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## ABSTRACT

The literature dealing with measurement of corrosion rates in soils via the polarisation resistance technique is reviewed. A specific focus on technical and academic aspects has been applied in order to determine the quality of information which can be made available to the practical applicator and the designers of instrumentation. The large range of corrosion rates commonly observed from field measurements has been attributed to soil variability factors such as moisture content, soluble salts, pH and the net conductivity of the soil. A case study is presented which examines the use of polarisation resistance measurements applied to the asset management of buried legs of galvanised steel structures. This field analysis involved an in-situ, electrochemical corrosion assessment of the buried components of six structures on the South Island of New Zealand. Electrochemical analysis and visual assessment was applied to metallic components following 40 years of burial and a normalising technique was used to present relative rates of corrosive losses. The correlation between the visual and the electrochemical analysis techniques demonstrated a significant level of variability. Research areas for future work are presented for the improvement of the accuracy of the polarisation resistance method applied to buried structures. These include calibration of the throwing power limitations associated with direct current polarisation techniques when applied within high resistance media and the use of simple polarisation resistance cells for the mapping of soil corrosivity. If a lack of customer confidence in the polarisation resistance method can be addressed through improved methodologies and data analysis, the efficiency of asset management can be improved and structural maintenance costs can be reduced. The potential market for this system is considerable.

## KEYWORDS

Polarisation resistance, galvanising, soil corrosion, buried structures.

# INTRODUCTION

## Polarisation resistance techniques applied to soils

In this section, the literature dealing with the effect of soil properties on buried mild steel and zinc corrosion rates has been reviewed in order to assess the state of current theoretical knowledge. Primary attention is given to the so-called 'linear polarisation resistance' (LPR) technique for the direct measurement of corrosion rates of buried structures, although polarisation resistance soil probes and electrochemical impedance spectroscopy (EIS) are also considered.

Both steel and zinc can be susceptible to accelerated corrosion in natural soils [1-7] and backfill material [8,9]. Water content [10,11], temperature [7], pH [3,12] and microbial activity [13-15] are all fundamental accelerants of the corrosion process. Chemical species influencing corrosion rate include chlorides, the sulphates and carbonates. These can arise from both natural and artificial sources. Moreover, non-uniform corrosion processes in soil, such as pitting and crevice corrosion [16], can rapidly reduce the effectiveness of metallic coatings and, ultimately, the service life of buried assets. Indeed, the relatively low conductivity of the soil electrolyte [6] reduces the throwing power of the galvanised coating, resulting in limited local protection properties of the coating at defects.

In the literature, modelling of soil corrosivity has been approached in some cases through the analysis of a multitude of factors, all of which interact in a non-simplistic manner [3,17] to produce an assumed overall corrosivity. These analyses, however, are time consuming, costly and the corrosion rate of the metallic structure is never directly measured. It must be advised, therefore, that the interpretation of an initial soil corrosivity analysis is supplemented with direct measurement of corrosion rate using in-situ sensing equipment, asset excavation, or local corrosion testing using weight loss coupons. Unfortunately, the currently available in-situ techniques, which are used to monitor the rate of underground corrosion, can be subjective and are often inaccurate and impractical. A reliable sensing technique is highly desirable, as the most accurate condition assessment methodology still involves the expensive, damaging and sometimes non-representative process of site excavation. Indeed, perturbation of the system through excavation may actually increase the rate of corrosion through the introduction of aeration, soil porosity and the destruction of protective passive layers.

Reviews of corrosion detection and monitoring for soils are available in the literature [18,19], where descriptions of condition assessment sensing methodologies include:

- ultrasonic/acoustic analysis
- radiometric probe analysis
- electromagnetic analysis
- thermal imagery analysis
- ground penetrating radar analysis, and
- electrochemical methods including EIS, current probes, galvanic sensors, electrochemical noise and polarisation resistance.

Using these methods it may be possible to determine the level of both general and non-uniform corrosion damage and, in some cases, pipeline coating holiday location [20-24]. A universally accepted system for the reliable detection and monitoring of uniform and selective corrosion (such as pitting) at complicated geometries in soil electrolytes does not appear to be commercially available.

