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Manual 5 – Atmospheric corrosion in fasteners in exposed timber structures

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MANUAL NO. 5

Atmospheric Corrosion of Fasteners in Timber Structures

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Contents

Executive Summary

Service life is one of the most important considerations in the use of timber in construction. About 10 years ago, the Forestry and Wood Products Research and Development Corporation (FWPRDC), now Forest & Wood Products Australia (FWPA), initiated a major national project on the design for service life of timber structures. The intention was to develop procedures for predicting the service life of all types of timber construction located anywhere in Australia. A major part of this project was to develop prediction models for the attack of timber by decay fungi, termites, corrosion (for fasteners) and marine borers.

This Manual describes the development of the model to predict the corrosion of fasteners' part exposed to the weather. The model was developed based on data obtained from the following sources of data:

- Extensive test programs of CSIRO, including exposed zinc and steel coupon tests across various locations in Australia,
- An extending test of atmospheric corrosion under effects of industrial pollution at various tropical places in 5 nations.
- Corrosion data obtained from the Draft Australian Standard for Atmospheric Corrosivity Zones in Australia,
- Measurements of corrosion rate at Melbourne and Newcastle beaches.

From the predicted corrosion depth, the residual cross-sections of fasteners can be estimated. The strength predictions for the residual cross-sections can then be made. The strength predictions are in quantified form, and hence the model can be used for risk managements, cost-optimised design, engineering design, application to timber engineering standard, and manuals for good practice. For the major outputs of the project, the model is being used to develop a major part of an education software package, a durability design guide, and a draft engineering code for timber durability design.

1. Model Equations

1.1 Introduction

This Section presents the final model and the calculation procedure for the atmospheric corrosion depths on metal fasteners' parts that are exposed to air, as depicted in Figure 1.1.1, which can be used to estimate the design corrosion depths on metal fasteners used in any timber construction located anywhere in Australia. Basis of the development of model equations will be given in Section 2. Then Section 3 will show how the model fits with available data.

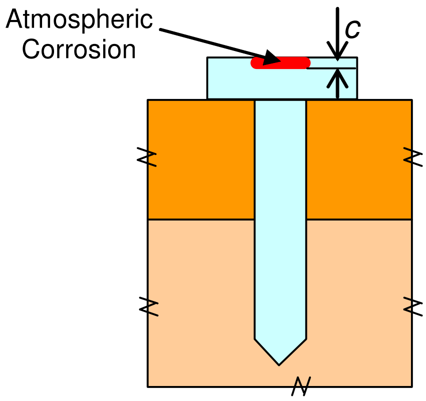


Figure 1.1.1 *Atmosperic corrosion depth*

The mean corrosion depth is estimated using the model equations in Section 1.2 for zinc, and Section 1.3 for steel. The required parameters for the model are given in the subsequent Sections. The coastal hazard zone and the coastal exposure condition of the structure location are determined from Sections 1.4 and 1.5, respectively. The airborne salinity and the airborne pollution are estimated from Sections 1.6 and 1.7, respectively. The time of wetness of the fastener surface is determined from Section 1.8. The design corrosion depths are then determined in Section 1.9.

Sections 1.10 and 1.11 presents the corrosion models for two specific cases, i.e. corrosion of bolts, and corrosion of screws under corrugated roofing

1.2 Corrosion of Zinc

The corrosion depth of zinc over time, c_z (μm), is determined by the following power-law equation,

$$c_z = c_{0,z} t^{0.6} \tag{1.2.1}$$

where t (year) is the time in service; $c_{0,z}$ is the basic corrosion depth. For zinc, the basic corrosion depth, $c_{0,z}$, is estimated by

$$c_{0,z} = 0.025\, t_{\text{wet}}^{0.6} S_{\text{air}}^{0.5} + 0.006 t_{wet}^{0.2} P_{air} \tag{1.2.2}$$

where t_{wet} is time of wetness, S_{air} (mg/m^2/day) is airborne salinity; P_{air} is airborne pollution of air in terms of level of airborne SO_x (μg/m^3)

1.3 Corrosion of Steel

The corrosion depth of steel over time, c_s (μm), is determined by the following power-law equation,

$$c_s = c_{0,s} t^{0.8} \tag{1.3.1}$$

where t (year) is the time in service; $c_{0,s}$ is the basic corrosion depth. The basic corrosion depth of steel, $c_{0,s}$, is estimated by

$$c_{0,s} = 0.5 t_{wet}^{0.8} S_{air}^{0.5} + 0.1 t_{wet}^{0.5} P_{air} \tag{1.3.2}$$

where t_{wet} is time of wetness, S_{air} (mg/m^2/day) is airborne salinity; P_{air} is airborne pollution of air in terms of level of airborne SO_x (μg/m^3)

1.4 Coastal hazard zones

Table 1.4.1 *Definition of hazard coastal zones and numbers of rain days*

Hazard Coastal zone	Approximate coastline range		Representative D_{rain} (No. of rain days / year)
	from (longitude, latitude)	to (longitude, latitude)	
A	(122°, -20°)	(129°, -15°)	70
B	(115°, -28°)	(122°, -20°)	40
C	(129°, -15°)	(149°, -23°)	100
D	(149°, -23°)	(150°, -36°)	130
E	(115°, -28°)	(150°, -36°)	130

Figure 1.4.1 *Coastal Hazard Zones. Zone E has the greatest hazard.*

1.5 Coastal exposure conditions

The coastal exposure condition is dependent on the opening angle, θ (degrees), and the radius, R (km), of the bay as shown in Figure 1.5.1. The exposure factor for an idealised bay, α_{bay}, is:

$$\alpha_{\text{bay}}^2 = \left(\frac{\theta}{85}\right)^2 + \left(\frac{R}{20}\right)^2 \tag{1.5.1}$$

The coastal exposure condition is then defined as follows

For $\alpha_{bay} < 1$	Closed bay
For $1 < \alpha_{bay} < 1.5$	Partially closed bay
For $1.5 < \alpha_{bay} < 2.5$	Open bay
For $\alpha_{bay} > 2.5$	Open surf

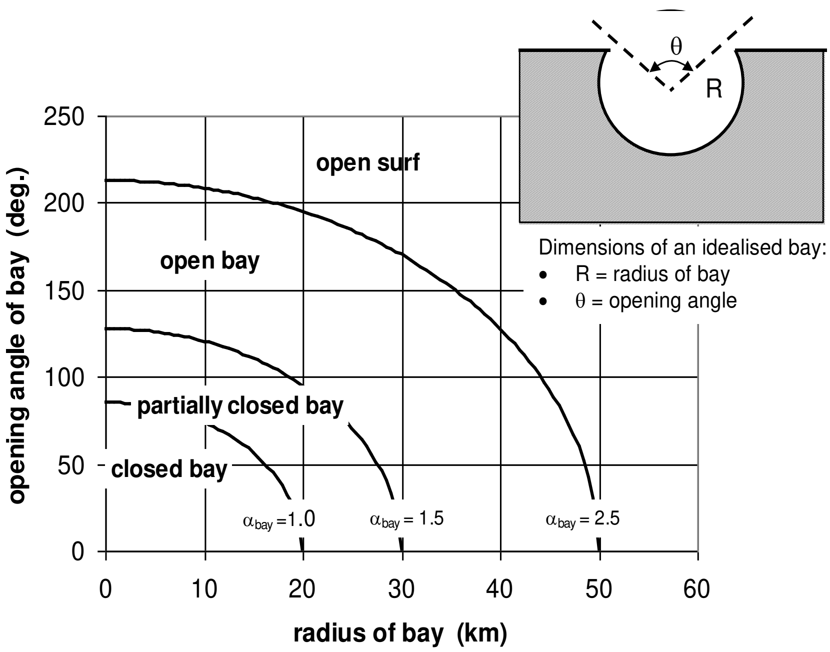


***Figure 1.5.1**. Definition of Coastal exposure condition*

1.6 Airborne Salinity

Airborne salinity at a site, denoted by S_{air} (mg/m^2 per day), is estimated from the following equation,

$$S_{air} = \max \begin{cases} \alpha_{exp}\alpha_{micro}\left[\alpha_{coast}\beta_{coast}\left(0.9e^{-10L_{coast}} + 0.1e^{-L_{coast}}\right) + \alpha_{ocean}e^{-0.02L_{coast}}\right] \\ 1.0 \end{cases} \quad (1.6.1)$$

in which L_{coast} is the distance to the coast in kilometres; the parameters α_{coast} and α_{ocean} take into account the effect of coastal zonation (Table 1.6.1); β_{coast} the effect of coastal exposure (Table 1.6.2); α_{exp} the effect of site exposure (Table 1.6.3); and α_{micro} the effect of local shelter factors (Table 1.6.4).

Table 1.6.1 *Factors for the generation of airborne salt*

Hazard zone	Zone factors	
	α_{coast}	α_{ocean}
A, C	50	2
B, D	150	6
E	500	20

Table 1.6.2 *Factor related to coastal exposure*

Coastal exposure condition	β_{coast}
Closed bay	0.05
Partially closed bay	0.10
Open bay	0.35
Open surf	1.00

Table 1.6.3 *Factor for site classification*

Site classification	α_{exp}
Open to sea	2.00
Suburban	0.50
City centre	0.25
Other sites	1.00

Table 1.6.4 *Factor for local shelter (rain protection)*

Micro Climate	α_{micro}
Outside but sheltered from rain	2.0
Wall cavity	0.5
Roof space	0.4
Sub-floor	0.6
Other	1.0

1.7 Airborne Pollution

An estimate of the pollution parameter, P_{air}, which is the airborne pollution of air in terms of level of airborne SO_x ($\mu g/m^3$), can be made by,

$$P_{air} = \frac{\alpha_{indus}}{L_{indus} + 1} \tag{1.7.1}$$

where L_{indus} (km) the distance to the nearest industrial complex; α_{indus} is defined in Table 1.7.1.

Table 1.7.1 *Industrial exposure factor*

Industry Type	Industrial exposure factor α_{indus}
Heavy industry (steel works, petrochemical)	110.0
Moderate industry (paper mills, large manufacturing)	22.0
Light industry (assembly plants)	5.5

1.8 Time of Wetness

The climate factor considered in the computation of corrosion depth is the time-of-wetness, t_{wet} (%), the percentage of time in a year when the relative humidity is above 80% and the temperature above 0°C. The factor t_{wet} is estimated by

$$t_{wet} = 0.22 D_{rain} \tag{1.8.1}$$

where D_{rain} is the number of rain days per year, D_{rain} (days/year), for which a rain day is defined as a day on which there is at least 0.2 mm of rain. D_{rain} is estimated by

$$D_{rain}\Big|_{L_{coast}} = 30 + \left(D_{rain}\Big|_{L_{coast}=0} - 30 \right) e^{-0.004 L_{coast}} \tag{1.8.2}$$

where L_{coast} is distance to the nearest coast (km); $D_{rain}\Big|_{L_{coast}=0}$ is the representative value of D_{rain} at the corresponding coast, listed in Table 1.4.2, depending on the hazard zones defined in Figure 1.4.1.

1.9 Design Depth of Atmospheric Corrosion

The design depth of atmospheric corrosion, c_{design} will be given by

$$c_{design} = c\left(1 + \alpha V_c\right) \qquad (1.9.1)$$

where

- c is the mean depth of the loss in fastener cross-section due to atmospheric corrosion, computed by Eq(1.2.1) or Eq.(1.3.1) for a chosen design life time.
- V_c is the coefficient of variation of c. From available data, it is recommended that V_c = 1.5.
- α is specified parameter related to the target reliability level.
  - α = 0.8 for normal consequence of failure elements.
  - α = 0.4 for low consequence of failure elements.

From the design depth of atmospheric corrosion, the residual cross-section is estimated; from which engineers compute the acceptable design load capacity by normal AS1720.1 procedure.

1.10 Corrosion of Bolts

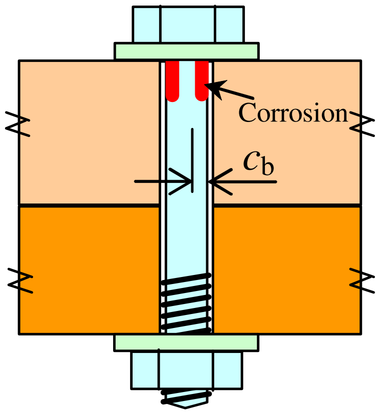


Figure 1.10.1 *Depth of corrosion at the neck of the bolt*

It is known that bolted joints can form a very special case of embedded fastener, because they are often placed in oversized holes pre-drilled into the timber, thus allowing moisture/water, salt and oxygen to enter, a situation that does not occur with other fasteners. To provide some sort of indication of the corrosion of bolts, an assumption is made that the worst corrosion occurs near the neck of the bolt, and this is either due to the embedded corrosion mechanism that is enhanced by water ingress into the bolt's hole; or due to atmospheric corrosion that is enhanced if the connector is near a beach. The procedures are as follows,

- To compute the corrosion depth due to the embedded corrosion, follow the procedure in Manual No. 6 (Nguyen et al., 2007), with a modification that the adjusted factor Δ_{rain} is multiplied by factor of 1.5 to take into account the increasing of timber moisture content due to water ingress into the bolt's holes.
- To compute of the corrosion depth due to atmospheric corrosion that is enhanced if the connector is near a beach, determine the normal first year corrosion depth by Eq. (1.2.2) for zinc or Eq. (1.3.2) for steel, which is then multiplied with an enhanced factor, λ_b, to obtain the *enhanced* first year corrosion depth. The corrosion depths then can be computed by Eq. (1.2.1) for zinc or Eq. (1.3.1) for steel, using the corresponding *enhanced* first year corrosion depth. The enhanced factor, λ_b, is computed by the following equation:

$$\lambda_b = 1 + e^{-\frac{L_{coast}}{2}} \tag{1.10.1}$$

where L_{coast} (km) is the distance to the beach.

The corrosion depth c_b near the neck of the bolt is taken to be the higher of these two computed corrosion values.

1.11 Corrosion of Screws under Corrugated Roofing

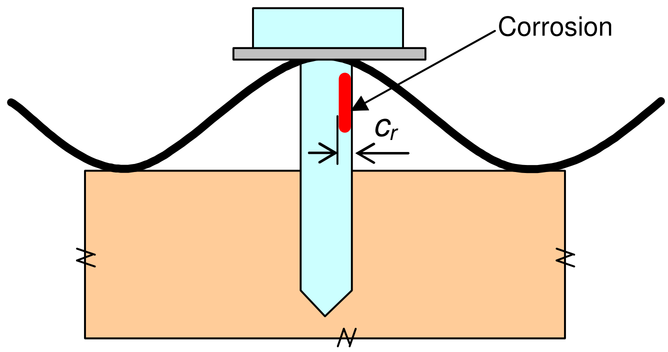


Figure 1.11.1 *Depth of corrosion on exposed part of fasteners under corrugated roofing*

It is known that the exposed parts of fasteners under corrugated roofing, as depicted in Fig. 1.11.1, form special cases, where the atmospheric corrosion is enhanced or reduced depending the distance of the structure to a beach.

To compute of the corrosion depth due to atmospheric corrosion that is adjusted (enhanced or reduced) if the connector is near or far from a beach, follow the procedure in Sections 1.2 or 1.3 to determine the normal first year corrosion depth, which is then multiplied with an adjustment factor, λ_r, to obtain the *adjusted* first year corrosion depth. The corrosion depths then can be computed by Eq. (1.2.1) for zinc or Eq. (1.3.1) for steel, using the corresponding *adjusted* first year corrosion depth.

A corrugate roof could be used above an open space (e.g. car port, open walk way) or a closed space (e.g. house). The adjusted factor λ_r, is computed by the following equation depending on the whether it is installed in an open or a closed space:

If installed in an open space:

$$\lambda_r = 0.5 + e^{-\frac{L_{coast}}{14}} \tag{1.11.1}$$

If installed in a closed space:

$$\lambda_r = 0.2 + 0.6e^{-\frac{L_{coast}}{9}} \tag{1.11.2}$$

where L_{coast} (km) is the distance to the beach.

2. Basis of Model Development

2.1 Atmospheric Corrosion Equations' Forms

Based on literature and with the need to put final equations in a form that engineers can use, we choose the following forms for atmospheric corrosion of metals, including steel and zinc.

The corrosion depth of steel c_s (μm), or zinc c_z (μm), over time, is determined by the following equations,

For steel: $$c_s = c_{0,s} t^{n_s} \qquad (2.1.1)$$

For zinc: $$c_z = c_{0,z} t^{n_z} \qquad (2.1.2)$$

where t (year) is the time in service; $c_{0,s}$, $c_{0,z}$ are the corrosion rate for steel and zinc, respectively. These are corrosion depth in one year (μm/year), or precisely, the corrosion depth in the 1st year, which are taken the following form

For steel: $$c_{0,s} = A_s\, t_{\mathrm{wet}}^{n_s} S_{\mathrm{air}}^{m_s} + B_s t_{wet}^{r_s} P_{air} \qquad (2.1.3)$$

For zinc: $$c_{0,z} = A_z t_{\mathrm{wet}}^{n_z} S_{\mathrm{air}}^{m_z} + B_z t_{wet}^{r_z} P_{air} \qquad (2.1.4)$$

where

- A_s, B_s, m_s, n_s, r_s are constant factors for the steel corrosion model. It is noted that the factor n_s is the same in both Eqs.(2.1.1) and (2.1.3).
- A_z, B_z, m_z, n_z, r_z are constant factors for the zinc corrosion model. It is noted that the factor n_z is the same in both Eqs.(2.1.2) and (2.1.4).
- t_{wet} is time of wetness, which is defined as the percentage of time in a year when the relative humidity is above 80% and the temperature above 0°C
- S_{air} (mg/m^2/day) is salt concentration in the air (airborne salinity)
- P_{air} is pollution of air in terms of level of airborne SO_x ($\mu g/m^3$)

The 1st term in Eqs.(2.1.3) and (2.1.4) is for corrosion due to salinity effect. The 2nd term is for corrosion due to air pollution agent SO_x effect.

Fittings with various sources of data as presented in Section 3 result in the following equations:

For steel: $$c_{0,s} = 0.1 t_{wet}^{0.5} P_{air} + 0.5 t_{wet}^{0.8} S_{air}^{0.5} \qquad (2.1.5)$$

For zinc: $$c_{0,z} = 0.006 t_{wet}^{0.2} P_{air} + 0.025\, t_{\mathrm{wet}}^{0.6} S_{\mathrm{air}}^{0.5} \qquad (2.1.6)$$

The following sections provide the basis of determining the model's factors/parameters. It is noted that in this report, 'pollution' or 'polluted' means effects relating to airborne SO_x agent on corrosion, whereas 'un-polluted' means effects relating to airborne salinity only.

2.2 Constant factors

2.2.1 Constants relating to Salinity Term

The factor n_s for steel and n_z for zinc may vary from 0.2 and 0.9 as reported in literature. In Guttman and Sereda (1968), measurements of corrosion at sites dominated by salinity effects were reported, and the results were fitted to a similar form of the corrosion rate. The fitting results presented in Table 13 of the paper for Panama and Kure Beach 800ft sites showed that the factor n_s for steel ranges from 0.88 to 0.78, with an average value of 0.83. The factor n_z for zinc ranges from 0.61 to 0.54, with an average value of 0.57. Referring these values for the models developed herein, we take $n_s = 0.8$ for steel, and $n_z = 0.6$ for zinc.

