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Drilling Challenges and Solutions for HT-ATES Systems in Poorly Consolidated Aquifers

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ABSTRACT

Underground thermal energy storage plays a vital role in supporting the energy transition by enabling more efficient use of renewable resources. Among the various technologies, High-Temperature Aquifer Thermal Energy Storage (HT-ATES) is a promising solution for large-scale seasonal thermal energy storage, offering the potential to store and extract heat over extended periods. HT-ATES systems are mostly implemented in unconsolidated aquifers, with ongoing extension to deeper formations, but relatively low-pressure, high-temperature conditions during injection and extraction of thermal energy. To ensure economic viability and long-term wellbore integrity of HT-ATES systems, the drilling process and well completion play a critical role. The long-term performance of HT-ATES systems is a function of the drilling process and drilling fluid design, well completion and annular materials, well development and rehabilitation. Drilling fluid must ensure borehole stability and be easily removable during well development to avoid a reduction in hydraulic conductivity. In addition, well completion and annular materials should withstand heating and cooling cycles, provide long-term zonal isolation, and be corrosion resistant, especially in saline aquifers. Well screen and gravel pack design should ensure reliable sand control while maximising flow efficiency. This paper presents field-scale case studies and experimental investigations that offer insights and provide practical considerations for the well design and implementation of HT-ATES systems in deep, unconsolidated formations. We address the specific challenges associated with drilling, well completion, and well development for high-temperature, low-pressure conditions. The findings contribute to a better understanding of creating an optimum well design, maintaining aquifer hydraulic conductivity, and ensuring the long-term integrity and efficiency of HT-ATES operations.

1 INTRODUCTION

As the global energy transition accelerates, drilling engineering is the science that assists utilising the Earth's energy potential. Whether for geothermal energy or underground thermal energy storage, the success of any well depends on well integrity, performance, and ability to withstand operational stress over time. Geothermal energy is available continuously throughout the year, while space heating commonly peaks in winter and declines in summer (Vardon et al., 2024). A technology that plays a key role in overcoming this temporal mismatch is High-Temperature aquifer thermal energy storage (HT-ATES), particularly for the large storage capacity required for seasonal balancing from large-scale renewable energy sources such as geothermal (Bloemendal et al., 2021). Figure 1 demonstrates the seasonal operation of an ATES system.

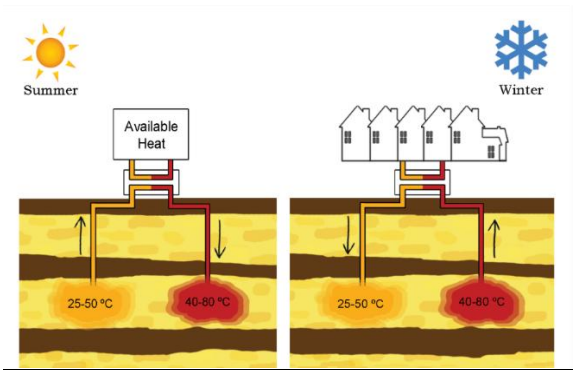


Figure 1. HT-ATES operating system. Left: Heat injection during summertime into the hot well; Right: Heat extraction from the hot well during wintertime and injection into the cold well

During geothermal drilling, depending on the thermal gradient and depth, challenges can be similar to those encountered in conventional oil/gas drilling, but can also be more challenging due to elevated temperatures. Nevertheless, drilling technologies, materials and strategies are relatively similar to those used in oil/gas (Augustine et al., 2006; Isania and Elahifar, 2025). For these types of wells, a substantial amount of research and textbook material exists on how to design them and select the optimal materials (Finger and Blankenship, 2012; Glassley, 2014).

The formation properties that allow us to store large volumes with relatively low pumping energy are porosity and permeability (Fleuchaus et al., 2018). Thus, the majority of ATES systems are placed in unconsolidated aquifers, with over 2500 systems in the Netherlands (Fleuchaus et al., 2018). There are additional characteristics, including low thermal conductivity confining layers, thick aquifers and injection/extraction rates (Beernink et al., 2024). From an application point of view, LT-ATES wells are drilled with a single drill bit size, reverse circulation and low-capacity drilling rigs, similar to conventional groundwater wells (Bloemendal et al., 2020). The conventional design of these wells consists of clay pellets and PVC pipes as completion materials, with a gravel pack placed at the screened depth intervals, supported by a filter screen. Piezometers are placed at various depths to collect water samples at specific time periods. When it comes to HT-ATES the challenge is that it combines shallow depth but elevated temperatures. Thus, storing temperatures up to 90°C creates additional challenges from various well design and life-cycle perspectives.

