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# Geomechanical behaviour of large diameter pressure water pipelines in unidimensional heterogeneous soils

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**Abstract:** A follow-up methodology of pressure buried concrete pipelines is given in this paper. The methodology allows to acquire a better knowledge of the determining factors of the mechanical behaviour of the pipelines in order to optimise the asset management. A bidimensional geo-mechanical finite element model of a pipeline, which integrates the spatial variability of the soil, is considered to illustrate the methodology. The results show the influence of the variability of the soil on the structural integrity of the pipe at a given time.

## 1 Introduction

Asset management of drinking water supply aims at maintaining the infrastructure facility in satisfactory condition in relation to technological, environmental, societal and/or socio-economic issues. Asset management includes the process of acquiring information (and its storage in the form of databases), the assessment of the performance of the infrastructure facility (by defining indicators/criteria [13]) and the refurbishment of elements or subsystems considered faulty or as being at risk. The current strategies and action programs (inspection, maintenance or refurbishment) concerning the asset management are applied at two scales:

- at the global (asset) scale, where the aim is to define the maintenance budgets;
- at the local (element) scale, where the aim is to justify the types and priorities of intervention and to establish a model for this intervention.

Statistical methods are well adapted to asset scale. At the element scale, management strategies are generally based on an expert knowledge. Some of these strategies are hardly formalised and partially meet alignment priorities. In fact, the elements in the decision-making process are defined with a partial vision of the system: available data are limited or absent, the degradation kinetics for this kind of pipelines are badly known, the numerical models to assess future degradation trends are rarely available and the effect of decisions taken by the asset managers is uncertain. Consequently, some elements in the main water supply are probably replaced at an early stage whereas others subjected to a much higher risk are ignored.

This paper aims firstly to give a proposed follow-up methodology of large diameter pressure pipelines. The main interest is to model, at the element scale, the behaviour of buried pipelines precisely from the point of view of the geo-mechanics and the physico-chemistry (soil-pipe-water flow interaction and durability). These aspects can bring additional value and acquire an important knowledge of some determinants of mechanical behaviour of pipelines. This information can then be used by asset managers to optimise the resource flows at the global scale.

A case study illustrates the follow-up methodology by considering a bidimensional geomechanical finite element model of a pipeline. This model integrates the spatial variability of the soil

which is modelled by a 1-D normal stationary random field (in the direction of the longitudinal pipe axis) generated by means of the Fast Fourier Transform method. For the case study, the spatial variability approach followed in [23] is used. The post-processing of results would then allow to assess the risk a pipe presents during operational service at a given time with respect to some limit state performance criteria (e.g. the structural integrity).

## 2 Follow-up methodology of large diameter pressure water pipelines

A proposed follow-up methodology of concrete pipes transporting drinking water under high pressure is discussed in this section. This methodology can be based on:

- the acquisition of interesting orders of magnitude which are relevant to the aging and the degradation of the concrete pipes;
- the use of some of the orders of magnitude cited above as data input into geomechanical models to study the behaviour of concrete pipes;
- the use of other orders of magnitude as following-up parameters of degradation to validate the models and to readjust them in order to enhance their predictive function;
- the integration of geomechanical models, used in a probabilistic context, into an optimisation approach for inspection and maintenance.

The methodology intends to optimise the resources for maintenance and thus to set up an efficient risk management which leads to associate the diagnostic, the prognostic and the decision-making concerning the desired performances (the structural integrity of pipes, the need to ensure continuity of service...). The different steps of the methodology are illustrated in Figure 1. They are described in the next sections.

