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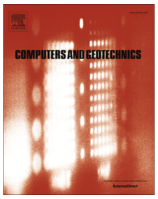

Research Paper

Modelling the effect of climate change induced soil settling on jointed drinking water distribution pipes

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ABSTRACT

Soil settlements related to groundwater lowering are expected to be accelerated by climate change and may damage underground infrastructure networks. A 1D mechanical model, previously developed for continuous pipelines, has been extended towards jointed pipelines to calculate the stresses and joint rotations induced by the soil settlements. From the mechanical model, curve fits were acquired that can be used to estimate the bending moments and joint rotation. The curve fits differ per soil type, joint stiffness, joint position and joint distance. The stresses calculated by the 1D mechanical model and curve fits were validated by means of 3D finite element modelling. Using the curve fits, a probabilistic approach was followed by means of a Monte Carlo method to calculate the probability of failure of the pipeline system. The effect of joints is that the pipe stresses are reduced as the joints absorb a part of the soil displacement. For the probability of failure, the pipe stresses have a larger contribution than the joint rotation, as the joint rotation remains small compared to the maximum allowable joint rotation.

1. Introduction

Soil settlements may damage underground infrastructure. Climate change may accelerate groundwater-related settlements, as consolidation of the soil occurs during periods of drought. Underground infrastructure networks are vulnerable to soil settlements, especially if differential soil settlements occur over small distances, for example at soil (property) transitions.

The effect of soil settlement due to tunnel building underneath a buried pipe has been extensively studied by mechanical models [1–7]. However, little research is conducted towards the effect of soil settlements caused by groundwater lowering on buried infrastructure. This topic is becoming increasingly relevant as a result of climate change. Statistical studies correlating pipe bursts with weather data show that the number of bursts, depending on pipe material, pipe diameter and pipe age, may be influenced by temperature [8–11] and soil moisture [12–15]. These correlations show that during hot and dry summers, pipes may burst more frequently, which is (partly) related to soil shrinkage and settlements [12–15], which is stronger in more expansive soils [14,15] and in soils affected by vegetation-induced desiccation [16]. In a previous paper [17], we developed a model that predicts pipe stresses in a pipe buried in soil that exhibits differential settlements due to consolidation. The numerical model is based upon the formulation of a beam on an elastic foundation using Winkler type springs. A parametric soil settlement function was introduced to characterize the consolidation settlement profile. Furthermore, by using an empirical curve fit of bending moments (analogous to Wang et al. [6] for tunneling problems), the numerical model could be simplified towards a set of algebraic equations. These equations allow fast calculations of pipe stresses, and can therefore be used in a Monte-Carlo analysis. The Monte-Carlo analysis incorporates the uncertainty in the model parameters to predict pipe failure probabilities. This approach is also implemented in a geographical information system (GIS), so that the vulnerability of water distribution networks towards soil settlements can be assessed [18]. These models were developed for continuous pipes. This approach is valid for buried pipes with rigid connections, however most pipes are installed with joints that are flexible to some degree.

In the current work, the model is extended towards jointed pipelines. Most PVC, asbestos–cementos and cast iron pipe systems contain flexible joints that may (partially) absorb the soil displacement. This may reduce bending stresses occurring in the pipe. For tunnelling problems, joints were considered by [4,7]. Klar et al. [4] showed than jointed pipelines generally experience smaller

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bending moments than continuous pipelines, although in some rare cases the opposite occurs. Zhang et al. [7] considered multi-layered soils with different soil elasticities. The soil was schematized in both researches as linear elastic. For the calculation of pipe stresses in jointed pipelines presented in this work, two non-linearities are included in the model: the soil may deform plastically and soil stiffness varies with the direction of the pipe displacement (soil is stiffer if the pipe moves in downward direction). Furthermore, the modelling approaches were validated by means of 3D finite element models (FEM).

2. Methods

2.1. 1D mechanical model

The following assumptions were made [17]:

1. A pipe is schematized by a beam (1D element).
2. A pipe remains in contact with the soil.
3. Elastic behaviour of pipe material.
4. No internal or external loading on the pipe ($q = 0$), except that resulting from soil-pipeline interaction.