Most research on HT-ATES has focused on operational performance (Daniilidis et al., 2022; Geerts et al., 2025), fundamental aspects of heat storage (Beernink et al., 2024), or individual components of the drilling process (Koulidis et al., 2025). However, despite growing interest in HT-ATES, no comprehensive study integrates drilling and completion design approaches with insights into how drilling and designs affect system development and performance. This paper presents field and experimental insights into the design and implementation of HT-ATES well drilling and completion in unconsolidated formations. It highlights the key challenges and possible solutions related to drilling, well completion, and development with the aim of ensuring long-term system performance and integrity.

2 DRILLING METHODS AND FLUIDS

2.1 Drilling methods and operational constraints

In the Netherlands, the ATES systems are drilled using (air lift) reverse circulation because the large borehole diameters, ranging from 600mm to 1000mm would not allow cutting transport to surface using direct flush. The corresponding surface wellbore area increases significantly compared to direct flush boreholes, allowing higher extraction and injection rates; thus, the economic viability of an ATES system is positively affected. However, using large drill bit diameters introduces additional challenges, including higher drilling fluid circulation requirements, as well as torque and weight limitations. Due to the large volume of fluid, this method requires up to three surface settling tanks to separate the drilling fluid from the cuttings (Figure 2a). These challenges become particularly significant when drilling deeper wells in consolidated rock formations, compared to unconsolidated sediments with limited strength and cohesion.



(a) (b) (c)

Figure 2. (a) Settling tanks; (b) sampling of cuttings; (c) clogged drill bit

In addition, reverse circulation can handle fluids with low viscosity, due to limitations in pumping and the separation of surface settling tanks. Thus, significant sedimentation is observed in all settling tanks, indicating that the drilling fluid pumped back into the well is contaminated with drilled particles and doesn't have the same rheological properties as designed. For shallow drilling applications, the problem is limited, but as the drilling applications extend deeper, they require a well-established circulation and solid control system to reach the

target depth. For instance, in the case of pack-offs (Figure 2b), they can have negative consequences for the drilling process by clogging the drill bit (Figure 2c), since the reverse circulation transfers the cuttings to the surface through the inner part of the drillstring. In contrast, conventional direct circulation methods utilise significantly smaller diameter drill bits, with the main advantage that they are able to reach greater depths, without being limited by formation type. However, the main disadvantage is that the injection and extraction rates are reduced. In the current state of the ATES and HT-ATES wells in the Netherlands, the target depths don't exceed the 400m benchmark, and the subsurface consists of highly unconsolidated formations. Thus, those wells are being drilled with a single-drill bit size. This introduces further challenges related to well-barrier design and the selection of drilling fluid chemistry suitable for environments where contact with groundwater may occur. The following Table 1 summarizes the advantages and disadvantages of reverse and direct flush drilling methods.

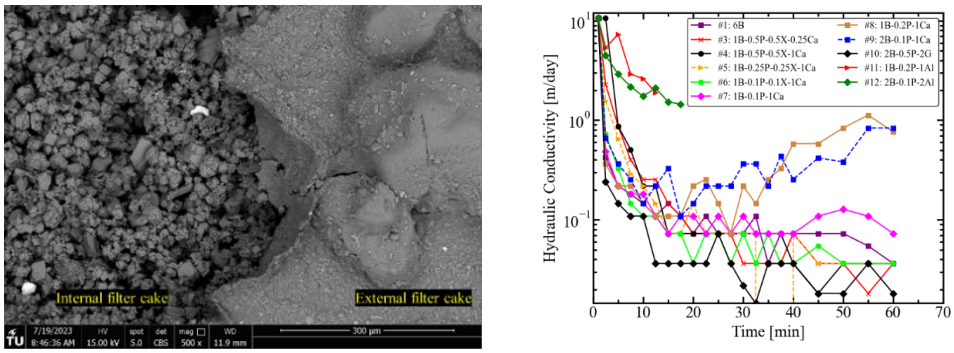
Table 1. Variables that affect the decision making of the optimum drilling method

