PIPE-SOIL INTERACTION IN LARGE SOLAR THERMAL HEATING AND COOLING PLANTS

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1. Introduction

Currently positive circumstances for the expansion of solar thermal heat can be observed in Europe. Because of climate change and the connected wish to reduce CO_2-emissions and because of doubts on the security of nuclear power generation the broad use of renewable heat sources are supported by the European Union. A very promising technology in this field is heating and cooling of urban areas with large solar thermal plants connected to a district heating pipe network. Coupled with seasonal storages and other efficient district heating technologies this technology can be integrated in the heat supply concept of European municipalities (Huther et al 2011). Nevertheless the integration of large solar thermal plants is a special technical challenge.

In solar thermal plants large collectors provide the heating of water by solar radiation. These collectors (Fig. 1) are usually connected to a storage and a district heating network.

Fig. 1: Solar collectors, Graz Austria

A leading position in solar thermal plants has Denmark with today more than twenty large solar thermal plants with a total nominal power well over 100 MW_{th}. The biggest plant has a nominal power of 12.9 MW_{th} and delivers heat for the Danish town Marstal with 2347 inhabitants. In Germany eleven large solar thermal plants were built with a total power of 17.5 MW_{th} so far.

During the last few years a growing interest for this technology in Europe has been observed. Solar district heating and solar block heating are today entering a phase of actual marketing (Pauschinger et al. 2010).

2. Temperature load in solar thermal pipes

Because the sun only shines during the daytime, the solar collectors provide no heat by night. Thus the connected pipelines are exposed only to the environmental temperature. A typical collector load curve is shown in figure 2 for a summer day.

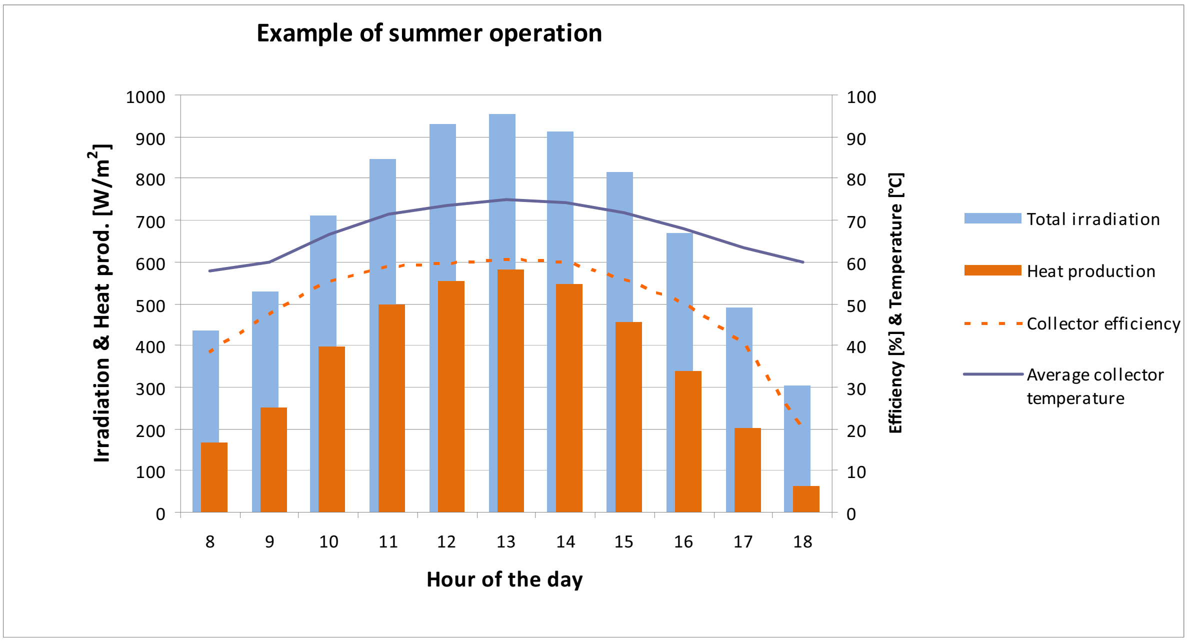

Fig. 2: collector load curve in summer, Hillerød Denmark

During the day that leads in this case to an average temperature of ~67°C in the pipes for solar district heating. Depending on the weather the water in the supply line can reach temperatures up to 100 °C and for pressurized systems sometimes even higher.

