Appendix B

Project Thesis Excerpts

The following excerpts are chapters 2, 4, 6 and 7 from Våpenstad [2021]

Contents

Energy Well Systems and Drill Techniques

1.1 Ground Sourced Heat Pumps

A GSHP system is used for heating and cooling and consists of three subsystems: ground loop system, heat pump system, and heat distribution system. The ground loop used for GSHP applications can be either an open loop or a closed loop. In an open loop system generally, the ground water around the well is used as a source for the heat energy. In a closed loop system a Bore hole exchanger (BHE) is used as a linking medium between the ground and heat pump [Sivasakthivel et al., 2015]. This system thus utilizes the stable geothermal ground temperature. Closed loop systems are the most common system in Norway [Norsk Standard, 2012].

1.1.1 Groundwater Heat Pumps / open loop

Speaking to the attendees at a NGU seminar on the 11.11.2021 about groundwater use for heating and cooling, and searching literature this author has not found any settlement issues related to open loop systems in Norway, besides the sinkhole at Papirbredden. However, water sourced /open loop GSHP systems are not that common in Norway. Ramstad [2011] shows that medium to big systems/well parks in good conductive soils, i.e sand or gravel, with stable groundwater-flow are more cost efficient than closed loop well park systems. It is recommended to use open loop rather then closed loop in more coarse grained soil with large depth to bedrock [Veslegard & Simonsen, 2014].

Open loop differs in that it utilizes the heat stored in the water directly and not the heat in the bedrock. Therefore two types of wells are required, production wells to utilize the water temperature, and infiltration wells to dispose of the resultant cooler water (see Figure 1.1). Infiltration wells also maintain the ground water table and therefore it is recommended to be placed to maintain the groundwater level (GWL) in the best manner possible. However not too close to interfere with the production wells' water, because this will cause a thermal short-circuit. Cui et al. [2018] show the effects on settlements long term, for open loop systems considering the particle-deposition effect.

This work will not look at open loop systems in detail, as all the case studies are closed loop systems. However, many of the same problem issues apply here as for closed loop, except for open loop there exists an additional possibility of taking out too much groundwater, reducing pore pressure.

1.1.2 Closed loop

The Closed-loop systems extract heat by vertical or horizontal collectors with the most commonly used being vertically installed borehole heat exchangers (BHEs). The BHEs are tubes of plastic (polyetylene) installed in boreholes. The tube is mostly configured as a double U-tube made of polyethylene [Rybach, 2001].These tubes are labeled collectors. It is filled with an antifreeze fluid or a mixture of antifreeze and water. Antifreeze fluids are often used in Energy wells systems to improve heat extraction [Dalla Santa et al., 2016]. As shown in Figure 1.2 the fluid is pumped in a loop, moving down and accumulating heat form the surrounding bedrock and comes up with a higher temper-

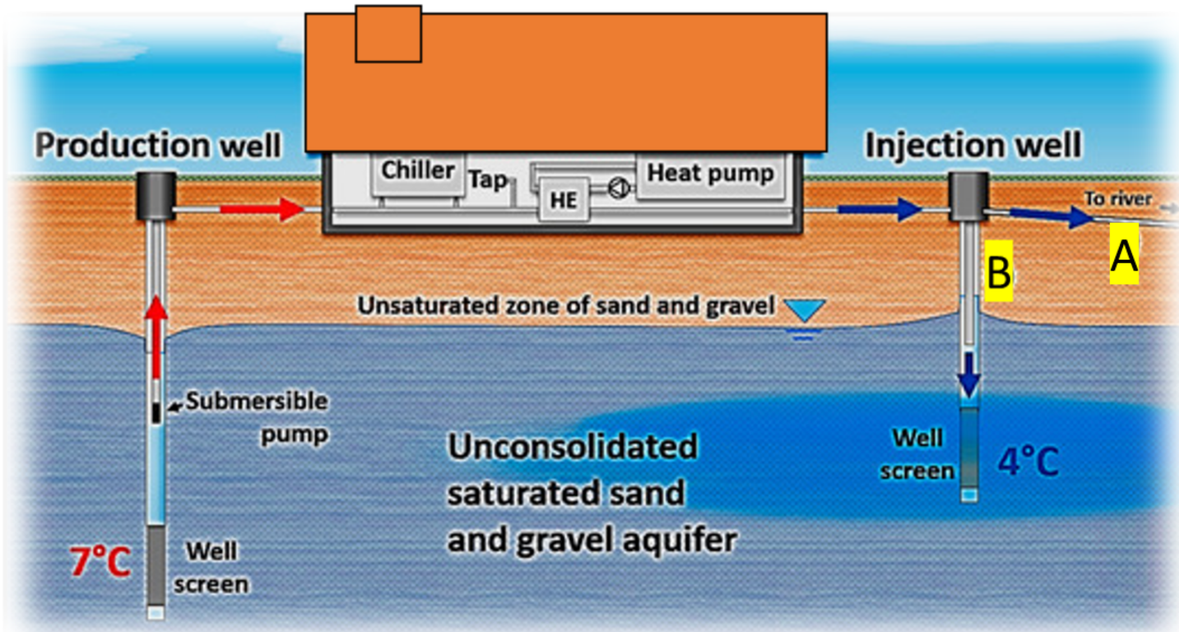

Figure 1.1: Open loop Energy Well. A is configuration using run-off to nearby river/lake. B is configuration using a re-injection well. Modified from Gjengedal et al. [2019]

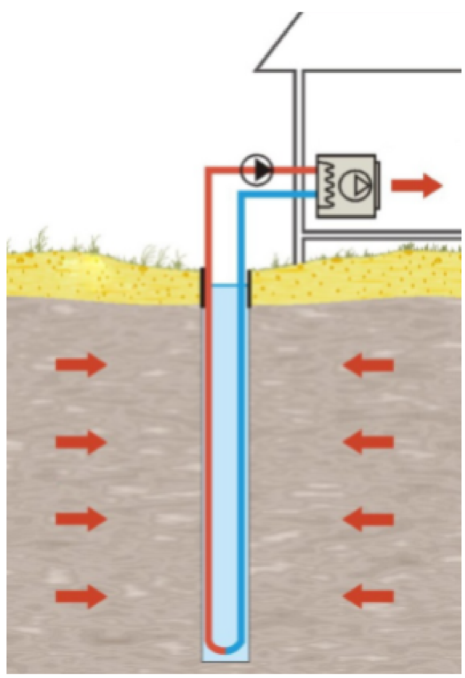

Figure 1.2: Closed loop Energy Well. Taken from NGU [2021]

ature. This is then used by the heat pump (shown inside the house in the figure below) to heat up the building. The resultant cooler water is pumped down and the cycle repeats. While for cooling purposes the heat pump increases the water temperature and lets the bedrock cool it off.
It is shown in Norsk Varmepumpeforening [2019] that typically for residential homes the borehole is between 80-350 m deep with a diameter around 11-14 cm. It is recommended to not be more than 20-50 m to bedrock. A 300 m deep well can give upwards to 10 kW heat depending on the ground conditions. If this does not meet the requirements, more wells are installed. The distance between them, r, must be at least 15 m [Norsk Varmepumpeforening, 2019].

1.1.3 Legal issues

Due to all of the cases in this case study (Chapter 2) being in court or having been settled outside of court, it is important to briefly go through the relevant laws and regulations regarding energy well installation. In most areas, drilling operations after groundwater and energy wells are not subject to an application. However, since 2018 it has been required by law to not act with negligence and not to interfere with the groundwater table (Vannressursloven, 2000, §43a). This legal obligation is also valid when drilling after ground water or for energy wells, both during installation and during production.

> Enhver skal opptre aktsomt for å unngå at grunnvann påvirkes til skade eller ulempe for allmenne eller private interesser
>
> (Vannressursloven, 2000, §43a)

In addition, future tunnels and other groundwork will interfere with existing or future energy wells and are another matter of topic in built up areas (e.g., Gran, 2012 ; Hyvang, 2021). A recent court case in 2018 shows the fact that the coordinates or information in the GRANADA database are not requried to be completely correct [Daler, 2018].

NGU supports Oslo Municipality's recommendation from Cerdeira et al. [2019] to implement a mandatory filing request when drilling after groundwater and geothermal energy wells in areas with marine clay. This will lead to better planning and reducing the risk for damaging or otherwise negatively affecting the groundwater table [Beer & Dagestad, 2020]. There are also other insentives to improve the current judicial regulations [Winge & Kvam, 2018]. In Oslo Municipality there is a regulation that requires that any installation of more than two Energy wells must first have an application submitted for approval. In addition to that, the Municipality since 2020 requires a geotechnical assessment for such projects, most likely due to the Tøyenhus/Engelsborg case (e.g., Hyvang, 2021; Iglebæk, 2021). It is usually the building lot owner that has the responsibility for the ground conditions [Veslegard & Simonsen, 2014].

1.2 Drill Techniques

Mud rotary drilling is applicable in fine-grained soils such as clay, silt and unconsolidated sediments [Veslegard & Simonsen, 2014]. This technique is used in Norway for clay, where it is effective in removing clay cohesion on the drill string wall. However, it experiences low performance in harder layers as for example moraine and bedrock. Hence, it is rarely used for GSHP system borehole drilling in Norway [Veslegard & Simonsen, 2014].

On the other hand, Percussion drilling techniques are common in Norway. Percussion drilling techniques utilize energy from a percussive hammer to strike the formation. There are two types of percussion drilling: The top hammer and down-the-hole (DTH) hammer techniques. In top hammer drilling, the hammer is located at surface on the drilling rig at terrain height. Strike energy from the hammer is transferred through the whole length of the drill string down to the drill bit at the end. The hammering of the formation produces cuttings that are transported up by a circulating fluid or compressed air. Because the strike energy has to travel through the entire drill string, the effective energy striking the formation is limited. Thus, drilling depth and borehole diameter is restricted [Veslegard & Simonsen, 2014]. Comparatively the DTH technique is not limited. THe DTH hammer is a machine lowered to the current bottom of the borehole making a direct transferal of strike energy to the drill bit, much more energy effective. DTH hammer drilling is favorable in hard rock and hard, cohesive soils.

1.2.1 The borehole installation procedure for closed loop

The NS 3056 [Norsk Standard, 2012] sets the requirements for drilled wells in rock for water supply and energy purposes. The casing through soils is often steel, but could be out of plastic in the future. The casing is a pipe with a larger diameter than the drill string. It is placed outside the drill string to prevent loose formations from caving in. Casing is expensive and is often the major cost of drilling the borehole. The casing is to continue at least 2 m into the bedrock per the regulation in NS 3056:2012 [Norsk Standard, 2012]. Grouting injected into the upper part of the bedrock is recommended when there is a risk for eventual change in groundwater level or pollution of the water ([Veslegard & Simonsen, 2014] and Norsk Standard [2012]).

See Figure 1.3 for the transition between the soil layer and bedrock. This transition is sealed with a mix of bentonite and or concrete. After the casing is set, a test to check for leaks is then carried out [Norsk Standard, 2012]. A conventional drillstring down the borehole (DTH) is used further down past the plug into bedrock, to reach the required depth for the BHE. Standard DTH hammer drilling equipment uses a crown diameter of d 115 mm or d 140 mm, d being pipe diameter.

1.2.2 Odex

Eccentric overburden drilling systems are widely used for drilling of soils in Norway (H. Grandetrø [Project manager Båsum Boring], personal communication, September, 2021). The ODEX system consits of a pilot bit and a wing acting as a reamer [Atlas Copco, 2008]. Standard Odex dimensions are Ø139.7 x 4 mm or Ø168.3 x 4.5 mm [Veslegard & Simonsen, 2014].

The wing folds out by rotating the drill string and retracts by reversing the rotation as shown in Figure 1.3 1 and 2. During downward drilling, the wing creates a hole wide enough for the required casing diameter. When drilling has reached a sufficient depth (2 meters or more into bedrock), the drill bit is pulled upward by reverse rotation, and a sealing mixture is added to secure the casing-bedrock sealment as shown in Figure 1.3 3. Veslegard and Simonsen [2014] show that there are several examples (Helleland Bruer) of uncareful drilling with pressurized air that have created large air pockets where there was previously soil. Also noted were large pools of disturbed quick clay that over time will consolidate resulting in volume-loss, the effect of which was not registered.

Different drill methods are shown in Table 1.1

1.2.3 Ring bit concentric system

This system is also called a reversible sinkhammer system and consists of a ring bit and a pilot bit. A figure is provided in Figure 1.4. This system is recommended to be used in in rock formations with ovals and fractures present [MAXDRILL ROCK TOOLS CO., LTD, Unknown]. The ring bit has a larger diameter, d, than the pilot bit. Typically, the ring bit diameter is 15 - 20 mm larger than the casing diameter. The two bits are screwed together, and can be loosened by reverse-rotation. Drilling is done with the two bits coupled together. The ring bit provides space to thread around the casing and when the casing has reached a sufficient depth, reverse rotation releases the pilot bit and the ring bit stays in the hole. The pilot bit continues downward for further drilling. The method demands a lower torque than eccentric systems, and is therefore favorable in large diameter boreholes [Veslegard & Simonsen, 2014]. Also, drilling takes place in one operation which gives a straighter borehole and better drilling rates in bedrock. A disadvantage is the loss of the ring bit [Veslegard & Simonsen, 2014]. However, there exists systems that have a retrievable ring bit [MAXDRILL ROCK TOOLS CO., LTD, Unknown].

