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Sensitivity Analysis On The Axial Soil Reaction Due To Temperature Induced Pipe Movements

Ingo Weidlich[a]*

[a]*HafenCity Universität Hamburg, Überseeallee 16, 20457 Hamburg, Germany*

Abstract

Seen from an international perspective preinsulated bonded pipe systems dominate in heat distribution. These pipe systems are usually buried in sand and soil-pipe interaction hinders thermal strains, which make economic solutions for bow- and T-sections possible. For static design pipe-soil interaction must be known as accurate as possible. However, several parameters are influencing the quantity of the expected soil reaction. Main influencing factors are dependent on the used bedding material and geometry. Furthermore current research results made additional soil-phenomena evident, which are hardening effects and stress redistribution during operation. A new calculation approach for the axial soil reaction was developed in 2015 based on existing test results and numerical simulations. A sensitivity analyses were carried out to estimate the significance of relevant parameters and the existing calculation approaches. This paper identifies the significant parameters and suggests parameter sets for lowest and highest axial soil reaction. Two main boundary situations are taken into account a) first movement b) during operation.

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Keywords: buried pipe design, pipe soil interaction, friction force

1. Introduction

Seen from an international perspective pipe laying according to state of the art in heat distribution is primarily based on preinsulated bonded pipe systems. These pipe systems are usually buried in sand. The interaction of soil

* Corresponding author. Tel.: 49-40-42827-5700
E-mail address: ingo.weidlich@hcu-hamburg.de

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and pipe hinders thermal strains, making economic solutions for bow- and T-sections possible. Regarding the static design, pipe-soil interactions must be known as accurate as possible.

Nomenclature

k_0	earth pressure coefficient at rest = 1-sinφ'	
G	effective weight of the pipe filled with water	
σ_v	effective soil stress at pipe axis	
for granular soils:		
σ_v	$\gamma_B *H_w+\gamma_{BW}*(Z-H_w)$	for $H_w < Z$
σ_v	$\gamma_s *Z$	for $H_w \geqslant Z$
Z	depth of the pipe axis	
H_w	depth of ground water table	
γ_B	unit weight of the soil	
γ_{Bw}	buoyant weight of the soil	
γ_S	weight of the saturated soil	
D_a	outer diameter	
μ	coefficient of friction	
δ	contact friction angle	
φ'	internal soil friction angle	
κ_1	factor for the relationship between initial stress state and subsequent stress state	
$\sigma_{r,avg}$	average contact pressure on the pipe perimeter	
$F_{r,u}$	ultimate friction force	
ΔT	temperature increment	
κ_1	factor for the relationship between initial stress state and secondary stress state	
H	depth of overburden to the top of the pipe	
D_r	relative density of soil bedding	
α_T	thermal expansion coefficient	
A_s	area of steel medium pipe	
E	Young’s Modulus	
F_R	ultimate friction force	
l_0	length of the gliding section	

However, several parameters are influencing the quantity of the expected soil reaction [1]. Main influencing factors are the bedding material utilized and its parameters (e.g. average effective unit weight, compactness or coefficient of lateral earth pressure) and the geometry of the pipe and trench (e.g. depth of the pipe (crown) below the surface or external pipe diameter). Furthermore, current research results evidently showed the influence of additional phenomena, such as hardening effects and stress redistribution during operation [2]. A new calculation approach for the axial soil reaction was developed in 2015 based on existing test results and numerical simulations [3].

Soil reactions relevant for the design of district heating pipelines are divided into two groups: Axial soil reaction and lateral soil reaction. Since the magnitude of the expected lateral soil reaction is a current research topic [4] the axial soil reaction, which is the skin friction among the perimeter of the pipe, was suggested to be described sufficiently by standard calculation approaches in the last decades. However, major deviations between calculated reactions and measurement of the bearing behaviour of district heating pipes in situ have been reported by engineers quite frequently. Against this background, a new approach for calculating the skin friction was developed taking into account contemporary research results.

