Structural Safety xxx (2016) xxx–xxx

Contents lists available at ScienceDirect

Structural Safety

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

Probabilistic physical modelling of corroded cast iron pipes for lifetime prediction

Jian Ji [a], D.J. Robert [b], Chunshun Zhang [a], David Zhang [c], Jayantha Kodikara [a,*]

[a] *Department of Civil Engineering, Monash University, Vic 3800, Australia*
[b] *School of Civil, Environmental & Chemical Engineering, RMIT University, Vic 3000, Australia*
[c] *Sydney Water, 210 William Holmes St Potts Hill, NSW 2143, Australia*

ARTICLE INFO

Article history:
Received 20 March 2015
Received in revised form 26 September 2016
Accepted 26 September 2016
Available online xxxx

Keywords:
Pipeline failure
Stress prediction
Corrosion
Physical modelling
Probabilistic analysis

ABSTRACT

Cast iron was the dominant material for buried pipes for water networks prior to the 1970s in Australia and overseas. At present, many water utilities still have a significant amount of ageing cast iron pipes. Cast iron is a brittle material and when large diameter cast iron pipes (diameters above 300 mm) further deteriorate, the consequences of failure can be substantial. Focusing on the likelihood of failure to assist risk assessment, this paper examines the performance of large-diameter cast iron pipes using probabilistic analysis, incorporating uncertainties of governing variables. Finite element analysis is first conducted to study the physical mechanism of buried pipes subjected to complex environmental conditions. The deterioration of cast iron pipes due to corrosion is considered on the basis of recent research. The uncertainties of governing variables, such as the physical properties of soil, cast iron, water pressure and corrosion patterns, in pipe failure risk assessment are considered. Using probabilistic physical modelling, the lifetime probability of failure is derived and a time-dependent sensitivity analysis is presented. The results of this probabilistic physical modelling are compared with cohorts of failure data from two Australian water utilities to examine the underlying trends from both physical modelling and statistical analysis.

1. Introduction

The management of water mains is an integral activity of water utilities in strategic planning, decision-making and asset management. Water mains can be broadly divided into small diameter (reticulation) (normally <300 mm) pipes or distribution mains of large diameter (normally >300 mm) pipes or trunk mains. Depending on the water network, a large majority of pipelines are small diameter pipes and the remainder are large diameter pipes. The large diameter pipes are normally given especial attention since their failures can incur significant consequences in the form of financial losses and societal or environmental impacts. Basically, all physical parameters are seen as various degrees of variation. As a result, in assessing pipe performance, there is less significance to define a lumped factor of safety, which essentially assumes that all physical parameters are well characterized by deterministic values. Instead, probabilistic analysis has proven to be a good alternative, and there has been an increasing demand for assessment of the lifetime probability of failure. This, in turn, can be used to evaluate the risk associated with failure [1]. In order to incorporate internal and external factors such as external loading changes, manufacturing material variations, internal water pressures, environmental effects, and variable deterioration due to pipe ageing, the probabilistic physical modelling approach is commonly utilized to analyse the lifetime probability of failure of pipelines. Typically, two types of probabilistic physical modelling approach are available: (1) numerical approximation based on engineering reliability methods; (2) Monte Carlo simulations. As an example of the first category, Ahammed and Melchers [2,3] used the first-order second-moment (FOSM) reliability method to conduct probabilistic analyses of underground cast iron pipelines subjected to loadings and corrosion effects. With idealizations of the failure mechanism and time-dependent corrosion behaviour, they demonstrated the computation of increasing failure probability or decreasing reliability index with time. DeSilva et al. [4] presented a probabilistic analysis to estimate the failure rates in metallic pipelines using FOSM. The condition assessment data were used to quantify the level of deterioration and to estimate the probability of failure of an entire pipeline over time. Li and Mahmoodian [5] demonstrated a methodology to quantitatively assess the lifetime risk of cast iron pipes and predict their

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* Corresponding author.
E-mail address: jayantha.kodikara@monash.edu (J. Kodikara).

http://dx.doi.org/10.1016/j.strusafe.2016.09.004
0167-4730/

Please cite this article in press as: Ji J et al. Probabilistic physical modelling of corroded cast iron pipes for lifetime prediction. Struct Saf (2016), http://dx.doi.org/10.1016/j.strusafe.2016.09.004