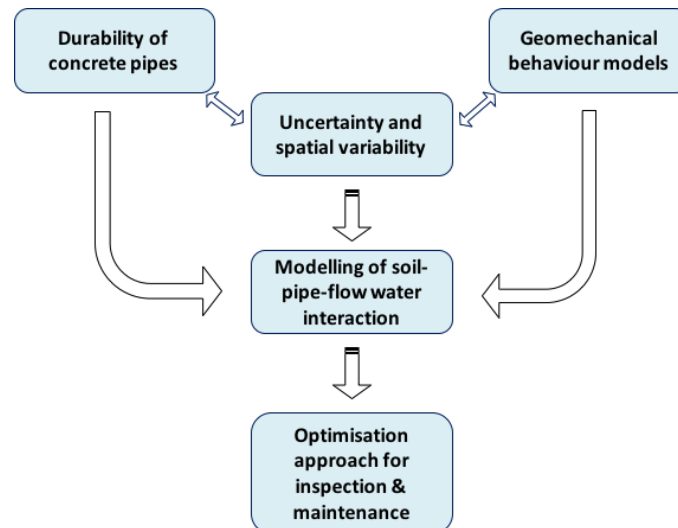


Figure 1: Steps of the follow-up methodology of concrete pipes

### 2.1 Durability of concrete pipes

#### 2.1.1 Concrete pressure pipes

Concrete pipes offer important benefits in relation to steel pipes since they resist to corrosion under severe conditions and they are a cost-saving solution to the renewal of old iron pipes. The most widely used type of concrete pipes to transport drinking water under high pressure are: (i) the lined cylinder pipe, this is a steel cylinder lined with a concrete core and (ii) the embedded

cylinder pipe, this is a steel cylinder embedded in a concrete core. These concrete pressure pipes are also known as *bonna pipes*. Figure 2 shows this kind of pipe such as those built in North America (USA) or in Europe (France). The outside diameter of this pipe is 250–4000 mm and its operational length is 2–6 m. The external concrete revetment is strengthened with steel wires. When steel wires are prestressed, the pipes are also known as Prestressed Concrete Cylinder Pipes, PCCP. Otherwise, they are known as Reinforced Concrete Pressure Pipes, RCPP.

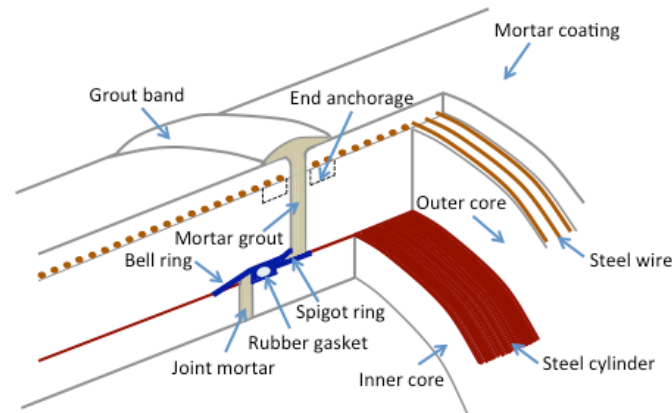


Figure 2: Diagram of a bonna pipe

### 2.1.2 Degradation mechanisms

The failure of bonna pipes because of the corrosion is progressive. In fact, such failure involves successive cracks in the vicinity of the circumferential steel wires as a consequence of stresses related to corrosion process. Global failure can be analysed, according to [20], by assessing the residual resistance of the pipe (evaluation of the tensile stress of the concrete under both the operational service and a transient pressure surge) resulting from damages following the loss of local corroded wires and therefore, when this is the case, the loss of prestress. The stress corrosion cracking usually causes abrupt brittle ruptures and does not show any signs of visible damage.

Concerning prestressed concrete pipes, when a broken wire due to corrosion occurs, a lump will often form at the surrounding area of the mortar layer. The effects of corrosion on the integrity of the pipe are then studied from the inspection of the damaged areas. For example, monitoring techniques as acoustic monitoring ([7], [17]) are used to detect broken prestressed wires. These monitoring techniques (generally used on visible pipes) let the asset managers identify an early detection of corroded zones (detection of macro-cracks and propagation of cracks) thus enabling the time to respond to an eventual rupture of the system. Nonetheless, these techniques can also be limited [7]. In fact, the assessment of broken wires in the joint zone is very difficult.

