From Concept to Implementation: Hands on the pipe test bench at District Lab in Kassel

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Abstract

The transformation of district heating networks (DHN) towards lower operating temperatures and more dynamic operating conditions provides an occasion to examine the mechanical and thermal behaviour of buried pre-insulated bonded pipes under these new conditions in detail. This paper presents the development and implementation of a full-scale pipe test bench (PTB) at the District Lab research facility in Kassel, Germany, established within the UrbanTurn research project. The PTB consists of a buried pipe loop with high- and low-temperature circuits and two test fields with different bedding materials, enabling an experimental investigation of pipe–soil interaction. A comprehensive measurement concept was implemented, comprising 54 local sensors and a distributed fibre-optic temperature monitoring system along the test section. The paper documents the iterative design process, the alignment of investigation objectives with the technical infrastructure, and the practical implementation under real construction conditions. The results highlight key challenges in integrating measurement technology into civil engineering works and underline the importance of detailed as-built documentation for experimental infrastructure.

Introduction

The transformation of German district heating (DH) networks in the course of decarbonisation is a challenging project, on the one hand, a major expansion of the networks (DHN) is forecasted (Agora Think Tanks, 2024), and on the other hand, these networks must be adapted to new, mostly decentralised heat generation and new operating parameters (Hay et al., 2022). To address this situation, it is essential accompany the transformation by broad-based research. The network-transformation often is being planned using digital simulations (Schmidt et al., 2023) and calculations. However, to improve simulations they should be validated, at least in part, by experimental investigations to ensure their transferability to reality. In Germany, there are a few DH test sections, e.g. the Chemnitz test-section (Villalobos et al., 2019 & Hay et al., 2022) the AGFW test-section in Frankfurt (Grimm et al., 2017) and other measuring points (e.g. in Dollhopf et al., 2025) in DHN to monitor the infrastructure and provide opportunities for scientific investigation.

To meet the need, a laboratory for experimental investigation of DH infrastructure, was set up at the Fraunhofer Institute for Energy Economics and Energy System Technology (IEE) in Kassel (see Figure 1). The so-called District Lab (Kallert et al., 2021) consists of the main building with heat generation, a consumer structure and a flexible-test-network. In addition, a pipe test bench (PTB) was also set up for the detailed investigation of buried pipes. Test-tracks are often connected to DH grids and are therefore limited in their performance. In implementing the District Lab, the capacity, was tailored to the research objectives to ensure the widest possible application for DH networks with operational temperatures ranging from second generation DH (2GDH) to fourth generation DH (4GDH) according to (Lund et al., 2014). This is necessary to account existing framework conditions, in Germany where these DH generations are represented (AGFW, 2024).

However, the broad spectrum of investigation-opportunities required a targeted, scientific development for the detailed design. Within the framework of the UrbanTurn joint research project, this was ensured by a broad-based project consortium, where the IEE took the lead, coordinating the overall project, while GEF Ingenieur AG developed the technical design. HafenCity University Hamburg (HCU) was responsible for planning and implementing the investigations on the pipe test bench (PTB) while the DH association AGFW

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supported the implementation of the PTB with their expertise. BRUGG Pipes provided the pre-insulated bonded pipes and was responsible for the pipeline construction works and DANFOSS provided equipment, such as heat exchangers and further technical facilities. The overall aim was to develop specific investigation objectives and align them to a corresponding infrastructure and measurement equipment.

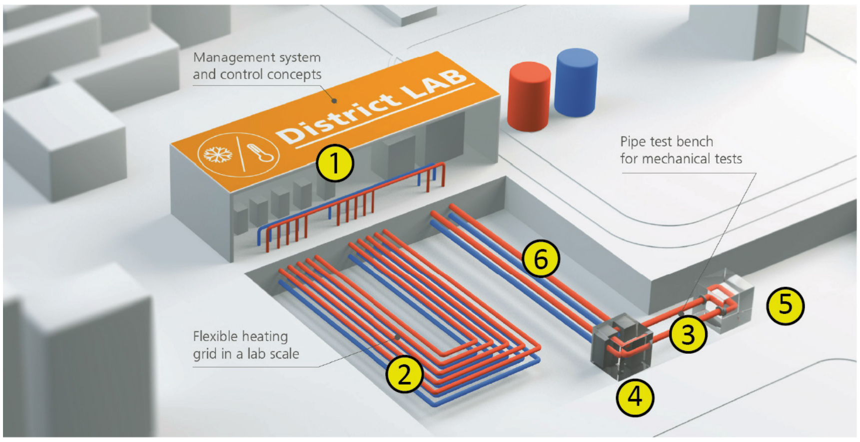

Figure 1: Concept-Drawing of District Lab (Fraunhofer IEE) with own edit (numbers)

