Predicting the In-Ground Performance of Galvanised Steel

John Robinson
Mount Townsend Solutions Pty Ltd

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Summary

- Steel has been used in-ground for many applications over many years both in Australia and overseas. In many cases it has been used to deliver cost and performance benefits over alternative materials.
- Corrosion management technologies are rarely used to achieve an overall asset cost saving. However, asset managers need to understand steel corrosion and maintenance issues over an asset's life.
- Although atmospheric corrosion of steel is well understood, in-ground corrosion performance of steel is less well known. There is, however, a significant body of data that deals with in-ground corrosion.
- Zinc coatings provide corrosion protection to steel firstly by acting as a physical barrier and secondly as an anode to steel. The cathodic protection provided by the zinc results in the coating corroding in preference to the steel.
- Hot dipped galvanised steel has been found to have superior performance and is metallugically different to other zinc coatings. The hot dip galvanising process provides the thickest coating. Most exposure testing of zinc coatings has involved the use of zinc sheet or pre-galvanised zinc-coated steel. Recent atmospheric exposure tests reveal that hot dipped galvanised coatings have significantly lower corrosion rates.
- Galvanised coating life is a function of the coating thickness. The rate of corrosion is nearly linear over time, so once the rate is established performance can be determined.
- The rate of in-ground corrosion is more difficult than assessment of atmospheric corrosion because soil chemistry is extremely varied and complex. Nonetheless, it is possible to classify soil types and thus estimate corrosion rates. Soil classification is based on the three key variables in its composition: particle type, water and oxygen content.
- Corrosion in-ground will accelerate in:
    - **highly acidic soils** – where geological composition or acidic plant material such as pine needles are present;
    - **the presence of soluble salts** – potassium, sodium, calcium and magnesium. These usually occur in lower concentrations in high rainfall areas;
    - **high bacteria concentrations** – acid sulfate soils can promote attack on steel by anaerobic bacteria.
    - **low resistivity soils** – low resistivity soil facilitates corrosion as some or all of the above factors can create this condition.
- Recent research indicates that individual soil parameters form a weak correlation between in-ground metal corrosion rates, where steel in-ground has performed better than the soil chemistry indicates. However, when tests were combined, the corrosion rate of uncoated steel did increase with increased temperature, with higher sulfate and chloride concentrations. The same result was not evident for galvanised steel where there was little impact on corrosion rates.
- Research conducted by the International Lead Zinc Research Organisation found that in-ground corrosion rates on uncoated and galvanised steel:
    - **gradually decreases over time**
    - **zinc provides a more uniform rate of corrosion** throughout the coating's life span
    - **thicker zinc coatings (60-80 microns) delay the onset of steel corrosion**
    - **thicker zinc coatings (60-80 microns) reduce the steel's corrosion rate once the zinc is exhausted**
- US and Australian studies into the performance of buried steel culverts revealed that these load-bearing structures were performing much better than anticipated in unfavourable soil conditions – resulting in a longer service life.
- Trials conducted for Reinforced Earth Group using aluminium alloy and stainless steel reinforcing strips to connect concrete panels in retaining walls and embankments indicated they had unpredictable corrosion performance compared to galvanised steel.

Introduction

In March 2005 BlueScope Steel commissioned an independent technical paper to review the in-ground performance of a number of steel structures (in Australia and overseas). This paper is the first in a series of technical reports relating to the SURELINE® steel distribution solution.

The various steel structures' performance and range of coatings' performance including the analysis and conclusions are provided to deliver a better understanding of the expected service life of the SURELINE® solution (specifically the service life of the steel pole in-ground).

There are many applications where steel is used in the ground, from simple applications like sign posts and fence posts, to engineered applications like reinforced earth structures, piling and foundations. Over the past 25 years new applications have been developed for screw-in steel foundation products. These products offer significant performance and cost advantages over traditional masonry and timber alternatives.

Alternative methods of installing steel utility poles for lighting and power distribution have also been developed using direct embedded poles to reduce the installation costs and environmental impact of installations.

It is not practical to install expensive corrosion management technologies on many of these embedded steel products, as is the case for more critical infrastructure such as pipelines and tunnels. An understanding of the mechanism of corrosion will allow a predictable life to be designed into utility steel products that are to be used in-ground for new piers, piling and pole applications. **This article has consolidated information from a number of authoritative sources to assist in evaluating the life of steel in-ground products.**

While the durability of hot dip galvanised coatings in atmospheric exposure conditions is well established[1], the performance of hot dip galvanised steel in under-ground conditions is less well documented or understood.

Because of the critical importance of the durability of steel in underground service in some civil engineering applications, a significant amount of data is being accumulated on case history performance of buried galvanised steel.

[1] AS/NZS2312:2002 Guide to the protection of iron and steel from atmospheric corrosion.

Characteristics of hot dipped galvanised coatings

Unlike other zinc-based protective coatings, hot-dip coatings predominantly consist of zinc-iron alloys that are crystalline in appearance. The surface of the coating is covered by a layer of zinc that freezes on the surface as the steel is withdrawn from the bath.

The thickness of the zinc alloy layers determines the final thickness of the galvanised coating. The alloy layer thickness is determined by a number of interrelated factors. These are:

- The steel's sections thickness
- The steel chemistry
- The galvanising bath temperature
- The time that the steel is immersed in the molten zinc
- The alloy additions to the zinc bath

At galvanizing bath temperatures that are normally in the range of 450-455^{0}C, three or four separate intermetallic layers form. The layer closest to the steel's surface is identified as the gamma layer. This phase is very thin – usually only a few microns in thickness.

The next layer is the delta phase, with 7-11% iron content. The top intermetallic layer is generally the thickest of the main alloy layers and is called the zeta phase, containing 6% iron.

