Ground freezing

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1 Introduction

Ground freezing is a very special technique applied in soil and rock engineering (e.g. tunnelling or shaft sinking) in case water bearing and unstable ground exist, where traditional methods do not allow safe construction. The idea is to create a frozen ring (mantle) around the planned excavation (tunnel, shaft, cavern, deep excavations etc.) which allows a safe construction by stabilizing the soil or rock mass in parallel with hydraulically sealing (Fig. 1). This technology is already used for more than 100 years (patented by Poetsch in Germany in 1883, however first used for a mine shaft construction in South Wales in 1862). In the time period between 1980 and 1990 ground freezing up to about 300 m freezing length was applied for several shafts in the Ruhr area (coal mining, Germany). In the Saskatchewan potash mining region (Canada) between 1960 and 2020 ground freezing was applied to several shaft with freezing lengths of up to about 600 m (Sopko & Auld, 2021).

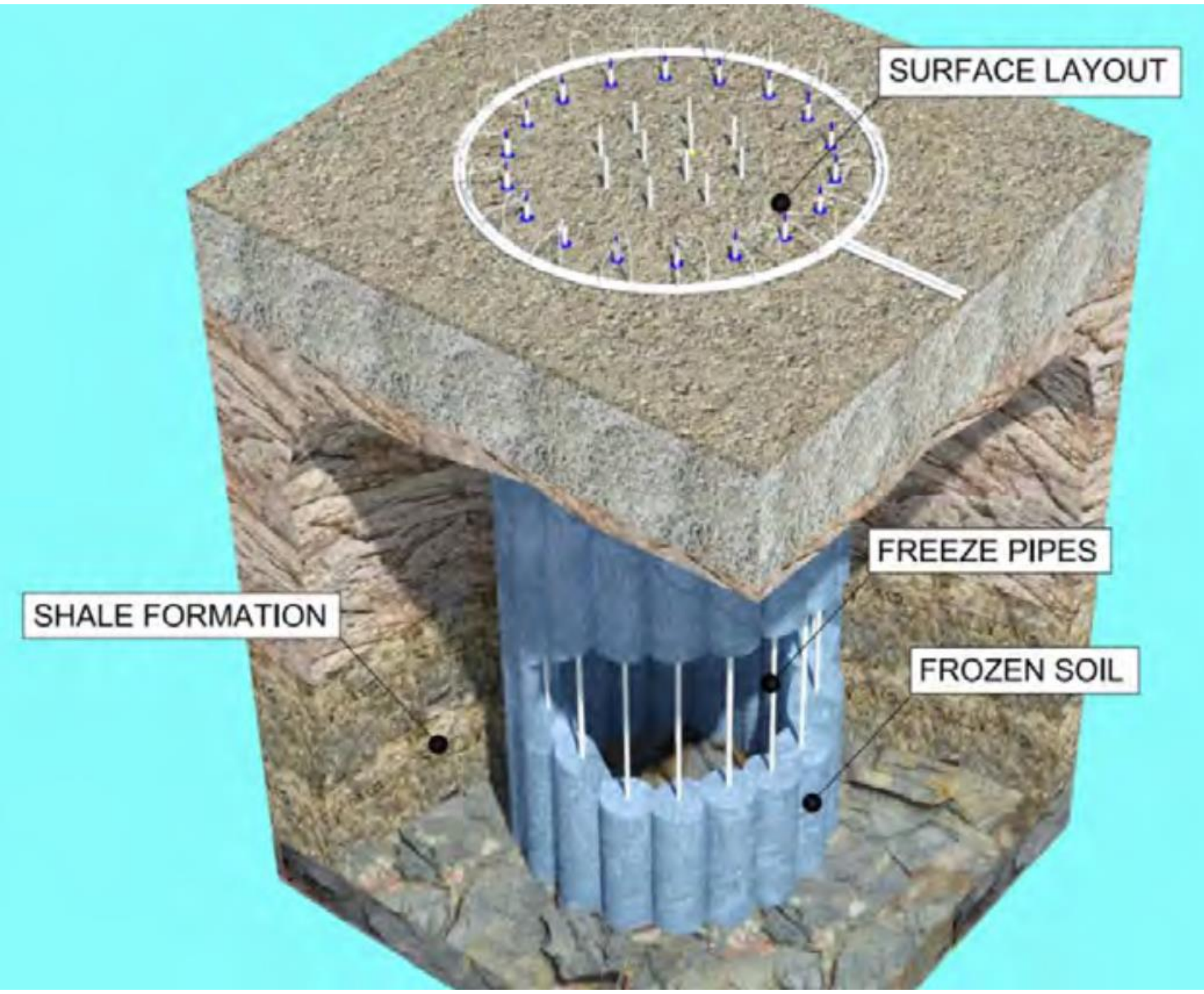

Fig. 1: Sketch to illustrate the ground freezing technology for shaft sinking (freeze pipes in white and frozen rock columns (frozen mantle) in blue; Sopko & Auld, 2023)

