Delft University of Technology
BSc Applied Earth Science

Thermal deformation in High Temperature ATES systems

AESB3410 - Bachelor End Project

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Contents

Abstract

High Temperature Aquifer Thermal Energy Storage (HT-ATES) is a technique for storing large amounts of residual heat in the subsurface. In this report, the thermal deformation resulting from the temperature change in the subsurface is investigated and the resulting risks for buildings are assessed. To do this a case study is done on the TU Delft campus subsurface. It has been determined that the thermal deformation due to HT-ATES systems is small with a maximal deformation of 14 cm. It has also been determined that the stability risks for buildings that are constructed in the vicinity of a HT-ATES system are very low.

1. Introduction

1.1. Research Relevance

High Temperature Aquifer Thermal Energy Storage (HT-ATES) systems have the potential to store large amounts of energy that could not be used directly, like waste residual heat or geothermal heat (Drijver et al., 2012). This means that such a system can contribute to increasing the efficiency of our energy consumption, something that is crucial in a time that humanity discovers the global effects of their consuming lifestyle. Heat is responsible for around half of the global total energy consumption (IEA, 2018), therefore an increase of efficiency in using thermal energy can make an enormous difference. However, when storing the energy underground, large temperature differences can cause deformation of the subsurface which may lead to either dilation or compaction at the ground level (Molz et al., 1983; Campanella & Mitchell, 1968). The risks of a HT-ATES system should therefore carefully be assessed.

The more we know about risks involved with high temperature storage, the better it can be implemented. The risks of possible deformation that results from a HT-ATES system could eventually lead to damage on buildings and this risk is especially important in the Netherlands. The houses that have been damaged as a result of the deformation induced by gas exploitation in Groningen has created a social crisis in the Netherlands (Van den Berg, 2018) and any significant deformation due to subsurface exploitation would be a very sensitive matter. Therefore, it is important to assess the thermal mechanical effects in a HT-ATES system. Former studies have indicated that land rise due to HT-ATES systems has occurred (Molz et al., 1983) and other research has shown that compaction can also be expected (Campanella & Mitchell, 1968). This study will take the next step into quantifying the expected deformation for HT-ATES systems and assessing the risks that this deformation causes.

1.2. Research Aim and Question

The goal of this study is to quantify the expected deformation due to the temperature change in an aquifer induced by a HT-ATES system and to assess the risks involved for buildings.

1.3. Approach

To investigate the deformation it is chosen to use the setting of the subsurface at the TU Delft campus as a case study. This report consists out of the following parts which build up to a final assessment on the risks for deformation due to temperature change in an aquifer induced by a HT-ATES system:

- The relevant processes and governing equations for thermal deformation in HT-ATES systems are identified in Section 3.
- Section 4 presents the conditions of the subsurface for the TU Delft campus case study and the scenarios that will be investigated.
- The results for the expected deformation for all scenarios are described in Section 5. This section also includes a sensitivity analysis for the parameters involved in calculating the thermal deformation.
- Section 6 follows up with a discussion on the results. The limitation of the approach, the uncertainty in the data and factors for thermal deformation that are not dealt with in this study are discussed.
- In Section 7, the conclusion and the recommendations for future research are listed.

Table 1: Three ATES systems (Drijver et al., 2012)

Aquifer Thermal Energy Storage (ATES)	<30 °C
Medium Temperature Aquifer Thermal Energy Storage (MT-ATES)	30-60 °C
High Temperature Aquifer Thermal Energy Storage (HT-ATES)	>60 °C

2. Background Information

To understand the problem that needs to be solved, first some background information is needed. In this section the concept of ATES systems is explained and how ATES systems are currently in use and in development in the Netherlands. Furthermore, a brief description of the geological area of Delft is given.

2.1. ATES Systems

Aquifer thermal energy storage (ATES) is a form of energy storage that has applications in many different ways and scales. The concept of an ATES system is that thermal energy, be it purposed for cooling or heating, is stored in water that is kept underground in an aquifer. Although potential thermal energy is lost over time, the subsurface is a good insulator and large portions of the energy stored can be retrieved. Three different types of ATES systems are distinguished depending on the range of temperature, which are shown in Table 1.

Besides temperature differences, ATES systems in general also have smaller storage capacity then medium or high temperature ATES systems. ATES systems are used for heating or cooling buildings as shown in Figure 2.1. ATES systems use the naturally cold water in the subsurface to provide cooling and then store the resulting hot water at another place in the subsurface. In cold days this system is reversed, and the stored hot water is used for heating.

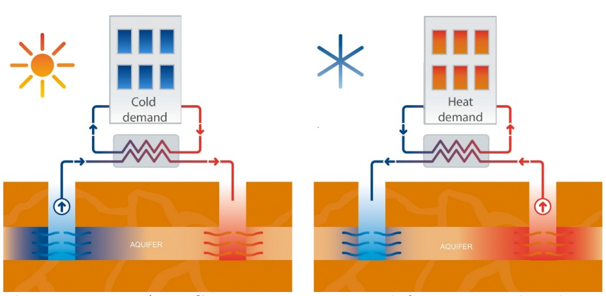

Figure 2.1: ATES system, retrieved from IFtechnology, https://www.iftechnology.nl/aquifer-thermal-energy-storage-wko-in-dutch-is-catching-on-in-japan

For MT- or HT-ATES systems the same principles are used but slightly different. Instead of using the natural temperature of the subsurface, extra heat is added to the aquifer in the summer using waste residual heat. Then in the winter, this stored heat is used for heating. The advantage of these systems compared to normal ATES systems is that due to the higher temperature, the energy stored per cubic meter is much higher and therefore MT- or HT-ATES systems can fulfil greater energy demands. When comparing medium temperature and high temperature ATES systems, the same principle applies. High temperature systems have the advantage of storing more energy per cubic meter then medium temperature systems. In addition to having greater storage capacity, higher temperatures also make it easier to use the water more directly for heating. A disadvantage of HT-ATES systems is that the water that is circulated needs treatment to prevent precipitation of minerals and due to the higher temperature, the thermal mechanical effects in the aquifer are higher (Drijver et al., 2019).

