Large Thermal Energy Storage at Marstal District Heating

Importante capacité de stockage de l'énergie thermique pour le chauffage collectif de Marstal

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ABSTRACT: For many years the district heating system in the town Marstal in Denmark has been based on oil fuels. During the last decade Marstal District Heating has turned towards 100 % renewable energies, so that in 2012 a solar heat system – covering 10 hectares of land – will produce more than 50 % of the heat consumption and the rest from biomass energy. In Denmark solar heat production is very modest during the winter, contrary to the heat consumption. The large percentage of solar heat coverage is made possible by seasonal thermal energy storage large enough to preserve the solar energy produced during summertime until winter. For this purpose a 75,000 m^3 pit thermal energy storage has been established. The pit measures 88 meters by 113 meters at the top and has a depth of 16 meters, filled with water. The excavation for the pit goes through various layers of sand and clay below groundwater at steepest possible slopes to ensure an economical design. In this article the geotechnical challenges during the planning and execution of the pit are described.

RÉSUMÉ : Au cours de nombreuses années le système de réseau de chaleur de la ville de Marstal au Danemark a été basé sur les combustibles pétroliers. Au cours de la dernière décennie, le chauffage urbain de Marstal s'est tourné à 100% vers les énergies renouvelables, si bien qu'en 2012, un système de chauffage solaire, placé sur une superficie de 10 hectares de terrain, va produire plus de 50% de la consommation de chaleur, le reste devant provenir de l'énergie verte. La production de chaleur solaire au Danemark est très modeste au cours de l'hiver, contrairement à son besoin de consommation de chaleur. Le pourcentage élevé provenant de la chaleur solaire est rendu possible grâce à l'utilisation de stockage saisonnier de l'énergie thermique permettant de garder l'énergie solaire produite en été jusqu'en hiver. Dans ce but, une fosse de 75,000 m^3, oú l'énergie thermique est stockée, a été établi. Cette fosse remplie d'eau mesure 88 mètres par 113 mètres sur une profondeur de 16 mètres. L'excavation de la fosse passe au travers de couches de sable et d'argile au-dessous de la nappe phréatique, avec des pentes raides au possible pour assurer une conception économique. Dans cet article, les défis géotechniques au cours de la planification et de l'exécution de la fosse sont décrits.

KEYWORDS: Pit thermal energy storage; PTES; Seasonal thermal energy storage; Solar heat; Renewable energies.

1 INTRODUCTION

Denmark is placed in a climate where buildings need to be heated during most of the year. In urban areas district heating is dominating and district heating covers approx. 2/3 of the consumers in Denmark. The district heating systems are dominated by combined heat and power plants (CHP) widely spreaded in Denmark. Traditionally the district heating is based on mainly fossile fuels of coal, oil and gas, but waste and biomass heating are also used. The remaining 1/3 of the population is covered by individual heating dominated by gas or oil. A minor part is heated by other types of energy e.g., wood, geothermal energy, heat pumps etc.

A lot of district heating systems are turning from fossile fuels towards renewable energies. Especially use of solar heating is preferred for medium-sized plants as the technology is developed and well proved. The energy production of solar heating systems is though very dependent on the solar radiation, and in Denmark the radiation is very modest during the winter, almost inversely proportional to the need of heat consumption. In figure 1 the average solar heat radiation and the solar heat production during a year are illustrated.

In addition, the low heat consumption during summertime dictates the maximum size of the solar heating system, and consequently the solar heating system covers usually less than 10 - 20 % of the total heating consumption.

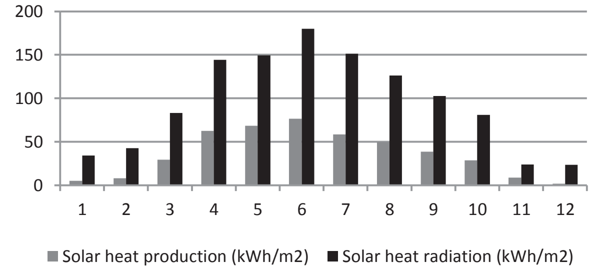

Figure 1. Monthly solar heat production and radiation at Marstal District Heating 2010-1012 (www.solvarmedata.dk).

The percentage of solar heat in the district heating may be increased by a seasonal thermal storage. The storage must be large enough to preserve the solar energy produced during summertime until winter.

