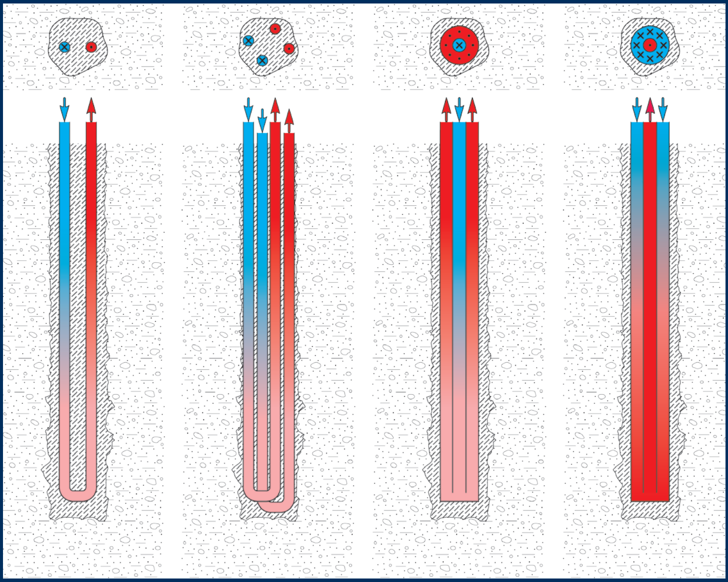
Shallow Geothermal Systems – Recommendations on Design, Construction, Operation and Monitoring



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Preface

The use of shallow geothermal energy has increased enormously over the past ten years. As the number of geothermal energy installations has risen, so has the number of technical developments in the field. There have been cases of damage in connection with the construction and operation of geothermal energy systems which have attracted much attention in the media. In particular, the cases of damage that have become public show that drilling to depths of several hundred metres is a technical activity that calls for responsible procedures in the sense of quality-assured design, construction and operation of the systems. Avoiding damage caused by shallow geothermal energy installations is a top priority for sustainable geothermal energy uses, especially when bodies of groundwater have to be protected against adverse effects. The recommendations in this book should be regarded as contributions to the quality-assured realisation of such systems. One of the aims of the Geothermal Energy Study Group at the specialist Hydrogeology Section of the German Geological Society (DGGV) and the Engineering Geology Section of both the German Geotechnical Society (DGGT) and the DGGV is to promote the widespread use of geothermal energy as an environment-friendly energy source while prioritising the protection of bodies of water. The authors as well as the DGGV and the DGGT have conceived these recommendations as advice and not as a set of technical regulations in the sense of a standard. Therefore, the recommendations of the Geothermal Energy Study Group include a number of textbook-like passages and much information on the legislation that affects approvals and permits. At the time of going to print, the preparation of a standard for shallow geothermal energy was not in sight; such a standard is, however, still regarded as essential.

The authors and their assistants in the study group are hydrogeologists, engineering geologists and engineers from design consultants, the construction industry, the building materials industry, authorities and universities. They drew up the recommendations over a number of years and all were well aware of the fact that some of the content could certainly trigger controversy in technical circles.

In order to guarantee the technical quality of the recommendations of the Geothermal Energy Study Group, the content was subjected to a peer review process. Prof. Dr. Ingrid Stober (Freiburg Regional Authority), Prof. Dr. Rolf Bracke (International Geothermal Center, Bochum) and Prof. Dr. Dmitry V. Rudakov (National Mining University, Dnipropetrovsk) undertook this important and demanding task, approaching it from different perspectives.

Their remarks and comments were carefully considered in the preparation of this current edition of the recommendations.

Besides the peer review process, the publishers made the recommendations publicly available on the Internet for three months. Anybody who was interested was invited to submit their remarks, comments and suggestions for improvements within those three months. The authors read and evaluated every single contribution received, which resulted in many improvements being made to the text and illustrations. We are very grateful to all who made contributions to the work of the study group in this way.

