The interaction between underground district heating pipelines and the surrounding soil

L'interaction entre une conduite de chaleur et le sol entourant

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ABSTRACT: Soil-buried district heating pipelines intensively interact with the surrounding soil due to varying temperatures during operation. In this paper an overview is given about the existing knowledge concerning these soil-structure interaction. Results received from calculations of the interaction forces - friction forces and bedding resistances - with numerical models are presented.

RÉSUMÉ: Les conduites thermiques enterrées sont soumises en raison des changement de temperature pendant l'exploitation à l'influence changeante et intensive du sol environnant. Une vue d'ensemble sur le savoir existant en ce qui concerne l'influence changeante vis à vis ces constructions est présentée dans cet article. Parmi ces forces agissantes une différence est faite entre les forces provenant de la friction et celles provenant de la résistance au sol. Le résultats des calculs de ces différentes forces avec modèles numériques sont présentés.

1 INTRODUCTION

District heating permits the use of waste heat from power plants. For this reason it can be an important contribution for the saving of energy. The costs arising are the most important factor in the extension of district heating supply. The main part of the costs arises from the capital needed for the construction of the pipelines for heat transport. The fact that a hot medium has to be transported leads to special demands on the pipelines. Firstly, the pipe has to be insulated in order to minimize the heat losses, and secondly, the considerable temperature strains have to be compensated or, when the strains are partially or totally prevented, temperature-induced stresses have to be withstood.

District heating pipelines are mostly installed buried in the soil. Normally two pipelines are placed side by side. In the flow line, water with temperatures up to 130 degrees Celsius is transported to the consumer, and in the return pipe the cooled down water flows back to the heat producer. The first district heating pipelines were laid in a concrete tunnel. Since a few years ago, for cost reasons, the pipeline buried directly in the soil is preferably used. At the present time the system used most in Germany is the plastic jacket pipe system.

The bearing behaviour of these plastic jacket pipes and the interaction between the pipe and the surrounding soil is the subject of intensive research. System optimization and a cost reduction are expected due to the better understanding and the more exact calculation of the interaction effects.

The object of this paper is to give an overview of the problems and the existing knowledge about the interaction and to present results received from calculations of the interaction forces with numerical models.

2 CHARACTERISTIC FEATURES OF PLASTIC JACKET PIPES

For district heating pipelines, stresses and strains caused by high temperature differences are characteristic and of great importance for the design. The deformation of soil-buried pipelines is hindered by the surrounding soil. The mobilized forces are differentiated into

1. friction forces and
2. bedding resistances.

The resistance to axial deformation generated by contact friction between pipe and soil is called the friction force. This force influences both the quantity of axial deformations and the quantity and the shape of normal stresses acting in the pipe. This is of particular importance, because for full strain prevention a temperature increase of about 95 K leads to the yield stress in the inner steel pipe.

Lateral deformations induced by the temperature loading occur at changes in the direction of the pipeline. This causes subgrade reactions acting against the deformation, which are called bedding resistances.

2.1 *Interaction of the pipe components*

Plastic jacket pipes consist of three tightly connected components: an inner steel pipe, in which the heat medium is transported, insulation of Polyurethane (PUR) foam and a coating pipe of High Density Polyethylene (HDPE).

The clarification of the question whether the stiffness of the PUR foam is sufficient to transmit the friction stresses working at the coating to the steel pipe is of great importance. Moser & Wieland (1972) have investigated the axial coupling of the plastic jacket pipe components. By varying the shear modulus of the PUR foam, for different nominal pipe diameters they calculated the axial displacements of HDPE coating, PUR foam and steel pipe resulting from temperature loading and friction forces. Herein they assumed an axialsymmetric stress state. The calculations indicated that the differences in axial deformation between coating and steel pipe are neglegible in most cases. Beilke (1993) also investigated the problem of axial deformation coupling. For a pipeline 200 m in length for large friction forces he calculated differences between steel and coating deformation of about 4 %, but he showed that for these high friction forces the admissible shear stresses in the PUR foam were exceeded. He concluded that the assumption of full axial deformation coupling is tolerable, because the design ensures that the admissible shear stresses will not be exceeded.

