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The Durability of a Concrete Sewer Pipeline Under Deterioration by Sulphate and Chloride Corrosion.

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Abstract

In the article an issue of corrosion impact both sulphate and chloride on the reliability index was solved by analytical methods. The pipeline was located in a homogenic soil backfill under communication load. The depth of corrosion penetration was estimated by selection of the maximum length of cracks. As a result of deterioration zone appeared to be a function of time in exploitation according to average environmental concentration which can initialise a percent of chemical and mechanical degradation of concrete. The work shows also the complete analytical way which help to assess the safety level of sewer pipelines what can be introduced to geographic information systems.

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Keywords: corrosion, sulphate, chloride, reliability, concrete sewer pipe

1. Introduction

The aim of the study was to analyse the parallel impact of two most significant type of corrosion: sulphate and chloride for reliability of sewer lines constructed as a concrete pipe without protective layers. Existing codes classify threats and point engineering protection as Eurocode [7]. These phenomena’s with confirmed negative impact for concrete [6] are both land origin chloride corrosion described as XD class and sulphate aggression ranked as a general risk of chemical aggression into XA class. The subject of our analysis is to complete information contain in

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the codes by presentation of complete design algorithm prepared taking into account the reliability theory. Available assessment of probability process [12], [2] were examined separately for two possible types of corrosion. In the study above this interaction was analyzed by the assumption of independent, simultaneous process. It was assumed that a corrosion is related to cross section reduction of a tube side. To describe actually non deterministic phenomena, like corrosion and substrate material on the long sewage pipeline (conditions of plain strains), a large number of random variables were used. Final pipeline capacity was estimated by the conservative approximative analytical method in [14]. To solve the reliability issues the method of Monte Carlo simulations was used. The approximate probability method has been developed in geotechnical sciences by many authors i.e. [3]. Each designed concrete structure exposed to active environment and it becomes a subject of deterioration. Although the concentration of liquid that flows inside the pipe can be high, it is not very aggressive towards concrete and the pH indicator of wastewater varies from 6.5 to 7.5. The main sources of risks are: sulphates, chlorides, various detergents and a large amount of organic substances. The main point of aggressive salts are usually sulphates but in winter time chlorides become the major threat. There is huge increase of de-icing agents drained from the streets into there are a lot of protein sediments. In addition to this there are a lot of protein sediments which rapidly decay and from hydrogen sulphide and other oxidation sulphur can concentrate on tube sides. Bacteria's that are present in the canal can oxidize sulphur into sulfuric acid VI which can react with calcium carbonate and finally calcium sulphate is formed. Gypsum crystallizes with water molecules and afterward increases its volume. Gypsum can react with monosulphate and tricalcium aluminate to form Erringit, which may drastically increase its volume under crystallization. It leads consequently to the increase of internal stress into concrete what can result in cracking or even complete destroying continuity of structure [6]. Theoretically, under appropriate down slope of the pipeline and with good ventilation the sediments should never accumulate but in real cases like plugging ventilation or construction errors it may be totally different. Aggression derived from hydrogen sulphide, converting into sulfuric acid may be the mayor threat to the channels because 40% of total damages [12] are made by the sulphides. Chloride impact is less risky to the sewer lines but the phenomenon of chloride aggression to concrete structures is real. We intend to show that in certain periods of exploitation chlorides also play periodical important for safety negative role. In the article chemical and crystallization process are described by approximately methods and correlated with limit loads of pipeline [1].