Table 1.1: Drill methods based on Veslegard and Simonsen [2014]

Modes	Advantages	Disadvantages
Top hammer	No drop in ground water level Only waterpressure flushing Tight borecrown ensures no risk that air wil escape to the soil medium	Limited depth 30-50 m Diameter 90-140 mm Boreholediviancy caused by hammerblows upwards Suseptible to ground movements along slid surfaces in rock
DTH, air	Great depths 50-100 m Same energy independent of depth Hammerblows give little borehole deviancy Ringcrown disturbs little while providing full cross-section	Waterlevel sinks to hammer Odex can give skrens Odex erodes due to borecrown located in front of casing
Pressurized Water/ Mud rotary	Affects little the formation Well suited for homoheneous and soft clays	Limited diameter Cannot bore in hard rocks
Revesible, with polymer	Polymer makes sealed layers on the outside of casing and in front of borestring	Price and struggles in hard mediums
Ring bit concentric system	Rotates air into borestring	Sealment of small channels in borecrown Price
Wassara (Water driven DTH)	Good in sensitive clays	High water demand

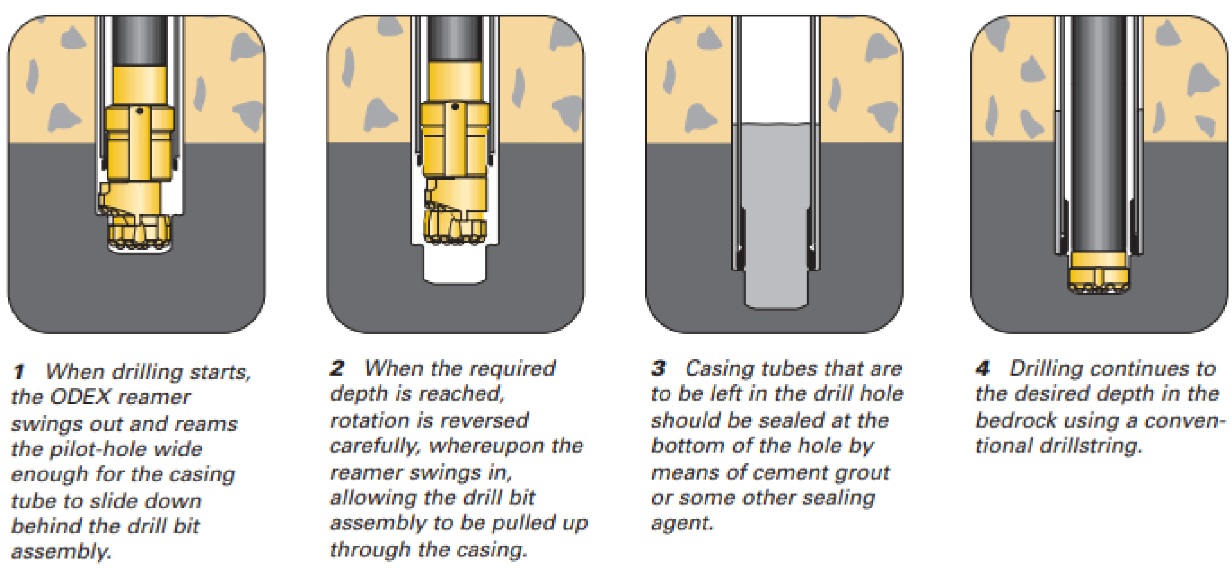

Figure 1.3: Odex drilling taken from Atlas Copco [2008]

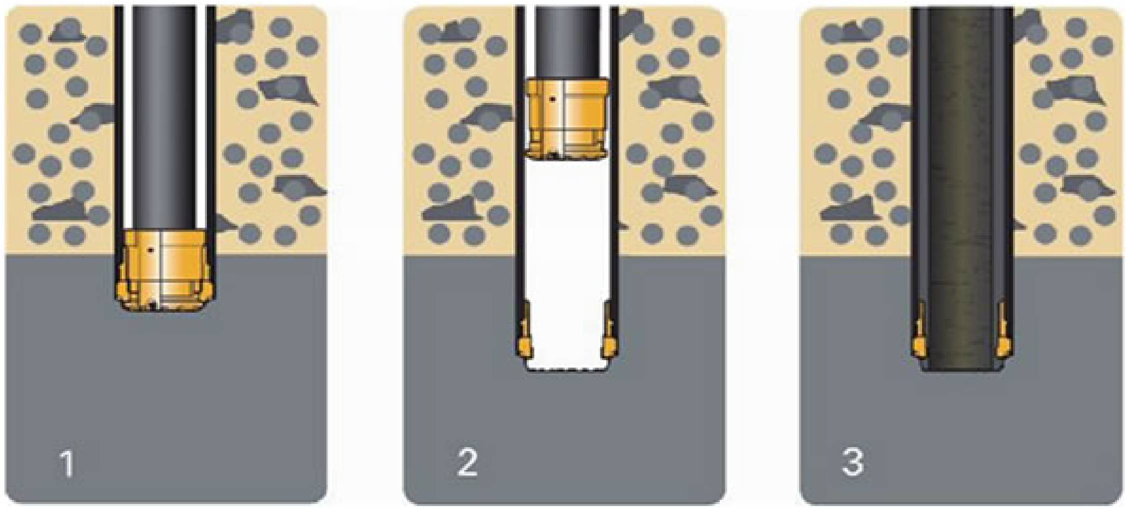

Figure 1.4: Ring Bit Concentric System, Taken from [MAXDRILL ROCK TOOLS CO., LTD, Unknown]. 1. When drilling starts, the pilot bit drive the ring bit down to the hole, followed the casing shoe and casing tube. 2.At the bedrock, start Reverse circulation of tools and pull the pilot bit from the drill hole leaving the ring bit in the hole. 3. Pour the concrete or do the next constructions work.

1.3 Destabilizing effects attributed from Energy well installation

1.3.1 Drilling

Veslegard and Simonsen [2014] are part of the bigger Norwegian research project "BegrensSkade", about risk reduction of groundwork damage, and concluded that: The most important mechanisms that lead to unintended consequences of drilling for pile or tie back anchors are

1. "Overboring", i.e more volume extracted than the volume of the borehole.
2. Disturbance of the clay following after consolidation/volume loss in the drilled clay.
3. Reduction of pore pressure following after consolidation of settlements.

The second mechanism is especially true for quick clay. While most piles and tie back anchors are bigger in size than energy well boreholes, the same issues most likely apply. Settlements caused by pore pressure reduction and consolidation as a consequence of drainage and or leakage up through bored piles and anchors, is pretty easily calculated on account of conventional consolidation theory if pore reduction is known or can be estimated and that the clay settlement parameters are well defined. Settlements as a consequence of a given pore pressure reduction, is clearly highest if the over consolidation ratio (OCR) is low and approaching 1.0. This can be the case in filled-in areas.

The effect of boring in the form of over-boring on settlements and disturbance/reconsolidation can be significant, but is harder to estimate. The effect is both strongly dependent on soil condition, drill method and the operator of the drilling rig. The potential for both over-boring and disturbance of the clay around a borehole increases with increasing sensitivity. This can give grave consequences if one is not careful when drilling [Veslegard & Simonsen, 2014]. Sensitivity is defined as the ratio between shear strength $S_{undrained}$ and remoulded/stirred shear strength S_{ur} of the soil: $S = \frac{S_u}{S_{ur}}$.
Horizontal displacements can be linked primarily to shear deformations in clay and be calculated with element

method based programs and available soil models, depending on whether the clay strength and stiffness is known with a satisfying reliability. It is shown in Veslegard and Simonsen [2014] that if one experiences flushing / material loss in thick layers of silt and or sandy masses in the transition between clay and rock, the potential for pore pressure reduction increases. Also in general if it is silt, sand or gravel rich masses throughout the transition to rock or higher up in the clay deposit. The hazard for DTH air drilling in moraine is notable in [Lande et al., 2020]. Having a lower pressure or using other systems such as Wassara or ring bit systems will mitigate this.

Norsk Standard [2012] discusses the risk after blasting with dynamite of lifting the casing, or causing cracks in the transition zone and or plug. While this is written with groundwater wells in mind (where usually dynamite is applied to give better waterflow though fractures), it will be useful to keep in mind that perhaps other explosions/blasting related to building construction can raise the same issues.

1.3.2 Water expulsion

In 2020, a well in Singsaker had a high risk of triggering a quick clay slide, which could have had disastrous consequences. Artesian water sprung out of the newly created well, but was quickly remedied by drilling a relief well and using a better grout [Beer & Dagestad, 2020].

The Norwegian Road Authority (SVV) report [Gundersen & Haugen, 2021] shows several examples where the grouting sealing was nonexistent or insufficient for geotechnical survey holes. These total sounding boreholes are smaller in diameter (57mm/45mm) than energy well boreholes (110-140 mm) (e.g., Veslegard and Simonsen, 2014; Gundersen and Haugen, 2021). These examples show that no or bad grouting will cause artesian water to escape upwards. Lesser leaks were often sealed with bentonite rods and stakes, but bigger leaks with larger water expulsion needed to be injected with anti-washout additives/substances in order to seal the leaks permanently at the waterbearing/leaking layer [Gundersen & Haugen, 2021].

The aforementioned report was a response to cases in Grønlia, Fredrikstad next to the "planned" train Intercity rail-station. Here there can be observed a band of settlements when looking at the area in InSAR. Old geotechnical survey boreholes were leaking out water for many years [Gundersen, 2018]. Long term, in addition to surface water, the pore pressure will be reduced leading to higher effective stress and settlements. Leaking boreholes due to bad or no grouting will lead to water working itself upwards into new soil layers or breaking through to the surface. No grouting was used in many of these boreholes. The report concludes that lack of grouting was irresponsible [Gundersen, 2018]. See figure 2 and 3 in Gundersen and Haugen [2021] and figure 4-17 in Baardvik et al. [2016] for possible mitigation measures.

1.4 Destabilizing effects caused by Energy well operation

1.4.1 Freeze-thaw

If the amount of extracted heat is so much that the water around the well reaches a temperature below zero, a freezing process occurs in the water bearing soil. This may be caused by incorrect dimensioning or an overuse of the system, where by too much heat is extracted out of too few wells. Successive freeze and thaw processes will negatively impact the well stability, even damaging the well in extreme cases and leads to settlements. The higher the water content in the soil, the bigger the effect. In the Benterud shcool, Lørenskog, old energy wells created sinkholes due to too much heat-extraction, i.e., going over the intended design and capacity for the energy wells. The energy effect did not equal the energy demand (L. Isaksen [Project manager at Rototec], personal communication, December 14, 2021).

Zymnis and Whittle [2021] presents a model for long term operation of BHEs, i.e over a time period from 10 to 50 years. Their model on a hypothetical site show that settlements are critically related to the stress history of clay, i.e OCR and to the heat exchange. This article is based on Zymnis' PhD from 2016 and provides figures to easily design systems to fit in the designated design space. The study shows significant settlements long term (10-50 years), especially for normal consolidated (NC) clay.

While soils get more hydraulic conductive due to freeze - thaw, this is a long term settlement issue [Dalla Santa et al., 2016]. It is important to assess a minimum temperature threshold for the BHE brines as lowering the working temperature could induce freezing–thawing cycles in the ground.

It is shown (e.g., see Dalla Santa et al., 2016) that the temperature alterations affects the vertical deformability of cohesive sediments. The results show that the irreversible compaction effect induced on sediments, increases with higher salinity concentration, despite the fact that increasing the salt content lowers the sediment freezing point, thereby protecting the soil from freezing processes. Further laboratory tests performed by Dalla Santa et al. [2019] show that the hydraulic conductivity, k, increases of about eight times in normal consolidated clayey sediments due to successive freeze thaw processes.

Case Studies

Three case studies are presented here, one in Sandefjord and two in Oslo. Additional pictures and InSAR data are in the appendix. InSAR data is taken from https://insar.ngu.no/, November 2021.