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1 Introduction

In Germany about 60% of the total energy consumption can be attributed to heating and cooling and the operation of buildings. There is great potential for using shallow geothermal energy systems to provide a large proportion of that energy demand. For example, around the year 2000, rising energy prices resulted in rapid developments in the use of shallow geothermal energy for heating buildings (increasingly cooling as well). The reason for the growing popularity of this technology is that up to 70–80% of heating requirements can be covered by geothermal energy, which means that only the rest has to be provided by conventional forms of energy. That results in potentially huge financial savings. Apart from that, geothermal systems save energy – in particular, they reduce the consumption of fossil fuels. The heat pumps needed for heating and the recirculating pumps needed for cooling can also be operated with electricity generated from renewable sources. In 2013, the proportion of renewable energy forms in the new-build sector in Germany was already 29% (22% heat pumps, 7% wood pellets + biogas), with a simultaneous decline in the proportion of oil heating systems down to <1% and gas heating systems down to <47% (BDEW, German Association of Energy & Water Industries, 2008). By 2008 some 64% of new heat pump installations were being used in conjunction with ground couplings. Only about 13% of heat pumps operated with geothermal energy sources are connected to well systems that enable the geothermal energy to be exploited directly. Most heat pumps in operation are based on indirect methods of extracting the geothermal energy through borehole heat exchangers (BHEs), ground heat exchangers and so on (BWP, German Heat Pump Association, 2009).

To some extent the state of the art is specified by guideline VDI 4640, the revised draft Part 1 of which has been available since 2010. One of the documents using this as a basis is the revised DVGW regulation W 120-2 (DVGW, 2013), which in future is intended to regulate quality control issues concerned with the provision of boreholes for heat exchangers. However, so far, training programmes for people in the industry to complement the technical documentation have been lacking. Therefore, when it comes to shallow geothermal energy, considerable responsibility is placed on the geoscientists and engineers who advise clients and design systems.

The provision of energy from below the earth's surface is mainly provided indirectly via borehole heat exchangers, which are also known as downhole heat exchangers (DHE); these can be as deep as 400 m. Most borehole heat exchangers are, however, typically between 70 and 200 m deep, although there is a trend towards deeper boreholes. Such boreholes use a closed

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system of pipes, usually made from high-density polyethylene (HDPE), in which a thermal transfer fluid (normally water-based) circulates. The operating temperatures are then made available through being coupled to a heat pump. Hundreds of thousands of boreholes that still have to be sunk will have to be assessed in terms of the quality of their design and execution in order to achieve optimum technical and economic efficiencies and, of course, to prevent damage on the one hand and latent risks to groundwater resources on the other.

The use of geothermal energy is constantly on the increase. According to the German Environment Ministry (BMUB, www.erneuerbare-energien.de, 2013), the proportion of heat in the final energy consumption rose from 4.9 to 7.1% between 2009 and 2012.

Figures for numbers of BHE systems in Germany vary – sometimes considerably – depending on the source consulted. According to the BMUB (2013), there are already about 350 000 heating (and cooling) systems in Germany using heat pumps to extract energy from below the ground. On average, a system consists of 2.5 BHEs. That means there could well be about 875 000 BHEs in Germany which also need to be inspected in the future, for example when valuing property prior to sale or for other reasons. However, in contrast to the BMUB, in 2009, the German Renewable Energies Agency (AEE) published a conservative figure of about 150 000 BHE systems as of 2008. Apparently, there were 27 000 new systems in 2007 and a further 35 000 in 2008. If we again assume 2.5 BHEs per system, we still arrive at a total number of about 375 000 BHEs in Germany.

Neither source includes BHE systems that have not been approved, for example in the form of an estimate of the numbers. We can therefore assume that, very roughly, half a million BHEs are already in operation in Germany. That is a very large number of significant changes to the ground, as it always involves a borehole up to several hundred metres deep. Despite a number of cases of damage that have become known in recent years, the number of installations will continue to increase significantly (Figure 1.0.1). The figure might well have doubled by 2015. At the moment, the frequency of damage cases related to BHEs can probably be regarded as low on the whole. More accurate figures are, however, not yet available and long-term damage has not been investigated yet.