Furthermore the heat can be used as well for cooling purpose. Feeding an absorption chiller with the required energy for cooling by solar collectors is one of the most environmental friendly cooling solutions. Even the timeline of cooling demand and the availability of radiation fit very well, because sunlight is available when the cooling is needed.

By night the temperature in the system drops to the environmental conditions. If the pipelines are buried in the ground the temperature of the surrounding soil is decisive. Fig. 4 show typical temperature distribution in the ground according to Dahlem (Dahlem 2000).

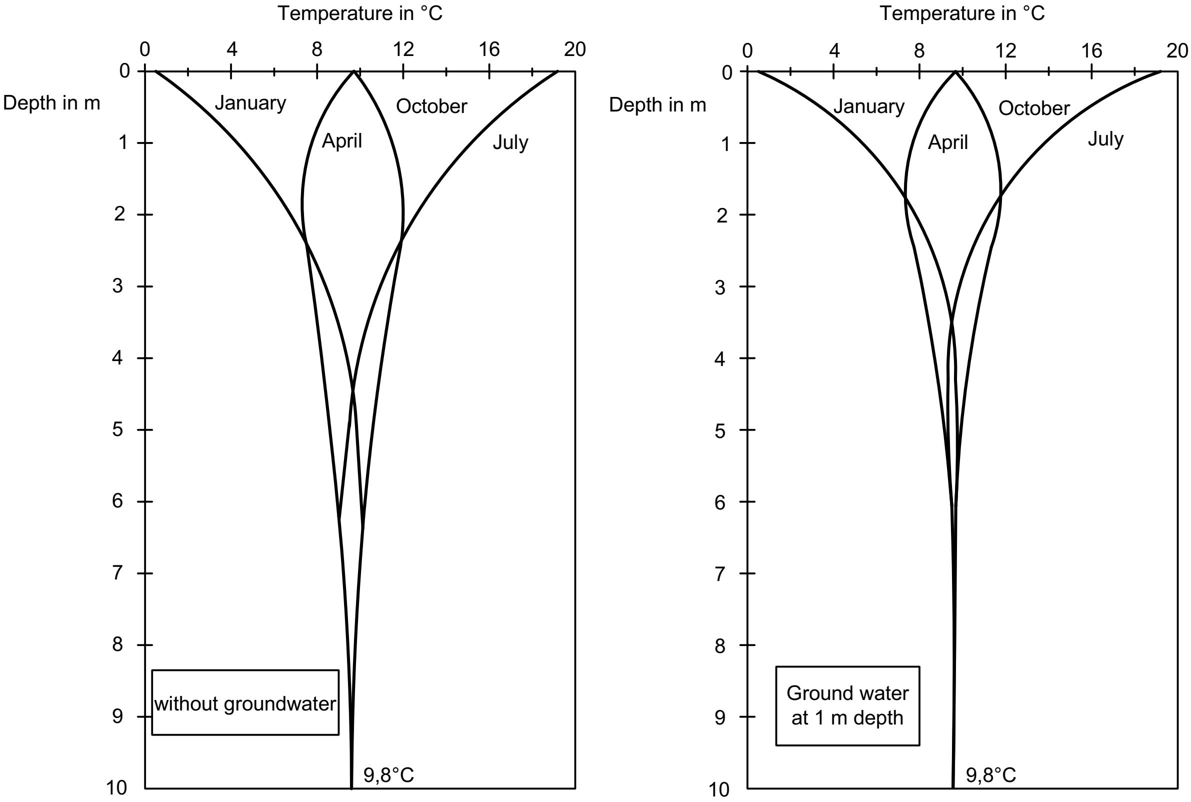

Fig. 3: Temperature in the ground (Dahlem 2000)

For an average environmental temperature of 20 °C a maximum temperature difference of $\Delta T = 80$ K has to be taken into account for the design of the district heating grid components. According to fig. 3 ΔT is even higher, when pipes are buried in the ground. In any case the system has to be able to cope with the ambient temperature levels throughout all different seasons during a year. Peak loads can be reduced by using water tanks as buffer-storages.