In the end of 2025, the pipeline construction work and the installation of the measurement technology on the pipe test track were successfully completed. Four years passed from the start of the UrbanTurn project to the implementation of the PTB. This provides an opportunity to reflect in detail on the process. The focus thereby is set on the consistent further development of the investigation-objectives and the test infrastructure within the detailed planning and the implementation at the District Lab construction site. Since the construction of a research test track is neither a trivial process nor a frequent occurrence, this work shares experience and should serve as a reference for future projects.

Methodology

This paper provides comprehensive documentation of the implementation of the PTB and analyses the process from the basic concept until the completion of construction work on the building site.

The implementation will be analysed using a three-phase approach based on the chronological sequence. This begins with the conceptual-design of the pipe test section at the start of the UrbanTurn research project in 2021, with a broad spectrum of investigation possibilities at the concept planning stage. The detailed-design of the pipe test track, which includes the specification of the investigation objectives, is then discussed. The designation of detailed investigation objective based on the current challenges of DHN expansion and approaches also innovative construction methods for DHN design. The detailed planning also included the development of the accompanying measurement-concept, the development of a test schedule and the technical final design for the test infrastructure (working drawings for structures etc.). The third phase represents the implementation of the buried pipe test track in the end of 2025, during which the structures and pipelines were constructed, and the measurement equipment was installed.

In the concluding discussion, a qualitative review will be drawn, optimisation possibilities will be identified, and correlations and critical points in the implementation will be presented. Furthermore, deviations from the planning will be presented and important inter-dependencies highlighted.

Conceptual-Design

The Distric Lab test centre (see Figure 1). consists of the District Lab main-building (1) where the central technical and control facilities are located, the flexible-test-network (FTN) (2) on a neighbourhood scale and the pipe test track (PTB) (3) for pipe-specific tests. For information regarding the FTN find the article "Fibre optic and embedded sensing concept for long term monitoring of district heating pipes at the District-LAB Kassel" by Dennis Lottis within the "Insights Vol. II" publication. The PTB is generally used to carry out mechanical tests on buried pipes for district heating networks. Within the conceptual-design the investigation opportunities at the PTB included testing extreme operational modes, component tests, installation techniques, the investigation of bedding materials and quality assurance on the construction site (Kallert et al., 2021). The test infrastructure of the PTB consists of two structures (4 and 5) and the test section between them (3), into which the pipes are fed for testing purposes. The heating and cooling water from the central generation units is fed to the control structure via pipes (6) coming from the main building. The PTB is operated via the technical facilities in the structure. The supply line from the main-building and PTB are separated water circuits. From the control structure (4), the pipes of the PTB are routed towards an additional shaft (5). There, they are deflected in a U-bend and returned towards the control structure. The length of the pipe test section has been defined as 42 m, which corresponds the production length of pre-insulated bonded pipes (usually lengths of 3/6/12 m). Due to the route layout and the deflection of the pipes in the shaft, it is initially only possible to carry out tests on a straight section of pipe.

During the conceptional-design, various options of pipe-types and -systems for the PTB were considered but no further details such as pipe dimensions or pipe types were specified. The focus on the pipe-soil interaction was outlined in the UrbanTurn investigation-objective and the further development was done within the detailed-design to align the infrastructure to the specified research objectives. The control building was planned with a basement from which the pipes would branch off towards the test section. These results in an overburden height of the PTB of approximately 80 cm. The capacity of the main building defined the upper limits for the pipe test section. Accordingly, temperatures of up to 140 °C and pressures of up to 12 bar can be applied to the PTB. The supply line from the District Lab main building to the control structure is defined as a pre-insulated bonded pipe of diameter DN 125.