Nomenclature

C	chloride ion concentration
D_{cl}	chloride diffusion coefficient in concrete
t	time
x	depth in the diffusion direction
C_s	chloride surface concentration
C_{th}	chloride concentration treshold
$[DS]_{lim}$	sulphide concentrations in a partly filled sewer will approach a limiting level
BOD_5	biochemical oxygen demand concentration
T	sewage temperature
i	slope of the pipeline
u	velocity of the sewage stream
b	surface width of the stream
P	wetted perimeter of pipe wall
j	pH-dependent factor for proportion of H_2S
k	factor showing the proportion of acid reacting
P'	perimeter of the exposed pipe wall
A	alkalinity of sewage
n	Manning’s coefficient
R_h	hydraulic radius
A	stream area

U	wetted perimeter
σ_R	tensile strength
σ_S	tensile stresses
α_k	correction factor taking into account the curvature of inner and outer edge fiber
R	resistance function
E	Young's modulus
q	surface load
S	load effect function
g	limit state function
P_f	probability of failure
N	total number of generated simulations
β_{Cl}	reliability index for chloride corrosion
β_S	reliability index for sulphate corrosion
β_{cor}	total reliability index

2. Corrosion models

2.1. Chloride corrosion

Chloride Corrosion takes place with presents of the solutions with high concentrations of chlorides, for example sea waters, mine waters or de-icing salt rinses. It is a major threat to the reinforced concrete structures, however for concrete itself, this type of corrosion is also destructive. There are created expansive alkaline chlorides, for example Magnesium and Calcium. Concrete destruction is caused by increase of the stresses from crystallization chloride, and by a decalcification phase C–S–H. The assumption for the following estimation of the chloride corrosion progress, will start to threshold concentration of chloride in the concrete. [13], in his work, proposed a model of the ingress of chlorides in concrete as function of time and depth using the Frick’s second law of diffusion:

$$\frac{\partial C}{\partial t} = D_{cl}\frac{\partial^2 C}{\partial x^2}, \tag{1}$$

where: C is the chloride ion concentration [%] weight of concrete, D_{cl} is the chloride diffusion coefficient in concrete [mm^2/s], t is the time [s], x is depth in the diffusion direction [m].

Assuming that concrete is an homogenous and isotropic material with the initial conditions: when time is zero, the concentration is zero and the chloride surface concentration is constant, then, the chloride ion concentration, $C(x,t)$, at depth x after time s is:

$$C(x,t) = C_s\left[1 - erf\left(\frac{x}{2\sqrt{D_{cl}\cdot t}}\right)\right], \tag{2}$$

where: C_s is chloride surface concentration [%] weight of concrete, *erf* is the error function:

$$erf(x) = \frac{2}{\sqrt{\pi}}\int_0^x s^{-t^2}\,dt. \tag{3}$$

The threshold concentration, C_{th}, is defined as the chloride concentration for which the concrete corrosion begins. The depth of threshold concentration C_{th} at time t, defined as a range of front chloride corrosion, is obtained for two substitutions: $C(x,t)=C_{th}$ and $x=D_{th}(t)$, then Equation (2) becomes:

$$D_{th}(t) = 2\sqrt{D_{cl}t}\,erf^{-1}\left(1 - \frac{C_{th}}{C_s}\right). \tag{4}$$

According to above equations, can be noticed, Sulphate corrosion rate depends on: chloride surface concentration, threshold concentration and chloride diffusion coefficient in concrete. It will be a function of random variables and time.

2.2. Sulphate corrosion

The surface *pH* of growing concrete is between 11 and 13. Calcium hydroxide neutralizes the acids and inhibits formation of bacteria, when the pipe is new. However, as the construction ages, calcium hydroxide is neutralized, the surface *pH* decreases and the sulfuric acid producing bacteria growth accelerates. In the active corrosion zones, *pH* value can drop even to 1.0, which cause a very strong sulfuric acid attack. Generated by protein digestion, the hydrogen sulphide oxidizes to sulphur, which builds up on the pipe wall. Afterwards bacteria *Thiobacillus thiooxidans* oxidize sulphur to the sulfuric acid. Produced acid attacks calcium hydroxide, resulting in the gypsum formation. The gypsum at crystallization increases its volume by 130%, moreover it can react with tricalcium aluminate creating Ettringite (also known as Candlot's salt). Crystallizing Ettringite can increased its volume up to 227% [8]. Formed salts generated additional stresses in the structure, resulting in the surface scratching, cracking until finally pipeline fails.