The factor m_s for steel and m_z for zinc vary around 0.5 in literature. Therefore for the models developed herein, we take $m_s = m_z = 0.5$. It is noted that in some works, the factor took value of 1.0 with an additional constant, i.e. $(S_{\text{air}} + c)$ as in Guttman and Sereda (1968), among others in literature. For the model developed herein, we neglect this constant c. due to the following reasons:

- This constant c has large uncertainty. Its values would vary largely from -14 to 217, as resulted from the fitting works reported by Guttman and Sereda (1968).
- For engineering purpose, we are interested in significant corrosion, not in negligible corrosion as represented by the additional constant c.
- For simplicity, we chose not to incorporate this constant c to avoid making the model more complex in having to choose another parameter with large uncertainty.

The constant A_s for steel is determined by calibrating the model's corrosion depth Eq.(2.1.3) with the typical corrosion rates for mild steel at various locations provided in the Draft Australian Standard DR07270 titled 'Atmospheric Corrosivity Zones in Australia' (AS, 2007). The data in this draft was resulted from a significant quantity of hard data on atmospheric corrosion rates for Australia, which has by far in the main been generated as a result of programs conducted by CSIRO since 1972. The fitting is presented in Section 3.1, in which A_s for steel is determined to be 0.5.

To determine the constant A_z for zinc, the ratio between corrosion values measured on steel specimen and corrosion values on zinc specimen at the same site is evaluated when data available. This ratio is approximately equal to the ratio between A_s for steel corrosion model and A_z for zinc corrosion model, and hence can be use to estimate constant A_z for zinc. Using data from Guttman and Sereda (1968), coupon test programs (King et.al., 1999, Ganther, 2002), and tropical atmospheric corrosion data (Cole, 2000), it is found that the ratio, while varying significantly within each set of data, has an average of about 20 for each set. For example, data from Tables 4 and 8 of Guttman and Sereda (1968) gives an average of 18; data from the coupon test programs (King et.al., 1999, Ganther, 2002) gives an average of 19; and the tropical atmospheric corrosion data (Cole, 2000) gives an average of 24. For the model developed herein, we take the ratio equal to 20. Given the constant A_s for steel of 0.5, then the constant A_z for zinc is 0.025. The estimation of this ratio is provided in Section 3.4.

The model for steel is then further checked with corrosion data resulted from coupon test programs (King et.al., 1999, Ganther, 2002). The model is found to agree reasonably with the measured data. The result of this check is presented in Section 3.3.

Note that in determining of these constants, it is assumed that the contribution from SO_x to the corrosion is negligible in these sets of data, and hence $P_{\text{air}} = 0$.

2.2.2 Constants relating to air pollution term

Cole (2000) provided a set data of corrosion rate at SO_x polluted environment, including sites in tropical areas of five countries. To find the constants B_s and r_s for steel and B_z and r_z for zinc in the air-pollution terms, Eqs.(2.2.3) and (2.2.4) are fitted to 5 data points that have the highest value of P_{air} in the 'tropical' data provided in Cole (2000). The data selected and the fittings are presented in Section 3.5. A check of final model prediction with all 'tropical' data is provided in Section 3.6.

2.3 Airborne Salinity (S_{air})

In this section, a model to estimate the salinity at a site will be presented. This model has been developed using the equation form presented in Cole et.al. (1999) and Cole et.al. (2004); and fitting the model prediction to the corrosion data measured at various site Melbourne beach and Newcastle beach presented in King et.al. (1982) and King and Carrberry (1992). The fitting is presented in Section 3.2.

2.3.1 Equation form

The equation form for prediction of air-borne salinity is taken from Cole et.al. (2004), where salt production at a site is divided into production by surf (at the coast) and production by oceans. The ocean production is dependent on whitecap activity, while surf production can be modelled as a function of local winds. The concentration of surf generated aerosol falls dramatically within 1 km of the coast, while ocean generated aerosol may be transported inland for over more than 50 km. The variation of salt concentration with distance from the shoreline can be approximated by an exponential decrease, as long as separate factors are defined for surf- and ocean produced aerosol. Thus, for surf produced aerosol:

$$A(L_{coast}) = A_i\left(0.9e^{-10L_{coast}} + 0.1e^{-L_{coast}}\right) \tag{2.3.1}$$

where A_i is the surf produced concentration at the shoreline, and $A(L_{coast})$ is the concentration at a distance L_{coast} (in kilometres) from the shoreline. For ocean produced aerosol:

$$O(L_{coast}) = O_i e^{-0.02L_{coast}} \tag{2.3.2}$$

where O_i and $O(L_{coast})$ are the concentrations of ocean produced aerosol at the shoreline, and at a distance L_{coast} (in kilometres) from the shoreline respectively.

2.3.2 Airborne Salinity Model for Engineering Uses

For the model presented herein, we use the above equation forms, and take into account the following factors:

- Define the airborne salinity at a site is proportional to the total salinity production from surf produced concentration and ocean produced concentration, ie, the sum of Equations (2.3.1) and (2.3.2).
- Factorise the equations with separate factors representing different effects on air-borne salinity. The initial values of the factors are estimated by referring to the empirical model in Cole et.al. (1999) and Cole et.al. (2004).

- Fit the corrosion model prediction using the airborne salinity model to the corrosion data measured at various sites of Melbourne beach and Newcastle beach presented in King et.al. (1982) and King and Carrberry (1992). The purpose of the fitting is to adjust the factors so that the corrosion model prediction would give a sharp increase at locations getting closer to the beach, as observed in the measured data. The final fitting result is presented in Section 3.2.

The final airborne salinity model is presented in the followings. The salinity at a site, denoted by S_{air} (mg/m^2 per day), is defined as the rate of deposition on a salt wick candle. Since salt deposition along the coast front of Australia varies from on site to another, the coastline of Australia is classified into three coastal zones, as shown in Figure 2.3.1. An estimate of salinity is obtained from the following equation,

$$S_{\mathrm{air}} = \max \begin{cases} \alpha_{\exp}\alpha_{\mathrm{micro}}\left[\alpha_{\mathrm{coast}}\beta_{\mathrm{coast}}\left(0.9e^{-10L_{coast}} + 0.1e^{-L_{coast}}\right) + \alpha_{\mathrm{ocean}}e^{-0.02L_{\mathrm{coast}}}\right] \\ 1.0 \end{cases} \qquad (2.3.3)$$

in which L_{coast} is the distance to the coast in kilometres; the parameters α_{coast} and α_{ocean} take into account the effect of coastal zonation (Table 2.3.1); β_{coast} the effect of coastal exposure (Table 2.3.2); α_{exp} the effect of site exposure (Table 2.3.3); and α_{micro} the effect of local shelter factors (Table 2.3.4). This local shelter factor values, including those for building envelope, were determined based on a microclimate measurement program at many Australian houses reported in Cole et.al. (1996, 2001) and Ganther (2001, 2002).

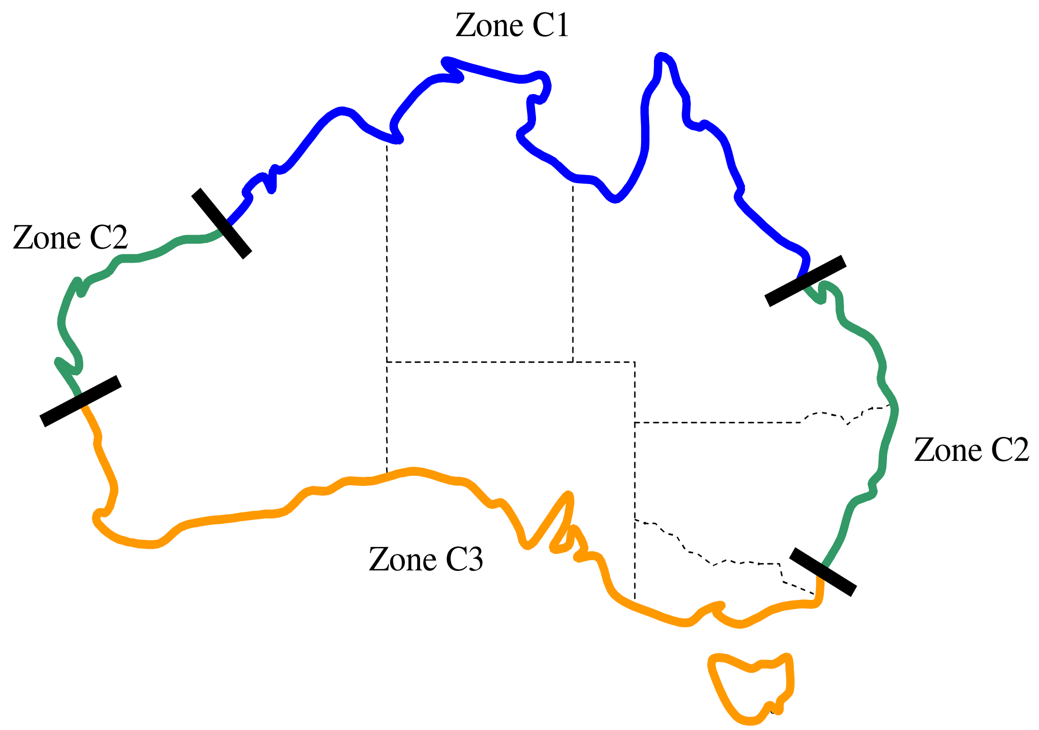


***Figure 2.3.1** Definition of coastal zones.*

Table 2.3.1 *Factors for the generation of airborne salt*

*Coastal zone**	Zone factors	
	α_{coast}	α_{ocean}
C_1	50	2
C_2	150	6
C_3	500	20
* See Fig. 2.3.1		

Table 2.3.2 *Factors for airborne salt related to coastal exposure*

Coastal exposure condition*	β_{coast}
Closed bay	0.05
Partially closed bay	0.10
Open bay	0.35
Open surf	1.00
*See Fig. 2.3.2	

Table 2.3.3 *Factor for site classification*

Site classification	α_{exp}
Open to sea	2.00
Urban (suburbs)	0.50
Urban (city centre)	0.25
Other sites	1.00

Table 2.3.4 *Factor for local shelter (rain protection)*

Microclimate	α_{micro}
Outside but sheltered from rain	2.0
Wall cavity	0.5
Roof space	0.4
Sub-floor	0.6
Other	1.0

For definition of coastal exposure in Table 2.3.2, we develop the following quantitative rules for engineering use. This was based on some data estimated by Cole (1999). The coastal exposure condition is dependent on the opening angle, θ (degrees), and the radius, R (km), of the bay. By using an exposure factor for the idealised bay, α_{bay}, calculated as follows for given θ and R,

$$\alpha_{\text{bay}}^2 = \left(\frac{\theta}{85}\right)^2 + \left(\frac{R}{20}\right)^2 \tag{2.3.4}$$

then the coastal exposure condition is determined by the α_{bay} value:

$$\text{Coastal exposure condition} = \begin{cases} \text{Closed bay,} & \text{if } \alpha_{bay} < 1; \\ \text{Partially closed bay,} & \text{if } 1 \le \alpha_{bay} < 1.5; \\ \text{Open bay,} & \text{if } 1.5 \le \alpha_{bay} < 2.5; \\ \text{Open surf,} & \text{if } \alpha_{bay} \ge 2.5. \end{cases} \tag{2.3.5}$$

The definition of Eq. (2.3.4) is schematically shown in Fig. 2.3.2.

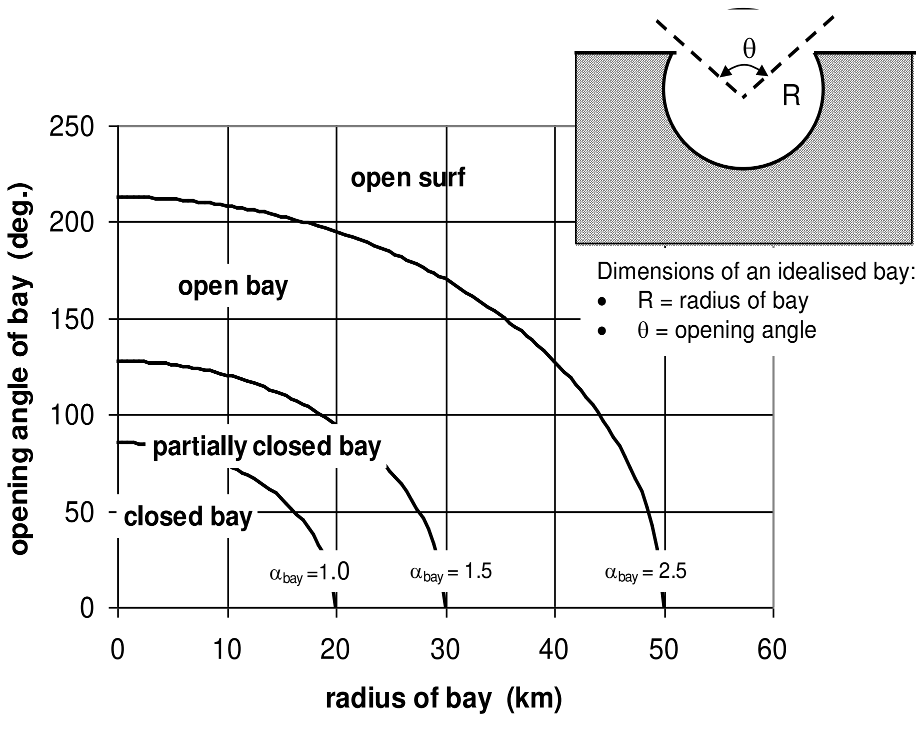


Figure 2.3.2 *Definition of coastal exposure condition.*

2.4 Pollution (P_{air})

An estimate of the pollution parameter, P_{air}, which is the pollution of air in terms of level of airborne SO_x (μg/m^3), can be made by,

$$P_{\mathrm{air}} = \frac{\alpha_{\mathrm{indus}}}{L_{indus} + 1} \tag{2.4.1}$$

where L_{indus} (km) the distance to the nearest industrial complex; α_{indus} is defined in Table 2.4.1. This equation is resulted from the fitting in Figure 2.4.1. The 4 data points were given by Cole (1999) for P_{air} near heavy industry complex. The reduction of P_{air} for the other industry types, as reflected by the value of α_{indus} in Table 2.4.1, was also estimated and provided by Cole (1999).

Table 2.4.1 *Industrial exposure factor* α_{indus}

Industry Type	Industrial exposure factor α_{indus}
Heavy industry (steel works, petrochemical)	110.0
Moderate industry (paper mills, large manufacturing)	22.0
Light industry (assembly plants)	5.5

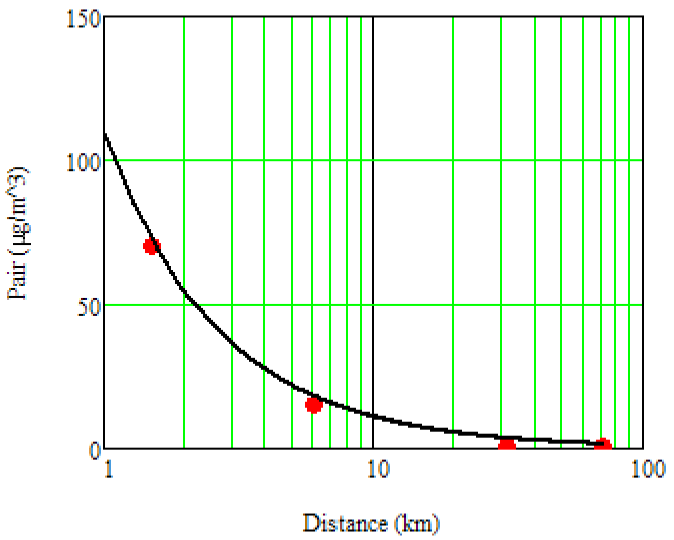


Figure 2.4.1 *Relation between* P_{air} *and* L_{indus} *in heavy industry zone [Eq.(2.4.1)] to fit with estimates from Cole (1999)*

2.5 Climate Related Parameters – Time of Wetness (t_{wet})

The climate factor considered in the computation of corrosion depth is the time-of-wetness, t_{wet} (%), the percentage of time in a year when the relative humidity is above 80% and the temperature above 0°C. This can be computed from the Bureau of Meteorology data. If the relevant data is not readily accessible, then, for practical purposes, t_{wet} may be estimated by

$$t_{wet} = 0.22 D_{rain} \tag{2.5.1}$$

where D_{rain} is the number of rain days per year, D_{rain} (days/year), for which a rain day is defined as a day on which there is at least 0.2 mm of rain. This can also be computed from the Bureau of Meteorology data. Figures 2.5.1 the relationship between D_{rain} and t_{wet} for Australia based on Bureau of Meteorology data, and also the lines corresponding to the assumed relationships by Equation (2.5.1).

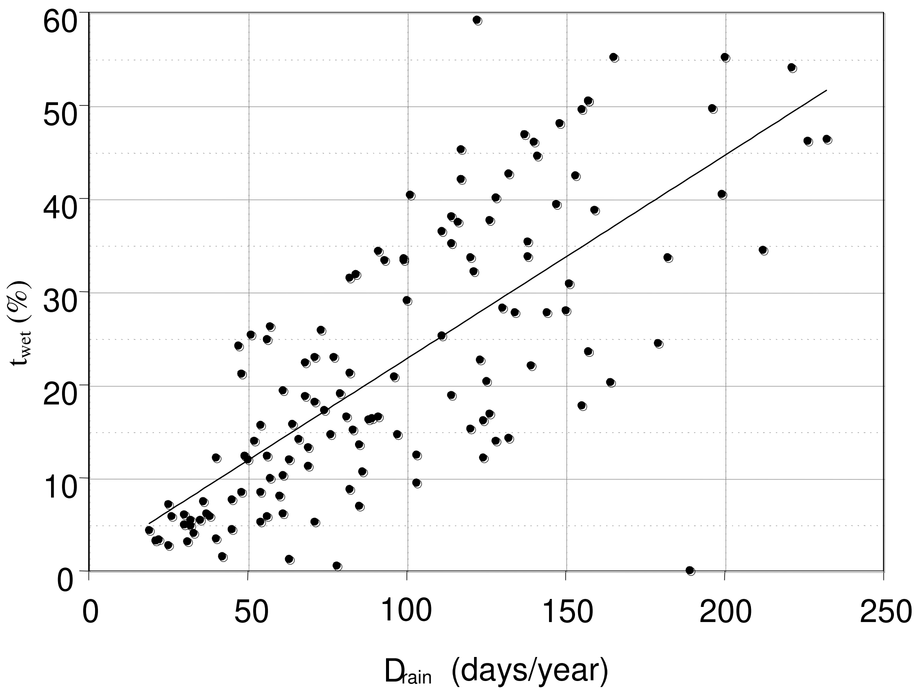


Figure 2.5.1 *Relationship between rain-days and time-of-wetness (Bureau of Meteorology sites).*

If the relevant BOM data for D_{rain} is not readily accessible, then, for practical purposes, D_{rain} for sites near the coast may take the representative values in Table 2.5.1, depending on the hazard zones defined in Figure 2.5.2.

For an inland site, D_{rain} be estimated by

$$D_{rain}\big|_{L_{coast}} = D_{rain-inland} + \left(D_{rain}\big|_{L_{coast}=0} - D_{rain-inland}\right)e^{-0.004 L_{coast}} \tag{2.5.2}$$

Where L_{coast} is distance to the nearest coast (km); $D_{rain\text{-}inland}$ is the representative value of D_{rain} for inland locations at about 1000 km or more from the coast. A contour plot of D_{rain} in

Australia is shown in Figure 2.5.3, from which it is estimated that $D_{rain\text{-}inland}$ = 30 days/year. Refer Manual 1 (Wang et.al. 2008) for more details on Climate Data used for the project.