Detailed-Design

Based on theoretical investigations at the start of the UrbanTurn project, the experimental investigations on the pipe test section were elaborated. A key element of the DHN transformation is the reduction of flow temperatures in the heating networks. Also, an increase of thermohydraulic dynamics is expected. The design criteria for static calculations must therefore be reviewed and aligned and these requirements are to be investigated on the PTB. The framework is set within three technology-sets, the commissioning of the PTB, investigation of mechanical stresses and thermal behaviour, both with focus on the pipe-soil interaction.

Various pipe systems were discussed as subjects for investigation. To best represent the transformation of existing networks, achieve the broadest possible application of the investigation results and to validate investigation results of other test-tracks, pre-insulated bonded pipes with steel medium pipes were selected as the subject of investigation. These are the most commonly used pipe systems in Germany (Weidlich, 2015) and will also be the major construction technology used in the upcoming network expansion. This also allows to test extreme operating modes and the performance limits of the laboratory. Other pipe systems, such as pipes with polymer medium pipes, wouldn't be suitable for this purpose.

The pipes are arranged as a single pipe system with two pipes per trench and are operated at different temperature levels as low-temperature (LT) and high-temperature (HT) lines (see Figure 2). In terms of dimensions, bonded pipes with DN 100 and an outer diameter of 200 mm were specified. By laying the pipes in a loop, two test fields with otherwise identical boundary conditions are created. Different installation conditions and bedding materials are used in the test fields. In test field 1, a conventional construction method is implemented, which represents the usual installation of district heating pipes in an urban environment. The pipe trench is filled with natural sand for pipe bedding and a sand-gravel-mix for backfilling. Due to the transformation of DHN, the use of alternative bedding materials represents a promising approach (Dollhopf & Weidlich, 2025; Weidlich & Grajcar, 2017) but further research into their application is needed. Therefore in the second test field, crushed concrete is used as bedding material (0/10) and backfill-material (0/32) to promote research into circular economy-compliant construction methods for the upcoming network expansion.

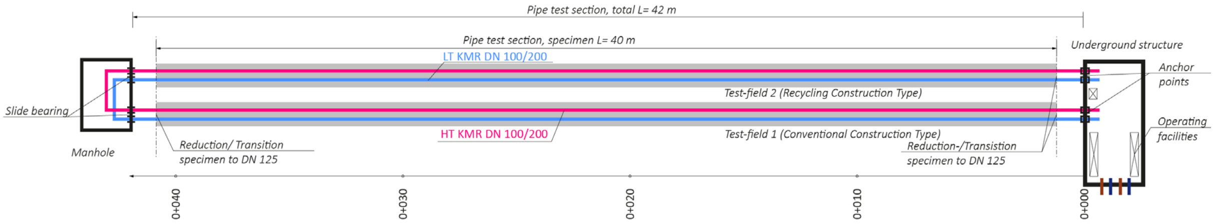

Figure 2: Overview of PTB (Detailed-Design)

Furthermore, due to advantages in execution and other planning requirements, it was decided that the control structure should be constructed as an underground shaft structure. Due to the change in construction details of the shafts, the elevation of the PTB also was adjusted. This results in an overburden-height of 1,05 m. Due to the trench depths, the ground conditions and the short distance between the test fields (see Figure 3), the pipe trenches were planned with an excavation pit shoring.

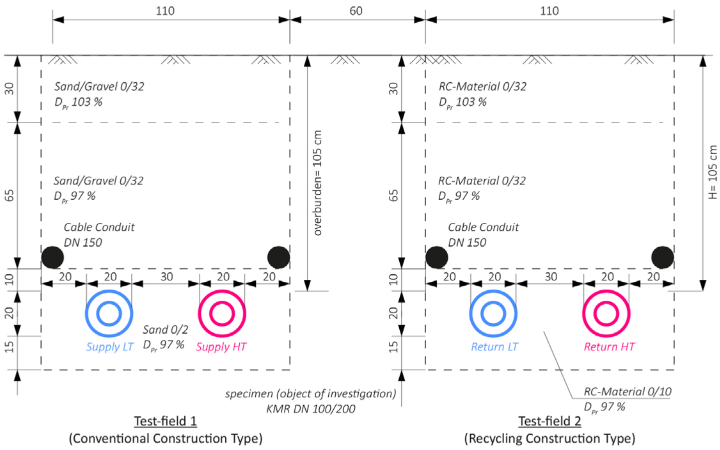

Figure 3: Cross-section of PTB with DN 100 bonded pipes(Detailed-Design)