In this context, the State Geological Surveys of Germany (SGD) organisation has looked at quality issues related to the known effects of geothermal projects and collated and evaluated these in a report (Geothermie, 2011). Concerns about the safety of technologies are understandable. However, it must be said

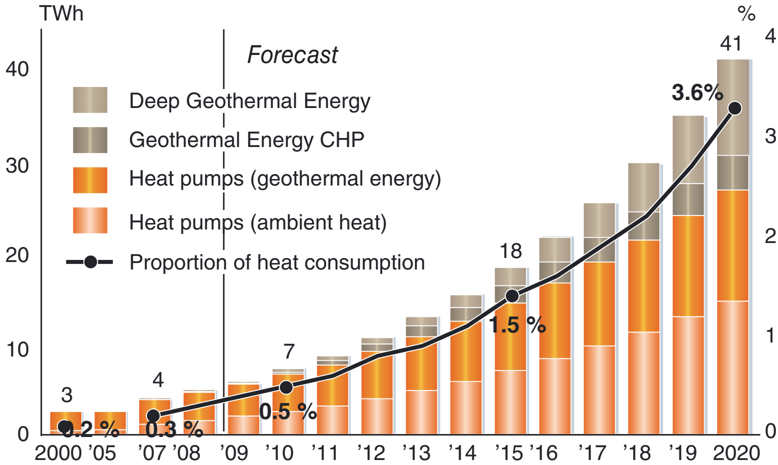

Fig. 1.0.1 Geothermal energy production forecast for Germany up to 2020; position as of October 2009. (Graphic: German Renewable Energies Agency, 2009.)

that so far the use of geothermal energy has not led to any injuries to persons. Not all energy sources can claim that.

Damage that can be caused by the sinking and operation of BHEs results from inadequate knowledge of the subsoil conditions and inappropriate drilling methods in particular. The following are some of the typical forms of damage:

- Leakage between aquifers (see Glossary for definition) in multi-layer groundwater systems
- Subsidence or heave affecting neighbouring infrastructure
- Transferring contaminants from higher to lower strata
- A rise in significantly mineralised groundwaters

Most boreholes for BHEs are sunk at least as deep as the uppermost aquifer of a multi-layer groundwater system. Boreholes as deep as this are definitely technically challenging alterations to the ground and, in principle, can impair or bypass the effects of confining beds.

If the pipes in the borehole heat exchanger are filled with a thermal transfer fluid that does not consist of just water, the fluid is classed as belonging to water hazard class 1 (WGK1 term of German Water Law). Therefore, in legal terms, BHEs are containers for WGK 1 substances, which require a double-wall construction when stored in the ground. This double-wall requirement is provided by, on the one hand, the closed system of pipes and, on the other, the backfilling to the borehole, which, being in most cases a cement-based bentonite slurry, constitutes a seal. Where public buildings and commercial geothermal energy systems are concerned, the technical specification given in the legislation on systems containing substances hazardous to water (*Verordnung über Anlagen zum Umgang mit wassergefährdenden Stoffen* – AwSV, cl. 35, para. 2, 2014) permits the use of single-wall BHEs.

In addition, the drilling and construction activities themselves constitute a potential hazard for the groundwater. Consequently, in Germany, BHEs <100 m deep must be approved by the local water authority. One quality assurance problem that still remains is the fact that in Germany the mining authority is in charge of approving and supervising boreholes for BHEs >100 m deep. And in many of Germany's federal states, the water and mining authorities have different ideas about dealing with geothermal energy! This can lead to the situation that, for example, one project must comply with more stringent technical stipulations than a neighbouring project whose final depth is, for example, 30 m deeper, even though both fall under the remit of water legislation (<100 m deep). Nationwide implementation of the technical aspects of quality assurance addressed in the recommendations of this book is therefore hardly possible. The work on these recommendations has revealed that there is an urgent need to set up a logical, unified approval and monitoring system for the whole country. Therefore, the specialists from the Engineering Geology Sections of the German Geological Society (DGGV) and the German Geotechnical Society (DGGT) plus the Hydrology Section of the DGGV got together and pooled their practical knowledge for applications. This book is the result of that work. It represents the current state of knowledge and state of the art and is also intended to help avoid damage in conjunction with the use of shallow geothermal energy systems.

of the BHE. That results in the fluid having a higher temperature where it enters the evaporator in the heat pump and hence a higher EER for the heat pump. Although this requires more auxiliary energy, the overall efficiency of the system is generally higher because of the higher EER.