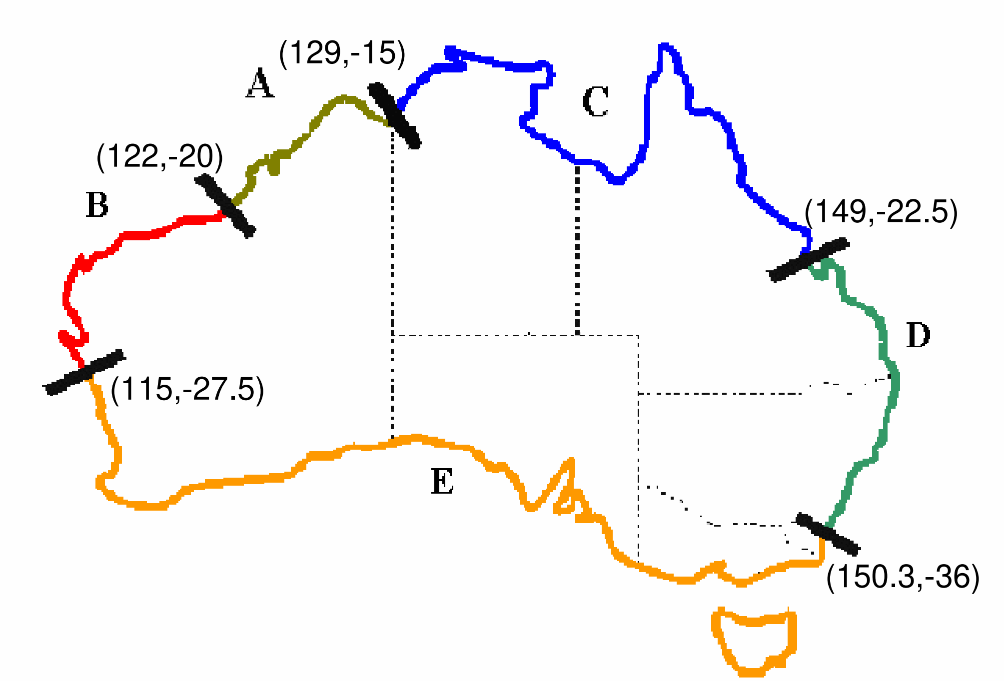


***Figure 2.5.2**. Hazard Zones related to corrosion due to airborne salt. (Zone E has the greatest hazard)*

***Table 2.5.1** Hazard zones and corresponding coastal zones and numbers of rain days*

Hazard Zone	Coastal type zone (Figure 2.3.1)	Representative D_{rain} (No. of rain days / year)
A	C1	70
B	C2	40
C	C1	100
D	C2	130
E	C3	130

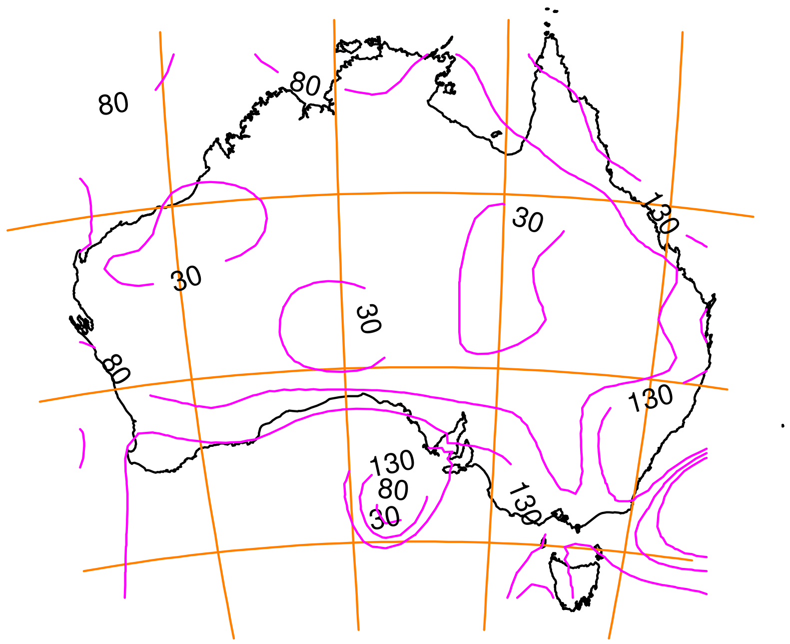


Figure 2.5.3 *Contours of D_{rain} (days/year) in Australia*

2.6 Model for Bolts

A typical installation of bolts is shown in Figure 2.6.1. By an expert opinion (King 2005), the section that is subjected to most severe corrosion is the neck section, as indicated by the red marks in Figure 2.6.1. Corrosion at the neck is assumed to be either due to the usual embedded corrosion mechanism or due to atmospheric corrosion. Prediction of corrosion of metal embedded in wood follows the procedure in Manual No. 6 (Nguyen et al.,2007), with a modification that the adjusted factor Δ_{rain} is multiplied by factor of 1.5 to take into account the increasing of timber moisture content due to water ingress into the bolt's holes.
From King (2005), atmospheric corrosion at the neck of bolts at the coast is about 2 to 3 times of the mild corrosion at the coast. When the distance to coast increases, the difference between the corrosion of bolt neck and mild steel drops exponentially with the distance, and becomes roughly the same when they are 10 or more kilometres away from the coast.

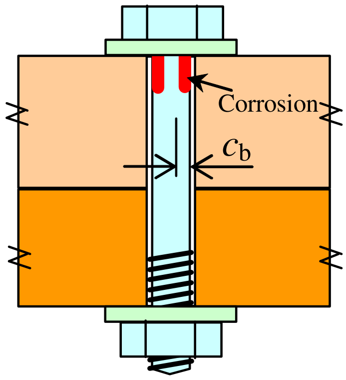


Figure 2.6.1 *Bolt connecting two pieces of wood (red marks show the neck section is subject to the most severe corrosion).*

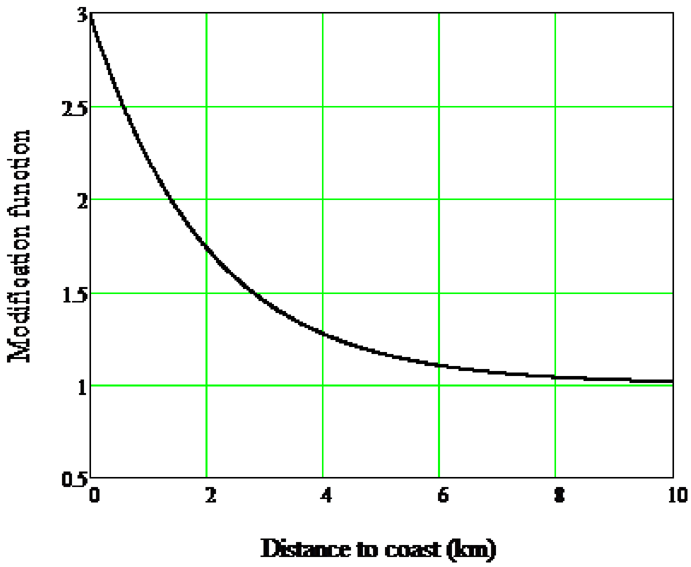


Figure 2.6.2 Modification function λ_b.

For this project, the following equation is used by assuming the bolt corrosion at the coast is 3 times of that of mild steel,

$$\lambda_b = 1 + 2e^{-L_{coast}/2} \tag{2.6.1}$$

where L_{coast} (km) is the distance to the coast. Eq. (2.6.1) is plotted in Figure 2.6.2. Therefore, the first-year corrosion of zinc coating, if any, is estimated by

$$c_{0,z,bolt} = c_{0,z}\lambda_b \tag{2.6.2}$$

where $c_{0,z}$ are calculated by Eq. (2.1.6). Corrosion depth of zinc at the neck section over time is then estimated by Eq. (2.1.2).

Similarly, the first-year corrosion depth of the steel base is predicted by

$$c_{0,s,bolt} = c_{0,s}\lambda_b \tag{1.6.3}$$

where $c_{0,s}$ are calculated by Eq. (2.1.5). Corrosion depth of steel at the neck section over time is then estimated by Eq. (2.1.1).

2.7 Model for Screws under Corrugated Roofing

This Section considers installation of fasteners under corrugated roofing. This circumstance arises when corrugated roofing is fastened on rafters by either nails or screws, as shown in Figure 2.7.1. In such cases, it is believed that (King 2005) the most severely corroded section is the exposed shank under the roofing, as indicated by the red marks in Figure 2.7.1, as it is sheltered from the rain.

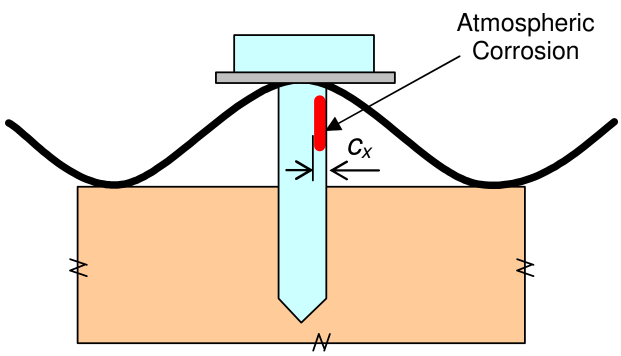


Figure 2.7.1 *Fastener connecting the corrugated roofing to wooden rafter (red mark shows the shank is subject to the most severe corrosion).*

According to King (2005), corrosion rate of the exposed shank of fasteners installed in an open environment (e.g. car port roofing) is higher than that installed in a closed environment (e.g. house roofing). The rates of the first-year corrosion for the two cases in comparison with that of mild steel exposed to weather are schematically plotted in Figure 2.7.2 as functions of distance to coast (km). The corrosion ratios shown at 10 and 100 km from the coast are derived by opinion solicitation (King 2005).

Figure 2.7.2 indicates that for fasteners installed in corrugated roof in an open environment, corrosion rate near the coast is higher, but when further inland is lower, than that of metal fully exposed to weather. The reasons are that when near the coast salt deposition is higher in areas allowing free airflow but sheltered from rain, whereas when further inland the influence of salt becomes trivial and it is the relative humidity and condensation that dominate the rate of corrosion. At an inland site, the underside of a corrugated car port roof has less relative humidity and condensation than the upper side.

Equations that approximate curves 1 and 2 in Figure 2.7.2 are derived proposed as follows:

- For fasteners in open environment:

$$\lambda_r = 0.5 + e^{-L_{coast}/14} \tag{2.7.1}$$

- For fasteners in closed environment (note that at coast the corrosion ratio of fastener shank to fully exposed mild steel is taken as 0.8):

$$\lambda_r = 0.2 + 0.6e^{-L_{coast}/9} \tag{2.7.2}$$

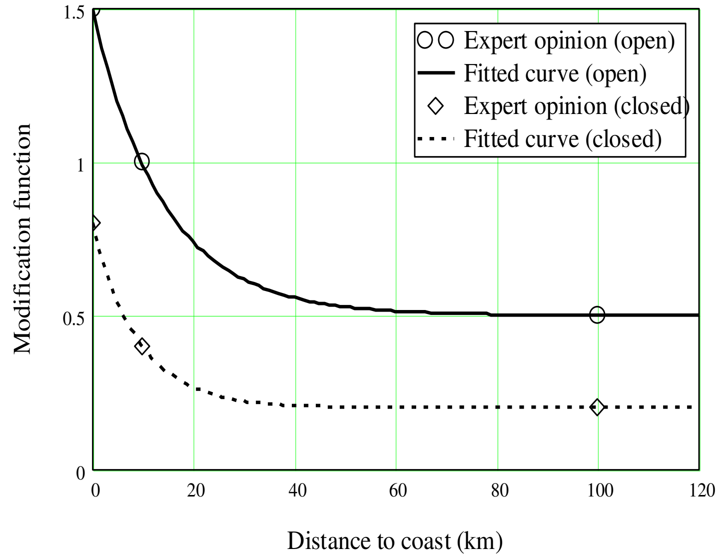


Figure 2.7.2 *Modification functions* λ_r *(Eqs. (2.7.1) and (2.7.2)).*

Eqs. (2.7.1) and (2.7.2) are plotted in Figure 2.7.. Similarly to bolt corrosion, the first-year corrosion of zinc coating, if any, is estimated by

$$c_{0,z,bolt} = c_{0,\mathrm{z}}\lambda_r \tag{2.7.3}$$

where $c_{0,\mathrm{z}}$ are calculated by Eq. (2.1.6). Corrosion depth of zinc at the neck section over time is then estimated by Eq. (2.1.2).

Similarly, the first-year corrosion depth of the steel base is predicted by

$$c_{0,s,bolt} = c_{0,\mathrm{s}}\lambda_r \tag{2.7.4}$$

where $c_{0,\mathrm{s}}$ are calculated by Eq. (2.1.5). Corrosion depth of steel at the neck section over time is then estimated by Eq. (2.1.1).

2.8 Design Corrosion Depths

2.8.1 Coefficient of variation between model predictions and measurements

The coefficient of variation of corrosion depths, V_c, is determined from the model predictions and measurements of corrosion depths given in the data fittings in Section 3. From the comparision of the corrosion depths that resulted from the measurement (c_m) with the model-prediction corrosion depths (c_p), log-normal distributions are assumed for the uncertainties of the predicted and measured corrosion depths over time. This leads to the coefficient of variation of the corrosion depth, denoted by V_c, evaluated as follows (Ang & Tang, 2007),

$$V_c = \sqrt{e^{\sigma^2} - 1} \qquad (2.8.1.1)$$

in which

$$\sigma^2 = \frac{1}{n-2}\sum\left(\ln c_m - \ln c_p\right)^2 \qquad (2.8.1.2)$$

where c_m is the measured corrosion depth, c_p is the predicted corrosion depth, and n is the number of data points. The values of V_c thus obtained for each set of data in Section 3. The results are listed in Table 2.8.1.1, including

- Data from Corrosion Draft Standard, presented in Section 3.1.
- Data from CSIRO Coupon Tests (King et.al., 1999, Ganther, 2002), presented in Section 3.3. The prediction using predicted airborne salt and time of wetness is used to capture the total variation of the whole model.
- 'Tropical' data (Cole, 2000) presented in Section 3.6

For the Engineering Code, the coefficient V_c for the whole model is set to be 1.5.

2.8.2 Design Corrosion Depths

The design depth of atmospheric corrosion, c_{design} will be given by

$$c_{design} = c\left(1 + \alpha V_c\right) \qquad (2.8.2.1)$$

where

- c is the mean depth of the loss in fastener cross-section due to atmospheric corrosion, computed by Eq(2.1.1) or Eq.(2.1.2) for a chosen design life time.
- V_c is the coefficient of variation of c, presented in Section 2.8.1.
- α is specified parameter related to the target reliability level.
  - α = 0.8 for normal consequence of failure elements.
  - α = 0.4 for low consequence of failure elements.

From the design depth of atmospheric corrosion, the residual cross-section is estimated; from which engineers compute the acceptable design load capacity by normal AS1720.1 procedure.

Refer Manual No.2 (Leicester et.al. 2008) for the derivation of the design corrosion depth.

Table 2.8.1.1 *Coefficient V_c for atmospheric corrosion model, derived from data in Section 3.*

Data	V_c
Corrosion Draft Standard - Steel	0.7
CSIRO Coupon Tests - Steel	1.3
CSIRO Coupon Tests - Zinc	2.2
‘Tropical’ data - Steel	1.0
‘Tropical’ data - Zinc	1.1
All data of steel	0.9
All data of zinc	1.5
All data, both zinc and steel	1.1

3. Data Fittings / Checks

3.1 Fittings with data from Corrosion Draft Standard

The data fitting is provided in Table 3.1.1, where

- Column 1 ~ 4: Corrosion rate and distance from sea were data from the draft standard
- Column 5 ~ 8: Coastal zone, D_{rain}, Coastal exposure, and Site classification were determined based on satellite image of the sites provided by Google Map.
- Column 9: Predicted corrosion rates are determined by Equation (2.1.5)

Comparison of given corrosion rate with prediction is in Figure 3.1.1. From this fitting, we determine constant A_s for steel corrosion in Eq.(2.1.3) to be 0.5.

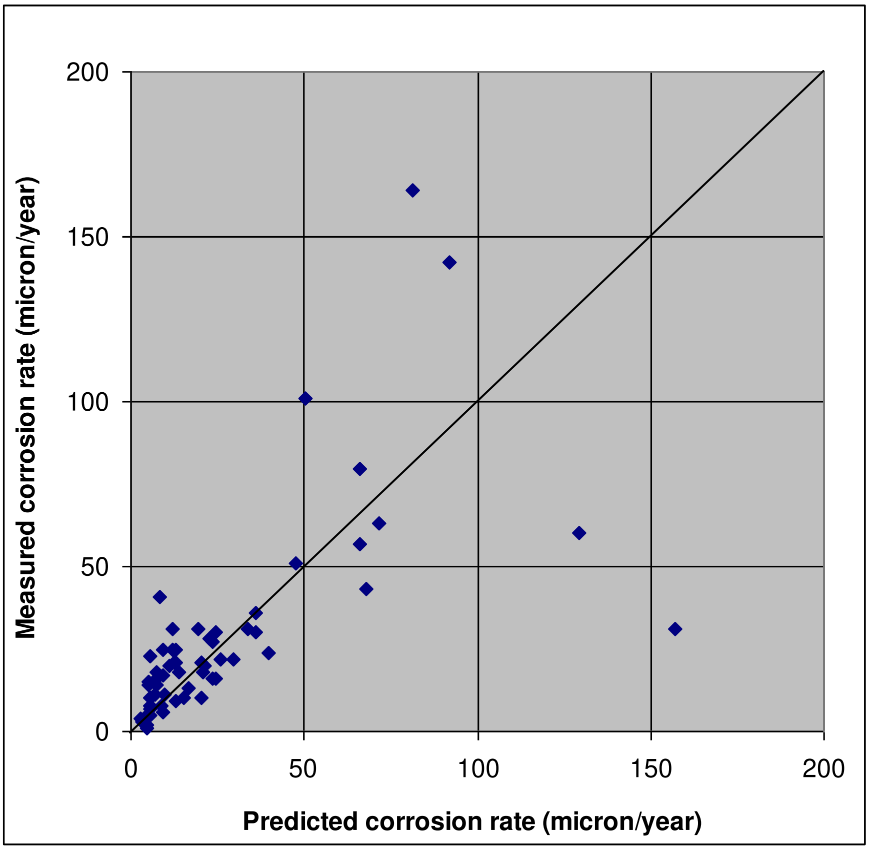


Figure 3.1.1. *Comparison of measured corrosion rate from the Draft Standard with predicted corrosion rate by the model Equation (2.1.5). Data from Table 3.1.1.*

Table 3.1.1. *Draft AS Data (Column 1 to 4) and Model Parameters (Column 5 to 8) and Model Prediction (Column 9)*