3. Cyclic loading

The described maximum temperature changes occur once a day. For a suggested lifetime of a district heating network of 30 years a number of cycles for the temperature load of $N = 30 \times 365 = 10950$ is accumulated. Compared to conventional district heating pipelines the cyclic load is much higher. In table 1 the estimated equivalent action cycles for conventional district heating pipes are shown according to EN13941 (EN13941 2010).

Tab. 1: Equivalent action cycles according to EN13941

Pipe type	Equivalent full action cycles in 30 years according to EN13941
Major pipelines	100
Main pipelines	250
House service connections	1000

Because of the significant difference in the cyclic load the structural design of conventional district heating pipes cannot be easily transferred to pipes in solar thermal driven grids. For a reliable assessment of the long-term behaviour of solar thermal pipes the cyclic behaviour of the used material must be known. On the one hand it is a question of durability of the material; on the other hand it is a question of the structural stability of the whole pipe-system.

For solar thermal plants preinsulated bonded pipes (steel medium pipe, polyurethane insulation and polyethylene coating) and special pipes for solar thermal conditions are used. The structural design of these pipes can be carried out according to EN13941. However only few known investigations take into account the cyclic behaviour of buried district heating pipes. For a safe design of solar heating pipelines this lack of information must be filled in the near future.

4. Structural analysis for cyclic temperature loading

In the EN13941 the structural analysis for the steel medium pipe is regulated. According to this standard the ultimate limit states A1 and A2 for one severe action and few actions respectively. B1 and B2 indicate low cycle fatigue and high cycle fatigue and have to be respected. Furthermore limit states C and D are defined, which are not explained here.

For the equivalent action cycles according to table 1 only the safety against low cycle fatigue is to be verified. For conventional district heating pipes the limit state B2, high cycle fatigue, is only of importance in the case of large diameter pipe, small soil cover and heavy traffic actions or pipes above ground subject to vibration, e.g. from wind. The EN13941 refers to Eurocode 3 (EN 1993), *Structural Use of Steel*, for high cycle fatigue analysis, which is relevant for solar thermal pipes with more than $N = 10^4$ cycles.

