Direct and Probabilistic Interrelationships between Half-Cell Potential and Resistivity Test Results for Durability Ranking

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ABSTRACT: Tests related to durability studies on structures often feature half-cell potential and resistivity data. An approximately linear relationship between half-cell potential testing and resistivity data has been discussed and well-researched. In spite of criticisms related to environmental sensitivity of resistivity tests it remains as a popular choice for investigations into durability of structures. This paper investigates the correlation between half-cell potentials and resistivity tests on reinforced concrete from field data from tests on six bridges. The empirical interrelationships from the six bridges with widely varying environmental exposure conditions and the variation of such interrelationships are observed. Similar investigations are carried out on different elements of bridges. The paper then discusses problems related to the interpretation and practical application of correlations carried out on absolute values and advocates the use of statistical measures obtained from test data. The percentile correlations are observed to be helpful when considering exceedances of different threshold values. A customised use of such data in an empirically correlated probabilistic format with can be useful in durability ranking and infrastructure maintenance management. The studies presented in this paper emphasize the advantages of using probabilistic formats over traditional formats when interpreting or quantitatively establishing field relationships between half-cell potential and resistivity data. The ability of this empirically correlated probabilistic format to support structure-specific thresholds of serviceability limit states is discussed. The need for a shared repository for the improvement of accuracy of such correlations and for the use of such correlations as a surrogate for other structures is emphasized.

1 INTRODUCTION

The stock of infrastructure elements throughout the world keeps degrading while the load effects on them tend to get more severe than what they were originally designed for. On the other hand, the available finance for maintaining these infrastructure elements has become more limited than ever (Znidaric, 2011). Durability of these elements, along with the prioritisation of rehabilitation and investment options on these elements are extremely important from the point of view of a long term, feasible, valid and cost-minimised infrastructure maintenance management. Consequently, any decision taken on infrastructural elements at an individual or at a network level is extremely important for the owners, the managers and the tax-payers (Enright and Frangopol, 1999; Estes and Frangopol, 2001;; Fu and Fu, 2006).

Establishing the markers related to the durability of the state of the structure depends heavily on the inspection and testing, computation and interpretations of such testing and computation. The interpretation of results can be significantly aided by observation, reporting and sharing of empirical interrelationahips of durability markers from test results. Development of site-specific empirical relationships among the various testing methods, levels of condition rating and assessment of structures are thus very important for a rapid, practical but dependable decision making. In the presence of enough data and appropriate representations of the relationships, the findings can be used as surrogate information on situations with similar conditions. This may lead to a better assessment of durability conditions in the absence of data or the minimisation of destructive or non-destructive testing. Additionally, this approach ties-in directly with a reliabilistic format of assessment (Pakrashi, 2011).

In this paper, the direct and probabilistic interrelationship among Half-Cell Potential (HCP) and resistivity is investigated on six bridge structures. An identified gap in successful commercial infrastructure maintenance management for durability markers is often the lack of sharing of field-data for the practising engineers. The importance of a centralised maintenance management has been felt for a long time (Znidaric et. Al (2004), Sustainable Bridges (2007), Brime (2001), Troconis de Rincon et.al (2007)). Limited studies on correlations exist for a few tests (Gulikers (2005); Gulikers and Elsener (2009)). The only studies attempting to address the visual and the true measure of safety (Estes and Frangopol (2003)) at a network level considers a number of bridges within an urban location. Presentation of test results on networks of structures under varied exposure and environmental conditions is thus deemed necessary to achieve a better understanding of the true level of correlations and the realistic uncertainties around such relationships. This is a significant motivation behind reporting field-data dependent interrelationships of the tests on a network of six concrete bridges in this paper.

2 EXPERIMENTAL DETAILS

Six concrete bridges of different ages were experimented in the Republic of Ireland. Resistivity and HCP were measured at various locations of each bridge. These bridges are apart by hundreds of kilometres and are exposed to a wide variation of environment. The ages of the bridges are significantly varied as well. Table 1 presents these broad variations of the tested bridges.

Table 1. Exposure conditions and variation of age of the bridges tested.

