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Effects of climate change on drinking water distribution network integrity: predicting pipe failure resulting from differential soil settlement

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Abstract

Climate change may result in lowering of ground water levels and consolidation of the soil. The resulting (differential) settlements, associated with soil property transitions, may damage underground pipe infrastructure, such as drinking water distribution systems. The work presented here offers an approach for the prediction of pipe failure under conditions of differential settlement. A probabilistic model for pipe failure has been implemented in a geographical information system (GIS) environment. The GIS tool uses information on the drinking water distribution system, soil properties and expected soil settlements to predict pipe bending stresses in a probabilistic framework, so that the vulnerability of a drinking water distribution network towards soil settlements can be assessed. This model approach allows water companies to perform a quick scan of their drinking water distribution network integrity towards different expected climate scenarios.

Keywords: Pipe stresses; pipe failure; climate change; soil settlements; GIS

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1. Introduction

Climate change is expected to result in more frequent severe heat waves and long dry periods (van den Hurk et al., 2006). As a consequence, lowering of ground water levels may occur and consolidation of the soil (Arnold et al., 2011). The resulting (differential) settlements, associated with soil property transitions, may damage underground pipe infrastructure, such as drinking water distribution systems. Little research has been conducted to the influence of climate (change) on the structural integrity of drinking water distribution networks. Temperature and soil moisture content appear to affect pipe failure rates (Kleiner and Rajani, 2002); an increase in pipe failure rates is often observed in dry (summer) periods due to soil shrinkage (Gould et al., 2011). No mechanistic models that predicts the deterioration of water distribution assets resulting from climate change have been presented in the literature. Recently, we

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proposed a mechanistic approach for the prediction of pipe failure under conditions of differential settlement (Wols and van Thienen, 2013). The implementation of that approach in a geographical information system (GIS) is described in the current paper.

Nomenclature

a	empirical parameter in pipe stress model
b	empirical parameter in pipe stress model
D	pipe diameter
E	elastic modulus
I	area moment of inertia (for a pipe: $I = \frac{\pi}{64}(D^4 - (D - 2t)^4)$)
i	characteristic transition length over which settlement occurs
K	subgrade modulus of pipe-soil system
$S_v(x)$	soil settlement profile
$S_{\max}$	maximum differential soil settlement
t	pipe wall thickness
σ_p	pipe stress

2. Materials and methods

Wols and van Thienen (2013) present an approach for the calculation of pipe bending stresses which is based upon the tunnelling method (Attewell et al., 1986, Vorster et al., 2005, Klar et al., 2005, 2008, Klar and Marshall, 2008, Marshall et al., 2010, Wang et al., 2011a,b). The pipe-soil system is schematized as a beam on an elastic foundation using Winkler type springs. A new settlement profile has been introduced that is specific for climate change related differential settlement (Wols and van Thienen, 2013). This profile assumes a smooth transition of settlements between soil layers of different stiffness, permeability or ground water level. The soil settlement profile is parameterized to account for variations in soil settlements and transition lengths:

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

Using this soil settlement profile, the stresses in the pipe can be calculated by solving the appropriate differential equations numerically. From these equations, a semi-empirical expression can be obtained for the maximum bending stress occurring in the pipe that is subjected to this differential settlement without the need of solving the numerical model for each pipe section. Both methodologies are described in more detail in Wols and van Thienen (2013). From the semi-empirical model, the maximum pipe stress can be calculated directly from the pipe and soil parameters (see Appendix):

$$\sigma_{\mathrm{p,max}} = \frac{\exp\left(-\frac{1}{2}\right)}{\sqrt{8\pi}} \frac{S_{\max} D}{i^2} \frac{E}{1 + a\left(\frac{EI}{Ki^4}\right)^b}, \tag{2}$$

where a en b are fitting parameters equal to $a = 1.3137(\pm 0.0193)$ and $b = 0.6332(\pm 0.0077)$ (Wols and van Thienen, 2013). Since the stress calculation is reduced to a single algebraic equation, the model can be used in situations where large numbers of pipe calculations are required, for example to apply a probabilistic approach or to assess many pipe segments in a large water distribution network. The semi-empirical model has been implemented in a GIS environment using Python scripts. The required pipe network and soil parameters can be obtained from databases and maps by means of geoprocessing (Table 1). In our GIS implementation, these parameters are determined for each pipe segment of the drinking water distribution network.

Table 1. Parameters required for the model.

