Life-cycle assessment of buried water-transmission concrete mains

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ABSTRACT: The progressive decline in performance of aged pipes is not always evident in practice, particularly for buried water-transmission mains. A geomechanical approach can provide interesting elements to asses and/or predict their integrity. Simplified Winkler-type models can effectively represent the complexity of soil-pipe interaction. The spatial variability of the soil is necessary to understand how this variability can be used to study the structural behaviour of the buried pipe. The numerical modelling of the soil-pipe system adopted in this study combines different strategies and steps in order to speed up and optimise the computation in an uncertain context that involves the execution of several simulations. The quantification of criticality indicators, in a context of asset management, allows to evaluate the performance of a pipe, according to a reliability approach, with respect to limit states defined in the framework of inspection, maintenance or renewal strategies of the pipelines.

1 INTRODUCTION

The renewal of drinking water buried pipes is necessary because of their "natural" and/or anthropogenic ageing, which leads to a progressive decrease in their performance level. Monitoring, during the implementation of the worksite as well as during the operation of new portions of a linear to be renewed, is an important issue in order to constitute an experimental record of the work. Indeed, this is a way of acquiring a better knowledge of the mechanical behaviour and mechanisms of the soil-pipe system The acquisition of data through the instrumentation of the renewed pipes brings on the one hand, information which is not contained in the data bases or exploitation and on the other hand, allows to validate and to qualify the mechanical/numerical models adopted to study the short- and long-term behaviour of the pipe.

Reinforced concrete pipes consist of a steel cylinder positioned between two layers of concrete (Fig. 1). The concrete not only acts as a passive layer on the steel cylinder core but also serves as a bending reinforcement. The outer concrete cover is reinforced with steel wire coils. These pipes are also known in France as Bonna pipes and are designed and manufactured according to the recommendations of French standards (Afnor 1995).

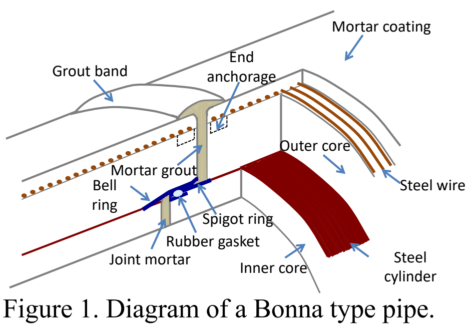


Figure 1. Diagram of a Bonna type pipe.

2 METHODOLOGY FOR LIFE-CYCLE ANALYSIS OF A BURIED PIPELINE

The proposed methodology for buried drinking water pipes aims at optimizing resources for maintenance (Yáñez-Godoy et al. 2017). It is about implementing an efficient risk management during the whole life cycle of the network which leads to associate diagnosis, prognosis and decision making concerning the desired performance (the structural integrity of the pipes, the need to ensure the continuity of the service, etc.). This methodology is based on:

- The acquisition of interesting parameters (e.g. embedded defects generated during pipe laying; long-term defects as corrosion of wires, steel joints or steel cylinder) that are relevant for aging and degradation assessment of concrete pipes
- The use of some of the identified parameters in the previous item as input to geomechanical models to study the behaviour of concrete pipes
- The use of other pipe degradation monitoring parameters (e.g. detection of broken wires; condition of joints) to validate the numerical models and readjust them to improve their predictive function
- The integration of geomechanical models, used in a probabilistic context, in an inspection and maintenance optimization approach

The first three items mentioned above imply a precise follow-up during the installation of the pipes as well as a long-term monitoring of the degradation mechanisms of the pipe materials. These points are outside the scope of this study. The last item (geomechanical models) can be considered in a geomechanical approach and is explained in the following section.