The pipeline behaviour is regarded as a beam on elastic grounds (assuming Euler beam theory):

$$\frac{d^2}{dx^2}\left(\mathrm{EI}(x)\frac{d^2u(x)}{dx^2}\right) + K_i(x)\cdot(u(x) - S_v(x)) = 0, \tag{1}$$

where the greenfield soil displacement is represented by $S_v(x)$, and the pipeline displacement by $u(x)$ [m]. The parameter $\mathrm{EI}(x)$, representing the bending stiffness of the pipe [Nm^2], is the product of the elasticity modulus and moment of inertia. The bending stiffness is a function of x as it is locally reduced at the position of the joints (explained further on, Eq. (4)). The parameter $K_i(x)$ [$\mathrm{N/m}^2$] represents the subgrade modulus, a spring constant of the soil that differs for upward or downward displacement (the soil is stiffer if the pipes move in downward direction). The subgrade modulus is therefore a function of relative pipe displacement to account for a difference in upward ($K_u(x)$) and downward subgrade modulus ($K_d(x)$) and to allow plastic deformation accounting for soil collapse (Fig. 1). The approach of Wang et al. [6] was used to calculate the upward and downward subgrade modulus as well as the threshold of plastic deformation, which is a function of burial depth, pipe diameter and soil properties (see Supporting Information). The following soil displacement profile caused by consolidation is assumed [17]:

$$S_v(x) = -0.5S_{\max}\left(1 + \mathrm{erf}\left(\frac{-x}{i\sqrt{2}}\right)\right), \tag{2}$$

which describes a smooth transition of a certain differential settlement $S_{\max}$ over a certain transition length scale i. By parameterizing the soil settlement profile, different types of differential settlements can be taken into account.

Analogous to the tunnelling settlement approach [6], a rigidity parameter is introduced that is representative of the relative pipe-soil stiffness:

$$R_3 = \frac{\mathrm{EI}}{Ki^4}, \tag{3}$$

where i is the characteristic length of the differential settlement. For K the average value of upward and downward subgrade modulus is taken.

The bending behaviour of joints is non-linear and can be schematized as a bilinear moment-rotation line (see Fig. 2), which is simplified by a single rotational stiffness constant k_J (dashed line). The slope of these lines is referred to as the rotation stiffness and depends on pipe material, joint configuration and pipe diameter.

The joints are modelled by locally reducing the bending stiffness EI over the length of the joint. The bending stiffness at the joint then becomes [7]:

$$\mathrm{EI}_J = \frac{1}{\frac{1}{\Delta x_J k_J} + \frac{1}{\mathrm{EI}}} \tag{4}$$

where Δx_J is the joint length and k_J the rotation stiffness of the joint [Nm/rad]. This approach differs from [4], where a stiffness matrix is introduced for the joint and pipe. As we directly solve the differential equation (Eq. (1)), such a stiffness matrix is not required.

The joint stiffness is characterized by the relative joint-pipe stiffness parameter T [4]:

$$T = \frac{k_J i}{\mathrm{EI}_p} \tag{5}$$

The joint length is normalized with the characteristic length of the soil settlement to obtain the relative joint distance (x_J):

$$x_J = \frac{\Delta x_J}{i} \tag{6}$$

As shown by [4] for the tunnelling problem, bending moments in the pipe and rotation of the joints depend on the position of the joint relative to the location of maximum displacement. They consider an odd configuration where a joint is placed at the point of maximum displacement and an even configuration where the middle of a pipe segment occurs at the maximum displacement. They

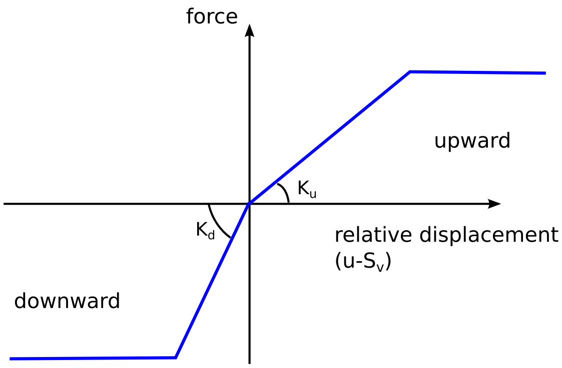

Fig. 1. Force versus displacement diagram, showing the soil subgrade modulus is a function of relative pipe displacement (compared to the soil) that differs in upward or downward direction and has a plastic regime.

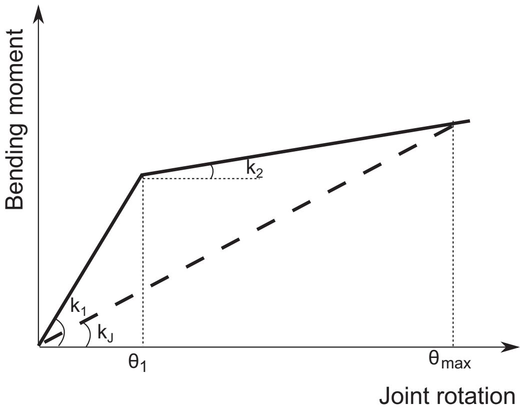

Fig. 2. Bending stiffness behaviour of joints. The bilinear moment rotation behaviour is schematized by a single linear rotation stiffness (dashed line).