Variable	Reverse circulation	Direct circulation
Cost	High	Low
Depth	Limited	Depends on rig size
Wellbore size	Up to 1000 mm	<300 mm
Surface area	High	Low
Formations	Low strength	Any
Separation unit	Settling tank	Shaker
Mixing and separation quality	Poor	High
Well design	Single-string	Multiply

2.2 Drilling fluid design

2.2.1 Filtration and filter cake formulation

As was stated, the type of aquifer can be either unconsolidated or consolidated. Any aquifer can be selected for HT-ATES as long as it has sufficient porosity and permeability. During drilling, filtration of the drilling fluid into the formation occurs due to a positive differential pressure (ΔP>0). As the drilling fluid filtrates into the formation, particles accumulate in the wellbore, creating a filter cake (Figure 3a). The filter cake reduces hydraulic conductivity in the near-wellbore region, thereby reducing hydraulic communication with the formation (Figure 3b).



(a) (b)

Figure 3. (a) SEM image showing the internal filter cake, mainly formed with calcite crystals and external filter cake mainly bentonite particles; (b) Modified filtration tests for various drilling fluids to simulate actual formation conditions (Koulidis et al., 2025)

The formulation of the filter cake is a function of several variables, including differential pressure, fluid additives, porosity and permeability. The primary difference between unconsolidated and consolidated formations lies in the state of the grains. Unconsolidated formations tend to have larger grain and pore throat size, compared to consolidated formations. Thus, the particles that form the internal and external filter cake might differ.

2.2.2 Wellbore collapse and strengthening

One of the key functions of drilling fluid is to provide and maintain wellbore stability. A poor-quality filter cake is thick and highly permeable, allowing excessive filtrate invasion into the formation. As drilling fluid flows into the formation, the pore pressure increases, resulting in a reduction of the circumferential (hoop) stress. This potentially leads to wellbore collapse (Feng et al., 2018; Bagheri et al., 2021).

A major challenge for drilling in permeable, unconsolidated formations is the significant fluid loss that corresponds to a reduction in wellbore pressure. Thus, as a result, the well is susceptible to collapse. An impermeable filter cake provides low filtration into the formation, which increases wellbore pressure improves stability and provides direct wellbore strengthening. The following Figure 4 shows an image obtained from a Scanning Electron Microscope (SEM) of a drilling fluid containing calcite crystals ($CaCO_3$) and bentonite (Koulidis et al., 2025). In the initial stage, calcite crystals flow into the formation and form an internal filter cake.

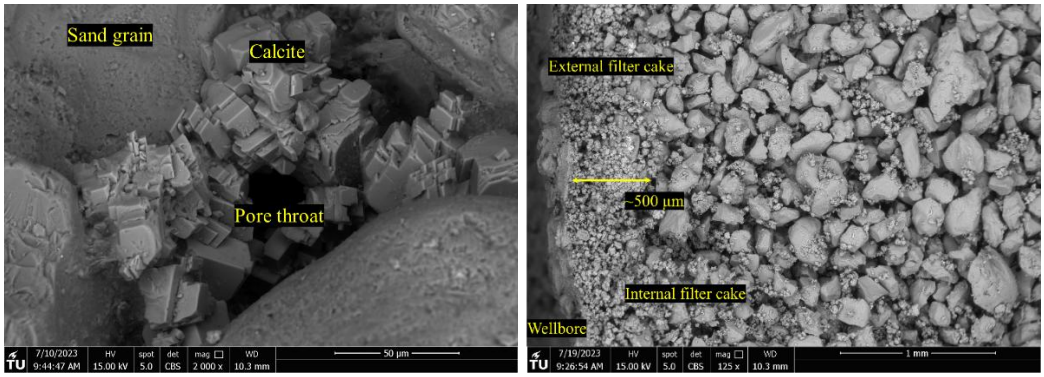


Figure 4. (a) SEM image showing the clogging mechanism of the calcite crystals within a pore throat; (b) The internal and external filter cake with relative thickness

In a scenario where the same fluid is utilised in a formation with a significantly smaller pore size, even a drilling fluid without calcite particles that only contains bentonite would form a filter cake. This indicates that, from the perspective of wellbore strengthening, the drilling fluid design depends on filtration losses and pore throat size. Thus, the optimum drilling fluid minimises fluid loss and forms a thin, impermeable filter cake.

HT-ATES is highly dependent on the injection and extraction flow rates; therefore, the drilling fluid should ensure wellbore stability while being easily removable during well development to recover the formation's hydraulic conductivity.

