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Sektion 8 a

Heat distribution – optimisation of existing solutions

Reduction of friction forces between soil and buried district heating pipes due to cyclic axial displacements

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Reduction of friction forces between soil and buried district heating pipes due to cyclic axial displacements

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1 Introduction

Nowadays in most cases district heating pipelines are buried in the underground. The displacement of buried district heating pipes due to internal pressure and temperature changes of the transported medium leads to intensive interaction with the surrounding soil. The expansion of the pipelines due to operating temperatures of up to 130°C is hindered by reaction forces of the surrounding soil. Friction forces are caused by axial displacements, and bedding resistances are caused by lateral displacements which occur in arc sections and junction sections.

The presented investigation focuses on the effect of cyclic axial pipe displacements, which induce a reduction of friction between soil and pipe. This is often called the „tunneling effect“. According to the recommendations of the German FW401 regulation, the decrease of friction during operation is considered in halving the coefficient of friction μ between pipe and soil [7]. This is only a rough estimation. The quantity of the friction forces acting on the pipeline determines the deformation behaviour, the course of axial stresses and the quantity of bending stresses in arc and junction sections of the pipeline [4]. Thus, it is a decisive parameter for the design of district heating pipelines. For economical design and maintenance it is inevitable to describe the interaction processes, i.e. the friction force reduction, more precisely.

It is well known from experimental investigations that the friction force acting on a district heating pipeline is not constant, but is dependent on the operating temperature, i.e. the temperature of the heat-transporting medium. The reason for this is the increase in the radial earth pressure due to the radial expansion of the pipe induced by the temperature increase. Additionally, the friction forces for the first loading or movement of the pipeline are different from the friction forces for repeated loading and unloading. Figure 1 gives experimental results for friction forces on pipes of nominal widths DN 150 and DN 250 obtained at the Fernwärme-Forschungsinstitut in Hannover [8]. A temperature-induced increase of the friction forces for first loading and an even more significant temperature-dependence of the friction forces for unloading and reloading were found.

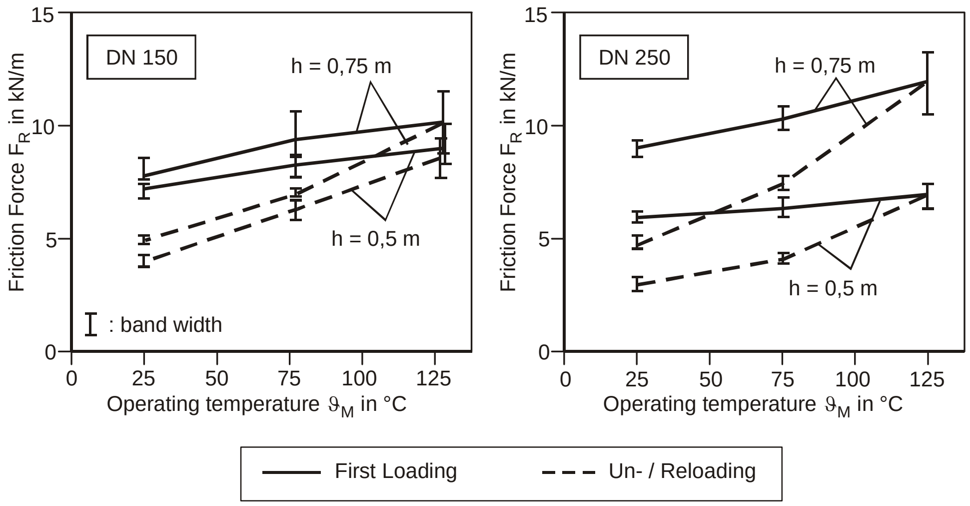

FIG. 1 — Experimentally determined friction forces on plastic jacket pipes DN 150 and DN 250 for first loading and un-/reloading [8]

Evidently, the change of the friction forces during pipeline operation is related to two different processes. On one hand, cyclic radial expansion and contraction of the pipe changes the radial stresses acting on the pipe and hence the friction force. A model for the determination of the friction force increase due to radial expansion was presented in [1] an [2]. On the other hand, a friction force decrease is also obtained without radial expansion of the pipe. Thus, the second important process is the repeated axial displacement of the pipeline.

