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Frost action on supporting structures

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ABSTRACT: Frost heave is the swelling of soil caused by the increased volume of water in the soil when freezing. It is a well-known problem in Nordic countries, and roads, foundations etc. need to handle this phenomenon. Usually this is done by using non frost heave-susceptible materials down to a depth which the subzero temperatures do not penetrate. However, for temporary excavations this is not a viable solution. In deep supported excavations, the frost will develop horizontally from the wall and inwards. To mitigate this, it is common to insulate the retaining wall with mineral wool or sprayed foams such as polyurethane. Installing the insulation is tedious work and contractors are often late, installing the insulation after winter has begun, or the work is skipped entirely. When frost action develops behind a supporting structure, it can lead to significant increases in the forces acting on the wall. This paper summarises data from three different sites in Norway where the strut forces and/or wall deflections were measured. These data were used to estimate a distributed frost-induced pressure acting on the retaining wall. Meteorological data from near the sites was gathered and the freezing index, defined as the time integral of the temperature below subzero, was determined. A relationship between the frost pressure and the freezing index was established and is discussed with regard to the conditions at the different sites. The findings are translated into practical guidance for implementing measures to mitigate unacceptable strut forces following the principals of the observational method.

KEYWORDS: Frost action, observational method, deep excavation, strut force, retaining wall.

1 INTRODUCTION

When temperature drops below freezing, the upper layers of soil begin to freeze. However, frost heaving is often greater than what can be explained by the volumetric expansion of pore-water upon freezing. Excessive frost heave is caused by water migration that supplies growing ice lenses (Taber, 1929). Water migrates toward the freezing front in soil due to a combination of thermal and chemical potential gradients (Henry, 2000). As the soil freezes, ice forms and draws liquid water from surrounding unfrozen areas through a process called cryosuction (Dash et al. 1995). This is driven by the lower chemical potential of water in the freezing zone compared to the unfrozen zone. Fine pores in the soil enable capillary action, allowing water to move towards the freezing front. Intermolecular forces, such as adhesion to soil particles and cohesion between water molecules, facilitate this movement, continuously feeding the growth of ice lenses (Rempel, 2010).

When deep excavations are carried out in cold climates, frost action on the retaining structure can develop unless preventive measures are taken (Morgenstern & Sego 1981). For permanent retaining walls, substitution of the soil behind the walls with a non-frost susceptible material is common. However, this soil exchange is not a viable solution for temporary deep excavations and insulation of the wall during the winter is a common measure to prevent the accumulation of frost-induced pressure (Eggestad, 1982). In some cases, heating behind a cover is performed to melt the ice lenses and reduce the frost action.

The main factors controlling the frost-induced pressure are the size of soil particles, water availability, size and percentage of voids and the cooling rate (Taber, 1929). The soils that facilitate excessive ice lens formation are sufficiently fine-grained so that the capillary effect can transport water from deeper layers, at the same time they are sufficiently coarse-grained so that the permeability is high which enables a continued supply of water to the growing ice lens (Rempel, 2010).

The numerical modelling of frost penetration and resulting heave is highly complex and various theoretical models have been proposed. Stefan-based Routanousu model (SSR) (Saarelainen, 1992), FROST (Guymon et al. 1993) and PC-Heave (Sheng, 1994) are some of the most known models which are mostly based on the employment of Calusius-Clapeyron equation by Miller (1972) and the segregation potential theory of Konrad & Morgenstern (1980). These models are developed for estimation of frost heave of roads, pavements, and buildings, and applying them to assess frost action on retaining walls would require significant adaptation of the codes. In recent years, constitutive models for implementation in FEM such as the Frozen and Unfrozen soil model (Ghoreishian Amiri et al. 2016; Aukenthaler, 2016) have been developed. These models provide the additional advantage of coupling frost action with soil-structure interaction (Hammad et al. 2022). However, validation of such numerical models for the problem of frost action on a supporting structure has not yet been substantiated through case study data.

The effect of frost action on the behaviour of retaining structures has been documented in several case studies (McRostie & Schriever 1967; Pappas & Sexsmith 1968; Morgenstern & Sego 1981; Eggestad, 1982; Sandford, 1997). These studies provide valuable insights into the mechanisms and consequences of frost action. However, beyond these cases, there is a notable lack of comprehensive data and predictive tools to guide designers in assessing frost-induced pressures on temporary and permanent retaining structures (Morgenstern & Sego 1981). In several documented failures, frost action has been partially attributed as a contributing factor (Sandegren et al. 1972; Stille, 1976; Schlosser, 1983; Byrne et al. 1993). This highlights the need for robust and simple techniques to estimate frost-induced pressure on retaining walls.