In general, it’s difficult to design a sewer pipeline system that will be free of Sulphide problems during working life. Thus, it’s useful to know what concentration levels of sulphide can be expected. The major determining factors for sulphide build-up are oxygen, temperature, *pH*, stream velocity, biochemical oxygen demand. The sulphide concentrations in a partly filled sewer will approach a limiting level $[DS]_{lim}$ as follows [12]:

$$[DS]_{lim} = \frac{0.0005 \cdot [BOD_5](1.07)^{T-20}}{(iu)^{\frac{3}{8}}} \frac{P}{b}, \tag{5}$$

where: BOD_5 is the biochemical oxygen demand concentration [g/m^3], T is sewage temperature [°C], i is the slope of the pipeline [–], u is the velocity of the sewage stream [m/s], b is the surface width of the stream [m], P is the wetted perimeter of the pipe wall [m].

The rate of corrosion of a concrete sewer can be calculated from the rate of production of sulphuric acid, which is in turn dependent upon the rate that H_2S is released from sludge digestion. The average flux of H_2S to the wall is therefore calculated as [12]:

$$\Phi = 0.7(iu)^{3/8} j[DS] \frac{b}{P'} \tag{6}$$

where: j is *pH*-dependent factor for proportion of H_2S [–] and P' is the perimeter of the exposed pipe wall [m].

The acid may react partly or entirely. The proportion of acid reacting (k) ranging from 30% (when acid is formed rapidly) to 100% (when it formation is slow). The average rate of corrosion [mm/year] can be calculated as [12]:

$$c = 11.43 k \Phi \frac{1}{A}, \tag{7}$$

where: k is the factor representing the proportion of acid reacting [–], A is the alkalinity [–]. When substituting equation number (7) into (8), received:

$$c = 8.05 k (iu)^{3/8} j[DS] \frac{b}{P' \cdot A}. \tag{8}$$

Therefore, the reduction in wall thickness of a concrete pipe due to sulfide corrosion in elapsed time t, is

$$d(t) = ct = 8.05 k (iu)^{3/8} j[DS] \cdot \frac{b}{P' A} t. \tag{9}$$

To calculations, there are needed some more parameters, such as: stream velocity, wetted perimeter and stream width. These values are depended on wastewater level, according to Figure 1a.

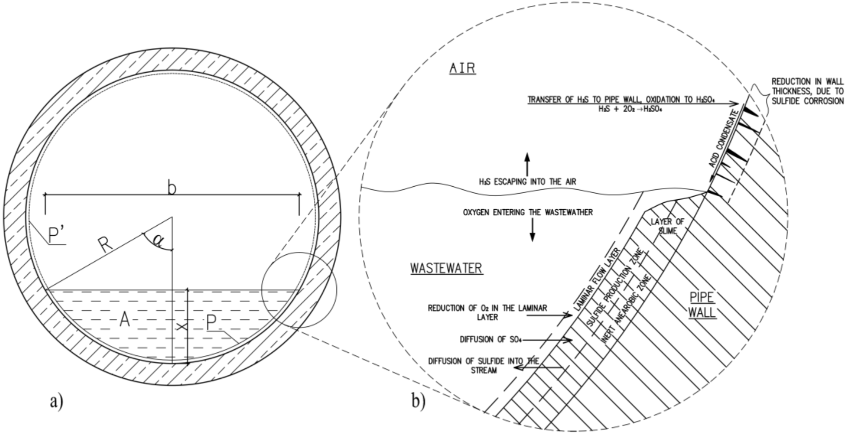

Fig. 1 a) Geometrical dimensions in the pipe cross-section. b) Processes in the sulphate corrosion.

Stream velocity was estimated from Manning's Equation:

$$u = \frac{1}{n} R_h^{\frac{2}{3}} i^{\frac{1}{2}}, \tag{10}$$

where: n is the Manning's coefficient [–] (for concrete n = 0.013), R_h is the hydraulic radius, from equation:

$$R_h = \frac{A}{U}, \tag{11}$$

here A is the stream area [m^2] and U is the wetted perimeter [m].