2 Freezing technology

The ground freezing is realized by boreholes which contain pipes. A cooling agent is flowing though theses pipes to freeze the ground. Depending on the specific conditions the freezing process takes typically weeks to months.

There are two common technologis for ground freezing based on the used cooling agent:

- Nitrogen freezing
- Brine freezing

During brine freezing (calcium chloride) the temperature is about -30 to -38 °C and during nitrogen freezing (cryogenic liquid nitrogen) the nitrogen evaporates at the boiling temperature of -196 °C. Nitrogen freezing is fast, but expensive because the production of liquified nitrogen is very energy consuming.

To design a ground freezing operation the following investigations have to be performed:

- Engineering geological charachterization incl. salinity, grain size etc.
- Determination of thermal parameters: temperature, heat capapcity and heat conductivity
- Hydrogeological characterization: water flow velocity, saturation etc.

Frozen and unfrozen lab tests should be performed prior to in-situ freezing operations (see for instance Chang & Lacy, 2008).

Drilling the boreholes with extreme precision is necessary. The boreholes should not cross each other and the spacing between them should be exactly maintained.

Fig. 2 shows exemplary a freezing plant for a potash mine in Russia incl. the corresponding brine pumps. This system has a total output of 4500 KW and a freez-depth capacity of 520 m.

Fig. 3 and 4 show show freeze pipe arrangements for a shaft. Depending on specific conditions 1, 2 or 3 rings (raws) of freeze pipes are used.

Two time periods can be distinguished: active phase (first phase to initialize the freezing process) and the passive phase (maintain the frozen state for a certain time span). The passive phase needs only 30% to 50% of the energy necessary for the first phase.

Fig. 2: Freezing plant at a Potsah mine and corresponding brine pumps (Van Heyden & Wegner, 2015)

Fig. 3: Set-up of a freezing systems for a shaft with 10 m diameter (Panteleev et al., 2017)

Fig. 4: Set-up of 3 rows of freeze pipes (Sopko & Auld, 2017)

3 Dimensioning and Monitoring

The ground freezing process can be roughly estimated (designed, dimensioned) by empirical and analytical solutions.

However, a detailed consideration of the freezing process requires the use of numerical simulation tools because a complex hydro-thermal-mechanical (HTM) coupling has to be considered like illustrated in Fig. 5.

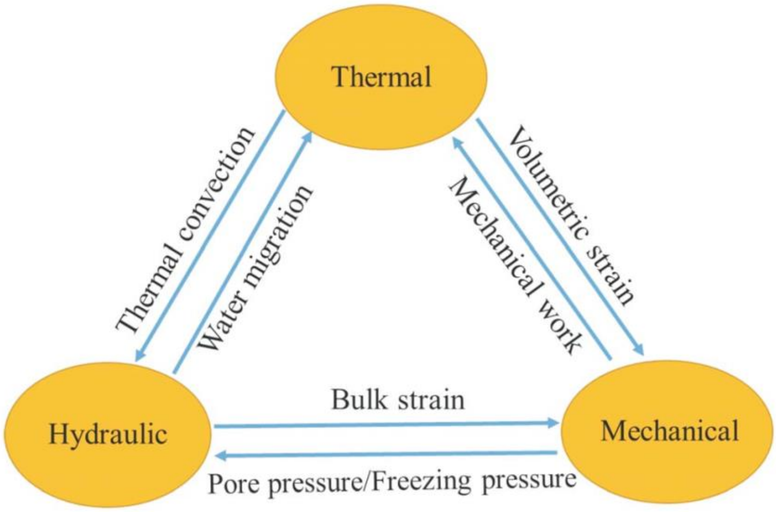

Fig. 5: HTM coupling for freezing process (Jiang, L. et al., 2019)

Several coupled processes are involved, like for instance:

- Change of thermal expansion coefficient with temperature
- Volumetric expansion of freezing rock volume due to temperature change and phase change water-ice
- Change of thermal conductivity and heat capacity based on percentages of the three phases: unfrozen water, ice and rock grains
- Water flow / migration

Fig. 6 illustrates the process of freezing as time-dependent process with development of three distict phases: frozen zone, transition zone and unfrozen zone. Observation boreholes are used to monitor the temperature evolution (Fig. 7). During the freezing process, the frozen zone is growing up to certain extension. The distance between the freezing boreholes must guarantee, that the frozen zones around each borehole overlap, so that a tight closed frozen ring (mantle) is created as documented for instance by numerical simulations (Fig. 8). The nomograph presented in Fig. 9 allows to roughly estimate the time to create the frozen mantle depending on different parameters.