2.1 Case 1, Sandefjord

Figure 2.1: Left is NGU's soil and GRANADA map on the right. Grey is fill material. Left corner shows bedrock at surface. Yellow denotes the waterpressure measuring wells, blue energy wells. [GRANADA, 2021] ; https://insar.ngu.no/

Hans Amundsens gate 5 and 10 demanded compensation from Hans Amundsens gate 7 in a recent court case finished in November 2021, due to ground settlement induced damage on their houses. Hans Amundsens gate 7 installed the singular Energy well and with the drill company are the defendants in the lawsuit. The court found the well not be the cause of settlements, due to insufficient evidence to prove otherwise. The case has since been appealed. While the technical reports are not provided by the court, the ruling document [Vestfold Tingrett, 2021] is. There are multiple geologist and geotechnical companies involved with their technical reports and or witness statements. In addition, a geotechnical investigation was done, with both pore pressure measurements (by Pizeometer) and total sounding tests, shown in Figure 2.2. The pore pressure decrease was agreed to be the cause of the settlements, but what caused the pore pressure drawdown was however a matter of debate. While the cause could be the Energy well (installed in December 2016), the nearby water and sewage works (W & S) had excavation and blasting done, and was also done around the same time period, 2016-2017. Hans Amundsens Gate 10 is surveyed with "omfattende skade" (extensive damage) by an appraiser/civil engineer. Deemed practically impossible to fix,

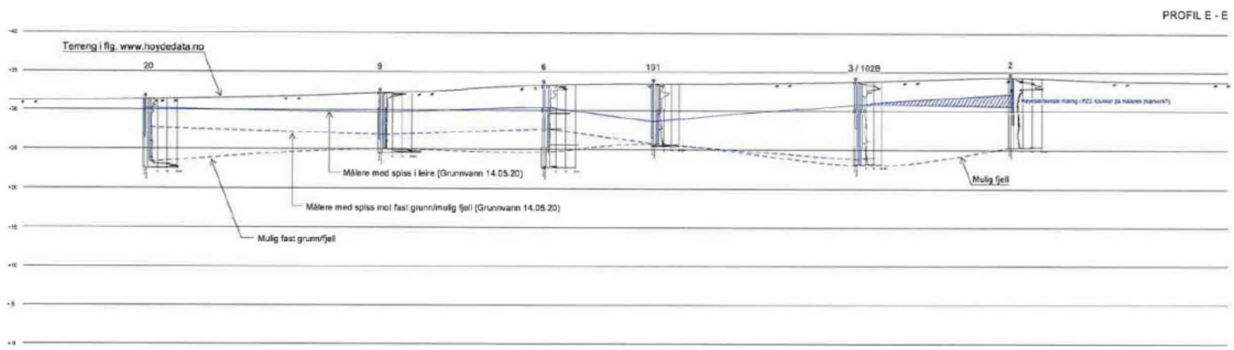

Figure 2.2: Energy well is next to the 101 pizeometer. Ground level in black, water level in blue and total sounding tests shown. Taken from Statsforvalteren i Oslo og Viken [2020]

a new house is recommended be built, with a price tag of around 10 million NOK in total. [Vestfold Tingrett, 2021] Fill material is shown in the NGU soil chart Figure 2.1 for the area. Since this is a fill material it likely is normal consolidated (NC) or has a low OCR, but this is just an assumption.

A quick clay layer is found between 8-10 m down. Depth to bedrock is varying in the area from 1.5m to 17m [Vestfold Tingrett, 2021] .
Weakness zone possibly to the west of the energy well, east of the hill of partly exposed rock indicated by topographical maps. The exposed rock is also visible in the left corner of Figure 2.1. An on site investigation showed the steepness of the bedrock outcrop increasing rapidly on its' eastern slope Figure B.2. The area of Sandefjord is an "ekser" (ridge) landscape with faultlines and deep erosion. Glacial scrubbing of the weathered material has since reduced the depth to bedrock [Olesen et al., 2007].

The (W & S) works where done in the surrounding area, mostly west and north east of the energy well, in the period February 2016-2018 in intervals. Blasting is mentioned for the April to May 2017 period to the northeast, but also groundwater lowering due to excavation can be a factor. It was described as "far away" (more than 100 m) by one witness who added that there is a rock boulder in between the works and the houses in question. In addition he said that there where dry conditions after blasting. Most of the witnesses, but not all, said that the (W & S) work was not the cause. A witness described his house being "shook" by the (W & S) work. Registered data shows vibrations within the acceptable limits [Vestfold Tingrett, 2021]. One well was drilled and installed in December 2016 to 200 m depth in Hans Amundsens gate 7. 9 m to bedrock was registered. A test to see if the casing between the soil and bedrock was sealed was not documented, but was claimed to have been done, as is regulated in NS 3056 Norsk Standard, 2012. The NS 3056 standard about drilling procedure/technique was followed as far as it was possible as per the drilling company. Visible signs of settlement months later for Hans Amundsens gate 10, shown in Figure 2.3. Bolts and measuring equipment installed in October 2017. A max measured total deformation of 110 mm for the northwest corner. Last measurement was done in July 2021 and it shows no signs of stopping. It is the same case but less severe (18mm) for Hans Amundsens gate 5 and multiple other neighbors have voiced concern, but not done any measurements. Hans Amundsens gate 5 noticed the settlement in May / June 2017. Hans Amundsens gate 5 has less settlements due to having more hydraulic conductive materials with less settlement potential under its foundation than clay, Vestfold Tingrett, 2021. Here the geotechnicial reports say the settlements will subside.

Hans Amundsens gate 7 noticed settlements in August 2019. A Surveyor experienced a 2.5-3 cm deformation, but said it was the Water and Sewage pipe (W & S)works that was at fault. A subsequent claim was raised against the municipality but was declined and the owners of Hans Amundsens gate 7 has given up to pursue this claim. A witness from Leikvollgata 39 noticed settlements around his house in June 2017. [Vestfold Tingrett, 2021]. InSAR data shows around 2cm /year Figure 2.1, but it varies see Figure 2.1. Total sounding tests and pore pressure measurements were done in several boreholes. The parties agree that an increase in seepage of water down to bedrock

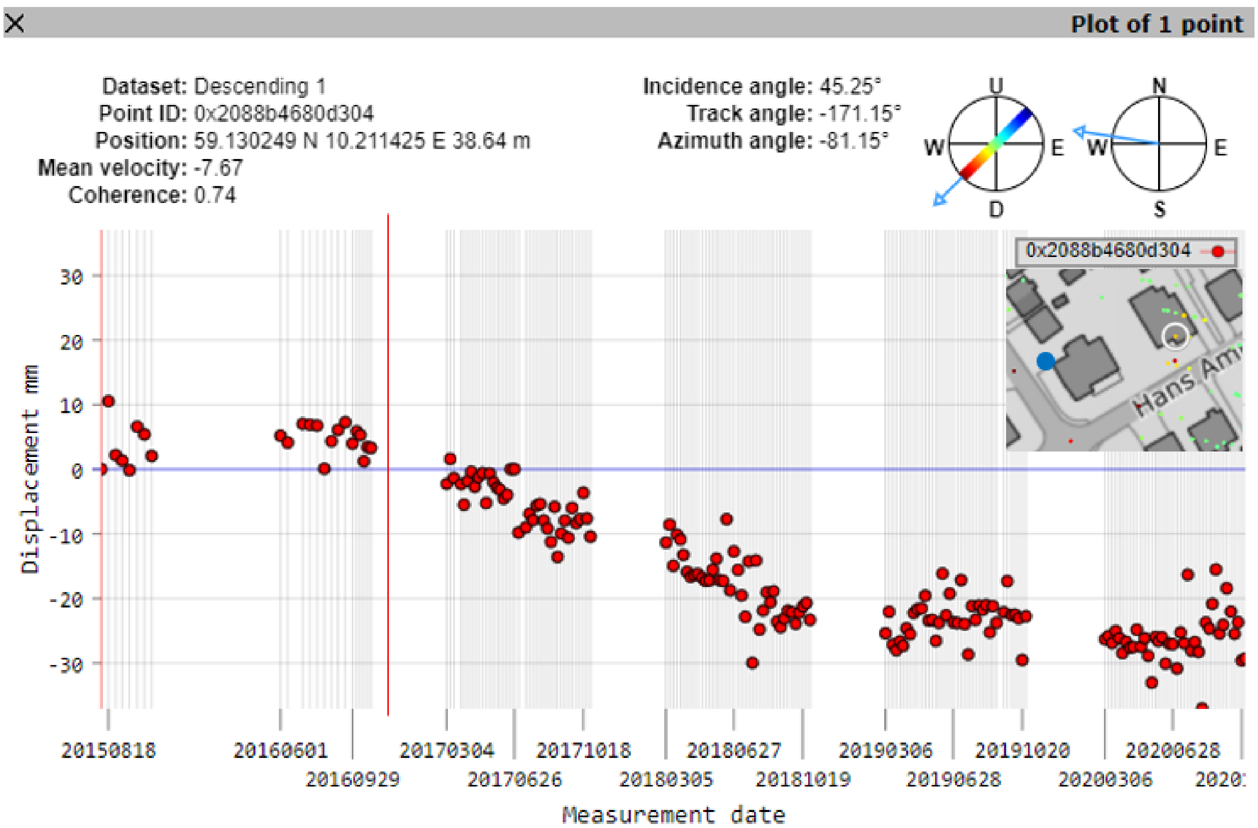

Figure 2.3: Deformation vs time for Hans Amundsens Gate 10. Red line is installation date 12.2016. Modified from https://insar.ngu.no/

is the cause of the settlements, but disagree about whether or not the energy well is to blame. Several expert witnesses agree that there is a leakage in the bedrock that drains the water in the soil next to the well down to the bedrock reducing the pore pressure, see Figure 2.2. Hydro-static pore pressure is not the same as the measured pore pressure in other words. While a video inspection and seepage test showed little signs of water on the inside of the casing, it was inconclusive to determine whether or not the well was sealed properly. For instance, there could be no groundwater outside the casing just for this period in time. A "mansjett" test of the plug was recommended as the only sure way to know whether or not it was sealed properly Vestfold Tingrett, 2021. Signs of ravine/weakness zone can indicate large variations in levels to the bedrock as seen in this case, which could explain why the InSAR data shows higher settlements in between the well and the hill see Figure 2.1 One theory by the suers is that it is a possibility that the drilling induced the hanging/perched watertable to seep downwards through new fractures in rock or through the borehole itself, Vestfold Tingrett, 2021. As the case has been appealed, a final verdict is not yet clear as of the date of writing.

2.2 Case 2, Tøyenhus/Engelsborg

This is a court case due to start in August 2022 and is possibly the reason why Oslo municipality mandated in 2020 stricter rules for energy well drillings. There were no other known construction works in that period, yet settlements were experienced in a neighbouring housing association Tøyenhus after the installation of 36 wells in Engelsborg housing association. In October 2019 after the well installations in February the same year, Tøyenhus said they experienced 6-10 cm settlements in a letter to Oslo municipality. However the housing association of Engelsborg and the drilling company did not find any signs of settlement and are defending themselves saying that they did their job correctly ([Haugen & Hjelme, 2019] and [Statsforvalteren i Oslo og Viken, 2020]). Relevant documents were gathered through case files available from Oslo Planning and building services website, and are publicly available.

2.2.1 Engelsborg well Park

The geological profile of geotechnical reports in the area are as follows. The soils are of filled material for the first 1 -2 m, with varying depth to bedrock. Where there is a large depth to bedrock it is dry crust in the second layer under the fill material, with stiff clay to a depth of 5 m. After 5 m there is soft/wet clay to bedrock. In several reports the clay is described as quick. NADAG reports 5165, 5177 (included in Appendix C) 5163. 5177 has soil-samples from under Tøyenhus. Normal consolidated clay indicated. Also comments about that the bedrock has alum shale and limestone shales in NADAG 1771. This fits well with the Granada comment for Helgesens gate 76 [GRANADA, 2021]. However, it should be noted that limestone shale is not the same as limestone rock. Ground water level around 2-2.5 m under terrain. Hard to assess if it exists a weakness zone or not by looking at topographical maps. A possible weaknesszone to the southeast under Finnmarksgata and/or under Sarsgate/Trondheimsveien.

36 energy wells were installed in February 2019, see Figure 2.6 They are called the Sars's gate 78 well park in GRANADA and are located within the Engelsborg housing association. Here the distance between the wells are 5-10 m [GRANADA, 2021]. Do note that the map in GRANADA only shows the approximate location. Measured groundwater level in the boreholes was lower than the original groundwater level according to the geotechnical report issued in November 2019. From a 2-2.5 m on the outside, to a 10-28 m depth to water in the borehole based on the installed borehole logs [Haugen & Hjelme, 2019] (page 6). This is a significant hydraulic potensial, but it is unknown how long time this lower water level is recorded for. There are multiple visual deformations in the building, and there has been relaying of the pavement next to Engelsborg/Tøyenhus. [Haugen & Hjelme, 2019] and [Statsforvalteren i Oslo og Viken, 2020]. Big variation in depth to bedrock registered in Granada for the boreholes. Some wells have as low as 3 m to bedrock, others have it up to 25m.