The surface layer is pure zinc (reflecting the galvanising bath's chemistry) but this may not be present on some galvanised products that are of heavy section, or that are slow cooled. This occurs because the zinc-iron reaction can continue as a solid-state reaction at a temperature well below that of the galvanising bath temperature (at 300^{0}C or less). This solid-state reaction will result in all the free zinc in the coating being converted to the zeta phase. This can be identified by the matt–silver or gray appearance of the finished coating.

The following three cross-section diagrams detail three coating strata formations formed as a result of different coating chemical reactions:

Diagram 1

Typical continuously galvanised coating approx. 20 microns in thickness and almost 100% zinc with no visible intermetallic layers.

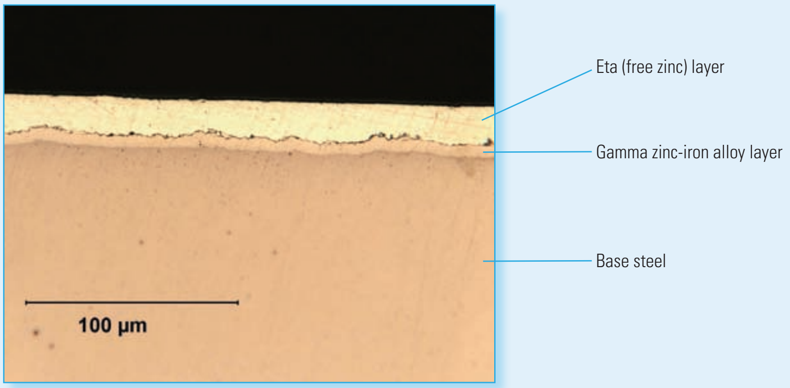
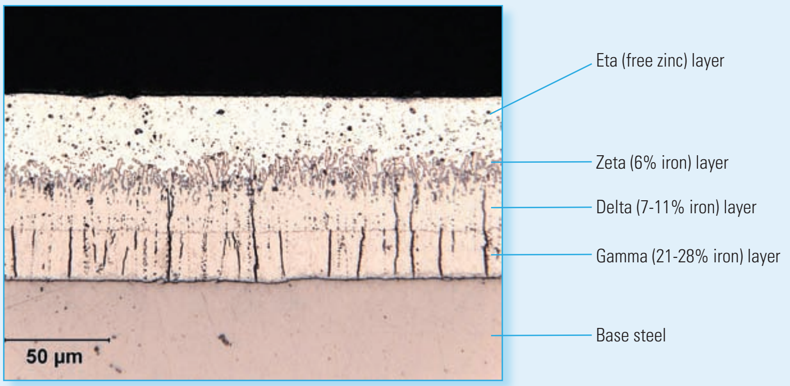


Diagram 2

Typical hot dip galvanised coating microstructure on structural steel. Intermetallic alloy layers comprise 60-70% of the coating. Total coating thickness approximately 125 microns.

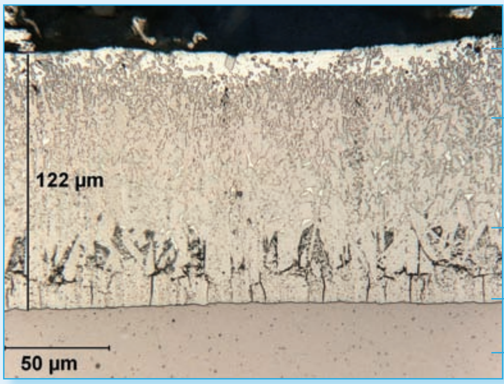
Diagram 2 details the galvanised cross-section typical of the SURELINE® coating



Characteristics of hot dipped galvanised coatings

Diagram 3

Typical coating on reactive (higher silicon content) steel or heavier section that has been air cooled. The 122 micron coating is almost 100% intermetallic zinc-iron alloy.



The presence of these intermetallic alloy layers in the hot dip galvanised coating is what differentiates it from other types of zinc coatings. In much of the exposure testing done historically, the assumption was made that hot dip galvanised coatings would be subject to the same rate of oxidation (corrosion) as any other zinc coating. For this reason, much of the exposure testing has been done with either solid zinc sheet or continuously galvanised panels because the uniformity of these materials facilitates measurement of coating condition.

The results arising from some of the in-ground evaluations mentioned elsewhere in this report, and recent atmospheric exposure testing in severe marine conditions, conducted by the CSIRO, has indicated that the corrosion rates measured to date on hot dip galvanised coatings are significantly lower (1/3) than those of other zinc coatings in the same exposure conditions.

The report, on the first 36 months of the exposure tests, was published initially in Corrosion and Materials Vol 29, no 1 and summarised in Corrosion Management, May 2004.

The morphology of these alloy layers is quite different to that of zinc. In addition to the apparent improvement in corrosion resistance, these intermetallic layers are much harder than zinc and the gamma layer in particular is much harder (2X) than the base steel.

This characteristic gives hot-dip galvanised coatings superior abrasion resistance compared to any other zinc-based or applied coating. This is a major advantage for transport and installation, as the hot-dip coating will be largely unaffected by these activities.

Factors that are likely to cause mechanical damage to the coating are just as likely to be of a severity that would cause structural damage to the base steel.

How zinc-based coating protects steel

Zinc-based coatings provide protection from corrosion for steel in two ways. Firstly, the coating forms a barrier coating to isolate the steel from its environment. **While the zinc-based coating is in-tact, no steel corrosion can occur.**

Secondly, and uniquely, zinc is anodic to steel, and in the event of the coating being damaged, the adjacent zinc will cathodically protect the steel from corrosion. It is this characteristic that makes the use of continuously galvanised products viable.