In this study, measurement data from three deep excavation sites are analysed to investigate the magnitude and behaviour of frost-induced pressure on retaining walls. Despite the availability of numerical models, their applicability to excavation scenarios remains largely unvalidated. This work aims to bridge that gap by establishing an empirical estimation method based on field data. In addition, practical strategies for applying the observational method are explored, acknowledgeing the inherent uncertainties associated with frost action in geotechnical contexts.

2 SITES AND INSTRUMENTATION RESULTS

Data from instruments measuring structural response to frost action were gathered from deep excavations at three different locations: Drammen UDK02, Eidsvoll Wergelandstunnelen and Oslo Campus Ullevål.

2.1 *Drammen UDK02*

UDK02 was a railway project in which a 534 m long cut-and-cover tunnel was constructed in Drammen, Norway. In the northern part of the tunnel, the excavation was approximately 10 m deep and 17.5 m wide. The deep excavation was supported by two levels of internal steel pipe struts and a sheet pile wall. The depth of the excavation increased to approximately 20 m, and the width narrowed to 15.1 m in the southern part of the project. In the south, three levels of struts were used together with a diaphragm wall. The site conditions varied from soft normally consolidated quick clay over moraine, with decreasing thickness of the clay layer toward the south. The clay had a water content of about 29%.

A total of nine electric load cells were installed in four cross sections to measure and verify the calculated strut loads. The excavation was carried out in several sections, with the first section starting in December 2020 and the last section ending in September 2023. Only data from the struts in sections where little to no work that would significantly influence the strut loads were included. This is typically after the bottom slab had been cast and the lowest strut level had been removed. In this phase, the tunnel lining trolley was assembled and moved stepwise, and the tunnel was cast in sections of about 20 m.

Table 1 summarizes the measured data. The naming of the monitoring point is based on the section stationing, the strut level and the winter period to which the measurements correspond (first or second). For UDK02 there are measurements from three sections. Only measurements from the upper strut are included as the second (and third) strut level did not record the entire winter period and/or was influenced by excavation works. Two winter periods were recorded for each strut. The freezing index is defined in ISO 13793 (CEN, 2001) as 24 times the sum of the difference between 0°C and daily mean external air temperature, accumulated daily over the freezing season (including both positive and negative differences). The maximum freezing index recorded during the specified winter period is given in Table 1. The air temperature was gathered from the closest weather station (Drammen Berskog), located about 4 km away from the construction site. The frost-induced pressure was calculated by dividing the strut load by the idealized tributary area of the strut, defined as the product of the horizontal and vertical spacing of the struts.

Table 1. Instrumentation data from Drammen UDK02.

Monitoring point	Winter period	Max freezing index [K·h]	Change in strut force [kN]	Max frost pressure [kPa]
Strut 53705-S1-1	2020-21	8874	788	25.6
Strut 53705-S1-2	2021-22	5078	483	15.7
Strut 53922-S1-1	2021-22	5078	265	8.15
Strut 53922-S1-2	2022-23	8526	365	12.0
Strut 54110-S1-1	2021-22	5078	500	28.4
Strut 54110-S1-2	2022-23	8526	479	27.2

Struts 53705-S1 and 53922-S1 had a diameter of 508 mm and a pipe wall thickness of 10 mm. Strut 54110-S1 had a diameter, D, of 610 mm and a wall thickness, t, of 12,5 mm. The horizontal spacing between the struts was 5 m.

2.2 *Eidsvoll Wergelandstunnelen*

Wergelandstunnelen was a 380 m long cut-and-cover railway tunnel constructed adjacent to an existing tunnel in Eidsvoll, Norway. The excavation reached a maximum depth of approximately 30 m and was 11 m wide. The sheet pile wall was supported by two to four levels of steel pipe struts. Wergelandstunnelen is located just south of Eidsvoll Station, in a ravine landscape where the ridges and plateaus consist of sand underlain by stiff overconsolidated clay. The sheet pile wall was primarily installed in the overconsolidated clay, which had a water content of about 26%.