2.2 *General loading behaviour and installation technique*

The temperature-induced deformation of the pipe is hindered by the surrounding soil. With increasing distance from the free end of the pipeline the normal stresses increase through the effect of the friction forces. At a certain distance, which is dependent on the quantity of the friction forces and the nominal pipe diameter, the "gliding section" with partial strain prevention changes over into the "adhering section" with no axial displacements. In this section the normal force is equal to the temperature-induced force for full strain prevention (Figure 1). For this reason the quantity of the friction forces is the most important parameter for the design of district heating pipelines.

According to the currently valid German design directive (AGFW 1983), the normal stress has to be less than an admissible

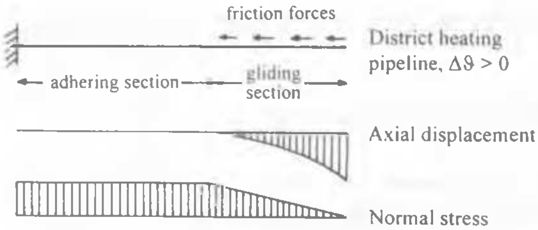

Figure 1. Axial displacements and normal stresses in a soil-buried district heating pipeline.

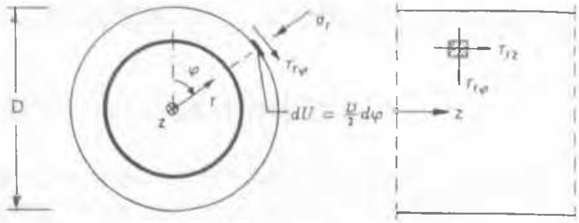

Figure 2. Coordinates and designations.

stress value, which is lower than the yield stress. This requirement can be fulfilled by operating the pipeline with a maximum temperature of about 75 degrees Celsius. This does not satisfy the operating demands of district heating. Two installation methods are mostly used for even higher operating temperatures to ensure that the normal stresses are below the admissible ones:

1. strain compensation,
2. thermal prestressing.

For strain compensation, expansion elements (u-arcs or special fittings) are installed at fixed distances to limit the length of the gliding sections and thus to limit the normal stresses in the pipe. Adhering sections do not occur.

For thermal prestressing the pipeline is elongated by warming it up to a prestress temperature before the trench is refilled. Tensile stresses are active in the state of zero temperature, and at maximum temperature loading the compressive stress is reduced.

Within the scope of efforts to reduce costs the method of "cold installation" was tested recently. This means the installation of long pipeline sections without compensation or prestressing. It is permitted to reach the yield normal stress in the steel. Yield stresses induced by temperature loading do not inevitably produce material failure, but impress plastic strains on the material. For design purposes, material failure due to fatigue failure has to be examined. A disadvantage of the cold installation method is the occurence of axial deformations which are about four times larger than deformations of equivalent prestressed pipelines. Despite this, cold installed pipelines were already tested successfully in operation (Hagemeister 1994).

At changes in the direction of a pipeline the axial deformations lead to lateral displacements, which produce bending in the plastic jacket pipe. The extent of these bending stresses depends on the quantity of the mobilized bedding resistances. In addition, the PUR insulation is very sensitive to lateral stresses, and at high stresses failure can occur, together with a loss of insulation effect. For this reason, district heating pipelines have until now been coated at arc and junction sections with expansion pads to avoid the development of large bedding resistances.

3 FRICTION FORCES

The general approach for the calculation of the friction forces is based on Coulomb's friction law, which can be formulated as follows (Figure 2):

$$\tau_{res} = \sqrt{\tau_{rz}^2 + \tau_{r\varphi}^2} = \mu\,\sigma_r \tag{1}$$

with μ = coefficient of friction.