Test site	State	Corrosion Rate (μm/yr)	Distance from sea (km)	Coastal zone	Drain	Coastal exposure (of nearest coast)	Site Classification	Predicted Corrosion Rate (μm/yr)
Canberra:Black Mountain	ACT	16	114	D	130	Open surf	Others	7.3
Canberra: Fairbarn	ACT	5	108	D	130	Open surf	Others	5.7
Queanbeyan	ACT	7	120	D	130	Open surf	Suburbs	5.5
Appin	NSW	18	20	D	130	Open surf	Others	14.0
Denman	NSW	10	120	D	130	Open surf	Others	5.5
Dubbo	NSW	4	300	D	130	Open surf	Others	3.9
Mount Kembla	NSW	13	10	D	130	Open surf	Others	15.8
Muswellbrook	NSW	23	110	D	130	Open surf	Others	5.7
Newcastle-Beach	NSW	176	0.125	D	130	Open surf	Open to sea	78.7
Nowra	NSW	18	21	D	130	Open surf	Others	13.8
Port Kembla jetty #4	NSW	60	0	D	130	Open surf	Open to sea	129.2
Quirindi	NSW	2	200	D	130	Open surf	Others	4.7
Scone	NSW	10	125	D	130	Open surf	Others	5.5
Singleton	NSW	14	70	D	130	Open surf	Others	7.5
Sydney: Alexandria	NSW	4	5	D	130	Open surf	Suburbs	12.0
Sydney: City	NSW	41	5	D	130	Open surf	City center	8.5
Sydney: Pyrmont	NSW	31	5	D	130	Open surf	Suburbs	12.0
Sydney: Rydalmere	NSW	54	20	D	130	Open surf	Suburbs	9.9
Sydney: Ryde	NSW	25	27	D	130	Open surf	Suburbs	9.1
Wagga	NSW	4	260	D	130	Open surf	Others	4.2
Williamtown	NSW	30	4	D	130	Open surf	Open to sea	24.7
Darwin	NT	11	5	C	100	Closed bay	Suburbs	9.7
Darwin	NT	6	7	C	100	Closed bay	Suburbs	9.4
Gove	NT	21	11	C	100	Open surf	Others	12.7
Mt Goodwin	NT	9	10	C	100	Open surf	Others	12.9
Tindal	NT	3	280	C	100	Open surf	Others	3.6
Amberley	QLD	11	75	D	130	Closed bay	Others	7.1
Brisbane: City	QLD	18	15	D	130	Closed bay	City center	7.4
Brisbane: Cannon Hill	QLD	26	9	D	130	Closed bay	Suburbs	11.3
Brisbane: Hamilton	QLD	28	12	D	130	Closed bay	Suburbs	10.9
Cowley Beach	QLD	142	0.03	C	100	Open surf	Open to sea	92.0
Cloncurry	QLD	4	600	C	100	Open surf	Others	2.6
Innisfail	QLD	17	10	C	100	Open surf	Suburbs	9.1
Innisfail	QLD	25	10	C	100	Open surf	Others	12.9
Innisfail	QLD	21	10	C	100	Open surf	Others	12.9
Toowoomba	QLD	8	120	D	130	Closed bay	Others	5.5
Townsville-open	QLD	36	0.4	C	100	Open surf	Open to sea	36.0
Townsville-sheltered	QLD	30	0.4	C	100	Open surf	Open to sea	36.0
Townsville	QLD	18	6.5	C	100	Open surf	Suburbs	9.5
Tully	QLD	25	15	C	100	Open surf	Others	12.1
Walkamin	QLD	8	43	C	100	Open surf	Others	8.6
Weipa	QLD	10	2	C	100	Open bay	Others	15.0

Table 3.1.1 *(cont) Draft AS Data (Column 1 to 4) and Model Parameters (Column 5 to 8) and Model Prediction (Column 9)*

Test site	State	Corrosion Rate (μm/yr)	Distance from sea (km)	Coastal zone	Drain	Coastal exposure (of nearest coast)	Site Classification	Predicted Corrosion Rate (μm/yr)
Adelaide Northern Beaches	SA	57	0.1	E	130	Partially closed bay	Open to sea	66.2
Adelaide Northern Beaches	SA	20	6.3	E	130	Partially closed bay	Suburbs	21.4
Adelaide Southern Beaches	SA	79.5	0.1	E	130	Partially closed bay	Open to sea	66.2
Adelaide Southern Beaches	SA	31	14	E	130	Partially closed bay	Suburbs	19.4
Adelaide Torrens Island	SA	27	0.5	E	130	Partially closed bay	Open to sea	49.7
Adelaide Urrbrae	SA	10	10	E	130	Partially closed bay	Suburbs	20.4
Adelaide Woodville	SA	16	5	E	130	Partially closed bay	Suburbs	21.7
Adelaide Woodville	SA	30	6	E	130	Partially closed bay	Suburbs	21.5
Ceduna	SA	51	1	E	130	Partially closed bay	Open to sea	47.8
Ceduna	SA	18	36	E	130	Partially closed bay	Others	20.9
Coober Pedy	SA	3	500	E	130	Open surf	Others	3.0
Kingston Southeast	SA	24	1.6	E	130	Open surf	Others	39.5
Naracoolie	SA	20	88	E	130	Open surf	Others	11.0
Port Augusta/Whyalla	SA	16	23	E	130	Closed bay	Others	24.6
Port Augusta	SA	43	0.01	E	130	Closed bay	Open to sea	67.7
Port Pirie	SA	74	5	E	130	Closed bay	Suburbs	21.7
Avenue	SA	22	19	E	130	Open surf	Others	25.8
Whyalla	SA	13	1	E	130	Closed bay	Suburbs	23.4
Whyalla	SA	43	0.01	E	130	Closed bay	Open to sea	67.7
Yorke Peninsula South	SA	164	0.4	E	130	Open surf	Open to sea	81.1
Yorke Peninsula South	SA	31	3	E	130	Open surf	Others	33.5
Burnie	TAS	29	0.5	E	130	Open surf	Suburbs	37.7
Hobart: City	TAS	13	1	E	130	Closed bay	City center	16.5
Hobart: Derwent park	TAS	16	1	E	130	Closed bay	Suburbs	23.4
Hobart: Moonah	TAS	17	2	E	130	Closed bay	Suburbs	22.8
Hobart: Risdon	TAS	71	0.5	E	130	Closed bay	Suburbs	23.9
King Island - open	TAS	63	0.25	E	130	Open surf	Others	71.5
King Island - sheltered	TAS	101	0.25	E	130	Open surf	Suburbs	50.6
Flinders	VIC	22	1.3	E	130	Open surf	Suburbs	29.7
Flinders	VIC	31	0.1	E	130	Open surf	Open to sea	157.1
Geelong: North shore	VIC	40	0.5	E	130	Partially closed bay	Others	35.1
Mt Buller	VIC	1	200	E	130	Open surf	Others	4.7
Western Victoria Edenhope	VIC	14	156	E	130	Open surf	Others	5.1
Curtin (South Derby)	WA	5	30	A	70	Partially closed bay	Others	4.4
Learmonth	WA	8	3	B	40	Open bay	Open to sea	5.6
Newman	WA	3	300	B	40	Open surf	Others	2.4
Perth: Bentley	WA	21	10	E	130	Open surf	Suburbs	20.4
Perth: Floreat park	WA	27	3	E	130	Open surf	Suburbs	23.7
Perth: Kwinana	WA	26	0.5	E	130	Open surf	Suburbs	37.7
Perth: Orelia	WA	28	4	E	130	Open surf	Suburbs	22.5
Perth: Kwinana	WA	45	0.5	E	130	Open surf	Suburbs	37.7
Port Hedland	WA	15	8	B	40	Open surf	Open to sea	5.2

3.2 Fittings with Data from Newcastle and Melbourne coastal areas

This section presents the comparison of the predicted corrosion rates with the measured rates from the corrosivity contour maps of Melbourne and Greater Newcastle areas (King et.al., 1982; King and Carrberry, 1992). From these maps, the corrosion rates at some suburbs along the coast and their variation with distance to coast can be estimated as shown in Table 3.2.1 for Melbourne and Table 3.2.2 for Newcastle. Table 3.2.3 presents the measured corrosion rates at some specific locations on or near the beachfronts within 250 m to the coast. Tables 3.2.4 and 3.2.5 present the calculation of the corrosion rate, $c_{0,s}$, by the prediction model presented in Section 1 for Melbourne and Newcastle, respectively.

Figures 3.2.1 and 3.2.2 show the comparison of the corrosion rates from the prediction model with that from the measured data. Note that $P_{air} = 0$ is assumed in this section.

Table 3.2.1 *Measured corrosion rate C_0 at some Melbourne suburbs. Values are estimated from corrosivity contour map of Melbourne (King et al. 1982)*

Beaumaris (steep area)		Frankston (flat area)		South Melbourne (flat area)	
L_{coast}	C_0	L_{coast}	C_0	L_{coast}	C_0
0.1	24	0.1	24	0.3	24
0.3	22	0.15	23.1	0.7	22
0.5	20	0.4	22	1.0	20
0.8	18	0.8	20	1.3	18
1.0	16	1.2	18	2.5	16
1.3	14	1.6	16		
1.7	11.5	1.7	15.6		
		2.4	14		
		3.8	11.8		

Table 3.2.2 *Measured corrosion rate C_0 at some Newcastle suburbs. Values are estimated from corrosivity contour map of Newcastle (King and Carberry 1992)*

Newcastle beach (very steep area)		Stockton Beach (flat area)		Glenrock Lagoon	
L_{coast}	C_0	L_{coast}	C_0	L_{coast}	C_0
0.0	100	0.35	100	0.05	100
0.15	32	0.65	70	0.1	70
0.2	30	1.05	50	0.2	50
0.5	28	2.4	32	0.45	32
0.85	26	2.7	30	0.5	30
1.15	24	5.3	28	0.9	28
		6.3	26	1.25	26
				1.6	24
				2.0	22
				4.25	20

Table 3.2.3 *Direct measured corrosion rate C_0 at some location at/near the beachfronts*

Melbourne		Newcastle	
Suburb	C_0	Suburb	C_0
Altona	31.1	Stockton	72.99
Williamstown	37.7	Nobbys beach	131.53
Brighton	38.4	Merewether	188.71
Sandringham	57.9	Red head point	153.27
Chelsea	68.5	Cave beach	122.2
Seaford	60.6	Catherine hill bay	126.44
Frankston	35.1		

Table 3.2.4 *Model prediction of corrosion rate of steel (Section 1.2) in Melbourne.*

L_{coast}	Location	Coastal zone	Bay open	Site	D_{rain}	t_{wet}	S_{air}	Predicted C_0
0	Melbourne	E	Partially closed bay	Open to sea	130	28.6	140.0	86.5
0.01	Melbourne	E	Partially closed bay	Open to sea	130	28.6	131.3	83.8
0.04	Melbourne	E	Partially closed bay	Open to sea	130	28.6	109.9	76.7
0.06	Melbourne	E	Partially closed bay	Open to sea	130	28.6	98.8	72.7
0.09	Melbourne	E	Partially closed bay	Open to sea	130	28.6	85.7	67.7
0.1	Melbourne	E	Partially closed bay	Urban (suburbs)	130	28.6	20.5	33.1
0.3	Melbourne	E	Partially closed bay	Urban (suburbs)	130	28.6	12.9	26.3
0.5	Melbourne	E	Partially closed bay	Urban (suburbs)	130	28.6	11.6	24.9
0.75	Melbourne	E	Partially closed bay	Urban (suburbs)	130	28.6	11.0	24.3
1	Melbourne	E	Partially closed bay	Urban (suburbs)	130	28.6	10.7	23.9
1.5	Melbourne	E	Partially closed bay	Urban (suburbs)	130	28.6	10.3	23.4
2	Melbourne	E	Partially closed bay	Urban (suburbs)	130	28.6	9.9	23.1
2.5	Melbourne	E	Partially closed bay	Urban (suburbs)	130	28.6	9.7	22.8
3	Melbourne	E	Partially closed bay	Urban (suburbs)	130	28.6	9.5	22.6
3.5	Melbourne	E	Partially closed bay	Urban (suburbs)	130	28.6	9.4	22.4
4	Melbourne	E	Partially closed bay	Urban (suburbs)	130	28.6	9.3	22.3
4.5	Melbourne	E	Partially closed bay	Urban (suburbs)	130	28.6	9.2	22.1
5	Melbourne	E	Partially closed bay	Urban (suburbs)	130	28.6	9.1	22.0

Table 3.2.5 *Model prediction of corrosion rate of steel (Section 1.3) in Newcastle*

L_{coast}	Location	Coastal zone	Bay open	Site	D_{rain}	t_{wet}	S_{air}	Predicted C_0
0	Newcastle	D	Open surf	Open to sea	130	28.6	312.0	129.2
0.03	Newcastle	D	Open surf	Open to sea	130	28.6	241.1	113.5
0.06	Newcastle	D	Open surf	Open to sea	130	28.6	188.4	100.4
0.1	Newcastle	D	Open surf	Others	130	28.6	69.2	60.8
0.3	Newcastle	D	Open surf	Others	130	28.6	23.8	35.7
0.5	Newcastle	D	Open surf	Others	130	28.6	15.9	29.2
0.75	Newcastle	D	Open surf	Others	130	28.6	13.1	26.4
1	Newcastle	D	Open surf	Others	130	28.6	11.4	24.7
1.5	Newcastle	D	Open surf	Others	130	28.6	9.2	22.1
2	Newcastle	D	Open surf	Others	130	28.6	7.8	20.4
2.5	Newcastle	D	Open surf	Others	130	28.6	6.9	19.3
3	Newcastle	D	Open surf	Others	130	28.6	6.4	18.5
3.5	Newcastle	D	Open surf	Others	130	28.6	6.0	18.0
4	Newcastle	D	Open surf	Others	130	28.6	5.8	17.6
4.5	Newcastle	D	Open surf	Others	130	28.6	5.7	17.4
5	Newcastle	D	Open surf	Others	130	28.6	5.5	17.2

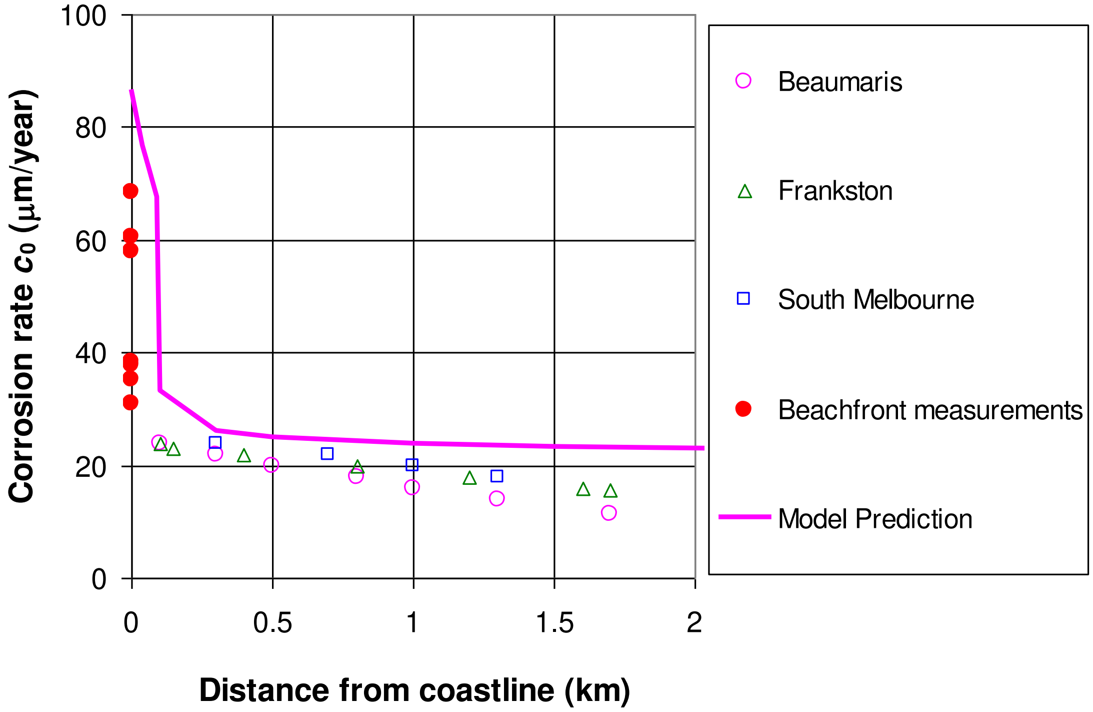


Figure 3.2.1 *Predicted corrosion rates of steel (Table 3.2.4) versus measured rates for Melbourne suburbs (Table 3.2.1) and beachfront locations (Table 3.2.3)*

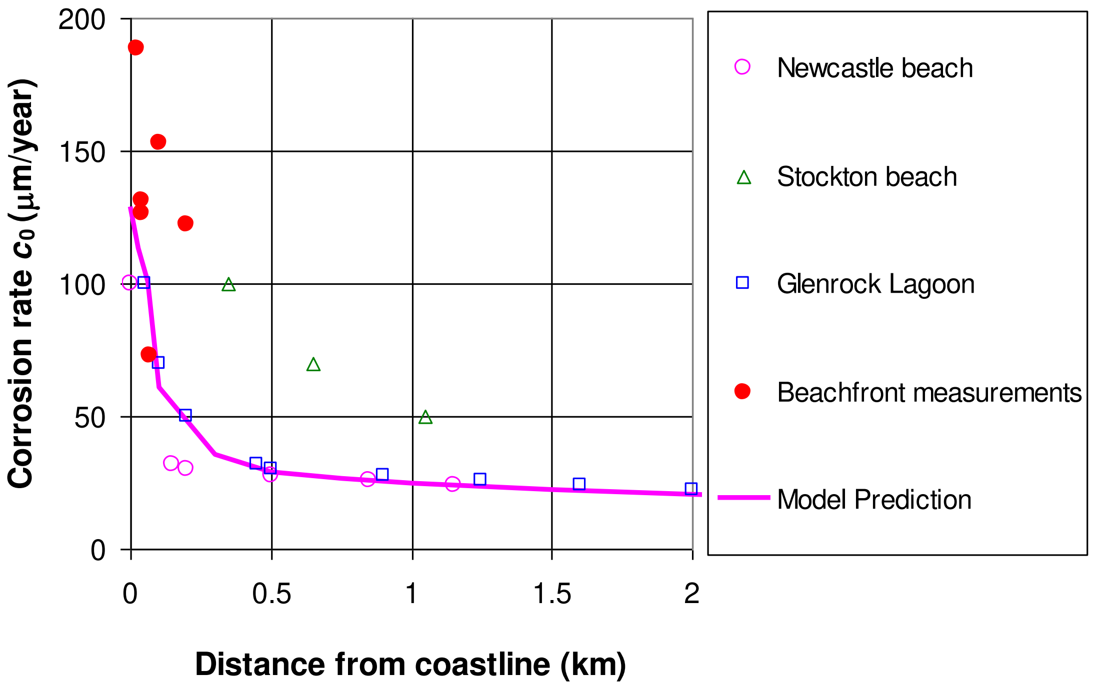


Figure 3.2.2 *Predicted corrosion rates of steel (Table 3.2.5) versus measured corrosion rates for Newcastle suburbs (Table 3.2.2) and beachfront locations (Table 3.2.3)*

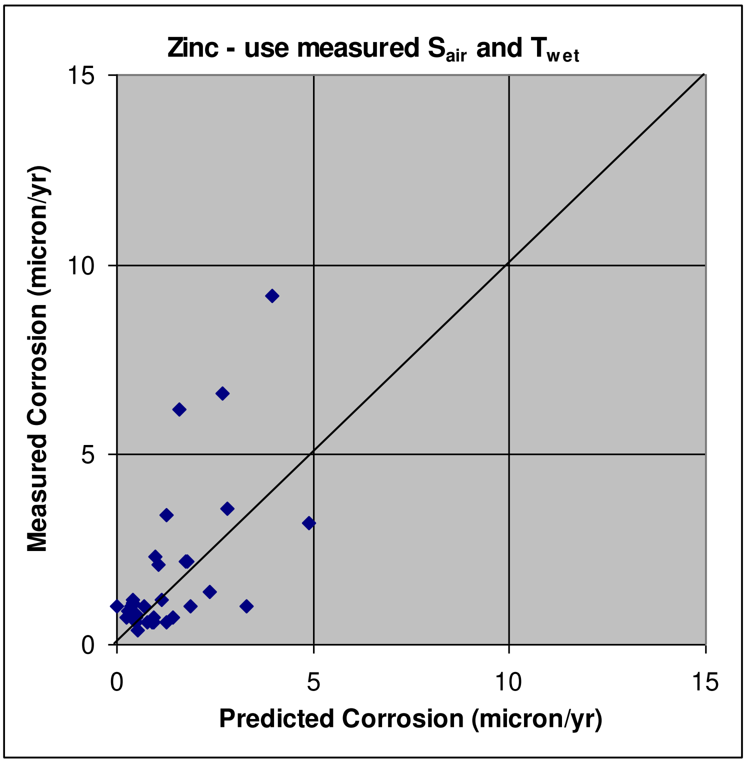
3.3 Checks with CSIRO Coupon Tests Data

Ganther (2002) provided a set of CSIRO Coupon test data. Description of the set-up of the test was reported in King et.al. (1999). Beside the corrosion rate and characteristic of the sites, measured S_{air} and t_{wet} of the test sites were also given in this data set.
Figure 3.3.1 presents the comparison of measured corrosion rates with the model predicted corrosion rates, which are computed using the measured S_{air} and t_{wet} of the sites.