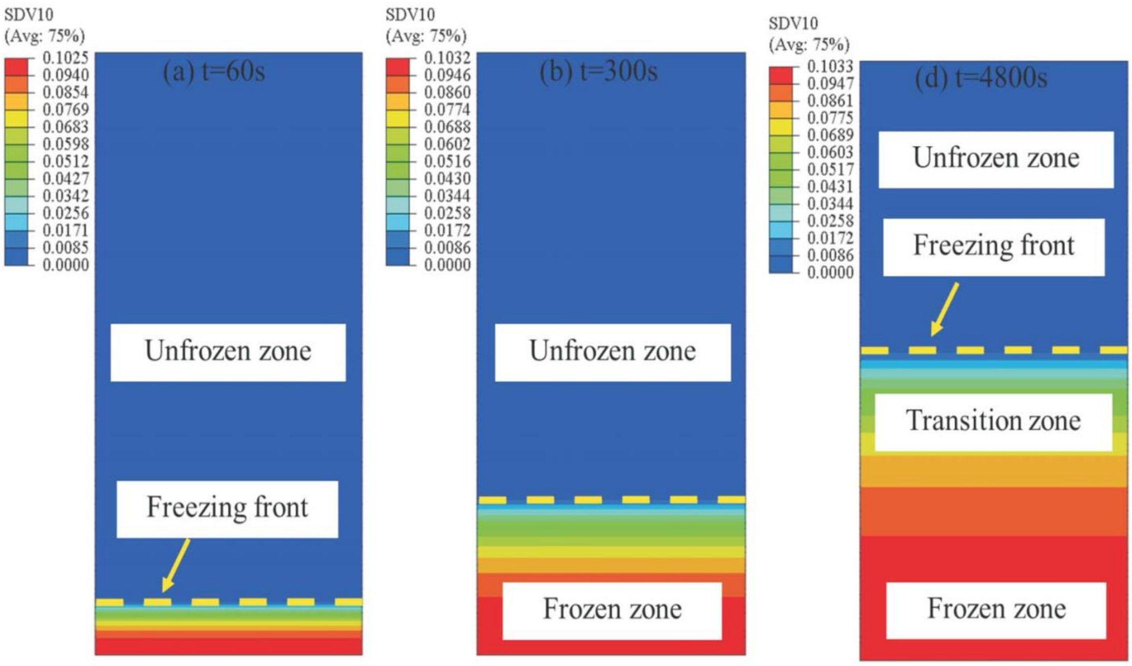

Fig. 6: Freezing front development with ongoing time (Jiang et al., 2019)