The relevant value for the present problem is the mobilizable shear stress $mob\ \tau_{rz}$:

$$mob\,\tau_{rz} = \sqrt{[\mu\sigma_r]^2 - \tau_{r\varphi}^2} \tag{2}$$

The mobilizable friction force per unit of length F_{Ru} is the integral of shear stresses $mob\ \tau_{rz}$ along the peripheral length of the pipe:

$$F_{Ru} = \int_0^{2\pi} \sqrt{[\mu\sigma_r]^2 - \tau_{r\varphi}^2}\,\frac{D}{2}\,d\varphi \tag{3}$$

The stresses σ_r and $\tau_{r\varphi}$ acting on a pipe buried in soil are dependent on several parameters, which are often difficult to determine. For this reason, simple approaches for σ_r with $\tau_{r\varphi} = 0$ are preferred in practice. Moser & Wieland (1972) set $\sigma_r = \gamma h = const.$ (γ = unit weight of soil, h = overburden height), which yields $F_{Ru} = \mu\,\pi\,D\,\gamma\,h$. In the German design directive (AGFW 1983) it is assumed that the radial stress at the top and the base of the pipe is $\sigma_{r,top} = \gamma h$ and at the abutment $\sigma_{r,ab} = k\,\gamma\,(h+D/2)$. Herein k is a horizontal earth pressure coefficient. Concerning the stress distribution between the boundary values a *sin*-function is assumed. For this stress distribution the mobilizable friction force is

$$F_{Ru} = \mu\gamma D\,\left[2h + k(\pi - 2)\,\left(h + \tfrac{D}{2}\right)\right] \tag{4}$$

From different investigations (described in Achmus 1995) a band width for the coefficient of friction μ between HDPE and sand of $0.30 \leq \mu \leq 0.55$ is known. The lower boundary value tends to be assigned to loose sand and the upper one to dense sand.

From recent investigations (HEW 1987, Gietzelt et al. 1991) it is known that the friction forces on district heating pipelines are not constant, but considerably dependent on the operating temperature. The reason for this is the increase of radial stresses σ_r due to the temperature-induced increase in the pipe diameter. As an example, Figure 3 gives experimentally determined friction forces for a pipe of nominal width DN 700. In the following a numerical model for the estimation of the temperature-dependent friction forces is presented.

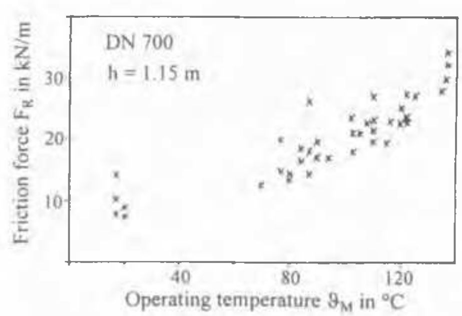

Figure 3. Experimentally determined friction forces (HEW 1987)

3.1 *Increase of the plastic jacket pipe diameter*

The calculation is simplified by assuming axi-symmetric conditions with temperature ($\Delta\vartheta$) and earth pressure (σ_r) loading. Thus the increase of the pipe diameter is fixed by the radial displacement of the pipe coating u_C.

The temperature distribution in the plastic jacket pipe for the assumption of axi-symmetry can be determined analytically. The ratio of the boundary temperature differences $\Delta\vartheta_C$ (coating) and $\Delta\vartheta_M$ (steel medium pipe) can be estimated based on theoretical analysis and a comparison with experimental results as follows:

$$0.05 \leq \frac{\Delta\vartheta_C}{\Delta\vartheta_M} \leq 0.10 \tag{5}$$

The radial displacements due to temperature and radial earth pressure are determined with the equations derived from Beilke (1993) for plastic jacket pipes. Calculation results indicated that the radial displacements are nearly independent of the earth pressure. The ratio of boundary temperatures given above is also of little influence. In Figure 4, results for the non-dimensional displacement u_C/D are given in dependence on the outer pipe diameter D for an operating temperature difference of 120 K.