Polarisation resistance is commonly used to measure assumed uniform corrosion rates of

metals in many different environments, and this technique also has the potential to be competitive relative to other remote sensing diagnostic tools for the condition assessment of buried structures in soils. It is clear, however, that the theoretical aspects of polarisation resistance measurements at complicated structures are generally not very well understood. Increased confidence in the polarisation resistance method in the soil environment will reduce the need to 'dig-up' assets. But the technical issues associated with small-scale current measurements in soils currently limits universal acceptance.

If a lack of customer confidence in the polarisation resistance method can be addressed through improved methodologies and data analysis, the efficiency of asset management can be improved and structural maintenance costs can be reduced. The potential market for this system is considerable.

## Polarisation resistance theory

Polarisation resistance determinations have been used for more than 50 years for the rapid and relatively accurate determination of corrosion rates or general corrosion trends in single and multiphase fluids [25-29]. The use of polarisation resistance for the determination of corrosion rates for simple systems has been reviewed by Callow et al [30].

For a simple and symmetrical anodic and cathodic charge transfer controlled process, the small section of the polarisation curve approximately $\leq$ 20 mV either side of the corrosion potential, $E_{corr}$, the current vs potential response is expected to be linear. The slope of such direct current (d.c.) steady state curves can be measured directly and the instantaneous corrosion rate (presented here as corrosion current density $j_{corr}$) can be derived. This simple case can be described by the Stern-Geary equation [29]:

$$j_{corr} = \frac{\beta_A \beta_C}{2.3 R_p (\beta_A + \beta_C)} = \frac{B}{R_p} \qquad (1)$$

$\beta_A$ and $\beta_C$ are the anodic and cathodic Tafel slopes (potential vs $\log^{10}$ current, typically in units of V decade-1 of current) respectively and B is the proportionality constant between $j_{corr}$ and $Rp$ for the reaction conditions under study. $Rp$ is termed the polarisation resistance (the slope of the potential vs current curve with units of the Ohm). This relationship assumes uniform current distributions which have received compensation for the electrolyte Ohmic/IR drop between the galvanised steel working electrode and the tip of the reference electrode.

To obtain a value of estimated corrosion rate, B must be determined from Tafel slope data or, as is usually the case under most practical circumstances, guessed from prior experience, published data or from a manual accompanying the instrumentation. Callow et al [30] observed that many workers quote $Rp$ values rather than absolute corrosion rates in an effort to compare relative corrosion resistance with traditional weight loss studies. It was stressed that in the majority of cases, for any values of $\beta_C$ and $\beta_A$ between 60 and 120 mV decade-1, a maximum error of only 20% can be expected [29]. Moreover, if one of the $\beta$ values is assumed to be infinite, the resulting error is generally only as much as 200%.

This electrochemical technique is commonly incorrectly referred to as LPR, although theoretically non-linearity of the polarisation curve is expected to dominate in the majority of cases [31]. In practice, the anodic and cathodic mechanisms and polarisation behaviour is not usually identical. Moreover a number of reactions which can occur simultaneously during either cathodic or anodic polarisation and mass transfer effects and which can influence the rate of reactant and product movement are not considered by Equation (1). The resistance measurement, however, is capable of providing a broad indication of relative corrosion rate

via $Rp$, regardless of non-linearities. Thus, states of surface condition, such as 'passivity' and 'activity', can be distinguished within reasonable limits.

With the application of polarisation resistance within poorly conducting electrolytes (such as soil) and complicated geometries (such as buried grillages and other support structures), Ohmic drop and the potential/current distribution reaching the object will become significant factors. From the fundamentals of electrochemical theory [32], it is clear that these complications must be included in any accurate discussion of the polarisation resistance analysis technique. It is essential to consider how far an applied current has to travel through a soil of a given resistance and how tortuous this path would be. In general terms, if the cell electrode design is not symmetrical there will not be uniform current distribution. In many cases the geometry of the buried structure will not be known, or cannot be defined within reasonable limits. Environmental factors will also affect soil conditions and the IR drop behaviour. Such conditions will usually vary locally, nationally and seasonally.

Thus, the introduction of a practical, reliable and simple polarisation resistance model is required. Flexibility and simplicity in application would be a huge asset, where relatively unskilled technicians can determine corrosion rates in reproducible manner at any time of the year.