To get a better insight in the processes, the effects have to be studied separately. This investigation focuses on the effect of cyclic axial displacement only. An experimental program was conducted to investigate the quantity of friction force reduction dependent on pipe width, overburden height and relative density of the sand fill.

2 Experimental set-up

The experimental set-up consists of a sand box with a cross section of 90 cm x 90 cm (width x height) and a length of 120 cm. In this box HDPE-coated district heating pipes (DN 40, DN 65 or DN 80) were placed and embedded in dry homogeneous sand. The pipe sections had lengths of about 150 cm. The pipe ends were led through holes in the end plates of the sand box. Cyclic axial displacement of the pipe section was carried out by means of an electrical push-pull device.

The force necessary to push or pull the pipe was measured by a 10 kN loading cell outside of the sandbox. Five displacement sensors were installed. One was used to measure the axial displacement and four (two at both ends of the pipe) to observe pipe settlements. Figure 2 shows the externally installed equipment at the head of the district heating pipe.

The used sand was a poorly graded quartz sand. The grain size distribution is shown in Fig. 3, and relevant parameters of the sand are given in Table 1.

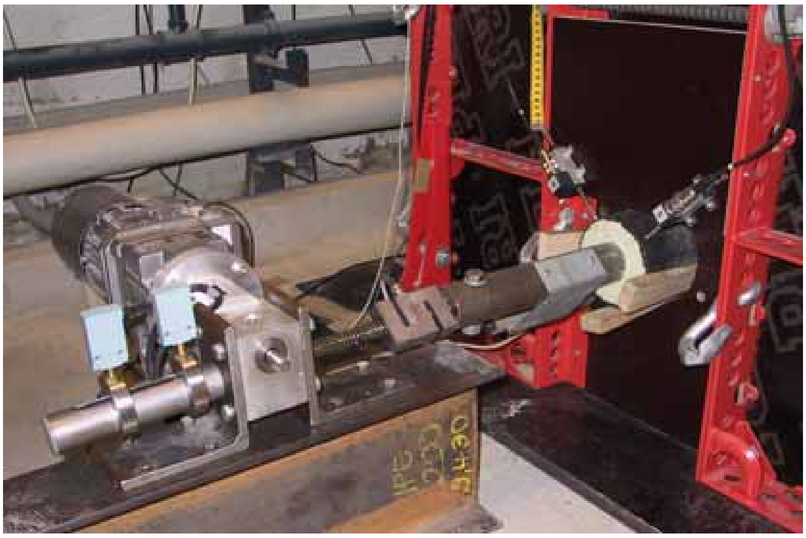

FIG. 2 — Load cell and displacement sensors

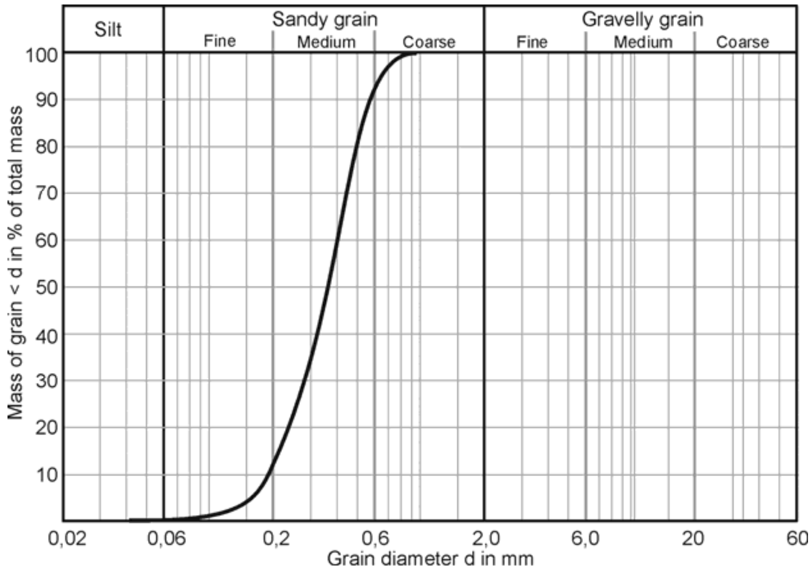

FIG. 3 — Grain size distribution of the sand used

Table 1 — Index properties of the sand used

Uniformity index:	U = 2.21
Index of curvature:	C_c = 1.0
Minimum porosity:	min n = 0.333
Maximum porosity:	max n = 0.442
Density of particles:	ρ_s = 2.634 g/cm^3

The internal angle of friction of the sand in medium dense state (D_r = 0.5) was determined in direct shear tests to φ' = 38°. The sand was compacted by tamping layer by layer with light compaction equipment, which is a common method used in comparable testing set-ups [3] [6] [9].