Bridge	Age* (years)	Type	Exposure
Bridge 1	53	PPC and in-situ RC	Low
Bridge 2	38	RC	Low
Bridge 3	60	RC	Medium to High
Bridge 4	38	PPC and in-situ RC	Medium
Bridge 5	74	RC	Low to Medium
Bridge 6	38	PPC and in-situ RC	Low
RC= Reinforced Concrete PPC= Precast Prestressed Concrete *Approximate Age			

Half-cell potential readings were typically taken in accordance with ASTM C-876 (2009) on a 500mm grid within the pre – wetted test areas of the structure. A saturated copper / copper-sulphate electrode was used as the constant reference source. Traditionally, the probability of corrosion is interpreted as low for potentials more positive than -210mV for a copper – copper suphate electrode. It is also assumed that the range -360mV to -210mV corresponds to an uncertain probability of corrosion while potentials more negative than -360mV corresponds to an almost sure chance of corrosion. If a silver – silver chloride reference electrode is used, then the critical limiting values are recommended to be adjusted by +80mV. In reality, the relative changes of half-cell potential readings are more important and statistical analyses have been presented in support of a relative interpretation of these values (Gulikers and Elsener, 2009).

Test areas were subjected to in- situ measurement of concrete resistivity using the “Wenner Four Point Method”. This involved the acquisition of surface contact readings with 50mm electrode spacing. The location of these readings corresponded to the half – cell potential readings. The corrosion rate of concrete, as obtained from Linear Polarisation Resistance (LPR) measurements are typically recorded as corrosion current density and expressed as micro – amperes per square centimetre (µA/cm2). This can be related to the loss of metal per unit time and expressed in micro – metres per year (µm/year) through Faraday’s law. As per Faraday’s law, the mass of steel consumed (w) can be related to the corrosion current density (I) through

$$w = (MIt)/(z\rho F) \quad (1)$$

where M is the atomic weight of the metal and is 0.056 kg for Iron, t is the time in seconds in a year, z is the number of electrons released by the metal ion and is 2 for Ferrous ion of iron, ρis the density of the metal and is 7860 kg/m3 for iron and F is the Faradays Constant equal to 96500 C/mol. Resistivity data should be interpreted in the light of the other tests carried out and that the section loss estimated from corrosion current density measurement underestimates the severity of pitting corrosion, if any is occurring. Additionally, the corrosion rate should only be realistically interpreted when depassivation has already occurred. Corrosion rate calculated employing resistivity is sensitive to environmental conditions. The corrosion current density generally holds a negatively correlated linear relationship with resistivity measurements on a log – log plot. The most popular relationship in this regard can be expressed as

$$icorr = K/\rho con \quad (2)$$

where icorr is the corrosion current, K is a constant regression coefficient with unit 1 V/m and ρcon is the concrete resistivity in kΩ.m (Gulikers, 2005). A linear relationship between current density and concrete resistance does not necessarily imply that concrete resistance is dominating the overall corrosion cell resistance. The significance of the resistivity results, from a purely qualitative viewpoint is usually followed based on thresholds of such values. Traditionally, values less than 5 kΩ.cm, the corrosion rate is interpreted as very high, values between 5 kΩ.cm and 10 kΩ.cm corrosion rates are interpreted to be high, values between 10 kΩ.cm and 20 kΩ.cm are interpreted as moderate and values above 20 kΩ.cm are generally attributed to low corrosion rates. Alternative, but similar interpretations on thresholds of resistivity are present.

3 DIRECT CORRELATION

The direct empirical interrelationship between HCP and resistivity tests is observed first. Figure 1 presents a scatter plot of the field data between HCP values and resistivity values for all six bridges. In the