## Instantaneous corrosion of buried structures

A number of testing contractors have applied the linear polarisation resistance method to the in-situ corrosion rate monitoring of buried structures in soil-based electrolytes. This includes the analysis of street lighting columns [33] and high voltage transmission towers [34-37]. Of particular interest to the owners of large structures with buried components is the condition of the actual materials at the time of testing. This involves a direct examination of the component itself (preferably without the damaging and costly process of excavation). As discussed in the preceding sections, testing using polarisation resistance introduces a number of problems associated with soil resistivity, the geometry of the structure and current distribution between the electrodes. The latter point is relevant not only to structures where the geometry is not known, but also to structures where the applied current is attenuated to an extent where it cannot sense all areas of the component of interest.

From the analysis of literature dealing with practical applications of polarisation resistance, only Japanese workers have seriously considered the effects of non-uniform polarisation signal current and surface area [38-40]. Solutions were presented based on computational modelling and electrochemical alternating current EIS coupled with $Rp$ d.c. measurements. Such computational methodology (e.g. boundary element analysis) is common for the simulation of current distribution associated with soil- and liquid-based cathodic protection systems [41,42]. Since the standard polarisation resistance methods also operate via the application of a d.c. 'impressed' current, it appears to be theoretically possible to adapt soil cathodic protection predictions to the current problem.

The majority of theoretical work dealing with non-uniform current distribution associated with the polarisation resistance-based analysis of buried structures in soil, however, has focused on general pipeline condition assessment [43]. But the application of computational models for such simple three-dimensional cylindrical structures is far removed from the complex predictions required for non-symmetrical components such as transmission tower legs and foundation grillages. A corrective methodology dealing with the simulation current distribution at complicated geometries is not currently available in the literature.

## Soil corrosivity probes

An alternative polarisation resistance-based technique for corrosion prediction involves the use of independent probes to test the corrosive nature of the soil [44-50]. In this case, the working electrode of the electrochemical cell is not the surface of a large-scale buried structure, but rather a small-scale electrode manufactured from a similar material to that of the structure. During developmental stages, comparisons are also usually presented between corrosion rates from the traditional weight loss method (using for example coupons). This soil corrosivity probe method does provide a relatively simple and rapid resolution to the negative influence of non-uniform current distribution and uncertainties regarding the limits of the buried structure. This methodology also presents actual corrosion rates within the environment of interest without the need for complex calculations of the effects of chemical and physical characterisation of soil.

Of obvious concern to the owner, however, must be the fact that the actual corrosion rate of the structure itself is not measured. In practice, corrosion rates do exhibit variable transient behaviour and the actual rate of degradation of the structure, or the present condition of its coating system, may not be identical to the soil corrosivity as indicated by the material of the probe electrodes (external factors may contribute). It is clear that both the in-situ and probe polarisation-based methodologies require careful consideration and neither may be applied universally without consideration given to the applied electrochemistry.

## Electrochemical impedance spectroscopy

The incorporation of alternating current-based EIS with d.c. based linear polarisation resistance measurements in soil has also received considerable attention [38,39,51-53]. Electrochemical impedance data can give information on the character of the corrosion reaction and can be used to determine voltage drop due to current losses between the working (subject material) and the counter electrode. This methodology has been proposed for use in the examination of localised corrosion, such as pitting [53] and coating defects [54]. For simple geometries, it has been possible to extract the corrosion rate when used in conjunction with traditional polarisation resistance measurements. This method, however, has not been applied to geometries more complicated than pipes [54,55] and round-bottomed tanks [53], and the problem of current distribution influencing large and complicated three-dimensional structures has not been addressed (further than that produced by the computational modelling of buried pipeline structures discussed earlier). However, it is apparent that a considerable amount of work has been performed in this area, presumably for specific field applications within the industry [44], but due to the complexity of data analysis, the utility of this measurement technique is not simple and is beyond the majority of most technicians and non-scientists. Indeed, there are no standards currently available in the open literature dealing with EIS measurement of corrosion processes in soil-based systems. The equipment and data handling cost can also be expected to exceed that of small-scale d.c. measurements. It may be easily understood, therefore, why it has not been developed into a fully flexible commercial system.

Overall, for the measurement of actual corrosion rates of buried structures, field polarisation resistance technology is currently applied in an extremely simplistic manner and a 'black box' mentality is usually applied. The key factors affecting performance are not considered either by the practising corrosion engineer in the field or the majority of publishing authors. Most technicians will be unaware that corrective methodology is required in most cases in order to simulate the influence of current distribution. But there is no single practical polarisation resistance solution commercially available for the direct measurement of the corrosion rates of buried structures with complicated geometries. It is not surprising, therefore, that industry confidence in the technique is low. However, due to the simplicity of application and successes with simple systems, an accurate methodology based on polarisation resistance determinations has the potential to initiate considerable demand.