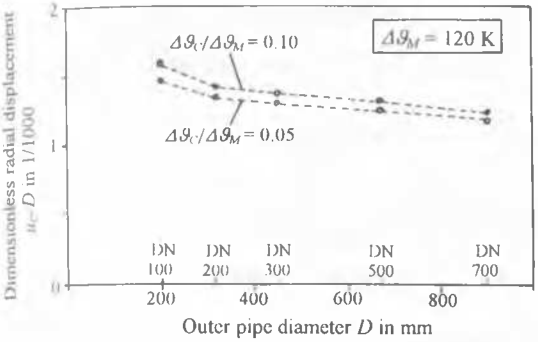

Figure 4. Dimensionless radial displacement for $\Delta\vartheta_M$ = 120 K.

3.2 *Soil reaction stresses*

A suitably simple approach is chosen for the initial stress state before first heating of the pipeline. At the top of the pipe the vertical stress is $\sigma_{r,top} = \gamma h$, at the abutments the horizontal stress is $\sigma_{r,ab} = k\,\gamma(h + D/2)$ and at the pipe base the vertical stress is $\sigma_{r\,base} = \gamma(h + D)$. Here k is a coefficient of horizontal earth pressure. For this approach the average initial radial stress is

$$\sigma_{rm}^{(0)} = \frac{1+k}{2}\gamma\left(h+\frac{D}{2}\right) \tag{6}$$

A finite element approach is used for the calculation of soil reaction stresses due to the radial expansion of a cylindrical cavity (pipe). The soil behaviour is simulated by an 8-parametric incremental-elastic material law first presented by Duncan & Chang (1970) and modified by Duncan (1980). Here the elastic parameters E (elasticity modulus) and ν (Poisson's ratio) depend on the actual stress state. Typical parameter combinations for sand with different relative densities were used in the calculations. Details concerning the finite element approach are given in Achmus (1995).

The symmetrical cavity expansion produces a slightly non-symmetrical shape of soil stress reaction p_r, because movement in the direction of the ground level causes lower resistances. However, with good accuracy the average radial stress p_{rm} was found to be a characteristic measure of the soil reaction stresses.

The coupling of the functions $u_C = f(\sigma_{rm}, \Delta\vartheta_M)$ and $p_{rm} = f(u_r)$ by compatibility and equilibrium conditions yields the dependence of average soil reaction stress σ_{rm} and operating temperature difference $\Delta\vartheta_M$. Results for a pipe of nominal diameter DN 200 are shown in Figure 5.

The experimentally established friction force increase with increasing operating temperature is confirmed by the numerical model. The influence of different parameters (relative density of sand, overburden height, nominal pipe diameter) can be investigated with the model. As a measure of temperature dependence, the factor κ_l is defined as follows:

$$\kappa_l = \frac{\sigma_{rm\,(\Delta\vartheta_M=100K)}}{\sigma_{rm}^{(0)}} = \frac{F_{Ru\,(\Delta\vartheta_M=100K)}}{F_{Ru}^{(0)}} \tag{7}$$

The results indicate that this factor is significantly dependent on the relative density of the sand and the overburden height, but is nearly independent of the nominal pipe diameter.

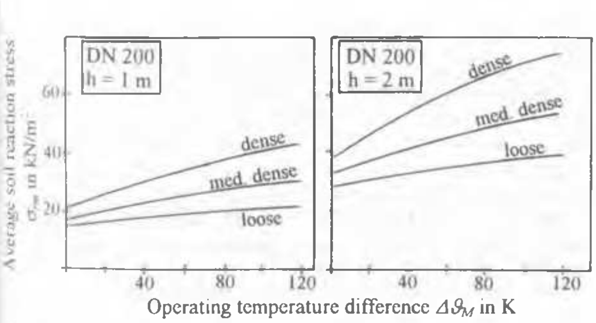

Figure 5. Calculated dependence of σ_{rm} on $\Delta\vartheta_M$.