2.2. ATES Systems in the Netherlands

The Netherlands have become the largest market for ATES systems in the world (Godschalk, 2017), already thousands of ATES systems are in operation (Fleuchaus et al., 2018) and two MT-ATES are operational as well (Drijver et al., 2012). However, only two High Temperature ATES systems have been realised and both are closed. One of the current problems for setting up a HT-ATES system in the Netherlands is that at this moment such systems are not permitted under the policy for protecting drink water aquifers and the ones that have been realized were granted a permit based upon research purposes. This is about to change, because in light of the energy transition the government is actively working on adapting the current laws to make way for commercial geothermal wells and HT-ATES systems (Platform Geothermie, 2018).

3. Governing Processes and Equations

To make a good estimate about the amount of deformation that can be expected due to the temperature change, it is first needed to know what factors play a role and how they can be described. Large changes in temperature has multiple effects on the soil.

- First of all it causes the thermal expansion of soil particles and the formation fluid.
- Secondly, the expansion of clay layers will eventually lead to a collapse of the clay layer causing the unusual behaviour of clay layers to shrink with increasing temperature (Laloui & François, 2009).
- A third effect of the increased temperature is that some particles will dissolve more into the water, whilst the solubility of other particles will decrease.

All these three effects will be discussed in this section and equations will be presented for the thermal expansion of the soils. Lastly it will be discussed how deformation can cause stability problems and what levels of deformation should be avoided.

3.1. Thermal Expansion

The increase of temperature causes an increase of internal energy for all material in the subsurface and therefore these materials will expand. Because the soil layers are experiencing horizontal stress from all directions, this expansion will mostly be in the vertical direction, causing a land rise. Depending on the material and its state, the rate of thermal expansion, will be different. The coefficient of thermal expansion, α, is expressed in change of length per unit length per unit temperature with units L L^{-1} $°C^{-1}$. Solid clay or sand particles have an expansion rate with typical values between 0.1-0.5$\cdot 10^{-4} °C^{-1}$ and 0.13-0.20$\cdot 10^{-4} °C^{-1}$ respectively (Campanella & Mitchell, 1968; Somerton, 1992). Fluid water particles will expand much more rapidly and will expand with a rate of 2.73-6.27$\cdot 10^{-4} °C^{-1}$ (Laloui & François, 2009) depending on the initial temperature.

Because of the difference in the rate of thermal expansion between water and the solid particles is a factor of 10, thermal expansion will cause an increase of pore water pressure. In high permeability layers like the sand layers that are used for storage, this increased pore water pressure will dissipate fast because the water can flow freely. In low permeability layers like the confining clay layers overlying the storage layer, the increased pore water pressure is not able to dissipate and will cause a decrease in effective stress. According to Campanella and Mitchell (1968) this increase in pore water pressure, F, is in the order of 0.014-0.018 $PaPa^{-1} °C^{-1}$.

3.2. Clay Contraction

Soil layers will expand when heat is added to the system. The same happens to clay layers, but the increased temperature in clay layers has an additional consequence. Due to the dilation, the strength in the adsorbed layers decreases and the distance between the clay particles is modified. This changes the equilibrium between the Van der Waals attractive forces and the electrostatic repulsive forces. Because the strength of the soil decreases with increasing temperature, the increase of temperature can make the soil experience failure and then the clay layer will contract. Figure 3.1 shows the decrease of soil strength with an increase of temperature. In the thermo-elastic domain the clay layer will expand. If the isotropic yield limit is reached the clay will contract.

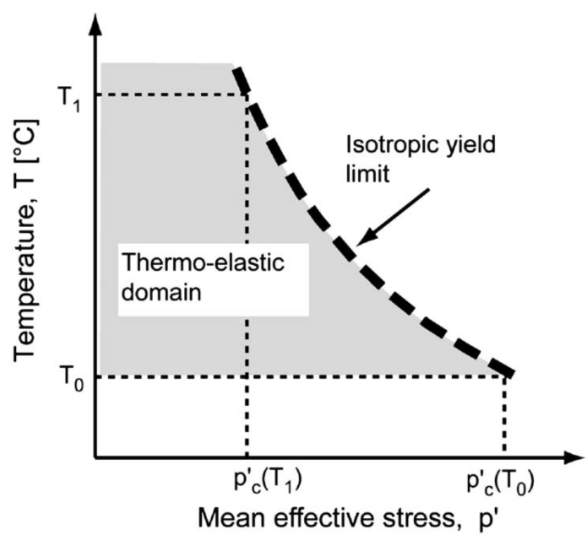

Figure 3.1: Yield stress over temperature. Taken from *ACMEG-T: Soil Thermoplasticity Model*, by Laloui and François, 2009.