Figure 3.3.2 also presents the comparison of measured corrosion rates with the model predicted corrosion rates, which are computed using the predicted S_{air} and t_{wet} from the given characteristics of the sites.

Table 3.3.1 lists the data and the model predictions for the 2 comparisons:

- Column 1~10 are measured data from Ganther (2002).
- Column 11 and 12 are predicted corrosion rates of zinc and steel, respectively, from measured S_{air} and t_{wet} given in columns 6 and 8, respectively. The prediction models are given in Sections 1.2 and 1.3.
- Column 13 and 14 are predicted S_{air} and t_{wet} by the models in Sections 1.6 and 1.8.
- Column 15 and 16 are predicted corrosion rates of zinc and steel, respectively, from the predicted S_{air} and t_{wet}. The prediction models are given in Sections 1.2 and 1.3.



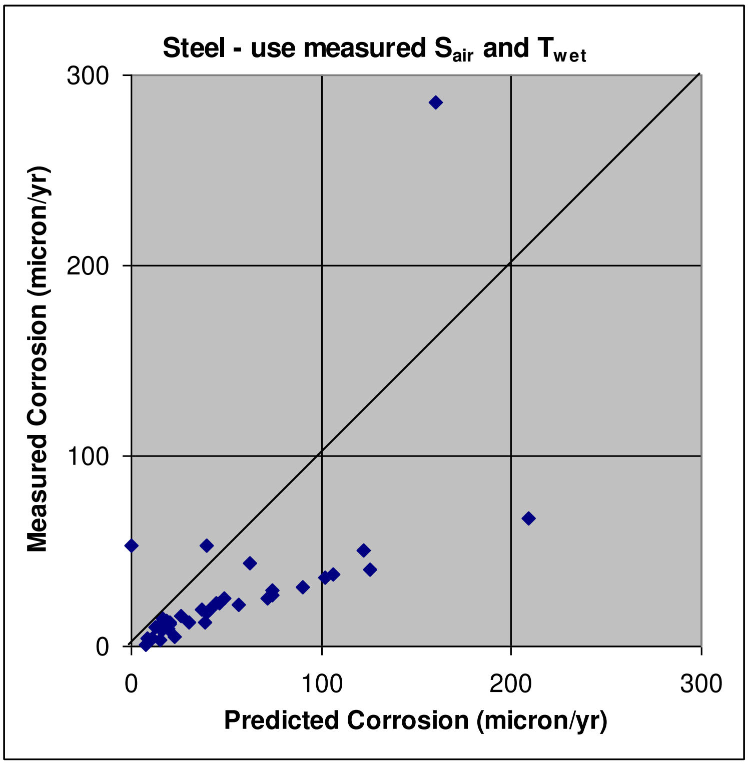


Figure 3.3.1 *Check with CSIRO coupon test data. The prediction used the measured salinity and time of wetness at the site. Data is presented in Table 3.3.1. The prediction models are given in Sections 1.2 and 1.3.*

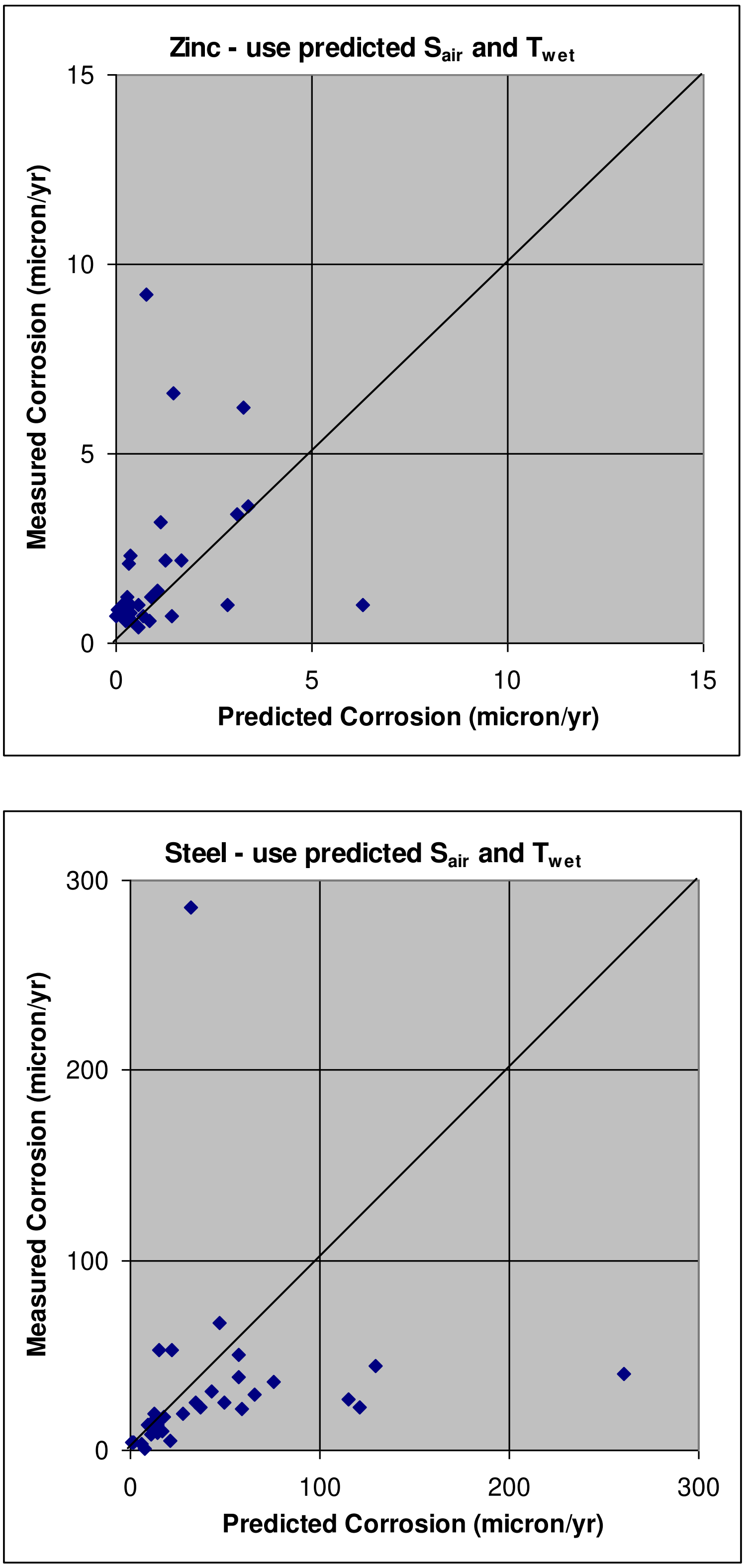


Figure 3.3.2 *Check with CSIRO coupon test data. The prediction used the predicted salinity and time of wetness at the site. Data is presented in Table 3.3.1. The prediction models are given in Sections 1.2 and 1.3.*

										Use measured S_{air} & T_{wet}				Use predicted S_{air} & T_{wet}	
Site Name	Coastal zone	Coastal Exposure	Site Exposure	Distance to Coast (km)	Salinity (mg/m2-day)	Rain days (days/yr)	tw (%)	Zinc corrosion (μm/yr)	Steel corrosion (μm/yr)	Predicted zinc corrosion (μm/yr)	Predicted steel corrosion (μm/yr)	Predicted S_{air}	Predicted T_{wet}	Predicted zinc corrosion (μm/yr)	Predicted steel corrosion (μm/yr)
Walkamin	C	Inland	Inland	44.42		147.5	37.117	0.4	8.3			2.5	32.5		
Butchers Creek	C	Open surf	Inland	33.75	22	165	34.551	2.3	53	1.0	39.9	3.1	36.3	0.4	15.5
Tolga	C	Open surf	Inland	46.16	3	152.1	35.953			0.4	15.2	2.4	33.5	0.3	12.8
Cowley Beach	C	Open surf	Open to sea	5	370	182	33.7	9.2	286	4.0	160.4	11.1	40.0	0.8	31.8
Darwin	C	Partially sheltered bay	Open to sea	7	6	114	38.1	0.4	5	0.5	22.5	10.4	25.1	0.6	21.3
Low Island	C	Partially sheltered bay	Open to sea	0.05	391	153.5	45.34	3.2	67	4.9	209.0	31.2	33.8	1.2	46.7
Townsville	C	Partially sheltered bay	Open to sea	1.12		104.4	33.311	1	53	0.0	0.0	12.7	23.0	0.6	21.9
Edmonton	C	Partially sheltered bay	Urban	11.25	5	153	42.5			0.5	22.4	2.4	33.7	0.3	12.9
Kewarra	C	Partially sheltered bay	Urban	0.91	3	153	42.5			0.4	17.4	3.2	33.7	0.4	15.0
Richmond	D	Inland	Inland	37.4	13.3	129.1	33.993	0.6	13	0.8	30.6	2.8	28.4	0.3	12.3
Wentworth Falls	D	Inland	Inland	63.29	5.2	212	34.5	0.8	9	0.5	19.4	1.7	46.6	0.3	14.1
Canberra AP *	D	Inland	Inland	99.21	3	114	35.2	1	3.4	0.4	15.0	0.8	25.1	0.2	6.0
Nerriga	D	Inland	Inland	40.72	5	120.1	27.504	1.2	8.5	0.4	15.8	2.7	26.4	0.3	11.2
Harbord	D	Open surf	City Center	0.63	4.1	137.1	33.055	0.8	13.7	0.4	16.6	3.5	30.2	0.4	14.4
Coledale	D	Open surf	Open to sea	0.02	71	133.8	19.916	3.4	22.4	1.3	46.1	262.5	29.4	3.1	121.2
Little Bay	D	Open surf	Open to sea	0.2	72.3	138	35.4	2.2	29	1.8	73.7	73.1	30.4	1.7	65.6
Narrabeen	D	Open surf	Open to sea	0.24	210	130.4	34.236		50.4	3.0	122.4	60.0	28.7	1.5	56.8
Prince Henry Hospital	D	Open surf	Open to sea	0.35	69	138	35.4	2.2	25	1.8	72.0	41.2	30.4	1.2	49.2
Sunshine1	D	Open surf	Open to sea	0.05	112	128.5	25.452			1.8	70.5	204.3	28.3	2.7	103.6
Wittig	D	Open surf	Open to sea	0.01	72	137.5	28.754	6.2	44	1.6	62.3	286.0	30.3	3.3	129.3
Illawong	D	Open surf	Urban	8.06	6.5	145.4	31.463	0.6	11.6	0.5	20.1	2.6	32.0	0.3	12.8
Johnson	D	Open surf	Urban	5.35	6	127	24.925	1.1	15.3	0.4	16.0	2.7	27.9	0.3	11.9
Wurtulla	D	Open surf	Urban	0.11	41	128.5	25.746			1.1	43.0	32.2	28.3	1.1	41.1
Albatross	D	Very open bay	Inland	15.5	18	124.2	22.627	1	16	0.7	25.7	4.4	27.3	0.4	14.8
Rooney	D	Very open bay	Open to sea	0.1	208	137.5	28.752	6.6	38.2	2.7	105.9	56.2	30.3	1.5	57.4
Bolton	D	Very open bay	Urban	4.81	32	137.5	28.79	2.1	19.6	1.1	41.6	2.7	30.3	0.3	12.7
Culburra	D	Very open bay	Urban	1.8	31	137.5	28.746			1.0	40.9	3.3	30.3	0.4	14.0
Hyde Park Barracks	D	Very sheltered bay	City Center	1.2	5	138	33.8	0.7	13.5	0.5	18.7	1.5	30.4	0.2	9.5
Sydney CBD	D	Very sheltered bay	City Center	6	5.8	138	33.8	0.7	13	0.5	20.1	1.3	30.4	0.2	8.8
Campbelltown	D	Very sheltered bay	Inland	20.37	3	158.7	27.903		9.8	0.3	12.4	4.0	34.9	0.4	17.1
Wollongong	D	Very sheltered bay	Urban	1.29	9	132	14.3			0.4	12.6	3.0	29.0	0.3	12.9
Mt Buller	E	Inland	Inland	144.03	2	126.4	19.379		0.8	0.2	7.6	1.1	27.8	0.2	7.6
Narrandera AP *	E	Inland	Inland	351.04	4	85	13.6	0.7	4.4	0.2	8.1	0.0	18.7	0.0	0.7
Wagga	E	Inland	Inland	253.75	3	90	23.241	0.9	3.8	0.3	10.7	0.1	19.8	0.1	1.9
Cameron Prop	E	Open surf	Inland	133.86	14	153.8	43.673	0.6	12.2	0.9	38.4	1.4	33.8	0.2	9.8
Hayes Prop	E	Open surf	Inland	8.31	41	168.6	27.151	1.2	23	1.2	44.9	16.9	37.1	0.9	37.1
Naracoorte AP	E	Open surf	Inland	79.92	18	159	38.8	0.6	18	1.0	39.6	4.0	35.0	0.4	17.3
Oliver Prop	E	Open surf	Inland	13.92	44	166.6	28.798	0.6	25	1.2	48.8	15.1	36.7	0.8	34.7
Sherwin Prop	E	Open surf	Inland	35.18	22	165.2	31.868	0.7	19.5	0.9	37.4	9.9	36.3	0.7	27.9
Aram Cove	E	Open surf	Open to sea	0.03	358	173.3	25.42	1	40	3.3	125.9	803.8	38.1	6.3	260.9
Cape Jaffa	E	Open surf	Otherwise	2.69	178	169.6	25.892	1.4	31	2.3	90.1	22.3	37.3	1.0	42.8
Chant	E	Open surf	Otherwise	0.65	178	170.5	25.599			2.3	89.3	46.5	37.5	1.5	62.0
Geelong	E	Open surf	Otherwise	0.94	4	208.7	46.921			0.5	21.7	39.2	45.9	1.6	66.9
Navy Base	E	Open surf	Otherwise	0.1	120	173.5	48.987	3.6		2.8	123.2	230.7	38.2	3.4	139.9
Kingston AS	E	Very open bay	Open to sea	1.6	58	160.6	29.282	0.7	22	1.4	56.7	45.8	35.3	1.4	58.6
Kingston LH	E	Very open bay	Open to sea	0.11	101	161.6	28.819	1	27	1.9	73.9	176.1	35.6	2.8	115.5
Kingston Pier	E	Very open bay	Open to sea	0.33	191	161	28.971		36	2.6	102.1	76.5	35.4	1.9	75.9
Highett	E	Very sheltered bay	City Center	2.85	5	146.7	41.071			0.5	21.8	4.8	32.3	0.4	17.6
Nick (Moorabbin)	E	Very sheltered bay	City Center	0.27	3	146.5	41.389			0.4	17.0	5.8	32.2	0.5	19.4
Endeavour Hills	E	Very sheltered bay	Inland	15.43		150	28					14.7	33.0		
Mornington2	E	Very sheltered bay	Open to sea	0.06		151.1	30.062					69.4	33.2		
Inlaws (Beaumaris)	E	Very sheltered bay	Urban	1.06		146.7	41.45					10.2	32.3		
Mornington1	E	Very sheltered bay	Urban	0.04		151.1	30.062					18.7	33.2		

Table 3.3.1 *Check with CSIRO Coupon Test Data*

- Column 1~10 are measured data from Ganther (2002).
- Column 11 and 12 are predicted corrosion rates of zinc and steel, respectively, from measured S_{air} and t_{wet}. The prediction models are given in Sections 1.2 and 1.3.
- Column 13 and 14 are predicted S_{air} and t_{wet} by the models in Sections 1.6 and 1.8.
- Column 15 and 16 are predicted corrosion rates of zinc and steel, respectively, from the predicted S_{air} and t_{wet}. The prediction models are given in Sections 1.2 and 1.3.

3.4 Estimation of constant A_z for zinc corrosion equation

For steel,

$$c_{0,\text{steel}} = A_{steel}\, t_{\text{wet}}^{0.8} S_{\text{air}}^{0.5} \tag{3.4.1}$$

For zinc,

$$c_{0,\text{zinc}} = A_{zinc}\, t_{\text{wet}}^{0.6} S_{\text{air}}^{0.5} \tag{3.4.2}$$

Then

$$\frac{A_{steel}}{A_{zinc}} = \frac{c_{0,\text{steel}}}{c_{0,\text{zinc}}} t_{\text{wet}}^{-0.2} \tag{3.4.3}$$

Data provided in Guttman & Sereda (1968) paper can be used to estimate this ratio. For an estimate of $t_{\text{wet}}^{-0.2}$, consider Kure Beach 80ft test site, which was least affected by SO_x pollution, as indicated in Table 5 of the paper. Monthly T_{wet} for this site was given in Table 7 of the paper, varied from 23.6 to 21.7 days, taking average of 22.5. Then roughly yearly t_{wet} is

$$t_{\text{wet}} = \frac{22.5}{30} = 0.75 \tag{3.4.4}$$

And then

$$t_{\text{wet}}^{-0.2} = 1.06 \tag{3.4.5}$$

For the ratio between $c_{0,\text{steel}}$ and $c_{0,\text{zinc}}$,using data for the site in Table 4 of the paper, we have

$$Max\left(\frac{c_{0,\text{steel}}}{c_{0,\text{zinc}}}\right) = \frac{5.525}{0.266} = 18.8$$

$$Min\left(\frac{c_{0,\text{steel}}}{c_{0,\text{zinc}}}\right) = \frac{3.346}{0.178} = 20.7$$

Then

$$Max\left(\frac{A_{steel}}{A_{zinc}}\right) = Max\left(\frac{c_{0,\text{steel}}}{c_{0,\text{zinc}}}\right) t_{\text{wet}}^{-0.2} = 20.7 \times 1.06 = 22.0$$

$$Min\left(\frac{A_{steel}}{A_{zinc}}\right) = Min\left(\frac{c_{0,\text{steel}}}{c_{0,\text{zinc}}}\right) t_{\text{wet}}^{-0.2} = 18.8 \times 1.06 = 19.9$$

We take the ratio of 20, given A_{steel}=0.5, then A_{zinc}=0.025

Furthermore, due to the fact that $t_{\text{wet}}^{-0.2}$ is very close to 1 for most cases, we can neglect this factor, and assume approximaltely

$$\frac{A_{steel}}{A_{zinc}} \approx \frac{c_{0,\mathrm{steel}}}{c_{0,\mathrm{zinc}}}$$

Then we can estimate this ratio without having to know t_{wet}. Using data from Guttman and Sereda (1968), coupon test programs (King et.al., 1999, Ganther, 2002), and tropical atmospheric corrosion data (Cole, 2000), it is found that the ratio, while varying significantly within each set of data, has an average of about 20 for each set. For example, data from Tables 4 and 8 of Guttman and Sereda (1968) gives an average of 18; data from the coupon test programs (King et.al., 1999, Ganther, 2002) gives an average of 19; and the tropical atmospheric corrosion data (Cole, 2000) gives an average of 24. For the model developed herein, we take the ratio equal to 20. Given the constant A_s for steel of 0.5, then the constant A_z for zinc is 0.025.

