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Simplified uncertainties analysis of continuous buried steel pipes on an elastic foundation in the presence of low stiffness zones

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ABSTRACT

In conventional design, continuous buried steel pipes are designed based on their transverse behavior where low stiffness zones of soil, uncertainties in soil and structure properties are not considered. Winkler's analytical model and the FOSM method are used to estimate uncertainties in terms of the coefficient of variation in the differential settlement (CV_{Δ}) and the bending moment (CV_M) as the function of the uncertainties in the subgrade reaction modulus (k_s) and the low stiffness zone length beneath the pipe. Results show that the values of CV_{Δ} and CV_M are very different depending on the uncertainties of k_s and the length of the low stiffness zone.

1. Introduction

If all the parameters influencing buried pipes performance were known (or could be determined) then the decision making process associated for their optimal use and maintenance would be relatively straightforward. However, when trying to forecast service life, uncertainties arise when considering the natural variability of the soil properties and the uncertainty in the geometrical and the mechanical properties of the structure. Consequently, the management of buried pipe networks is based on uncertain or incomplete information.

Continuous buried steel pipes, like oil and gas transmission networks for example, undergo disorders which are correlated with uncertainties in the soil properties and the geometrical dimension of the structure, along the longitudinal direction which lead to relative differential settlements. These settlements can induce cracking and consequently liquid leakages which, in their turn, by modifying the characteristics of the surrounding medium, induce additional settlements. In conventional design and dimensioning computations, the transverse behavior of buried pipe is taken into account but the soil–structure interaction is often neglected. The difficulty lies in modeling the soil–structure interaction along the longitudinal direction of the buried pipe in order to perform an accurate analysis leading to a correct design.

Different analytical models are used for the study of soil–structure interaction on an elastic soil such as Winkler's model [1], Pasternak and Vlassov's models [2,3] and Kerr's model [4–6]. The common parameter for these models is the modulus of soil reaction (k_s).

The finite element method has also been used in numerous studies: Dubost et al. [7] and Niandou and Breysse [8] analyzed soil–pile interaction, Elachachi et al. [9–11] and Buco et al. [12–14] studied soil–buried pipe interactions. However, in order to simplify the soil–structure interaction, analytical approaches can be used [15–18].

In this paper, we are interested in the influence of the uncertainties of the soil properties and the geometrical and the mechanical properties of pipes in the particular case where a differential settlement may appear due to the presence of low stiffness zones on a construction site. This can be observed on alluvial terraces where rapid changes between sand and clay are common [19,20]. A low stiffness zone of soil beneath the pipe can lead to pipe breaking or even collapse of an overlying pavement.

Six semi-empirical models, the most commonly used in buried pipes design, are chosen to determine a value of the subgrade reaction modulus (k_s). This modulus is not an intrinsic parameter of soil; it depends on the mechanical parameters of soil and mechanical and geometrical parameters of the structure.

First, FOSM (First Order Second Moment) and SOSM (Second Order Second Moment) methods are used on these semi-empirical models to estimate the uncertainty of k_s from the uncertainties on the soil and the structure parameters and to determine the most influential parameters on this uncertainty. The analytical

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equations of the deflection and the bending moment from the Winkler model are then used and combined with the FOSM method in order to determine the uncertainty in the differential settlement and the bending moment for different lengths of low stiffness zones along a pipe.

2. Methods and models

This section explains the different soil–structure interaction models and presents the six semi-empirical models which give the coefficient of subgrade reaction. The calculation methods of the coefficient of variation based on the first order (FOSM) and the second order (SOSM) of the Taylor series are additionally discussed in this part.

2.1. Soil–structure interaction model

In the conventional calculations of the continuous steel pipe network design, the behavior is only modeled in a cross section to represent the transverse behavior of the pipe elements. In the case of a buried pipe and especially when a differential settlement may appear, the longitudinal behavior of the pipe should be studied.

In the past, many researchers have worked on the soil–structure interaction which is referred to as beams and plates on elastic foundations. Most of the previous work began with Winkler's well known model with one parameter [1], which was originally developed for the analysis of railroad tracks. This model is expressed by the following formula (Eq. (1)):

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

where k_s is the coefficient of subgrade reaction (or constant of proportionality of Winkler in $[F/L^3]$), $w(x)$ is a vertical displacement (settlement), b is a width of the foundation (d in the case of buried pipes) and $p(x)$ is the reactive pressure of the foundation. Winkler's idealization considers the soil as being a system of identical but mutually independent, closely spaced, discrete, linearly elastic springs. One of the most important deficiencies of Winkler's model is that a displacement discontinuity appears between the loaded and the unloaded part of the foundation surface. Furthermore this model cannot transmit the shear stresses which are derived from the lack of spring coupling [21,22].

Vlassov and Leontiev [3], recognizing the difficulty to determine values of k_s for soils, postulated a two-parameter model. Vlassov's model considers the effect of the shearing interaction between neighboring soils. Kerr [4] attempted to make Winkler's model more realistic by assuming some forms of interaction among the spring elements that represent the soil continuum (three-parameter mathematical model).