About 80 tests have been carried out. In each test 10 displacement cycles have been applied. The following parameter variations were considered:

- Outer diameter of the pipe: D = 110 mm (DN40), D = 140 mm (DN65), D = 160 mm (DN80),
- Relative height of cover: H/D = 2, 3 and 4 (H = soil overburden height, D = outer diameter),
- Relative density of the sand embedment:: D_r = 0.1, 0.3, 0.5 and 0.7 (D_r = (max n – n)/(max n- min n)),
- Peak axial pipe displacement : 55 mm; 5.5 mm,
- Velocity of pipe displacement: 15.28 mm/min; 3.83 mm/min.

3 Measurement of radial stresses acting on the pipe

It seems obvious that the observed decrease of friction forces is mainly due to a reduction of the radial stresses acting on the pipe. In order to measure this effect directly, an innovative measurement technology, the grid-based tactile pressure sensor [10], was used in some tests.

With usual earth pressure sensors the pressure acting on the pipe can not be measured accurately. Only the pressure at discrete locations beneath the pipe can be measured, and since the pressure cell has another stiffness than the soil, the stress to be measured is falsified by the sensor itself. These shortcomings are avoided by the tactile pressure sensor. It consists of a thin foil, which can be wrapped around the pipe. Pressures are recorded in the nodes of a fine grid placed on the foil. With this system, the stress state around the whole pipe perimeter can be measured without significant disturbance.

The pressure foil used had a size of 530 mm x 492 mm and a thickness of 0.33 mm. In Figure 4 the foil mounted on the pipe is shown. The data logger unit and the cable were placed inside the pipe to avoid disturbance of the stress state. In order to do that, a part of the pipe was cut out and replaced after installation. Subsequently, a PE foil was wrapped around the sensor foil to protect it from damage by the shear stresses occurring during axial pipe displacement.

FIG. 4 — Pressure sensor, data logger and cable mounted on the pipe

The calibration of a pressure sensor has to be carried out after installation and is thus a difficult procedure. Different constant and uniform pressures have to be applied to determine the calibration parameters [10]. Since these parameters change with time, also the time-dependency has to be taken into account (see e.g. [11]).

Here the calibration was carried out by means of air pressure application. For this an acrylic tube was placed around the district heating pipe and sealed at its ends. The whole pipe was surrounded by an airtight rubber hose to avoid air losses through the flap for the data logger. The set-up is shown in Fig. 5. Filling the volume between tube and pipe with air led to different pressures on the sensor, which were used for the calibration procedure.

FIG. 5 — Set-up for the calibration with air pressure

4 Results

A test procedure began with a forwards movement of the pipe with constant velocity until the desired maximum axial displacement was reached. In nearly all tests (except the tests with very loose sand) the maximum friction force was measured during this first movement. This force is termed F_0. Subsequently, the pipe was moved with the same velocity backwards to its initial position. This process was repeated 10 times, i.e. 10 deformation cycles were executed. After 5 to 8 cycles in all tests the friction forces measured kept constant. Usually this was the minimum or residual friction force, which is termed F_{res}.

The maximum force during one displacement period was reached after only a few millimetre and kept constant during the rest of the period. Hence, the variation of the maximum displacement had no effect on the friction forces F_0 and F_{res}. The same result applies for the displacement velocity.

In Fig. 6 the friction force decrease measured is shown exemplary for a relative density of the sand of D_r = 0.7 and a relative overburden height of H/D = 2. For this relative density even after 5 cycles the friction forces remain constant.

