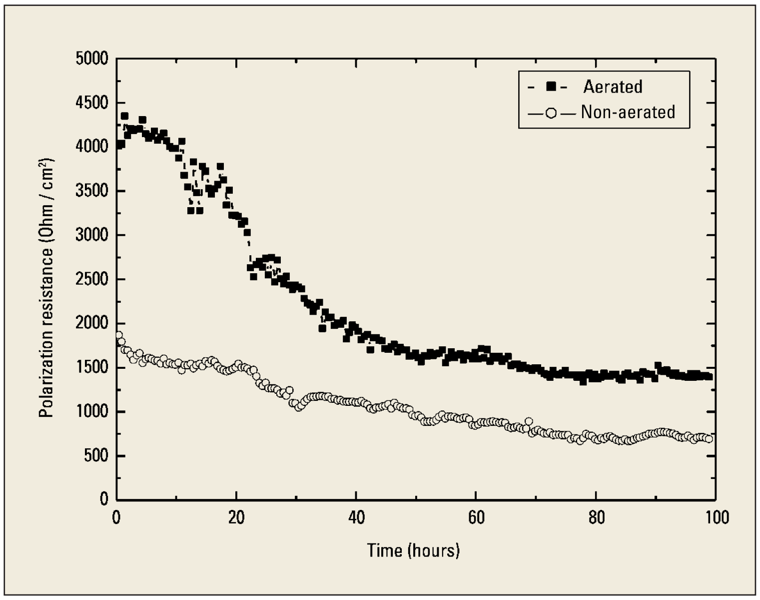


Fig. 2. Evolution of the polarization resistance of the steel in an A-3 water sample, as a function of time.

Table 7. Corrosion rate of the steel after 100 h exposure-time in aerated and non-aerated waters of different origins.

Water sample	Aerated		Non-aerated	
	I_{corr} (A/cm^2)	CR (μm/year)	I_{corr} (A/cm^2)	CR (μm/year)
A-1	4.9 × 10-7	6	8.8 × 10^{-6}	102
A-2	7.8 × 10-6	91	1.2 × 10^{-5}	143
A-3	8.4 × 10-6	97	9.8 × 10^{-6}	114

Table 8. Corrosion rate of an embedded steel in different water samples.

Water sample	I_{corr} (A/cm^2)	CR (μm(year)
A-1	1.8 × 10^{-7}	2
A-2	5 × 10^{-7}	6
A-3	8.2 × 10^{-7}	1

Final appearance of the sensor. (left) before embedding in porous mortar; (centre) after embedding in porous mortar; (far right) sensor installed in pier number 3.

