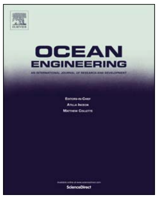
Ocean Engineering 126 (2016) 129–137

Contents lists available at ScienceDirect

Ocean Engineering

journal homepage: www.elsevier.com/locate/oceaneng



Probabilistic remaining life estimation for deteriorating steel marine infrastructure under global warming and nutrient pollution

Igor A. Chaves*, Robert E. Melchers, Lizhengli Peng, Mark G. Stewart

Centre for Infrastructure Performance and Reliability, The University of Newcastle, Australia

ARTICLE INFO

Article history:
Received 18 March 2016
Received in revised form
7 August 2016
Accepted 6 September 2016

Keywords:
Structural steel
Corrosion
Climate change
Reliability
Modelling

ABSTRACT

The longer-term serviceability and structural safety of steel infrastructure exposed to seawater conditions may be affected by global warming and by seawater nutrient pollution. These may affect abiotic and biotic (microbial) corrosion. A model for long-term corrosion is developed from data obtained from steel piling exposed for 33 years in a seawater harbour. The effects on corrosion losses on the structural reliability of steel sheet piling as used in harbours world-wide were investigated as a function of seawater temperature rise from global warming and of seawater nutrient pollution. The results show that structural reliability is more sensitive to likely nutrient pollution than to predicted increases in seawater temperature, noting also that global warming also could increase nutrient pollution from anthropological sources.

1. Introduction

The estimation of the long-term structural reliability and remaining safe life is important for items of major structural steel infrastructure subject to aggressive corrosion conditions (Paik and Melchers, 2008). Many steel infrastructure assets are provided with protective measures such as paint coatings or sacrificial or impressed current cathodic protection, but these are not always effective, commercially feasible or economic in the long-term (Paik and Melchers, 2008). Visual inspection is a commonly used technique for *in-situ* condition assessment but is feasible only for those parts of the steel structure that are sufficiently accessible for inspection and that can be sufficiently exposed. Such inspection, aided by well-established techniques for *in-situ* inspection such as ultrasonic testing, is, however, limited in the practical information it can provide and this must be considered in any assessment of reliability and potential future remaining life. Inspection techniques and the various tools available also have associated with them a considerable degree of measurement uncertainty, in part as a result of operator error and in part because of the interpretation required for the results obtained (Chaves and Melchers, 2013). Taken together, this implies that any estimate of expected life of physical infrastructure will need to consider such uncertainties and thus should be based on (well-established) probabilistic risk or structural reliability analysis (Stewart and Melchers, 1997).

In parallel to the more conventional definition of risk, corrosion risk can be expressed as the product of the probability of failure resulting from corrosion and the consequences from such corrosion (Stewart and Melchers, 1997). The probability of failure for a given corrosion risk can be estimated on the basis of the severity and the extent of corrosion damage expected to occur on a component. The likely consequence(s) should failure occur can be estimated from the impact of such failure, evaluated against a number of criteria. These include personnel safety, environmental and operational impacts. Once these assessments have been made, the overall corrosion risk assessment then ranks the equipment or the infrastructure according to the corrosion related risks involved. This may then lead to identification of mitigation and management options, following conventional practice (NACE International, 2010). The tools and techniques for such probabilistic risk assessments are well-developed and readily available in the literature (Stewart and Melchers, 1997; NACE International, 2010; Melchers, 1999).

The present paper focuses on the practical problem of the long-term reliability of steel piling such as used extensively in commercial and other harbours. Fig. 1a shows a simple example after failure. Such sheet piling is known to be prone to a phenomenon known as accelerated low water corrosion (ALWC) (Melchers and Jeffrey, 2013). Recently ALWC (Melchers and Jeffrey, 2012) and also immersion corrosion (Melchers, 2014) has been shown to be influenced strongly by both water temperature and anthropological and other forms of water pollution. As reported earlier for reinforced concrete infrastructure, increased water temperatures as

---

* Corresponding author.
E-mail address: igor.chaves@newcastle.edu.au (I.A. Chaves).

http://dx.doi.org/10.1016/j.oceaneng.2016.09.013

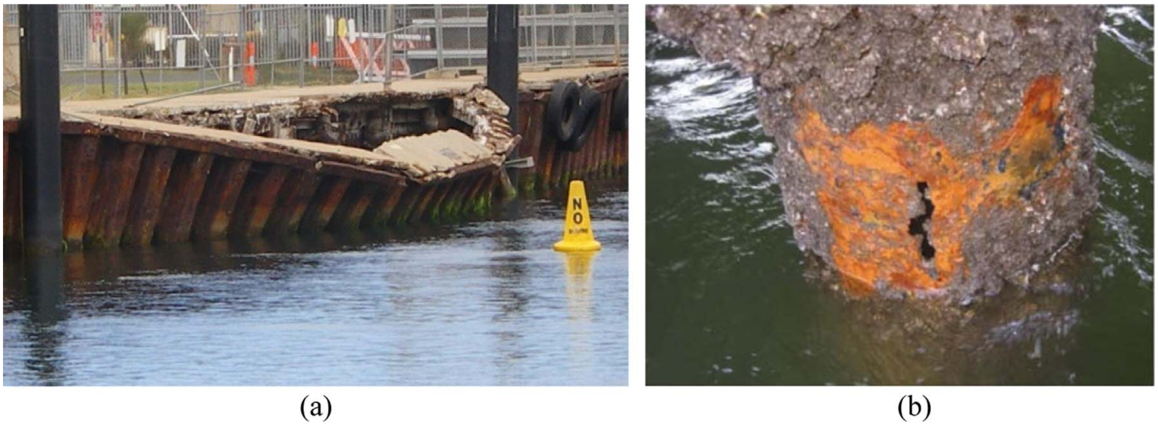

(a) (b)