3 GEOMECHANICAL APPROACH

3.1 *Input data*

For the modelling of the geomechanical behaviour of Bonna pipes, it is necessary to build a numerical model which represents the pipe laid in a heterogeneous medium. The input data required for this model include:

- The geometric characteristics of the pipe section: most of these data are the easiest to obtain as there are generic documents from the supplier
- The mechanical characteristics of the pipe section: if the data are not available, the assumptions that can be made will be the most appropriate ones based on the characteristics of typical materials such as steel and concrete
- The geomechanical properties of the surrounding soil: the uncertainties of these data are more easily identified and their treatment is more efficient when geotechnical data are available; pressuremeter tests should be considered for example to determine the Young's modulus of the soil
- The spatial structure of the soil: data from instrumented sites (Yáñez-Godoy et al. 2019) makes it possible to simulate a random field to model the spatial variability of the soil along the axis of the pipe; this random field would make it possible to deduce the response of the structure under certain loading conditions and to observe its sensitivity to differential settling
- The vehicle loading: this data has some sensitivity due to its variability
- The temporal variability of the properties of the soil-pipe system: on the one hand, access to information from databases (e.g. http://www.ades.eaufrance.fr) that record the monitoring of groundwater management for a specific area and for several years seems very relevant in order to assess possible seasonal stresses on the pipe; on the other hand, non-destructive testing techniques (e.g. geophysical measurements with geological radar), would allow the study of natural seasonal fluctuations of the site (soil moisture) and look at their effect on the mechanical behaviour of the structure; this point is outside the scope of this study

3.2 *Geomechanical model*

In order to ensure a safer design of a new pipe or to assess the residual life of an existing buried pipe, a reliable assessment of the soil stresses applied on the pipe due to soil and pipe movement is required. The design of longitudinal pipes in the literature is approached by models which consider pipes as articulated elastic beams laying on an elastic continuum (Yu et al. 2013). These models are grouped in two categories: the local continuous medium models (the soil is represented by a linear or non-linear medium with a mechanical behaviour described by stress-strain relationships) or the global simplified models (the local behaviour of soil is replaced by a simplified mechanical model; the most used common model to represent soil-structure interaction is the unidimensional Winkler model). The rigid or flexible pipes are vulnerable due to generated stresses due to soil displacements. Some studies addressing the influence of settlements on the behaviour of pipes and particularly on the behaviour of joints exist (Buco et al. 2008). The rigidity of joints depends on the used technology and their geometry (flexible joints, welded joints). In order to represent the non-linear and non-homogeneous soil characteristics, spatial variability and uncertainties have to be taken into account.

The pipeline model used in this study consists of a set of pipe segments. Each pipe segment of finite length is decomposed into a number of beams connected to each other by nodes. At the ends of segments, a pair of two independent nodes is used to represent the joints. Each beam element is subjected to a uniformly distributed loading, q, and rests on a soil modeled, according to the Winkler model, by a set of independent springs with a coefficient of subgrade reaction or soil reaction coefficient, k_s, in order to take into account the soil-structure interaction. This model is described by a uniaxial distribution of the form:

$$p(x) = k_s \cdot w(x) \tag{1}$$

with $p(x)$ the pressure applied to the abscissa x, $w(x)$ the displacement in the direction transverse to the abscissa x. The soil reaction coefficient, k_s is not a measurable physical quantity and depends on the properties of the pipe, in addition to those of the soil it is supposed to represent. The determination of its value has been the subject of many studies and several semi-empirical relationships have been proposed (Elachachi et al. 2004). These formulas involve geometric and mechanical characteristics of the pipes as well as mechanical properties of the soil, including the soil modulus, E_s and the soil Poisson's ratio, υ_s. The values derived from these models are not only quite different but also result in values that are widely dispersed. Here, k_s is related to the mean soil modulus, E_s by Vesic model (Vesic 1961):

$$k_s = \frac{0.65}{d} \sqrt[12]{\frac{E_s d^4}{E_p I_p}} \cdot \frac{E_s}{1-\upsilon^2} \tag{2}$$

with E_p the modulus of elasticity of the pipe, I_p the moment of inertia of the pipe, ν the soil Poisson coefficient and d the diameter of the pipe.

The pipe sections and the soil are considered to have a linear behaviour. The main limitation of this longitudinal model is that it is unable to take into account the effects in the cross-section, such as the effect of the internal hydraulic pressure and the effect of the lateral soil, hence the interest in thinking about the coupling of longitudinal and transverse effects, which we have translated into a hybrid model with a transverse model of the pipe cross-section, called 2.5D model.