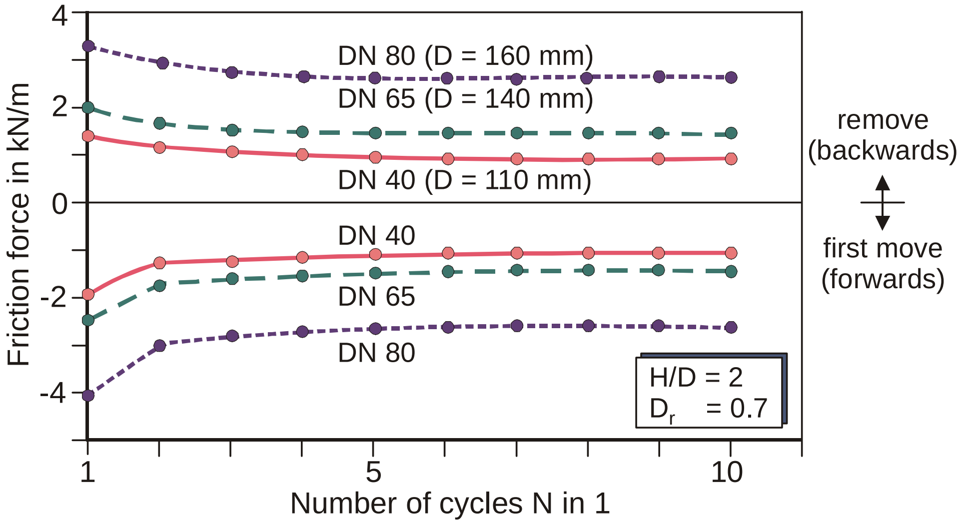

FIG. 6 — Measured reduction of friction forces for different pipe diameters

As a measure for the friction force decrease, a degradation factor C_F is defined as follows:

$$C_F = \frac{F_0}{F_{res}} \tag{1}$$

For the results shown in Fig. 6 C_F-values of 1.57 (DN 80), 1.75 (DN 65) and 1.77 (DN 40) are obtained.

The relative density of the sand embedment has a significant influence on the friction force development. This is elucidated in Fig. 7, where results for a pipe with outer diameter of D = 140 mm (DN 65) and a relative overburden height of H/D = 3 are given. For a very loose state (D_r = 0.1) a slight friction force increase is obtained instead of a decrease. However, such an extremely loose state is unusual and even unadmissible in practice. In most cases medium dense to dense or even dense compaction states are required due to pertinent regulations. Hence, the results for D_r = 0.5 and D_r = 0.7 are most relevant for practice. For D_r = 0.7 (dense state) C_F = 1.75 and for D_r = 0.5 (medium dense to dense state) C_F = 2.0 is obtained.

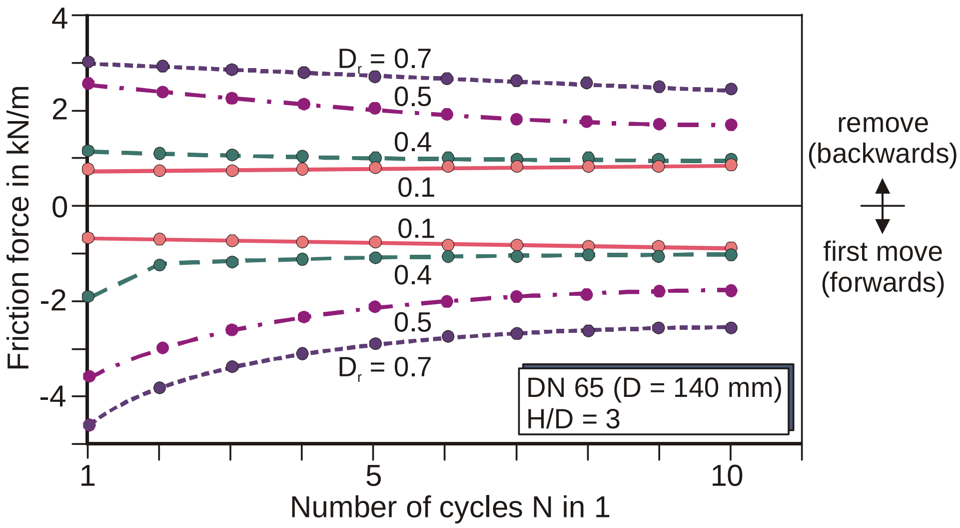

FIG. 7 — Reduction of friction forces dependent on the relative density of the sand