It depends on the pre-existing effective stress state if the clay layer will contract or not. If the clay is in an effective stress state in which it is experiencing the maximum historic effective stress[1], this stress

[1] With the maximum historic effective stress state is meant the maximum effective stress state the soil has experienced since its formation

state is called normally consolidated. Any decrease in strength of the soil by a temperature increase will cause the clay to fail and contract. The stress path of a normally consolidated soil is shown in Figure 3.2 with the green line.
If the clay is in an effective stress state in which it is experiencing an effective stress which is less than the maximum historic effective stress, this stress state is called overconsolidated. A decrease in strength of the soil by a temperature increase will not immediately cause the clay to fail. It will expand as long it is in the thermo-elastic domain and will contract when it reaches the yield limit. The stress path of a overconsolidated soil is shown in Figure 3.2 with the orange line.

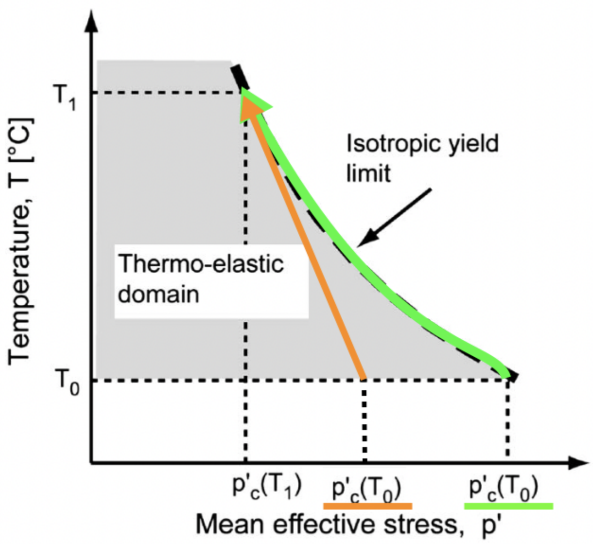

Figure 3.2: Stress paths of consolidated and overconsolidated soils. Adjusted from *ACMEG-T: Soil Thermoplasticity Model*, by Laloui and François, 2009.

An increase of temperature will cause an increase in pore water pressure and therefore a decrease in effective stress. Since both the effective stress and the yield limit of the clay layer decrease with temperature, it is hard to define if a clay layer will fail or not. An approximation on the change of effective stress over temperature is known, but to make a similar approximation on the change of the yield limit over temperature is already much more complicated. Laloui and François (2009) did find a relation, but this relation is only valid for a specif sample and was not made generic yet. In this study it is assumed that both decrease in more or less the same rate. This means that in undrained conditions a normally consolidated clay layer will experience constant contraction with increasing temperature and that an overconsolidated clay layer will only dilate. When this overconsolidated clay layer is drained it will then later contract when it reaches the yield limit. The thermal contraction coefficient for clay, in this study denoted by γ, is taken from Campanella and Mitchell (1968) and is $0.50 \cdot 10^{-4} {}^{\circ}C^{-1}$.

3.3. Solubility

Another effect of the temperature increase is that in general solid particles will dissolve more in the water. When the water is pumped up for heat production these solved particles could be caught by the filter in the heat exchanger. When this cycle is repeated multiple times over the years with vast volumes of water, this could eventually lead to a decrease of soil particles in the reservoir and thus contraction of the aquifer. However, it is unclear if this decrease of soil particles is significant and in this study it is considered to be negligible compared to the factors of deformation described before. In an operating HT-ATES system, the ion content of the pumped water can be monitored to see if the ions dissolve at a rate that would be significant or not.

3.4. Deformation Equations

To calculate the deformation that can be expected from the thermal energy increase, the following formulae will be used:(Campanella & Mitchell, 1968)
The thermal expansion of the soil is dependent on the thermal expansion coefficient, the thickness of the layer and the change in temperature. To calculate the thermal dilation of the clay and sand layers Equation 3.1 will be used, with H denoting the height of the layers.

$$dL = \alpha_{\text{dilation}} * dT * H \qquad (3.1)$$

If the yield limit is reached, the clay will also contract. To calculate the thermal contraction of the clay layers Equation 3.2 will be superimposed on Equation 3.1 as proposed by Campanella & Mitchell (1968).

$$dL = -\gamma_{\text{contraction}} * dT * H \qquad (3.2)$$

3.5. Stability Problems

To know if any deformation that is caused by the HT-ATES system is of any risk for the stability of buildings, a limit value for deformation is needed. Generally speaking, an absolute deformation until 50 mm is permissible. If the deformation is greater than 50 mm, it is important that the slope created by the deformation stays below 1:500, an angle of 0.11°(Peters, 2014). If these conditions are met, the risk for damage on buildings are kept at a minimum. To calculate the slope that is created, not only the vertical deformation is needed, but also the horizontal distance to the point where the deformation is equal to zero. To define a horizontal spread for the slope of our case study, it is assumed that at the thermal boundary of the HT-ATES system, the temperature changes abruptly and no deformation occurs outside the thermal boundary. A Poisson's ratio of 0.25 is taken for the entire system, which results in a horizontal spread of two times the depth of the system as shown in Figure 3.3. The figure shows the boundary between the HT-ATES system and the unaffected part of the subsurface.

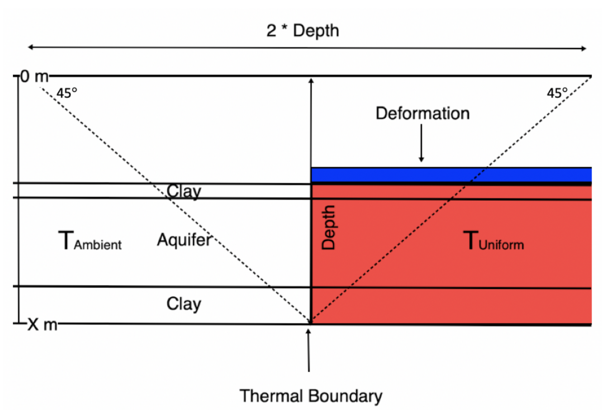

Figure 3.3: Horizontal Spread Scenario 1

4. Case Description

As a case study, the thermal deformation of a HT-ATES system will be presented in a specific situation, the Delft subsurface. It is an interesting location, because the Technical University of Delft is planning to drill a geothermal well in 2020 at the campus and a HT-ATES system would be a perfect addition to optimise the heat production of the (*Geothermal Well Planning*, 2018). This section provides the geological setting of the Delft area and the location of the HT-ATES system within the subsurface.