Continuously galvanised sheet, wire and tube products will all have exposed steel edges arising from the manufacturing processes. Without the cathodic protection provided by the zinc-based coatings, these products would immediately corrode at these exposed steel sites.

Hot-dip galvanising applies a very heavy zinc coating and thus its performance as an anode in protecting steel from corrosion is enhanced. In the case of the SURELINE® steel poles, more than 500g/m$^{\Omega}$ of zinc is applied to each 4.4mm x 273mm diameter pole in the hot-dip galvanising process in accordance with AS4680.

About in-ground corrosion

In the atmosphere, most materials have predictable modes of corrosion that are largely dependent on pollution levels, temperature and relative humidity. Once the important parameters are identified, the mechanism of metallic corrosion will then be common to all the products that are within that climatic zone.

In-ground situations are vastly different because of the wide local variations in soil chemistry, moisture content and conductivity that will affect the way coated or uncoated steel will perform in the ground.

Following on from Romanoff's research, many other corrosion-in-soil research projects were undertaken concurrently or subsequently. Much of this activity has taken place in Australia sponsored by various road authorities and private enterprise companies such as BlueScope Steel and Ingal Civil Products, in evaluating in-ground corrosion performance on a range of products from culverts to piling.

Corrosion of metals in soil is extremely variable and while the soil environment is a complex one, it is possible to make some generalisations about soil types and corrosion.

Any given soil will appear as a very heterogeneous electrolyte that consists of three phases:

- The solid phase made up of the soil particles, which will vary in size and will vary in chemical composition and level of entrained organic matter
- The aqueous phase, which is the soil moisture - the vehicle which will allow corrosion to take place.
- The gaseous phase, which consists of air contained in the soil's pores. Some of this air may dissolve in the aqueous phase.

The Solid Phase

Soils are commonly classified according to the general size range of their particulate component. Sandy, silty and clay soils are thus identified from the predominant size range of their inorganic particles. Convention classifies particles over 0.07mm to around 2mm as sands, particles from 0.005mm to 0.07mm as silts and 0.005mm smaller as clays. Soils rarely exist with only one of these components present.

The various groups of sand, silt and clay make up the soil classifications on the basis of their particle size. Clay soils are characterised by their ability to absorb water readily, the level of which is determined by the nature of the clay. For this reason, clay soils present a significantly higher corrosion risk than sandy soils. For this reason also, the nature of the soil on the surface may not reflect its nature below the ground.

The Aqueous Phase

Corrosion will only occur in the presence of moisture that contains ions that will transmit the electric current maintaining corrosion activity. There are several types of soil moisture. These are:

- free ground water
- gravitational water
- capillary water

The free ground water is determined by the water table, which may range from near ground level to many metres below the surface. This is the least important factor in determining corrosion of buried steel as most installations are above normal water tables.

Where high water tables bring ground water in contact with embedded steel, corrosion will progress as if the steel were in an immersed environment.

Gravitational water arises from rainfall or man-made irrigation and will soak into the soil at a rate determined by its permeability. This will increase the period of wetness of the steel's surface and this in turn will impact on the soil's corrosive effects, depending on the conductivity of the gravitational water. Where regular rainfall occurs, most soluble salts may be leached from the soil over time, which will reduce the corrosive effects of gravitational water. Gravitational water will ultimately end up in the water table.

Capillary water is water that is entrained in the pores and on the surfaces of the soil particles. The ability of soil to retain moisture is obviously important to plant growth. It is the capillary water that is the prime source of moisture in determining corrosion rates of steel in soil.

The Gaseous Phase

Poorly compacted or porous soils will allow more air access and higher oxygen concentrations can increase the oxidation rates of steel. This has a lesser effect on zinc coatings as the zinc oxidation products are essential to its corrosion resistance.

In ground corrosion studies

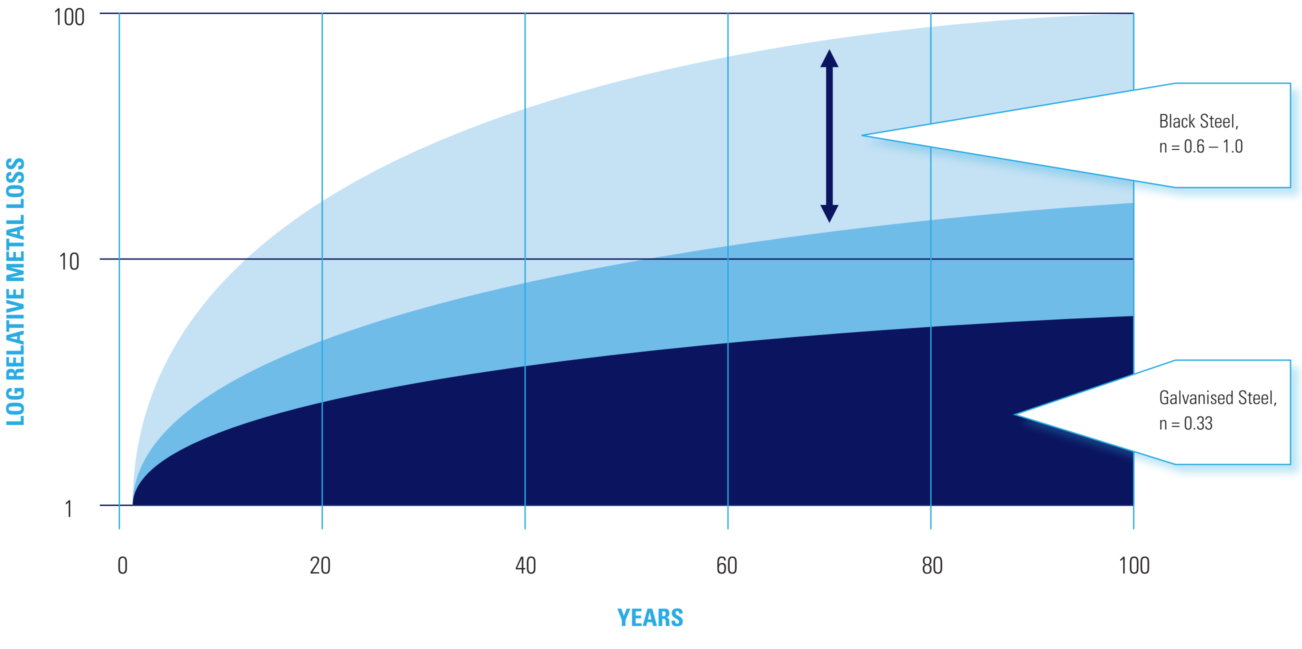
The most extensive original studies on corrosion of galvanised steel in soils were those conducted between 1910 and 1955 by Melvin Romanoff at the US National Bureau of Standards (NBS). His 1957 report established a foundation of much of the current knowledge of the in-ground performance of steel and galvanised steel. In 1936, Putnam evaluated the interim NBS data and plotted the trajectory of corrosion of zinc on both linear and logarithmic axes, and was able to confirm that the parabolic equation (as in atmospheric corrosion of zinc) proposed by Romanoff was correct.