2.2.3 Environmental and other considerations

As mentioned, shallow wells, unlike deep wells, are usually drilled to the target depth using a single-drill bit size. This indicates that drilling fluid additives come into direct contact with the groundwater from shallow aquifers. To minimize water quality risks, polymers with low bacterial growth potential are preferred. For example, Polyanionic Cellulose (PAC) is favoured in groundwater wells because it limits microbial growth. In contrast, xanthan gum can promote biological clogging and elevated microbial activity, sometimes exceeding drinking water quality standards. The various considerations in designing a drilling fluid include operational limitations, environmental factors, drilling process, wellbore strengthening and stability, and well development.

3 WELL DESIGN CONSIDERATIONS

An HT-ATES well utilises water temperatures up to 90 °C, in low-pressure conditions. Even though the wells are relatively shallow, the material consideration is directed more to deep wells engineering rather than shallow wells. Due to the shallow depth and elevated temperatures, additional regulatory requirements must be considered during the well design phase, with the following considerations:

1. Well life cycle

2. Well integrity

3. Cost

4. Groundwater sampling

5. Well development and rehabilitation

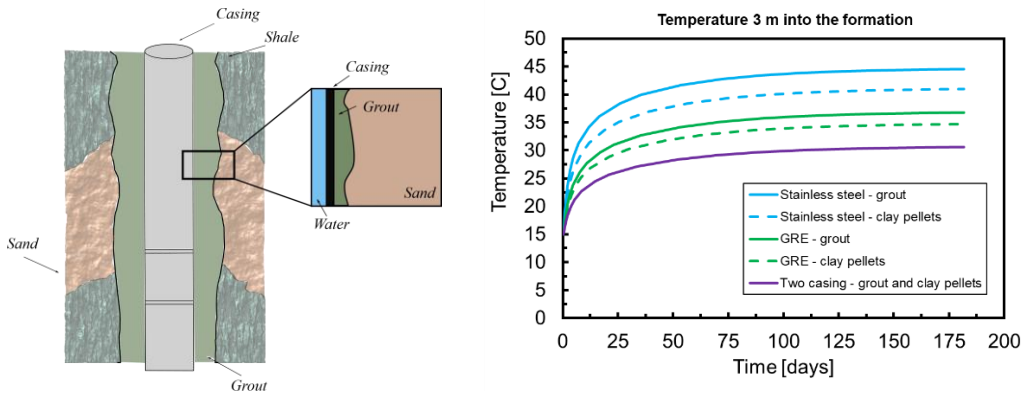
6. Thermal pollution

The following subsections incorporate, either directly or indirectly, the key aspects of the above considerations, highlighting their influence on overall system performance.

3.1 Well completion and annular materials

3.1.1 Heat losses and thermal pollution

The economic viability of an HT-ATES system depends on its efficiency, which is influenced by heat losses as the produced water transfers heat to the casing, the annular materials and subsequently to the formation (Figure 5a). Figure 5b presents 2D heat transfer simulations to illustrate the magnitude and temperature evolution within the material, taking into account the dimensions and thermal properties of various materials. In particular, wells completed with stainless steel casing and grout as an annular material exhibit the highest temperature propagation into the formation. In contrast, the well design with two casings and Glass Reinforced Epoxy (GRE) with clay-based annular materials shows the lowest. The results indicate that the casing and annular materials, as well as the well design, affect the temperature change within 3 meters of the formation during a single (first) charging cycle, equivalent to 180 days.



(a) (b)

Figure 5. (a) Schematic of the completion and annular materials; (b) Numerical simulation of the temperature variations 3 m into the formation while injecting 90°C