A total of fourteen electric load cells were installed in four cross sections. Temperature was also measured in the load cells. During the winter of 2020-2021, the bottom slab had been cast, the lowest strut had been removed, and formwork and casting of the tunnel were ongoing. As temperatures dropped below zero and frost began to develop, large increases in strut load were observed. Table 2 summarizes the measured data. For the third strut level, increases of up to 2500 kN were observed. The initial load of strut 66724-S3 was just below 5000 kN before frost development, meaning that the strut load increased by 51% during the winter.

Table 2. Instrumentation data from Eidsvoll Wergelandstunnelen.

Monitoring point	Pipe dim. (Dxt) [mm]	Max freezing index [K·h]	Change in strut force [kN]	Max frost pressure [kPa]
Strut 66585-S2	508x10	8191	356	23.0
Strut 66585-S3	610x12,5	7938	1368	37.0
Strut 66590-S2	508x10	8189	703	46.1
Strut 66719-S1	406,4x8	8255	675	47.6
Strut 66719-S2	610x12,5	7874	1186	63.5
Strut 66719-S3	813x14,2	7790	2193	66.3
Strut 66724-S1	406,4x8	8276	759	51.9
Strut 66724-S3	813x14,2	9254	2517	75.6

The struts were not designed to withstand frost pressure, and insulation of the excavation pit was delayed and inadequate. In early February, a tarpaulin was installed to cover the retaining wall and provide shelter, and heating of the enclosed area behind the tarpaulin was initiated using a coke-fuelled stove. The horizontal spacing between the struts was 5 m in sections 66585 and 66590 and was reduced to 4.5 m in sections 66719 and 66724.

2.3 *Oslo Campus Ullevål*

Campus Ullevål is the new office building of NGI in Oslo, Norway. The building consists of two structures with seven and ten storeys, respectively, as well as two basement levels, with a gross floor area of 36,800 m^2. The structure is cast in place up to the slab above level 2, and the superstructure is made of prefabricated concrete elements, glass/aluminium façade panels, and blue-green roofs. The site is covered by 1–2 m of fill and dry crust overlying soft quick clay with a water content of about 29%. The bedrock plunges from a depth of 20 to 40 m near the centre of the site, where the rock surface features local overhangs. The building is founded on driven HP piles and concrete piles to bedrock.

Excavation was enabled using lime-cement columns in the passive zone, a sheet pile wall, and internal inclined bracing against the base slab. The centre of the excavation pit was excavated first, and the base slab was cast. Excavation then proceeded step by step in sections, with internal bracing installed along the way. Once the bracing was in place, the remaining parts of the excavation were completed, and the base slab was cast up against the sheet pile wall before the bracing could be dismantled.

During the winter of 2023-2024, the internal bracing had been dismantled in the northern part of the excavation pit, and the sheet pile wall acted as a cantilever against the base slab. Ten In-Place-Inclinometers (IPI) and a laser total station with 37 prism targets were installed. 16 of these targets were located on top of the sheet pile wall. Air temperature data were gathered from the closest weather station (Oslo Blindern), located about 900 m away from the construction site, and a maximum freezing index of 9009 K·h was recorded during the winter of 2023-2024. Table 3 summarizes the measured data.

Table 3. Instrumentation data from Oslo Campus Ullevål.

Monitoring point	Excavation height [m]	Free length top [m]	Displacement [mm]	Max frost pressure [kPa]
Inclinometer IN3	6.25	0.00	62.7	28.9
Inclinometer IN5	6.35	0.00	38.0	14.2
Prism N01	6.69	0.36	74.6	21.1
Prism N10	6.55	0.50	61.4	18.4
Prism N12	6.56	0.49	65.7	19.6
Prism N15	6.54	0.51	81.6	24.6

Since the inclinometers and the total station measure horizontal deformation, converting these data to an equivalent frost pressure is not straightforward. The structural system was idealized as a cantilever beam, and the horizontal deformation at the top of the sheet pile wall is then given by the equation:

$$u_{top} = \tan\left(\frac{pH^3}{6EI}\right) * L_{free} + \frac{pH^4}{8EI} \tag{1}$$

where H is the excavation height (distance from terrain to excavation base), L_{free} is the length from terrain to the top of the sheet pile wall, p is the frost pressure, EI is the flexural stiffness of the sheet pile wall, and u_{top} is the horizontal deformation at the top of the sheet pile wall.