3.5 Fittings with 5 most Polluted Sites from 'Tropical' Data

Data of the five most polluted sites, ie. site having the highest value of P_{air}, are selected from the 'Tropical' data (Cole 2000). The full set of the data is in Appendix A. The data of the 5 selected sites are listed in Table 3.5.1. The fitting of the model prediction with the data are plotted in Figure 3.5.1, resulting in the 2nd term of Eqs. (2.1.5) and (2.1.6), ie.

For steel: $$c_{0,s} = 0.1 t_{wet}^{0.5} P_{air} + 0.5 t_{wet}^{0.8} S_{air}^{0.5} \quad (3.5.1)$$

For zinc: $$c_{0,z} = 0.006 t_{wet}^{0.2} P_{air} + 0.025\, t_{\mathrm{wet}}^{0.6} S_{\mathrm{air}}^{0.5} \quad (3.5.2)$$

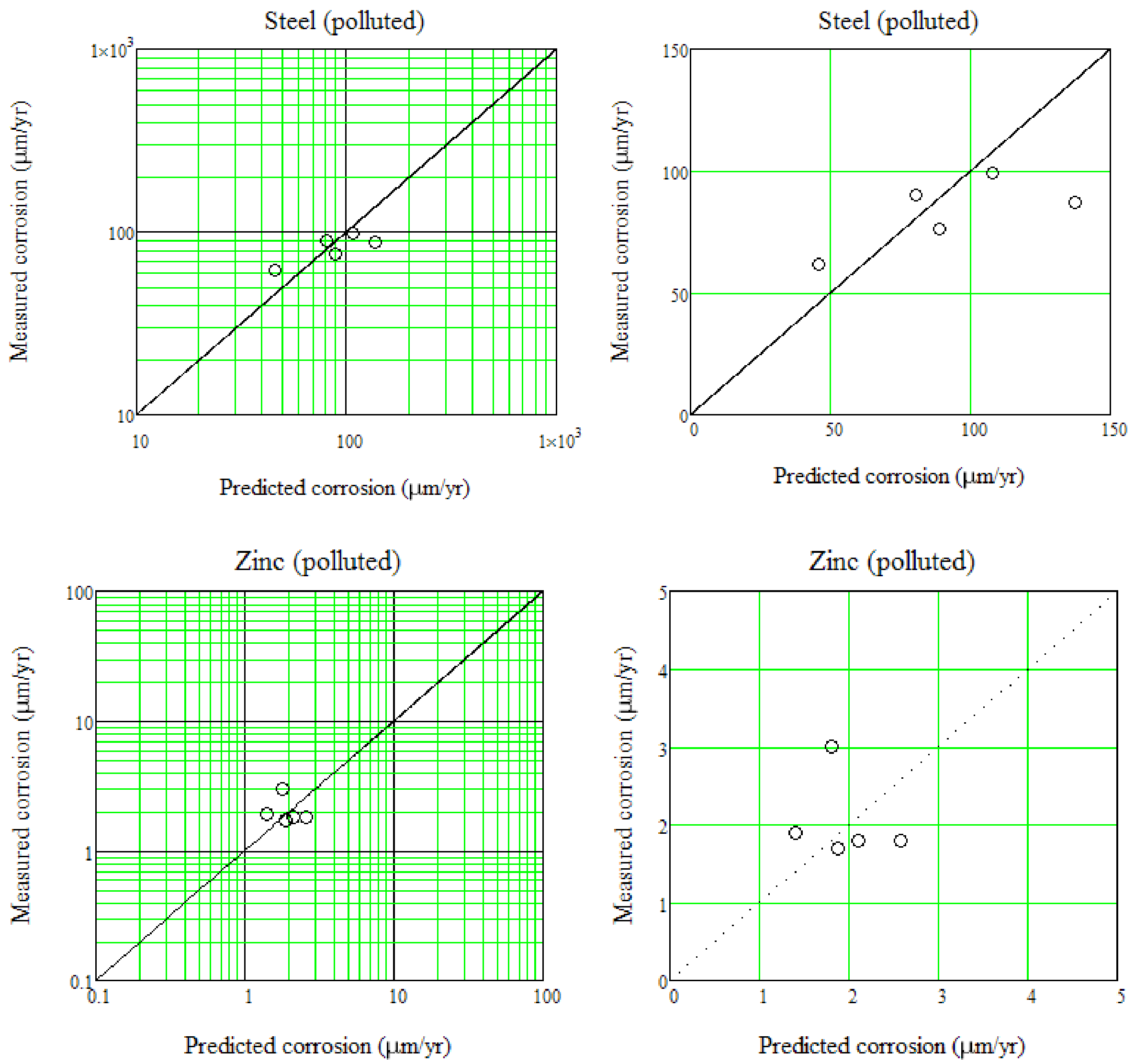


Figure 3.5.1 *Fittings with 5 most Polluted Sites from 'Tropical' Data. Data is in Table 3.5.1.*

Table 3.5.1 *Data of the 5 selected sites having the highest value of P_{air}. Columns 1~7 are measured data given in Cole (2000).Columns 8 and 9 are predicted corrosion rate of steel and zinc, respectively by Eqs.(3.5.1) and (3.5.2), which are also the model prediction in Sections 1.2 and 1.3.*

Location	Steel corrosion (micon/yr)	Zinc corrosion (micon/yr)	Twet (%)	Arain pH	Sair (mg/m2/day)	Pair (microgram/m3)	Predicted C0,steel, polluted	Predicted C0,zinc, polluted
	90	3	57	6.3	7.4	61	88.4	1.6
	99	1.8	89	5.9	6.1	67	118.6	1.7
Mentok	61.6	1.9	15	5.4	20	67.9	112.0	2.5
	76	1.7	59	5.9	6.7	72	120.2	1.7
Phrapradaeng	87	1.8	62	5.7	16.1	105	193.8	2.4

3.6 Checks of Model Prediction with the 'Tropical' Data

This section provides a check of Eqs. (2.1.5) and (2.1.6) with the full set of the 'Tropical' data (Cole, 2000). Note that the equations was developed by fitting to only 5 data points that were most polluted by SO_x, as presented in Section 3.5. The checks are presented in Figures 3.6.1 and 3.6.2. The data is in Table 3.6.1. Columns 1~7 are measured data given in Cole (2000).Columns 8 and 9 are predicted corrosion rate of steel and zinc, respectively by the model equations in Sections 1.2 and 1.3.

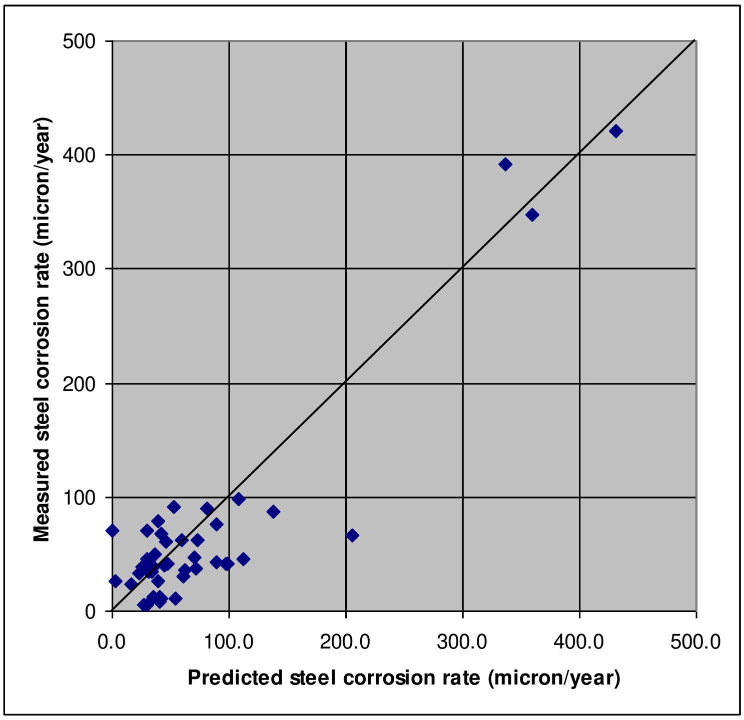


Figure 3.6.1 *Comparison of measured steel corrosion rate given in 'Tropical' data and Model prediction. Data is in Table 3.6.1. The prediction models are given in Section 1.3.*

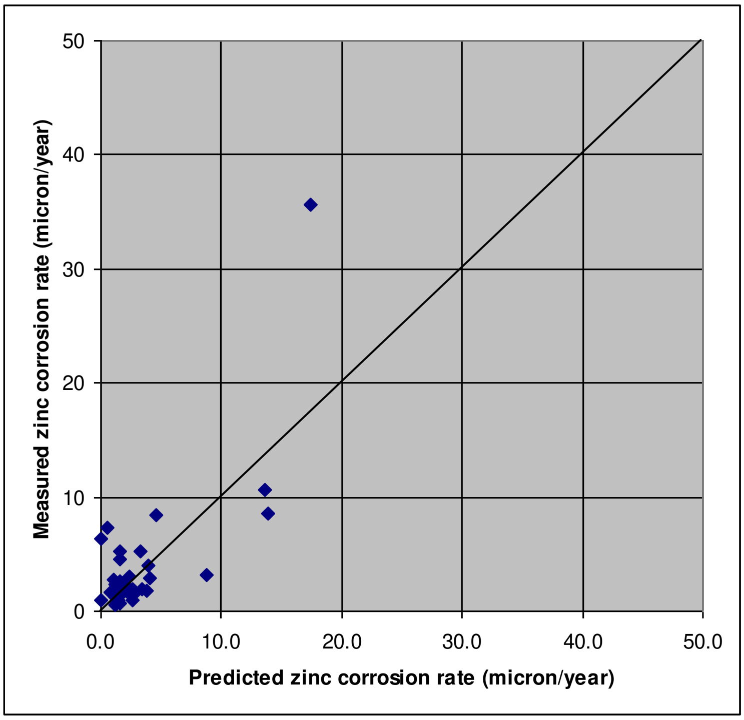


Figure 3.6.2 *Comparison of measured zinc corrosion rate given in 'Tropical' data and Model prediction. Data is in Table 3.6.1. The prediction models are given in Section 1.2.*

Table 3.6.1 *Checks with tropical data. Columns 1~7 are measured data given in Cole (2000).Columns 8 and 9 are predicted corrosion rate of steel and zinc, respectively by the model equations in Sections 1.2 and 1.3.*

Location	Steel (micon/yr)	Zinc (micon/yr)	Twet (%)	Arain pH	Sair (mmg/m2/day)	Pair (microgram/m3)	Predicted C0,steel, polluted	Predicted C0,zinc, polluted
Baguio	13	1.4	80	5	4	2.2	35.3	1.4
	11.8	2.6	92	5.4	4	2.9	40.0	1.6
	8.5	5.2	100	5	4	1.4	41.2	1.6
	11	2.5	100	4.9	4	1.8	41.6	1.6
Bicutan	41.5	2.1	34	4.1	10	10.3	32.6	1.4
	26.4	0.7	40	4.4	10	14	39.1	1.6
	92.1	1.7	41	4.4	10	34	52.6	1.9
	67.8	2.3	41	4.1	10	16.7	41.5	1.7
Cabuyao	35.7	1.7	83	4.6	10	8.9	62.3	2.4
	33.6	1.2	24	4	10	5.8	22.9	1.1
	62.4	2.9	63	5.1	10	20.9	60.1	2.2
	62.6	2	91	4.9	10	15.4	73.1	2.6
Phrapradae	87	1.8	62	5.7	16.1	105	137.2	3.8
	90	3	57	6.3	7.4	61	80.6	2.4
	50	2	34	5.9	4	33.9	36.6	1.2
	76	1.7	59	5.9	6.7	72	89.1	2.5
	99	1.8	89	5.9	6.1	67	108.0	2.8
Rayong	38	5.2	51	6.4	36.6	2.4	72.0	3.2
	42	4	74	6.3	33.2	8.9	97.8	3.9
	41	1.7	55	5.9	3.9	30.7	47.1	1.5
	47	1	72	5.9	12.7	18.1	69.9	2.6
	46	8.4	82	5.9	42	3	112.8	4.6
Phuket	30	1.7	43	5.7	34.1	3.2	61.3	2.8
	66	3.2	70	5.9	184.1	2.7	205.3	8.7
	41	2.9	64	5.8	43.7	8	98.5	4.1
	27	0.9	56	6.5		3	2.2	0.0
	71	7.3	86	6.4		32	29.7	0.5
Bangkok	39	0.9	22	6.3	12.3	31	35.3	1.5
	39	2.8	32	6	4	18	26.2	1.0
	24	1.6	16	5.6	6	13.2	16.5	0.8
	35	0.6	35	5.2	4.4	21.2	30.6	1.1
	46	1.7	28	5.6	8	17.8	29.8	1.3
Saigon	35	0.8	39	6.7	7	14	33.5	1.4
	40	1.8	39	6.6	4	15	28.1	1.1
		1.2	44	6	4	20	33.9	1.2
Cowley Bea	348	8.5	91	6.5	317	33	360.1	13.8
	392	10.6	92	5	326		336.2	13.6
	421	35.6	94	5.5	516	0.7	431.0	17.4
	71	6.3			48	1.1	0.0	0.0
Walkamin	6.2	0.7	66	4.9	4	1	29.4	1.2
	11	1.7	77	3.9	11	1	54.4	2.3
		2.5	67	4.9	9	0.6	43.8	1.9
Lembang	6.2	2.4	39	5.1	7	3.9	27.2	1.2
Cikampek	43.4	2	70	5.1	25	17.2	89.2	3.4
Gresik	78.4	4.6	30	4.8	10	28.8	39.8	1.6
Jebus	39.5	1.9	24	7.1	47	1.8	44.5	2.3
Mentok	61.6	1.9	15	5.4	20	67.9	45.8	1.8

4. Score System

4.1 Derivation of Score System Equations for Atmospheric Corrosion of Fasteners

Steel fasteners used for timber construction are often galvanised by zinc coating, both zinc and steel are involved in consideration of corrosion. An ideal score system for corrosion hazard estimation shall be applicable to both zinc and steel. The corrosion models for steel and zinc used in this project have similar mathematical formulation and functional dependence, it is therefore possible to have one score system applicable to both steel and zinc corrosion.

It is noted that in this report, 'pollution' or 'polluted' means effects relating to airborne SO_x agents (air pollution) on corrosion, whereas 'un-polluted' means effects relating to airborne salinity only.

Development of the score system is initiated by considering the prediction model for unpolluted steel corrosion, i.e.

$$\begin{aligned} c_{0,\mathrm{s,unpoll}} &= 0.5 S_{air}^{0.5} t_{wet}^{0.8} \\ &= 0.5 \alpha_{exp}^{0.5} \alpha_{micro}^{0.5} \alpha_{ocean}^{0.5} \left[25 \beta_{coast} \left(0.9 e^{-10 L_{coast}} + 0.1 e^{-L_{coast}} \right) + e^{-0.02 L_{coast}} \right]^{0.5} \left(0.22 D_{rain} \right)^{0.8} \end{aligned} \quad (4.1.1)$$

If $L_{coast} = 0$ is considered, then

$$c_0 = 0.5 \alpha_{exp}^{0.5} \alpha_{micro}^{0.5} \alpha_{ocean}^{0.5} \left[25 \beta_{coast} + 1 \right]^{0.5} \left(0.22 D_{rain} \right)^{0.8} \quad (4.1.2)$$

Taking logarithm of the expressions on both sides of Eq. (4.1.2) leads to

$$\ln c_0 = 0.5 \left[\ln \alpha_{exp} + \ln \alpha_{micro} + \ln \left(25 \beta_{coast} + 1 \right) + \ln \alpha_{ocean} \right] + 0.8 \ln \left(0.22 D_{rain} \right) + \ln 0.5 \quad (4.1.3)$$

Let S_{zone}, S_{coast}, S_{exp}, and S_{micro} be the scores considering coastal zone, coastal exposure, site classification, and microclimate conditions, respectively, and defined as

$$\begin{aligned} S_{zone} &= 0.5 \ln \alpha_{ocean} + 0.8 \ln \left(0.22 D_{rain} \right) \\ S_{coast} &= 0.5 \ln \left(25 \beta_{coast} + 1 \right) \\ S_{exp} &= 0.5 \ln \alpha_{exp} \\ S_{micro} &= 0.5 \ln \alpha_{micro} \end{aligned} \quad (4.1.4)$$

In Eq. (4.1.4), the values of α_{coast}, β_{coast}, α_{exp}, and α_{micro}, are from Tables 1.6.1 to Tables 1.6.4, respectively. Some scores computed directly from Eq. (4.1.4) have negative values, the minimum of which equals –0.693 which occurs when $\alpha_{exp} = 0.25$, a site exposure factor value used when it is located in an urban (e.g. city centre) area. To avoid negative scores, each raw score computed by Eq. (4.1.4) is increased by 0.693. It is then rounded to the multiple of 0.1. This gives values of S_{zone}, S_{coast}, S_{exp}, and S_{micro} in Tables 4.2.1 to 4.2.4, respectively. The computed total scores compared to the computed corrosion rates for all possible scenarios are shown in Figure 4.1.1, in which the ranges of application for the four hazard ratings; i.e. HR1, HR2, HR3, and HR4 are shown as well. Definitions of the four hazard ratings are in Table 6.2.7.

The development of hazard scores for steel and zinc subject to pollution is done by considering the corrosion model for polluted steel:

$$c_{0,s,poll} = 0.1 t_{wet}^{0.5} P_{air} + 0.5 S_{air}^{0.5} t_{wet}^{0.8} \tag{4.1.5}$$

The pollution hazard scores are determined such that the predicted corrosion (representative corrosion rate) based on the score is comparable to the corrosion given by Eq. (4.1.5). The comparison between the representative corrosion rate and that given by Eq. (4.1.5) is shown in Figure 4.1.2. The hazard score for pollution is in Table 4.2.5.