Since the second and third foundation parameters are difficult to estimate, we chose to use Winkler's analytical model which seems, from a practical point of view, to be appropriate for buried pipes [9].

The differential equation governing the deflection, $w(x)$, of a homogeneous elastic bending beam with constant bending stiffness resting on Winkler's model and subjected to a transversal continuous load, $q(x)$, can be written as [23]:

$$E_p \cdot I \frac{d^4 w(x)}{dx^4} + k_s \cdot b \cdot w(x) = q(x) \tag{2}$$

where E_pI is the constant bending stiffness of the beam (E_p and I are respectively Young's modulus of pipe and the moment of inertia of the cross section of the structure). Eq. (2) is a continuous differential equation whose general solution $w(x)$ is the sum of the solution $w_0(x)$ of its homogeneous part and of a particular solution $w_q(x)$. The solution $w_0(x)$ has the following form [23]:

$$w_0(x) = e^{\beta x}(C_1 \sin \beta x + C_2 \cos \beta x) + e^{-\beta x}(C_3 \sin \beta x + C_4 \cos \beta x),$$
$$\beta = \left[\frac{k_s \cdot b}{4E_p \cdot I}\right]^{\frac{1}{4}} \tag{3}$$

The expression of the particular solution $w_q(x)$ depends on the load $q(x)$ type. For example, if the load is constant, then $w_q(x)$ is constant too, and given by $w_q(x) = q/(k_s \cdot b)$. The general solution $w(x)$ is completely defined once the constants C_i (i = 1 to 4) are evaluated by imposing the natural and essential boundary conditions. When the deflection $w(x)$ is known, the bending moment and shear force can be determined.

2.2. Soil reaction modulus, different semi-empirical models

Different analytical models for the study of soil–structure interaction on elastic soil are available (see Section 2.1). The common parameter for all of these models is the soil reaction modulus (k_s). Numerous expressions or semi-empirical models are available to determine this modulus as a function of the studied applications [9,24]. Six semi-empirical (models of Biot [25], Vesic [26], Meyerhof and Baikie [27], Kloppel and Glock [28], Matsubara [29] and Selvadurai [30]), commonly used in the design of buried pipes, are considered in this study in order to obtain a value of the soil reaction modulus (k_s) (Table 1).

The calculation of k_s is a function of soil parameters such as the soil modulus (E_s) and soil Poisson's ratio (ν_s), the parameters related to the geometry of the pipe (external diameter (d) and thickness (e)) and a mechanical property of the pipe (the Young's modulus of the pipe (E_p)) (Table 1).

In order to compare these models with each other, we take the common dimensions of a continuous buried steel pipe: external diameter of 1.5 m and thickness of 0.02 m. Young's modulus of the pipe and soil (E_p, E_s) are respectively equal to 210 GPa and 15 MPa, Poisson's ratio of 0.3 and the magnitude of parameter λ being non-defined, it is taken to be equal to 10. Matsubara's model gives the greatest value of k_s equal to 24.15 MN.m^{-3} and Vesic's model gives the lowest value of k_s equal to 5.07 MN.m^{-3}. The value of k_s for Kloppel's model is almost the average of the values of these two models. Biot's and Selvadurai's models give almost the same value of k_s equal to 7 MN.m^{-3} and the value of k_s for the Meyerhof model is nearly twice that of the value of the Vesic model for the considered values in this example. The multitude of models giving very different results, it underlines the difficulty for the practitioner to choose a value of the subgrade reaction modulus for a given value of E_s.

Table 1
Semi-empirical models proposed for the modulus of soil reaction (k_s).

Authors	Semi-empirical methods
Biot (1937) [25]	$k_s = \frac{0.95}{d} \cdot \left(\frac{64 \cdot E_s d^4}{E_p \pi (d^4 - (d-2e)^4)}\right)^{0.108} \cdot \frac{E_s}{1-\nu_s^2}$
Vesic (1961) [26]	$k_s = \frac{0.65}{d} \cdot \left(\frac{64 \cdot E_s d^4}{E_p \pi (d^4 - (d-2e)^4)}\right)^{0.083} \cdot \frac{E_s}{1-\nu_s^2}$
Meyerhof and Baikie (1963) [27]	$k_s = \frac{E_s}{(1-\nu_s^2)d}$
Kloppel and Glock (1979) [28]	$k_s = \frac{2E_s}{(1+\nu_s^2)d}$
Matsubara (2000) [29]	$k_s = \frac{2\pi}{\log \lambda} \cdot \frac{E_s}{2(1+\nu_s)} \cdot \frac{1}{d}$
Selvadurai (1985) [30]	$k_s = \frac{0.65}{d} \cdot \frac{E_s}{(1-\nu_s^2)}$

E_s: Young's soil modulus, ν_s: Poisson's ratio of soil, d: external diameter of the pipe, E_p: Young's modulus of the pipe, e: thickness of the pipe and λ the ratio between the distance to the point at which the displacement is regarded as null and the radius of pipe.