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Reliability Analysis of Buried HDPE Pipes

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Abstract: Safety range quantification of buried pipes such as gas pipeline is an important tool for controlling risk specifically, when unexpected events occur like earthquakes and landslides. Usually deterministic approach is used to analyse the behaviour of the structure considering an idealised soil model. Reliability approach involves soil loading as random variable leading to better modelling of the tube soil interaction. The approach uses FORM/SORM methods to determine a reliability index of the pipeline structure. A mechanical model is developed, with a failure mode which includes the main parameters that can improve safety in these structures. The interest of this study is to provide a realistic treatment of uncertainties and an evaluating method of safety factors. The aim of this reseaech is to present a reliability approach to assess the lifetime of buried High-Density Polyethylene (HDPE) gas pipes with regard to temperature gradient, fluctuating internal pressure, external loads and residual stress.

Key words: Reliability index, HDPE, safety margin, pipe, lifetime

INTRODUCTION

Traditional structural metals such as steel and aluminium are being replaced with plastics, ceramics and composites, in a number of applications. Recent statistics indicate that more than 90% of newly installed piping gas systems in the world are exclusively made of polyethylene PE because of its ease of fabrication, relatively low cost, flexibility, lightness, ease of installation and maintenance, corrosion resistance and long-term reliability against environmental degradation. These properties made it a real alternative to metallic systems (GRI, 2002, Cheron, 2001). Moreover, 90% of the new piping installations are made of HDPE (Rajendra, 2005). Therefore the need of understanding their behaviours during the service time is increasingly required. Therefore, in terms of service lifetime (Chudnovsky and Sulkin, 1999; Zhou *et al*., 1996) much attention is paid on aspects related to mechanical characterization and structure relationship (Bradley *et al*., 1998) loading modes (Hamouda *et al*., 2001) failure mechanisms (Baer, 2000) and environmental effects (Bradley *et al*., 1998; Hamouda *et al*., 2001; Baer, 2000). In this research, we present a reliability analysis for an underground HDPE gas pipes. However, many uncertainties in the geometry, loading and service conditions can not be avoided. Therefore the use of probabilistic approach is greatly recommended. For instance, when considering the service loadings of a gas HDPE pipe, there is always fluctuation in internal pressure service and in the wall thickness of the pipe. Therefore, a reliability assessment will be of great help in understanding the service lifetime of the pipe. Reliability is defined as the capability of the structural system to ensure the functioning conditions for which it is designed, during its lifetime.

Ahammad and Melchers (1994) proposed a methodology which was presented for the reliability analysis of underground pipelines. However, the effect of longitudinal stresses was not considered. So, they suggested an approach employing a probabilistic procedure to model the behaviour of steel corrosion in underground pipelines (Ahammad and Melchers, 1997).

The aim of this research is to assess the dimensional reliability of a gas HDPE pipeline under internal pressure, external loads and residual stresses. Reliability lifetime analyses is conducted to investigate the temperature gradient effect on gas HDPE pipeline, when increasing pressure and reducing thickness.

MECHANICAL MODEL IN THE POLYETHYLENE PIPES

In general, underground pipelines (Fig. 1 and 2) are mainly subjected to radial, longitudinal and circumferential stresses. As circumferential are dominantly the main stresses contributing in the longitudinal cracking in buried pipe, the mechanical model is developed according

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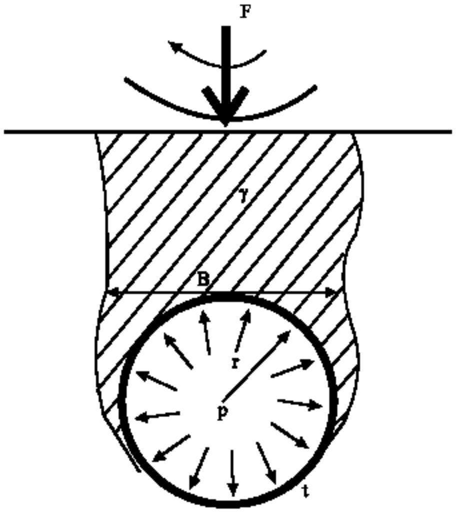

Fig. 1: Configuration of underground natural gas pipe

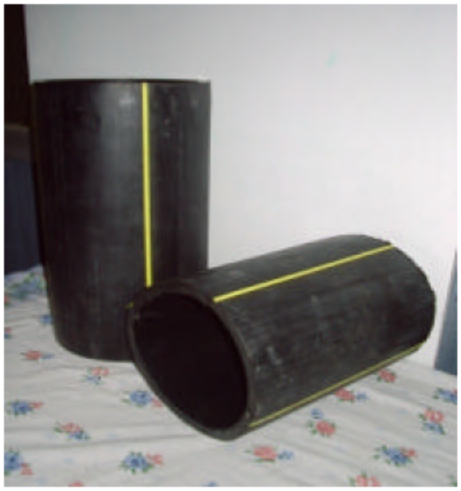

Fig. 2: Tube in HDPE-100 intended for transport

to the circumferential ones. Then, the total circumferential stress σ_c is determined by the superposition of four principal stresses:

$$\sigma_c = \sigma_{p_c} + \sigma_{s_c} + \sigma_{t_c} + \sigma_{res_c} \tag{1}$$

Where σ_{pc} is the stress due to internal pressure,σ_{sc} is the stress due to soil loading, σ_{tc} is bending stress and σ_{resc} is residual stress; the subscript c indicates circumferential components.