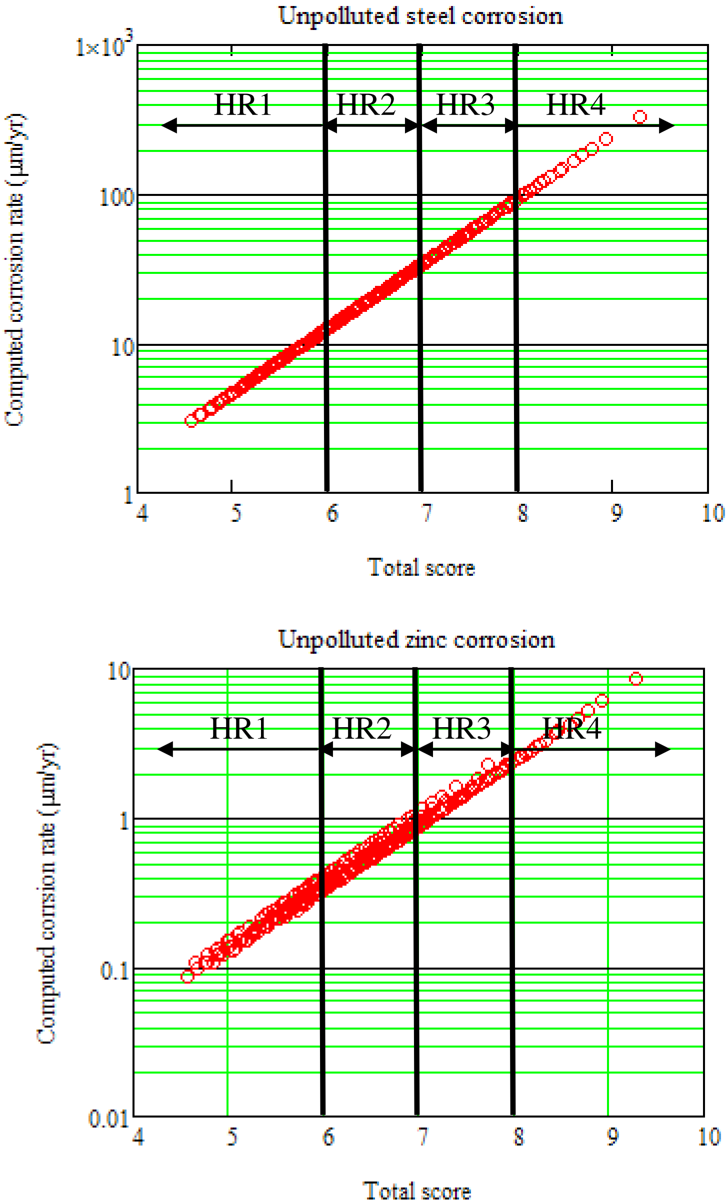


Figure [illegible]: Computed unpolluted corrosion versus total score

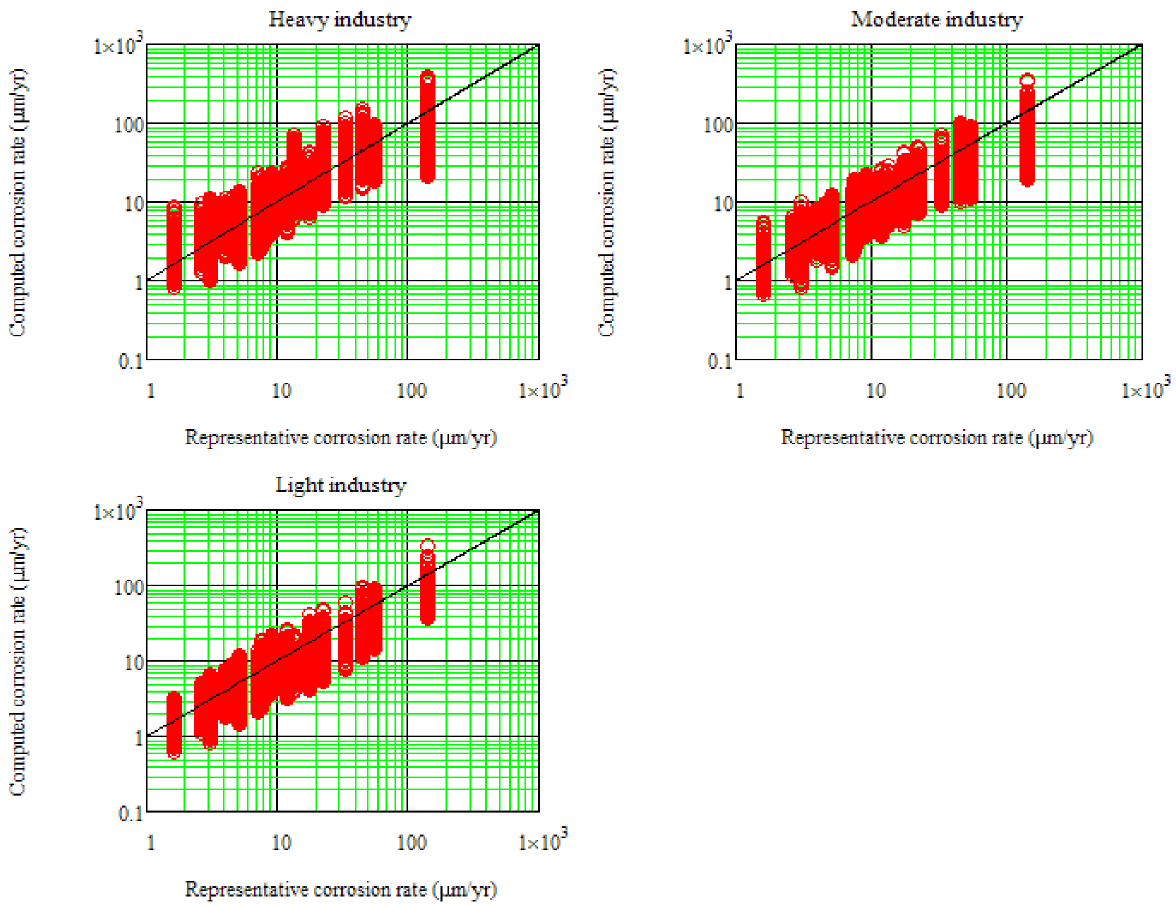


Figure 4.1.2. *Comparison of the representative polluted steel corrosion determined by scores with the corrosion predicted by model*

4.2 Score System for Atmospheric Corrosion of Fasteners

The purpose of the score system is to enable a fast assessment of the hazard of atmospheric corrosion to metal fasteners exposed to air. To assess the hazard, first find the individual score for each of the five parameters, namely, (1) coastal zone where the site is located, (2) coastal exposure, (3) site classification, (4) microclimate condition, and (5) corrosive pollution agents, from Tables 6.2.1 to 6.2.5, listed below. Then add up the scores found from Tables 6.2.1 to 6.2.5, as shown in Table 6.2.6, to obtain a total score. From Table 6.2.7, find the range in which the total score falls in, and determine the hazard rating of the environment which the fasteners of concern is in. The average basic corrosion depths for zinc and steel, $c_{0,z}$ and $c_{0,s}$, for the corrosion of embedded parts of fasteners that are in a tight contact with wood, e.g. nails, screws, staples, assigned for each hazard rating are listed in Table 6.2.8 and Table 6.2.9, respectively. The average basic corrosion depths for zinc and steel, $c_{0,z}$ and $c_{0,s}$, for the corrosion of bolt shanks, assigned for each hazard rating are listed in Tables 6.2.10 and 6.2.11.

The estimates of mean corrosion depth then can be computed using Eq.(1.2.1) for zinc or Eq.(1.3.1) for steel.

Table 4.2.1 *Hazard score for coastal zone*

Hazard zone	**Hazard score**
A	3.2
B	3.3
C	3.5
D	4.3
E	4.9

Table 4.2.2 *Hazard score for coastal exposure*

Coastal exposure(1)	**Hazard score**
Sheltered bay	1.1
Partially closed bay	1.3
Very open bay	1.8
Open surf	2.3

Table 4.2.3 *Hazard score for site classification*

Site classification	**Hazard score**
Open to sea	1.0
Urban (suburb)	0.3
Urban (city centre)	0.0
Other site	0.7

Table 4.2.4 *Hazard score for microclimate*

Microclimate(1)		**Hazard score**
Wall cavity(2)		0.3
Roof space(2)		0.2
Sub-floor(2)		0.4
Outdoor	Sheltered from rain	1.0
	Exposed to rain	0.7

Table 4.2.5 *Hazard score for pollution*

Industry type	**Hazard score**(1)			
	$L = 1$	$L = 5$	$L = 10$	$L \geq 20$
Heavy industry (steel works, petrochemical)	3	1	0.5	0.0
Moderate industry (paper mills, large manufacturing)	1	0.5	0	0
Light industry (assembly plants)	0.5	0	0	0
No industry	0.0	0.0	0.0	0.0

(1) L is the distance to the industry (km).

Table 4.2.6 *The total hazard score*

Item	**Hazard score**
Coastal zone (Table 6.1)	
Coastal exposure (Table 6.2)	
Site classification (Table 6.3)	
Microclimate (Table 6.4)	
Pollution (Table 6.5)	
Total hazard score	

Table 4.2.7 *Definition of hazard rating*

Total hazard Score (Table 6.6).	**Hazard rating**
<6	HR1
≤6<7	HR2
≤7<8	HR3
≥8	HR4

Table 4.2.8 *Basic corrosion depth of steel (μm) used for service life computation in Design Guide for fasteners other than bolt shank*

Hazard rating	Distance to the Coast			
	0 km	1 km	10 km	50 km
HR1	12.9	8.9	8.0	6.2
HR2	27.5	14.7	12.5	9.2
HR3	61.6	27.6	22.1	15.4
HR4	151.4	53.4	39.4	26.3

Table 4.2.9 *Basic corrosion depth of zinc (μm) used for service life computation in Design Guide for fasteners other than bolt shank*

Hazard rating	Distance to the Coast			
	0 km	1 km	10 km	50 km
HR1	0.4	0.3	0.2	0.2
HR2	0.8	0.4	0.3	0.3
HR3	1.6	0.7	0.6	0.4
HR4	3.8	1.3	1.0	0.7

Table 6.10 *Basic bolt corrosion depth of steel (μm) used for service life computation in Design Guide for Bolt shanks*

Hazard rating	Distance to the Coast			
	0 km	1 km	10 km	50 km
HR1	38.7	19.6	8.2	6.2
HR2	82.4	32.6	12.7	9.2
HR3	185	61.0	22.4	15.4
HR4	454	118	39.9	26.3

Table 6.11 *Basic bolt corrosion depth of zinc (μm) used for service life computation in Design Guide for Bolt shanks*

Hazard rating	Distance to the Coast			
	0 km	1 km	10 km	50 km
HR1	1.1	0.6	0.2	0.2
HR2	2.3	0.9	0.3	0.3
HR3	4.8	1.6	0.6	0.4
HR4	11.5	3.0	1.0	0.7

5. Equations for Draft Engineering Code and TimberLife

5.1 Scope and Application

This Section provides the calculation procedures for the design corrosion depths on exposed parts of metal fasteners, which can be used to estimate the corrosion depths for metal fasteners used in any timber construction located anywhere in Australia. Corrosion of bolts and of fasteners under corrugated roofing of an open space are considered as special cases and therefore treated separately in Sections 5.4 and 5.5, respectively.

5.2 Notations

c_0 : the first-year corrosion depth (μm)
c_b : corrosion depth near the neck of the bolt
c_{design} : design corrosion depth
D_{rain} : number of raindays (days)
L_{coast} : distance to coast (km)
L_{indus} : distance to the industry (km)
P_{air}: airborne pollution agent (μg/m^3)
S_{air} : airborne salinity (mg/m^2/day)
t : time (years)
t_{wet} : time of wetness (%)
V_c : coefficient of variation of corrosion depth
λ_b: enhancement factor for bolts
λ_r: enhancement factor for fasteners under corrugated roofing of an open space

5.3 Corrosion of Exposed Parts of Fasteners (Atmospheric Corrosion)

This Section provides the calculation procedures for the design corrosion depths on metal fasteners' parts that are exposed to air, as depicted in Figure 5.3.1.

The design corrosion depths is to be determined by

$$c_{design} = c\left(1+\alpha V_c\right) \tag{5.3.1}$$

where

- c is the mean depth of the loss in fastener cross-section due to atmospheric corrosion for a chosen design life time. To evaluate the mean corrosion depths, the coastal hazard zone and the coastal exposure condition of the structure location are determined from Sections 5.3.1 and 5.3.2, respectively. The airborne salinity and the airborne pollution are estimated from Sections 5.3.3 and 5.3.4, respectively. The time of wetness of the fastener surface is determined from Section 5.3.5. The mean corrosion depth is then estimated using the procedures in Section 5.3.6 for zinc, and Section 5.3.7 for steel.

- V_c is the coefficient of variation of c, and α is specified parameter related to the target reliability level. The values of these parameters are set in Section 5.3.8.

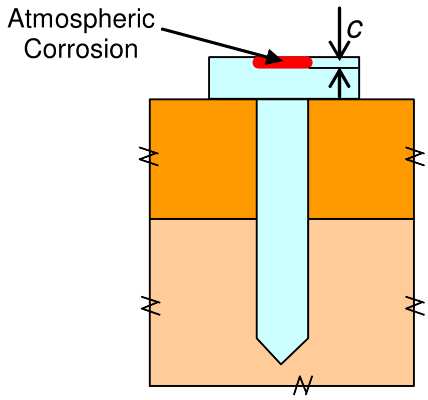


Figure 5.3.1 Atmospheric corrosion depth

5.3.1 Coastal hazard zones

Figure 5.3.1.1 *Coastal Hazard Zones. Zone E has the greatest hazard.*

Table 5.3.1.1 *Definition of hazard coastal zones and numbers of rain days*

Hazard Coastal zone	**Approximate coastline range**		**Representative D_{rain}** (No. of rain days / year)
	from (longitude, latitude)	to (longitude, latitude)	
A	(122°, -20°)	(129°, -15°)	70
B	(115°, -28°)	(122°, -20°)	40
C	(129°, -15°)	(149°, -23°)	100
D	(149°, -23°)	(150°, -36°)	130
E	(115°, -28°)	(150°, -36°)	130

5.3.2 Coastal exposure conditions

The coastal exposure condition is dependent on the opening angle, θ (degrees), and the radius, R (km), of the bay as shown in Figure 5.3.2.1. The exposure factor for an idealised bay, α_{bay}, is:

$$\alpha_{\text{bay}}^2 = \left(\frac{\theta}{85}\right)^2 + \left(\frac{R}{20}\right)^2 \qquad (5.3.2.1)$$

The coastal exposure condition is then defined as follows

For $\alpha_{bay} < 1$ Closed bay

For $1 < \alpha_{bay} < 1.5$ Partially closed bay

For $1.5 < \alpha_{bay} < 2.5$ Open bay

For $\alpha_{bay} > 2.5$ Open surf

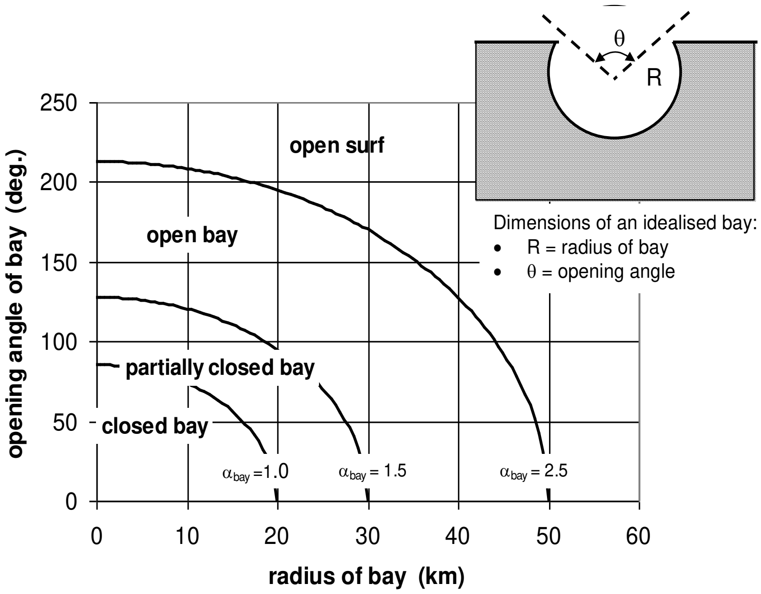


Figure 5.3.2.1. Definition of Coastal exposure condition

5.3.3 Airborne Salinity

Airborne salinity at a site, denoted by S_{air} (mg/m^2 per day), is estimated from the following equation,

$$S_{\text{air}} = \max \begin{cases} \alpha_{\text{exp}}\alpha_{\text{micro}}\left[\alpha_{\text{coast}}\beta_{\text{coast}}\left(0.9e^{-10L_{coast}} + 0.1e^{-L_{coast}}\right) + \alpha_{\text{ocean}}e^{-0.02L_{\text{coast}}}\right] \\ 1.0 \end{cases} \quad (5.3.3.1)$$

in which L_{coast} is the distance to the coast in kilometres; the parameters α_{coast} and α_{ocean} take into account the effect of coastal zonation (Table 5.3.3.1); β_{coast} the effect of coastal exposure (Table 5.3.3.2); α_{exp} the effect of site exposure (Table 5.3.3.3); and α_{micro} the effect of local shelter factors (Table 5.3.3.4).

Table 5.3.3.1 *Factors for the generation of airborne salt*

Hazard zone	Zone factors	
	α_{coast}	α_{ocean}
A, C	50	2
B, D	150	6
E	500	20

Table 5.3.3.2 *Factor related to coastal exposure*

Coastal exposure condition	β_{coast}
Closed bay	0.05
Partially closed bay	0.10
Open bay	0.35
Open surf	1.00

Table 5.3.3.3 *Factor for site classification*

Site classification	α_{exp}
Open to sea	2.00
Suburban	0.50
City centre	0.25
Other sites	1.00

Table 5.3.3.4 *Factor for local shelter (rain protection)*

Local Shelter	α_{micro}
Sheltered from rain	2.0
Exposed to rain	1.0

5.3.4 Airborne Pollution

An estimate of the pollution parameter, P_{air}, which is the airborne pollution of air in terms of level of airborne SO_x (μg/m^3), can be made by,

$$P_{\mathrm{air}} = \frac{\alpha_{\mathrm{indus}}}{L_{indus} + 1} \tag{5.3.4.1}$$

where L_{indus} (km) the distance to the nearest industrial complex; α_{indus} is defined in Table 5.3.4.1.

Table 5.3.4.1 *Industrial exposure factor*

Industry Type	Industrial exposure factor α_{indus}
Heavy industry (steel works, petrochemical)	110.0
Moderate industry (paper mills, large manufacturing)	22.0
Light industry (assembly plants)	5.5

5.3.5 Time of Wetness

The climate factor considered in the computation of corrosion depth is the time-of-wetness, t_{wet} (%), the percentage of time in a year when the relative humidity is above 80% and the temperature above 0°C. The factor t_{wet} is estimated by

$$t_{wet} = 0.22 D_{rain} \tag{5.3.5.1}$$

where D_{rain} is the number of rain days per year, D_{rain} (days/year), for which a rain day is defined as a day on which there is at least 0.2 mm of rain. D_{rain} is estimated by

$$D_{rain}\Big|_{L_{coast}} = 30 + \left(D_{rain}\Big|_{L_{coast}=0} - 30 \right) e^{-0.004 L_{coast}} \tag{5.3.5.2}$$

where L_{coast} is distance to the nearest coast (km); $D_{rain}\Big|_{L_{coast}=0}$ is the representative value of D_{rain} at the corresponding coast, listed in Table 5.3.3.1, depending on the hazard zones defined in Figure 5.3.3.1.