4.1. Geological Setting

Multiple boreholes have been drilled on or near the TU Delft campus and can be viewed on the website of DinoLoket and NLog and two of them are shown in appendix 8.1. According to the NLog data, the first 400 meters of soil is all classified under the Upper North Sea group. This group consists of shallow marine deposits and terrestrial beds. This groups is then further subdivided into formations. Since the interests are in shallow HT-ATES systems, only the first 250 meters will be discussed in detail. The first 250 meters are made up out of four different formations: the Holocene deposits, the Kreftenheye formation, the Peize and Waalre Fromation and the Maassluis formation. (Hacking, 2017)

4.1.1 Holocene Deposits

The Holocene deposits cover the first 16 meters and contain clay, sand and peat. These sediments have been deposited in the last 12.000 years.

4.1.2 Kreftenheye Formation

The Kreftenheye formation is build up out of coarse sand and gravel and is 15 to 20 meters thick. Although the soil is suiting for aquifer storage purposes, this formation misses a cap on top of the formation and it is probably close to drinking water extraction. Therefore, this layer too is unsuitable for the HT-ATES system.

4.1.3 Peize and Waalre Formation

This Peize and Waalre formation is a sequence of clay and sand layers and is around 60 to 70 meters thick. The sand is mostly made up out of coarse grains, but smaller grains ans silt particles are also present, decreasing the permeability of the formation.

4.1.4 Maassluis Formation

The Maassluis formation contains coarse sand and shells with a few clay layers in between. It is similar to the Waalre formation with the exception of the shells.

4.2. Aquifer Selection

In the past, multiple research papers have investigated the possibility of an ATES system in the Delft subsurface. Two of those papers, "Cooling T.U. Delft by combining thermal energy from surface water and ATES" by E.J. Vester (Vester, 2017) and "Energieopslag TU Delft" by the company IF Technology (IF Technology, 2011), have done detailed research to the subsurface and aquifer selection in the Delft area. Both have decided for the same aquifer to be their

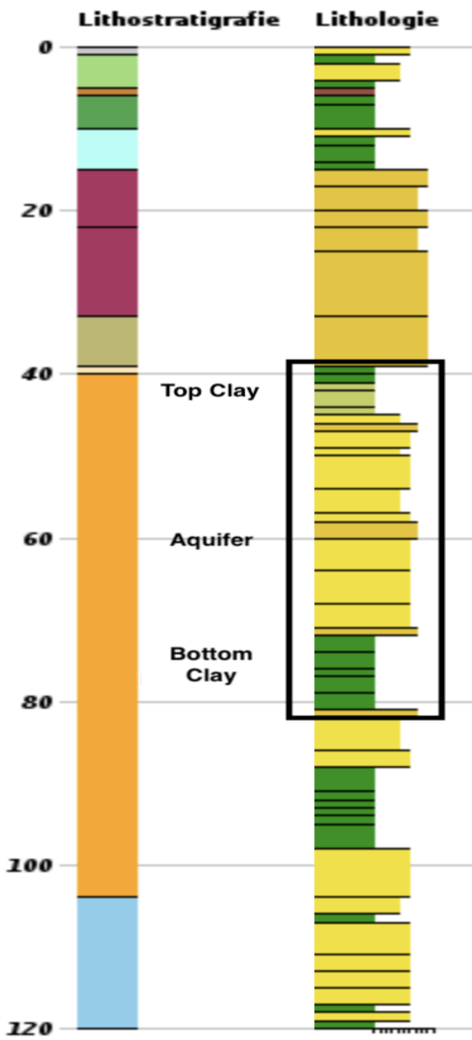

Figure 4.1: Location of Aquifer and Clay layers, adjusted from DINOloket, https://www.dinoloket.nl/ondergrondgegevens

ideal ATES location and in this paper the same location has been chosen for the HT-ATES system. The aquifer is located in the Waalre formation and is 40 to 80 meters deep, as can be seen in Figure 3.3. The aquifer of 24 meters thick is enclosed by two low permeability clay layers, the top one having a thickness of 6 meters and the bottom clay layer has a thickness of 10 meters. The average temperature in the aquifer and the clay layers is 11.5 °C. The location of the aquifer and clay layers is shown in Figure 4.1. It can also be seen that the first 16 meters are Holocene deposits and that in between the Holocene deposits and the first confining clay layer is a sand layer of 20 meters thick.

To be able to give a more general answer to the question of how much thermal deformation can be expected for a HT-ATES system, also models with modifications to this Delft subsurface will be run. The thickness of the aquifer and clay layers will be modified and also different soil types for the aquifer will be used.