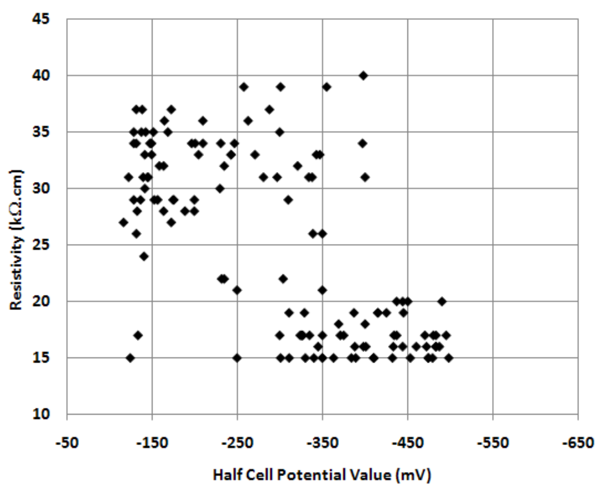

Figure 1. Empirical relationship of absolute values of HCP and resistivity for all six bridges. A linear relationship can be observed.

presence of a limited range of values of data, the relationship is observed to be approximately linear. This observation is expected to hold true under a wide range of working circumstances since the bridges are exposed to a significant variation of environmental exposure conditions. The six bridges tested indicate an approximate 15mV/kΩ.cm linear relationship on an average. Discussions related to the pH values of the solution within concrete are avoided since it is rarely available within a traditional structural testing framework.

Although an approximate linear relationship is obtained from the tests, it is important to establish whether this linear relationship is significant enough for all types of bridges or environmental exposure conditions. Additionally, it is also required to investigate how the empirical relationship vary around the observed average of 15mV/kΩ.cm.

Figure 2 presents the computed correlation coefficients between HCP and resistivity of the six bridges under consideration. A significant variability of the correlations are observed. The bridges with lower levels of correlation typically correspond to a wide variation of resistivity values for similar HCP values. Broad classifications of the exposure conditions of the structure do not directly correspond to an expectation of a higher or a lower correlation and such expectations can only be made when local information of exposure and environmental conditions are available. For most realistic cases, such local information are unavailable.

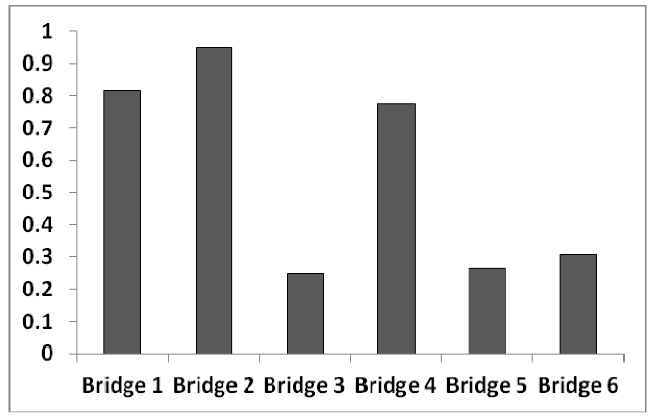

Figure 2. Empirical correlation levels between HCP and resistivity of six bridges under consideration.

Figure 3 presents the observed interrelationships between HCP and resistivity values from best fit linear relationships, independent of the degree of correlation achieved for each bridge. The bridges exhibiting a high degree of correlation between HCP and

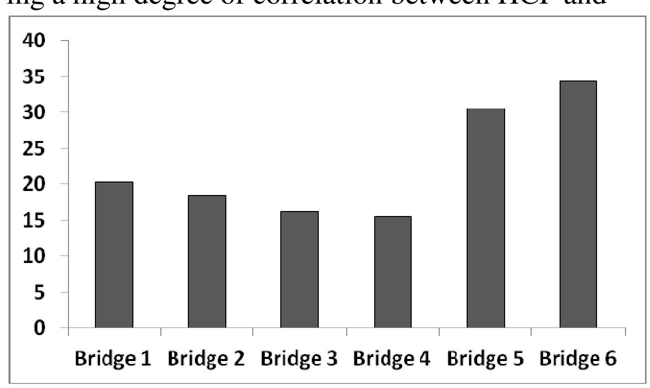

Figure 3. Empirical calibrations between HCP and resistivity of six bridges under consideration in mV/kΩ.cm.

resistivity tend to show a consistent empirical relationship around 15mV/kΩ.cm to 20mV/kΩ.cm. However, there are bridges with higher range of relationship (Bridges 5 and 6) within 30mV/kΩ.cm to 35mV/kΩ.cm. Additionally, it is also observed that the consistency of the calibration values of these correlations is not dependent on broad classifications of environmental exposure.