When carrying out the hydraulic design of the entire BHE system, the diameters and lengths of the pipes in the BHEs and connecting lines must be compatible with each other in terms of hydraulic pressure losses. The total pressure loss, and hence the power consumption of the recirculating pump, are always greater than the sum of the pressure losses of individual BHEs.

Figure 7.1.1 shows, as an example, the hydraulic pressure losses depending on the volume flow rate for the two most common U-pipe BHE types made from

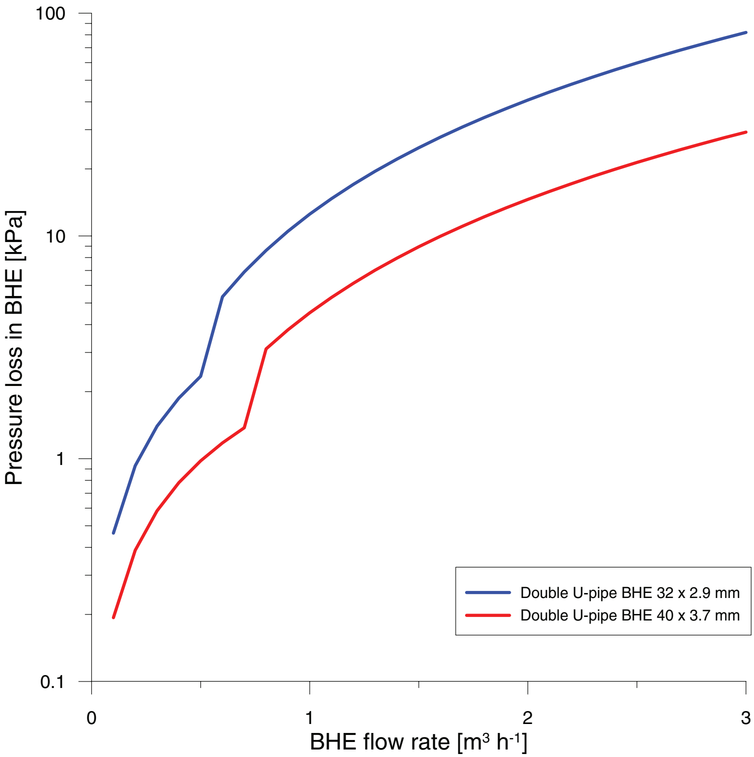

Fig. 7.1.1 Pressure losses depending on the flow rate for double U-pipe BHEs with 32×2.9 mm and $40 \times 3.7\,mm^2$ pipes; thermal transfer fluid = water at 4 °C, BHE length = 120 m.

HDPE (32 × 2.9 mm and 40 × 3.7 mm). The clear increase in pressure losses between 0.5 and 1.0 · $m^3 \cdot h^{-1}$ for both types is due to the change from laminar to turbulent flow. As expected, lower pressure losses are calculated for the larger BHE diameter.

Figure 7.1.2 shows how the pressure losses are dependent on the BHE length for U-pipe BHE types with 32 × 2.9 mm and 40 × 3.7 mm pipes. For the