The state of joints is also important. For example, [8] presents prestressed pipe breaks due to both the corrosion in the joint because of a thin mortar layer and the corrosion in the steel cylinder area near to joint. The combination of degradation mechanisms leads to an accelerated failure of pipes. A physical model which estimates the failure of a pipe has to include at least two models: one that describes the degradation process and another one that describes the geo-mechanical aspects.

## 2.2 Geomechanical behaviour models

The design of longitudinal pipes in the literature is approached by models which consider pipes as articulated elastic beams laying on an elastic continuum ([9], [10], [24]). These models are grouped in two categories according to [1]:

- 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; these models can be solved by 2-D or 3-D numerical techniques limited to finite dimensions of the system ([2], [11], [16]);
- 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 ([5], [6], [9], [10]).

The rigid or flexible pipes are vulnerable due to stresses generated by soil displacements. Generally, the settlements of pipes are often underestimated or neglected during the design phase. Some studies addressing the influence of settlements on the behaviour of pipes and particularly on the behaviour of joints exist (e.g. [18]). The rigidity of joints depends on technology and geometry (flexible joints, welded joints). A realistic numerical value of joint stiffness remains very difficult to identify, although some laboratory experiments have focused on this issue [3].

## 2.3 Uncertainties and spatial variability

In order to represent the non-linear and non-homogeneous soil characteristics, spatial variability and uncertainties have to be taken into account. According to [5], for a Winkler model, the non-linear aspects of the soil behaviour can be modelled by considering some types of law such as  $k(t)$  and  $k(w)$  (where  $k$ , represents the coefficient of subgrade reaction). The first one describes the progressive degradation of the soil properties and the second one the non-linear soil characteristics.

According to [4], the variation of parameter  $k$  is not necessarily due to spatial variability of soil properties but to uncertainties of a chosen model. On the other way, whether empirical model of  $k$  is given or not, the impact of spatial variations of  $k(x)$  needs to be measured. According to [6], the role of longitudinal variability can be studied by considering random fields (e.g. [21]). Random fields let to model the spatial variability characteristics of  $k$  (or of the soil properties as the Young modulus of the soil  $E_s$ , the poisson ration of the soil  $\nu_s, \dots$ ) through some parameters: the mean value  $m_k$ , the variance  $\sigma_k^2$  and the correlation length  $l_c$ . This last parameter is linked to autocorrelation function  $\rho(\tau)$ , where  $\tau$  indicates the distance between two points and describes the spatial structure of the correlation of soil properties.

A statistical post-processing of results allows the analysis of the effect of soil variability on the pipe mechanical behaviour. For example, it would be interesting to know more about the influence of both the correlation length of the soil and the joint stiffness [5] on the local mechanical loadings for a transversal section of pipe. Another question arises about how to translate the results of simulations in terms of risk analysis of pipes [6]: for example, from a probabilistic view by the analyse of the distribution functions in order to assess the risk of exceeding certain displacement or stress thresholds; from a reliability view by the assessment of both the limit states functions and the reliability indices.

## **2.4 Modelling of soil-pipe-flow water interaction**

Modelling the behaviour of soil-pipe-flow water interaction remains limited in the literature. In fact, this behaviour is a complex three-dimensional problem that requires very sophisticated numerical models expected to make use of robust soil models (elastic-plastic perfect model, Cam-Clay modified model, non-linear elastic model, elastic-plastic strain hardening model). The soil is a multi-phasic material, it is not easy to forecast its behaviour with respect to materials as steel or concrete and its properties can strongly vary in an entirely different area. Furthermore, a soil is a highly heterogeneous material, and this heterogeneity is proving to be the main cause of both uncertainty and variability. The variability may also involve another feature called “regionalizing data” [4]. This means that the soil properties (permeability coefficient, porosity, internal angle friction, water content, etc.) in two adjacent points of the material (in both vertical and horizontal direction) are statistically closer than the measured ones in two more remote points. The soil properties can then be considered as spatially structured and therefore allow the use of autocorrelation functions making possible to identify the distance (correlation length) from which soil properties become independent [6]. The dispersion of soil properties also needs to be determined (standard deviation or coefficient of variation).