In GRANADA the casing-pipe length is different (it is shorter) here than the depth to bedrock. Likely just a registration error. In [Haugen & Hjelme, 2019] it is noted that the casing was put 2-3 m into bedrock. It also notes

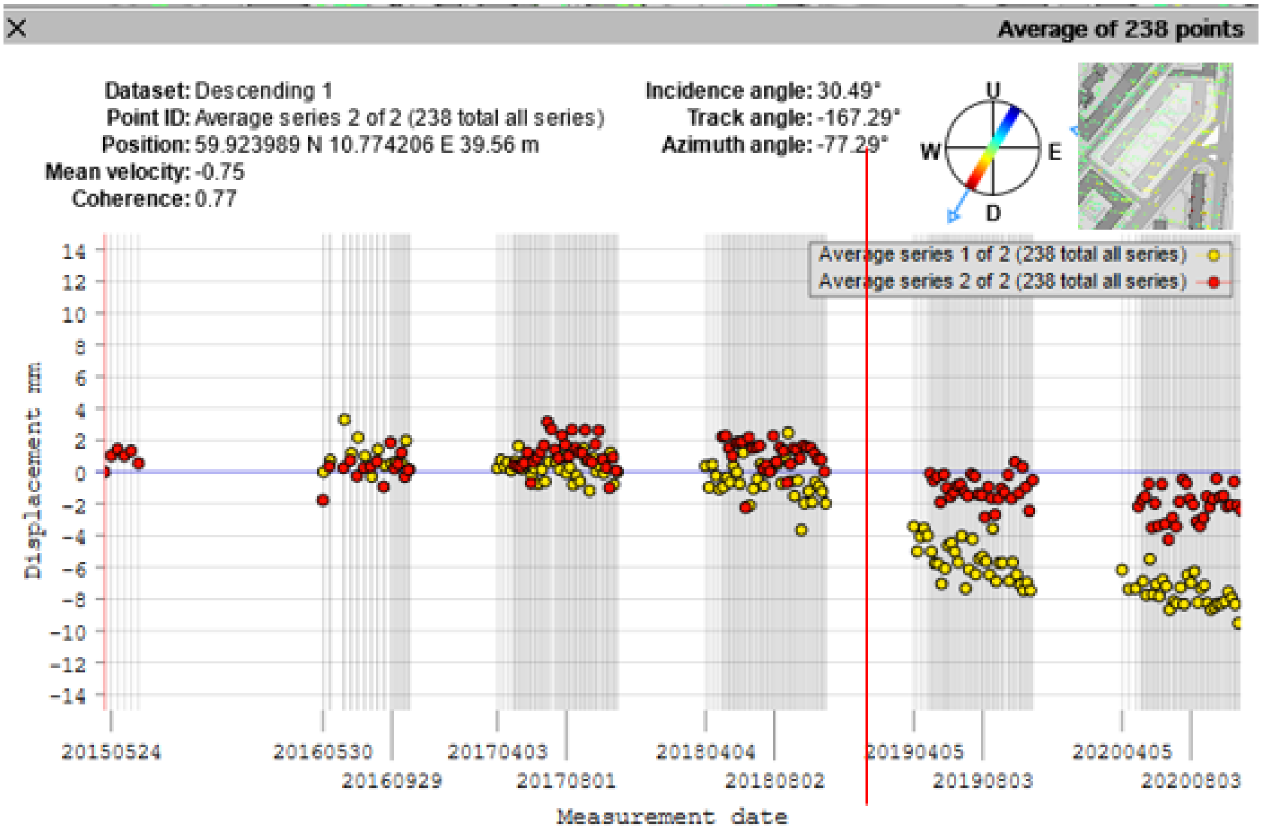

Figure 2.4: Engelsborg. Red line is 36 wells installed 02.2019. Modifed from https://insar.ngu.no/

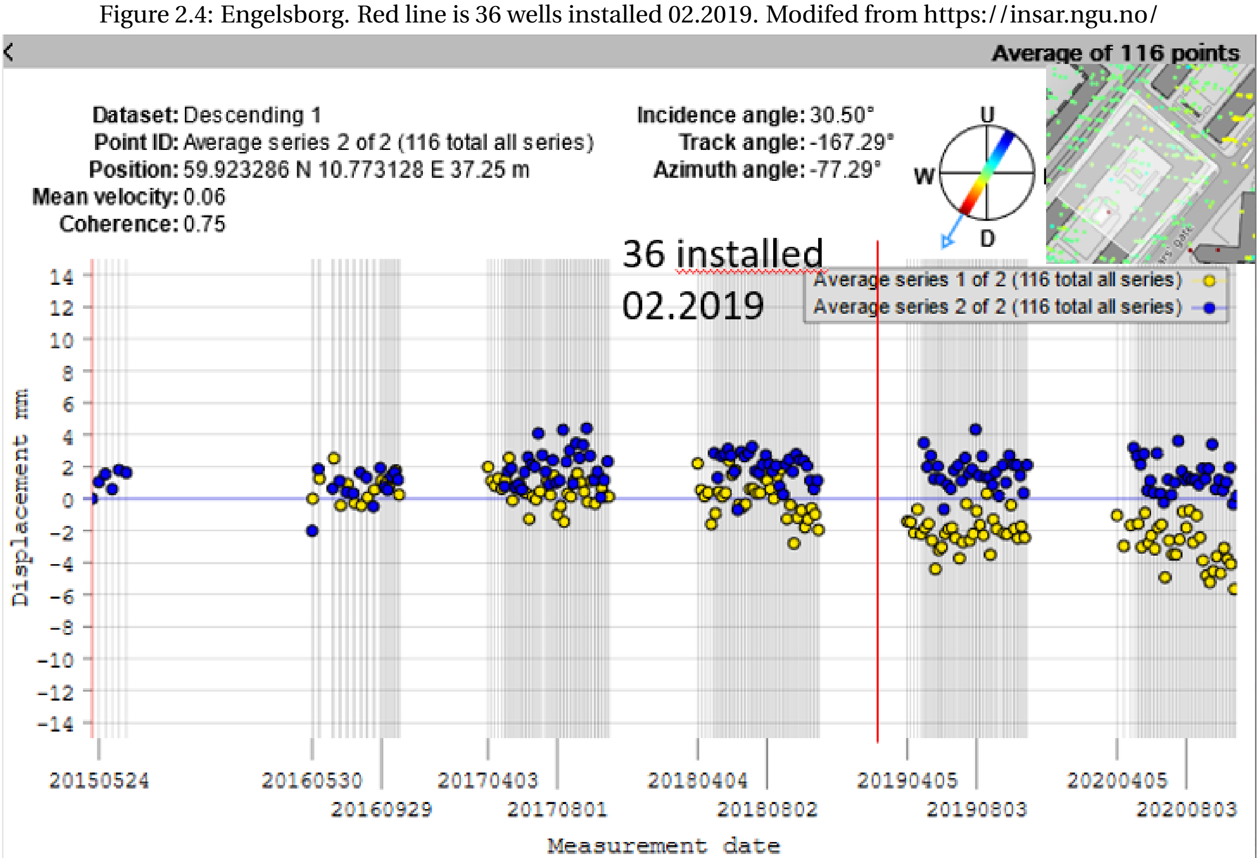

Figure 2.5: Tøyenhus. Red line is 36 wells installed 02.2019. Modified from https://insar.ngu.no/

that the alum and limestone shale was likely broken up to the degree that the pore pressure decreased after boring due to increased seepage to rock. The aforementioned report also comments they should have used better drill methods and references [Veslegard & Simonsen, 2014]. A better method should have been used, arguing that they likely used air as a flushing medium.The combination of air under pressure and quick clay (an highly sensitive clay) poses a risk for overboring and disturbance of clay around bore-crown and casing. It has been suggested that further data measurements should be carried out using piezometer readings along Solhauggata, between Tøyenhus and Engelsborg. [Haugen & Hjelme, 2019] In Statsforvalteren i Oslo og Viken [2020] the drilling company defends themselves saying: They did all that was required of them and based on risk analysis and previous well installation in the area no significant risks were noted. Challenges exist for the Oslo area but this rather demands good drill methods. DTH method was used and the Normbrunn 16-standard was used. The drilling company refutes that they should have used better methods and that they use centric ringcrowns and grouting? with reduced air pressure where necessary. Drilling through quick clay is done by pressing the casing through the soil and thus reducing the need for pressurized air. Such methods keep the clay minimally disturbed. [Statsforvalteren i Oslo og Viken, 2020].

Multiple other well parks are close by in the area, see Figure 2.6 and will be discussed below.

Helgesens Gate 58

Helgesens Gate 58. Marked as D in Figure 2.6. 400 m to Engelsborg, with 3 wells drilled in 08 2020 with tubex mentioned in GRANADA. 3 wells at 3.5 m, 7.5 m and 13.5 m depths to bedrock. Note that this is a large variation for just three wells placed 13-17 m apart. Composite cap for tightening between casing and collector [GRANADA, 2021] The occupants in Karlstadgata 4 in the immediate vicinity (30-40 m) of the wells, had to evacuate due to settlement issues in October 2021. see Figure B.5. They were quickly allowed to come back after an engineer deemed the house safe [Hagfors et al., 2021]. The newest InSAR data show no vertical settlements see Figure B.4. Horizontal displacements can possibly happen due to excavation pits [Veslegard & Simonsen, 2014]. InSAR shows only vertical settlements. A sudden horisontal shift can possibly go without registering. InSAR does show some indication by azimuth (the two "compasses") in Figure B.4. Quick clay and clay indicated in the geotechnical reports nearby, NADAG 5165, 5177, 5163 and 5177.

Helgesens Gate 76

This wellpark marked as C in Figure 2.6 is close (200 m) to Engelsborg. This area has a very good geotechnical report, NADAG 5212 (provided by Oslo Planning and building services), for the same location as the energy well park at Helgesens gate 76. The report indicates varying depths to bedrock (10-14 m). Quick clay from 8 or 9 m to 11-12 m. In report 5212 they label the quick clay as remoulded at depth 11. Clay with gravel or sand in the soil/rock transition. Alum and limestone shale described in GRANADA as the bedrock. The report and the drillers comments about soil profile on Granada lines up. Waterbearing layer at 166-171 m depth noted in [GRANADA, 2021].

The 6 wells were installed in 2006 with 10-14 m depth to bedrock. No inSAR data available that early, and between 2008-2016 the inSAR data is less precise as it is now. Casing 1 m into bedrock. This case was referred to by the drilling company for the Tøyenhus/engelsborg 2.2 in [Statsforvalteren i Oslo og Viken, 2020]. They argued that this drilling did not produce any settlements.

The available InSAR data can support this, however there are settlements in the period 2019-today. Worsening to the east, away from the wells in Helgesens gate 76 see Figure 2.7 Neighboring construction project, or as a consequence of Engelsborgs well park are two possible causes.

Other well parks

An 11 well park (Rodeløkka) around 300 m to the north of Tøyenhus was installed in 2014, not included in the Figure 2.6 shows no settlements in InSAR. 2 well parks south of Sofienbergparken have very small signs of settlements if

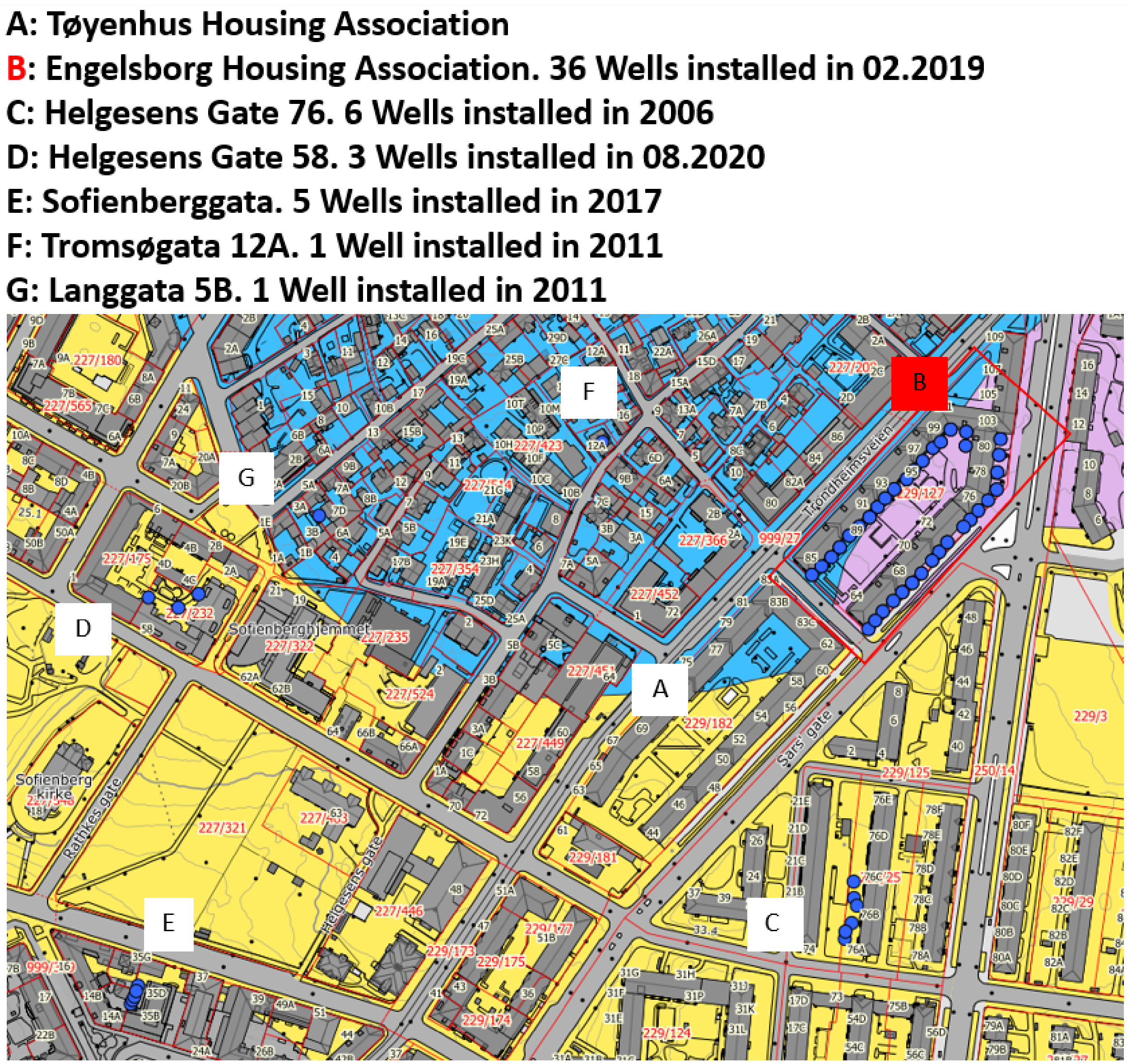

Figure 2.6: Overview of the area, taken from GRANADA [2021]. Yellow denotes alluvial soils, blue marine soils, magenta weathered material/soils and Black fill material. Energy wells shown as blue circles