Thermal energy is usually stored by heating up a material, and later on the heat can be recycled to the consumers using a heat pump. Water has shown to be an excellent heat storage material. Water is cheap and has a reasonable heat capacity compared to other materials. A relatively low value of the thermal conductivity of water is compensated as water is easily movable by pumping. Soil is also very cheap, but soil has poorer heat capacities and the heat is not easily movable. Figure 2 and 3 show typical values of the thermal conductivity and heat capacity for selected soils and water (Verein Deutscher

Ingenieure 2004). The figures show that the natural water content of the soils is very important for the thermal parameters.

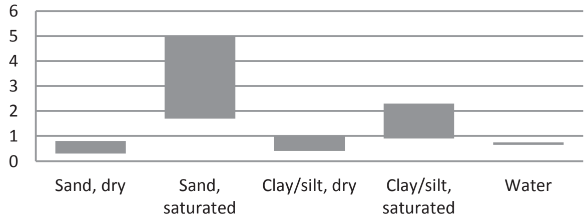

Figure 2. Typical values of thermal conductivity in W/(m·K).

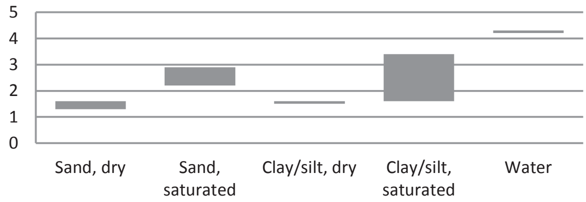

Figure 3. Typical values of volumetric heat capacity in MJ/(m^3·K).

The range of operational temperature must be as large as practically possible, as the range will impact on the necessary volume of storage.

Large seasonal thermal energy storages may be established as one of the following systems: TTES, PTES, ATES or BTES.

The TTES (Tank Thermal Energy Storage) system consists of an insulated steel tank filled with water and is widely used in the short-term regulation of the heat consumption against the heat production at heating plants. A volume of 1,000 – 5,000 m^3 is often adequate for most Danish medium-sized district heating systems. Typically operational temperatures are T = 30 - 90°C, i.e. $\Delta T \approx 60$°C.

The PTES (Pit Thermal Energy Storage) system is an excavated pit, which is lined by a membrane and filled with water. Operational temperatures are typically 30 - 90°C. The upper temperature affects the lifetime of the membrane and long term exposure of the upper temperatures therefore has to be avoided. The permissible level and exposure time of the upper temperature is a trade-off between the lifetime of storage and storage capacity. Usually the storage is not insulated towards the soil, as the energy loss through these areas is acceptable low under certain circumstances. The top of the storage – the water surface – is exposed to alternating climate conditions, including cooling by wind, which requires insulation. The insulation may be floating on the water or carried by a supporting system. For larger storages a PTES system is very cost-effective. In Denmark a few pilot PTES plants are in use with volumes up to 10,000 m^3, but larger plants are under construction, as this article describes.

The ATES (Aquifer Thermal Energy Storage) system stores the heat in a groundwater aquifer. The extend and characteristics of the aquifer must be well-known as the groundwater is pumped from a number of wells and – after passing a heat exchanger to impact or extract heat energy - infiltrated into the aquifer in another part of the aquifer. Typically operational temperatures are 5 - 30°C with $\Delta T \approx$ 25°C, i.e. the volume of water must be larger than for the above mentioned storages. This type of plant requires a groundwater aquifer with high permeability. In Denmark most of the drinking water supply is based on groundwater, and this implies that large ATES's will not be allowed in areas with special interest of drinking water supply. A growing number of ATES's have though been established, mainly initiated by a need of cooling during summertime of large building complexes.

The BTES (Borehole Thermal Energy Storage) system consists of a large number of boreholes with loops of heat pipes installed. The heat is transferred to the soil by circulating brine in the heat pipes and vice versa when the heat is to be consumed. As operational temperatures are 20 - 60 °C, i.e. $\Delta T \approx$ 40°C, and the heat capacity of soil is small compared to water, a larger soil volume is needed than for storages based on water. This is compensated as the boreholes usually go to 50 – 100 meters depth. The thermal conductivity of soil is moderate, and the response of the storage is thus relatively slow. At present only one pilot plant has been established in Denmark at a district heating plant.