This equation has been solved numerically to estimate the frost pressure (p). It represents a simplification, as the sheet pile wall is not fully fixed to the base slab. Instead, the embedment length and the earth pressure against the embedded wall contribute to its rotational stiffness. However, the deformation pattern observed in the inclinometers closely matches the pattern obtained when assuming full fixation at the base slab level, as in an idealized cantilever beam. Moreover, reducing the rotational stiffness would result in greater deformation for a given pressure, meaning that assuming full fixation leads to a conservative (higher) estimate of the frost pressure.

3 REGRESSION ANALYSIS

To further investigate the relationship between frost action and structural response, regression analysis was performed on the collected data. A clear influence of frost is observed in the collected data. Figure 1 shows the measured strut load and the freezing index over time for strut 66719-S2 of Wergelandstunnelen. Similar trends are observed in the other measurements.

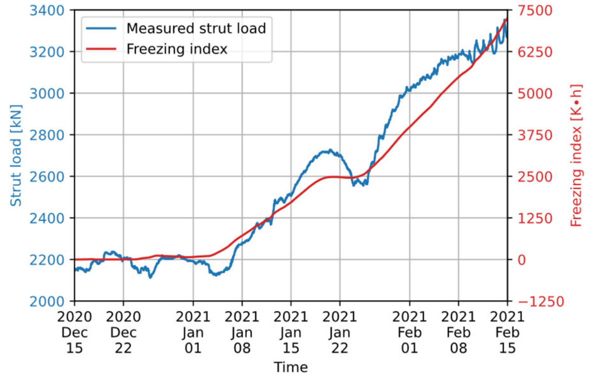

Figure 1. Freezing index and measured load in strut 66719-S2 against time.

Figure 2 shows the calculated frost pressure plotted against the freezing index for each of the monitoring points. All points exhibit a general trend of increasing frost pressure with increasing freezing index. The Michaelis-Menten equation, $\frac{aF}{b+F}$, where F is the freezing index and a and b are optimization parameters, provides a good fit between frost pressure and the freezing index for each individual monitoring point. However, the scatter between the different data points is significant.

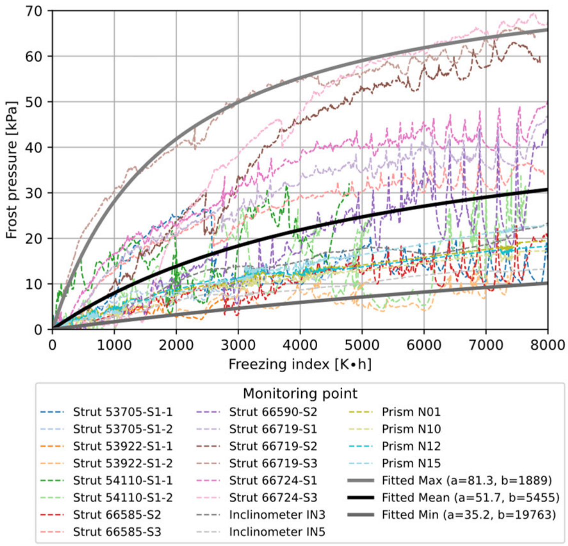

Figure 2. Frost pressure against freezing index.

There appears to be a tendency for higher frost pressures to develop in stiffer, more rigid support systems, which is expected. To investigate this further, the mean frost pressure was plotted for different ranges of freezing index values against various variables, such as depth to the strut level, excavation height, stiffness of the strut, stiffness of the waling beam and stiffness of the retaining wall. The strongest correlation was found between excavation height and mean frost pressure. Figure 3 shows the mean frost pressure for freezing index values in the range of 4000-4500 K·h plotted against excavation height. The mean frost pressure increases with increasing excavation height, and the relationship is best described by an exponential function.