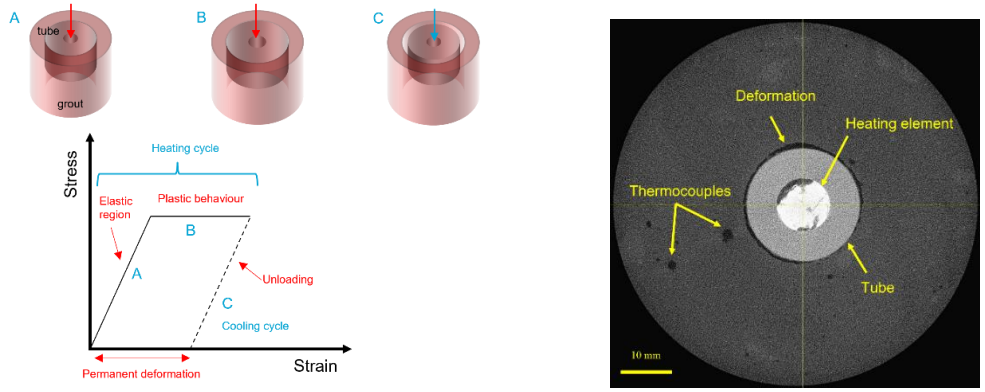
For the initial injection or extraction cycle, the well experiences relatively high heat losses. That's because the surrounding formation is at ambient temperature. In the following cycles, the temperature of the surrounding formation gradually increases. As a result, the heat losses per cycle are reduced, and the recovery efficiency improves.

Heat losses are not only important from the perspective of economic viability, but also thermal pollution. Temperature increase in drinking water aquifers can affect microbial activities and water quality (Riedel, 2019). Over the past decade, casing materials including Vacuum Insulated Tubing (VIT) and Glass-Reinforced Epoxy have become increasingly utilised for shallow and deep applications. The VIT consists of two concentric tubes with a vacuum between them. It has been currently utilised for various applications, but largely in deep wells (Śliwa et al., 2018). The extremely low thermal conductivity provides excellent thermal insulation with the surrounding annular material and formations.

A rubber material that acts as an insulator is used at each coupling between two tubings, with the type selected based on the operating temperature. Since the VIT consists of two tubes that are welded together and between vacuum, the weight is relatively higher compared to other casings. Most of the rigs used to drill groundwater, ATES and HT-ATES wells have low load capacity. Conventional PVC pipes are limited to temperatures below <50°C, even though they have low thermal conductivity. Carbon and stainless-steel casings are favourable materials for deep wells due to high strength, but for shallow wells, their combination with annular material selection and well design is critical. On the other hand, GRE has emerged as a material with low thermal

conductivity and a cost comparable to that of stainless steel. The HT-ATES system drilled in Middenmeer (the Netherlands) was completed with GRE casing to withstand high-temperatures and to provide corrosion resistance. The annulus was backfilled with layers of sand and clay-pellets (Oerlemans et al., 2022).

In the initial state, the temperatures of the completion and annular materials are equal to the ambient conditions. During the first charging cycle, the water transfers heat to the casing and annular material. As the materials heat up, they expand, and the degree of expansion varies depending on their thermal expansion coefficient and thermal conductivity. For example, a GRE casing transfers lower thermal stress to the annular material than stainless steel does, due to its lower thermal expansion coefficient. The casing is mounted in place with annular material such as clay-pellets, grout or cement. As the casing expands, it transfers mechanical stress to the material. Figure 6a illustrates plastic deformation during heating and cooling cycles, as well as the resulting micro-annulus in a grout cured for 7 days (Figure 6b).



(a) (b)

Figure 6. (a) illustration of stress and strain during thermal cycles; (b) Experimental results showing plastic deformation in the interface between tube and grout (Koulidis et al. 2025, 2026)

High strength and stiffness materials, such as Portland cement, have been proven to withstand high temperatures and provide well integrity. But the cement sheath has been a field of investigation by various researchers (Ogienagbon and Khalifeh, 2022; Wu et al., 2024). The critical variable in the HT-ATES is their operation. The wells often require rehabilitation, which corresponds to a decrease in temperature, even to ambient, and in the case of the Netherlands, that temperature is 12°C. This results in a large temperature difference that corresponds to contraction of the completion and annular materials.

Currently, the majority groundwater and ATES wells are completed with clay-pellets and grout. A recent study by Koulidis et al. (2025) showed that clay-pellets showed resilience to thermal cycles. However, well integrity shows compromised while using grouts as annular materials with the formation of micro-annulus. A compromise in well integrity can lead to preferential flow of water, which not only undermines the well integrity but also induces the mixing of waters from different aquifers.

3.1.2 Corrosion resistance in saline environments

In conventional ATES wells, corrosion is not a major concern. The wells are typically completed with PVC, which is resistant to the saline conditions of the target aquifers. In contrast, HT-ATES requires completion materials capable of withstanding high temperatures, making PVC unsuitable. Deep wells are commonly completed using carbon steel, where corrosion becomes a factor. While chloride concentration alone is already a challenge, the interaction with high temperatures significantly accelerates material corrosion and can compromise well integrity. Figure 7 illustrates the combined effects of temperature and chloride concentration on the corrosion behavior of stainless steel (Mameng et al., 2017). In the Netherlands, the groundwater environment for HT-ATES systems is unchlorinated. Thus, reducing chlorine-related corrosion mechanisms.