2 SEASONAL ENERGY STORAGE IN MARSTAL

Marstal is a town with 2400 citizents on the Danish island Aeroe. For many years the district heating system in the city of Marstal has been based on oil fuels. During the last decade Marstal District Heating has turned towards 100 % renewable energies, so that from 2012 a solar heat system – covering 33,000 m^2 solar heat panels on 10 hectares of land – will produce more than 50 % of the heat consumption and the rest will come from biomass energy. At present the plant is the largest solar heat plant for district heating in the world, but this ranking will presumable only be held for a short period.

Marstal has been a Danish pioneer in thermal energy storage. In 1998 a 3,000 m^3 combined gravel and water pit has been built, and the plant was followed by a 10,000 m^3 PTES in 2003. Calculations have shown that the requested large percentage of solar heat coverage in Marstal needs a volume of 75,000 m^3 water in which case *all* surplus solar energy produced during summertime can be stored until winter. This volume is established by a PTES plant. The project is economically supported by the European Union (EU).

Performing a PTES has some preferred technical conditions in relation to an economic design in regards of both the establishment phase and the operation phase as described in the following:

The pit *must* be performed as an open pit without using e.g. a framing sheet pile wall which would increase the cost considerably. To minimize excavation costs the ground must consist of soils which can be excavated and handled by traditionally methods and with no significant groundwater handling.

To reduce heat loss into the air the pit must be covered by insulation with guaranteed resistance to temperatures up to 90°C for the lifetime of the storage. The top insulation and the bottom membrane (in this case a 2.5 mm HDPE liner) are some of the most expensive parts in a PTES and the area of the insulation must consequently be minimized.

Dry soils insulate better than moist or saturated soils, and moreover groundwater may introduce unwanted heat loss if heated groundwater flows across the site. Therefore, the groundwater level must be at a convenient depth below the bottom of the pit, alternatively a higher groundwater level is tolerated, but in that case no significant groundwater flow across the site is allowed.

The loss of heat is reduced to a theoretical minimum when the pit has a spherical shape. This is not obtainable in practice and excavation is often performed as an upturned frustum of pyramid. The width must be minimized, for which reason the slopes of the sides of pyramid must be as steep as practical possible. This reduces moreover the area of the expensive top insulation.

In order to establish soil balance in the project the excavated soil is to be used in building up embankments around the excavated pit. The excavated soil must be well suited and compactable for this purpose.

3 CONSTRUCTION AND SITE INVESTIGATIONS

In Marstal the PTES is placed on the top of a smooth hill in the outskirts of the town.

Due to area restraints the pit is slightly rectangular and measures 88 meters by 113 meters at the top, i.e. a bit larger than a football field. The water depth is 16 meters, of which approx. 12 meters go below the natural ground level and 4 meters are established by embankments of the excavated soil at the perimeter. As mentioned above the total volume of water is 75,000 m^3.

Early in the design process the slope of the sides was chosen to 1:2 which in a practically view is the steepest possible inclination for the installation works of the liner. This corresponds to an angle of 26.6° against horizontal level. Figure 4 shows a stylized cross section of the pit.

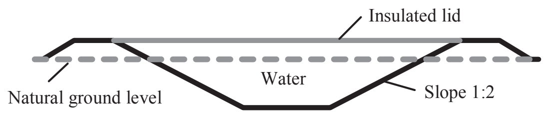

Figure 4. Stylized cross section of the PTES in Marstal.

A site investigation has been performed prior to the design phase. The investigation consisted of 10 borings, of which two borings in the centre were taken to 25 meters depth and 8 borings at the perimeter of the excavation were taken to 13 meters depth. The borings were performed as traditionally geotechnical borings with soil sampling, in-situ tests and installation of standpipes at adequate depths.

The investigation showed a thin layer of top soil covering various glacial deposits of primarily clay till and glacially relocated marine clay of interglacial origin (Cyprina Clay). At the northern side three meters of melt water sand were covering the clay. Besides, stripes and zones of melt water sand and sand till were found, apparently randomly in the clay.