According to above equations, can be noticed, Sulphate corrosion rate depends on: biochemical oxygen demand concentration, sewage temperature, the slope of the pipeline, pH–dependent factor for proportion of H_2S, proportion of acid reacting and alkalinity of the pipe material. The variability of these parameters are simulating by appropriately selected probability density distributions.

3. Definition of failure for a buried concrete pipe

Moment of the destruction of pipe was the state, where maximal tensile stresses in edge fibres reached flexural tensile strength (as shown in Fig. 2). In practice, invert od pipe is covered by slime, which protects concrete from corrosion influence, so progress of the analysed corrosion cases in invert will be irrelevant. Maximal tensile stresses were checked in characteristic points, for sulphate corrosion: in crown and haunches, due to deposition of acidic condensate on pipe walls (points A and B in Fig. 2). For chloride corrosion only in haunches, due to very limited deposition of chloride condensate on crown area. Values of maximal stresses in edge fibres were calculated according to [1] standard, for constant: subsoil conditions, embedding and covering conditions, groundwater level and foundation level (according to Fig. 2).

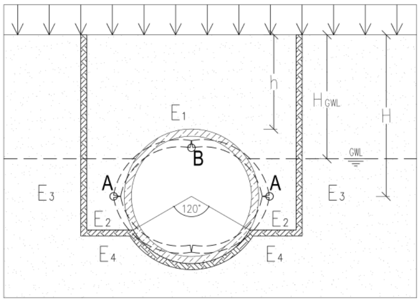

Fig. 2 Model of buried pipeline with collapsing scheme.

In failure mechanical model, random variables were selected as: Young's modulus of backfill, angle of internal backfill friction, traffic loads, uniformly distributed loading q concrete tensile strength.

The randomness were simulated by appropriate probability distributions supported by literature data. We assumed other parameters as deterministic with predicted their less influence for reliability results: concrete (C40/50, $f_{ck} = 40$ MPa, $f_{ctk} = 2.5$ MPa, $E_{cm} = 35$ GPa), pipe type DN800, subsoil as silty sand (siSa), belonging to third soils group G3 from normative [1], ground water level on 1.5 m and pipeline buried 2.0 m below ground level. After passing through the calculations algorithm, it’s necessary to determinate the internal forces in the characteristic points. In this work we present only short resume from code calculations because this procedure is common and well known for engineers. Total bending moment and axial force are sums of the following components: vertical loads (qv indexes), horizontal loads (qh indexes), dead weight load (g indexes), and load from sewage weight (w indexes):

$$\sum M_k = M_{qv}(q,\varphi,s,\mathrm{E}_1) + M_{qh}(\varphi,s,\mathrm{E}_1) + M_g(s) + M_w(s), \tag{12}$$

$$\sum N_k = N_{qv}(q,\varphi,s,\mathrm{E}_1) + N_{qh}(\varphi,s,\mathrm{E}_1) + N_g(s) + N_w(s). \tag{13}$$

Limit State:

$$\sigma_R \geq \sigma_S(q,\varphi,s,\mathrm{E}_1), \tag{14}$$

where: σ_R is the Flexural tensile strength [MPa], σ_S are the tensile stresses in inner and outer edge fibre:

$$\sigma_{S_i} = \frac{N_i(q,\varphi,s,\mathrm{E}_1)}{A(s)} \pm \alpha_k(s)\frac{M_i(q,\varphi,s,\mathrm{E}_1)}{W(s)}, \tag{15}$$

where: $\alpha_k$is the correction factor taking into account the curvature of inner and outer edge fiber [–].

4. Reliability analysis

Probability of failure was estimated using Monte Carlo simulations. Structural failure has been described by limit state function as follows:

$$g(R,S,t) = R(t) - S(t), \tag{16}$$

where: *R(t)* is the resistance function, and *S(t)* is the load effect function. Then probability of failure is equal to:

$$P_f = P[g(R,S,t) \leq 0]. \tag{17}$$

Using the direct Monte Carlo method, the overall probability of failure will be approximately equal to:

$$P_f \cong \frac{n(g(\hat{x}_i)\leq 0)}{N}, \tag{18}$$

where: $n(g(\hat{x}_i) \leq 0)$ is the number of realization which were finished as construction failure, and N is the total number of generated simulations.