2. State of the art

The European state of the art for the calculation of pipe skin friction of district heating pipes is defined in EN13941

[5]. According to this approach, the skin friction F_R is assumed to be proportional to the radial contact pressure around the pipe and may be calculated using equation (1).

$$F_R = \mu\left(\frac{1+k_0}{2} * \sigma_v * \pi * D_a + G - \gamma_B * \pi * \left(\frac{D_a}{2}\right)^2\right) \tag{1}$$

The term in brackets describes the resulting earth pressure acting on the pipe. However, several other methodologies are available for the calculation of the resulting earth pressure on pipes (e.g Marston [6], Spangler [7], Leonhardt [8]). μ is the coefficient of friction according to COULOMB, generally ranging between μ=0.3 to 0.4 for normal conditions, cf. according to EN 13941 [5]. Alternatively, equation 2 may be used for the calculation of μ.

$$\mu = \tan\delta = \tan\left(\frac{2 * \varphi'}{3}\right) \tag{2}$$

Since the internal friction angle ranges between φ'=32° to 40° for sands, equation (2) leads to μ=0.39…0.5. Considering fast movements, μ=0.6 is given in [5], which is 1.5-times higher than the value occurring due to normal movement.

3. Initial stress condition

Regarding constant geometric boundaries, the initial stress condition after installation depends on the properties of the bedding material. In order to avoid settlements of the surface, a high degree of compactness is usually wanted for the trench backfill. The compactness achieved within the trench influences the unit weight of the soil and the earth pressure coefficient [1]. Thus, an increased coefficient of earth pressure probably occurs and has to be taken into account when calculating the maximum friction force in the sense of a worst case scenario.

4. Stress conditions during operation

During initial operation of the pipeline, two main effects have to be taken into account for the description of axial soil reaction: 1. Due to temperature dependent radial expansion Δr_e the normal soil stress increases along the perimeter of the pipe and 2. Temperature driven axial expansion leads to axial pipe movements resulting in a hardening effect due to dilatant soil reaction. Both effects are illustrated in Figure 1.

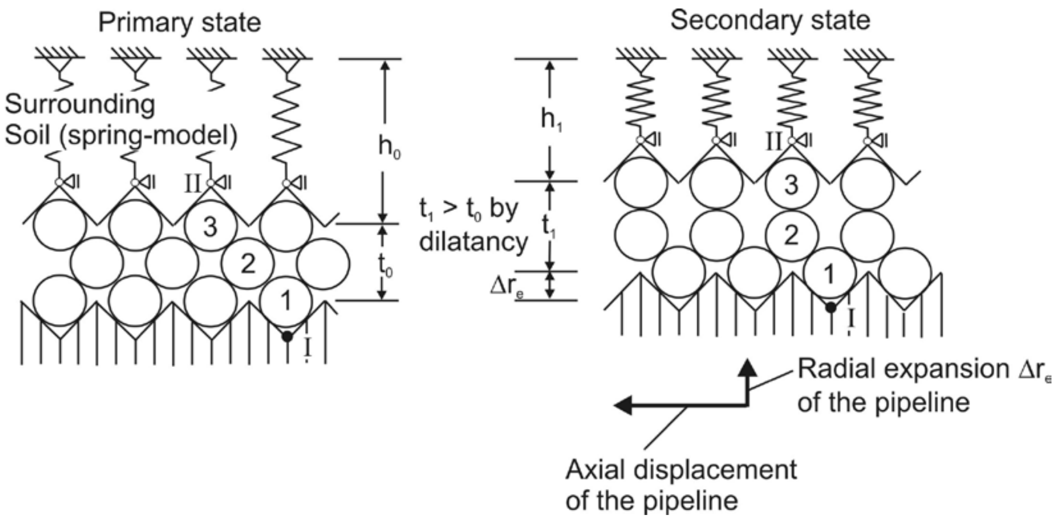

Fig. 1. Two major effects during initial operation.