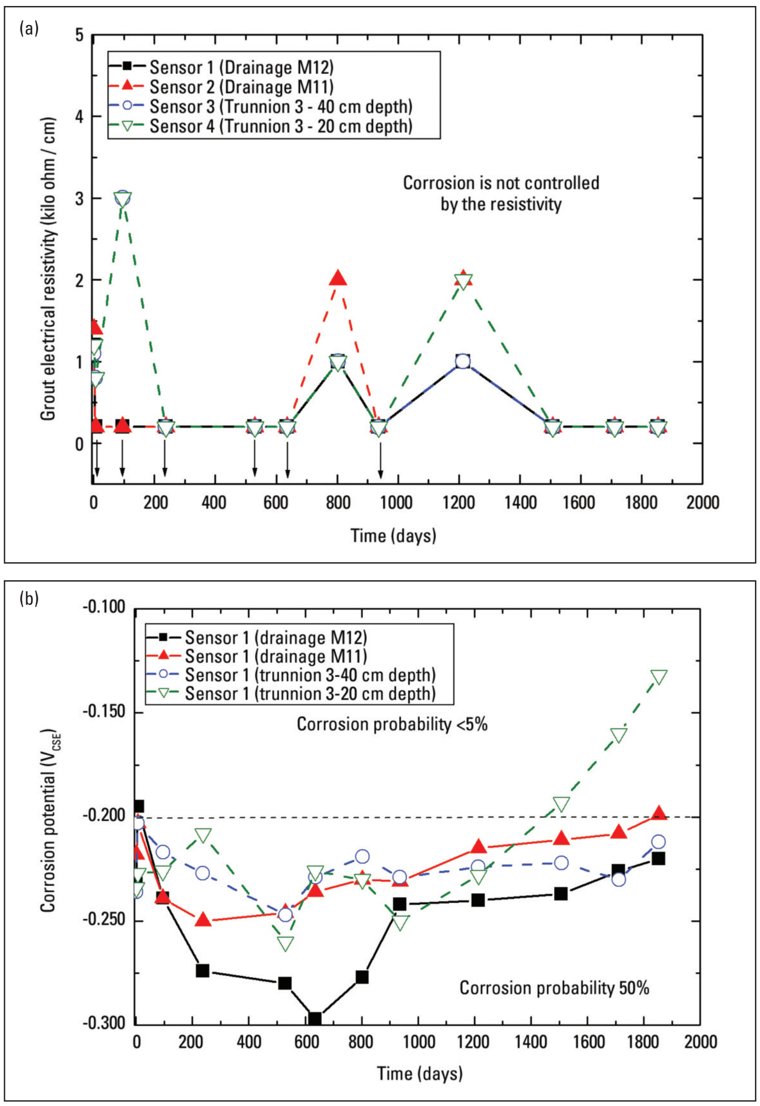


Fig. 3. Results obtained with the sensor embedded in different places: (a) evolution of the grout electrical resistivity; (b) evolution of the corrosion potential.

The concept of the monitoring programme was to install corrosion sensors in several places in the dam and the spillway channel, which were representative of the physical and chemical condition of the actual grouted strands. This decision arose because it was not possible to carry out electrochemical corrosion measurements directly on the grouted steel of the tendons. Two locations were chosen. One was inside the dam galleries where the draining water is collected and drained. The other was in pier number 3 of the spillway, beneath the unbounded end of the tendons where indications of water leakage had been found. In each location, 15 cm-wide, by 20 and 40 cm-deep holes were drilled in the concrete to install the sensors. After this, the holes were filled with porous grout (0.6 water/cement ratio) to obtain, after two or three months, a perfect integration of the sensor and the concrete wall. The connection cables were left outside the grout and were protected against the effect of the weather conditions

The photos above show the sensor before and after grouting and the installation sites in the gallery and near the unbounded ends of the strands at the trunnions.

During the past 5 years, records of the different parameters measured with the combined sensors were taken approximately twice a year, and graphically presented as a function of time.

The electric resistivity and the oxygen flow through the concrete are parameters that provide information about the humidity and pore density of the grout. They revealed the wetting capacity of the environment around the grouted strands and, indirectly, the steel corrosion risk level at each place. The evolution of these parameters with time can be seen in Figs. 3a to c. The records show that the resistivity is quite low, which is indicative of the permanent wetting of the concrete at the testing places. Wet concrete allows corrosion of the steel because the water content needed to sustain the corrosion process is present in the media. Resistivity values between 1 and 3 kΩ show that there is no ohmic control of the corrosion process [McCarter *et al.*, 1983[12]; McCarter *et al.*, 1981[13]]. The oxygen flow measured in current density units shows

Table 9. Corrosion rate of a naked steel coupled with an embedded steel in water of different origin.

Water sample (aerated)	I_{corr} (A/cm^2)	CR (μm(year)
A-1	5 × 10^{-6}	58
A-2	1.9 × 10^{-6}	22
A-3	7 × 10^{-6}	81

that after 1850 days of monitoring, there is a trend to constant values between 15 and 40 μA/cm^2. These values indicate dissolved oxygen content around one half of the level found in water at room temperature and normal atmospheric pressure, so there is oxygen enough to sustain steel corrosion.

The parameters directly linked to the steel corrosion process are the corrosion potential, the corrosion rate and the evolution with time, which are shown in Fig. 3. The thermodynamic parameter (the corrosion potential) shows values below -0.200 V_{CSE}, indicating certain corrosion risks (50 per cent corrosion likelihood). Nevertheless, the tendency clearly shows an increasing trend of the corrosion potential with time, up to a level close to the low corrosion probability. This trend is particularly clear at the trunnion monitoring site.

The corrosion rate is the kinetic parameter that shows the actual degradation rate of the steel. The data recorded over 1850 days in all the installed sensors are at a level of moderate-low corrosion rate, with values ranking from 2 to 6 μm/y. A strong seasonal trend can be seen where data taken in the hotter spring/summer time are higher than those taken in winter. The negative slope of the corrosion rate-time curves indicates that the corrosion of a steel sample embedded in concrete in the most representative places on the dam, decrease with time. It can be estimated that, if the corrosion rate of the tendon's steel stays stable in the worst condition (6 μm/y), a loss in diameter of 1.2 mm after 100 years should be produced. This condition can be rated as a low to moderate corrosion condition.

