Evaluation of the Corrosion Activity of Reinforcement in Drainage Gallery of Concrete Dam Using Half-Cell Potential (HCP)

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Abstract:
Dams are essential structures for water management, providing various benefits crucial for human survival and economic growth. However, steel corrosion in concrete dams poses a significant threat, leading to structural deterioration and potential collapse. Detecting corrosion in the early stage is critical to prevent catastrophic failures. This study investigates corrosion risk in a concrete dam's drainage gallery using half-cell potential (HCP) measurements, a common method for assessing corrosion activity in reinforced concrete.

The electrochemical process of steel corrosion in concrete, influenced by factors like chloride or carbonation exposure and temperature, is discussed. The HCP method is a nondestructive technique for determining the corrosion rate of steel reinforcement in concrete structures. It involves measuring the potential difference between reinforcing steel and reference electrodes; typically, a copper/copper sulphate electrode is used. The potential difference between the two electrodes is then used to calculate the corrosion rate of the reinforcing steel.

The HCP method is a reliable and cost-effective way to identify potential corrosion problems before they become severe. The present study used CorMap II® to measure HCP on the upstream face of the dam's drainage galleries. Results indicate predominantly low corrosion risk across tested locations, with minimal uncertainty. However, interpretations must consider environmental factors' influence on measurements. The study's findings offer valuable insights for future corrosion assessments and underline the importance of preventive measures for concrete dam integrity.

Keywords: concrete dams, steel corrosion, half-cell potential, corrosion assessment, environmental factors, preventive maintenance.

1. Introduction

A dam is a structure built across rivers, streams, or estuaries, specifically designed to impound water and create a reservoir. The reservoir, in turn, serves as a reliable source for several purposes, including drinking water, industrial activities, power generation, and irrigation. The significance of dams cannot be overstated, as they are critical to human survival and the continued growth of economy of country. As such, they require continuous monitoring and inspection to ensure their structural integrity and detect any potential problems before they escalate convert into catastrophic failures that could have devastating consequences.

In concrete dams, reinforcement corrosion is one of the deterioration issues that can cause serious damage. Corrosion occurs when the reinforcement within the concrete is exposed to chloride and carbonation environment in presence of moisture and air, leading to rust formation and expansion. Over time, this can cause the concrete to crack, spall, mass reduction in reinforcement, and reduce load carrying capacity, sometimes to the point of collapse. One of the major challenges with steel corrosion in concrete is that by the time the visible sign of surface deterioration appears, the damage may already be quite extensive. For example, rust stains, cracking, and spalling are often visible indications of corrosion, but they typically only appear when the damage is already well underway. Once these signs appear, it may be too late to restore the damage and prevent additional degradation. Therefore, it is crucial to start repairs before the corrosion becomes visible. Routine inspections and assessments of the potential for corrosion in concrete structures are also essential. By identifying and addressing problems early, it is possible to prevent serious damage and ensure the safety and longevity of the structure.

Measuring half-cell potential (HCP) is a commonly used, quick, and inexpensive method to evaluate the risk of reinforcement corrosion in concrete structures. In this present study, the risk of reinforcement corrosion in a drainage gallery (i.e., foundation and transverse gallery) of concrete dam was assessed by measuring the half - cell potential (HCP) at selected locations on the surface of the gallery. The typical cross-section view of the dam body and the plan and cross-section of the drainage gallery were represented in detail in Figure 1 and Figure 2, respectively.