In addition to working out the structural details, the requirements for the operating parameters were also further specified and refined to design load cases. The facilities in the main building of the DistrictLab and in the control building are designed so that operating temperatures of 20 to 130°C and temperature gradient (TG) of up to 100 K/h can be achieved in the HT pipe loop, and operating temperatures of 10 to 80°C and TG of up to 10 K/h can be achieved in the LT pipe loop. A test schedule was also developed during this. The plan is to initially carry out the commissioning in two scenarios. The target temperature is a flow temperature of 60°C in the HT pipe loop. During the first heating, this is carried out at a TG of 10 K/h in accordance with the DIN EN 13941 standard. After cooling down, a second process with a TG of 60 K/h will be carried out. Subsequently, the temperatures at the pipe test section will be gradually increased in various test scenarios. This phase is designated as “transformed operating modes I”. Temperatures of 75/85/90/110/130°C will be approached for the first time. High pipe friction is expected when the temperatures are first reached. The aim is to generate findings for district heating networks with lower design temperatures (< 130°C). After 130°C has been reached cyclically over a longer period of time and at different rates of change, the “transformed operating modes II” phase follows. Here, the temperatures are gradually reduced again. The aim is to simulate the effects of reducing the flow temperature in existing networks.

A comprehensive detailed measurement concept was further developed within the detailed design. In particular, the measurement resolution within the pipe trench area was increased. In order to measure mechanical and thermal behaviour, approximately 50 sensors are installed in the pipe test section. These are located in measurement fields (see Figure 4 and Figure 5) in areas relevant to the investigation, e.g. strain measurement points at the point furthest away from the slide bearing. Rod extensometers, and earth pressure sensors are installed to record the mechanical behaviour. Resistance thermometers, soil moisture sensors, heat flux sensors and a fibre-optic linear temperature measuring device are installed to investigate the thermal interactions. The sensor cables are routed to the nearest shaft via cable conduits where the sensor signals are recorded.