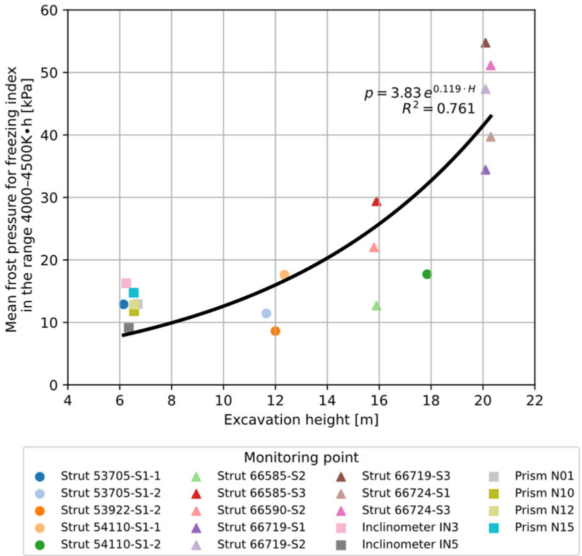

Figure 3. Mean frost pressure for freezing index in the range of 4000-4500 K·h against excavation height.

If the exponential function and the Michaelis-Menten equation are combined, the frost pressure can be estimated by:

$$p = \frac{aF}{b+F} * e^{cH} \tag{2}$$

where p is the frost pressure, H is the excavation height, F is the freezing index and a, b and c is the optimization parameters.

The coefficient of determination when fitting Equation (2) to the dataset becomes $R^2 = 0.84$, with a root-mean-square error (RMSE) of 7.84. If only the Michaelis-Menten equation is used, without the exponential term e^{cH}, the fit yields $R^2 = 0.58$ and RMSE = 12.8. Other regression models were tested as well, but Equation (2) provided the best-fit model to the dataset.

Figure 4 shows the residual plot for the model described by Equation (2). The plot on the left shows the best-fit model, while the plot on the right shows the model fitted with a conservative loss function. The conservative loss function weights the residuals during model fitting: positive residuals are given a weight of 1, while negative residuals are given a weight of 0.01. This penalizes underprediction of the frost pressure and results in a more "conservative" model. Figure 5 shows the freezing index plotted against the frost pressure, with contour lines representing the conservative regression model.

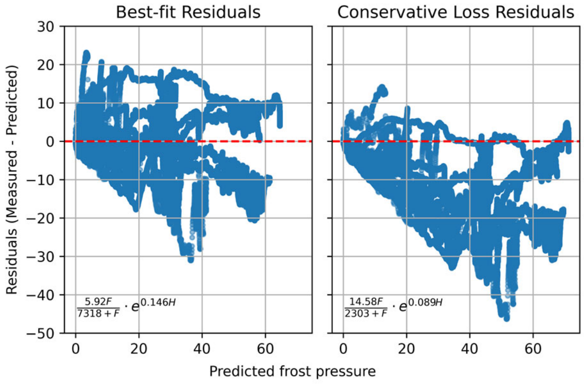

Figure 4. Residual plots of Equation (2) with best-fit optimization parameters (to the left) and with conservative optimization parameters (to the right).

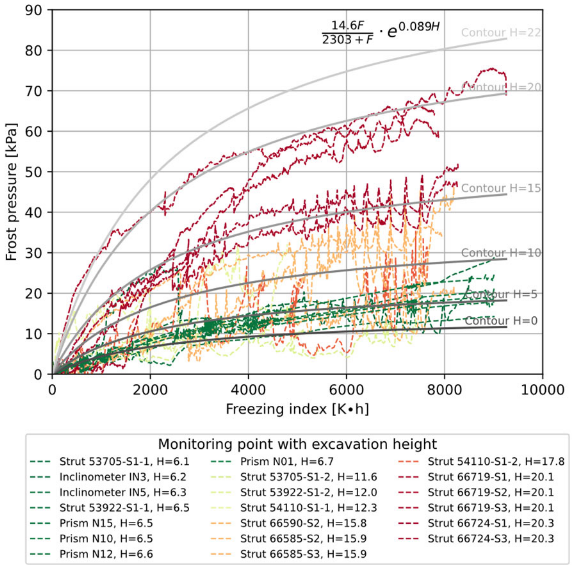

Figure 5. Frost pressure against freezing index with relation to excavation height.

4 DISCUSSION

Frost pressure develops on the retaining wall because the soil is not free to expand. The expansion of the soil leads to the development of passive earth pressure between the unfrozen soil and the ice lens, which equals the frost pressure that the retaining wall and struts transfer across the excavation pit. Frost pressure depends on the frost susceptibility of the soil and the cooling conditions, among other factors (as explained in the introduction). In the case of a deep excavation, it also depends on the stiffness of the structural system, which defines how much deformation is allowed in the structural components, and on the stiffness and strength of the soil, which determine how much deformation occurs in the soil (Eggestad, 1982).