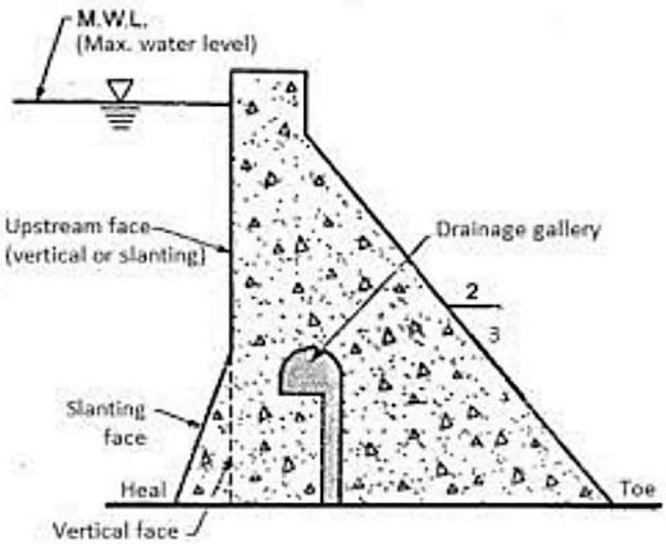
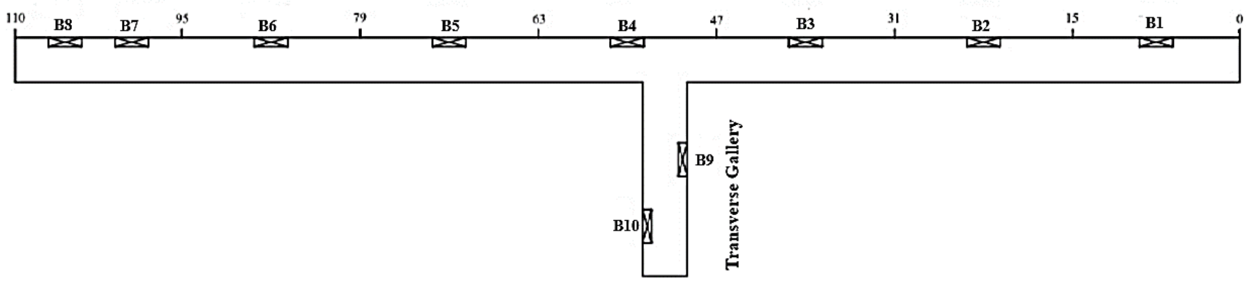


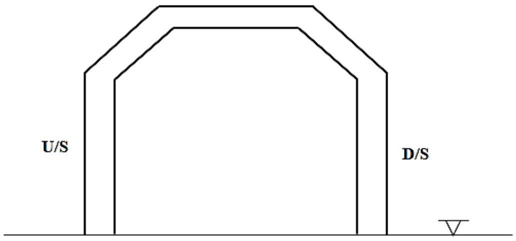
Figure 1: Typical cross-section of the concrete dam

Drainage Gallery

Foundation Gallery



Plan of Drainage Gallery



Cross-section of Gallery

Figure 2: Plan and cross-section of drainage gallery

2. Theory of Reinforcement Corrosion in Concrete

Corrosion is an electrochemical process involving two reactions, i.e., anodic and cathodic. The anodic and cathodic processes occur at different potentials, primarily influenced by the constituent materials and species concentrations (Fe^{2+}, OH^-, O_2, and Cl^-). The corrosion process consists of an anode, a cathode, an electrolytic connection (ionic current), and a metallic connection (electronic current). When steel in concrete corrodes, oxidation takes place, i.e., it dissolves in pore water and gives up electrons:

$$Fe \rightarrow Fe^{2+} + 2e^-$$

Further, a reduction reaction (consumption of electrons) occurs at the cathode, which is the driving force of the corrosion process. The reduction reaction is given below:

$$2e^- + H_2O + \frac{1}{2}O_2 \rightarrow 2OH^-$$

This cathodic reaction suggests that oxygen and water are necessary for corrosion. A galvanic cell is formed, where electrons pass through the reinforcement from anodic to cathodic sites, and the electrical charge is passed as ions in the electrolyte. The formation of rust involves further reactions, such as the transformation of ferrous hydroxide into ferric hydroxide and ultimately hydrated ferric oxide or rust:

$$Fe^{2+} + 2OH^- \rightarrow Fe(OH)_2 \quad (3)$$

Ferrous Hydroxide

$$4Fe(OH)_2 + O_2 + 2H_2O \rightarrow 4Fe(OH)_3 \quad (4)$$

Ferric Hydroxide

$$2Fe(OH)_3 \rightarrow Fe_2O_3.H_2O + 2H_2O \quad (5)$$

Hydrated Ferric Oxide (Rust)

A schematic diagram of reinforcing corrosion in concrete as an electrochemical process is presented in Figure 3.