The absolute values of either of the tests may not necessarily indicate durability conditions of rankings. However, if the correlations between the different percentiles of the data are established, such a comparison may be made within a bridge or between bridges based on the exceedances of certain percentiles of each test. Additionally, if such correlation exists, the extreme percentiles can be used from either test to estimate and check the extent of the affected regions in terms of durability. Since percentile values are statistically described and are non-dimensional quantities, a field-calibrated relation of this sort can immediately compare a number of different structures. The relationship is also important from the point of view that it attempts to correlate two fundamentally different regimes of degradation - the estimated time to initiation of corrosion and the rate of corrosion after the initiation has taken place. It should be remembered though that the estimated time to corrosion initiation and rate of corrosion are model-dependent derived quantities and they may not exhibit the same level of interrelationship following transformations of raw data or their statistical descriptions depending on the appropriateness of the choice of the models.

4 PERCENTILE CORRELATION

The percentile correlations between the HCP and resistivity values from all six bridges tested are presented as a scatter plot in Figure 4. The scatter of the percentile correlations is relatively higher for lower percentiles of resistivity values. However, the correlation may be immediately interpreted against arbitrary level crossing values of either measurement. Consequently, the generality and the importance of comparison in this format is recommended.

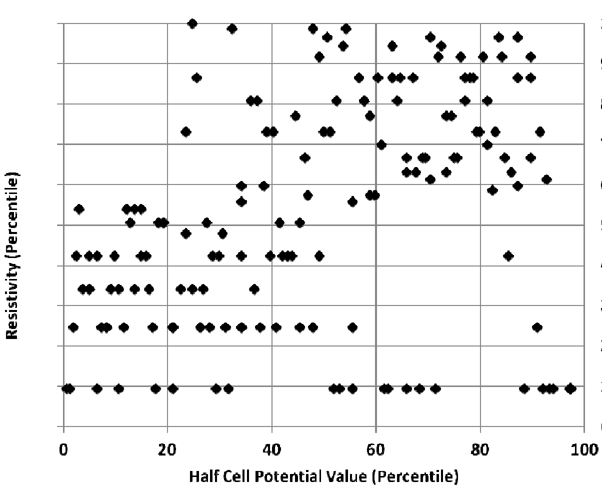

Figure 4. Empirical relationship of percentile values of HCP and resistivity for all six bridges.

The correlation coefficients obtained from the scatter plot of percentile values are presented for each bridge in Figure 6. It may be argued that these correlation values are more appropriate for use in ranking durability since the relative distribution of the values have been considered in this case than absolute values. A limited lowering of correlation is observed in the correlation values due to the slightly extra scatter of data through rescaling for obtaining percentile values. However, the relative correlation strengths are not influenced at all and the change in absolute values are also not significant.

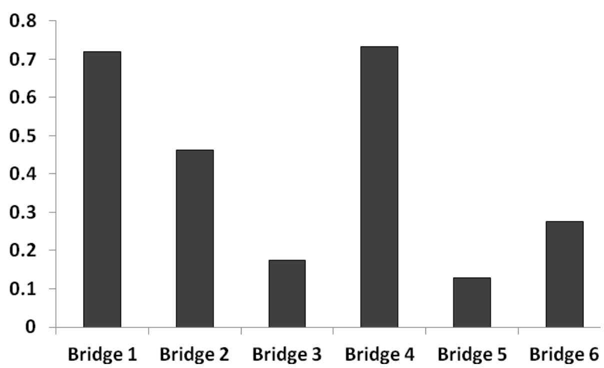

Figure 5. Empirical correlation levels between HCP and resistivity of six bridges under consideration from percentile values.

Figure 6 presents the observed interrelationships between HCP and resistivity values from best fit linear relationships obtained from the percentiles computed from each test, independent of the degree of correlation achieved for each bridge.