## CASE STUDY – CORROSION ASSESSMENT OF GALVANISED STEEL SUPPORTS USING POLARISATION RESISTANCE

To determine if a simple polarisation resistance technique can be used as an effective tool for in-situ corrosion assessment, the partially buried legs of six galvanised steel structures were examined using electrochemical analysis (polarisation resistance measurements). These results were then compared to those of a visual analysis post-excavation.

The extent of corrosion, when measured visually, was determined by averaging the estimated zinc-coating failure observed on the buried area of each sample. The polarisation resistance and visual data was then compared using a normalising method, whereby all values were divided by the maximum value within the same population to produce Corrosion Factors (a direct indicator of the relative rate of corrosion with a sampled population). When using this methodology, the maximum value is unity in all cases and the relative distribution of values can be easily compared between a number of different population types, for example, visual and electrochemical data. This method is particularly useful when comparing results that are related, but a direct mathematical function has not been determined. It is important to note, however, that significant error will be introduced if the strict rejection of anomalous data is not applied.

The amount of visual corrosion is expected to be directly proportional to the magnitude of inverse $Rp$ (resistance polarisation) i.e:

$$\text{Percentage Area of Coating Failure} \propto \left( \frac{1}{Rp} \right) \propto \text{Corrosion Rate} \qquad (2)$$

In this work, maximum value for normalising was taken from either:

Method A      The total combined population of leg values (x24) for all six structures, or

Method B      The total population of leg values (x4) for the particular structure under study.

In the latter method, each structure is effectively assessed in isolation. But if the polarisation resistance method is accurate over a wide range of environmental and surface conditions, Method A should give equivalent results to that of Method B. Structure Averaged Corrosion Factor results were also produced, whereby the average of the percentage coating failure and average of the inverse $Rp$ for each structure was calculated for the total population of four legs associated with each structure. This 'structure averaging' approach was used to provide an estimate of the overall corrosion associated with a single structure, even when the variation in the response between the four legs of the structure is extremely high. There were a total of six structures with four legs (labelled: A, B, C and D). Each structure was located in a different area within a single broad non-disclosed geographical location on the South Island of New Zealand. The electrochemical $Rp$ method was applied through the use of a commercially available portable potentiostat with automatic linear regression software. The polarisation resistance testing was then followed by excavation and visual analysis. The visual assessment included an estimation of the surface area of zinc-coating failure and the application of a normalising technique, which enabled relative rates of corrosion to be presented. Finally, a direct comparison was made between the visual and electrochemical condition assessment methodologies.

### Analysis using polarisation resistance

The results obtained using the polarisation resistance technique are presented in Table 1. Using the electrochemical methodologies, the sampled components would have included all buried metallic components of the buried structure. Since all four 'legs' were part of a single

structure, there is a possibility that the results may also include a small component of potential measured from the remaining three legs. It is probable, however, that any interference from this source in terms of the linear resistance measurement will be minimal and of a low order due to the generally high resistance of the soil electrolyte. Absolute values of corrosion rate, measured either in current density (current per unit area of buried structure), or yearly thickness loss, were not quoted in favour of inverse resistance polarisation (1/$Rp$, quoted in Ohms-1). The potential measurements were produced relative to a copper sulphate reference electrode. Note that those $Rp$ results not shown in Table 1 were considered to be outside of normal limits of polarisation resistance data sets and have not been included.

## Visual examination – procedure

All visual examinations of the samples (see for example Figure 1) were made during a daylight site visit of good visibility under dry atmospheric conditions. In every case, two supporting diagonal sections were also attached to each of the leg pieces. Only the areas presumed to be in direct contact with the soil were examined for corrosive losses. Depending on their position relative to the 'external' surface of the leg, associated 'diagonal supports' were consistently labelled as DIAG 01 (left) and DIAG 02 (right). Initially, a Positector 6000-FNS3 DeFelsko Coating Thickness Gauge was used to measure zinc-coating thicknesses. Data collection was attempted from a population of 10 dry film thickness estimations from each section of the structure legs and diagonals. It became apparent, however, that under the conditions of the site such measurements would not be useful for the determination of coating thickness variation. Even after the washing of soil and other debris from the samples, the surfaces remained covered with considerable amounts of both zinc- and iron-based corrosion products which led to obvious over-estimations of film thickness. Accurate measurements would have required all corrosion products and surface debris to have been removed under controlled conditions. This was beyond the scope of the site visit and an improved level of in-situ surface conditioning was not attempted.