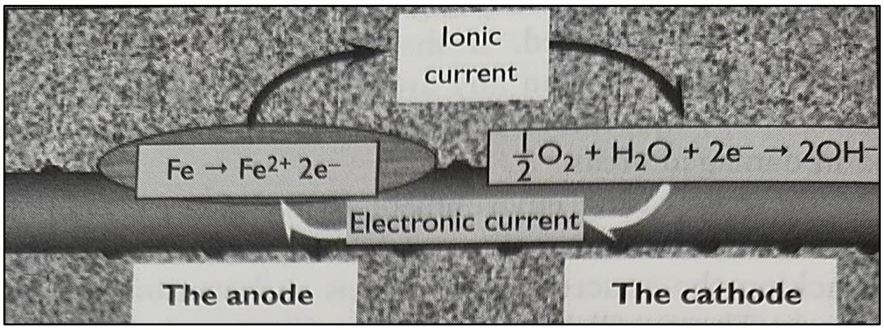


Figure 3: Electrochemical process of reinforcing steel corrosion in concrete

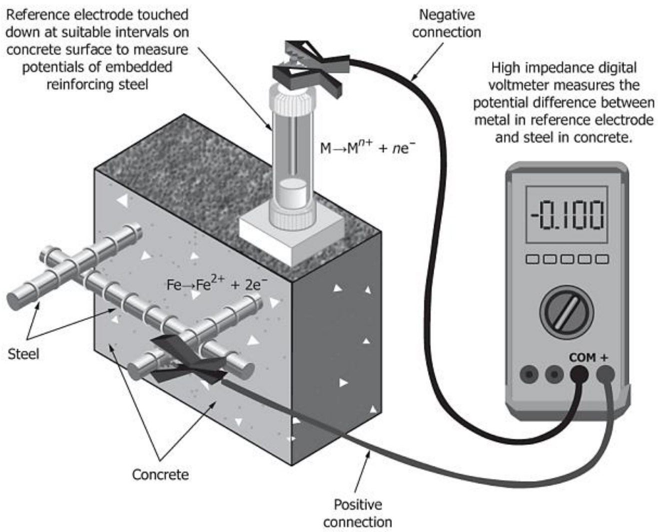
Reinforcing steel corrosion is a process that follows the same principles and produces the same reactions as other corrosion processes. In normal corrosion, the electrolyte is usually water or salt solutions in water. However, in the case of reinforcing steel corrosion, the electrolyte is the porous concrete. In comparison to aqueous solutions, the electrical resistivity of concrete is substantially higher, which is the controlling factor for the corrosion rate. The concrete resistance can also indicate the ease of chloride penetration into the concrete, which is an essential factor in the initiation and progression of steel corrosion in concrete. There are several critical criteria that can influence the initiation and progression of steel corrosion in concrete. These criteria include permeability, electrical resistance, humidity level, oxygen availability, chloride concentration, depth of carbonation, and temperature. Temperature has an overall accelerating influence on all degradation processes, including steel corrosion. The initiation phase is mainly influenced by the density of the concrete, which is closely related to chloride ingress and indirectly related to resistivity. However, humidity level is the most critical factor that influences the initiation and propagation of corrosion. Humidity in concrete affects all the essential factors for corrosion such as carbonation, chloride penetration, critical chloride content, oxygen supply, and electrical resistance of the concrete. It governs both the initiation and propagation of corrosion, making it a crucial consideration in any analysis or action plan aimed at preventing or mitigating steel corrosion in concrete.

3. Basic Principle of Half-cell potential method

The Half-Cell Potential (HCP) method is a technique used to assess the corrosion activity in the reinforcement present in concrete structures. Half-cell potential measurements usually involve measuring the potential of an embedded reinforcing bar relative to a reference half-cell placed on the concrete surface. Mostly the half-cell used is Copper-Copper Sulphate (CSE) or Silver-Silver Chloride cell (Ag-AgCl). The concrete functions as an electrolyte and the risk of reinforcement corrosion are empirically related to the measured potential difference.