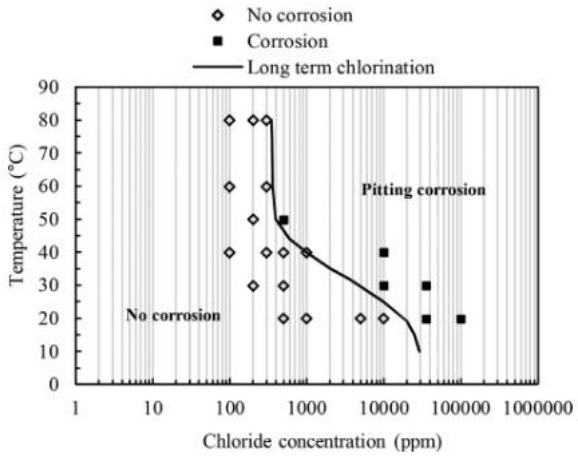


Figure 7. Engineering diagram for EN 1.4404 based on immersion testing in chlorinated environments (Mameng et al., 2017)

Corrosion and thermal cycles can compromise the well integrity of HT-ATES if the material selection is not properly considered. Groundwater or LT-ATES wells utilize PVC pipes as a casing material due to low cost and easy installation. The following Table 2 summarizes some of the important considerations while selecting the casing material.

Table 2. Casing materials

Variable	PVC	GRE	Carbon steel [L80]	Stainless steel [316]	Vacuum insulated tubing [L80]
Cost	Low	Medium	Medium	Medium	High
Temperature [°C]	<50	<120	-	-	-
Corrosion resistance	NA	High	Low	Medium	Low
Weight for 9.625 [lb/ft]	10	14	58.4	58.4	77.5
Thermal conductivity [W/mK]	0.19	0.6	50	25	0.004
Additional	-	-	Coating	Coating	Coating

Note* GRE = Vacuum insulated Tubing (VIT), Glass-Reinforced Epoxy (GRE)

3.2 Groundwater sampling

The operation of an HT-ATES system requires both a hot well and a cold well, involving the extraction and injection of water from distinct aquifer zones. This process leads to the transport of drilling fluid additives, microorganisms, and suspended particles such as sand/silt/clay between wells. Therefore, regular water sampling is required to monitor and assess potential changes in water quality (Bonte et al., 2011). To sample water, piezometers (MP) are installed in the annular space at different depths. To allow groundwater to flow towards the piezometers, gravel is placed in that small interval. Figure 8a illustrates the well design of the monitoring borehole DEL-HTO-P01 (Bloemendal et al., 2025; Koulidis et al., 2026), which was drilled at the TU Delft campus.

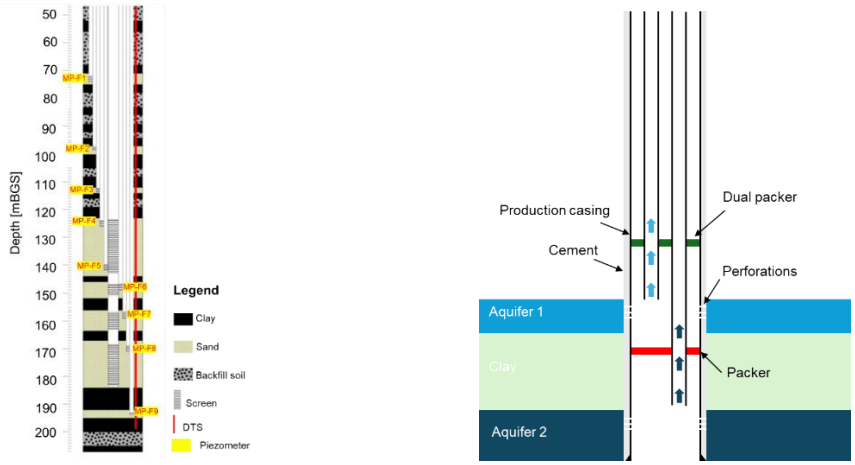


Figure 8. (a) HTO-01 TU Delft well design; (b) Example of dual tubing completion

The demonstrated well design is feasible to achieve due to the large diameter wellbore size, which allows installation of piezometers in the remaining annular space. Furthermore, as depth increases, it becomes more challenging to place gravel or backfilled material on a specific depth interval. For deep HT-ATES, a solution requires an outer casing and an inside completed with two tubings. An example is shown in Figure 8b with a dual completion design. The packers are set on the tubing to isolate the interval and flow to the surface through the tubing. This dual inflatable packer scenario allows us to isolate just those two zones and be able to collect water samples at the surface.