In order to ensure a safer design of a new pipe or to evaluate the residual life of an existent buried pipe, a reliable assessment of soil stresses on the pipe due to soil-pipe displacements is necessary. What we have to keep in mind is that the behaviour of a pipe depends on the stiffness of each section of the pipe, on the position, the stiffness and the behaviour of the ring joints and on the nature of the soil displacements.

## **2.5 Optimisation approach for inspection and maintenance**

This step is the keystone of the follow-up methodology. Here, the construction of both the global methodology and a suitable numerical tool has to allow a coherent link in line with early needs expressed by an asset manager. The optimisation approach is thus based on the assessments/forecasting (outputs) of the precedent steps. These outputs become then interdependent and each of them constitutes one brick or module that has its place into a global numerical tool.

## **3 Case study**

The follow-up methodology of concrete pipes is purposefully focused on the modelling of soil-pipe-flow water interaction system taking into account both the geomechanical behaviour of the pipe and the durability. The interaction between the different steps of the methodology (Figure 3) is explained in this section. The steps “Geomechanical behaviour models” and “Durability of concrete pipes” have a double dimension: experimental observations and theoretical models. The experimental observations allow access to data not available in current database and that are needed to a better understanding of the involved physical mechanisms as well as to validate and to qualify the developed models. The main purpose of the probabilistic and reliability approaches (time-variant type) involved in the step “Uncertainty modelling and Spatial variability” and applied to the developed models in the other steps (“Geomechanical behaviour models” and “Durability of concrete pipes”) is to assess the risk a pipe presents during operational service in relation to limit states to be defined. Updating of probabilistic distributions of pathological indicators through the identified degradation models in step “Durability of concrete pipes” would be considered. In fact, the probabilistic approach will, in particular, help to confirm both the forecasts on the sensitive zones to degrade with time and the forecasts

for the key performance indicators over the long term. These approaches bring to risk/asset managers essential elements for an optimal inspection and maintenance policy decision-making.

The case study, presented in Figure 4, illustrates the follow-up methodology. This is a mechanical model constituted by a concrete pipeline buried in a soil. It was developed within the CAST3M finite element computer code (<http://www-cast3m.cea.fr>). The characteristics of the concrete pipeline (48 m length), constituted by 8 individual pipe segments (each of 6 m length), are given in Table 1. A combination of self weight (pipe, soil, water), service pressure (600 kPa) and working load (62 kPa on the compacted layer above the two central pipe segments) is considered. The depth dimension of the natural ground corresponds to the dimension normally used in the literature (above 5 times the external diameter of the pipe [19]). The pipe is modelled with planar elements and is assumed to act in an isotropic and linearly elastic manner. The mechanical model employs the Mohr-Coulomb model to describe the soil behaviour. The interfaces between the soil and the structure and between two individual pipe segments are modelled using joint elements. These are numerical interfaces with small thickness values, very close or equal to zero.