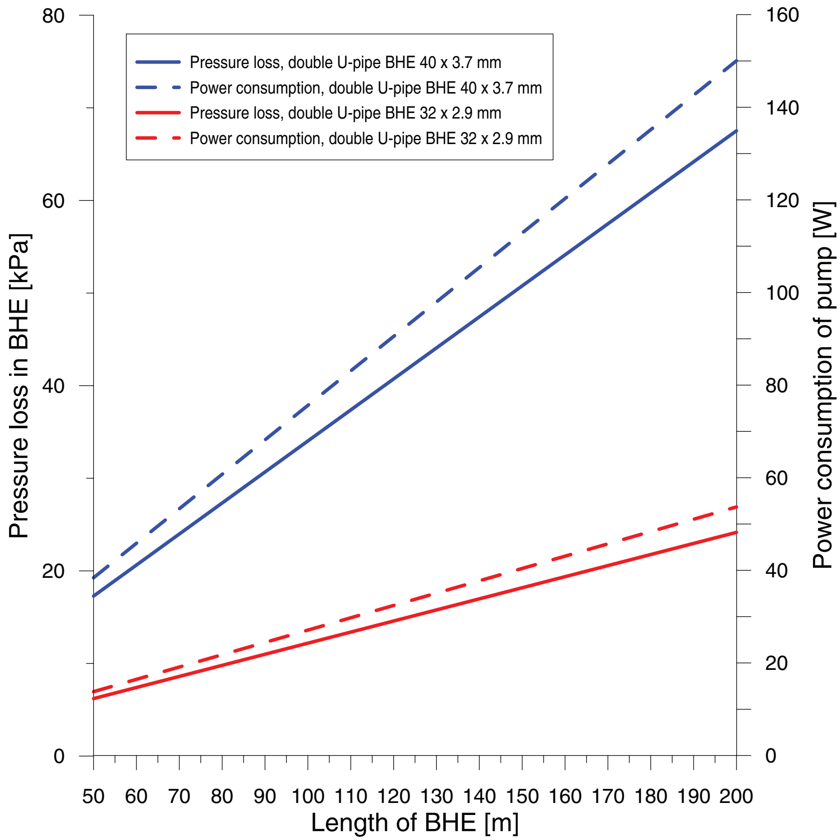

Fig. 7.1.2 Pressure losses depending on the BHE length for typical double U-pipe BHEs with thermal transfer fluid = water at 4 °C, flow rate = 2 · $m^3 \cdot h^{-1}$ (turbulent flow) and associated power consumption of recirculating pump (assumed degree of efficiency: 25%).

example chosen here (see caption), the pressure losses of the 32 × 2.9 mm BHE are about 2.8 times higher than those of the 40 × 3.7 mm BHE. The increase in the recirculating pump power consumption needed to overcome the pressure loss is also shown. The power consumption was in each case calculated from the product of pressure drop and flow rate while assuming a 25% degree of efficiency for the recirculating pump.

The pressure losses shown in Figures 7.1.1 and 7.1.2 were calculated using the formula specified by Huber and Ochs (2007). Pressure losses in heat pump, horizontal pipes, manifold and other fittings are not included, but the 180° bend at the bottom of the BHE is taken into account. Owing to the erratic increase in the pressure losses as the length of the BHE increases, a BHE with 40 × 3.7 mm pipes should be used for BHEs ≥120 m long in order to minimise the pressure losses.

7.1.1.2 Centre-to-centre spacing of BHEs

BHEs can exert a thermal influence on each other. This applies to the BHEs in an array and to single BHEs on adjacent plots of land. Therefore, minimum spacings for BHEs must be considered during the design in order to guarantee long-term operations – in heavily built-up areas, too.

The following points must be considered when specifying BHE spacings:

- In Germany, the spacings prescribed by the federal states and in mining legislation
- Spacing stipulations due to underground mining situations
- The vertical deviation of the method of drilling used in the specific rock formation
- Geological features that affect the design
- The average interstitial velocity of the groundwater
- Fluctuations in the groundwater flow direction
- The geometry of the plots of land affected
- The use of the system (heating, heating/cooling, storage)

In Germany, the minimum centre-to-centre spacing of two vertical BHE boreholes lies between 5 and 10 m depending on the regulations of the respective federal state. Numerical analyses must be carried out for larger multiple BHE arrays in order to determine suitable spacings. The same applies to distances of BHEs from plot boundaries. For example, the City of Berlin guidelines recommend a minimum spacing of 10 m between two BHEs, but do not specify a minimum distance from an adjacent plot of land.

The extent to which BHEs have a thermal influence on each other depends on the geological and hydrological conditions specific to the location (see Chapter 5) and also neighbouring geothermal energy applications.

Horizontal and vertical deviations from the intended line of a borehole can affect the minimum spacings required. The mechanisms and possible measures are described in Section 6.3.