3.2.1 *2.5D hybrid model*

The model used to represent the studied soil-pipe system was based on 1D (Euler-Bernoulli beam model) and 2D (plane stress model) models. The 1D model allows to obtain the settlement profile of the pipe, as well as the stresses coming from the bending effects. The 2D model allows the evaluation of the various circumferential stresses developing in the cross-section of the pipe, taking into account the transverse effects of the soil and the effect of the internal pressure. The combination of the two models has been named “2.5D hybrid model” (Darwich 2019) as a coupling is taken into account. Placing the pipeline in a frame of reference where the x-axis is the axis passing through the left and right ends of the pipe, the y-axis is the vertical axis, and the z-axis is the longitudinal axis of the pipe (Fig. 2), the assumptions made for this 2.5D modelling result in the combination of two stress systems, based on different assumptions in the state of planar stresses. In the 1D model, the stresses in the cross-section, σ_{xx}, σ_{yy}, and σ_{xy} are assumed to be zero and the axial stress σ_{zz} can vary longitudinally. Whereas in the 2D model, non-zero stresses σ_{rr}, $\sigma_{\theta\theta}$, and $\sigma_{r\theta}$ are sought to be calculated, with the axial stress σ_{zz} assumed to be constant along the pipe. Three points in the thickness of the pipe cross-section are considered at four critical locations: left and right ends and top (crown) and bottom (invert) ends. As the left and right ends are symmetrical, only one end is retained. The combination of stresses for the proposed 2.5D model is based on the following assumption:

$$\sigma_{2.5D} = \sigma_{1D} + \sigma_{2D} \tag{3}$$

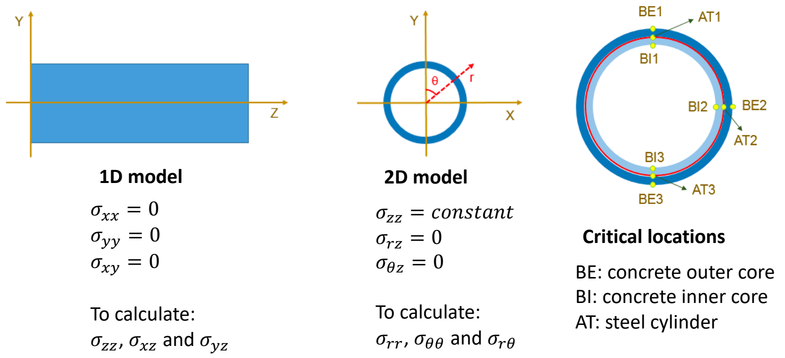


Figure 2. Assumptions for stresses in 1D and 2D models and critical locations in the pipe cross-section.

3.2.2 *Uncertainties and random variability of soil properties*

The variability and/or uncertainty related to soil characteristics and therefore to the soil response coefficient comes from: the soil which is in fact a material with spatial heterogeneity resulting from its deposition and aggregation process; the inaccuracy of measurements; the model's uncertainty. The soil modulus, E_s, is assumed to characterize the spatial randomness of the soil as it is a geomechanical property which is indirectly dependent on soil density and soil moisture. A cross section of a pipe is shown in Figure 3 where the interaction with the soil is done by springs of stiffness k_{sh} for springs not belonging to the support arc of angle α of the pipe and of stiffness k_{sb} for springs belonging to it. k_{sb} parameter is associated with the pipe laying bed supposed to be compacted. This modelling allows to take into account the different horizontal and vertical loads on the pipeline, q_h and q_v respectively, but also the reaction of the laying bed. It should be noted that the vertical loads are mainly due to the weight of the soil and surface overloads due to road traffic or to overlying buildings and structures.

The role of longitudinal variability can be studied by considering random fields (Vanmarcke 1977). Random fields let to model the spatial variability characteristics of k_s through some parameters as the mean value m_{ks}, the variance σ_{ks}^2 and the correlation length l_c. This last parameter is linked to autocorrelation function, $\rho(\tau)$, where τ indicates the distance between two points and describes the spatial structure of the correlation of soil properties. Both parameters, l_c and E_s are important factors for understanding the spatial behaviour of the soil–pipe system (Elachachi et al. 2012, Onyejekwe et al. 2016).

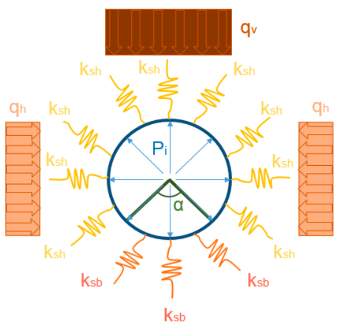


Figure 3. 2D model representing soil-pipe interaction and applied loads, q_h and q_v and internal hydraulic pressure P_i.