The C_F-values determined in about 60 tests with dense sand (D_r = 0.7) and different overburden heights and pipe diameters are presented in Figure 8. Some tests were repeated several times, but a certain scatter in the results could not be avoided due to the problems in achieving a homogeneous sand bed with the method of placement chosen. However, a clear tendency of increasing C_F-values with increasing relative overburden height is found. For the straight line shown in Fig. 8 the following equation obtained by a linear regression analysis applies:

$$C_F = 0.095\frac{H}{D} + 1.36 \tag{2}$$

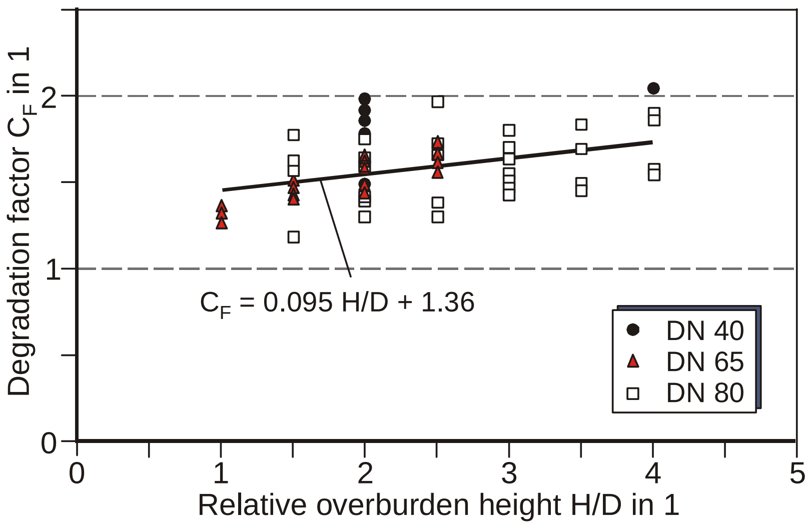

FIG. 8 — Degradation factor C_F dependent on relative overburden height for D_r = 0.7

Results of the pressure sensor measurements are shown in Fig. 9. In the left, the stress distribution after placement of the sand fill and before the begin of the test is shown. The primary or initial stress distribution is characterized by the typical concentration of pressures at the top and the bottom of the pipe, which has been expected. During the cyclic displacement the contact stresses between soil and pipe decrease, whereby a much stronger decrease occurs in the regions where initially higher pressures applied. Thus, after 10 cycles an approximately constant and uniformly distributed residual stress around the pipe was measured (Fig. 9 right).