In 1988, Darbin, Jailloux, and Montuelle published a comprehensive report studying the corrosion effects of "reinforced earth" structures, encompassing 17 years of buried galvanised steel strips as well as 10 years of continuous laboratory (container) monitoring and testing. The results of the laboratory tests confirm the field exposure data. (See "Durability of Reinforced Earth Structures: the results of a long-term study conducted on galvanised steel," Proc. Instn Civ. Engrs, Part 1, 1988, Vol. 84, p1029-1057). The findings from their experiments and monitoring highlighted the important advantages of galvanising as buried steel corrosion protection:

1. "Zinc ensures uniform corrosion throughout the coating's lifespan. Samples taken from containers and, to some extent, in situ inspections verify the fact that the steel base went unharmed as long as average thickness loss was less than the zinc coating thickness. This was due to the cathodic protection offered to steel by zinc."
2. "Whatever the zinc coating thickness, an important gradual decrease in the rate of corrosion was observed with 'n' approximately 0.33. For uncoated steel, 'n' varies between 0.6 and 1."

The relative metal loss for black and galvanised steel using the above values for "n" are plotted in the table below using a logarithmic scale on the coordinate:

Relative Metal Loss versus Years



Note: the logarithmic scale "visually" compresses the ordinate axis, and therefore the difference between the black steel and galvanised steel is less dramatic in appearance than in actual fact.

Darbin, et al, documented a very valuable phenomenon, which has been validated by other corrosion investigations. They found that, at least for higher zinc coating thicknesses (as would be typical for galvanised piers), the corrosion rate of the steel after the encapsulating zinc had corroded away, was significantly lower than that expected by the same steel which had not had the original encapsulation by the galvanised coating. The subsequent corrosion rate of the then-exposed steel was effectively the same as the zinc at the later stages of its corrosion life. The diminishing corrosion rate experienced by the galvanised steel continued for the newly exposed steel as if the zinc were still there ("n" remains relatively constant). After further examination the authors concluded that:

"The explanation for this phenomenon is found in the thick corrosion crust that forms around the metal. It is composed of fine soil particles and zinc corrosion residues and continues to protect the underlying steel core against corrosion even though all the zinc has been dissolved away."

About in-ground corrosion

The following variables contribute to accelerated corrosion:

Acidity and alkalinity

Acid or alkaline conditions develop in the soils depending on their parent rock and the geological or man-made activity that may impact on them over time. Most soils are in the pH range of pH 5.0 to pH 8.0. However, highly acidic soils exist but are relatively rare. They generally occur in swamp soils or areas subjected to high accumulations of acidic plant material such as pine needles.

Soluble salts

Soluble salts are essential to plant growth and are a major factor in corrosion. These salts may include salts of potassium, sodium, calcium and magnesium. Salts such as calcium and magnesium, while initially promoting corrosion, frequently act beneficially as their insoluble oxides and carbonates become corrosion inhibitors over time.

Regions of moderate or high rainfall will commonly have low levels of soluble salts in the soil, while desert soils may have very high salt levels. Some of the most aggressive soils in Australia are located in desert areas and test work done by BHP Wire Products has[2] found that Simpson Desert clay pans have higher corrosion rates for galvanised coatings than surf-side environments.

Bacteria

Bacteria in soil are another factor that is important in corrosion activity. Sulfates can promote rapid bacteriological corrosion of steel because of the favorable environment created for sulfate reducing bacteria. Hydrocarbon-using bacteria can accelerate failure of organic coatings used underground also.

Conductivity versus resistivity

Soil has to be able to conduct electricity to participate in the corrosion of buried steel. The resistivity of the soil is used as an important measure of soil corrosivity. The higher the resistivity, the more the resistance to current flow that can carry corrosion currents to the steel's surface, and the lower the rate of corrosion.