4 WELL DEVELOPMENT AND REHABILITATION

4.1 Preventing well clogging

Clogging of the wells can, over time, lead to higher head loss (and hence higher electricity cost for pumping water) and a change in thermal efficiency in case certain depth ranges of the well are clogged thus changing inflow patterns. The optimal strategy for operating a well is also controlled by the type of well clogging that is expected.

Mechanical clogging by sand particles (>60 micron) and silt particles (>10 micron) can partly be prevented in the construction phase by selecting a gravel pack that is not too coarse in relation to the grain size of the formation and by not screening layers with high silt content (SIKB, 2021). During the operation phase a filter can be placed between the hot and warm well. In the Netherlands, conventional ATES wells (<25°C) are considered less prone to clogging because the flow direction in the well is reversed depending on whether the ATES system is used for heating or cooling. Drinking water companies in the Netherlands employ this strategy more intensively by using daily backflush injection wells for Aquifer Storage Transport and Recovery Systems (van der Schans et al., 2022). More frequent periodic backflushing of an HT-ATES well, in combination with a filter may thus be a fruitful strategy to limit mechanical clogging.

It is important to state that rehabilitation strategies must consider the temperature ranges and chemical resistance of the completion materials. In HT-ATES, calcite precipitation occurs because heating the groundwater decreases the solubility of calcium carbonate (Oerlemans et al., 2022). This can lead to scaling in wells and clogging of the pores, reducing near-wellbore permeability. As a result, the system's efficiency reduces over time. In practice, the primary strategy for reducing calcite precipitation is CO_2 injection or another acid such as HCl. A concern is to limit dosing to a minimum, since adding acids to the aquifer also leads to dissolution of calcium, thus enhancing it in the long term.

Biological clogging depends on the water quality (mixture, nutrients, organic carbon) that is being pumped and temperature. In the hot wells (>80°C) the microbial activity is likely to be limited. But in warm wells (approx. 40°C) the microbial activity is much higher than under ambient conditions (12°C). Microbial growth can be limited by adding biocides. However, choices are limited since they need to be in line with existing regulations and using acid requires a very high dosage, leading to the dissolution of calcite within the aquifer. A possible strategy to limit microbial growth is to apply periodic backflushing. In the warm wells, this may be combined with periodic injection of hot water (90°C) to inactivate micro-organisms. Note that such measures are temporary, since microbial organisms are always likely to re-colonize the well.

4.2 Rehabilitation strategies

It is not always possible to prevent well clogging. A major concern in well rehabilitation is determining the optimal timing. Rehabilitating too early leads to frequent, excessive interruptions of operations and increased costs. Waiting too long when the well is too far clogged means the rehabilitation may be unsuccessful and the well needs to be written off. In the Netherlands, wells are generally rehabilitated when their specific volume flux (flow rate divided by drawdown) is at 50% of their original value; international handbooks recommend action at 80% of the original specific volume flux. Rehabilitation techniques for HT-ATES wells are, in general, similar to those for conventional ATES wells and include bailing, intermittent pumping, and chemical treatment (such as acid, sodium hypochlorite, or a clay-dispersing agent, depending on the cause of the clogging). A main concern when cleaning HT-ATES is the high temperature, which requires additional HSE measures.

5 CONCLUSIONS

This study provides a comprehensive overview of the drilling challenges and technical considerations associated with HT-ATES systems in unconsolidated aquifers. The work highlights that the success and long-term integrity of these systems depend strongly on the integration of drilling methodology, drilling fluid, and well completion. HT-ATES wells introduce new challenges for the shallow systems due to the elevated operating temperatures, including thermal pollution, accelerated biological growth, and well clogging. However, these challenges can be effectively mitigated through proper design and planning, careful selection of completion materials, and systematic monitoring and groundwater sampling programs.

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