5.3.6 Corrosion of Zinc

The corrosion depth of zinc over time, c_z (μm), is determined by the following power-law equation,

$$c_z = c_{0,z} t^{0.6} \qquad (5.3.6.1)$$

where t (year) is the time in service; $c_{0,z}$ is the basic corrosion depth. For zinc, the basic corrosion depth, $c_{0,z}$, is estimated by

$$c_{0,z} = 0.025\, t_{\mathrm{wet}}^{0.6} S_{\mathrm{air}}^{0.5} + 0.006 t_{wet}^{0.2} P_{air} \qquad (5.3.6.2)$$

where t_{wet} is time of wetness, S_{air} (mg/m^2/day) is airborne salinity; P_{air} is airborne pollution of air in terms of level of airborne SO_x (μg/m^3)

5.3.7 Corrosion of Steel

The corrosion depth of steel over time, c_s (μm), is determined by the following power-law equation,

$$c_s = c_{0,s} t^{0.8} \qquad (5.3.7.1)$$

where t (year) is the time in service; $c_{0,\mathrm{s}}$ is the basic corrosion depth. The basic corrosion depth of steel, $c_{0,\mathrm{s}}$ is estimated by

$$c_{0,s} = 0.5 t_{wet}^{0.8} S_{air}^{0.5} + 0.1 t_{wet}^{0.5} P_{air} \qquad (5.3.7.2)$$

where t_{wet} is time of wetness, S_{air} (mg/m^2/day) is airborne salinity; P_{air} is airborne pollution of air in terms of level of airborne SO_x (μg/m^3)

5.3.8 Design Depth of Atmospheric Corrosion

The design depth of atmospheric corrosion, c_{design} will be given by

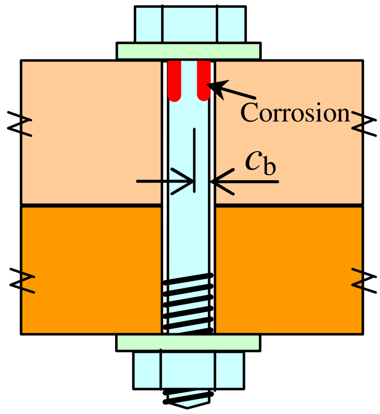
$$c_{design} = c\left(1 + \alpha V_c\right) \qquad (5.3.8.1)$$

where

- c is the mean depth of the loss in fastener cross-section due to atmospheric corrosion, computed by Eq(5.3.6.1) or Eq.(5.3.7.1) for a chosen design life time.
- V_c is the coefficient of variation of c. From available data, it is recommended that V_c = 1.5.
- α is specified parameter related to the target reliability level.
  - α = 0.8 for normal consequence of failure elements.
  - α = 0.4 for low consequence of failure elements.

From the design depth of atmospheric corrosion, the residual cross-section is estimated; from which engineers compute the acceptable design load capacity by normal AS1720.1 procedure.

5.4 Corrosion of Bolts



It is known that bolted joints can form a very special case of embedded fastener, because they are often placed in oversized holes pre-drilled into the timber, thus allowing moisture/water, salt and oxygen to enter, a situation that does not occur with other fasteners. To provide some sort of indication of the corrosion of bolts, an assumption is made that the worst corrosion occurs near the neck of the bolt, and this is either due to the embedded corrosion mechanism that is enhanced by water ingress into the bolt's hole; or due to atmospheric corrosion that is enhanced if the connector is near a beach. The procedures are as follows,

- *To compute the corrosion depth on bolts due to the embedded corrosion, see Section 2.5 in Manual 6.*
- To compute of the corrosion depth due to atmospheric corrosion that is enhanced if the connector is near a beach, follow the procedure in Section 5.3 to determine the normal first year corrosion depth, which is then multiplied with an enhanced factor, λ_b, to obtain the enhanced first year corrosion depth. The corrosion depths then can be computed by Eq. (5.3.6.1) for zinc or Eq. (5.3.7.1) for steel, using the corresponding *enhanced* first year corrosion depth. The enhanced factor, λ_b, which depends on the distance to the beach (L_{coast}) in km is computed by the following equation:

$$\lambda_b = 1 + 2e^{-\frac{L_{coast}}{2}} \tag{5.4.1}$$

The corrosion depth c_b near the neck of the bolt is taken to be the higher of these two computed corrosion values.

5.5 Corrosion of Fasteners under Corrugated Roofing

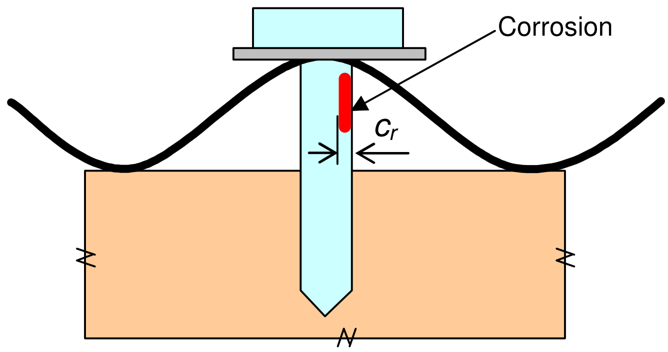


Figure 5.5.1 Depth of corrosion on exposed part of fasteners under corrugated roofing

It is known that the exposed parts of fasteners under corrugated roofing, as depicted in Fig. 5.5.1, form special cases, where the atmospheric corrosion is enhanced or reduced depending the distance of the structure to a beach.

To compute of the corrosion depth due to atmospheric corrosion that is adjusted (enhanced or reduced) if the connector is near or far from a beach, follow the procedure in Sections 5.3 to determine the normal first year corrosion depth, which is then multiplied with an adjustment factor, λ_r, to obtain the *adjusted* first year corrosion depth. The corrosion depths then can be computed by Eq. (5.3.6.1) for zinc or Eq. (5.3.7.1) for steel, using the corresponding *adjusted* first year corrosion depth.

A corrugate roof could be used above an open space (e.g. car port, open walk way) or a closed space (e.g. house). The adjusted factor λ_r, is computed by the following equation depending on the whether it is installed in an open or a closed space:

If installed in an open space:

$$\lambda_r = 0.5 + e^{-\frac{L_{coast}}{14}} \tag{5.5.1}$$

If installed in a closed space:

$$\lambda_r = 0.2 + 0.6e^{-\frac{L_{coast}}{9}} \tag{5.5.2}$$

where L_{coast} (km) is the distance to the beach.

6. Equations for Design Guide

The purpose of the score system is to enable a fast assessment of the hazard of corrosion to metal fasteners exposed to weather. Five hazard parameters related to atmospheric corrosion, namely, (1) coastal zone where the site is located, (2) coastal exposure, (3) site classification, (4) microclimate condition, and (5) corrosive pollution agents, are considered for this purpose. To assess the hazard score for unpolluted corrosion of fasteners under consideration, first find the individual score for each of the five parameters from Tables 6.1 to 6.5, listed below. Then add up the scores found from Tables 6.1 to 6.5, as shown in Table 6.6, to obtain a total score. From Table 6.7, find the range in which the total score falls in, and determine the hazard rating of the environment which the fasteners of concern is in.

Table 6.1 *Hazard score for coastal zone*

Hazard zone	Hazard score
A	3.2
B	3.3
C	3.5
D	4.3
E	4.9

Table 6.2 *Hazard score for coastal exposure*

Coastal exposure(1)	Hazard score
Sheltered bay	1.1
Partially closed bay	1.3
Very open bay	1.8
Open surf	2.3

Table 6.3 *Hazard score for site classification*

Site classification	Hazard score
Open to sea	1.0
Urban (suburb)	0.3
Urban (city centre)	0.0
Other site	0.7

Table 6.4 *Hazard score for microclimate*

Microclimate(1)		Hazard score
Wall cavity(2)		0.3
Roof space(2)		0.2
Sub-floor(2)		0.4
Outdoor	Sheltered from rain	1.0
	Exposed to rain	0.7

Table 6.5 *Hazard score for pollution*

Industry type	Hazard score(1)			
	$L = 1$	$L = 5$	$L = 10$	$L \geq 20$
Heavy industry (steel works, petrochemical)	3	1	0.5	0.0
Moderate industry (paper mills, large manufacturing)	1	0.5	0	0
Light industry (assembly plants)	0.5	0	0	0
No industry	0.0	0.0	0.0	0.0

(1) *L* is the distance to the industry (km).

Table 6.6 *The total hazard score*

Item	Hazard score
Coastal zone (Table 6.1)	
Coastal exposure (Table 6.2)	
Site classification (Table 6.3)	
Microclimate (Table 6.4)	
Pollution (Table 6.5)	
Total hazard score	

Table 6.7 *Definition of hazard rating*

Total hazard score (Table 6.6)	**Hazard rating**
<6	HR1
≤6<7	HR2
≤7<8	HR3
≥8	HR4

The service lives given in Tables 8.17 and 18 of the Design Guide are computed by Eqs (5.3.6.1) and (5.3.7.1), in which the basic corrosion depths of steel and zinc, $c_{0,s}$ and $c_{0,z}$, respectively, used are given in Tables 6.8 and 6.9, respectively. It is noted that this is for the corrosion of embedded parts of fasteners that are in a tight contact with wood, e.g. nails, screws, staples; but not for bolt shanks.

Table 6.8 *Basic corrosion depth of steel (μm) used for service life computation in Design Guide*

Hazard rating	Distance to the Coast			
	0 km	1 km	10 km	50 km
HR1	12.9	8.9	8.0	6.2
HR2	27.5	14.7	12.5	9.2
HR3	61.6	27.6	22.1	15.4
HR4	151.4	53.4	39.4	26.3

Table 6.9 *Basic corrosion depth of zinc (μm) used for service life computation in Design Guide*

Hazard rating	Distance to the Coast			
	0 km	1 km	10 km	50 km
HR1	0.4	0.3	0.2	0.2
HR2	0.8	0.4	0.3	0.3
HR3	1.6	0.7	0.6	0.4
HR4	3.8	1.3	1.0	0.7

The service lives of bolt shanks due to atmospheric corrosion given in Tables 8.19 and 8.21 of the Design Guide are computed by Eqs (5.3.6.1) and (5.3.7.1), in which the basic corrosion depths of steel and zinc, $c_{0,s}$ and $c_{0,z}$, respectively, used are given in Tables 6.10 and 6.11, respectively.

Table 6.10 *Basic bolt corrosion depth of steel (μm) used for service life computation in Design Guide for Bolt shanks*

Hazard rating	Distance to the Coast			
	0 km	1 km	10 km	50 km
HR1	38.7	19.6	8.2	6.2
HR2	82.4	32.6	12.7	9.2
HR3	185	61.0	22.4	15.4
HR4	454	118	39.9	26.3

Table 6.11 *Basic bolt corrosion depth of zinc (μm) used for service life computation in Design Guide for Bolt shanks*

Hazard rating	Distance to the Coast			
	0 km	1 km	10 km	50 km
HR1	1.1	0.6	0.2	0.2
HR2	2.3	0.9	0.3	0.3
HR3	4.8	1.6	0.6	0.4
HR4	11.5	3.0	1.0	0.7

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Appendix A

A.1 Fitting Equations from Cole (2000, 2007)

Cole (2000) provided a set of equations and data of corrosion rate at polluted environment, including sites in tropical areas of five countries. We found that the equation in the paper (Cole, 2000), however, needed some adjustments to fit to the data. The adjustments have been made by Cole (2007), resulting in the following equations, which have the same form as in Cole (2000) with different constants' values.

In polluted environment, i.e. nearby industrial zones, Cole (2007) suggested that the corrosion rate for zinc, $c_{0,\mathrm{z,poll}}$, is estimated by

$$c_{0,\mathrm{z,poll}} = 0.85 + 0.29\left(t_{wet}\right)^{0.2(5.8-A_{\mathrm{rain}})} + 0.013\left(0.25P_{\mathrm{air}} + 4\,S_{\mathrm{air}}\right) \geq c_{0,\mathrm{z,unpoll}} \tag{A.1}$$

And the corrosion rate for steel, $c_{0,\mathrm{s,poll}}$, is estimated by

$$c_{0,\mathrm{s,poll}} = \left(t_{wet}\right)^{0.09(7.5-A_{rain})}\left(0.9P_{air} + 0.3S_{air}\right) \geq c_{0,\mathrm{s,unpoll}} \tag{A.2}$$

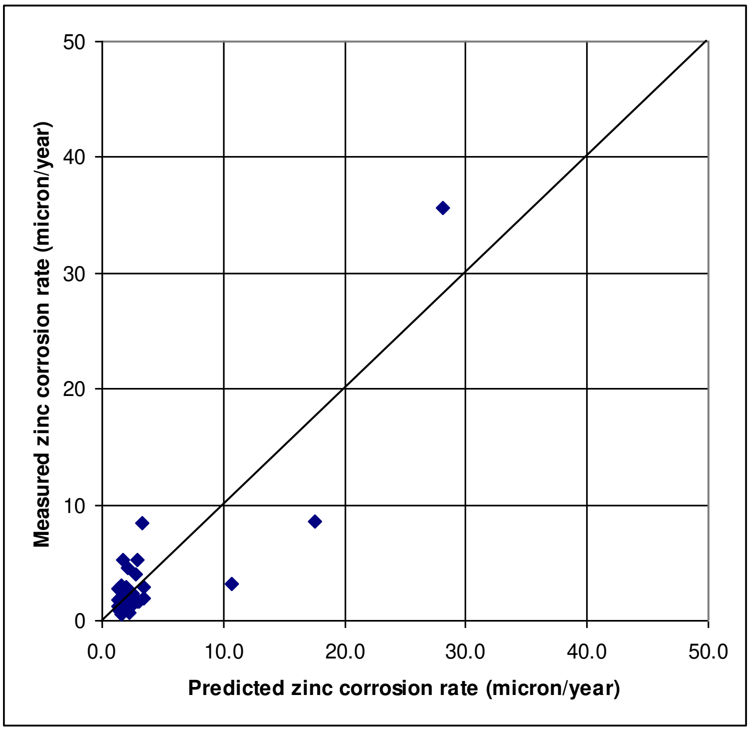
where: A_{rain} is acidity of rain water (pH), P_{air} is pollution of air in terms of level of airborne SO_x ($\mu g/m^3$)

The fitting of the equations to the 'tropical' data is presented in Figure A.1. The data is in Table A.1. However, although the fitting is quite good, especially for steel corrosion, the equations are found to be un-suitable for uses, because of the following reasons

- When P_{air} is set to be 0, the equations were expected to give comparable results to the case where there is no SO_x pollution. However the equations (A.1) and (A.2) always give much higher values of corrosion rate than the other sets of measured data obtained from sites with negligible effects of SO_x. It appeared that the equations (A.1) and (A.1) are only valid at the 'tropical' sites, where the effect of salt might be enhanced by the pollution agents. This effect was captured well in the equations (A.1) and (A.2), but does not diminish as it should do at low SO_x-polluted or non SO_x-polluted sites.
- Parameter A_{rain} is very difficult to predict or measure. In principle, A_{rain} should relate to P_{air}, but from measured data (Cole, 2000) there is no correlation found between P_{air} and A_{rain}.

Table A.1 *'Tropical' data and prediction using Cole (2007)'s model*

Location	Steel corrosion (micon/yr)	Zinc corrosion (micon/yr)	Twet (%)	Arain pH	Sair (mg/m2/day)	Pair (microgram/m3)	Predicted C0,steel, polluted	Predicted C0,zinc, polluted
Baguio	13	1.4	80	5	4	2.2	8.5	1.7
	11.8	2.6	92	5.4	4	2.9	9.0	1.5
	8.5	5.2	100	5	4	1.4	6.9	1.7
	11	2.5	100	4.9	4	1.8	8.3	1.8
Bicutan	41.5	2.1	34	4.1	10	10.3	36.1	2.4
	26.4	0.7	40	4.4	10	14	43.7	2.3
	92.1	1.7	41	4.4	10	34	94.7	2.3
	67.8	2.3	41	4.1	10	16.7	56.2	2.5
Cabuyao	35.7	1.7	83	4.6	10	8.9	34.9	2.3
	33.6	1.2	24	4	10	5.8	22.4	2.3
	62.4	2.9	63	5.1	10	20.9	53.4	2.0
	62.6	2	91	4.9	10	15.4	48.4	2.1
Phrapradaeng	87	1.8	62	5.7	16.1	105	193.8	2.4
	90	3	57	6.3	7.4	61	88.4	1.6
	50	2	34	5.9	4	33.9	52.7	1.4
	76	1.7	59	5.9	6.7	72	120.2	1.7
	99	1.8	89	5.9	6.1	67	118.6	1.7
Rayong	38	5.2	51	6.4	36.6	2.4	19.4	2.9
	42	4	74	6.3	33.2	8.9	28.6	2.8
	41	1.7	55	5.9	3.9	30.7	51.3	1.4
	47	1	72	5.9	12.7	18.1	37.2	1.8
	46	8.4	82	5.9	42	3	28.9	3.3
Phuket	30	1.7	43	5.7	34.1	3.2	24.1	3.0
	66	3.2	70	5.9	184.1	2.7	106.3	10.7
	41	2.9	64	5.8	43.7	8	38.4	3.4
			56	6.5		3	3.9	1.0
			86	6.4		32	44.8	1.1
Bangkok	39	0.9	22	6.3	12.3	31	44.1	1.8
	39	2.8	32	6	4	18	27.8	1.4
	24	1.6	16	5.6	6	13.2	22.0	1.5
	35	0.6	35	5.2	4.4	21.2	42.6	1.6
	46	1.7	28	5.6	8	17.8	32.6	1.7
Saigon	35	0.8	39	6.7	7	14	19.1	1.4
	40	1.8	39	6.6	4	15	19.8	1.3
		1.2	44	6	4	20	32.0	1.4
Cowley Beach	348	8.5	91	6.5	317	33	187.3	17.6
			92	5	326		270.5	18.4
	421	35.6	94	5.5	516	0.7	352.1	28.1
					48	1.1	0.0	3.3
Walkamin	6.2	0.7	66	4.9	4	1	5.6	1.7
	11	1.7	77	3.9	11	1	17.2	3.0
		2.5	67	4.9	9	0.6	8.7	2.0
Lembang	6.2	2.4	39	5.1	7	3.9	12.4	1.7
Cikampek	43.4	2	70	5.1	25	17.2	57.5	2.7
Gresik	78.4	4.6	30	4.8	10	28.8	66.1	2.1
Jebus	39.5	1.9	24	7.1	47	1.8	17.6	3.4
Mentok	61.6	1.9	15	5.4	20	67.9	112.0	2.5



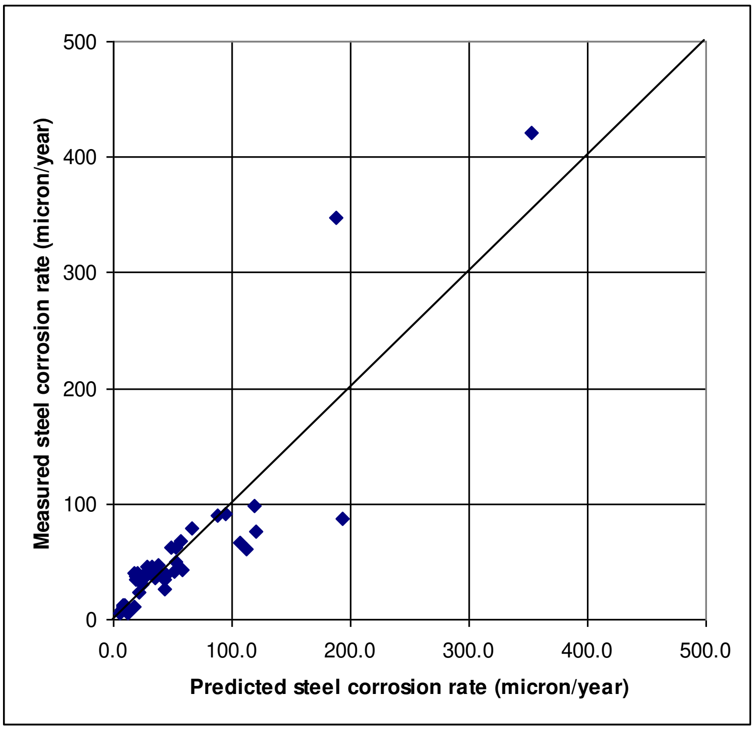


Figure A.1 *Checks of Cole (2007)'s model with the 'Tropical' data*