Table A

pH versus zinc corrosion rate		
SOIL pH	AVERAGE ZINC COATING LOSS - /YEAR	
	Drained soils	Undrained soils
<4	<4	>6.5
4-4.9	4-4.9	2.6 – 5.2
5-7.9	5-7.9	2.2 – 4.3
8-9	8-9	3.3 – 6.5
>9	>9	>8.6

[2] see corrosion Management, May 1996, Pp 8-12

About in-ground corrosion

Table B

Resistivity versus zinc corrosion rate	
SOIL RESISTIVITY – ohm.cm	**AVERAGE ZINC COATING LOSS - /YEAR – ALL SOILS**
<500	>3.5
500 - 1000	1.5 – 3.5
1000 – 2000	1.3 – 1.5
2000 - 5000	0.9 – 1.5
>5000	<0.9

Tables A and B are taken from AS/NZS 2041:1998 Buried corrugated metal structures.
The tables identify the expected metal loss (in microns) for zinc exposed to soils with differing pH and resistivity values.

Depth of corrosion

Corrosion rates are usually higher at or near the soil's surface because of the availability of oxygen and moisture. The top 300 mm is typically subject to the highest corrosion stress. At greater depth, the lack of oxygen is beneficial to steel in particular.

The corrosion of metal in soil is a result of complex interactions, and past and current research has shown that there is a weak correlation between metal corrosion rates and individual parameters.

$$P = kt^n$$

Where P = thickness loss
T = time in years
K and n are constants that yield corrosion rates that slow with time as n<1.

For plain carbon steel, Romanoff suggested n values of 0.5 to 0.6.

Romanoff and his associates (Darbin, Sagüés and Nürnberger) found that the performance of steel deteriorated with increased temperature and the sulfate and chloride concentrations, while they had little influence on galvanised steel.

In support of Romanoff's work, Darbin noted that plain carbon steel in aggressive soils produced an n value of 0.6 to 1, while galvanised steel had a significantly lower n value of 0.33.

A great deal of case history data and specific research information has been accumulated and this is invaluable in evaluating the potential for corrosion for various types of buried structures. While there is no simple answer, the German Gas and Water Works Engineers Association developed a standard soil corrosivity assessment technique that rates the various factors that influence corrosion of steel in the ground detrimentally or beneficially. The sum of these factors gives an approximate corrosion rating. This rating system is shown in Table 1.

About in-ground corrosion

Table 1

Soil corrosivity assessment technique		
ITEM	**MEASURED VALUE**	**MARK**
Soil composition	Calcareous, marly limestone, sandy marl, not stratified sand.	+2
	Loam, sandy loam (loam content 755 or less), marly loam sandy clay soil (silt content 75% or less)	0
	Clay, marly clay, humus	-2
	Peat, thick loam, marshy soil	-4
Ground water	None	0
	Exist	-1
	Vary	-2
Resistivity	10,000 ohm.cm or more	0
	10,000 - 5,000	-1
	5,000 - 2,300	-2
	2,300 - 1,000	-3
	1,000 or less	-4
Moisture content	20% or less	0
	20% or more	-1
pH	6 or more	0
	6 or less	-2
Sulfide and hydrogen sulfide	None	0
	Trace	-2
	Exist	-4
Carbonate	5% or more	+2
	5-1%	+1
	1% or less	0
Chloride	100 mg/kg or less	0
	100 mg/kg or more	+1
Sulphate	200 mg/kg or less	0
	200 -500 mg/kg	-1
	500 - 1000 mg/kg	-2
	1000 mg/kg or more	-3
Cinder and coke	None	0
	Exist	-4

Soil rating	
0 or above	Non-corrosive
0 to -4	Slightly corrosive
-5 to -10	Corrosive
-10 or less	Highly corrosive

Corrosion case histories

In 2003, the International Lead Zinc Research Organization released a report that was the outcome of a sponsored project (ZC-12-2) *Review of Data Available on the Corrosion Rate of Galvanized Steel in Soils*. This report surveyed over 120 published documents and standards relating to in-ground corrosion of steel (and galvanised steel) in soil. The executive summary concluded the following:

- Corrosion rates of metals in soil generally decrease with time.
- Zinc corrosion rates are lower than steel in soil environments
- After a thick (hot-dip galvanised) coating has been completely removed from a substrate by soil corrosion, the remaining steel corrodes at a lower rate and more uniformly than does a steel surface that has not been galvanised.
- Zinc coatings reduce corrosion rates, promote uniform attack and ultimately increase service life of structures in soil.

A section of this report that is of considerable interest with respect to SURELINE® galvanised steel poles is a commentary on the research work done by Darbin (P16 ZC-12-2 Report). It states:

Darbin conducted a study of 10-year old galvanised strips obtained from full scale structures. The corrosion of this material decreased with time and increased coating thickness significantly increased the time it took to penetrate the steel substrate. Darbin noted that when a 25 micron thick zinc coating is completely removed the corrosion (rate) increases to that observed for uncoated steel. He found though that this was not the case for 60-80 micron thick coatings, where the rate of steel corrosion was much reduced after the coating was removed. Darbin concluded that:

- Zinc ensures a uniform rate of corrosion throughout the coating's life span.
- The rate of corrosion of the coating gradually decreases.
- A thicker zinc coating (60-80 microns) delays the onset of steel corrosion and reduces the steel's corrosion rate once the zinc is gone.

There are significant metallurgical differences between continuously galvanised (CG) coating applied to sheet, tube and wire, and hot dip galvanised (HDG) coatings applied to structural steel fabrications. The longer immersion time in the galvanising bath for HDG coatings (typically 5-8 minutes) results in the coating consisting mainly of zinc iron alloys that are approximately 5% iron and 95% zinc. It is this alloy layer that allows the galvanised coating to reach its significant thickness.

CG coatings, on the other hand, are applied with very short immersion times of several seconds, resulting in a coating made up of a very thin (less than 5 micron) alloy layer and a majority of zinc. It is technically difficult to apply continuously galvanised coating to thicknesses exceeding about 30 microns as the fluidity and surface tension of the molten zinc determined how much zinc remains on the steel's surface.