Then the stresses can be evaluated as follows (Spangler and Handy, 1982):

$$\sigma_{p_c} = \frac{P\,r}{h} \tag{2}$$

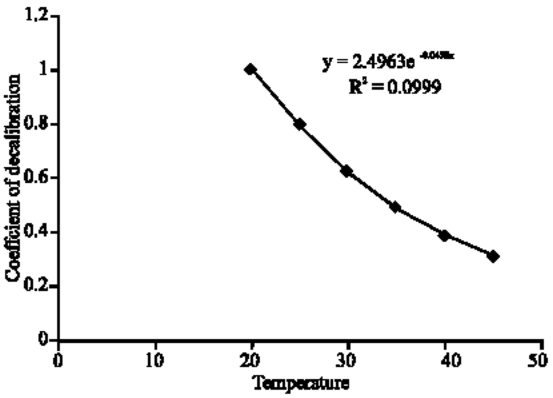

Fig. 3: Coefficient of decalibration as function temperature (Khelif *et al*., 2006)

with: P is the maximum pressure of service, r internal pipe radius and h pipe wall thickness. P is given by the following expression:

$$P = p.D_f \tag{3}$$

Where p is internal pressure and   calibration coefficient (Fig. 3).

$$D_f = 2,4963\exp(-0,0458)T \tag{4}$$

where T is the temperature.

The bending stress in the circumferential direction produced in the pipe wall due to the loading of the overlying soil can be estimated from the following expression (Khelif *et al*., 2006).

$$\sigma_{s_c} = \frac{6\,k_m\,C_d\,\gamma\,B^2\,E\,h\,r}{E\,h^3 + 24\,k_d\,p\,r^3} \tag{5}$$

with: σ_{sc} circumferential bending stress due to overlaying soil, B width of ditch at the pipe top level, C_d coefficient of earth pressure, E modulus of elasticity, k_m bending coefficient depending on load and soil reaction, k_d deflection coefficient, γ soil density. The circumferential bending stress due to the external traffic loads is given by Eq. 6:

$$\sigma_{t_c} = \frac{6\,k_m\,I_c\,C_L\,\gamma\,F\,E\,h\,r}{L_e\left(E\,h^3 + 24\,k_d\,p\,r^3\right)} \tag{6}$$

where: σ_{tc} circumferential stress due to traffic loads, I_c impact factor, C_L surface load coefficient, F magnitude of surface wheel load, L_e effective pipe length on which the load is computed.

Residual stress is generated during the production process of the pipe. For instance, in extruded HDPE pipes, the hoop radial and longitudinal residual stresses are the principal components of residual stress.. Meanwhile, the maximum residual stress ($\sigma_{res\ max}$) in plastic pipes, are obtained by approximation involving the creep modulus at time t (E(T)) and the pipe thickness (Kiass *et al*., 2004):

$$\sigma_{resmax} = \frac{+E(t)hD_2(t) - D_1}{(1-\nu^2)D_2(t)D_1} \tag{7}$$

Where D_1 and D_2 are pipe diameters before and after ring slitting and V is the Poisson's ratio.

The stress acting on the pipe wall (σ_R) should obey an equation of the following form to ensure safe working conditions (Kiass *et al*., 2004):

$$\sigma_R \geq \frac{2(K_C)^2(1-\nu^2)}{\pi D} \tag{8}$$

where D is the average diameter and K_C, the material fracture toughness.

RELIABILITY MODEL

The prediction safety range quantification in buried PE pipes can be assessed through reliability analyses using probabilistic models. Each variable implied in dimensioning of the pipe has to be represented by a random variable, described by distribution type and parameters (generally, mean and standard deviation). To perform the reliability analyses, the PHIMECA software (2002) has been used by applying specific algorithms for searching the most probable failure configuration. This software offers several methods for reliability calculation such as Monte Carlo simulations and First/Second Order Reliability Methods (FORM/SORM). The analysis of reliability consists in, initially, defining a function of performance or state of the system.