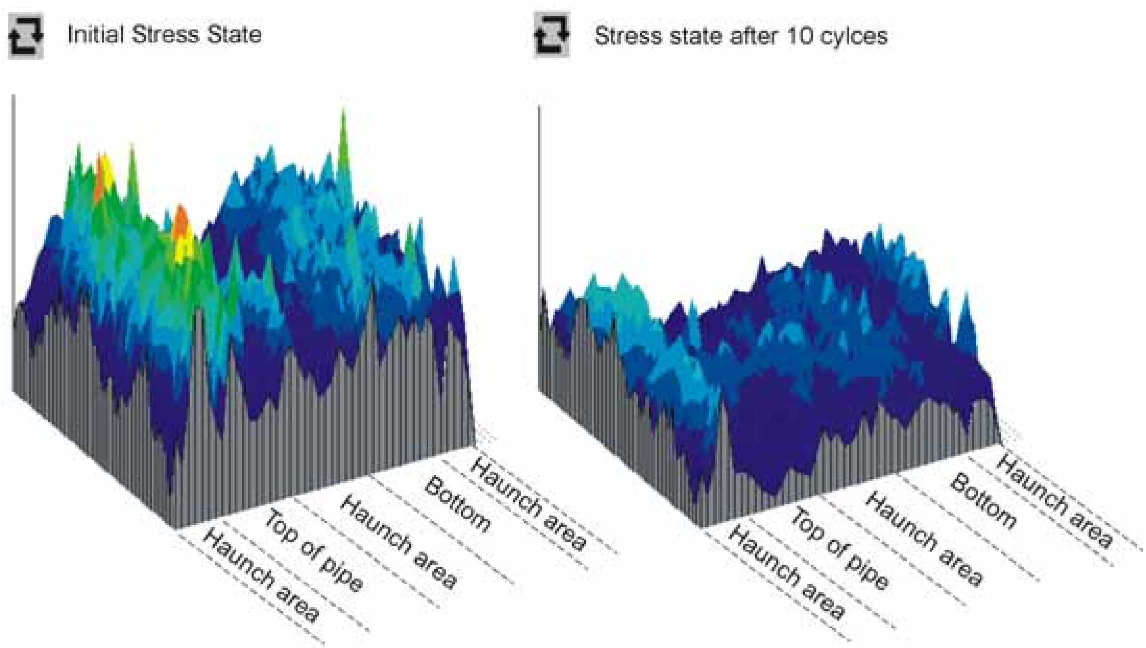

FIG. 9 — Results of the pressure sensor measurements (DN 65, H/D = 3, D_r = 0.4)

In Figure 10 the degradation factor measured with the load cell and obtained by evaluation of the sensor foil results are compared. The factors show similar tendencies for different relative densities.

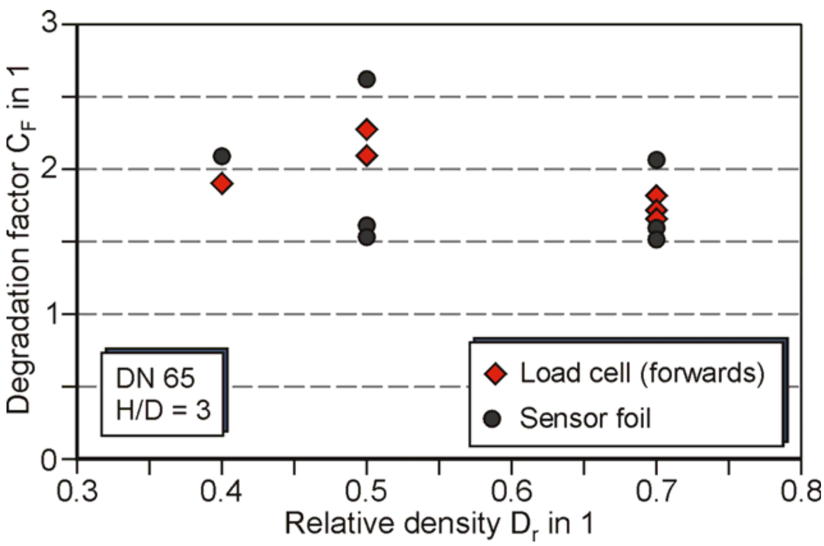

FIG. 10 — Degradation factor C_F dependent on relative density

5 Conclusions

Earth-buried pipes are subjected to a soil – pipe interaction, which is due to the displacements of the pipe induced by temperature loading. Cyclic axial movement of a pipe leads to a reduction of friction forces acting on the pipe with the number of cycles. Experiments have been conducted to examine the most important influences concerning the reduction of friction. Separated from lateral displacements and radial pipe diameter expansion only axial cyclic displacement was investigated in a pipe – soil testing box. Based on the experimental test data it is concluded, that

- relative density of the soil embedment and
- relative height of cover (H/D)

are important factors for the problem described.

For dense sand, friction degradation factors between about 1.2 and 2 were determined. The factor increases with increasing relative height of cover. For medium dense sand, tendentially slightly higher values were obtained.

With a pressure sensor foil the initial earth pressure on the pipe and the residual earth pressure after cyclic loading could be measured directly. With this it could be proved that the reduction of friction is mainly induced by the reduction in earth pressure acting on the pipe.

The friction forces strongly influence the behaviour of and the stresses on district heating pipelines and should thus be determined as exact as possible. It seems obvious that the variability of the friction forces dependent on the site and soil conditions should be considered in the design in order to ensure safe and economic construction. The results of the experiments showed that the way of consideration of the “tunnelling effect” suggested in the German FW401 regulation should be modified to take the influences of relative density of the soil and relative height of cover into account. In that respect, additional research is desirable.

6 References

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