While corrosion rates can be estimated using theoretical assessment, the one certainty is that in real life, the unexpected will always happen. For this reason, case history studies are very important for establishing performance benchmarks. Interest in the corrosion of steel buried structures has always been maintained, and a constant stream of information from a wide variety of sources is available.

There are two issues that determine the life of buried steel. The first is the life of the protective coating and the second is the corrosion rate of the steel. The item can be deemed to have failed when the steel loss is sufficient to prevent the steel performing its structural function.

Polymer coatings

Where polymer coatings are applied to buried steel items, most commonly pipelines, the failures are rarely caused by general deterioration of the coating. Localised failure due to holidays in the coating or pin holing or large-scale corrosion related to electrolysis are common causes of failure in these installations.

Metallic coatings

Metallic coatings, specifically galvanising, and to a lesser extent aluminium, fail through progressive consumption of the coating by oxidation or chemical degradation. The rate of degradation is approximately linear, and with galvanised coatings of known thickness, the life of the galvanised coating then becomes a function of the coating thickness and the corrosion rate.

Steel corrosion can be assessed similarly, although the body of case history evidence indicates that corrosion rates of steel in soil decrease with time as corrosion products block access of the corrodents to the steel surface. Studies of steel piling corrosion in the USA in severe environments have shown initial corrosion rates exceeding 100 microns per year in the first two years of service, falling to an average of 50 microns per year over the first 20 years to stabilise at 25 microns per year after that.

Corrosion case histories

Galvanised corrugated steel pipe and culvert has been used for decades, and the corrosion and erosion phenomena, including soil-side, has been studied and reported extensively. It is examined in more detail through recent research:

Recent research

While large amounts of in-ground performance data have been accumulated in the USA and in Australia (in Victoria in particular) over several decades, the most recent research that has been done was sponsored by Ingal Civil Products (Kirrawee, Sydney), the major manufacturer of galvanised steel culvert products in Australasia.

This research program commenced in 1999, with an annual research project being allocated to a university to investigate buried corrugated steel culverts in its region. The final studies were completed in 2003, and the collation of the data was completed at the end of 2004.

As an example of the information derived from this research, data from the 1999 work done by undergraduates from the University of Sydney on Stage 1 of the project is shown in Table 2 below:

Table 2

STRUCTURE NUMBER	DATE OF INSTALLATION	1967 SERVICE LIFE ESTIMATE	SERVICE LIFE PREDICTION	1999 SERVICE LIFE ESTIMATE	SERVICE LIFE PREDICTION
56	1952	32	1984	80	2032
57	1958	90	2048	100	2058
58	1964			85	2049
61	1960	30	1990	88	2048
62	1964	90	2054	80	2044
63	1960	30	1990	80	2040
64	1961	60	2021	78	2039
65	1960	70	2030	99	2059
66	1965	100	2065	100	2065
67	1964	100	2064	100	2064
75	1959	34	1993	80	2039
76	<1952	100	2052	100	2052
77	1958	19	1977	86	2044
78	1958	24	1982	90	2048
81	1964	90	2054	99	2063
82	1964	90	2054	99	2063

The 1999 study follows on a 1967 study of galvanised culvert and corrugated pipe in soils, from which, after field study and core sample analysis, estimates were made in 1967 of the total corrosion life of the structure. The third column above is the initial expected life estimate, which when applied to the date of installation in the second column, gives the year in which the service life would be defined at the time of installation. Following the testing of the structures, the revised service life is shown in the fourth column.

Many of these structures should have reached the end of their service lives at the time of the 1999 study. In virtually every case, the 1999 study showed that the galvanised coatings on the structures were still intact and serviceable. The “new” estimates add extensively to the expected service dates in almost every case.

This phenomenon can only be explained by a lowering of the corrosion rate from that predicted in 1967. These findings are entirely consistent with the work of Darbin, et al, with similar studies in concrete matrices, other embedment corrosion studies, and widely accepted and validated general corrosion theory.

Corrosion case histories

The National Corrugated Steel Pipe Association (NCSPA) in the USA has conducted studies on the corrosion performance of buried pipe, the vast majority of which is galvanised. The most significant reports and guidelines issued by the NCSPA were the results of field evaluations by Corrpro, Inc, issued in 1986, and 1991. The data presented is extensive and the conclusion drawn in these reports stated:

"Survey results indicate that 93.2 percent of the plain galvanised installations have a soil-side service life in excess of 75 years, while 81.5 percent have a soil-side service life in excess of 100 years"

Galvanised steel corrosion is related to soil type, soil pH, soil resistivity, soil moisture, and soluble salts such as chlorides. The Corrpro study found that:

"Under most circumstances corrosion rates are directly related to soil moisture content -- When the soil moisture content was below 17.5%, the chloride ion concentration did not have any significant effect on the corrosion rate of the zinc coating"

This report came to the following major conclusion:

"National models have been established on the basis of both water and soil parameters, but both show relatively weak statistical significance in predicting the life of a culvert."

This means that buried steel structures have generally performed much better than would be expected in unfavorable soil conditions. Corrugated steel culverts are load-bearing structures designed to meet static and/or dynamic loads. Loss of strength due to corrosion is thus the most important factor in determining the service life of a buried steel culvert structure. In highway and mining applications, very high dynamic loads may be imposed.

The results of these NCSPA studies led to recommended ranges for pH and soil resistivity for uncoated galvanised steel for a minimum 50-year service life. These ranges are almost identical to those recommended under the Australian/New Zealand Standard AS/ANZ 2041: 1998 and follows:

RESISTIVITY (ohm. com)	ACCEPTABLE pH RANGE
>10,000	0-12
2,000-10,000	5.8-10
500-2,000	---

Assessment of buried culverts

Because both the outer (soil side) and inner (invert) side of the culverts were required to be evaluated in the Ingal Civil Products research program, the Mueller Rating Method[3] was used to assess the condition of the culvert (see Table 3). The Mueller Rating Method is useful in that it provides a scalar, regressable rating that can be used in a statistical model to define corrosion variables.