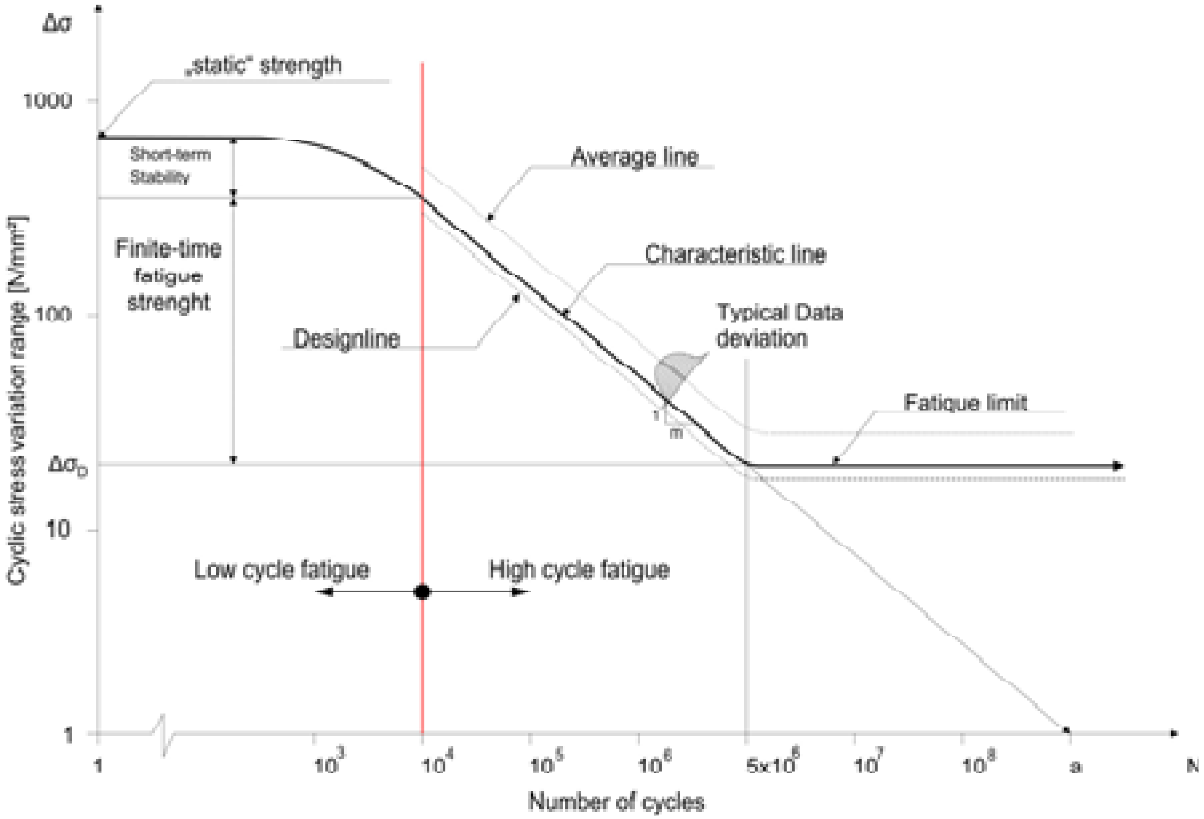

Fig. 4: Stability curve for steel under cyclic loading (Puthli 1998)

For the insulation polyurethane foam changes in the mechanical properties due to cyclic loading are expected. However cyclic testing of insulation foams for district heating is underrepresented in current testing standards (e.g. EN253 2009, EN498 2009). For a better understanding of the whole district heating pipe network investigations on the mechanical behaviour of insulation foams under cyclic loading have to be carried out.

5. Cyclic pipe – soil interaction

5.1. Cyclic soil behaviour

Due to cyclic loading the bearing capacity of soils can be significantly reduced compared to the initial state. The manner of the reduction of the bearing capacity depends on the properties of the soil, the load boundary conditions and on the geometry of the construction element. The soil behaviour under cyclic loading is currently seen as a form of creeping-reaction.

Different creeping-reactions of soils are known. Proportionally increasing plastic displacements with increasing number of cycles are known as „ratcheting“ or „incremental collapse“. The rate of displacement remains approximately constant. This cyclic soil behaviour leads finally after a certain number of cycles to failures in the system.

Another creeping-reaction is the „shakedown“-behaviour. This soil behaviour is characterised by plastic deformations reaching a stable state during cycling. The displacements occurring have no remaining influence on the system. The remaining deformation rate is zero (Goldscheider et al. 1976).

The third form of creeping-behaviour is the „sedation“. The deformation rate decreases with increasing number of cycles. A linear relationship between deformation and the number of cycles in logarithmic scale can be observed. This soil reaction will lead step by step to the failure of the system.

In some cases a combination of the different reaction-types can happen. An apparent stable state may change to a non stable soil reaction during cycling, that lead to a failure.