The freezing index has been shown to be correlated with frost depth (ISO 13793 CEN, 2001; Berggren, 1943) and provides some insight into the amount of frost heave. However, it does not account for the rate of cooling, or freezing/thawing cycles, both of which have been shown to influence the frost heave (Taber, 1929). Excavation depth provides insight into both structural and soil stiffness. The stiffness and the strength of the soil are highly correlated with overburden pressure, which increase with excavation depth. For deeper excavations, the number and dimensions of the struts and the retaining wall also increase. Therefore, the observed correlation between frost pressure, excavation height, and freezing index is not surprising.

Soil grading, initial water content, and thermal properties would also be expected to influence frost pressure, but these properties were not characterized in sufficient detail in the projects to allow for correlation analysis. The three sites are also too similar in terms of soil characterization and properties. All three sites have clay as the main lithological unit, but with a clay content below 40%, classifying the soil as frost-susceptible at all three locations. The water content of the clay is also comparable across the sites, with the groundwater table located close to the terrain surface.

5 OBSERVATIONAL METHOD

5.1 *Description of the method*

The principal of the observational method is described in Eurocode 7 (CEN, 2020), but one of the first descriptions of this method related to field of geotechnics was provided by Peck (1969). Eurocode 7 states that when it is difficult to predict geotechnical behaviour, it may be appropriate to use the approach known as the observational method, where the design is verified during construction. The following requirements must be fulfilled before construction begins according to Eurocode 7 (CEN, 2020, 2.7 (2)P):

- Acceptable limits of behaviour shall be established.
- The range of possible behaviour shall be assessed and it shall be shown that there is an acceptable probability that the actual behaviour will be within the acceptable limits.
- A plan of monitoring shall be devised, which will reveal whether the actual behaviour lies within the acceptable limits. The monitoring shall make this clear at a sufficiently early stage, and with sufficiently short intervals to allow contingency actions to be undertaken successfully.
- The response time of the instruments and the procedures for analysing the results shall be sufficiently rapid in relation to the possible evolution of the system.
- A plan of contingency actions shall be devised, which may be adopted if the monitoring reveals behaviour outside acceptable limits.

Each of the requirements set by Eurocode 7 can be fulfilled for the case of frost-induced pressure on a retaining wall using the scheme suggested below.

5.2 *Prediction*

Firstly, the design must show that there is an acceptable probability that the actual behaviour will remain within the acceptable limits. For a given site, the freezing index for different return periods can be calculated based on meteorological data, and together with the excavation height, a first estimate can be made using the empirical regression model shown in Figure 5. More advanced numerical simulations can be performed if deemed necessary. However, most codes and computer programs designed for estimating frost heave (e.g., SSR, FROST, PC-Heave) are developed for roads, pavements, and buildings, and cannot model the issue at hand. Constitutive models for implementation in FEM, such as the Frozen and Unfrozen soil model (Ghoreishian Amiri et al. 2016; Aukenthaler, 2016), are recommended for accurately estimating soil-structure interaction with frost action included.

Once the most likely frost-induced pressure is determined, the capacity of struts, waling beams, and retaining wall can be checked for the combined effect of earth pressure and frost pressure. The robustness of the system (i.e. the extra capacity of the structural elements) is ultimately the designer’s choice. However, knowing that contingency actions can be taken implies that excessive conservatism should not be applied when estimating frost pressures. If the dimensions of the struts, waling beams, and retaining walls need to be increased due to frost pressures, it is likely that remedial measures such as insulation and/or heating would be more cost-effective.

In many Norwegian construction projects, frost-induced pressures are not accounted for in the design, and the contractor is responsible for prevention. This typically means that the retaining wall should be insulated during winter, but insulation is often applied late (after substantial frost has already developed) or not at all. If strut loads are measured, heating is initiated when loads approach the ultimate capacity of the struts. If strut loads are not measured, which is often the case for smaller excavations, the structural system is typically not designed to withstand extensive frost pressures, and measures such as insulation or heating are not always implemented. In such cases, both the designer and the contractor may be unaware of the potential for serious failure. Such a scenario lacks a proper contingency plan, a monitoring strategy, and a reliable assessment showing that the situation is likely to remain within acceptable limits.