The Half-cell consist of porous wooden or plastic plug that stays wet through capillary action, a rigid tube made of non-reactive dielectric material with copper-copper sulphate, and a copper rod submerged inside the tube in a saturated solution of copper sulphate. One end of the lead wire is connected to the half-cell and the other end to the negative terminal of the voltmeter. The bar is connected to the positive terminal of the voltmeter, where concrete acts as an electrolyte. The ferrous ions (Fe^{2+}) dissolve at the anode, and electrons are set free. These electrons drift to the cathode, forming hydroxide (OH^-). The electrical potential difference between a reinforcing bar and a standard portable reference electrode in contact with the concrete surface is measured.

The measured Half-Cell potentials interpretation shall be interpreted as per IS 516 (Part 5/Sec 2): 2021. The schematic diagram of the half-cell potential measurements setup is presented in Figure 4.



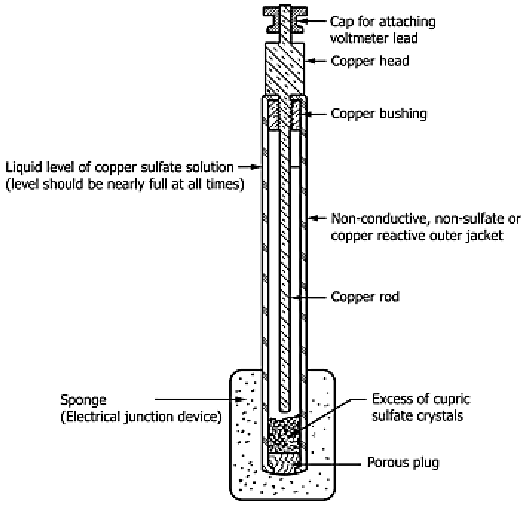


Figure 4: Schematic diagram of the half-cell potential apparatus

Corrosion in concrete structures can be assessed using the guidelines provided in Table 1 in compliance with IS 516 (Part 5/Sec 2):2021.

Table 1: Criteria for Corrosion Condition of Reinforcing Steel in Concrete as per IS 516 (Part 5/Sec 2):2021

Potential, Volts	Likely Corrosion condition ($Cu/CuSo_4$ Electrode)
-0.000 to -0.200	Low (90% chance that no corrosion activity is present over this area)
-0.200 to -0.350	Corrosion activity over this area is uncertain
-0.350 to -0.500	High (90% chance that corrosion is occurring in this area)
More than -0.500	Severe corrosion

3.1 Importance and limitation of the Half-Cell Potential method

a. This test method applies to projects involving in-service evaluation and research and development works.
b. This test method applies to all structural elements regardless of the size and depth of cover concrete over the reinforcing steel.
c. This test method cannot apply to epoxy-coated reinforced concrete structures.
d. This test method is inappropriate for reinforced concrete structures protected with water-proofing membranes, as these membranes can prevent the conduction of electricity and result in inaccurate readings.
e. This test method is more effective for assessing the risk of corrosion in mature reinforced concrete.
f. Temperature and humidity play vital roles in influencing the potential readings. This is especially crucial for repeated testing at the same location. As temperature rises, ionic mobility increases, affecting the potential of the reference electrode. The influence of temperature can be neglected if the measurements are taken within the range of 22.2°C ± 5.5°C (72°F ± 10°F). Otherwise, the temperature dependency of the measurements must be taken into account.

4. Experimental Methodology

A half-cell potential apparatus was used to evaluate the risk of corrosion activity in the reinforcement present in the concrete structures of the upstream face of the drainage gallery of the dam. In this study, CorMap II® (Make: James NDT) was used to measure the half-cell potential. The CorMap II® picture is presented in Figure 5.

Before taking Half-cell potential measurements on the concrete surface of the upstream face of the drainage gallery, the test surface was carefully examined for an exposed reinforcement bar near the test location. If no exposed reinforcement bar was found, a small portion of the concrete was chipped off in order to expose the reinforcement bar. Once the reinforcement was exposed, a direct electrical connection was made to it through an alligator clip. The reinforcement bar was then connected to the positive terminal of the high-impedance voltmeter, one end of the lead wire to the half-cell, and the other end to the negative terminal of the high-impedance voltmeter. Ten test locations (B1, B2, B3, B4, B5, B6, B7, B8, B9, and B10) were selected for corrosion risk assessment, as shown in Figure 2. Each test location was then marked into a grid with 40 cm spacing in both horizontal and vertical directions, and the surface was made wet by spraying water. Half-cell potential measurements were recorded at nodal points on the grid. This process was repeated across the entire grid by shifting the reference electrode to the next node until the entire grid was covered. The acquired data were then analyzed and compared against the guidelines specified by IS 516 (Part 5/Sec 2):2021. By comparing the acquired data to these guidelines, it was possible to determine the risk of corrosion activity in the reinforcement of the concrete structures.