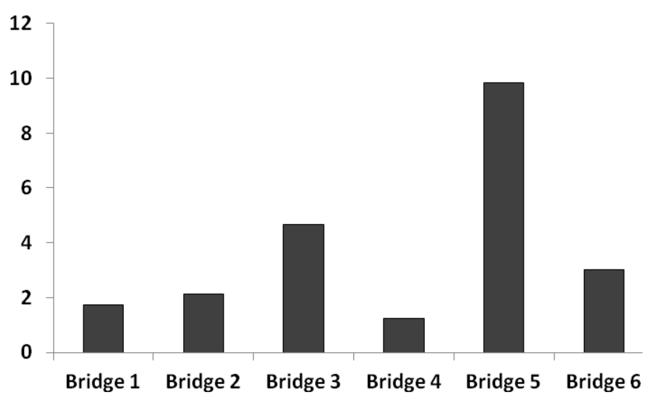

Figure 6. Empirical calibrations between HCP and resistivity of six bridges under consideration obtained in percentile mV/ percentile kΩ.cm.

The interrelationship calibration values between the bridges are different for percentile values as compared to absolute values and the variability of the resistivity test data can be easily obtained from the figure, as is evident from the higher values. It is observed, that for relatively stable measurements the typical percentile change for the HCP values lie between 2-5 per unit percentile change of resistivity values. However, a wide range of bridges must be examined before making an exact statement on the approximately identified numbers through this study. The percentile based correlations also provide us with the level of resolution at which we may compare the results of the two tests.

5 RELATIONSHIPS OBSERVED ON DIFFERENT ELEMENTS OF BRIDGES

The absolute and percentile value based interrelationships of a number of different components of bridges are considered next in terms of HCP and resistivity testing. Figure 7 presents the levels of correlation obtained from the absolute values. The results were fairly correlated except for the tests carried out in a hanger. The hangers tested in this set of experiments had low environmental exposure.

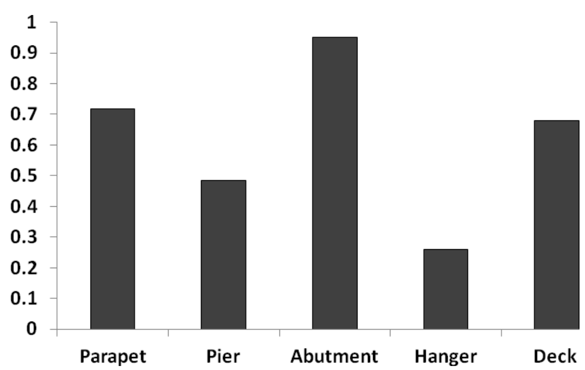

Figure 7. Empirical correlation levels between HCP and resistivity of different components of bridges under consideration.

The calibration values related to the observed correlation for different components of bridges are presented in Figure 8 through a best line fit estimate. The best correlation values were obtained for the abutment in Figure 7 and the calibration value corresponding to this linearity was observed to be approximately 10mV/kΩ.cm. This matches the existing rule of thumb quite well (Gulikers, 2005) and there is reason to believe that a very highly correlated situation between the two tests will probably exhibit a calibration behaviour between 10mV/kΩ.cm to 15mV/kΩ.cm. The converse is not necessarily obvious, as is shown in Figure 3. These calibration ranges obtained also provide an idea of levels of correlation that can be assumed when using these relationships to surrogate tests in other bridges partially or in its entirety.

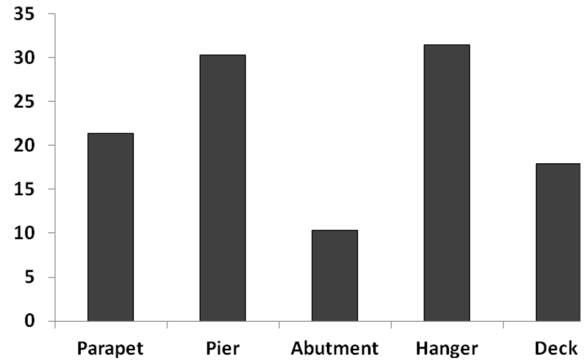

Figure 8. Empirical calibrations between HCP and resistivity of different components of bridges under consideration in mV/kΩ.cm.

Figure 9 presents the levels of correlation observed by comparing the percentile values of the tests computed on locations relating to different component of the bridges.