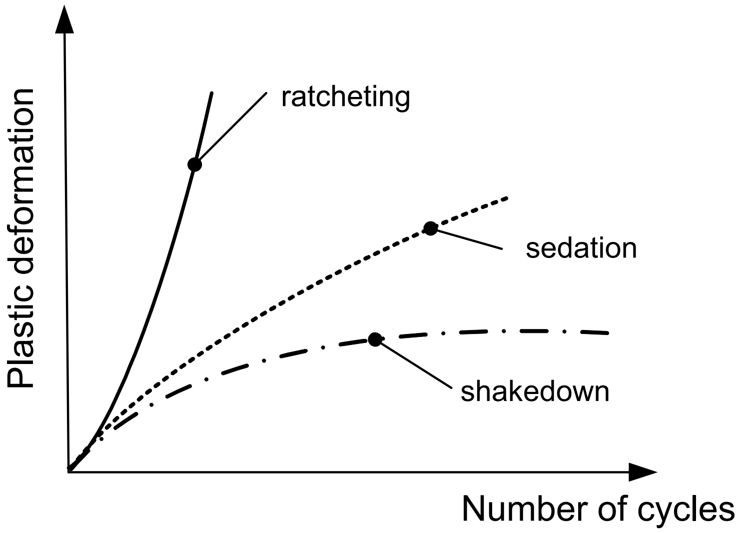

Fig. 5: Soil reaction types due to cyclic loading (Lesny et al. 2005)

Schwarz collected 2002 results for the „Critical Level of Repeated Loading (CLRL)“ (Schwarz 2002). The CLRL is the ratio between the cyclic load amplitude to the static failure load. When the CLRL is exceeded the cyclic loading leads to a failure. Schwarz identified values for CLRL according to table 2.

Tab. 2: CLRL - values

Type of soil	CLRL
Sand	0.1 – 0.4
Silt	0.4 – 0.6
Normal consolidated clay	0.35 – 0.55
Over consolidated clay	0.85 – 1.0

According to the results of Schwarz sand has the highest potential for failure due to cyclic loading. Already a small cyclic loading ratio related to the static failure load lead to decreasing effects of the bearing capacity.

This must be respected for buried district heating pipes, because the favourite refill material for pipe trenches is usually a poor graded sand.

5.2. Axial cyclic pipe soil interaction

Several laboratory tests and in situ measurements showed a reduction of friction on buried pipelines due to cyclic axial displacements (so-called tunnel-effect). It was observed, that the reduction of friction happens during the first 5 to 10 cycles. After that a constant remaining residual value for the friction force is reached (Weidlich 2008). Today the halving of the initial friction force is assumed for the residual state.

According to EN13941 the recommended coefficient of friction for initial movement of the pipes is $\mu = 0.4$ and considering long term effects (tunnel-effect) the recommended coefficient of friction is $\mu = 0 - 0.2$. The low values should be used e.g. when designing expansion.

For high numbers of cycles no changes in the residual friction force are expected.

5.3. Lateral cyclic pipe soil interaction

The lateral cyclic pipe soil interaction is not well known today. The calculation of lateral bedding pressures on pipelines are based on laboratory tests with monotonic loading. According to EN13941 the coefficient of horizontal soil reaction or “horizontal bedding constant” k_h is defined as the ratio between horizontal soil pressure (p) and horizontal movement of the pipe system (v) as shown in equation 1.

$$k_h = \frac{p}{v} = \frac{p_u}{0.15 \cdot v_u + 0.85 \cdot v} \qquad \text{(eq. 1)}$$

Where p_u is the ultimate resistance of the soil and v_u is the ultimate displacement related to p_u. The ultimate horizontal soil resistance p_u can be assessed using the equivalent action capacity formula for side support (in cohesion-less soils) given by equation 2.

$$p_u = \gamma \cdot H \cdot K_q \qquad \text{(eq. 2)}$$

Where γ is the weight of the soil and H is the overburden height. The soil pressure coefficient K_q can be chosen in Fig. 6 depending on the relative overburden height H/OD and the angle of internal friction Φ of the soil.