6. Conclusions

To assess the integrity of the tendons of the gates support system at the Piedra del Aguila spillway channels, corrosion sensors were installed inside the concrete walls. The concept was to monitor on-site the corrosion of steel samples from strands in the same environment as the actual tendons. The parameters related to the environment's characteristics, showed that there was low concrete resistivity and therefore conditions for corrosion to occur. This indicated the presence of water and ions, and a certain level of oxygen diffusion through the concrete.

The parameters directly linked to the corrosion process also showed values that are indicative of corrosion processes but, the amount of corrosion seems to be low, with a decreasing trend. A strong temperature dependence of the corrosion process was detected when comparing the corrosion values obtained in summer and winter.

Unfortunately, no corrosion rate values have been found in the literature referring to grouted tendons in fresh water systems that allows for a comparison with the corrosion behaviour of the Piedra del Aguila spillway tendons. It would be useful to gather all the information on this subject and create a database to develop the real significance of the corrosion rate measured at every place and in each condition.

The Piedra del Aguila spillway tendons show a low level of measurable corrosion rate, which is indicative of an ongoing corrosion process at the grouted tendons. This process seems, at the moment, to be acceptably low and all parameter trends show favourable indications. Nevertheless, potential problems exist and require ongoing monitoring of the corrosion rates as part of the regular integrity control measurements. ◊

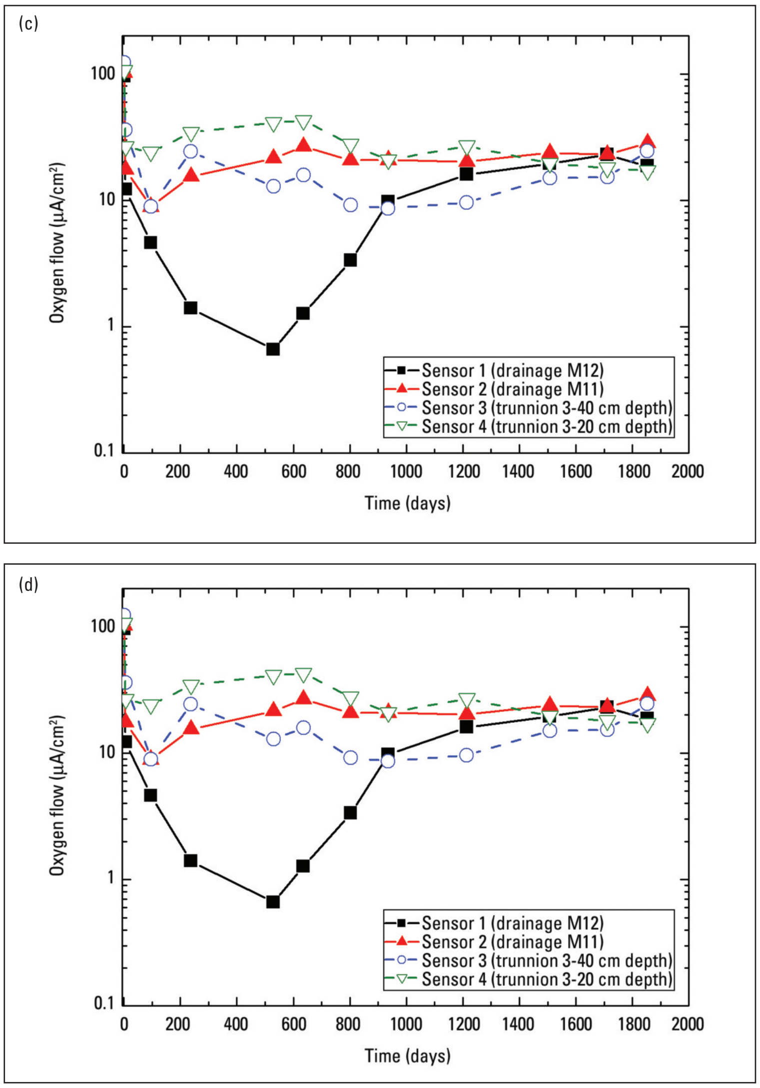


Fig. 3. Results obtained with the sensor embedded in different places: (c) evolution of the oxygen flow; and, (d) evolution of the corrosion rate.

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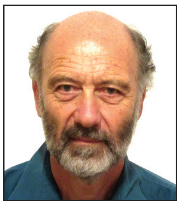

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