Figure 5: Half-Cell Potential test apparatus Cor Map II® (Manufacturer: James NDT)

5. Discussion of Test Results

Half-cell potential measurements were taken in the selected ten locations of the drainage gallery of the concrete dam. A summary of the measurements taken is given in Table 2 below:

Table 2: Corrosion Condition of Reinforcing Steel on the upstream face of drainage gallery and transverse gallery of concrete dam based on Half-Cell Potential (HPC) measurements in Volts

Test Location	No. of Measurements	>-0.200	<-0.200 > - 0.350	<-0.350 > -0.500	< -0.500
		Low	Uncertain	High	Severe
1	57	57	0	0	0
2	39	39	0	0	0

3	39	39	0	0	0
4	45	45	0	0	0
5	45	43	2	0	0
6	45	43	2	0	0
7	45	45	0	0	0
8	45	45	0	0	0
9	30	30	0	0	0
10	56	56	0	0	0

6. Conclusion and Recommendation

Through the analysis of half-cell potential data obtained from the drainage gallery, the current field experiment has provided valuable insights into the corrosion levels of the material under investigation. The results show that 99.10% of the readings indicate low corrosion levels, while only 0.90% of the readings suggest uncertain corrosion levels. It's worth noting that the half-cell potential measurements may be influenced by various in-situ and environmental factors, such as temperature, humidity, and the presence of contaminants. Therefore, it's essential to take into account the effect of these factors on the measurements and interpret the results accordingly. Overall, the findings of this experiment provide a useful starting point for further investigation into the corrosion levels of the material and can serve as a reference point for future studies in the field.

Acknowledgments

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References:

1. ASTM International. (2022). ASTM C 876-22b: Standard test method for corrosion potentials of uncoated reinforcing steel in concrete.
2. Elsener, B., Andrade, C., Gulikers, J., Polder, R., & Raupach, M. (2003). Half-cell potential measurements – Potential mapping on reinforced concrete structures. RILEM TC 154-EMC: 'Electrochemical Techniques for Measuring Metallic Corrosion.
3. Elsener, B. (2001). Half-cell potential mapping to assess repair work on RC structures. Construction and Building Materials, 15, 133–139.
4. Broomfield, J. P., Rodriguez, J., Ortega, L. M., & Garcia, A. M. (1993). Corrosion rate measurements in reinforced concrete structures by a linear polarization device. In P. D. Cady International Symposium, ACI Fall Convention, Minneapolis, Minnesota.
5. Bungey, J. H., & Millard, S. G. (1996). Testing of concrete in structures. Blackie Academic & Professional.
6. James Instruments Inc., Cor Map II Instruction Manual.
7. Bureau of Indian Standards. (2021). IS 516 (Part 5/Sec 2):2021: Hardened concrete—methods of test part 5 non-destructive testing section 2 half-cell potentials of uncoated reinforcing steel in concrete.

8. Adriman, R., Ibrahim, I. B. M., Huzni, S., Ariffin, S. H. K. A., & Ahmad, S. F. (2022). Improving half-cell potential survey through computational inverse analysis for quantitative corrosion profiling. Case Studies in Construction Materials, Elsevier Ltd, https://doi.org/10.1016/j.cscm.2021.e00854.
9. Vennesland, M., Raupach, M., & Andrade, C. (2007). Recommendation of RILEM TC 154-EMC: ‘‘Electrochemical techniques for measuring corrosion in concrete’’—measurements with embedded probes. Materials and Structures, 40, 745–758. DOI: 10.1617/s11527-006-9219-4.
10. Almashakbeh, Y., Saleh, E., & Al-Akhras, N. M. (2022). Evaluation of half-cell potential measurements for reinforced concrete corrosion.