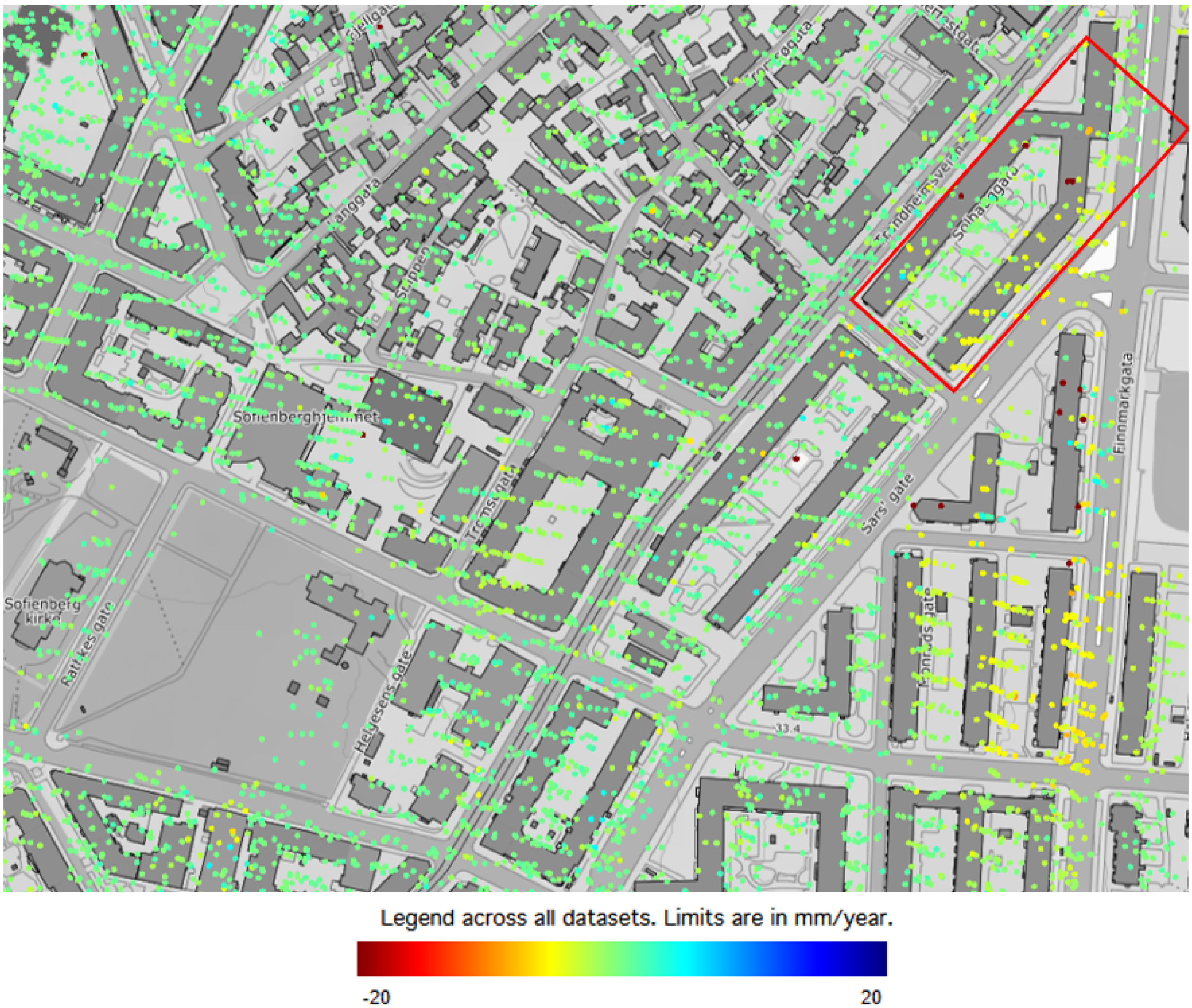

Figure 2.7: Overview of the area in InSAR. Red rectangle showing Engelsborg. Modified from https://insar.ngu.no/

at all. The closest (500 m), see marked as E in Figure 2.6, was installed in April 2017. 4 m to bedrock for all 5 wells registered in GRANADA [GRANADA, 2021]. The other (700 m away) was installed in April 2016 with 16 wells in total. 6-16 m to bedrock registered in GRANADA. There are a few singular energy wells to the northwest, they show no settlements either. The one closest (Marked as F in Figure 2.6) has depth to bedrock 5.4 m and 8 m to water level in GRANADA May 2011. This might indicate seasonal variation of the groundwaterlevel in the area, or that since there are big variations in depth to bedrock, perched groundwater tables. Another possibility is that the groundwater table has been lowered over time since last geotechnical report by better surface water mangement and infratructure. A underground water tunnel is shown in Cerdeira et al., 2019 close-by, north of here.

2.3 Case 3, Sigurds Gate 20

2.3.1 Kampen Well park

This case is a lawsuit that was settled outside of court, therefore no reports or court files are publicly available. Kampen well park is 1.2 km south of Engelsborg, but still in the same alluvial deposit as Tøyenhus/Engelsborg, as shown in Figure 2.9. Sigurds gate 20 had 10 energy wells installed in September/October 2013. They are called Kampen well park in [GRANADA, 2021]. Neighbouring houses and road affected. In 2.8 the neighbouring house (kolstadgata 17) has noticeable settlement issues, with half of the building lowered. The white building (Sigurds gate 20) has only some signs of settlement when comparing the facade and pavement to Kolstadgata 17.

Old geotechnical reports have ground water level at 2,5 m below terrain, NADAG 5057. Quick clay indicated Southwards on Borggata 5 (see page 5 5057) and Jens Bjelkes gate 60 11-12m down NADAG 5112. Varying depth to bedrock (page 4) 5112. First 0-2,5 m layer consisting of hard clay with sand or gravel, with up to 20 m clay below. Between Gruegata and Jens Bjelkes gate (<100m away from Sigurds Gate 20) it is quick-clay indicated at 10-12 m depth. 15-18m depth to bedrock indicated in [GRANADA, 2021].
InSAR data shows settlements, see Figure 2.9. The backyard of Sigurds gate 20 were the wells were installed have been redone and filled in (Ana Golub, Personal communication, October, 2021). The settlements are still visible elsewere. Here the casing is to a lower depth for some of the wells then the depth to bedrock in GRANADA. While for others the same depth is registered. Likely a registration error, when putting the data inn from the drill company's system into GRANADA.

As shown in Figure 2.9 the wells are very close to each other. Most are around 2 m from each other. It must be noted that the map only shows approximately where they are. See Figure 2.10 for kolstadgata 17 amd Figure 2.11 for the neighbouring house to the west. Insardata for Sigurds gate 20 is not included due to a backfill around the well area. However, settlements for the eastern corner of Sigurds Gate 20 is shown in Figure B.6. They show settlements still ongoing.

2.3.2 The nearby Tøyenhus gata 47

3 wells installed in August 2018 (300 m) away from Sigurds gate 20. Foundation and drainage work in the period 2017-2019 done for these three buildings HAB [n.d.], thus the InSAR data is likely due to this. Unable to inspect visually due to work on the facade. Very little information in GRANADA [2021] given by the drilling company with no depth to bedrock registered.

Figure 2.8: Half of the Kolstadgata 17 has facade damage. The white building is Sigurds Gate 20. Personal communication with Jenny Ingeløv October 2021

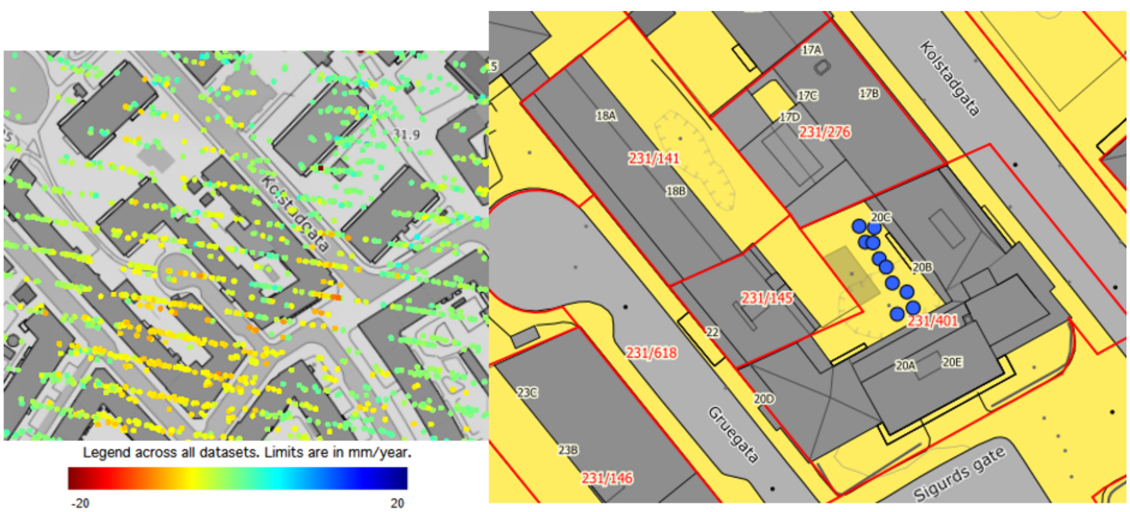

Figure 2.9: Overview of Sigurds gate 20. Taken from https://insar.ngu.no/ on the left, GRANADA [2021] on the right. Yellow in GRANADA is alluvial soils. The picture shown in Figure 2.8 is taken from Kolstadgata, shown in the top middle here.

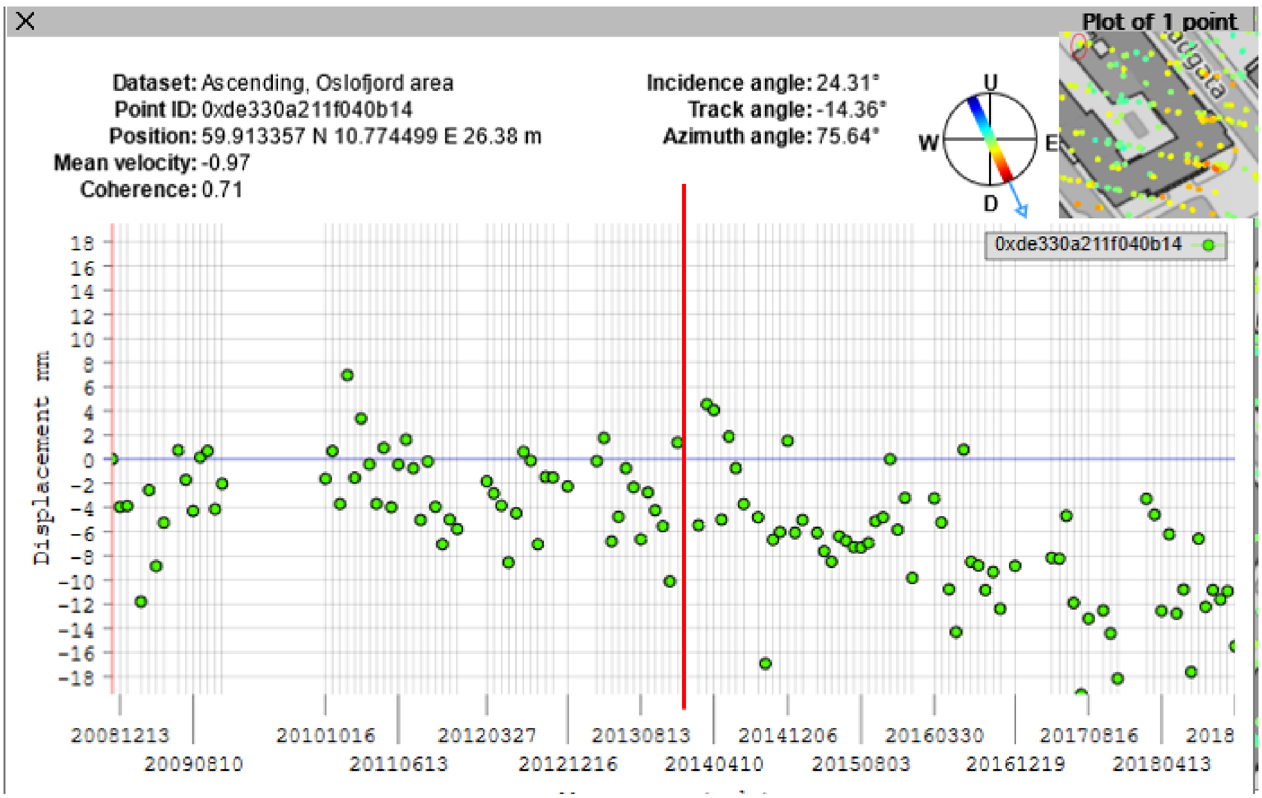

Figure 2.10: Deformation vs time for Kolstadgata 17. Red line is installation date 10.2013. Modified from https://insar.ngu.no/