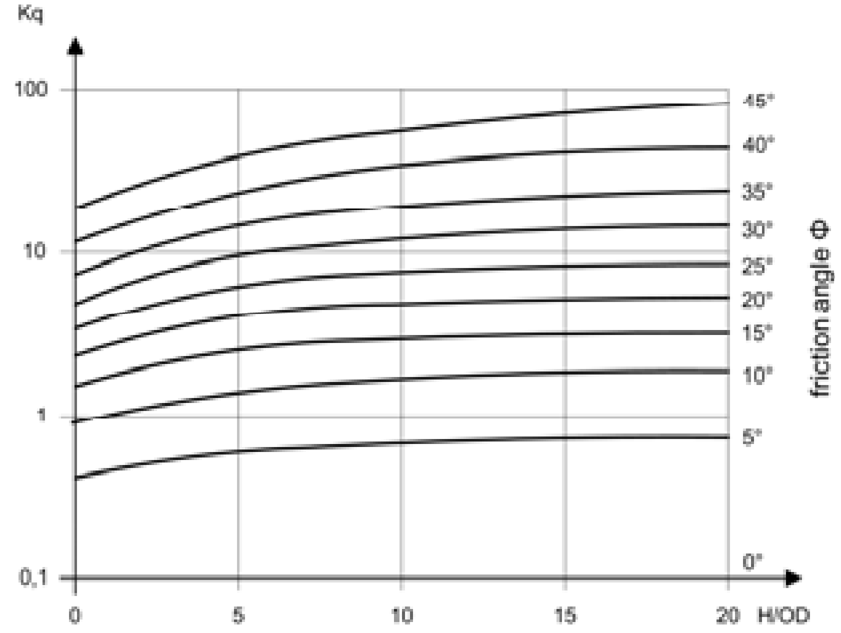

Fig. 6: Soil pressure coefficient K_q

The ultimate horizontal displacement v_u is not known precisely and depends also on soil properties. The results of a number of tests with small diameter pipes are summarised in table 3.

Tab. 3: Ultimate horizontal displacement v_u for small diameters

Outer diameter (OD)	Loose Sand	Dense Sand
75 mm	4.5	2.7
120 mm	3	2
300 mm	2	1.5

The value for the line bedding constant k_{soil} is derived from k_h as shown in Equation 3.

$$k_{soil} = k_h \cdot OD \qquad \text{(eq. 3)}$$

Cyclic effects are not respected in the above presented equations. Because of the lack of scientific investigations in the field of lateral cyclic pipe soil interaction only the analogy of pipes to other cylindrical structural elements may give an outlook towards possible cyclic soil response.

Because of the massive expansion of offshore platforms for wind energy the design of cyclic loaded piles got into the focus of scientific research. The often used analogy between pipes and piles seems to be useful for the described problem. Since spring models are often used for numerical calculation of district heating pipe systems simple calculation methods using a cyclic spring model for the design of cyclic lateral loaded piles may be adapted to district heating pipelines.

Such a calculation method is for example the already well established p-y-methodology (p = bedding pressure, y = lateral displacement) of the American Petroleum Institute (API 2000). For the ultimate lateral bedding pressure p_u of offshore piles two general failure mechanisms were suggested. 1st: Wedge mechanism near soil surface (equation 4) and 2nd: Plastic flow of the soil around the pile in deeper areas (equation 5). Thus two equations are given for p_u, in which the lower value is decisive.

$$p_{us} = (C_1 \cdot z + C_2 \cdot OD) \cdot \gamma \cdot z \qquad \text{(eq. 4)}$$

$$p_{ud} = C_3 \cdot OD \cdot \gamma \cdot z \qquad \text{(eq. 5)}$$

Where p_{us} is the bedding pressure for the surface area, p_{ud} is the bedding pressure for the deeper area and z is the overburden height. The coefficients C_1, C_2 und C_3 are empirical derived parameters and have to be chosen depending on soil conditions from API diagrams (Fig. 7).