3.2.3 *Criticality indicators or performance criteria*

Three main potential failure modes for a buried pipe are identified: an excessive displacement of the pipe; an excessively high stress on the pipe, thus compromising the structural integrity of the pipe; and an excessively high joint opening (which could compromise the tightness of the pipes and result in a drop in pressure, unserved users, etc). These failure modes are linked through three different criticality indicators, I_{cri} $(i = 1, 2, 3)$, which will help to understand which phenomenon or potential event has the highest occurrence. Indeed, the models developed are used in a probabilistic context and allow the formation of a set of performance criteria that are defined from the definition of limit states. The criticality indicators help to optimize pipeline renewal strategies, e.g., through a proactive approach, by identifying alert thresholds, etc. The probabilistic approach makes it possible to identify the areas that are likely to deteriorate in a pipe and to forecast the evolution of the indicators in the long term.

For each of the failure modes, two reliability indices β will be calculated for two distinct limit states:

- The serviceability limit state (SLS), the exceeding of which compromises normal service conditions (induces minor effects)
- The ultimate limit state (ULS), corresponding to the state which, if reached, could lead to damaging consequences at the level of a portion of the pipe or in its totality.

The expression for the reliability index β is given by:

$$\beta = \frac{ln\left\{\frac{R}{S}\left[\left(1+CoV_S^2\right)/\left(1+CoV_R^2\right)\right]^{1/2}\right\}}{\left\{ln\left[\left(1+CoV_S^2\right)\left(1+CoV_R^2\right)\right]\right\}^{1/2}} \quad (4)$$

with R the value of the acceptable stress, S the mean maximum stress, CoV_R the coefficient of variation of the acceptable stress (here taken to be zero, as R is supposed to be deterministic) and CoV_S the coefficient of variation of the maximum stress, assuming that both R and S follow a lognormal distribution. The values of β for the ULS and SLS can be specified by the user according to the standards or the desired performance levels. For example, Eurocode 0 (Afnor 1990) recommends a value of 1.5 for the SLS, which corresponds to a probability of failure of 6.7×10^{-2}, and a value of 3.8 for the ULS, which corresponds to a probability of failure of 7×10^{-5}.

For buried pipes, 3 levels of performance or criticality indicators, I_{cri}, can be considered:

- Safe pipe: no intervention by the manager is necessary; all calculated β values are higher than the value indicated as acceptable, that is to say $I_{cri} = 0$
- Pipe to be inspected: the manager must carry out a follow-up in terms of inspection for the pipe studied; there is at least one computed β value (not several) that is lower than the value indicated as acceptable, that is to say $I_{cri} = 1$
- Pipe to be maintained or renewed: there is a high probability that a failure of the pipe would have occurred; maintenance or renewal is then necessary because several calculated β values are lower than the value indicated as acceptable, that is to say $I_{cri} = 2$

4 CASE STUDY

The case study presented in this section concerns the renewal of a Bonna type pipe of 1100 mm inner diameter in an urban municipality. The pipeline consists of 15 individual segments, each 6 m long, for a total length of 90 m. The pipe is laid at a mean depth of 2 m in a sandy clay soil. The laying quality is assumed to be good. The pipe operating pressure is 6 bar. The static load due to road traffic is considered to be 67 kN/m^2 (mean value). In order to arrange the large amount of input data and outputs, the following sections present the organization process.

4.1 *IT tool for decision-support*

The computer tool developed in Matlab is an autonomous set of scripts allowing to execute, through a graphic interface, a geomechanical computation (in an uncertain context) of a buried pipe. It allows, according to parameters given by the user such as the geometrical, mechanical or geotechnical characteristics, to obtain as output of a probabilistic computation:

- The values of maximal displacements, stresses and joint opening angles
- Then, by post-processing, quantify and display on a window, criticality indicators that will indicate to the user the global state of the pipe and thus know, thanks to the model, where the pipe is in terms of structural integrity and tightness (these are the two monitored performances)

4.2 *Data acquisition from available databases*

The characteristics of the concrete pipe, the geomechanical properties and the loads and boundary conditions are shown in Table 1.