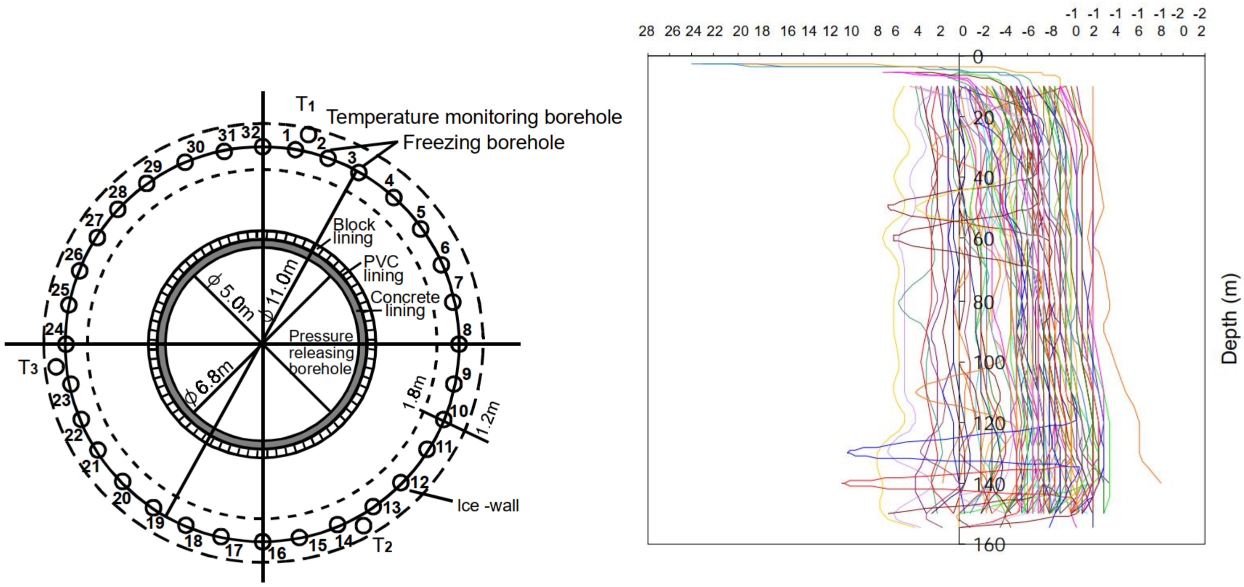

Fig. 7: Arrangement of freezing boreholes (left) and measured temperatures (right; Jiang et al., 2019)

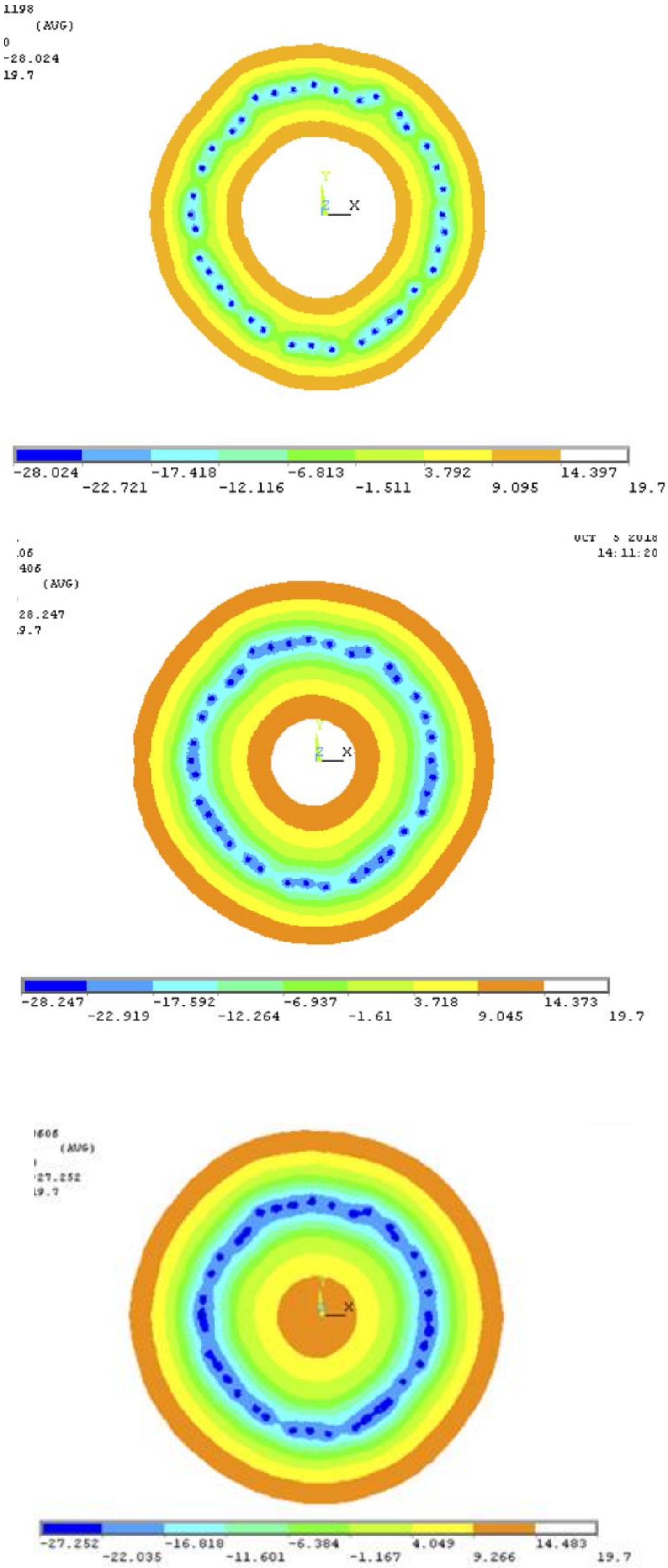

Fig. 8: Temperature field [°C] of the shaft freezing operation after 50, 100 and 150 days of freezing (from top to bottom; Yao et al., 2019)