4.3. Scenarios

To estimate the deformation caused by the increase of heat in the system, it is first needed to make a thermal model describing the distribution of heat in the subsurface. In this study, two different scenarios will be examined. First a simplified thermal model is used in which the temperature is assumed to be uniform throughout the entire reservoir and clay layers with the temperature equal to the injection temperature. Secondly, a closer look is taken near the well where the temperature increase and the resulting deformation is expected to be the greatest.
Before the details of the two models are discussed, the conditions both models have in common shall be mentioned first. An injection temperature of 80 °C is chosen for all models unless indicated otherwise. Also the assumption has been made for both models that the vertical propagation of the conductive and convective heat exchange due to the injected water is limited to the aquifer and the surrounding clay layers only. This assumption was made based on the fact that the clay layers are very impermeable and therefore convective heat will not reach other layers. The conductive heat can propagate through the clay layers into other layers, but the resulting thermal deformation is considered to be negligible compared to the thermal deformation in the aquifer and clay layers. The horizontal propagation is limited to the thermal radius of the well. Within this radius the temperature is assumed to be constant. In reality however, the temperature will decrease with distance from the well. This assumption is made to simplify the model.

4.3.1 Scenario 1: uniform temperature deformation

In this scenario a simplified end scenario is used to calculate the deformation. The temperature within the thermal radius in the aquifer and the enclosing clay layers is assumed to be uniform and equal to the injection temperature. Outside the thermal radius the natural temperature of 11.5 degrees Celsius is assumed. The overall situation can be seen in Figure 4.2 and this scenario calculates the deformation along

Table 2: Default parameters

Parameters	*Magnitude*
Ambient Temperature	11.5 °C
Injection Temperature	80 °C
Sand Expansion Coefficient (α_{sand})	$0.15 \cdot 10^{-4} °C^{-1}$
Clay Expansion Coefficient (α_{clay})	$0.30 \cdot 10^{-4} °C^{-1}$
Clay Contraction Coefficient (γ_{clay})	$0.50 \cdot 10^{-4} °C^{-1}$
Aquifer Thickness (Ha)	24 m
Top Clay Thickness (Hct)	6 m
Bottom Clay Thickness (Hcb)	10 m

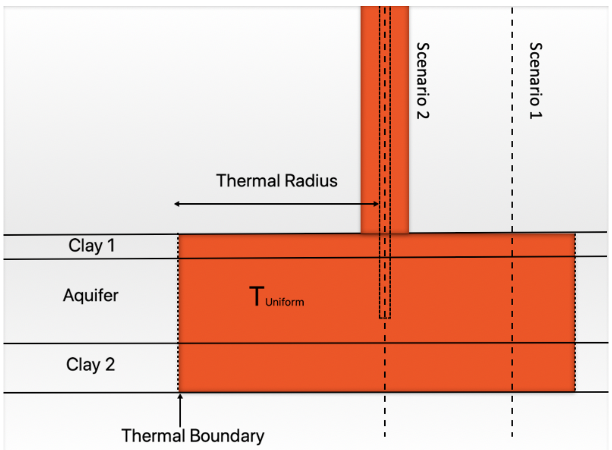

Figure 4.2: Scenario 1

the line of 'Scenario 1'. In this scenario it is neglected that the temperature will decrease over radial distance from the well and that the temperature increase in the clay layers will be smaller. This means that the deformation calculated for this scenario should be more than it would be in reality. First a thermal deformation estimation is made with average values chosen for all parameters, as shown in Table 2. Then a sensitivity analysis will be done using the extreme values for all parameters.

4.3.2 Scenario 2: near-well deformation

The second scenario is an extended version of scenario 1 with the addition of near-well deformation in the layers laying on top of the aquifer and the two clay layers under investigation in scenario 1. The extra deformation along the line of 'Scenario 2' in Figure 4.2 is calculated in this scenario. This near-well deformation in the layers above the confining clay layer are caused by the conductive heat that is exerted by the well casing. The reason for this second scenario is that amplified deformation has been recorded around the well in a test with a HT-ATES system in Alabama (Molz et al., 1983) It is assumed that the conductive heat exerted by the well casing will only have a limited spatial effect. The spatial radius that was effected by the well in Alabama was around 5 meters and this spatial radius will also be assumed in this model. Secondly, it is assumed that the conductive heat exerted on the high permeability sand layers will only cause negligible deformation, since the heat will dissipate by advection due to buoyancy flow. Therefore, the clay layers that are penetrated by the well are the layers of interest for this second scenario.

5. Results

Now all governing processes and scenarios are explained, Equations 3.1 and 3.2 can be used to calculate the deformation for the different scenarios. For all scenarios the expected results for will be presented.

5.1. Uniform Temperature Deformation

Because of the low permeability of the clay layers, undrained conditions can be assumed during the temperature increase. However, over time the excess pore water pressure will dissipate and the effective stress will increase. In the overconsolidated situation this will lead to contraction and thus over time the deformation in the overconsolidated situation will eventually reach the same values as for the normally consolidated situation. For the normally consolidated situation the excess pore water pressure already dissipates during the failure of the soil and therefore there is no change in the deformation in either drained or undrained conditions.
In undrained normally consolidated conditions the clay and sand will expand and the clay will also contract. Combining Equations 3.1 and 3.2, it results in

Table 3: Sensitivity Analysis: Range

	Set 1	*Default Parameters*	*Set 2*
Injection Temperature	70 °C	80 °C	90 °C
Sand Expansion Coefficient	$0.10 \cdot 10^{-4} °C^{-1}$	$0.15 \cdot 10^{-4} °C^{-1}$	$0.20 \cdot 10^{-4} °C^{-1}$
Clay Expansion Coefficient	$0.10 \cdot 10^{-4} °C^{-1}$	$0.30 \cdot 10^{-4} °C^{-1}$	$0.50 \cdot 10^{-4} °C^{-1}$
Clay Contraction Coefficient	$0.60 \cdot 10^{-4} °C^{-1}$	$0.50 \cdot 10^{-4} °C^{-1}$	$0.40 \cdot 10^{-4} °C^{-1}$
Aquifer Thickness	10 m	24 m	30 m
Top Clay Thickness	15 m	6 m	5 m
Bottom Clay Thickness	15 m	10 m	5 m