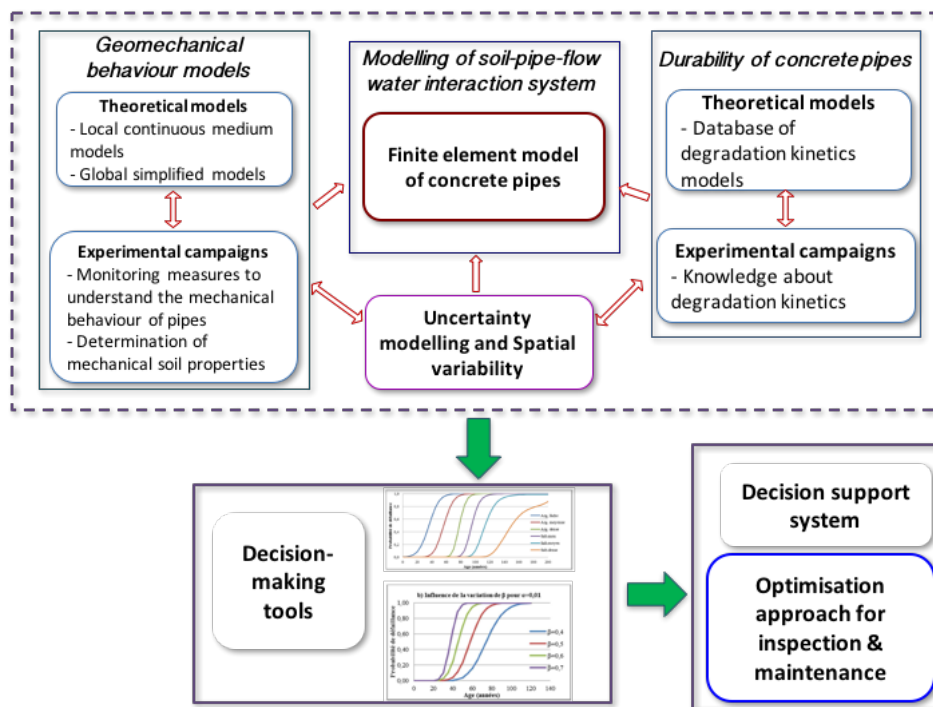


Figure 3: Interaction between the different steps of the follow-up methodology of concrete pipes

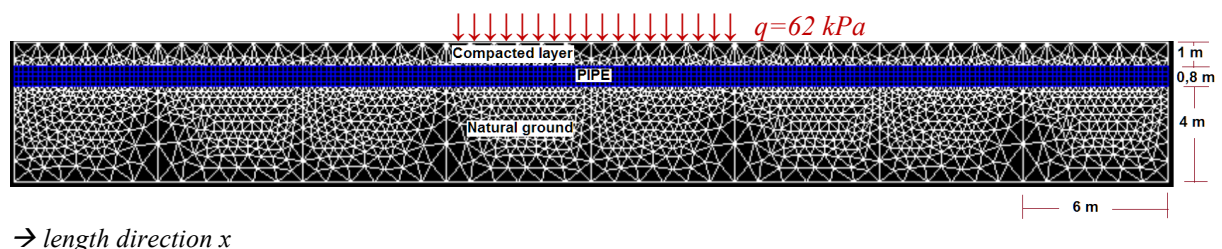


Figure 4: Finite element mesh used for the case study

Table 1: Concrete pipeline and surrounding soil characteristics

Geometrical concrete pipe characteristics	Surrounding soil characteristics		Loading
Total length: $L = 48$ m External diameter: $D_{\text{ext}} = 0.8$ m Thickness: $e_p = 0.072$ m Pipe length: $l_p = 6$ m Young's modulus of bonna pipe: $E_c = 36$ GPa (short-term strength) Poisson coefficient of bonna pipe: $\nu_c = 0.2$ Young's modulus of steel joint: $E_j = 210$ GPa Poisson coefficient of steel joint: $\nu_j = 0.3$	<i>Compacted layer:</i> <ul style="list-style-type: none"> <li>Depth: <math>H_{s1} = 1</math> m</li> <li>Young's modulus: <math>E_{s1} = 50</math> MPa</li> <li>Friction angle: <math>\varphi'_1 = 25^\circ</math></li> <li>Poisson coefficient: <math>\nu_{s1} = 0.3</math></li> <li>Cohesion: <math>c_1 = 1</math> kPa</li> <li>Dry unit weight: <math>\gamma_1 = 20</math> kN/m<sup>3</sup></li> </ul>	<i>Natural ground:</i> <ul style="list-style-type: none"> <li>Depth: <math>H_{s2} = 4</math> m</li> <li>Young's modulus: <math>E_{s2} = 6</math> MPa</li> <li>Friction angle: <math>\varphi'_2 = 25^\circ</math></li> <li>Poisson coefficient: <math>\nu_{s2} = 0.35</math></li> <li>Cohesion: <math>c_2 = 1</math> kPa</li> <li>Dry unit weight: <math>\gamma_2 = 20</math> kN/m<sup>3</sup></li> </ul>	<ul style="list-style-type: none"> <li>Service pressure: <math>W_p = 600</math> kPa</li> <li>Working load: <math>q = 62</math> kPa</li> </ul>