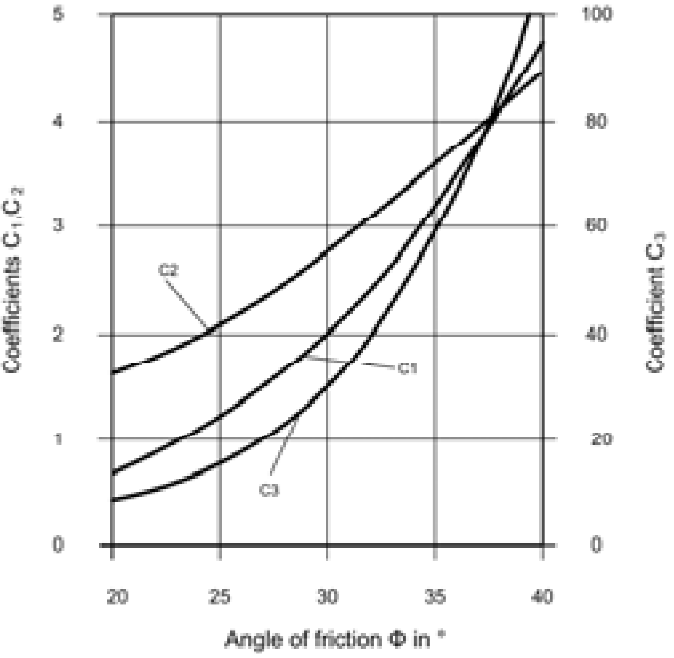

Fig. 7: Coefficients for p-y curves

According to API the p-y curves can then be derived using a tangent hyperbolic formula shown in equation 6.

$$p = A \cdot p_u \cdot \tanh\left[\frac{k \cdot z}{A \cdot p_u} \cdot y\right] \tag{eq. 6}$$

The bedding modulus k depends on the relative density and the inner shear strength of the soil and can also be chosen from API-diagrams (API 2000). Cyclic effects are respected by setting A = 0.9. For the static case A is to be calculated as shown in equation 7.

$$A = \left[3.0 - 0.8 \cdot \frac{z}{OD}\right] \geq 0.9 \tag{eq. 7}$$

Simple calculations for standard trench conditions of buried district heating pipes showed a significant discrepancy determining p_u according to EN13941 and API 2002. It was observed, that p_u according to EN13941 is twice to four times higher than after API 2000. Furthermore assuming A to be at least 1.0 for static conditions lead to equation 8:

$$z \leq 2.5 \cdot OD \tag{eq. 8}$$

For standard trench conditions this term can be followed only in some cases. From this observation it is evident, that the API approach is not suitable for buried pipes. This may be the case because of its empirical character and the purpose of the approach to be used for piles with a diameter of several meters - even though the shown relationship was derived from model tests with small diameter of D=0.61m (Reese et al. 1974). Furthermore pipes are buried at shallow depth. Small diameter and shallow depth lead according to equation 4 and equation 5 to low p_u-values and small differences for the parameter A in the static and cyclic case. Because of this scale effect and the differences in the confining pressure the application of the API approach to buried pipelines is not recommended without further investigations and modifications.

This leads directly to the strong need of research in the field of cyclic lateral loaded pipelines. Model tests should be carried out in a sensible statistical extent. Other approaches for cyclic loading should be tested (e.g.

the stiffness degradation methodology) and its transferability to pipelines should be examined.

6. Conclusions

From the presented investigation a highly cyclic loading must be assumed for solar thermal pipelines due to daily temperature changes from maximum heat load to environmental temperature by night. The assessment of long term behaviour of this kind of pipelines and also the assessment of the investment security of a solar thermal plant can only be accurate, when the cyclic behaviour of the used material in the pipes and the cyclic interaction with the surrounding soil is well known and respected in the pipe design.

However only a few investigations on the cyclic behaviour of a whole district heating system are known (EnEff:Wärme 2010, Weidlich 2008). In current testing standards cyclic loading is underrepresented too (EN253 2009, EN498 2009).

On the one hand we need answers concerning the serviceability of the used material components under cyclic loading, for example the deterioration of polyurethane insulation foams due to 10^4-times compression and shearing. On the other hand the cyclic pipe-soil interaction behaviour must be known as exact as possible for an accurate design of the pipe-system. Furthermore additional technical challenges are expected for the integration of solar thermal plants in existing grids because of the different technical conditions in solar systems and conventional systems.

Research is needed here. Especially investigation of the cyclic bearing behaviour of buried pipelines in extensive research projects and the modification of recommendations and standards is strongly recommended.

7. References

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