3.3 *Unloading / reloading processes*

The results given in the foregoing section are valid for monotonic initial loading. Through the initial expansion of the plastic jacket pipe the arising soil deformations are partly elastic due to the compression of the grains, and partly plastic due to grain rearrangement. The development of plastic deformations is the reason for a reduction of the stresses on the pipe after unloading compared with the initial state. For this reason the temperature dependence of the friction forces is even more intensive for unloading and reloading processes than for initial loading. This was verified by the experimental results of Gietzelt et al. (1991).

Experimental tests are indispensable for the reliable quantification of the stresses acting on the pipe after reloading. For the tests of Gietzelt et al. (1991) and HEW (1987) a factor κ_{ur} was determined which is the ratio of the mobilizable friction forces at an operating temperature difference of 100 K and after reloading (Index $^{(1)}$):

$$\kappa_{ur} = \frac{F_{Ru\,(\Delta\vartheta_M=100K)}}{F_{Ru}^{(1)}} \tag{8}$$

In contrast to the factor κ_l for initial loading, this factor is significantly dependent on the nominal pipe diameter. For a DN 700 pipe κ_{ur} was determined to be about 3.8 to 4.0, while for DN 80 the factor was about 1.6. These are only indication values, because the number of test results is not sufficient for the development of a calculation approach on an empirical basis.

4 BEDDING RESISTANCE

In arc or junction sections the axial displacement of a district heating pipeline during operation leads to lateral (horizontal) displacements perpendicular to its axis. This causes bedding resistance of the surrounding soil. Until now, expansion pads have been used in such sections to reduce the resistance, and the reaction stresses heve been neglected in the design. This is not correct, because bedding resistances also occur on pipes coated by expansion pads. Beside this, arcs without expansion pads have been tested in operation in the meantime. The quantity of the bedding resistance and its dependence on different parameters is therefore of great interest.

In model tests Audibert & Nyman (1977) and Trautmann & O'Rourke (1985) investigated the bedding force on a steel pipe in homogeneous sand for steady horizontal displacement over its whole length. The system coss section is shown schematically in Figure 6.

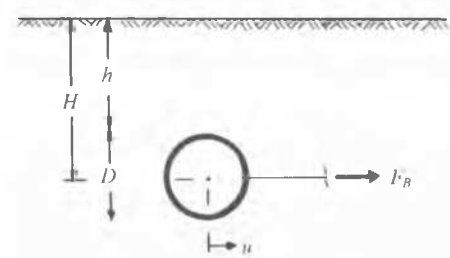

Figure 6. Designations for the bedding resistance problem.

With regard to the shape of the force deformation curves both tests gave similar results, indicating an underlinear increase of the bedding resistance with increasing lateral displacement until the maximum bedding resistance F_{Bu} is reached.

For the maximum bedding resistance in both papers the following approach is made:

$$F_{Bu} = N_u \gamma H D \tag{9}$$

with N_u = force coefficient.

It is assumed that this force coefficient depends on the dimensionless overburden height h/D and the angle of friction φ

(relative density) of the sand. The experimentally determined force coefficients are given in a diagram in Figure 7. It is noted that the values determined by Trautmann & O'Rourke (1985) are partly significantly less than the values from Audibert & Nyman (1977).