Table 1. Characteristics of the soil-pipe system.

Geometrical characteristics	Mechanical characteristics
Inner diameter: 1100 mm Number of pipe segments: 15 Pipeline length: 90 m Thickness: 88 mm Burial depth: 2 m Type of joint gasket: welded	Young's modulus of concrete: 30 GPa Young's modulus of steel: 210 GPa Diameter of steel wire: 10 mm Number of steel wires per meter: 25
Geomechanical properties	
Type of soil: sandy clay Volume weight of the backfill: 20 kN/m^3 Soil modulus: 125 MPa Poisson coefficient: 0.4 Modulus of subgrade reaction: 58.78 MN/m^3 (calculated by Vesic model) Quality of the pipe laying bed: good	
Loads and boundary conditions	
Internal pipe pressure: 6 bar Intensity of rolling surface loads: 67 kN/m^2 Ratio of horizontal to vertical stresses in the pipe (this parameter depends on both the quality of the pipe laying bed and the type of soil): 1	
Threshold values for the limit states	
Circumferential pipe stresses: SLS: 5 MPa; ULS: 8 MPa Pipe displacement: SLS: 30 mm; ULS: 60 mm Pipe joint opening: SLS: 0.01°; ULS: 0.02°	

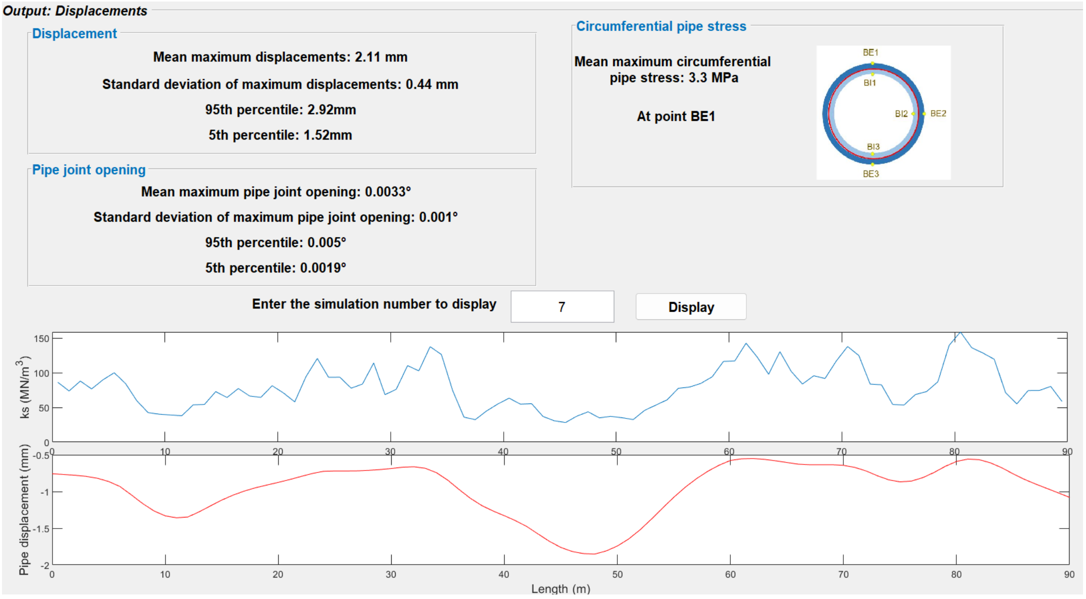
4.3 *Data acquisition by instrumentation of a pipe: correlation length of soil modulus*

The experimental acquisition of quantities of interest such as the correlation length, l_c, of soil properties was presented in (Yáñez-Godoy et al. 2019). Results in (Yáñez-Godoy et al. 2017) showed that for horizontal l_c values between 6 and 18 m, the increase in the probability of failure of the pipeline (i.e., the reliability index decreases) is greater than for smaller values. A forthcoming study by the authors suggests that the horizontal l_c of the soil below the pipeline could have a more important effect on the structural integrity of the pipe. The spatial variability below the pipeline was assumed to correspond to the soil modulus parameter, E_s, in the model.