Parameter	Source	Alternative if unavailable
Pipe diameter (D)	Network information system	-
Pipe wall thickness (t)	Network information system	Estimated from pipe diameter
Pipe installation depth (H)	Network information system	Estimated from common practise
Pipe material	Network information system	-
Pipe elasticity (E)	Material properties (Table 2) of pipe material	-
Pipe yield stress (σ_f)	Material properties (Table 2) of pipe material	-
Soil type	Soil type map	-
Soil density (ρ)	Soil properties (Table 2) of soil type	-
Soil angle of internal friction (ϕ)	Soil properties (Table 2) of soil type	-
Soil differential settlement (S_{max})	Settlement calculations map	-
Length of differential settlement (i)	Estimation of 2 m	-

2.1. Pipe data

The pipe material, diameter, wall thickness and installation depth can be obtained from the network information system maintained by the water supply company. These information systems contain information of all water distribution pipes in the supply area (e.g., pipe diameter, material, installation depth, year of installation). Some parameters, such as the pipe wall thickness or installation depth, may be unknown and need to be estimated. For example, in The Netherlands pipes are usually installed at a depth of 1 m. Furthermore, the pipe material deformation is assumed to be exclusively linear elastic; plastic deformation is not considered. Pipe failure occurs when the yield stress is exceeded. The elastic modulus and yield stress for commonly used materials are shown in Table 2.

2.2. Soil data

A rough classification of soils into sand, clay and peat has been made. From the soil type, the soil density and angle of internal friction are obtained (Table 2), which are used to calculate the subgrade modulus. The subgrade modulus is in essence a spring coefficient that is used to characterize the pipe-soil system. The formulation of the downward subgrade modulus by Wang et al. (2011a) is used in our model, both for the upward and downward movement of the pipe in the soil. The calculation of the subgrade modulus requires the soil internal angle of friction, soil density, pipe diameter and pipe installation depth as input parameters (see Appendix).

Soil type maps are usually available as GIS data from local municipalities. In these maps, for example in soil type maps of the Netherlands, information in urban areas may be missing because in many places the soil may have been reworked. Soil types in these areas can then be estimated from interpolation of the known areas using a GIS tool called expand (from the ESRI ArcGIS Spatial Analyst Toolbox).

2.3. Soil settlement

Soil settlements maps for different climate scenarios are currently being developed for the Netherlands (Deltamodel, 2013). These maps show the expected soil settlements on a 100 m by 100 m grid. However, this resolution is too coarse to determine the differential settlement along an individual pipe. It is therefore assumed that the soil settlement along the pipe follows the parametric settlement profile of equation 1. As a worst-case scenario, the maximum differential settlement S_{max} is set equal to the settlement calculated in each cell, and the transition length is set to i = 2 m (corresponding to a total length of transition zone of 10 m). In other words, it is assumed that somewhere in the 100 m x 100 m cell the expected settlement occurs, and somewhere else in the same cell (10 m further away) no settlement occurs. In the GIS tool, each pipe segment in this cell is assigned the maximum stress that may occur in the pipe segment calculated from this settlement profile.

Table 2. Pipe and soil properties.

Pipe properties	Elasticity (Pa)	Yield stress (Pa)
Steel (ST)	$210 \cdot 10^9$	$355 \cdot 10^6$
Asbestos-cement (AC)	$25 \cdot 10^9$	$25 \cdot 10^6$
PVC	$3 \cdot 10^9$	$12.5 \cdot 10^6$
Soil properties	**Density (kg/m^3)**	**Angle of internal friction (°)**
Sand (loose)	1700	34
Clay (soft)	1600	25
Peat	300	23

2.4. Monte Carlo analysis

A Monte Carlo analysis is applied to account for the uncertainties in the model parameters by introducing probability density functions. For each Monte Carlo repetition, the model parameters required in equation 2 are sampled from the appropriate probability density functions shown in Table 3. The pipe parameters are well-defined, so that narrow normal distributions are chosen. The soil and settlement parameters are more uncertain, so that wider lognormal distributions are chosen. By using a large number of Monte Carlo repetitions (typically between $1 \cdot 10^5$ and $1 \cdot 10^7$), a probability density function of the pipe stress is obtained. The probability of failure is calculated from the number of repetitions that exceed the pipe material yield stress. The Monte Carlo analysis is also implemented in the GIS environment, so that the vulnerability of a water distribution network to soil settlements can be assessed.

Table 3. Probability densities of parameters used in Monte-Carlo analysis.