Table 4: Sensitivity Analysis: Absolute and percentage difference for every parameter

Normally Consolidated	*Set 1*	*Set 2*	**Overconsolidated**	*Set 1*	*Set 2*
	(cm)	(cm)		(cm)	(cm)
	(%)	(%)		(%)	(%)
Temperature	-0.04	0.04	Temperature	-0.84	0.84
	14.6	14.6		14.6	14.6
Sand Expansion Coefficient	-0.82	0.82	Sand Expansion Coefficient	-0.82	0.82
	300	300		14.3	14.3
Clay Expansion Coefficient	-2.19	2.19	Clay Expansion Coefficient	-2.19	2.19
	800	800		38.1	38.1
Clay Contraction Coefficient	-1.10	1.10	Clay Contraction Coefficient	0	0
	400	400		0	0
Layer Thickness	-3.36	1.44	Layer Thickness	1.44	-0.62
	1225	525		25.0	10.7

the following equation for the final deformation.

$$dL = (\alpha_{\text{sand}} * Ha + \alpha_{\text{clay}} * (Hct + Hcb)) * dT - \gamma_{\text{clay}} * (Hct + Hcb) * dT \quad (5.1)$$

To determine the expected deformation the default parameters of Table 2 are plugged into the equation and the deformation with normally consolidated clay is 0.27 cm.
In undrained overconsolidated conditions the clay and sand will expand and the clay will not contract. This leads to almost the same equation as for normally consolidated conditions, only the contraction part is left out.

$$dL = (\alpha_{\text{sand}} * Ha + \alpha_{\text{clay}} * (Hct + Hcb)) * dT \quad (5.2)$$

The deformation in undrained overconsolidated conditions is 5.75 cm.

5.1.1 Sensitivity Analysis

Since the exact values of the expansion and contraction coefficients are uncertain and HT-ATES systems at different locations will have different injection temperatures and subsurface compositions, a sensitivity analysis is done on these five parameters. The ranges used for the five parameters are shown in Table 3. The parameters in Set 1 and 2 are chosen in a way to influence the deformation negatively and positively, thus resulting in more contraction/less expansion and less compaction/more expansion respectively. The ranges that were chosen for the sand and clay expansion coefficients follow from the ranges found in the literature that were presented in Section 3.1. For the clay contraction coefficient, only one single value has been found in literature and not a range. A deviation of 0.1 $°C^{-1}$ has been chosen to use for the sensitivity analysis. Two different set-ups are used for the subsurface layer thicknesses, one situation with thick clay layers compared to the aquifer and one situation with a thick aquifer compared to the clay layers, both keeping a total thickness of 40 meter. The sensitivity analysis is done using the One-at-a-time method, changing one parameter every time. The absolute difference in deformation and the percentage deviation is calculated for every parameter and shown in Table 4.
The composition of the subsurface and the clay expansion coefficient make the biggest impact. Notable is that a ten degrees difference for the injection temperature in normally consolidated soils hardly makes a difference. Except for the temperature, the percent-

age deviation for the normally consolidated situation is much higher than for the overconsolidated situation. This is because the absolute difference is more or less the same, but the relative difference is much greater for the normally consolidated situation. If the deviations in the expansion and contraction coefficients, injection temperature and layer thickness are all arranged in a way for maximal dilation or contraction the following ranges of deformation can be expected for the normally and overconsolidated scenarios. The ranges of deformation for the normally consolidated and overconsolidated scenarios are -11.0 to 7.85 and 2.34 to 14.1 cm respectively.

The horizontal spread of the deformation is twice the depth of the system. Since the system is 80 meters deep, the horizontal spread is 160 meter. If the maximum absolute deformation of 14.1 cm is taken, a slope is created of 0.05°.

5.2. Near-well Deformation

The near-well deformation module is an extension of the uniform temperature deformation module. The extra deformation that can be expected in this scenario comes from the clay layers that are penetrated by the well. In Figure 4.1 it can be seen that 12 meters of clay are located above the HT-ATES system. Since these clay layers all are located near the surface, it can be expected that the clay layers are overconsolidated.(Phil Vardon, personal communication, October 25, 2019) The extra deformation due to the near well conductive heat can be calculated with the following formula:

$$dL2 = \alpha_{\text{dilation}} * dT * H2 \qquad (5.3)$$

with H2 for the thickness of the clay layers overlying the HT-ATES system. The deformation near the well in scenario 2 will then be 2.11 cm. The deepest clay layers above the well are located at 16 meters depth, thus the horizontal spread will be 32 meters. This will lead to a slope angle of 0.04°.

6. Discussion

The scenarios that were investigated in this study were simplifications of a real HT-ATES system. The first simplification is that for the thermal dispersion in the subsurface an assumption was made that created a uniform temperature throughout the entire system and a sudden change of temperature at the thermal boundary. In a real system, temperature will decrease over the radius and the temperature in the clay layers will be lower as well. These simplifications cause that the temperature increase is higher than would be expected resulting in greater deformation than can be expected.

A second simplification is that the thermal boundary is kept undefined, for a real HT-ATES system this thermal boundary needs to be defined. Depending on the needed quantity of thermal storage, a volume of injected hot water shall be calculated resulting in a defined thermal boundary. This thermal boundary will define the location of the slope as shown in Section 3.5 and thus the thermal boundary will define at which locations buildings will experience a sloped deformation.