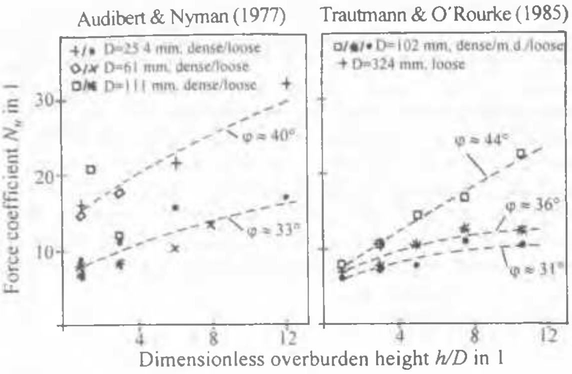

Figure 7. Experimentally determined force coefficients N_u

4.1 *Numerical model*

The finite element approach used for the treatment of the radial expansion problem was also used for the case of horizontal movement of the pipe. The relative density, the overburden height and the pipe diameter were varied.

The calculated shape of the force-displacement curves was in good agreement with the experimental results. The calculated force coefficients N_u are shown in Figure 8. It is noted that the coefficient is not only dependent on the dimensionless overburden height, but also on the absolute value of the outer pipe diameter, thus $N_u = f(h/D, D)$. Thus, the differences in the experimental results stated above can be plausibly explained. Audibert & Nyman (1977) used pipes of smaller diameters than Trautmann & O'Rourke (1985) and obtained higher force coefficient values.

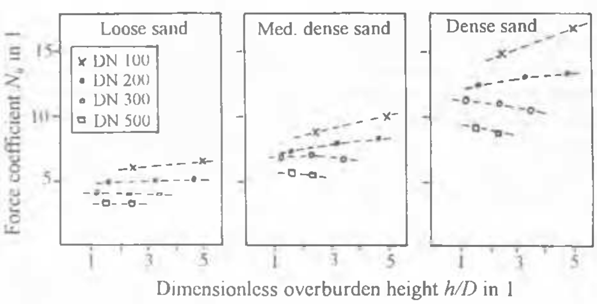

Figure 8. Calculated force coefficients N_u

4.2 *Effect of expansion pads*

Through the coating of a pipe with expansion pads the horizontal displacements are first compensated by the pad with corresponding lower bedding resistance. However, the general neglect of bedding resistance is not admissible.

The combined effect of expansion pad and soil reaction, which principally act like springs connected in series, is elucidated in Figure 9. For small displacements the reduction of the soil reaction is significant, but with increasing displacements the compressibility of the pad is run down and the related reduction is less.

In Achmus (1995) a first simple approach is presented which allows one to determine the force-displacement curve for the expansion pad from results of a uniaxial compression test. The dependence on the initial stress state and on the outer pipe diameter is taken into account. Such a method permits the design of expansion pads (material, thickness) dependent on the admissible bedding stress. Nevertheless, additional theoretical and experimental investigations are necessary for this.

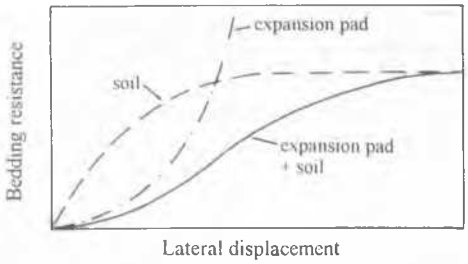

Figure 9. Effect of expansion pads (schematic)

5 CONCLUSIONS

Soil-buried district heating pipelines intensively interact with the surrounding soil due to varying temperatures during operation. Knowledge about the quantity of friction forces and bedding resistances is of decisive significance for the design.

Due to the radial expansion of the plastic jacket pipes the friction forces are not only dependent on the initial stress state in the pipe trench and the coefficient of friction, but also on the operating temperature. The numerical model presented here permits the estimate of friction forces for initial loading. Additional investigations are necessary concerning the forces for unloading and reloading processes.

The model presented for the calculation of bedding resistances permits the estimation of the influences of the relative density of sand, the overburden height and the nominal pipe diameter. For this model, just as for the approach to cover the effect of expansion pads, verification by field measurements is needed, because the complex field conditions (3-dimensional loading, inhomogeneous soil etc.) can hardly be determined solely by theoretical analysis.

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