Parameter	Probability density function	Coefficient of variation ($= \sigma/\mu$)
Pipe diameter (D)	Normal	0.04
Pipe elasticity (E)	Normal	0.04
Pipe wall thickness (t)	Normal	0.04
Pipe yield stress (σ_f)	Normal	0.08
Subgrade modulus (K)	Lognormal	0.5
Soil differential settlement ($S_{\max}$)	Lognormal	0.5
Length of differential settlement (i)	Lognormal	0.5
Fit parameters (a, b)	Normal	0.0147, 0.0122

3. Results

3.1. Stresses in a single pipe

The stresses in a 0.5 m diameter steel pipe that was subjected to a soil differential settlement of 0.05 m over a length of 10 m are shown in Figure 1. The stresses were calculated by the full numerical model as presented in Wols and van Thienen (2013). The maximum stress calculated by the semi-empirical model (equation 2), shown by the dash-dotted line, corresponds well with the numerical model. Since the pipe is relative stiff compared to the soil, the curvature of the pipe is less than the curvature of the soil, reducing bending moments and stresses.

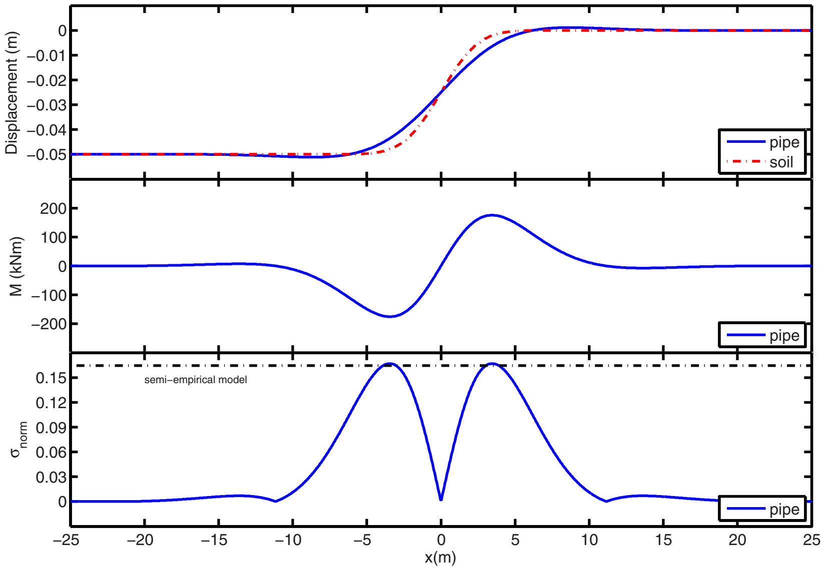

Fig. 1. Model result for a steel pipe (D=0.5 m) in a sandy soil: displacement of pipe and soil (upper panel), bending moments in pipe (middle panel) and stresses in pipe normalized with respect to the yield stress (lower panel)

3.2. Assessment of synthetic drinking water distribution network

The GIS tool was applied to a synthetic drinking water distribution network: a network representative for a small town has been placed in an area in the Netherlands with known soil types and expected settlements. The pipe network consisting of several materials and pipe diameters is shown in Figure 2a and 2b, representing a realistic pipe network of an arbitrary small town. Most of the pipes are made of polyvinyl chloride (PVC) and asbestos-cement (AC), whereas the larger transport pipes mainly consist of AC and cast iron (CI). The soils in which the pipes are buried are shown in Figure 2c. The expected settlements are shown in Figure 2d. The largest expected settlement occur in the areas with peat and clay soils. The GIS tool was used to calculate the pipe stresses in each pipe segment (Figure 2e). The stresses were normalized to the pipe material yield stress. High stresses occur in the western area where large settlements occur in peat and clay soils. The highest settlements occur in the peat soils. Although the settlements in the clay soils are lower, similar high stresses as in the peat soils occur in regions with moderate settlements. The combination of a stiffer soil and moderate settlements causes strong curvatures of the buried pipes, so that stresses become high. The opposite occurs in the peat area, where the pipe is relatively stiff compared to the soft peat soils so that pipe curvatures are smaller than the soil curvature, reducing pipe stresses despite the high settlement. The AC pipes seem to be more vulnerable to settlements than PVC pipes, visible from the higher normalized stresses occurring in AC pipes compared to PVC pipes in adjacent areas. The PVC pipes are more flexible than AC pipes, and although this results in larger curvatures, the stresses are lower due to the low elastic modulus of PVC. Monte-Carlo analysis was also applied to determine probabilities of failure using $2{\cdot}10^6$ Monte-Carlo repetitions (Figure 2f). Similar trends as for the pipe stresses can be observed for the failure probabilities.