The radial pipe-soil interaction was investigated in a two-dimensional numerical model by ACHMUS in 1995 [9]. Axial hardening effects due to dilatancy are known from buried structural components such as piles and anchors. These effects were considered to understand skin friction of district heating pipelines by the author in 2007 [10].

Achmus calculated 1995 typical parameter combinations for sand with different relative densities. As a measure of temperature dependence, the factor κ_l, was defined:

$$\kappa_l = \frac{\sigma_{r,avg}(\Delta T = 100K)}{\sigma^{(0)}_{r,avg}} = \frac{F_{r,u}(\Delta T = 100K)}{F^{(0)}_{r,u}} \tag{3}$$

The results indicated that this factor significantly depends on the relative density of the sand, as well as the overburden height H. Achmus derived equation (4) for the calculation of κ_l from the results (valid for ΔT=100K). For lower ΔT, κ_l may be interpolated.

$$\kappa_l = 1.18 - 0.1 * H[m] + 1.22 * D_r \tag{4}$$

Systematic fundamental investigations on the interacting effects of radial expansion and hardening due to dilatancy are missing. However, few isolated single results exist but an overall evaluation has not been carried out yet. An example for current results is the investigation of HUBER et al. from 2014 [2], which are shown in extracts in Figure 2.

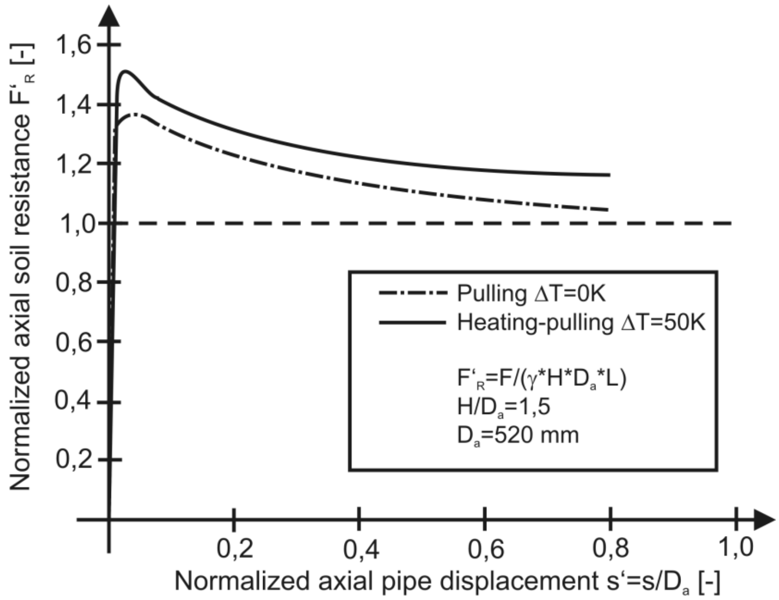

Fig. 2. Results from HUBER et al. [2].

HUBER et al. observed an increased friction force, represented by $\kappa_{l,Huber}$=1.5 for a temperature increment of ΔT=50K. Medium dense boundary conditions of the bedding were reported, which is related to $D_r \approx 0.5$. After interpolation, equation (4) delivers $\kappa_{l,Achmus}$=1.36 for ΔT=50K. Thus, experimental 3d-results approximately showed values 10% above the results of the 2d-approach. Values of this magnitude for axial hardening were observed before without temperature load in [11].

Merging the two-dimensional numerical investigations of ACHMUS with the axial hardening effect due to dilatancy, a more realistic approach for the calculation of friction force during initial loading is assumed, see equation (5).

$$\kappa_{l,\mathrm{mod}} = \frac{F_{R,\Delta T=100K}}{F_{R,0}} = \kappa_{l,Achmus} * 1.1 = 1.30 - 0.11 * H[m] + 1.34 * D_r \quad (5)$$

Considering repeated thermal loading, the soil contact pressure will decrease due to stress redistribution in the surrounding soil. In present practice, the initial friction force is assumed to drop by 50% simulating the residual state upon cyclic loading according to EN13941 [5]. The actual phenomena of friction degradation were investigated by the author, whereas additional equations describing stresses occurring during operation are given e.g. in [10].