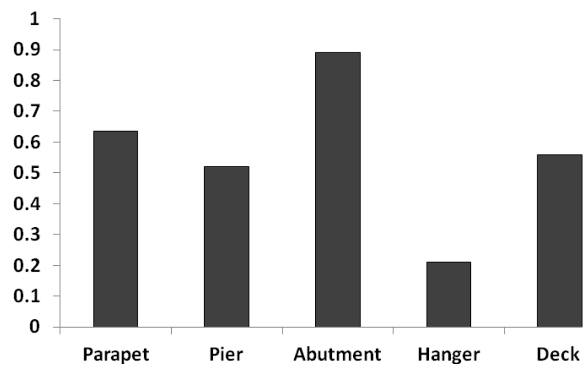

Figure 9. Empirical correlation levels between HCP and resistivity of different components of bridges under consideration from percentile values.

It is observed that the relative ranking of the different components related to the correlation and the levels of correlations are comparable with those obtained from absolute values. There is a very minor change of the correlation levels due to the rescaling of data when computing the percentiles.

The calibration values from the percentiles of the two tests for the different components on the bridges are presented in Figure 10. The calibration values indicate that the stable correlations between the two tests tend to result in less than 3 percentile change in HCP values for unit percentile change in resistivity values. These results corroborate well with the observations from Figure 6. Consequently, this change in percentile values can be used to assess the stability or the consistency of obtained data when carrying out tests on durability. Additionally, these relationships can be useful in the absence of data and for using archival data.

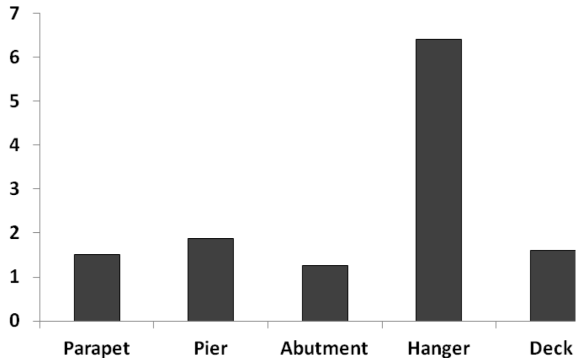

Figure 10. Empirical calibrations between HCP and resistivity of different component of bridges under consideration obtained in percentile mV/ percentile kΩ.cm.

6 DISCUSSION AND CONCLUSION

HCP and resistivity tests were carried out on different components of a number of bridge structures. The direct and the probabilistic empirical correlations of the two tests were investigated based on the collected data. The exposure condition, age and the distance of the bridges from each other were very significantly varied.

Generally, a linear correlation was observed to exist between the HCP and the resistivity tests from the absolute values and the percentile values. The scatter of the test results indicated that the variability of the levels of correlation among bridges and among different components should be investigated using absolute and percentile values.

Correlation levels of the tests among the bridges varied. Computation of percentile values rescales the HCP and resistivity data differently and leads towards a marginal increase in scatter. However, the correlations observed from absolute values are changed little through the use of percentiles.

The calibration values for relating the two tests varied significantly from a rule of thumb indicating an approximate relationship of 10mV/kΩ.cm. However, for tests with good correlations, the deviation of this calibration value from the general rule of thumb is less.

A calibration value obtained from the correlations using percentile values of tests results was observed to be within 3-5 percentile of HCP result variation for a unit percentile variation of resistivity. Such relationships are marked in this paper as a measure of stability of the two tests. Correlation between the percentiles also serves as an indicator of the extent of problem related to corrosion and durability within a structure.

Investigation on different components of the bridges corroborated the findings presented in the previous sections. Additionally, the observations on the different components indicate the possibilities of using the general findings of the calibration values as a surrogate for other bridges with partial information or with archived data. However, it is recommended to conservatively approach the variability of the data and the correlation when using it as a surrogate. The findings may be directly incorporated into a reliability format since the interrelationships of the two tests can be related to the time to initiation and the rate of corrosion respectively. The findings in this paper will be helpful in establishing the probabilistic format of the HCP or resistivity values used.

When measured at different instants in time, the change of these results or calibrations indicate the change within the structure and the durability measures may be monitored. When compared with a number of bridges, the changing characteristics from absolute and percentile values can help rank the durability conditions.

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