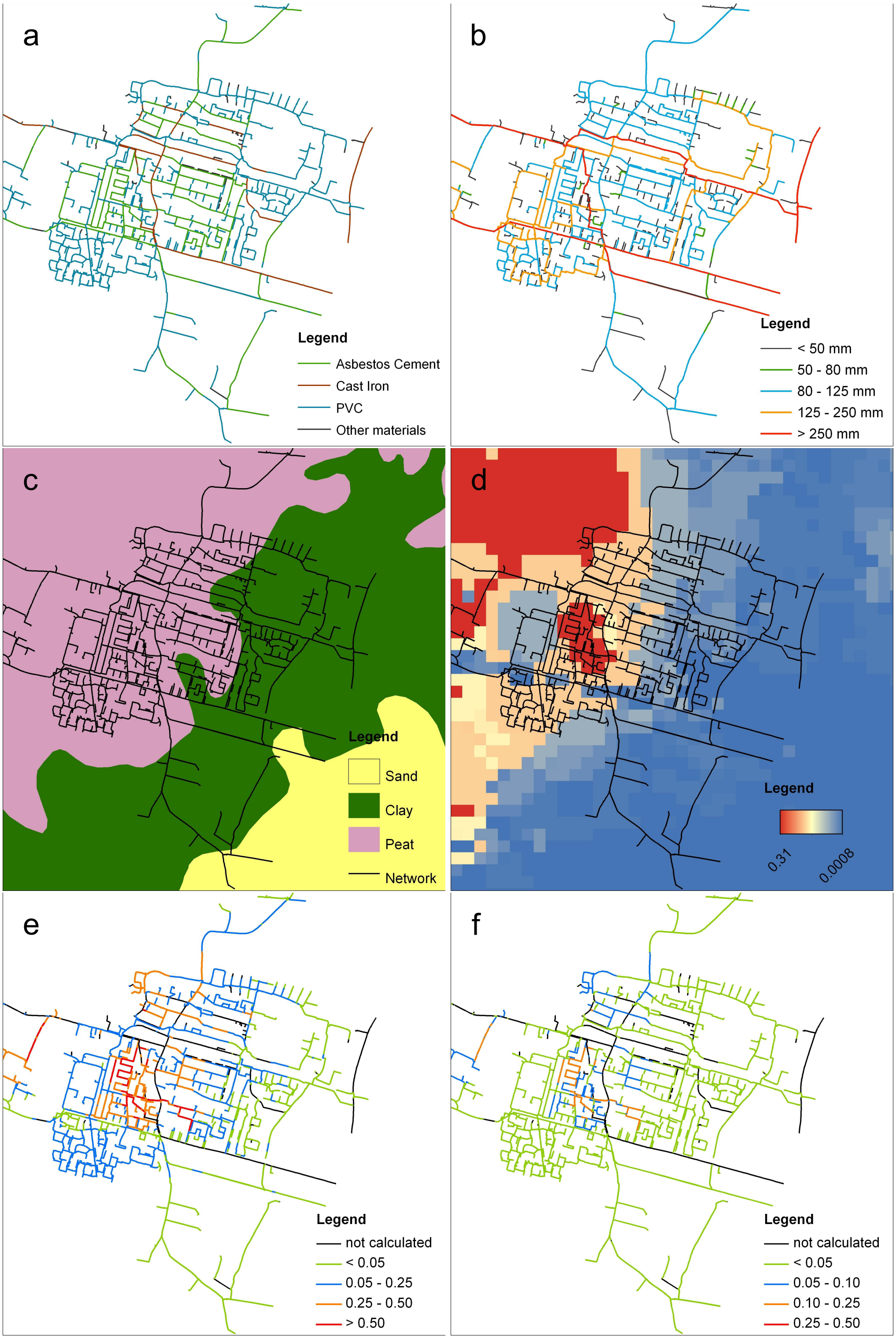

Fig. 2. Assessment of the vulnerability of a drinking water distribution network to climate change induced settlements: (a) Pipe materials; (b) Pipe diameters; (c) Soil types; (d) Expected soil settlements; (e) Calculated pipe stresses as a function of yield stress; (f) Calculated probability of failure.