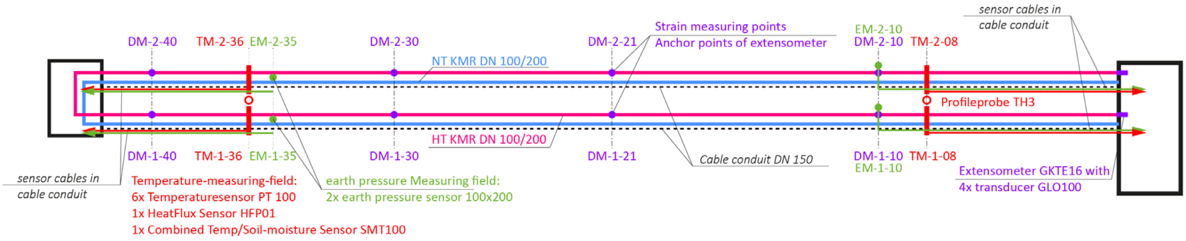

Figure 4: Measurement Concept - Sensor Locations

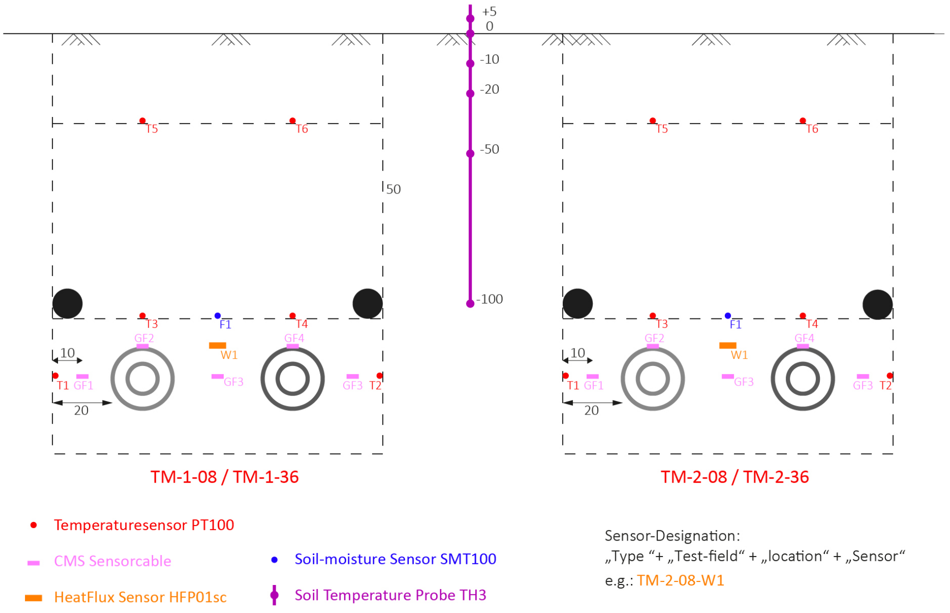

Figure 5: Measurement Concept - Cross section Temperature-measuring-field

As the measurement equipment contents various sensors with different measurement signals, external conversion of the measurement signals is often necessary to simplify connection to the programmable logic controller. A concept for signal conversion for data acquisition was therefore also developed.

Implementation of the PTB

Due to the complexity of the entire laboratory, it was initially not possible to find a general contractor for the implementation. Only after the construction work had been divided among several building-trades, construction companies could be found. This resulted in a delay in the start of construction work and a significantly shorter time span for execution. The excavation of the pipe trenches and thus the start of construction on the pipe test section began on September and the work was completed on December with the final backfilling of the trenches.

The construction with the use of continuous trench shoring proved to be impractical. Due to the obstacles created by the shoring, such as the cross struts between the shoring panels and a reduced working space, it would not have been possible to install the sensors and their cabling in the time available. Pulling the shoring boxes within the backfilling process would also have posed a major risk to the position and integrity of the sensor technology. Therefore, an open construction method with a sloped pipe trench was chosen (see Figure 6). As a result, the existing soil between the test fields was not interlocked with natural soil as originally planned. Nevertheless, the excavated soil was reinstalled during the pipe trench backfilling between the test fields, creating a clear separation between the test fields (see Figure 7). The modified design is not expected to have any relevant impact on the research results. During the construction work, soil samples were taken from the existing soil and the delivered building materials, which are to be examined at the HCU laboratory as part of the project.

The distance between the shaft structures is 41,85 m, which represents the length of the pipe test section. The pipe test section was constructed as a loop with two single pipes, each with a diameter of DN 100/200 with three joint connections within the DN 100 route and two joint connections at the reduction from DN 125 to DN 100. Before being inserted into the shafts, the diameter was adjusted to DN 125, as all pipes within the shafts are DN 125 pipes. This ensures a simplified change of testing objects within the PTB for future investigations. At the control shaft the pipes are fixated within the shafts wall, at the additional shaft, slide bearings ensure the axial elongation of the pipes into the shaft.

Figure 6: Trenching with sloped Walls

Figure 7: Backfill with different Materials for test-fields

The pipe bedding and backfilling were carried out as planned with different materials for the test fields. Within Test-field 1 a natural Sand with grain-size 0/2 was used. In Test-field 2 recycled material of Class RC-1 according to the Substitute Building Materials Ordinance with a 40 % content of crushed concrete, 35 % crushed rock and 25 % crushed asphalt material was used. Because of changes within the implementation of the shafts also the overburden height had to be aligned to the situation. The overburden height of the route corresponds to 95 cm, with the height adjusted to 1,5 m close to the control shaft and approx. 85 cm above the additional shaft. As deviations occurred within the implementation subsequently the terrain heights were measured.

The tight schedule for the construction work meant that the installation of the measurement technology had to take place partly in parallel with the civil engineering work. Due to the flexible construction process, the implementation had to be planned and adapted during construction, which required close cooperation between the project participants. The installation of the measurement technology was successfully implemented with only minor deviations from the original plan, and the measurement concept for the pipe test section was thus fully realised by the project partners Fh IEE and HCU, as well as external support. To investigate the mechanical stress, extensometer (see Figure 8 and 10) anchors and earth pressure sensors (Figure 9) were applied to the pipeline at the designated locations. This was done using plastic-saddles, which were first positioned, then calibrated and finally attached to the pipe jacket using a plastic welding process. The implementation proved to be very practical as the position of the sensors is well secured.