In a geotechnical matter the marine clay was of special interest. The clay was of high to very high plasticity with plasticity index $I_P \approx 50$ %. The natural water content was w_{nat} = 21 – 30 % close to the plasticity limit. A fissured structure was detected in several samples, presumably caused by shear stresses during the glacial period and/or passive earth pressures at the end of the glacial period.

The clay deposits were generally stiff to very stiff. Field vane tests showed undrained shear strength c_{fv} between 250 and >700 kPa, thus with a slightly softened zone near the surface.

The effective strength parameters in the clay were estimated from a priori knowledge of similar soils. The characteristic value of the angle of friction of the marine clay was estimated to $\varphi \approx 20°$ and of the clay till to $\varphi \approx 30°$ with mean values approximately 5 degrees higher. Some effective cohesion in the clay must be expected, but according to Danish calculation practice the cohesion was limited to c' = 20 kPa in unfissured clay and c' = 0 kPa in fissured clay (on the safe side for decreasing stress level).

Standpipes had been installed at differing depths, separated by bentonite sealing materials. Groundwater levels were measured at very varying depths between a few meters depth and large depth (below excavation level). These measurements are assumed to be variably ground water build-ups depending on precipitation and season, whereas a stable ground water table in a primary aquifer is at large depth.

4 CONSIDERATIONS FOR THE CONSTRUCTION

Establishment of a PTES at the actual site was subject to four geotechnical concerns: the excavation stability, the groundwater and soil handling during the construction phase and the long term consequences of thermal influence on deformations in the operational phase.

4.1 *Excavation stability*

The stability of the excavation sides was to be sufficient during the construction phase. Provided that the ground water issue was handled, it was evident that a quickly performed excavation and refilling with water would be advisable as the clay would be stable in the short term undrained condition. On the other hand, calculations based on long term drained strength parameters showed unstable slopes in the marine clay, especially when adding prescribed safety factors according to Eurocode 7.

The period from starting excavation until fully filling the pit with water was planned to last 6½ months. One month had to be reserved the liner work, and as the available capacity for filling the pit with water was limited to 50 m^3/h the filling would itself take two months.

Undrained conditions were evaluated to last at least one month, but exceeding this period by several months caused severe considerations of the time for developing drained conditions and consequently collapses due to unstable slopes. It was evaluated that further tests and evaluations would not improve this engineering judgement significantly, and therefore the stability had to be evaluated for drained conditions.

Introducing less steep slopes than 1:2 was not an option, but a series of slope stability calculations based on different cross sections showed that it was possible to establish stable slopes of 1:2 by replacing layers of the marine clay until certain depths with sand or even clay till, see figure 5, forcing the rupture line at greater depth to involve more stable materials. The replacement of the marine clay would increase the volume of soil to be handled in the project by approximately 15 % which was acceptable.

During the excavation phase it was decided to abstain from replacements until indications of failures were observed. This reduced replacements to an absolute minimum.

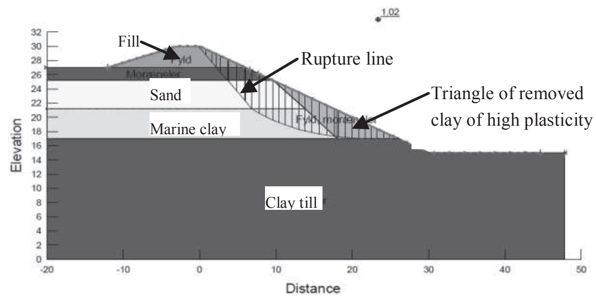

Figure 5. Example of slope calculations.

4.2 *Groundwater handling*

The potential energy loss due to groundwater flow across the site was evaluated to be very limited.

The groundwater build-ups had to be eliminated to enable dry excavation and a proper handling of the membrane. Furthermore groundwater lowering was necessary to prevent uplift, damages due to seepage from the excavation sides and sliding of the sides, which especially would be problematic if the sides were sliding after covering with the membrane.

The circumstance that the bottom of the pit was to be covered with a membrane implied that the groundwater lowering works was directed to take place on the outer side of the pit, i.e. at some distance from the excavation. This might reduce the draw-downs in the centre of the pit.

The chosen groundwater lowering system consisted of a combination of well-points, bored wells and a drainage system beneath the membrane.

The well-points were closely spaced at approx. 6 meters depth at the perimeter of the pit to deal with the groundwater flow in the upper layers of sand.