4. Discussion

The accuracy of the model results depends on the quality of the input data and accuracy of the model itself. The modelling framework that schematizes the pipe as an elastic beam on a spring foundation using Winkler type springs has been extensively validated for the tunneling settlement profile (Vorster et al., 2005, Marshall et al., 2010, Zhang et al., 2012). The semi-empirical model used here is valid when the following restrictions are applied: no joints; elastic behaviour of pipe and soil; and the pipe remains in contact with the soil. When the GIS tool is applied to a drinking water distribution network, the "no joint" criterion is not met: the AC and PVC pipes will all have joints that will reduce the bending moments in the pipe. Also, plastic deformation will result in some additional bearing capacity of the pipe-soil system (for steel and plastic pipes). Concerning the quality of the input data, one is restricted by resolution and availability of data. For example, soil composition maps often have no information in urban areas, which needs to be interpolated from surrounding areas. Because of the large amount of reworking of the ground in these areas, this is a somewhat uncertain approach in any case. Also, the resolution of the soil settlement map is often insufficient to obtain a settlement profile at the level of individual pipes. Therefore, the soil settlement profile given in equation 1 is applied using conservative estimates for the settlement parameters.

Under these assumptions, the pipe stresses and probability of failures visualized in maps for drinking water distribution networks will represent an upper limit. The GIS tool can therefore mainly be used as a quick-scan to identify the pipes that are most vulnerable towards soil settlements. These parts of the distribution network can then be further examined using the full mechanical model described in Wols and van Thienen (2013), incorporating joints (if necessary) and using higher resolution settlement profiles and soil parameters derived from local soil investigations.

5. Conclusions

We have presented a model and GIS implementation that can assess settlement induced failure probabilities of individual segments of complete drinking water distribution networks for different scenarios of climate change. This model approach allows water companies to perform a quick scan of their drinking water distribution network integrity towards different expected climate scenarios.

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Appendix A. Derivation of pipe stress formula

Assuming a linear stress-strain relation (Hooke's law), the pipe stresses (σ_p) and strains (ε_p) can be calculated from the bending moment in the pipe (M_p):

$$\begin{aligned}\sigma_p &= E\varepsilon_p,\\ \varepsilon_p &= \kappa_p \frac{D}{2},\\ \kappa_p &= \frac{M_p}{EI},\end{aligned} \tag{A.1}$$

where κ_p is the curvature of the soil.

The maximum bending moment in the pipe (M_p,max) can be obtained as the fraction (MMnorm) of the bending moment that occurs if the pipe would follow exactly the soil displacement (M_g,max) (Wols and van Thienen, 2013):

$$\begin{aligned} M\text{norm} &= \frac{M_p,\text{max}}{M_g,\text{max}}, \\ M_g,\text{max} &= EI\frac{S\,\text{max}}{i^2\sqrt{2\pi}}\exp\left(-\frac{1}{2}\right). \end{aligned} \tag{A.2}$$

By using these expressions in combination with the empirical expression of the normalized bending moment:

$$M\text{norm} = \frac{1}{1 + a\left(\frac{EI}{Ki^4}\right)^b}, \tag{A.3}$$

where a and b can be obtained from fitting (Wols and van Thienen, 2013), the maximum bending moment in the pipe is obtained:

$$\sigma\text{p,max} = \frac{\exp\left(-\frac{1}{2}\right)}{\sqrt{8\pi}}\frac{S\,\text{max}D}{i^2}\frac{E}{1 + a\left(\frac{EI}{Ki^4}\right)^b}. \tag{A.4}$$

Appendix B. Subgrade modulus

In Wang et al. (2011a), separate springs are considered for upward and downward forces, because the soil reacts differently to an upward or downward moving pipe. The subgrade modulus is estimated from the maximum resistance force of the ground (F) and the threshold of pipe-soil relative displacement (δ). This threshold represents the displacement at full mobilization of the resistance force. The subgrade modulus then becomes:

$$K = \frac{F}{\delta} \tag{B.1}$$

The forces and displacements differ per soil type and can be obtained from the pipe installation depth (H), soil internal angle of friction (ϕ), soil density (γ) and pipe diameter (Table B.4). In our semi-empirical model, we only use the downward subgrade modulus to simplify the model.

Table B.4. Soil properties

Forces (F)	Expression	Bearing capacity (N_x)
Upward	$F_u = N_v\gamma HD$	$N_v = 1 + \frac{H}{D}\tan\phi - \frac{\pi D}{8H}$
Downward	$F_d = N_q\gamma HD + 0.5N_\gamma\gamma D^2$	$N_q = \tan^2(\frac{\pi}{4} + \frac{\phi}{2})\exp(\pi\tan\phi)$
		$N_\gamma = 1.8(N_q - 1)\tan\phi$
Displacement (δ)	**Sand**	**Clay**
Upward	0.005-0.015 H	0.1-0.2 H
Downward	0.10-0.15 D	0.10-0.15 D

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