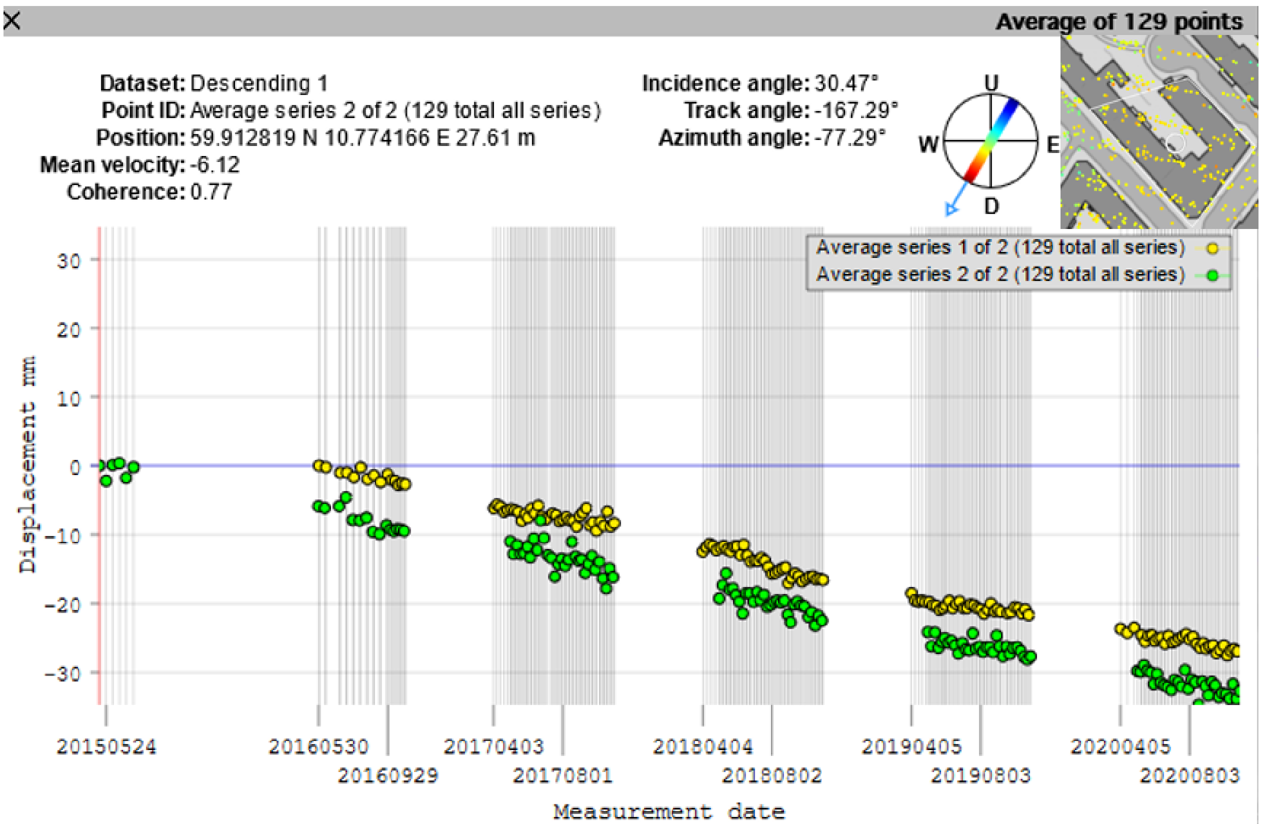

Figure 2.11: Deformation vs time for neibouring block to the west. Sigurds gate 20 is to the far topright. Installation date 10.2013 is not in this plot. Modified from https://insar.ngu.no/

Discussion

Surveys and GRANADA data show that artesian layer puncturing and borehole collapse in rock are the two most common problematic issues for borehole drillers.

The cause for settlements next to energy wells, can be excavation pits, (W & S) works or rehabilitation of old buildings (refoundation or better drainage sytems). In built up areas several construction works can be ongoing simultaneously along with energy well installation, making it hard to prove the cause, as the Sandefjord (2.1) shows. And this was in a low density suburban area, not downtown Oslo. In the Tøyenhus/Engelsborg case, there are no other known building projects however. Another reason for the groundwater level dropping can be due to better pipes and more efficient surface water management/pipesystems, allowing for quicker consolidation processes or lowering of the groundwater table.

The lack of many cases leads to the belief it is not a big problem short term and possibly in the long term too, and that the main Oslo case of Tøyenhus/Engelsborg is possibly either that the drill technique chosen was not optimal, leading to the causes mentioned in Section 2.3 or some local geological dependent phenomenon. It can also be several factors at once. There could be an up-tic in cases related to the topic in the future due to the continued high construction activity in Energy wells and because of increasing public awareness. If more people are familiar with the problems, it would be more often reported, as shown in the Sandefjord case were one neighbour initially suspected the (W & S) works to be the cause. Consolidation processes on clay are long term with possible high consolidation potential, so further professionalization and awareness to use the right method is vitally important. Since 2019 a certificate of the Craft for well drillers has been made available [Daler, 2020]. The Oslo municipality requirement to have a geotechnical assessment for energy well parks could be changed in the future to only be required in areas with either medium to high building density and those that have varying depths to bedrock and soft clay. This could be done when more conclusive research on the topic has been conducted.

3.1 Comparison of Cases

As shown in Table 3.1 quick clay is indicated in all three cases. Other energy wells are close by, but they show minimal to no signs of deformation in InSAR after installation. The variation in depth to bedrock is evident in all three areas, but most notably in the first two and can indicate hydraulic potential differences in perched water situations. These aquifers might be separated by bedrock or other aquitards/aquicludes.

In case 2.2 the well park south of it 2.2.1 did show settlements to the east of it after the Tøyenhus well park was installed. This can either possibly be because the depth to bedrock is higher here, in general, then under Tøyenhus. Again, no other construction work is known in this area. All cases show visible building damage, but vary in InSAR to what degree. As mentioned in section 3.3, differential settlement are much more likely to produce visible cracks. Some buildings in the cases seem to have it worse, going by InSAR data relative to the buildings with reported damage, but can have better foundations. Or overall settlements affecting the whole building will not be as critical as opposed to high incremental settlements. The foundation is unknown in the two latter cases in this work, and the

Table 3.1: Differences and Similarities

Factor:	Case Study and Well installation (year) Sandefjord (2016)	Tøyenhus/Engelsborg (2019)	Sigurds gate 20 (2013)
Number of wells:	1	36	10
Depth to bedrock:	9 m, but 2-17m in the area	5-25 m	15-18 m
Time to visible settlements	Less than a year	Less than a year	No data given
Drill technique	Odex? Not explicity stated	Odex? Not explicity stated	No data given
Quick clay:	Yes	Yes	Yes
Court case:	Yes, no final ruling yet	Yes, set to August 2022	Yes, settled outside of Court
Adjacent wells (<300m):	Yes	Yes several	Yes
with settlements?:	No	No	No
Less than a year to experience visible damage?:	Yes	Yes	Unclear No data given
InSAR settlements after well installation:	10-20 mm/year Even worse to the west	5-10 mm/year but varies	5 mm/year, but varies and backyard filled in
Groundwater table lowered?:	Slightly, but pore pressure reduced	Unknown No data given	No data given
Other construction nearby in the same period?:	Yes Water and sewage	Unlikely, none known	Unlikely, none known
Type of Foundation:	Direct	Unknown	Unknown

foundation and soil underneath the foundation has critically much to say. As in the section 2.1, Hans Amundsens Gate 10 has less settlements then Hans Amundsens 5 due to having a more hydraulic conductive soil underneath its' foundation then nr. 5. This means less consolidation potential in the former even with a direct foundation for both houses.

In our other two cases, they are big, older type brick complexes with possible direct foundation on or without wooden rafting. These are more susceptible then piled foundations of steel to bedrock. It is an limitation in all cases to not know for certain the type of foundation under the affected buildings, but such residential housing as case 2.1 in Norway, uses likely direct concrete slab foundation. Also, pictures from Hans Amundsen gate 5 show a such concrete floor in the basement, with cracks see Figure B.1.

Drilling with airdriven DTH sink hammer has under trials in the Begrens skade project Veslegard and Simonsen [2014] shown significant increase in pore pressure and settlements in comparison with other bore methods. But the drilling company for Engelsborg defends themselves saying they know of this in the Statsforvalteren i Oslo og Viken [2020] and that they followed the Normbrunn 16-standard. It is the same company who drilled both the Oslo cases. Where as the first case (Sandefjord) was done by another one. In the Sandefjord case the drill methods were not discussed in court, only that they followed the NS 3056 standard.

So if bad rock or fractured rock due to drilling is to blame then it is very local since Helgesens gate 76 is only around 200 m from Engelsborg. Another possibility is bad plugs or bad drill technique in the Engelsborg well park. There is also the difference in the well number. 36 for Engelsborg and 6 for Helgesens gate 76. This perhaps lead to much more fractures and therefore more water seepage.

Varying depth to bedrock can lead to differences in settlements i e. differential settlements. With possible NC and wet/saturated clay in Engelsborg and possibly in the Sandefjord case also. The potential for significant settlements therefore is higher.

3.2 Determining the possible cause

The final verdict is yet to be determined in the two first cases, but if the energy wells are the cause, then the settlements have caused damage in the short term and possibly long term also. Most of the InSAR data shows linearly increasing settlements that will only get worse with time.

In table 3.2 it is presented several possibilities. And it could be several failure mechanisms and not just the one. The unavailability of heat-pump data means that Zymnis and Whittle [2021] model might be impossible to use to back calculate the settlements. Water table draw down or reduced pore pressure suggests previously impermeable rock has been fractured, leading to reduced pore pressure as water drains downward through these new fractures.

A risk of settlements by energy wells borehole drilling in depths to bedrock > 25 meters is mentioned in Veslegard and Simonsen [2014]. In the cases it was less than 25 m, see Table 3.1. The report mentions the Wassare drill method, which is a water driven (as opposed to air) DTH method that disturbs the soil less. Not often used in Norway due to the high watervolume required. Grouting of rock is mentioned as a consideration in areas with high fracturing and or bad rock that is dependent on not changing the groundwater level. Having water eroding on the outside of the pipe is also noted in Veslegard and Simonsen [2014] That the settlements are due to the disturbance of quick clay is unlikely as the drilling company defends themselves well, and bore techniques are not even discussed in the Sandefjord case. Similarly the same arguments could be applied to overboring. Artesian water erosion and leakage can be dismissed as there is no mentioning of surface water. For overboring, artesian water expulsion, freeze-thaw and disturbance of quick clay the effects would be highest in the immediate vicinity of the boreholes and decrease with increasing radius away. This does not seem to be the case, but varying depth to bedrock might offset this to some degree.

The settlements were visually noticed in less than a year; 3 months and 8 months in the two cases there is data for. This would suggest that the freeze-thaw processes are not the cause as these are more long term processes before settlements get to be significant. Even though there is possible saline marine sediments and many BHEs in likely NC or low OCR clay. In addition, one can calculate the radius in the BHE array from the GRANADA map in Figure 2.9, it is only in the last case for Sigurds gate 20 that the distance between the boreholes is small (around 2-3 m for most of them), although the map only shows approximate locations of the boreholes. The settlements away from the well park is too high to lend credibility to the Freeze-thaw possibility, as the settlements are highest next to the boreholes as shown by Zymnis and Whittle [2021]. In the Sandefjord case it was only one well. While Freeze-thaw processes are likely not the cause, it might have increased the hydraulic conductivity, easing the water travel downwards.

If the drilling company for the two latter cases in Oslo is to be trusted, then the overboring and quick clay disturbed causes for settlement can be crossed out. They are a big company with many successful projects and do argue their case well in Statsforvalteren i Oslo og Viken [2020]. However, this author has not been provided proper documentation of installation/bore-log. The Sigurds gate 20 case had their backyard filled in, indicating possible bad drill technique, but it is not known to what degree or when. Only that the damage was visible after well installation. This leads to the bedrock fracturing caused by drilling as the main possible cause for the first case. The second and third case has no ground water level measurements during or after well installation and is thus harder to determine the cause for. Another explanation for the pore reduction near bedrock, is that there is a possible moraine layer here. In addition to the higher chance for excess pore pressure due to drilling here, (e.g., Lande et al. [2020]), it will be here the pore pressure reduction is first measured due to its' higher hydraulic conductivity.

Table 3.2: **Possible** Failure Modes/Settlement Causes

	Case Study and Well installation (year)		
Failure Mechanisms	Sandefjord (2016)	Tøyenhus/Engelsborg (2019)	Sigurds gate 20 (2013)
Bedrock layer cracked?	Possibly	Possibly	No data given
Artesian layer punctured?	Not mentioned in Court	Unknown	Unknown
Bad plug?	Unlikely, but Judge in doubt and cannot be dismissed yet	Unknown	Unknown
Overboring?:	Not mentioned in court	Unknown. Not according to the drilling company	Unknown
Freeze/thaw?:	Unlikely	Unlikely	Unlikely
Quick clay disturbed?	Not mentioned in Court	Unknown, drilling Company says no	Unknown

3.3 Fracturing of the Rock under drilling

This is mentioned in the geotechnical report about Tøyenhus/Engelsborg and is a possible cause talked in the Sandefjord case ((Haugen and Hjelme, 2019 and Vestfold Tingrett, 2021).

The plug is done after NS 3056 Norsk Standard [2012], but that the rock is fractured is an alternative theory in the 2.1 Sandefjord case. To elaborate, due to fractured rock with higher water conductivity, the water can drain downwards decreasing the pore pressure [Vestfold Tingrett, 2021]. If this was the case then whether the plug between the casing and bedrock is sealed or not is of less importance, the water travels up or down via these fractures, in this case downwards regardless. There is a possibility that grouting into the fractures should have been used. Haugen and Hjelme [2019] says that the drilling has possibly caused the shale to be much more hydraulic conductive, and causing a drawdown of the ground water level. A similar possibility is discussed in the Sandefjord case Vestfold Tingrett [2021]. A Lugeon test or "mansjett" test might disprove or confirm this possibility.