A sensitivity analysis would be necessary to identify the most sensitive parameters in order to simplify probabilistic computations. In this case study, the natural randomness of the soil is considered by looking at the Young's modulus  $E_{s2}$  (natural ground) as a sensitive parameter. The other parameters (geotechnical and geometrical concrete pipe parameters, external and internal loading) are considered as deterministic. A normal probabilistic distribution is considered for the uncertain Young's modulus  $E_{s2}$  parameter. Mean value is  $\mu_{E_{s2}} = 6$  MPa, a coefficient of variation, COV (10%, 20% and 30%), is applied to  $\mu_{E_{s2}}$ , standard deviation is then  $\sigma_{E_{s2}} = COV \times \mu_{E_{s2}}$ .

The normal distribution is adopted to generate simulations of the random field of  $E_{s2}$ , with the soil length direction  $x$ , according to Figure 4. The normal inverse cumulative distribution function,  $F^{-1}$ , is obtained as follows:

$$E_{s2}(x) = F^{-1}(F(M(x)|\mu, \sigma)) \quad (1)$$

where  $F(M(x)|\mu, \sigma)$  is the cumulative distribution function of a zero-mean,  $\mu$ , normal random process,  $M(x)$ , with  $\sigma = \sigma_{E_{s2}}$ . The random field is generated by using the fast Fourier transform method ([15], [22]). The generated  $M(x)$  process associates a single exponential correlation function  $\rho(\tau)$  defined as:

$$\rho(\tau_H) = \exp\left(-2 \frac{|\tau_H|}{\delta_H}\right) \quad (2)$$

where  $\tau_H$  and  $\delta_H$  are the distance between data points in the random field and the correlation length of  $E_{s2}$  in the soil length direction  $x$ , respectively.

The internal and external degradations of the pipe are expressed in a comprehensive manner as follows:

$$e(t) = e_0(1 - \alpha\sqrt{t}) \quad (3)$$

where  $\alpha$  is a coefficient that represents the kinetics of degradation front motion in the concrete material and depends on the local degradation conditions;  $e_0$  and  $e(t)$  are respectively the initial thickness and the thickness of the pipe at a given time  $t$ .

Three dysfunctions leading to an exceedance of a limit state can be defined:

- the structural integrity
- the hydraulic performance
- the tightness dysfunction

Only the structural integrity is considered in this case study. This is expressed in terms of bending stresses with a limit state function that assesses the cracking state for a concrete pipe as:

$$g_\sigma = \sigma_R - \sigma_S \leq 0 \quad (4)$$

where  $\sigma_R$  is the yield tensile strength of concrete (mean = 2.2 MPa, standard deviation = 0.1 MPa) and  $\sigma_S$  is the maximum bending stress computed with the mechanical model (Figure 4).  $\sigma_R$  and  $\sigma_S$  are considered to follow Lognormal distributions. The Hasofer-Lind reliability index  $\beta$  is defined as [12]:

$$\beta = \frac{\ln \left\{ \frac{R}{S} [(1 + COV_S^2)/(1 + COV_R^2)]^{1/2} \right\}}{\{ \ln[(1 + COV_S^2) \times (1 + COV_R^2)] \}^{1/2}} \quad (5)$$

where  $R, S$  are respectively  $\sigma_R, \sigma_S$  and  $COV$  is their coefficient of variation. The corresponding probability of failure is  $P_f = \Phi(-\beta)$ . The target value of  $\beta$  to be reached in Eurocode 1 is equal to 1.5 for the serviceability limit state (SLS) [14].