**Table 1: Site polarisation resistance and corrosion potential data**

| Component | Measured $R_p$ / Ohm (V A$^{-1}$) | 1/$R_p$ / Ohm$^{-1}$ (A V$^{-1}$) | $E_{corr}$ / mV vs Cu |
|---|---|---|---|
| **1, A LEG** | 11 | 0.09 | -710 |
| **1, B LEG** | - | - | - |
| **1, C LEG** | - | - | - |
| **1, D LEG** | 9 | 0.11 | -709 |
| **2, A LEG** | 12 | 0.08 | -723 |
| **2, B LEG** | 10 | 0.10 | -719 |
| **2, C LEG** | 13 | 0.08 | -716 |
| **2, D LEG** | 12 | 0.08 | -719 |
| **3, A LEG** | 38 | 0.03 | -680 |
| **3, B LEG** | 1783 | - | -639 |
| **3, C LEG** | 158 | 0.01 | -658 |
| **3, D LEG** | 40 | 0.03 | -666 |
| **4, A LEG** | 14 | 0.07 | -679 |
| **4, B LEG** | 20 | 0.05 | -685 |
| **4, C LEG** | 14 | 0.07 | -672 |
| **4, D LEG** | 13 | 0.08 | -677 |
| **5, A LEG** | 10 | 0.10 | -686 |
| **5, B LEG** | 22 | 0.05 | -716 |
| **5, C LEG** | 23 | 0.04 | -710 |
| **5, D LEG** | 11 | 0.09 | -704 |
| **6, A LEG** | 12 | 0.08 | -703 |
| **6, B LEG** | 11 | 0.09 | -712 |
| **6, C LEG** | 112 | 0.01 | -638 |
| **6, D LEG** | 87 | 0.01 | -658 |

**Figure 1: Example images of buried Structure 4, Leg A (buried coating failure percentage factor 390) and Structure 4, Leg B (buried coating failure percentage factor 36). Note the extreme variation in coating failure between different components of the same structure.**

The condition of the hot-dipped galvanised coating was characterised using:

| | |
|---|---|
| Condition 0 | New galvanising, or coating with low level of corrosion product typified by a dull grey finish. |
| Conditions 1-3 | Zinc corrosion products are evident, but very little evidence of coating failure or red rust. |
| Condition 4 | Zinc corrosion products are evident, as well as coating failure or red rust in the form of pinpoint corrosion. |
| Condition 5 | General red/Fe-rusting and spot-coating failure. |

During the visual examination procedure Conditions 1-3 were ignored and the presence of Condition 4 was noted in general observations where necessary. Only surface observations relating to Condition 5 were used in the estimation of percentage coating failure of each individual section of the previously buried component and associated diagonals. In these cases, the coating was observed to have completely failed and strongly coloured (orange/red/black) Fe-based corrosion products were observed to be covering the non-zinc-coated underlying steel substrate.