Figure 8: Rod-Extensometer applied to Shaft-Wall

Figure 9: Earth-pressure sensor on plastic saddle

To investigate the thermal interaction between the pipeline and the surrounding bedding material, fibre optic measuring equipment from OSSCAD was laid along loops within the pipeline trench. In addition, temperature sensors (see Figure 11), humidity sensors and heat flow plates were installed at various measuring points. The sensors were laid layer by layer after the pipe zone had been constructed. To do this, the positions of the sensors were subsequently exposed by hand and, after securing the sensor layers and pulling the sensor cables into empty conduits, backfilled by hand. This procedure was developed during the execution phase.

Figure 10: Extensometer - Anchor and fibre-optic cable(blue)

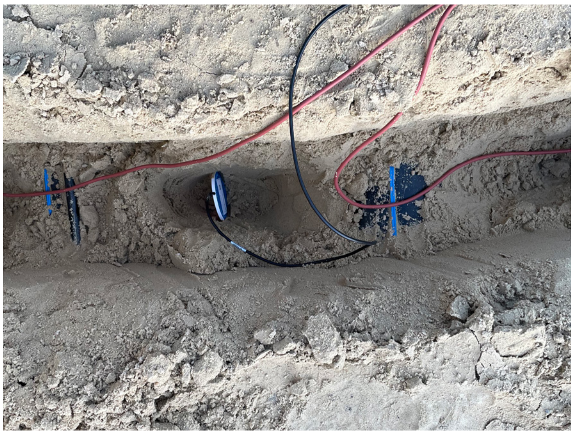

Figure 11: Temperature and HeatFlux sensors (Dennis Lottis, IEE)

A total of 54 measuring points were implemented and the linear measuring device from OSSCAD, which was laid in a total of 10 loops, additionally provides the temperature at approx. 400 positions within the pipe test section. This corresponds to a very high density of measuring points. Due to the above-mentioned adjustments in the design of the pipe test section and the adjustment of the sensor positions, etc., it is necessary to digitally process the documentation in a high level of detail (see Figure 12). This is mandatory to enable scientific evaluation of the measurement data.

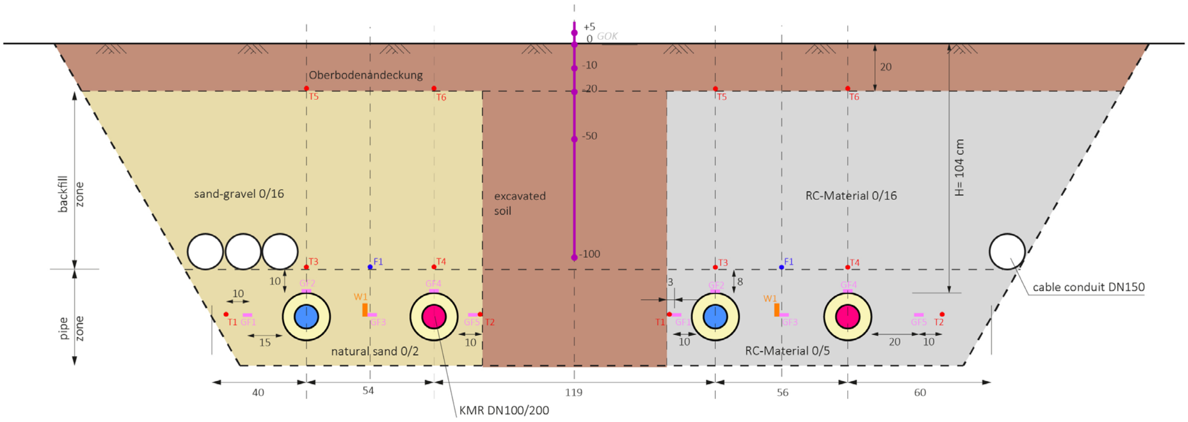

Figure 12: As-Built Documentation of Temperature measuring field 0+008

Discussion and conclusion

In the course of the project, the infrastructure was subsequently adapted to the further developed project goals. This proved to be necessary in light of the dynamic transformation of heating networks and elaborated construction technologies in DHN constructions. Specific investigation scenarios (technology sets) and installation conditions for both network expansion and the transformation of existing networks were created. The implementation of the PTB served as a reality check for the full-scale laboratory. The limited construction time required a particularly flexible approach. As is common on real construction sites, manufacturing-related deviations occurred and improved the transferability of scientific findings into practice.