3.4 Mitigation measures

There seems to be a prevalent line of thinking that an energy well is such a small ground-disturbance, that the geotechnics of the earth surrounding the well would not change in any significant way to cause problems. This might or might not be true and could be different for each well drilled. The outcome of the two court cases is of great interest and will have an impact on how the industry goes forward with regards to changes that could be made to decrease the likelihood of problems associated with new energy wells in the future.

In best case scenarios, the settlements can also be insignificant, due to the masses under the foundation being thin or already drained, leading to almost no settlements. In addition, if the foundation is good (piles to bedrock for example) then the building will probably not experience settlements.

If the energy wells are ruled to be the cause, the NS 3056 and other regulations would most likely need to be updated, as the drillers claim to have followed the regulations.

An in depth investigation to the Tøyenhus/Engelsborg case with finite element modeling could give more answers to wheter or not the over-boring or disturbing of clay was the cause. Odeometer testing etc, would be needed to give the parameters for this aforementioned model. More data by piezometer installation regarding the water-level in Tøyenhus/Engelsborg would also be important to confirm how low the groundwater table level is after well installation and if there is an increased drainage to fractured bedrock.

Making available and sharing the knowledge and experience gained from past incidents with the drill rig operators, so that they are aware of the hazard potential of drilling in wet/soft soils with varying depths to bedrock. New certifications for energy well drillers or having permission to drill being the more drastic measures. Careful to avoid high airpressures during drilling with better procedural regulations. It is advised to show caution when drilling in areas with thick soft clay and varying depths to bedrock that have groundwater level dependacy. When fratures are seen in the bedrock near the end of the casing, a grouting into could be adviced. A pore measurement short term is done as per NS 3056 Norsk Standard [2012], but long term measurement could be done in hazardous areas also. Grouting all the way up to ensure no artesian water leakage in such areas can also be recommended. A risk assessment zone system could be implemented with varying levels of risk in urban areas. This would possibly need mapping of the bedrock to ensure its accuracy. Data gathered for tunnel planning, as shown in (Olesen et al., 2007 and Karlsrud et al., 2003) would be of great help. A quick internet search shows that some Swedish Municipalities have local regulations mandating grouting of energy wells. A look into Swedish experience and regulation would be useful for further work. Although heavy use of grouting in fractured rock in a well park might increase the groundwater level and pose new risks. Putting a sealant / welded lid on the inside of the borehole in the soil to bedrock as (shown in figure 8 in Sveriges geologiska undersökning [2016]) below the plug could be advised to stop the drainage to bedrock via the borehole.

It is also a big difference in how well the data is logged in GRANADA. Some companies do a good job, while others say almost nothing of the ground conditions or how the well was drilled and how far, etc. Keeping the information available is important for other projects in the future, so a better effort on logging is recommended. While it is standard to do a test to see if the plug is sealed, no such test is required long term or even a pore pressure test on the outside of the well. A mandatory use of such tests and / or grouting in groundwater table dependent and built areas could be enacted.

Summary and Recommendations for Further Work

4.1 Summary and Conclusions

The few cases of settlements due to energy wells in Norway can lead to the belief that this is not a big issue in the short term and possibly not in the long term too, and that the cases in Oslo and Sandefjord are the exceptions in the bigger picture. However, there could be an up-tic in cases in the future due to all the recent court cases bringing this to public attention. The case study shows that the wells had other well installations in the vicinity (<300 m) and these did not have settlement issues, showing that it is either the drilling operation and / or that it is something very geologically locally dependent that is the cause. The difficulty/impossibility of getting the technical reports due to that the lawsuits are still ongoing or settled outside of court, hampers the research and must be considered the biggest limitation of this work. There exists possible ground settlement issues related to Geothermal energy wells, but very rarely, and hard to know with certainty. The settlement issues persist, once they happen. The cases lead to visible settlements not long after installation and are still experiencing settlements. The likely presence of quick clay in all the three cases and the role it plays is unknown. Possibly as an additional cause of settlements, but the industry has good procedures to deal with drilling in sensitive clays. If they always use the correct method is perhaps a matter for future work.

In conclusion: The fracturing of the rock under drilling is the leading possibility as the cause of the settlements for the first case in the case study. The two other cases can possibly be due to artesian leakage or fracturing of the bedrock. The resulting loss of pore pressure, the difference in depth to bedrock and presence of soft clays are the main possible factors leading to incremental settlements and damage to the buildings for all cases. However, the final conclusions should not be taken before the final verdicts of the court cases.

The recommendations/mitigation measures may be classified as:

- Choosing the right drill technique.
- Not to puncture artesian layers or fracturing the rock. Surveying the geology by existing maps and avoiding fractures that have been "opened" by drilling, leading away the groundwater. A lowering of groundwater level or/and pore pressure reading lower then the hydrostatic pressure outside the well can indicate that the bedrock has been cracked and leads water away. Lugeon and / or Mansjett tests can possibly verify if this is the case.
- Grouting on the outside of the casing as well as grouting fractured rock and including a welded lid on the inside of the well is recommended in built up areas, or other areas with groundwater level dependency.

- Veslegard and Simonsen [2014] and other Begrens Skade procjects conclusions can be referenced/applied in the geotechnical assessments/reports for energy well projects in Oslo, and more focus on the right drill methods and ensuring that the right drill techniques are followed.

4.2 Recommendations for Further Work

- The use of grouting for energy wells can be looked further into. A mandatory use in groundwater table dependent and built up areas could be enacted. A hazard map can also be mapped.
- With the Tøyenhus/Engelsborg case set in court for August 2022, a review of the geotechnical assessment criteria for energy well parks in Oslo municipality can be done after the rulings conclusions.
- A look into Swedish experience and knowledge surrounding the topic.
- Installation of pizeometers along Solhauggata will be required for further analysis regarding Tøyenhus/Engelsborg.
- A "mansjett" test in the Sandefjord case would be required to conclude if the plug is sealed or not.

Bibliography

Atlas Copco. (2008). Overburden drilling systems. atlas copco ground engineeringproducts [Available at https://www.rockdrillsales.com/fullpanel/uploads/files/odex.pdf Accessed: 2021.12.18].

Baardvik, G., Engen, A., Kalsnes, B., Karlsrud, K., Lande, E. J., Langford, J., Simonsen, A., Tvedt, G., & Veslegard, G. (2016). *Begrensning av skader som følge av grunnarbeider, Sluttrapport* (tech. rep.). NGI.

Beer, J., & Dagestad, A. (2020). Risiko ved brønnboring i områder med marin leire [Available at https://www.ngu.no/blogg/risiko-ved-bronnboring-i-omrader-med-marin-leire Accessed: 2021.12.08].

Cerdeira, C. T., Stujacic, A., Johnsen, O., Brochgrevink, J., Engvall, O., Antonsen, K. R., Henriksdatter, M., Stenseng, J., Stræte, O. B., Fergus, T., Borthen, L., Fredrikssen, U., Hallén, M., Daviknes, H., Ulle, L., Haahjem, M., Røiom, A., Korsaksel, A., Sæther, M., . . . Jensen, H. (2019). *Undergrunnen* (tech. rep.). Oslo Municipality.

Cui, X., Liu, Q., Zhang, C., Huang, Y., Fan, Y., & Wang, H. (2018). Land subsidence due to groundwater pumping and recharge: Considering the particle-deposition effect in ground-source heat-pump engineering. *Hydrogeology Journal*, *26*, 789–802. https://doi.org/10.1007/s10040-018-1723-4

Daler, R. (2018). Ny dom om brønnboreres rapporteringsplikt til ngu [Available at https://anleggsmaskinen.no/2018/10/ny-dom-om-bronnboreres-rapporteringsplikt-til-ngu/ Accessed: 2021.12.08].

Daler, R. (2020). Dreven brønnborerbedrift – ny fagutdanning [Available at https://anleggsmaskinen.no/2021/12/dreven-bronnborerbedrift-ny-fagutdanning/ Accessed: 2021.12.08].

Dalla Santa, G., Cola, P. p. E. S., Secco, M., Tateo, F., Sassi, R., & Galgaro, A. (2019). Multiscale analysis of freeze-thaw effects induced by ground heat exchangers on permeability of silty-clays. *Géotechnique*, *69*, 95–105. https://doi.org/10.1680/jgeot.16.P.313

Dalla Santa, G., Galgaro, A., Tateo, F., & Cola, S. (2016). Modified compressibility of cohesive sediments induced by thermal anomalies due to a borehole heat exchanger. *Engineering Geology*, *202*, 143–152. https://doi.org/10.1016/j.enggeo.2016.01.011

Gjengedal, S., Stenvik, L. A., Storli, P. T. S., Ramstad, R. K., Hilmo, B. O., & Frengstad, B. S. (2019). Design of groundwater heat pump systems. principles,tools, and strategies for controlling gas and precipitation problems. *Energies*, *12*(19), 3657. https://doi.org/10.3390/en12193657

Gran, M. A. (2012). Tunnel viktigere enn energibrønner. *Aftenposten*. https://www.aftenposten.no/oslo/i/9mE9q/tunnel-viktigere-enn-energibroenner.

GRANADA. (2021). Norges nasjonale grunnvannsdatabase [Data available at https://kartkatalog.geonorge.no/metadata/82cd33ef-52dd-4c83-b2d6-e55a0941b33b. Map aviailable at https://geo.ngu.no/kart/granada_mobil/ Acessed 2021.12.08]. https://www.ngu.no/emne/kart-pa-nett

Gundersen, E. (2018). *Tetting av borehull fra grunnundersøkelser* (tech. rep.). Bane Nord and Statens vegvesen.

Gundersen, E., & Haugen, E. (2021). *Sealing leaking boreholes with grout* (tech. rep.). Norwegian Public Roads Administration. https://hdl.handle.net/11250/2732407

HAB. (n.d.). Tøyengata 47 – refundamentering [Available at https://hab.no/toyengata-47-refundamentering/ Accessed: 2021.12.08].

Hagfors, C. L., Røset, H., Ording, O., & Sfrintzeris, Y. (2021). Beboere evakuert etter sprekkdannelse i Oslo-bygård. *VG*. https://www.vg.no/nyheter/innenriks/i/z78nGw/beboere-evakuert-etter-sprekkdannelse-i-oslo-bygaard.

Haugen, I. H., & Hjelme, J. (2019). *Geoteknisk notat 1 Vurdering av Setningskader* (tech. rep.). DMR MILJØ OG GEOTEKNIKK AS.

Hyvang, J. (2021). Boretslaget får blankt nei til å bore etter bergvarme: – saken er frustrerende og nesten litt absurd. *avisa OSLO*. https://www.ao.no/boretslaget-far-blankt-nei-til-a-bore-etter-bergvarme-saken-er-frustrerende-og-nesten-litt-absurd/s/5-128-228513.

Iglebæk, S. A. (2021). Energibrønner kan bli priset ut. *NemiTek*. https://nemitek.no/energibronner-novap-oslo-kommune/energibronner-kan-bli-priset-ut/140843.

Janbu, N. (1970). *Grunnlag i geoteknikk*. Tapir Forlag.

Karlsrud, K., Erikstad, L., & Snilsberg, P. (2003). *Undersøkelser og krav til innlekkasje for â ivareta ytre miljø* (tech. rep.). Statens Vegvesen.

Lande, E. J., Karlsrud, K., Langford, J., & Nordal, S. (2020). Effects of drilling for tieback anchors on surrounding ground: Results from field tests. *Journal of Geotechnical and Geoenvironmental Engineering*, *146*, 05020007. https://doi.org/10.1061/(ASCE)GT.1943-5606.0002274

MAXDRILL ROCK TOOLS CO., LTD. (Unknown). Concentric overburden drilling systems. [Available at http://max-drilling.com/2-4-2-concentric-overburden-drilling-system/ Accessed: 2021.01.01].

NGU. (2021). Energibrønn [Available at https://www.ngu.no/grunnvanninorge/bore-en-bronn/energibronn Accessed: 2021.12.08].

Norsk Standard. (2012). Krav til borede brønner i berg til vannforsyning og energiformål. *NS 3056*.

Norsk Varmepumpeforening. (2019). Bergvarme- og jordvarmepumpe [Available at https://www.varmepumpeinfo.no/varmepumpetyper/bergvarmepumpe-og-jordvarmepumpe Acessed: 2021.12.08].

Olesen, O., Dehls, J. F., Ebbing, J., Henriksen, H., Kihle, O., & Lundin, E. (2007). Aeromagnetic mapping of deep-weathered fracture zones in the Oslo Region – a new tool for improved planning of tunnels. *Norwegian Journal of Geology*, *87*, 253–267.

Ramstad, R. K. (2011). *Grunnvarme i norge - kartlegging av økonomisk potensial* (tech. rep.). NVE. http://publikasjoner.nve.no/oppdragsrapportA/2011/oppdragsrapportA2011_05.pdf

Rybach, L. (2001). Design and performance of borehole heat exchanger/heat pumpsystems. *Proceedings European Summer School of Geothermal Energy Applications*.

Sivasakthivel, T., Murugesan, K., & Sahoo, P. K. (2015). Study of technical, economical and environmental viability of ground source heat pump system for himalayan cities of India. *Renewable and Sustainable Energy Reviews*, *48*, 452–462. https://doi.org/10.1016/j.rser.2015.04.008

Statsforvalteren i Oslo og Viken. (2020). Ny vurdering av saken vedtak i klagesak 229/127 oslo klage tilatelse energibrønnpark [Available at https://innsyn.pbe.oslo.kommune.no/saksinnsyn/showfile.asp?jno=2021047005&fileid=9553115. Acessed: 2021.11.04].