Areas of exposed Fe-rich zinc-coating sublayer (indicative of an attenuated coating close to the steel substrate within the Zn/Fe layer) were not included as coating failures. Such areas are an actively protective component of the hot-dipped galvanised coating and the polarisation resistance measurements, in theory, would have reflected this as being the case. When applicable, a range of percentage coating failure was noted followed by an overall estimation of the mean value of failure. This included all surfaces of each component at each arbitrarily assigned depth level.
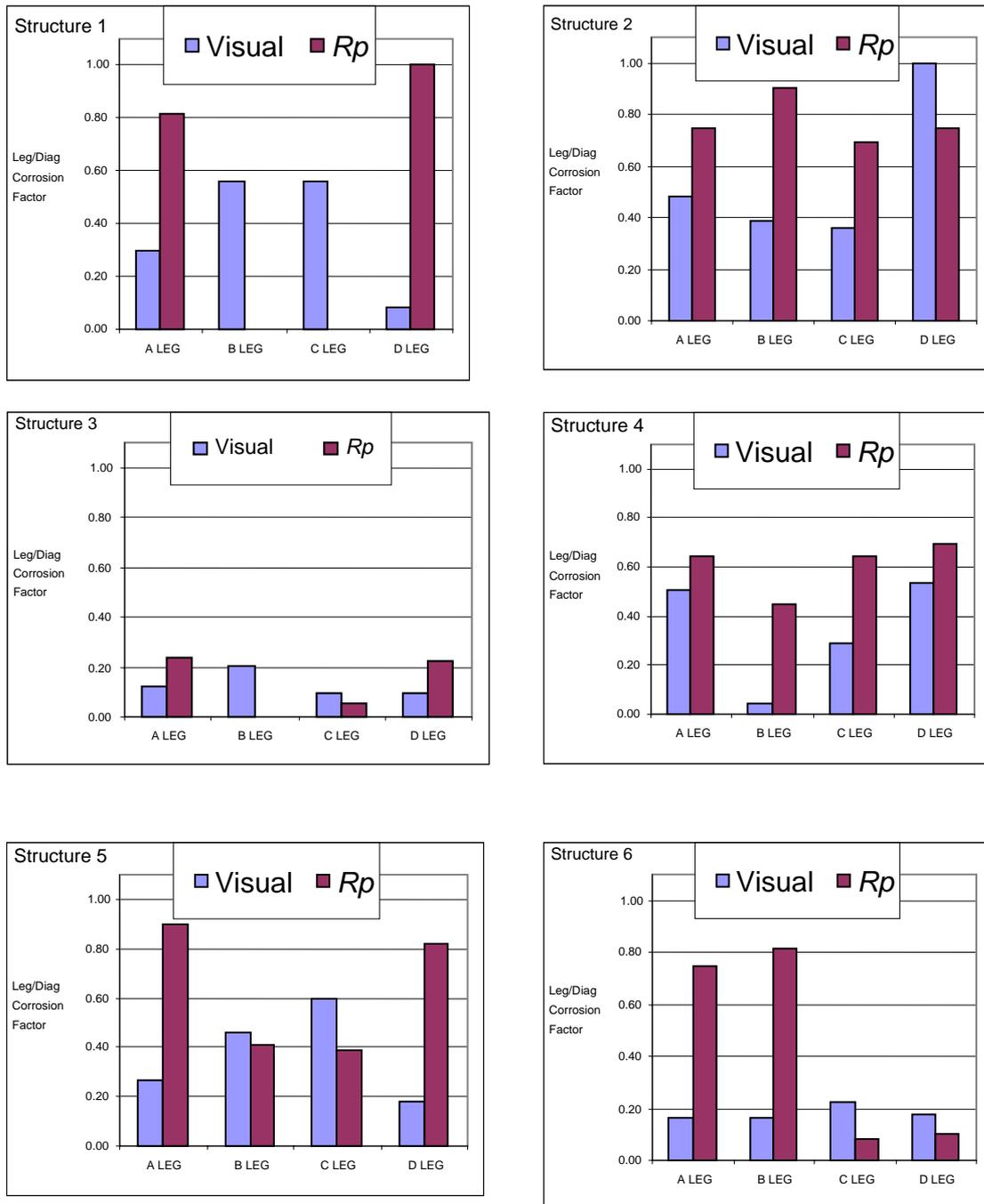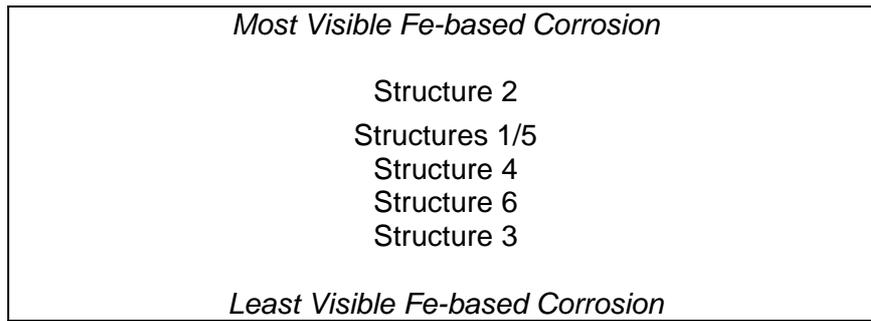
**Figure 2: Corrosion Factors for all six structures using Method A and the total buried area. Note that each leg is considered on an individual basis.**