Figure 5a presents the results of the variation of the reliability index in function of time for four values of correlation lengths varying from 3 m to 60 m (in Figure 5a,  $\lambda$  is the ratio between the correlation length  $l_c$  and the pipe length  $l_p = 6$  m). The variability of Young's modulus in natural ground, that is to say, the coefficient of variation  $CV$  of  $E_{s2}$ , is fixed to 0.1. The number of simulations for each step of time is 300. The initial state is considered at  $t = 0$  years. The target value of  $\beta$  is not attained over the life span of the pipeline (70 years). As observed in Figure 5a, when  $l_c = 60$  m ( $\lambda = 10$ ), the index  $\beta$  has almost the same values that  $l_c = 3$  m ( $\lambda = 0.5$ ). These four values of  $\lambda$  let to suppose an interval (between 3 m and 18 m) where the correlation length value would be the most representative to assess the index  $\beta$ .

Figure 5b shows the effect of  $CV$  of  $E_{s2}$  on the variation of the index  $\beta$  for  $\lambda = 0.5$ . As it can be seen from Figure 5b, the longer the dispersion of  $E_{s2}$  (highly heterogeneous soil) the longer its notably effect on the early achievement of the target value (about  $t = 40$  years).

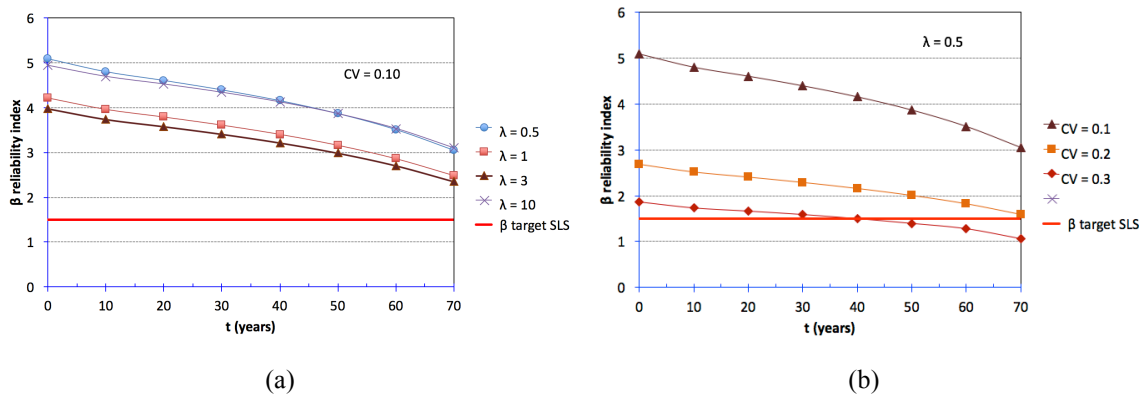


Figure 5: Variation of the reliability index, (a): four correlation lengths varying from 3 m to 60 m, (b): effect of  $CV$

This case study shows the need to take the soil spatial variability into account. In fact, a significant impact on the assessment of the reliability index is observed over time. These tools can provide experts with decision-making elements for an improved calibration of safety in soil-structure interaction problems when the soil variability is an important parameter.

## 4 Conclusions

In this paper, a general vision was presented to optimise the management of pipelines through a follow-up methodology. This provides a best understanding of the mechanical behaviour of buried concrete pressure pipes. Furthermore, an emphasis was also placed on the effect of different mechanisms of degradation, particularly the corrosion, and the effect of the surrounding soil on both the spatial-temporal behaviour and the integrity of a pipeline. Although these effects can be studied separately, it seems necessary to take into account all the possible interactions and the relevant physico-chemical phenomena and the application of a “mechano-probabilistic/reliability” approach to acquire a better apprehension of both the risk involved at a given time (structural integrity, service disruption,...) and the long-term life of the structures. Experimental campaigns would allow to access some determinant elements as the soil-pipe interaction, the effects of the soil variability and the degradation kinetic of the main structural components of the pipe. In fact, these key elements that let a better understanding of the physical of different coupled systems in concrete pressure pipes are not well enough known. These experimental campaigns will make it possible to validate and to qualify the numerical decision-making tools. The different steps of the follow-up methodology of concrete pipes proposed in this paper intend to optimise the resources allocated to the asset management by an efficient risk management process.

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