The Mueller Rating on a new structure is 100% (based on 0 corrosion). The ratings used to define degrees of deterioration are shown in Table 3. A circular cored coupon sample is extracted from the culvert and is rated on each side using the Mueller Rating Method. The ratings from each side are treated independently, and the worst side is deemed to determine the end of the culvert's life.

In the Ingal Civil Products investigation, a 40% Mueller rating was set as the end of life point of the buried structure. **For other engineered buried structures, different Mueller Rating end points may need to be established based upon the structural load requirements of the product's application.**

[3] The Mueller rating is a visual rating system for assessing the condition of galvanised coatings on steel.

Corrosion case histories

Table 3

Mueller Rating Chart	
RATING PERCENTAGE	DESCRIPTION
95.0%	Galvanising like new
92.5%	Galvanising dull
90/0%	Galvanising very dull
87.5%	Pin-point rust spots
85.0%	Galvanising entirely gone
80.0%	Light rust film
70.0%	Shallow pitting
60%	Scaly rust or pits less than 50% penetration of metal
45.0%	Heavy rust or pits 1⁄2 way through metal
30.0%	Heavy rust or pits approx. 3⁄4 way through metal
15.0%	Localised complete perforation
0.0%	General complete perforation

Steel piling performance

BlueScope Steel has done extensive testing of its uncoated steel piles over a number of years and has drawn the following conclusions about corrosion rates based on case history measurements of piles in Victoria:

FILL TYPE	CORROSION RATE
Undisturbed soil/compacted	Ranges from 10-20 microns per year
Low compaction	Ranges from 20-30 microns per year
Subject to tidal movement	Ranges from 30-50 microns per year

The Third Edition of the Shrier, Jarman &, Burstein textbook; Corrosion (Vol 1, Effect of soil on iron and steel (p 3:19) states that:

"The maximum general corrosion rate (of steel) reported in tests carried out by the US National Bureau of Standards is 0.068 mm/y, the maximum rates obtained in tests carried out in the United Kingdom by BISRA and the National Physical Laboratory are 0.035 mm/y and 0.050 mm/y (respectively)".

An understanding of the corrosion rates of buried uncoated steel is important in the estimation of durability of buried steel poles, as additional steel can add significantly to the design life of the buried section of the pole.

Corrosion case histories

Reinforced Earth structures

Reinforced Earth Pty Ltd produces in-ground steel reinforcing systems. As a company they have operated in Australia for 30 years and are part of the Reinforced Earth Group operating internationally for over 40 years in more than 30 countries.

Reinforced Earth has undertaken a significant amount of test work on Reinforced Earth structures both overseas and in Australia.

The Reinforced Earth system: The system uses reinforcing strips connected to pre-cast concrete panels to form vertical retaining walls and embankments. The reinforcing strips are bolted to tabs on the pre-cast panels, and laid out on the compacted soil base. A layer of graded soil is then compacted over the course of reinforcing straps, and the process is continued layer by layer until the required embankment height is reached.

The friction developed between the soil and the ribbed steel reinforcing strap along its length literally holds the pre-cast panel in place. The long-term integrity of the structure is thus dependent on the durability of the steel reinforcing straps.

The Reinforced Earth design selected galvanised steel because of the steel's ability to handle the tensile loads involved and the expectation that the galvanising of the steel would provide a coating capable of handling the mechanical stresses typically encountered during the construction phase, while also providing sufficient corrosion resistance to satisfy the required design life of the structures.

During the construction of a Reinforced Earth structure, the straps are subjected to transport and handling impacts and abrasion, dragging and abrasion during installation followed by the backfilling operation which includes dumping of fill, spreading and being run over by earthmoving vehicles and abrasion and twisting during compaction.

Corrosion Testing: Four major topics were included in an extensive research program carried out by Terre Armee Internationale (TAI), which is the technological co-ordination centre of the Reinforced Earth Group, in co-operation with the Central Roads and Bridges Authority in France.

These topics included:

1. Knowledge of the chemical and electrochemical characteristics of soils used for backfill.
2. Laboratory studies measuring corrosion rates using electrochemical methods adapted to the soil medium, verified by tests performed under simulated conditions.
3. Full-scale corrosion testing on an experimental project accelerated to failure by corrosion of reinforcement.
4. Observation of actual projects.

Results: The work performed by TAI provided the basis for recommendations used throughout the world and the results obtained from investigations on projects in service for over 20 years have confirmed the basic theoretical predictions. The French government in fact adopted the same criteria for other underground structures, such as galvanised steel culverts.

Nearly 100 structures have been closely observed and in the early structures samples or reinforcing strips were obtained using holes in the structure to gain access to working reinforcement. In later structures, and this has continued to the present, sample strips were placed in the structure during construction for which exact strength, weight and coating properties were known and these samples can be easily recovered at scheduled intervals so that their performance can be measured.

Other test work: Work undertaken in 1991 in Australia through The University of Technology in Sydney (UTS) on behalf of Reinforced Earth and the NSW Roads and Traffic Authority has examined the oldest Reinforced Earth structures in service in NSW, which were built in 1977. It has revealed that the hot dip galvanised coating has performed exceptionally well with coating loss well below the predicted 3.5 microns/year level.

On some projects, where soil chemistry has fallen outside the range specified and is considered to be highly corrosive, additional coatings have been applied in the form of fusion bonded epoxy coatings, which provide barrier protection to the galvanised steel. It is necessary to take additional care with these organic coatings during installation to ensure that their integrity is not compromised during the construction phase.