Sveriges geologiska undersökning. (2016). Normbrunn –16 vägledning för att borra brunn. *SGU*.

Vannressursloven. (2000). *Lov om vassdrag og grunnvann.* (LOV-2000-11-24-82). Lovdata. https://lovdata.no/dokument/NL/lov/2000-11-24-82#KAPITTEL_8

Veslegard, G., & Simonsen, A. S. (2014). *State of the art Boreteknikk 1 +2.1 Erfaringsinnsamlingog analyse av skadeårsaker* (tech. rep.). NGI. https://www.ngi.no/download/file/4437

Vestfold Tingrett. (2021). 20-120276tvi-tves/tlar.

Winge, N. K., & Kvam, M. E. (2018). Energibrønner - en rettslig analyse av nye utnyttelsesmetoder i undergrunnen. *Tidsskrift for eiendomsrett*, *14*(2), 178–205.

Zymnis, D. M., & Whittle, A. J. (2021). Geotechnical considerations in the design of borehole heat exchangers [https://doi.org/10.1139/cgj-2020-0118]. *Canadian Geotechnical Journal*, *58*(9), 1247–1262. https://doi.org/10.1139/cgj-2020-0118

Additional Figures

Figure B.1: The basement of Hans Amundsens Gate 10 (photo by Atle Dagestad)

Figure B.2: South west of the Energywell in Sandefjord, Fractures in rock (photo by Atle Dagestad)

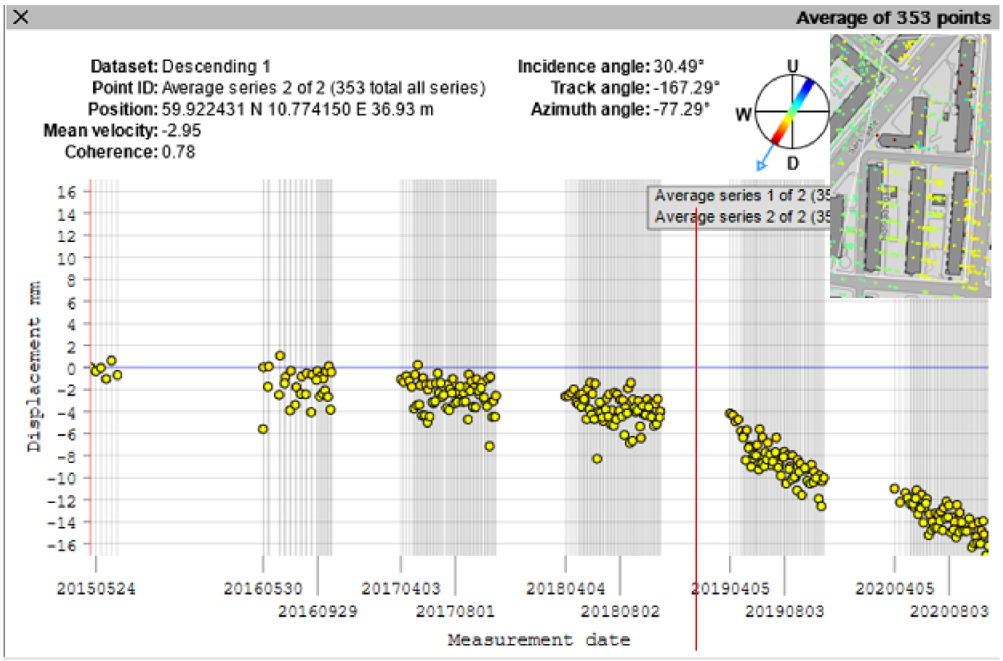

Figure B.3: Triangle between Helgensens gate, Sars gate and Finnmarksgata, south of Engelsborg. Red line shows installation date of the Engelsborg well park in 02.2019. Modified from https://insar.ngu.no/

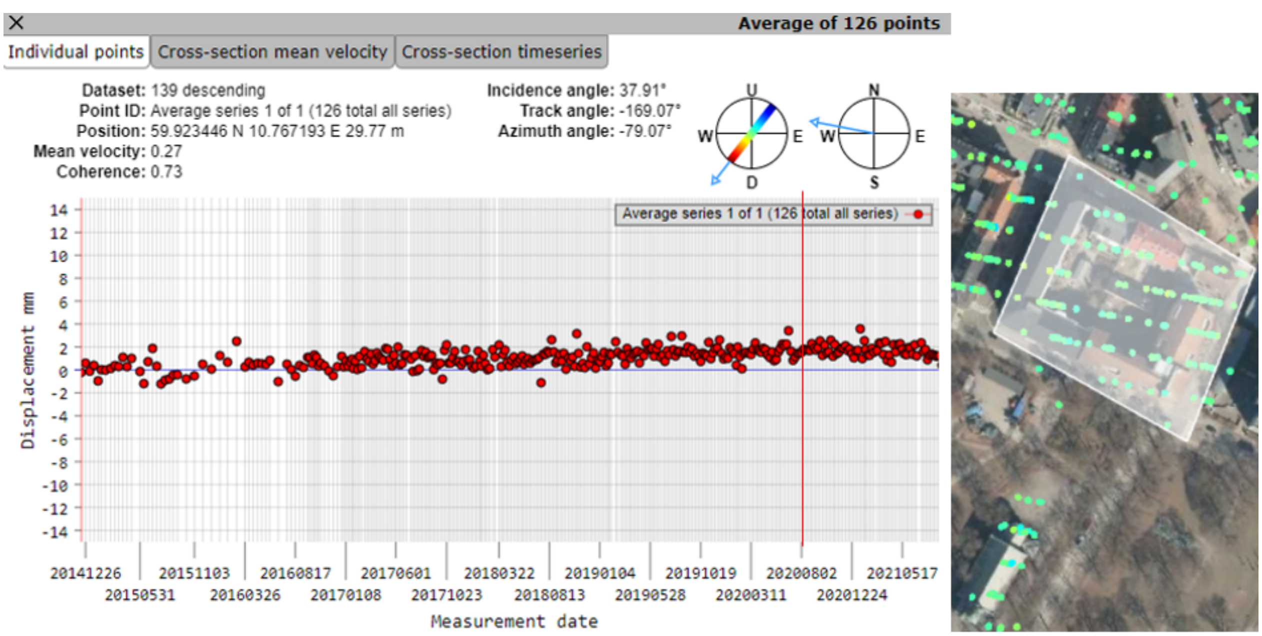

Figure B.4: West of Engelsborg labeled D in Figure 2.6. No vertical settlements in InSAR for the area around the 3 wells installed in 08.2020, here marked as a red line. (I. Mørck, personal communication, December 8, 2021)

Figure B.5: West of Engelsborg labeled D in Figure 2.6. In October 2021 Karlstadgata 4 experienced facade damage leading to the evacuation of the occupants. They were quickly allowed back after the building was deemed safe by an engineer.Hagfors et al., 2021

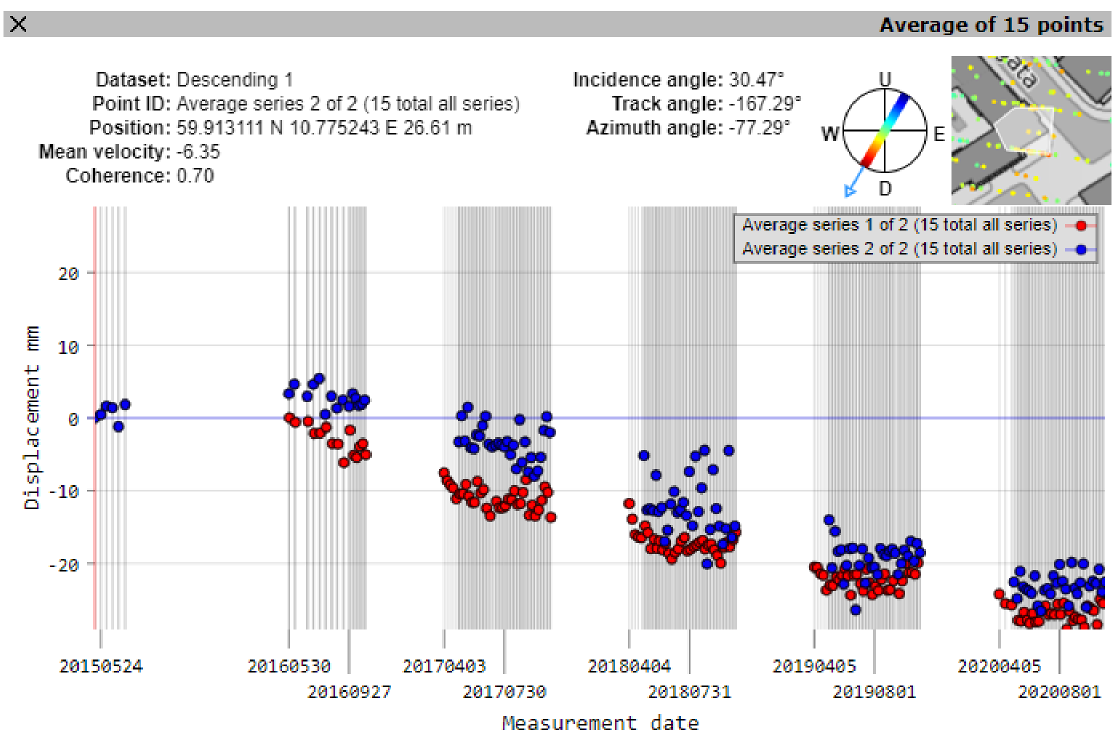

Figure B.6: Deformation vs time for sigurds gate 20s eastern corner and pavement. Installation date is before this plot begins. Taken from https://insar.ngu.no/

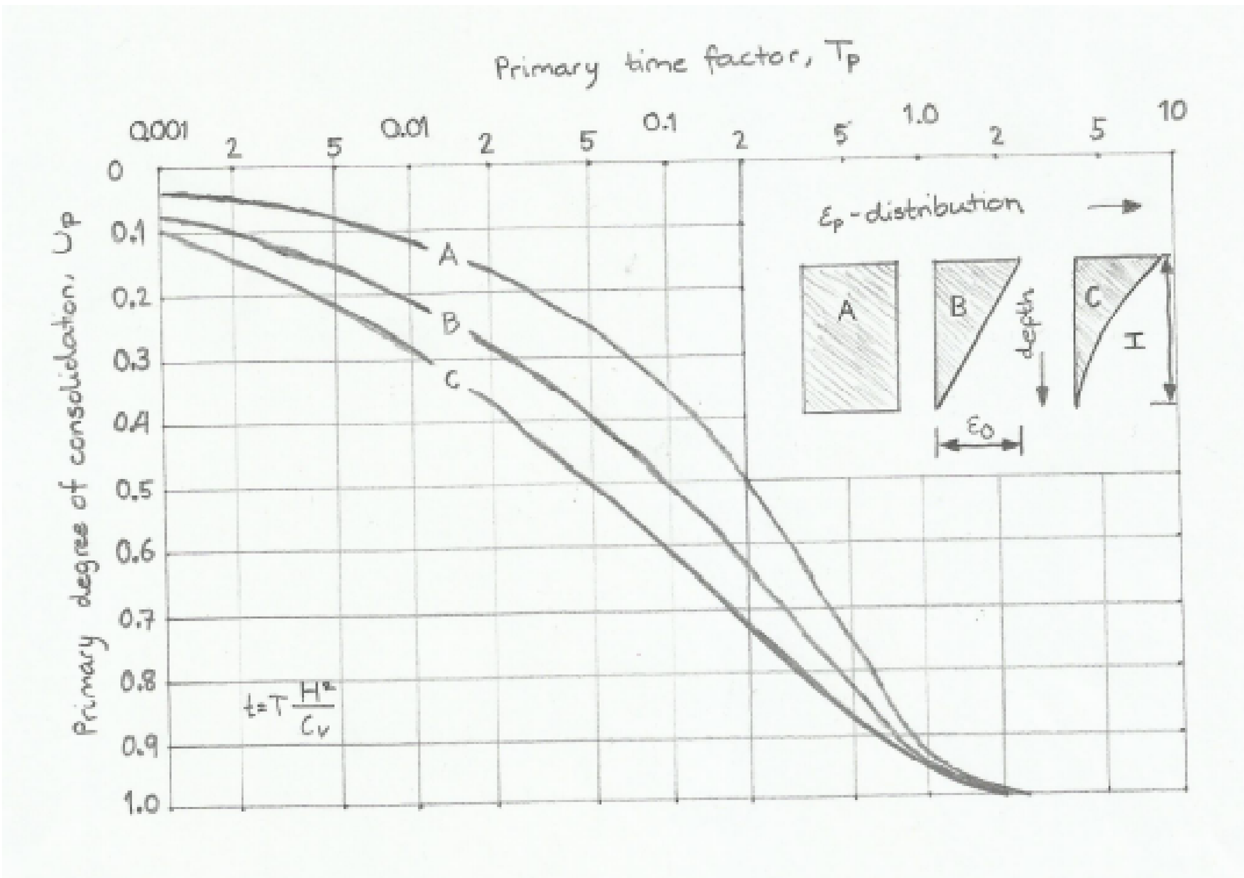

Figure B.7: Refrence table and chart for $t < t_p$. Based on [Janbu, 1970]