## Results of visual examination procedure

As shown in Figure 1, an extreme variation in the level of coating failure was commonly observed during the inspection. This variability was included in the analysis of the visual results. Overall, the relative mean state of extent of surface coating failure of each structure (averaged over the four buried leg components) was broadly placed in the following order:

| Most Visible Fe-based Corrosion |
|:---:|
| |
| Structure 2 |
| |
| Structures 1/5 |
| Structure 4 |
| Structure 6 |
| Structure 3 |
| |
| Least Visible Fe-based Corrosion |

## Results of Method A

The normalised data for each structure is presented in Figure 2. In this figure, the visual and LPR normalising factors were taken from the overall population of legs accepted for examination. From this series of plots, it can see seen that Structure 2, D provided the highest level of visual coating failure of all the leg samples examined (i.e. a Corrosion Factor of 1.0). The equivalent sample for the polarisation resistance derived data, however, was Structure 1, D (a leg known from the visual analysis to have performed better than most). In another example, the correlation between methods when applied within Structure 3 was excellent. Clearly, the results of the analysis deviated from an ideal correlation and it is important to note that a large variability between legs was noted in all of the measurements.

**Table 2: Relative order of coating failure of each structure**

| Coating Failure | Structure ID | | | | | | | |
|:---:|:---:|:---:|:---:|:---:|:---:|:---:|:---:|:---:|
| | **2** | | **4** | | **5** | | **6** | |
| | **Visual** | **LPR** | **Visual** | **LPR** | **Visual** | **LPR** | **Visual** | **LPR** |
| **High** | D | B | D | D | C | A | C | B |
| | A | A/D | A | A/C | B | D | D | A |
| | B | A/D | C | A/C | A | B | A/B | D |
| **Low** | C | C | B | B | D | C | A/B | C |

The relative order of leg-coating failure within each structure is shown in Table 2. Only in one case in four was the polarisation method sufficiently accurate to fully replicate the order of Corrosion Factor for each leg within a given structure. Note that this analysis was also repeated without the inclusion of the diagonal elements in the visual assessment of the leg, but no improvement was noted. Structures 1 and 3 which gave poor and good correlations, respectively, were not included as one or two legs of these specimens were not included in the analysis after being statistically assigned as outlier data.

Figure 3 presents the averaged results for each structure. The mean of the total Buried Percentage Factors for each structure was used to produce a normalised Corrosion Factor for each structure relative to the others. Although currently not available outside of commercial reports, this methodology is commonly used in the field by many non-destructive testing companies for components which are buried and electronically connected. In must be stated that this approach is not clearly understood and currently has no clear scientific basis for use.
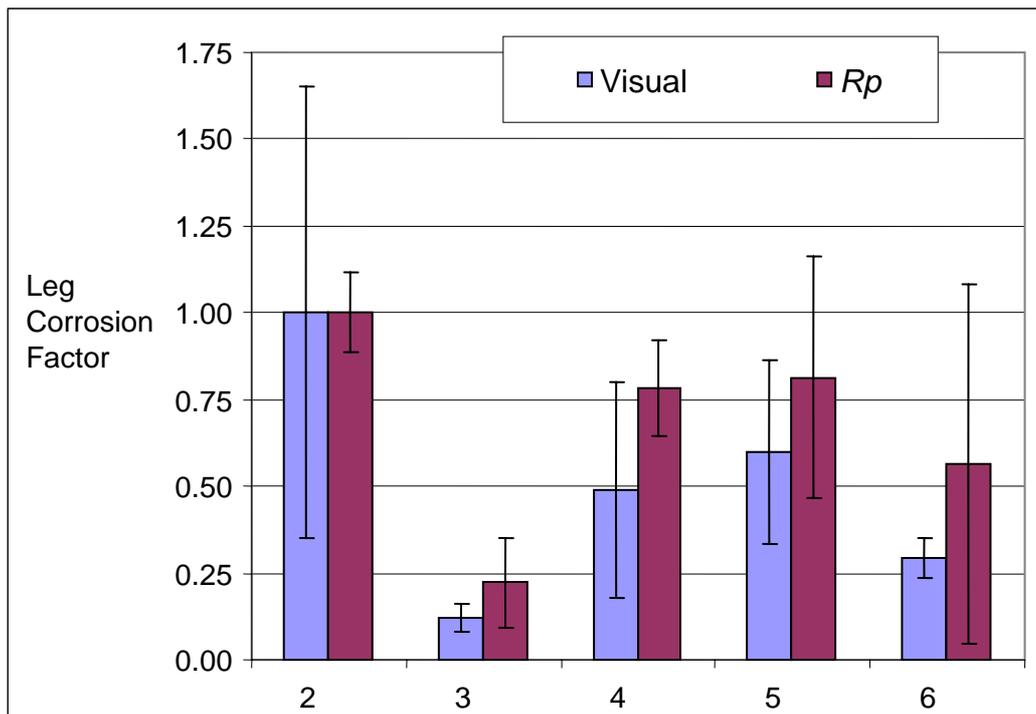
**Figure 3:** **Structure Averaged Corrosion Factors for Method A (total buried area). Each structure is considered on an individual basis and results are compared within the selected population of five structures.**