This extensive, well documented history based on the hot dip galvanised steel reinforcing strap (used in Reinforced Earth structures) over 25 years has proven the performance of galvanised coatings underground in controlled soil[4] conditions.

[4] Reinforced Earth structures used graded soils to ensure correct compaction and soil friction characteristics. Using soil of known chemistry enhances the durability of the galvanised steel reinforcement used in the structures.

Corrosion case histories

The potential of alternative materials: Reinforced Earth has also extensively investigated the use of passive metals (stainless steels and aluminium) and plastics. The following is a summary of the experience Reinforced Earth has had with these materials from a technical paper given by the inventor of Reinforced Earth, M Henri Vidal in 1986:

"Encouraged by Pechiney and the LCPC (Department of Concrete and Metals) when constructing the first marine structure, we considered using the aluminium alloy AG 4 MC. A joint study carried out by Pechiney, LCPC and Terre Armee, carried out in the laboratories of Pechiney, made it possible to compare the behavior of several metals (AG4, black steel and galvanised steel) buried in soils selected by LCPC. The results of these tests were very satisfactory and we executed about ten works with reinforcements of AG4."…

"In 1975, following a mishap in a construction area and given the fact that it was impossible for corrosion experts to provide a satisfactory explanation, we decided to stop using passive metals and notably F17 stainless steel. This was a good thing, for eleven years later a localised failure occurred in a structure built with stainless steel reinforcements in the region of Paris. Examination of structures of the same type has confirmed major corrosion." …

"From these experiences, no short-term (2-4 years) laboratory test, however well conceived, is of a nature to guarantee knowledge of corrosion of metals buried in backfill. ***Only real experience with different backfills that are inevitably heterogeneous makes it possible to set forth general and appropriately conservative laws concerning the nature and speed of corrosion."***

The Reinforced Earth company has continued to monitor the performance of the steel reinforcing in its structures up to the present time. These results indicate that hot-dipped galvanised steel performs more reliably than passive metals such as aluminium and stainless steel.

Other significant research studies carried out in Australia by Ingal Civil Products on its buried corrugated galvanised steel culverts have supported this view.

Determination of in-ground product life

Given the amount of information available (some of which is detailed in this paper) it is possible when designing steel products for use in soil to make reasonable estimates of the service life of the structure.

For products like screw-in piles used for house foundations, and lighting and power poles, these considerations are important in determining their service life.

For direct-buried steel structures, an understanding of both the performance of the protective coating and that of the steel allows for corrosion management parameters to be engineered into the installation. This can include the provision of a corrosion allowance in the steel section over and above the structural requirements of the steel, as a relatively small increase in steel thickness can result in a significant increase in service life.

About SURELINE®

In the instance of no protective in-ground solution, the service life of a SURELINE® galvanised steel pole can be determined using the thickness of the hot-dip galvanised coating in contact with the soil, coupled with the steel thickness. Unless exposure conditions are exceptional, the above-ground section of the SURELINE® pole will not be a factor in determining service life[5].

The hot-dip galvanising process can be managed to deliver a pre-determined minimum coating thickness. A minimum average galvanised coating thickness of 70 microns[6] has been established for the galvanised coating on the SURELINE® poles. In practice, this minimum is usually comfortably exceeded and over-standard galvanised coatings can be applied by special arrangement.

The SURELINE® pole system includes the option of sleeving the ground line zone of the SURELINE® with a waterproof membrane and high-density polyethylene sleeve which provides total barrier protection barrier to the most critical section of the SURELINE®.

This technology has been well proven in the underground pipeline industry and its performance on SURELINE® will ensure that maximum service life can be achieved for a direct buried SURELINE® installation.

SURELINE® poles have been engineered for maximum durability and the knowledge and technology is available to develop whole-of-life asset management systems for SURELINE® steel pole networks that minimise future risk and maximise the return on investment in reliable power distribution.

[5] Generally, in-ground corrosion occurs at a faster rate than above ground corrosion.

[6] Australian Standard AS4680

Conclusion

The use of steel in in-ground structural applications is well established, and the benefits are recognised by engineers and specifiers. Given an understanding of the corrosion issues involved, it is possible to engineer an acceptable life for these buried steel structures.

Instrumentation is also available that allows non-destructive corrosion rate measurements to be undertaken on buried steel structures, providing an additional asset management tool to support the case history performance of buried galvanised steel structures such as SURELINE® products.

The option of using high performance coatings in conjunction with additional steel is a reliable method of ensuring a long service life for these installations.

Corrosion rates and Australian Standards

The use of corrugated steel culverts has been long established in Australia. A standard has been developed and the most recent revision, AS/NZS 2041:1998, contains a significant amount of useful information in its Appendix C on durability issues.

There are a number of informative tables in this Standard that addresses corrosion issues for a variety of coatings as well as the base steel. These tables base corrosion rates on soil resistivity and pH as well as soil classifications. These tables nominate corrosion rates for galvanised coating from around 3 microns per year in well-drained soils with neutral pH to over 20 microns per year in un-drained acidic (pH<4) soils.

Metal loss for steel is nominated at less than 10 microns per year in well-drained soils with high resistivity and pH greater than pH5, to 300 microns per year in poorly drained soils with low resistivity (usually related to chloride concentration). Reasonable averages derived from these tables for both zinc and steel in contact with soil are for zinc, 6-10 microns per year, and for steel, 20-30 microns per year.

No corrosion of the steel can occur while any zinc (galvanised) coating is present. Zinc coatings are easily remediated and if done in a timely manner, no steel loss need occur. Other in-ground protection barriers can also be applied for increased service life.

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