5. Sensitivity analysis

A sensitivity analysis was carried out considering two boundary parameter sets resulting in low and high friction, s. Table 1. A high temperature increment ΔT was used for operation temperatures up to 120°C according to EN13941 [5].

Table 1. Parameter set.

Parameter	Low friction	High friction
Overburden height	H=0.8 m	H=0.8 m
Nominal Diameter/Outer Diameter	DN100/200	DN100/200
Temperature Increment	ΔT=100K	ΔT=100K
Unit weight of soil	γ=16kN/m³	γ=20kN/m³
Earth pressure coefficient	K=0.5=1-sin(φ'=30°)	K=1.0
Coefficient of friction	μ=0.36=tan(2*(φ'=30)/3)	μ=0.54=tan(2*(φ'=43)/3)
Relative density	Loose	Dense, D_r=0.7
Equations	(1)	(1) and (5)

Furthermore, equation (1) was used according to EN13941 representing the lower boundary. In addition, $\kappa_{l,mod}$ was applied for describing the upper boundary. A common single beam static model was used for the sensitivity analysis, which is shown in Figure 3.

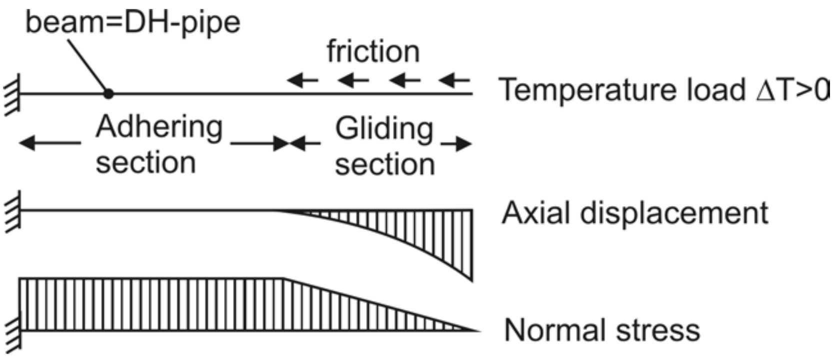

Fig. 3. Single beam model for DH-pipe.

According to equations (6) and (7), the length of the gliding section l_0 and the maximum displacement u_{max} may be derived for this model.

$$l_0 = \frac{\alpha_T * \Delta T * A_s * E}{F_R} \tag{6}$$

$$u_{\max} = \frac{F_R\, l_0^2}{2\, EA_s} \tag{7}$$

The results of the calculations are given in table 2. The ratio of high and low friction is 5.41. This difference demonstrates the importance of choosing accurate parameters for the bedding conditions in the field in order to calculate the friction forces occurring correctly.

Table 2. Results.

Results	Low friction	High friction	Ratio High vs. Low
Skin friction F_R	2.33 kN/m	12.6 kN/m	5.41
Gliding length l_0	137.26 m	25.35 m	0.18
Maximum displacement u_{max}	84.6 mm	15.6 mm	0.18

Basing on the examinations on a future development of the supply flow temperatures for district heating conducted by LUND et al. in 2014 [12], the sensitivity analysis was enhanced for a future scenario according to the temperature development shown in Fig. 4.