5.3 *Monitoring*

The exact type and amount of instrumentation required for a specific project is not straightforward to determine on a general basis. Some general guidelines for monitoring the response to frost action in an excavation pit are provided below.

Direct measurements of the force in structural elements require fewer assumptions when defining the acceptable limits. The capacity of a strut with a given dimension is easily determined, and when combined with measurements of strut force using electric load cells, threshold limits for the struts can be clearly defined. However, if only strut force is measured, these limits should also account for the capacity of the waling beam and the retaining wall. If the capacity of the waling beam or the retaining wall is more critical, one should consider installing strain gauges or using fibre optic sensors to directly monitor the bending moments in these elements at critical locations.

Measurements of deformation using inclinometers, prisms etc., are also valuable for overall system monitoring. However, direct measurements of the response in critical elements are preferable when monitoring frost action, to accurately determine when contingency actions should be applied. Monitoring should be placed in the most critical cross-sections of the excavation to minimize risk. If the dimensions of structural elements vary across the excavation area, instrumentation should be considered for the most critical section within each area of varying dimensions.

5.4 *Contingency actions*

If the winter becomes colder than expected and the instrumentation reaches the threshold limits, contingency actions must be implemented. A common immediate measure used in Norway involves installing a tarpaulin over the retaining wall to provide shelter and heating the enclosed area behind the tarpaulin using a coke-fuelled stove or similar device. This method is simple to implement and effective. If the frost pressure is expected to become too large, the retaining wall can be insulated before winter to reduce the estimated frost pressure. As explained above, insulation is often not applied early enough or performed adequately. However, with satisfactory insulation, the freezing index in the soil will reduce and thereby reduce the frost pressure on the retaining wall.

Eurocode 7 also includes requirements regarding the response time of instruments, analysis of measurements, and implementation of contingency actions. In essence, Eurocode 7 requires that monitoring provides results early enough for contingency actions to be implemented before failure occurs. In the case of frost action, this is relatively easy to achieve. Frost pressure develops gradually, and weather forecasts can be used in combination with measured response to predict when contingency actions must be taken, often well in advance.

In the three projects mentioned above, strut loads were measured at intervals ranging from hourly to every 10 minutes and transmitted to a monitoring website via a field logger with an IoT modem. Multiple threshold limits were defined, with alerts sent via email, SMS, and phone call depending on the urgency of the warning. Systems like these are well-suited to this type of problem, offering instrumentation frequencies and update rates far higher than necessary for monitoring frost action.

6 CONCLUSIONS

This study has demonstrated that frost action can exert significant pressures on retaining structures in deep excavations, particularly when insulation is delayed or omitted. Through detailed instrumentation at three Norwegian construction sites, a clear relationship was established between frost-induced pressure, freezing index, and excavation height. The empirical model combining the Michaelis–Menten equation with an exponential function of excavation depth provided a strong fit to the observed data, offering a practical tool for estimating frost pressures in similar conditions.

The findings underscore the importance of proactive planning and monitoring in cold-climate excavation projects. While traditional design approaches often neglect frost pressures, this research highlights the potential for structural overload and failure when such effects are ignored. The observational method, as outlined in Eurocode 7, offers a viable framework for managing these risks. By integrating predictive modelling, real-time monitoring, and predefined contingency actions, such as insulation or ground heating, designers and contractors can ensure structural safety without excessive conservatism.

Ultimately, this paper advocates for a shift in practice: from reactive to predictive and adaptive management of frost action in temporary excavations. With appropriate instrumenttation and contingency planning, frost-induced pressures can be effectively mitigated, ensuring both safety and cost-efficiency in geotechnical design and construction.

7 FURTHER WORK

Future research should expand the dataset to include diverse soil types and better characterize thermal and hydraulic properties influencing frost action. Validation of the empirical model and optimization using a larger dataset that includes a broader range of soil types and site conditions would improve the model's generalizability and reliability. Additionally, advanced numerical simulations utilizing FEM and constitutive models that include the freezing/thawing effects should be calibrated against field data. Once validated, these models can be used in parametric studies to explore the influence of soil properties, structural stiffness, and thermal conditions on frost pressure on retaining walls, offering deeper insights for design and risk mitigation.

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