In addition eight bored wells were placed at the perimeter to deal with the deeper water built-ups. Besides pumping from the wells vacuum was applied to the wells to reduce pore water pressures in the soil and increase the effective stresses in the soil, at least to some distance from the wells.

Furthermore, a well in the centre of the pit was performed to prevent uplift. This well was initially installed with a pump, and during excavation the well was successively cut down to excavation level and the pump was removed.

Before covering up the bottom and the sides with the membrane, a drainage system in connection with the (weeping) well was established in the bottom. To prevent a lifting problem caused by accumulation of water beneath the membrane, pumping on the drainage system was made possible by traditionally well pumps mounted through two installed pipes laid in inclining ditches up the sides.

Pumping from the drainage system, the well-points and the bored wells at the perimeter of the pit was sustained until the pit was filled with water unto the measured highest natural ground water level approx. 1 meter below the surrounding level.

4.3 *Soil handling*

The excavated soil had to be built-in in the embankments around the pit. The soil mainly consisted of clay, where moisturing/weathering normally must be avoided in order to obtain reasonable compaction (more than 95 % Standard Proctor) and confined deformations of the embankments. Therefore, the earth works must take place during a period with favourable weather conditions, which in Denmark means the summer period.

Furthermore, the poor strength properties of the marine clay of high plasticity – especially in a remoulded condition - was dictating that the clay only had to be rebuilt in areas where the requirements to the soil were less critical.

4.4 *Consequences of thermal influence to the soil*

In the operational phase the temperature in the adjacent soil will increase, maybe up to 90°C close to the pit. This heating of the soil might cause a drying-up effect of the soil above the ground water table if no water is added from e.g. precipitation. In the actual case the clays seemed so preconsolidated that the natural water content was considered to be close to the shrinkage limit. Consequently the risk of development of a long term deformation problem was evaluated as a minor issue.

5 CONSTRUCTION PHASE

The PTES was established during the summer 2011 which happened to be very wet with precipitation more than twice the normal precipitation. In addition, a cloudburst occurred with more than 100 mm precipitation overnight which caused damages to the just finished surfaces and obstacles for the subsequent works. Consequently, the construction period was delayed 3 months into the winter.

This entailed that the preconditions for the project was severely challenged. Especially the maintenance of the stability of the sides was alarming. The predicted long term problem with poor drained strength parameter might be worsened if the efficiency of the ground water lowering system was reduced (due to clogging etc.). This problem period was not to end until the filling-in of water was above the surrounding ground level.

In spite of this no severe ruptures were recorded. Figure 6 shows a photo of the pit at a late stage of the excavation work.

Figure 6. Photo of pit during completion of excavation and laying out of the membrane in progress. The tower in the centre of the photo is a 16 m tall water in- and outlet for the operational phase of the PTES.

6 CONCLUSIONS AND PERSPECTIVES

The PTES project in Marstal has demonstrated that a thermal energy storage with 75,000 m^3 water is obtainable in connection with solar heat based district heating systems. The construction cost of the Marstal storage was 41 € per m^3 of water (exclusive VAT) including all pipe connection to the plant, control system, geotechnical support, etc. The construction cost also includes research and development costs of the storage and different lid designs. The costs are cost-competitive compared to other storage systems (e.g. TTES, ATES and BTES) and there is a potential to bring the costs further down.

The project has encountered difficulties in matters of soil and ground water conditions and challenges due to circumstances in the actual climate, but these challenges has been dealt with in order to minimize the costs of the PTES. Details in the project still needs to be optimized, but the project is a stepping stone in the development of the necessary techniques for decreasing the use of renewable energies.

The aim of the authors of this article is to pinpoint the challanges to be encountered during planning and execution of a PTES illustrated by an actual project. It is the authors' perception that a PTES is applicable for a lot of sites.

Denmark has approximately 400 district heating plants of varying size. Most of these plants are placed in rural areas, where establishment of solar heating plants supplemented by a PTES is an obvious solution. As an example the planning of a 60,000 m^3 PTES in connection with 35,000 m^2 solar heat panels at Dronninglund Destrict Heating in Denmark is ongoing and will presumable be established in 2013 - 2014. Some PTES's have been established in other countries, e.g. Germany, but none as large as in Denmark.

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