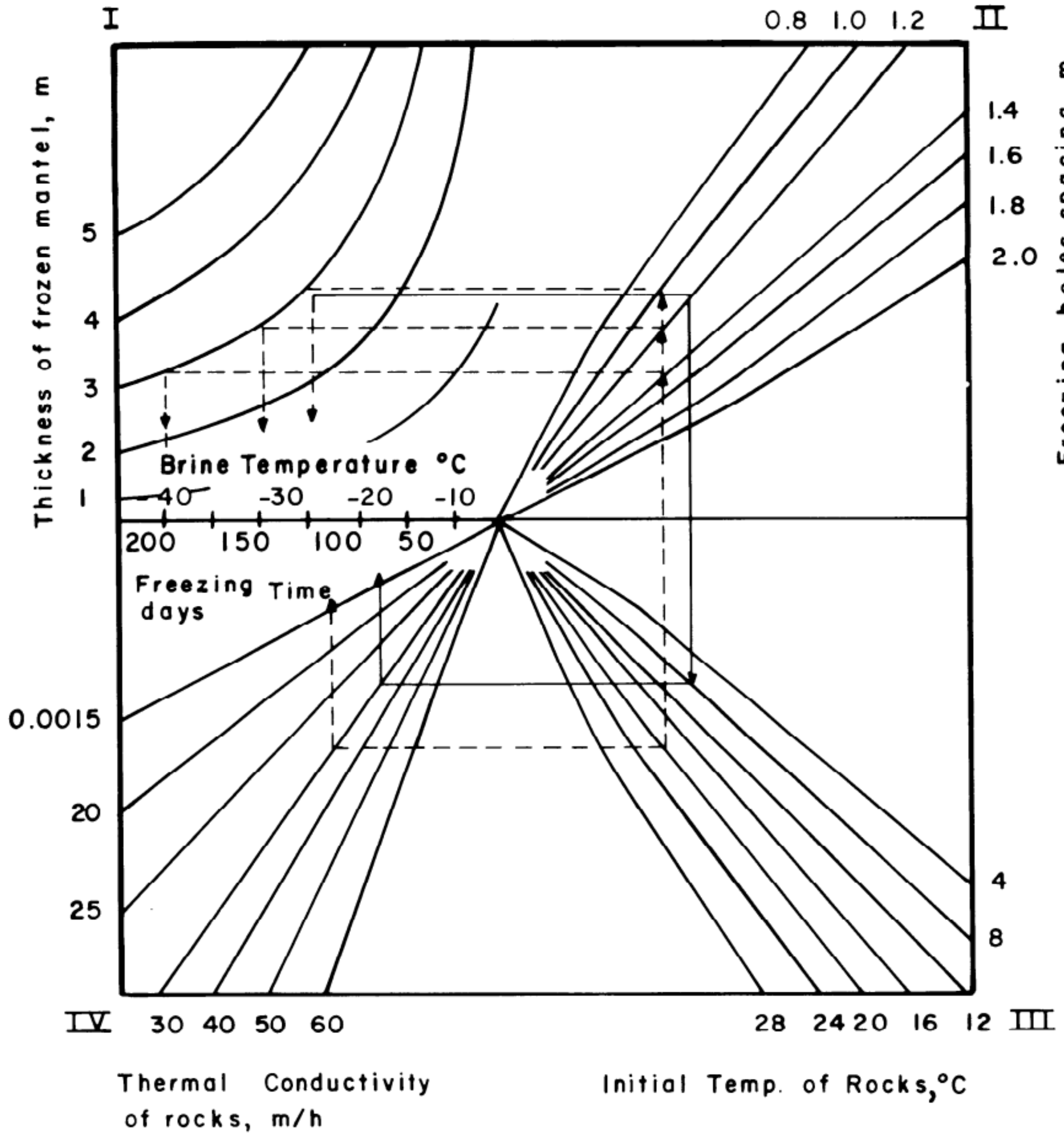

Fig. 9: Nomograph for determination ot time required to create a frozen mantle with given thickness, depending on brine temperature, hole spacing, natural rock temperature and thermal conductivity of rocks (SME, 1992)

4 References

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