At the PTB, the construction works involves earthworks which, despite GPS-supported surveying and controlled construction equipment, lead to deviations from the planning due to the construction equipment used and the heterogeneity of soils. Higher requirements regarding the precision must be explicitly specified in the items of the service specifications. In road construction, for example, usually tolerances of between -10% and 20% are permissible for the thickness of unbound layers. The excavation of the pipe trench as a continuous trench across both test fields with sloped trench walls deviates significantly from the planned route cross-section with built-in vertical trench shoring. Also, the overburden height also deviates from the plan. However, as explained above, these changes were discussed during the implementation and jointly decided upon in consideration of the static design and the scientific research approach.

In addition to deviations in civil engineering during the excavation and backfilling of trenches, deviations also occur in pipeline construction. This is due to numerous factors, such as surveying tolerances, but also production-specific deviations such as pipe connections or the introduction into shaft structures. Furthermore, the reduction in diameter from DN 125 to DN 100 had to be planned and implemented in situ. The measured length of the pipe test section shows a deviation of approx. -15 cm, which corresponds to a relative deviation of 0,03 %. Deviations here are due to inaccuracies in the surveying of the shaft structures and their construction. Due to an on-site adjustment of the shaft height, the elevation of the pipeline was also changed. The adjustments have no negative impact on the function or investigation possibilities at the PTB. While minor inaccuracies in actual construction work are generally accounted within the static calculation, for a Research-Facility it is important to document the exact “As-Built” inventory to provide a basis for scientific investigations. Therefore, manual measurements of the structural implementation were carried out, particularly at the measurement cross-sections.

Adjustments were also necessary on site regarding the measurement technology. The position of the extensometer anchors had to be adjusted to the lengths of the extensometer rods. Shortening the rods on site would have caused further delays to the work. As a result, the measuring points were moved slightly. The position of the plastic saddles was subsequently measured and documented. Sensors also had to be adjusted to the position of the pipes in the cross-section, but the measuring points were fixed in position in the bedding material and calibrated. Here, too, however, deviations from the plan occurred. In general, installing sensors in the bedding material during the accompanying civil engineering work is a challenging task and required a flexible and coordinated approach. For example, the empty conduits for cable routing had to be constantly adjusted to the height of the backfill, and the sensors could only be installed retrospectively by digging them in manually after the layers had been backfilled. This also led to minor changes in the sensor position.

For future tenders, it is recommended that installation breaks for measurement technology be explicitly and specifically provided for this task. The high number of sensors used leads to a considerable amount of coordination effort for sensor cabling and data acquisition. These aspects should be considered when selecting the sensor technology and, if necessary, optimised in an iterative process. Under certain circumstances, it may be advisable to engage external services to ensure combability. The routing of empty conduits must also be consistently adapted to the construction process. Radio-based sensor technology may be an alternative in the future, provided that its suitability for installation in the ground is guaranteed.

The position of the sensor technology in the bedding material should be secured manually after backfilling, as compaction work and construction activities otherwise pose an increased risk. Overall, the application of sensor technology directly on the pipeline (e.g. fibre optic measuring cables, earth pressure sensors and extensometers) has proven to be practicable. After calibration, the measuring points can be assumed to be stable. Also, for the implementation of the measurement equipment a high-resolution inventory is required to compare simulation results with measurement data.

In principle, deviations between planning and execution are always to be expected in construction projects, which is why precise documentation of the existing situation, close construction supervision and clear communication on site are particularly important. Overall, the implementation of the pipe test section represents a significant milestone for the realisation of the DistrictLab. It creates a comprehensive and, in this form, unique test infrastructure for in-depth scientific investigations and practical insights into the transformation of heating networks.

Acknowledgement

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