$$G(X) = G(X_1, X_2, ..., X_n) \tag{9}$$

G(x) known also as the limit state function G(x) corresponds to the conventional safety margin defined by the difference between the material yield strength and f_Y the applied circumferential stress. This margin is defined such that $G(x_j) \succ 0$ indicates safety and $G(x_j) \prec 0$ corresponds to conventional failure; x_j are the random variables in the system. $G(x_j) = 0$ is a surface of (n-1) dimension which can be called surface of ruin. If $f_x(X)$ the density of joint probability of the vector represents, Xthe probability of ruin of the system can be expressed as follows:

$$P_f = p[G(X) \leq 0] = \int_D f_X(X_1, ...X_n)dx_1...dx_n$$

Where $D = [X_i / G(X_i) \leq 0]$ the field of ruin in the space of the basic random variables represents.
Reliability is then expressed by:

$$P_R = 1 - P_F \tag{10}$$

RESULTS AND DISCUSSION

The probability of failure of a buried HDPE pipe under internal pressure, external loads and residual stresses is calculated with and without considering the temperature gradient. Figure 4 illustrates the importance of the variables (Table 1) in reliability calculation. When investigating the effect of pressure and thickness, in both cases, E with 40% is the most important variable, followed by the effective length of the pipe 35 and 36%. The next

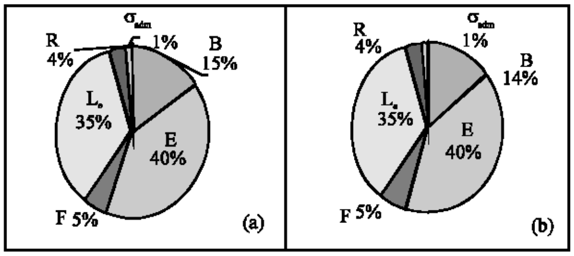

Fig. 4: Variables importance in reliability buried gas HDPE pipe a) with temperature gradient; b) without temperature gradient

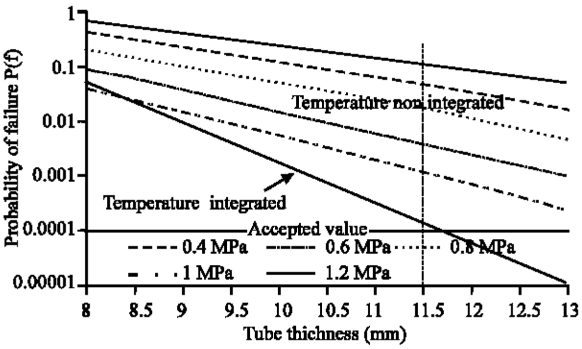

Fig. 5: Probability of failure in pehd pipe as a function of thickness and mean pressure

Table 1: Random variables and corresponding parameters

Type of variables	Symbol	Description	Mean value	Coefficient of variation (%)
Material	E	Modulus of elasticity	1150 MPa	20
	v	Poisson's ratio	0.46	15
Geometry	r	Internal pipe radius	100 mm	10
	h	Pipe wall thickness	11.4 mm	10
	D_1	Diameter before ring slitting	200 mm	10
	D_2	Diameter after ring slitting	200 mm	10
	D	Average diameter	200 mm	20
	L_e	Effective length of the pipe	1000 mm	40
	B	Width of ditch	450 mm	30
Coefficients	K_C	Material fracture toughness		10
	K_m	Bending coefficient	0.235	10
	C_d	Coefficient of earth pressure	1.32	10
	γ	Soil density	1.89×10^{-5}	10
	K_d	Deflection coefficient	0.039	10
	I_C	Impact factor	1.5	10
	C_L	Surface load coefficient	0.12	10
Loading	p	Internal pressure	0.4 Pa	30
	F	Wheel load traffic	15000 N	20

variable is the width of ditch. This is logical as the external loads are spread around and over. Then the external load and pipe diameter take part with 9%. The admissible stress is present with 1%. Therefore, the safety margin of the underground pipe, in this loading conditions is mostly dependant at 76% of two main variables, the elastic limit and the effective length of the pipe.

When inspecting the effect increasing internal pressure and reducing tube thickness, it is very important to sort out the main difference in the behaviour of the probability of failure of the pipe as illustrated in Fig. 5. When neglecting, the temperature gradient, the lifetime of the tube is highly dependant on both parameters, internal pressure and thickness. In this case, if an accepted probability of failure of 10^{-4} which is used in industrial plants is the reference value, then the tube will have blown up for all the considered pressures and thicknesses. This means that to be in the safe margin, the thickness should be increased. Now, as the temperature gradient is considered in the calculation, for all pressures investigated in this research, thickness is the controlling parameter of the safety margin of the tube.

CONCLUSION

Reliability assessment is revealed to be very much more informing than deterministic approach.

The safety margin in dimensioning an buried HDPE pipe is dependent on the temperature gradient, thickness and applied pressure. The main conclusion that may be drawn from this study can be summarized as follows:

- The reliability analysis method must be used in order to assess the safety of pipes more reasonably;
- The aim of sensitivity analysis is to search for the key random variables whose scatter has made significant contribution to the probability failure of the structure;
- The information produced by the reliability assessment is a better tool for pipes inspection and optimisation.

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