The limit values for deformation that have been defined in Section 3.4 are good indications if the deformation could lead to any instability, but exceeding these limit values will not per definition lead to stability risks. Peters (2014) mentions that for a lot of constructions a slope of 0.11 degrees is a threshold, but that for other constructions slopes of 0.19 to 0.29 degrees are safe as well.

During the literature study it became clear that thermal expansion behaviour of soil is scarcely investigated, which leads to a shortage of data on thermal expansion and contraction coefficients. Since these coefficients have big influence on the deformation that can be expected from a HT-ATES system, the expected deformation has uncertainties too. Especially the thermal contraction coefficient for clay needs more investigation. Until now only one value for one specific sample is known. The clay layers in Delft or at any other location could show a very different rate of contraction and there is no indication to what order those clay layers contraction would deviate from the sample that Campanella & Mitchell (1968) investigated.

In this study, not all factors that play a role on the thermal deformation in HT-ATES systems and the resulting slope could be investigated. One of those factors is the change of expansion to contraction behaviour in overconsolidated soils. If a clay layer is overconsolidated it will initially start to expand with increasing temperature, but when the yield stress is reached it will contract. This is shown in Figure 6.1. Because this study focused on the possible stability problems resulting from HT-ATES systems, the extreme situation of just expansion or just compaction were investigated. However, if the expected deformation needs to be known from a specific HT-ATES system, this change in behaviour needs to be accurately predicted.

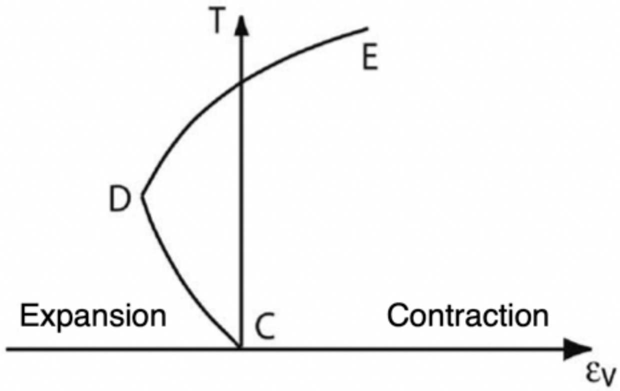

Figure 6.1: Change from expansion to contraction behaviour. Adjusted from *ACMEG-T: Soil Thermoplasticity Model*, by Laloui and François, 2009.

Another factor is the decrease of effective stress due to the rise in temperature. In clay layers, the increase of pore pressure cannot dissipate because of the low permeability of the soil, leading to a decrease in effective stress. Campanella & Mitchell (1968) estimated that the pore pressure would increase with 0.014-0.018 $PaPa^{-1}°C^{-1}$. This means that in fully undrained conditions for every °C a pore pressure increase of 1.4 to 1.8 % can be expected. A temperature rise of 70 °C would then lead to a pore pressure increase of 265 percent. With such an increase there is a big possibility that the clay layers will experience liquefaction.

The maximum expected deformation in scenario 1 is higher than the limit value of 50 mm, but the relative rotation angle remains under the limit value of 0.11°. It seems unlikely that a HT-ATES system will cause a deformation which will exceed this relative rotation angle. The maximum deformation was a result of a worse case scenario for all parameters and the model was already overestimating the temperature change throughout the entire aquifer.
The deformation that is expected for scenario 2 is less than 50 mm and the slope angle is lower than 0.11°. Therefore, this scenario will not lead to any risks for the buildings as well.
Two major parts that determine the deformation and the slope are the thickness and the depth of the HT-ATES system. The thickness of the system is in direct relation to the expansion in overconsolidated soils, thus an increase of thickness would be disadvantageous. The depth of the system determines the horizontal spread of the deformation. The deeper the system, the larger the spread. If a thicker HT-ATES system is build at a shallower level, it might be possible that unstable situations would occur.

7. Conclusion and Recommendations

The goal of this study is to quantify the expected deformation due to the temperature change in an aquifer induced by a HT-ATES system and see if this deformation could lead to damage on buildings. It is concluded that the thermal deformation resulting from a HT-ATES system is small. While using extreme values for the deformation parameters in a scenario which exaggerates the deformation the maximal deformation that could be expected was 14 cm. The hazards involved for buildings turned out to be negligible. Due to the depth of the HT-ATES system, the deformation is spread out over a large horizontal distance and therefore the resulting slope is of no magnitude that could induce problems. Also the slope induced by near-well deformation is small. However, the risks for soil liquefaction are present and need to be quantified in further research.

To be able to create a model that could predict thermal expansion or contraction of soil layers with more accuracy, the following needs more research.
First of all, more data is needed on the expansion of soils with increasing temperatures to be able to state the expansion coefficients of soils with greater accuracy. Little information is known for numerous soils. The values that are known for some soils are based on just a few samples, meaning that there is still a big uncertainty in these values.
Second of all, the characteristic behaviour of clay to contract with increasing temperature needs to be investigated more. Only one single value could be found for the contraction coefficient.
Furthermore the transition between expansion and contraction, the yield limit, needs more investigation. Laloui and François (2009) did find a relation between rising temperature and a decreasing yield limit, but that was only for one specific sample.
To be able to assure that the thermal deformation that is induced by HT-ATES systems is within

safe boundaries, it is needed to assess the risk of liquefaction. Further research should find out if this risk can be mitigated.