7.1.1.3 Borehole diameter and equipment installation

The double U-pipe exchanger is currently the most common type of BHE (Section 3.1.1). The borehole diameter should be chosen depending on the diameter of the heat exchanger pipework so that adequate backfill around the heat exchanger is guaranteed (Section 7.1.2). Encasing the pipes with at least 30 mm of backfill material between pipes and side of borehole is recommended. In accordance with the requirements given in the heat pump guidelines of the federal state of Hesse (HLUG, 2011), the borehole diameter d_b according to Equation 7.1 should thus be at least 60 mm larger than the diameter of the heat exchanger pipework d_{Sspa} (Figure 7.1.3):

$$d_b \geq d_{spa} + 60\,\text{mm}. \tag{7.1}$$

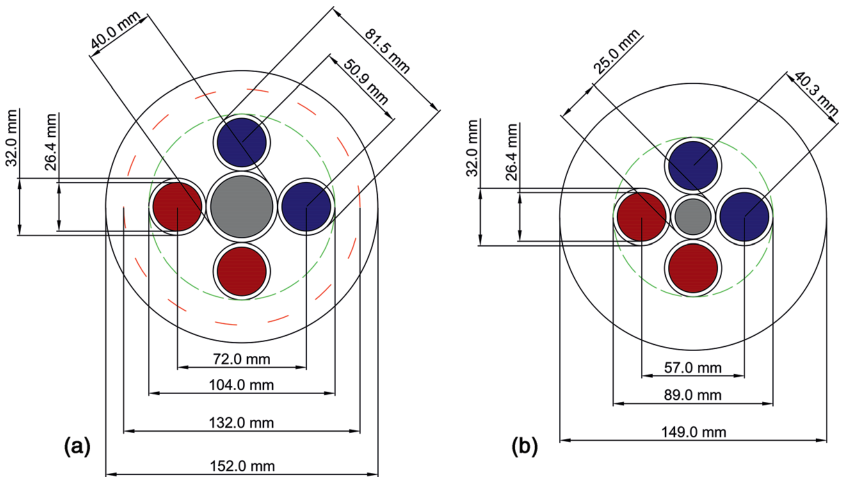

Fig. 7.1.3 Guideline figures for embedding the heat exchanger pipework with examples of grouting pipes (grey) and common borehole diameters. (Graphic: Heske, 2008.)

The use of spacers and/or centralisers is recommended in order to prevent contact between the individual pipes or between pipes and side of borehole. Such spacers/centralisers should guarantee a minimum spacing of 30 mm to the side of the borehole all round. This results in a minimum borehole diameter equal to the diameter of the heat exchanger pipework + 60 mm. In practice, a somewhat larger diameter should be chosen so that it is easier to install the pipework. The example shown in Figure 7.1.3b uses 32 mm diameter heat exchanger pipes and a 25 mm diameter grouting hose, which results in a pipework bundle with an outside diameter of 89 mm. So the theoretical minimum borehole diameter is 149 mm.

Normally, the annular space around the heat exchanger pipework is fully backfilled. However, that might not be possible or necessary in certain hydrogeological conditions. Technical alternatives are described in Section 7.1.4.

In most cases, BHEs consist of pairs of U-shaped pipes made from high-density polyethylene (HDPE-RC), which are connected to a heat pump in the building via a main pipe laid near the surface. Other pipe materials are also used, for example cross-linked polyethylene (PE-X, Figure 7.1.14), but these are less common than HDPE-RC pipes.

The aim should be to install PE material with a minimum grade of 100. HDPE-RC pipes are normally designated by their outside diameter and wall thickness in millimetres, for example 32 × 2.9 mm.

The relationships among borehole diameter, dimensions of pipework in borehole, annular space and so on depend on many factors specific to the project. The decision as to whether to use a larger number of shallower boreholes or a few deep ones is also influenced by non-geothermal factors (size of plot, buildings, equipment availability, cost–benefits analyses, etc.). It should be noted that the pressure losses in the pipes of a BHE system increase linearly with the depth. When using 32 mm diameter HDPE pipes, the flow resistances beyond a depth of about 120 m are already so great that they must be assessed quantitatively. A poor degree of efficiency reduces the profitability of the entire installation.

Earth pressure increases with increasing depth and so the stability of the borehole always becomes more important during drilling, installation and backfilling operations. The material of the pipes in the BHE should therefore be designed accordingly for the pressures at greater depths. In doing so, the filling pressures of the water and thermal transfer fluid, the external water column, the lithostatic properties of the geological stratification and the

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