Surprisingly, however, the Structure Averaged Corrosion Factors correlated very well, although the standard deviation (95% confidence limits) within the structures was extremely large in some cases. The relative order of coating failure within each structure was reproduced in all cases as Structure 2 > 5 > 4 > 6 > 3. In most instances, there was an apparent over-estimation of corrosion rate when using the polarisation resistance method, but this fell within the standard deviation of the measurements. It would appear, therefore, that an apparent higher level of accuracy can be obtained from the polarisation resistance method by considering each structure as a whole. This behaviour cannot be rigorously explained at this point and further work is required to validate this approach.

As the good correlation observed with the structure averaging was not present when the legs were considered in isolation, it may be possible that the on-site convention used to label the structure legs prior to examination was not identical in both cases. This possibility was reported by the excavators to be of a low order, but it would lead to poor correlation when examining individual legs. Note that the likelihood of the mean structure values correlating so well by chance (when the individual legs do not) is not at all probable.

## Results of Method B

The analysis presented above was repeated using Method B. In this case, the maximum value used for the normalising methodology was taken only from the population of the four legs associated with each structure, and the individual results were calculated assuming a total buried area contribution from the legs and diagonal components. In terms of correlation between the visual- and the electrochemical-based Corrosion Factors, this method did not improve the quality of the analysis. An identical number of successes and failures were observed when this comparison was made.

## CONCLUSIONS

The case study given in this paper has shown that when galvanised steel legs were considered on an individual basis the polarisation resistance method was not able to universally predict the order of corrosion/coating failure. Indeed the predictive capacity of the electrochemical method was rather poor. However, when the mean behaviour of each individual structure was considered, i.e. when the response of all four legs was averaged, the correlation between the visual and electrochemical data was improved. The variability (standard deviation) of these latter mean values, however, was rather high. Although commonly applied during commercial testing, the apparent beneficial influence of structure averaging when multiple legs are electronically connected is certainly unusual and currently not understood. Further work is required to verify the benefits of the structure averaging data analysis methodology.

The large range of variation observed for within the population of legs of each structure when buried can be attributed to local soil variability, moisture content, conductivity and possibly even interference from the structure itself. One or more legs may have also acted galvanically to cathodically protect the others. The physical geometry of the structures would also have considerably affected the quality of the electrochemical results through poor current distribution under polarisation.

The poor reproducibility of the electrochemical methodology currently limits the resolution of the polarisation resistance meter in terms of defining precise limits of zinc-coating failure. The technique can only be improved when the raw data issuing from the potentiostat is calibrated for geometry effects. Indeed, in this work the polarisation resistance method has been used at its crudest level, where no calibration for environmental or geometric factors has been considered. It is predicted, however, that either physical scaling or computational modeling could be incorporated for the calculation of a geometric resistance factor. Calibration may be achieved by varying the resistivity of laboratory soil electrolyte for both the symmetrical and non-symmetrical polarisation resistance cells. Practical verification of the calibration methodology can then be assessed through comparison of the calibrated and non-calibrated results with visual analysis results taken in the field.

Alternatively, a program of soil corrosivity mapping involving the discrete use of polarisation resistance probes may offer a cheaper and more reliable methodology. Here, asset management would be based on an investigation/replacement policy guided by the measured corrosivity of the microclimate and associated durability predictions derived from an analysis of galvanised coating thicknesses. In this case, however, an initial investment must be made into a systematic corrosivity assessment of the geographical locations of interest.

## ACKNOWLEDGEMENTS

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