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A. Boreholes Delft Campus

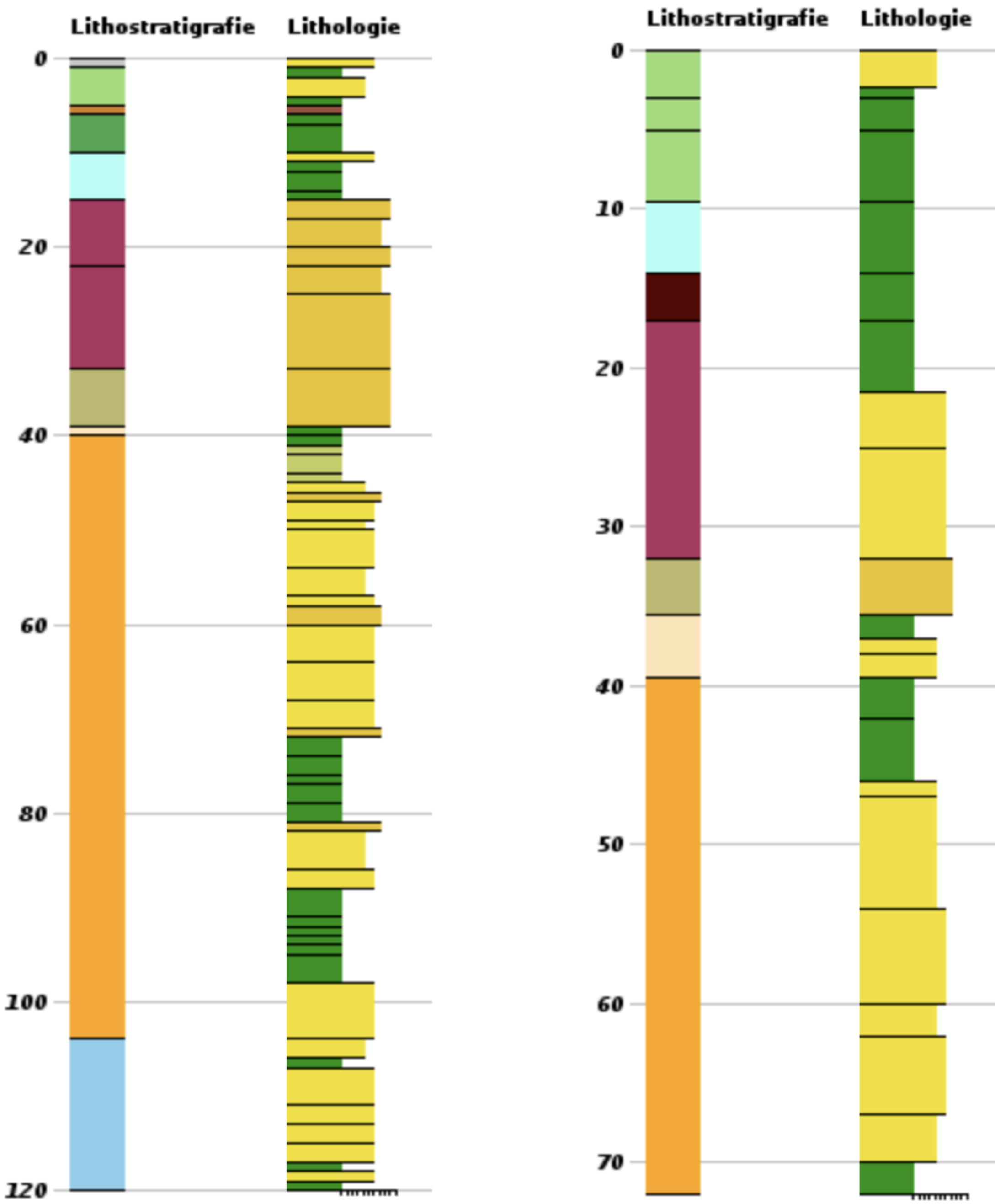

Figure A.1: Well B37E0581 and B37E0583, retrieved from DINOloket, https://www.dinoloket.nl/ondergrondgegevens

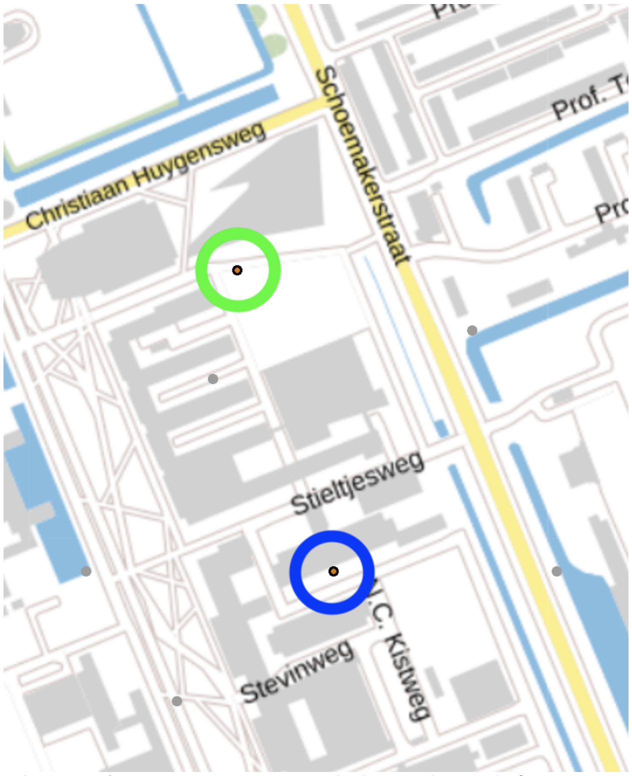

Figure A.2: Location Boreholes, adjusted from DINOloket, https://www.dinoloket.nl/ondergrondgegevens

Figure A.2 shows the location of the boreholes in Delft. Well B37E0581 is located at the green spot and well B37E0583 at the blue spot.