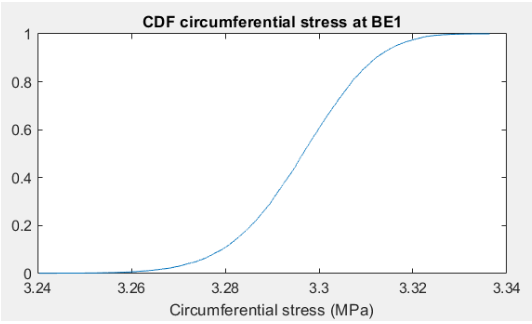
From these studies we know that for the correlation length of E_s a mean value of 6 m is a good choice for assessing the effects of spatial variability. A coefficient of variation, COV, of the order of 0.5 (relationship between the standard deviation and the mean value of E_s) is taken into account, it will define the variability of this parameter. Although naturally the variability of E_s can be very large, in the case of non-linear soil behaviour problems, very high values of COV (higher than 0.5) tend to a numerical non-convergence of the result.

4.4 *Tool outputs: geomechanical responses of the pipe*

The values of the calculated stresses, displacements and joint openings are shown in Figure 4. For all N simulations ($N = 1 \times 10^4$), the mean and standard deviation of the maximum values of the three relevant outputs and the 5% and 95% fractiles of the maximum displacements and pipe joint openings are calculated (top of Fig. 4a). It is possible to display for each of the simulations performed (here, simulation number 7 at the bottom of Fig. 4a) the spatial variability of the modulus of subgrade reaction in parallel with the displacement of the pipe. In particular, Figure 4b shows the cumulative distribution function of the circumferential stress at the point BE1 of the pipe where the mean maximum value occurs.



(a)



(b)

Figure 4. (a) Values of the calculated stresses, displacements and joint openings; (b) Cumulative distribution function of the mean maximum circumferential stress at the point BE1 of the pipe.

4.5 *Tool outputs: criticality indicators of the pipe*

In the IT tool, three criticality indicators are present. They are calculated by the method described in 3.2.3 and allow a quick understanding of whether or not an intervention should be considered on the studied pipeline. Figure 5, shows that the three indicators are green, which means that for the three main failure modes, the study has not revealed any particular risk.

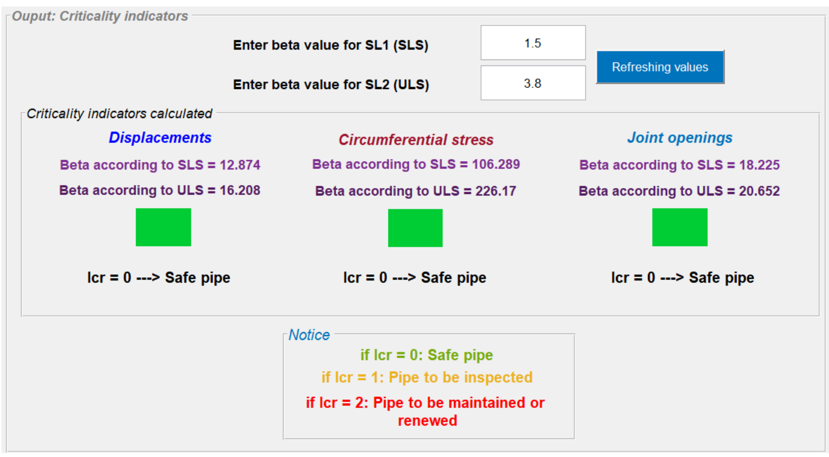


Figure 5. Criticality indicators of the pipe.

5 CONCLUSIONS

This study presented the different steps of a geomechanical approach to allow a drinking water network manager, thanks to an IT tool, to evaluate its performance with regard to the different performance criteria. These steps aim to optimise the resources allocated to asset management through an effective life cycle risk management process. The experimental campaigns provide access to key elements for the understanding of the soil-pipe behaviour. Indeed, these elements provide a good knowledge of aspects that are not sufficiently known, such as soil variability, on real sites with pipelines in operation. The coupling of the geomechanical approach with durability aspects, which take into account degradation kinetics, is feasible and constitutes a very complete analysis tool. This IT tool can provide experts with decision elements for better safety calibration in soil-pipe interaction problems where soil variability is an influential parameter.

6 ACKNOWLEDGMENTS

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