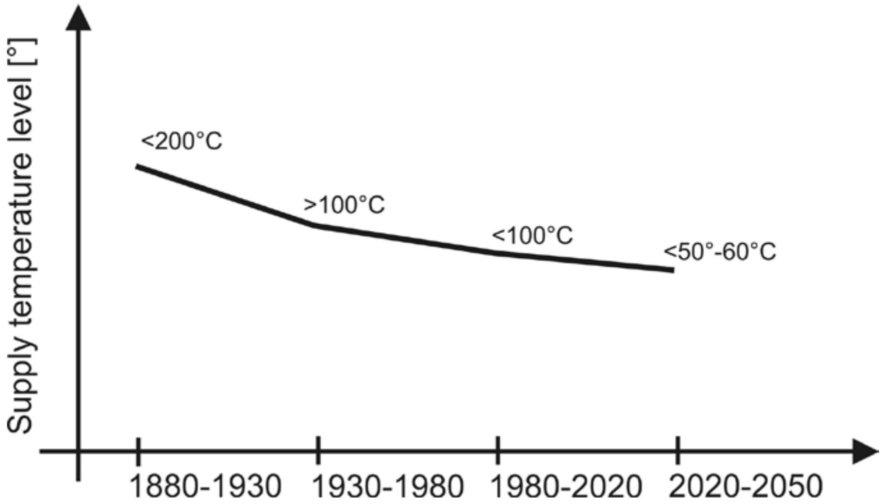

Fig. 4. Future supply temperature according to [12].

For a fictitious average ambient temperature T_a=20°C, the relevant temperature increment ranges here between ΔT_{1880}=180K and ΔT_{2050}=30K. The results for u_{max} and l_0 under low friction condition according to Table 1 are given for decreasing ΔT in Fig. 5.

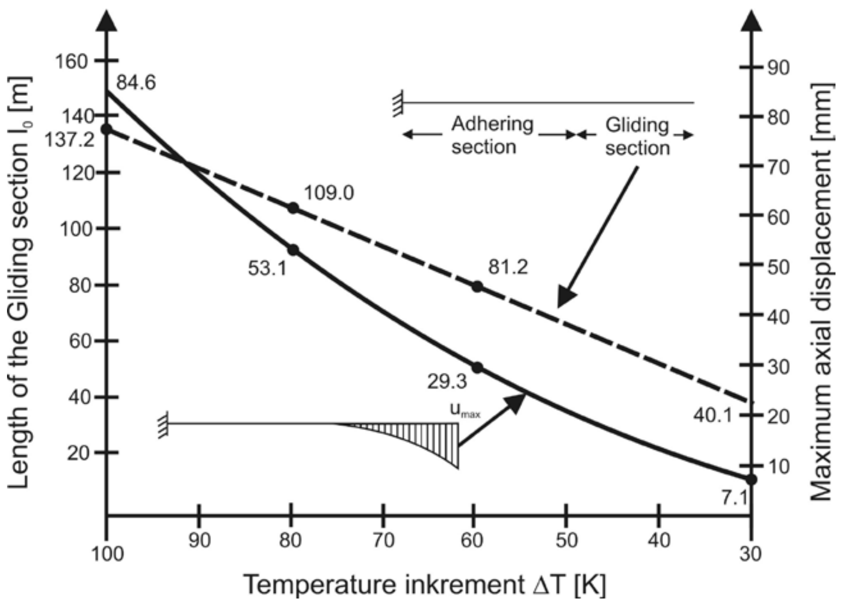

Fig. 5. Significance of decreasing supply temperature.

This simple parametric study for the single beam system shows a significant reduction of maximum displacement and gliding length as well as the related strains and stresses. For a future temperature increment of ΔT=30K only a displacement of 7.1 mm remains which is less than 10% of the displacement for ΔT=100K.

6. Conclusions

After a review of scientific results from numerical and experimental investigations, higher values for the friction force during initial temperature loading are expected for dense bedding conditions. Since two soil-mechanical phenomena have been examined independently in the past, a new empirical calculation approach is suggested. A sensitivity analysis is done, applying two boundary parameter sets, showed major discrepancies in friction forces assessing the magnitude of the characteristic designs. However, the presented merged calculation approach for initial skin friction is based only on limited data. Before practical implementation the approach shall be evaluated by field measurements and additional experimental investigations.

Finally it must be noted for the suggested future scenarios with decreasing supply temperatures in district heating networks static engineering and soil-pipe interaction issues may play a minor role in the future.

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