Fig. 1. (a) Failure example of a sheet pile retaining wall (photo courtesy R Jeffrey), (b) "Bright orange" localized corrosion of a tubular pile showing local wall perforation just above the water line at extreme low tide (Green et al., 2010).

a result of expected global warming (Stewart et al., 2012; Peng and Stewart, 2014) also may have an important influence on the long-term reliability of steel (and other) infrastructure. Also, water pollution largely as a result of anthropological influences has been observed in harbours and coastal regions in many parts of the world, including in regions of high economic activity and generally well-regulated industrial, chemical and agricultural practices (AS/NZS 2452.3, 2001). The effect of these influences is considered herein using as a typical application low alloy steel sheet piling such as widely used for quays and retaining systems in seawater harbours.

The next section outlines the development of a simple linear model to represent long-term corrosion loss. Based on observations of the corrosion of similar piling of steel infrastructure directly exposed to seawater conditions this paper reports data and statistical interpretations of data or loss of cross-section loss of mild steel piling exposed for some 33 years in 20 °C (aver.) Pacific Ocean seawaters in Newcastle harbour, Australia. The parameters of the proposed model are treated as random variables. A probabilistic analysis of the steel sheet piling is then described, using as input random variables to describe the material and loading characteristics. The effects of feasible changes in water temperature and in water quality are then considered. The results are discussed in the context of the effect of climate change and consequent elevation of average seawater temperature on long-term reliability, safety and serviceability.

2. Marine corrosion of steel

Information and data for the long-term corrosion of steel in marine conditions largely is confined in the literature to exposures much less than 10 years. The few data for up to 16 years exposure (Melchers, 2003; Southwell and Alexander, 1970; Larrabee, 1953; Mercer and Lumbard, 1995) indicate that the long-term trend in uniform corrosion $c(t)$ and also in maximum pit depth tends to follow an anaerobic steady state (Melchers, 2003) linear trend as a function of time t that can be described, for exposure periods greater than about 5 years by Eq. (1):

$$c(t) = c_S + r_S \bullet t, \qquad t > 5\ years \tag{1}$$

where c_s is the 'y-intercept' at time $t=0$ and r_s is the slope of the long-term trend. Also, it is well-established that corrosion is an integrative process and that spikes and similar changes have a relatively small effect on the net result. It follows that any increase in water temperature as a result of possible longer term global warming also will be a linear function. For the present study data for both immersion corrosion and for the ALWC zone became available as a result of renovation of steel sheet piling in Newcastle harbour, Australia. This harbour is known to have relatively low levels of water pollution owing to high tidal flushing (Solomon et al., 2007). Typically, steel sheet piling in older harbours are not protected since the historical corrosion losses were considered to be acceptably low (AS/NZS 2452.3, 2001). However, in 2008 'bright-orange' localized corrosion of steel sheet piling was observed just below low water level and within the lower half of the tidal zone of some steel piles. These showed high cross-section losses or even complete wall perforations (Fig. 1b). At the time both microbiologically induced corrosion (MIC) and Accelerated Low Water Corrosion (ALWC) were suspected as contributing to the high corrosion losses observed (Stewart et al., 2012; AS/NZS 2452.3, 2001; Solomon et al., 2007) and this has since been shown to be consistent with observations elsewhere (Melchers and Jeffrey, 2012; Melchers, 2014). Port Corporation records showed that the piles were around 33 years old and had not been given protective coatings when first installed. Replacement of the affected piles permitted measurement of their corrosion losses to obtain estimates of the parameters c_s and r_s (Eq. (1)) both for long-term ALWC and for long-term immersion corrosion, as described below.

The piles showing high corrosion losses were withdrawn from service. Four of these the parts, exposed in the tidal zone and in the upper part of the immersion zone, were made available to the present study (Fig. 2a). The locations of high and low tide levels were marked (Fig. 2b), identified by barnacle growth. The four piles also were arranged so as to correlate the tidal range zone. An electric jack-hammer was then used to remove dried barnacles as well as to remove loose rust, leaving only the harder denser interior rusts (Fig. 2b). Each region was examined in particular for the location of complete wall perforations. Samples (250×250 mm in size) were cut from the tidal and the ALWC zones for measurement of localized corrosion and pit depth relative to the surrounding metal in a manner similar to that previously reported for weld zones (Chaves and Melchers, 2013). In addition, ultrasonic testing was used to take two independent set of measurements (*i.e.* A and B) of the remaining wall thickness of the parent metal every 150 mm in the longitudinal direction. It is then reasonable to assume that the readings are statistically independent as they were taken in longitudinal strips along the piles equally distant and away from the two longitudinal welds, one on each side of each tubular pile. These two sets of readings are labelled 'A' and 'B'. The results are shown in Figs. 3–6.

In Figs. 3–6 the grey area represents profile of the remaining wall thickness along the line of ultrasonic measurements as constructed from the readings at each point. Each of individual