Table 1 Statistical data for used random variables.

Variable	Symbol	Probability distribution function type	Probability distribution function parameters		Source of data
			Mean	Est. Dev	
Factor showing the proportion of acid reacting	k	normal	0.8	0.16	[9] Sulphate
pH-dependent factor for proportion of H_2S	j	normal	0.5	0.05	[9] Sulphate
Biochemical oxygen demand concentration	BOD_5	log–normal	350 mg $0_2/dm^3$	40 mg $0_2/dm^3$	[5]
Alkalinity	A	normal	0.2	0.07	[9] Sulphate
Wastewater level	h/D	beta	beta distr. par. $\alpha = 3, \beta = 6$		
Temperature	T	beta	$\alpha = 8, \beta = 6$		[4] Sulphate
Chloride diffusion coefficient	D_{cl}	log–normal	50 mm^2/year	16 mm^2/year	[2] Chloride
Chloride concentration threshold	C_{th}	log–normal	0.40 [%]	0.[%]	[2] Chloride
Chloride on wall surface concentration	C_s	log-normal	0.65[%]	0.078 [%]	[10] Chloride
Internal angle of friction in CM hypothesis	ϕ	normal	25.0°	2.5°	[1] calculation algorithm
Young's modulus	E_1	normal	2.0 MPa	0.2 MPa	[1] calculation algorithm
Load	q	half – normal	half – normal dist. par. $\Theta = 0.125$		[1] calculation algorithm
Concrete tensile strength	σ_R	normal	7.0 MPa	0.70 MPa	[11]

Figure 3 illustrates reliability indexes depending on corrosion type during services live.

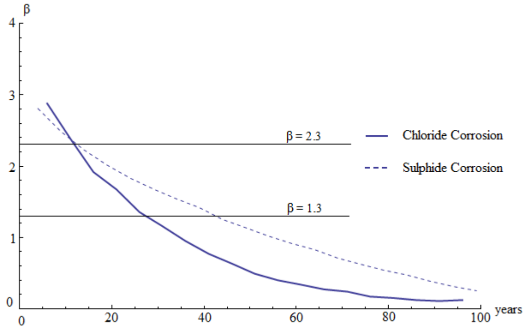

Fig. 3 Reliability Index for both corrosions presented separately.

Final reliability index of sewer pipeline during construction lifetime according to earlier assumptions will be described as follows:

$$\beta_{cor} = min\{\beta_{Cl}, \beta_S\} \tag{19}$$

where: β_{Cl} is the reliability index for chloride corrosion and β_S *for* sulphate corrosion. In early stage of construction life the main influence for reliability index has chloride corrosion after 10 years major role takes sulfate aggressive front.

5. Conclusions

The results show a significant detrimental effect on a construction reliability caused by deterioration. For example, the probability of failure of 0.1 corresponding to relatively little rigorous reliability index β of 1.3, we can expect operational trouble free time is about 27 years (concrete material without protective coating). Due to the high cost of possible repairs and the impact of possible disasters there is a rule to set more challenging security levels of reliability. For β ratio equal to 2.3 the period of trouble free work is expected to be about 10 years. Because of low resistance of concrete there are used various kinds of protection such as anti-corrosion coatings as obligatory elements. The theoretical model to describe corrosion was used random variables with distributions consistent with laboratory and field experiments – [4],[5]. These factors act by naturally random manner to describe nondeterministic phenomenon. The assumption of parallel activity of both type of corrosion was made and solved. The thesis put into operation [12], describing predomination of sulfate corrosion has been confirmed but with expectation for the first period of service. However it is highly recommended to undertake more laboratory results to detailed describe of the progressive deterioration process by the maximum impact of the split-corrosion into material and in the future we are going to undertake clarifying the interrelation of both by chemical composition as the liquid.

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