Nomenclature

t	pipe lifetime or pipe age, year
$P_f(t)$	probability of pipe failure at age t
$E(t)$	expected lifetime or lifetime expectation
$F(t)$	cumulative distribution function of random variable (lifetime) t
$H(t)$	hazard rate
$Q(t)$	failure rate, in terms of number of failures/100 km/year
$\mu(T_r)$	mean residual lifetime when the pipe survival age is T_r, year
$\tau(t)$	corroded depth when pipe is t years old, mm
c_s	intercept of initial corrosion rate, mm
r_s	long-term corrosion rate, mm/year
$T*$	transition point of a bilinear corrosion model, year
$\sigma(\mathbf{x}), \sigma(\mathbf{x}, t)$	time-independent and -dependent maximum tensile stress in pipe, MPa
$g(\mathbf{x}, t)$	limit state function defining the pipe failure and/or safety
$\mathbf{x}$	a vector containing all physical parameters
σ_y	tensile failure stress of pipe materials, MPa
SCF_{TWC}	stress concentration factor of through wall corrosion hole
SCF_{RWC}	stress concentration factor of remaining wall corrosion pit/patch
h	burial depth, m
E_s	elastic modulus of soils, MPa
γ	unit weight, kN/m^3
k	lateral earth pressure coefficient
υ_s	poisson's ratio of soils
E_p	elastic modulus of cast iron pipes, GPa
υ_p	poisson's ratio of cast iron pipes
d	wall thickness, mm
d'	minimum remaining wall thickness in corrosion pit/-patch, mm
d_e	effective wall thickness of pipes subjected to uniform corrosion, mm
D	nominal pipe diameter, mm
R	nominal pipe radius, mm
W	surface load (traffic), kN
P	operating water pressure, kPa
Ω	corrosion pit/patch radius, mm
θ	corrosion patch inclination, degree
ζ	ratio of uniform corrosion rate to pitting corrosion rate
α	shape parameter in Weibull distribution
β	scale parameter in Weibull distribution
T_o	location parameter in Weibull distribution, year

remaining service life, based on the first passage probability theory. The concept of stress intensity in fracture mechanics is employed to establish the failure criterion of pipe collapse. An empirical model is derived for the maximum pit growth of corrosion from the available data based on mathematical regressions. As of the second category, Pandey [6] and Sinha and Pandey [7] presented a time to failure assessment of oil and gas pipelines using Monte-Carlo simulations (MCSs) that allow the incorporation of inspection and repair activities over their service life. Sadiq et al. [8] studied the performance of grey cast iron water mains by comparing the external stress with residual ultimate strength. A two-phase corrosion model was introduced to describe the wall thickness reduction in corrosion pits. MCSs were combined with their pipe failure models to derive the time to failure probability. Davis et al. [9] used MCSs to estimate lifetime probability distributions for PVC pipelines. Linear elastic fracture mechanics theory was used to predict the time to brittle fracture of pipes, and the uncertainty was taken into account for the failure process, and inherent defect size. The predicted failure rate was compared with the existing failure database recorded by water utilities. For metallic pipelines, the deterioration process is commonly approximated by corrosion that occurs at variable rates within the subsurface environment. Hence, it is imperative to base the estimation of corrosion progression on models that are validated by field evidence. A recent study comparing different corrosion models in pipeline reliability assessment is given in [10]. An extensive literature review of the probabilistic physical modelling technique is presented in [11,12]. In contrast to these probabilistic physical modelling studies, on the other hand, substantial research has been undertaken to introduce purely statistical approaches for pipeline failure prediction using the observed failure data [13–17]. However, comparisons between probabilistic physical modelling and the observed failure data are less commonly reported.

The aim of this paper is to study the likelihood of failure of aged cast iron pipelines using probabilistic physical modelling techniques. Realizing the fact that cast iron pipes were vastly used in Australia spanning from the year 1880 to 1970, this study will classify the cast iron pipes into different cohorts, for example, the pit cast iron pipes (mainly laid before 1925) and/or spun cast iron pipes (mainly between 1929 and 1970). The concept of pipe cohorting is very important to properly predict the pipe lifetime failure because it helps to reduce the variation within each of the cohorts. Using a field-validated corrosion model, the effect of time-dependent corrosion behaviour on pipe failure is examined. The significance of the proposed research is in advancing the knowledge of deterioration science of materials (cast iron and general metals) and the failure theory of infrastructure (buried pipelines), incorporating metal corrosion, soil mechanics, structural failure mechanics, and time-dependent reliability methods. The basic failure mechanism is investigated using finite element analysis, which is then used to derive a closed-form solution to predict maximum pipe stresses. Subsequently, an efficient first-order reliability method (FORM) [18–20] combined with the importance sampling Monte Carlo simulation technique [21] is used to estimate the probability of failure of the pipe. Finally, a comparison is provided between the results of the probabilistic physical modelling and comparable results derived from observed failure data from two Australian water utilities.

Note that the findings in terms of the lifetime failure probability is based on the early designed cast iron pipes in Australia. Thus any prediction such made will be only valid to similarly defined pipe cohorts, and not for the recently designed pipes having different material properties.

2. Deterioration of pipe structural capacity due to corrosion

As cast iron pipelines were laid half a century ago, in most cases, their condition has deteriorated primarily by electro-chemical and (or) micro-biological corrosion. The corrosion activity (internal and external) can manifest in various forms, but generally leads to a reduction in pipe thickness, thereby causing deterioration of the pipe's structural capacity with respect to external and internal loads. On the basis of field evidence [22], the corrosion induced thickness loss is idealized into two patterns: uniform corrosion and pitting corrosion. Uniform corrosion applies when there is an all-round reduction in pipe wall thickness and pitting corrosion applies when there is a localised corrosion patch or pits. The latter

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