A glimpse into rapid freezing processes in clay with x-ray tomography

Giorgia Amato1,2 · Edward Andò1,3 · Chuangxin Lyu2 · Gioacchino Viggiani1 · Gudmund Reinar Eiksund2

Received: 22 September 2020 / Accepted: 30 March 2021 / Published online: 7 May 2021
© The Author(s), under exclusive licence to Springer-Verlag GmbH Germany, part of Springer Nature 2021

Abstract
This short paper proposes time-series x-ray tomography as a valuable tool for quantifying freezing processes in a remoulded clay. As an example, three simple closed system (i.e., no water entry) experiments are performed and analysed, all of which were frozen under relatively high but different thermal gradients. The progressive appearance of a zone of ice-lenses, and the deformation of the sample due to freezing and cryogenic consolidation is quantified with time—with the hope of providing data to THM models, and to this end the data presented are made available online. The rich patterns in the frozen zone are also illustrated and discussed. The measurement technique used has satisfactory performance and further work on open systems, different materials and different thermal gradients is expected to contribute significantly to understanding of the complex phenomena surrounding freezing in soil.

Keywords Freezing · Remoulded clay · Timeseries x-ray tomography

1 Introduction

Some soils are susceptible to frost heave when freezing. Frost heave is the upwards swelling of soil caused by an increasing volume of ice as it segregates into ice lenses in the ground, see Peppin and Style [19]. Because this can cause damage to road surfaces and foundations, it is a hot topic in geotechnical engineering, especially in regions characterised by long periods with freezing temperatures [10, 20]. Access to water from the unfrozen subsoil promotes growth of ice lenses [23]. Besides temperature and temperature gradient, soil permeability and water content play an important role in the speed of the frost front and amount of frost heave. Soil susceptibility to frost heave essentially depends on grain size distribution and fines content [13]. Soil freezing can also be an objective in itself, viz. ground freezing techniques for ground stabilisation, permeability reduction, as well as retrieval of “undisturbed” samples of non-cohesive soils.

The first laboratory experiments on soil freezing date back to almost a century ago [5, 23, 24]. The most important finding from these early studies is that the increase in volume is not only due to the increase in volume of frozen water, but also to a water migration process, from the unfrozen region of the soil towards the freezing front. This cemented the use of so-called open systems for the study of the geotechnical problem of freezing—these systems allow water supply to the sample during the freezing process. Miller [14] suggests the existence of an unfrozen water film surrounding the ice at temperatures below the freezing point, which allows the slow transport of liquid water through the partially frozen region of the soil. Later work from Miller [15, 16] suggests the existence of a “frozen fringe”—a zone between the 0°C isotherm and the warmest ice lenses.

There is no doubt that freezing processes in water-saturated fine-grained soils are complex, due to phase changes in the water and a number of resulting thermo-hydro-mechanical couplings—see Coussy [8] for a comprehensive description and framework. From the experimental point of view, the (typically) vertically aligned temperature gradient creates spatial heterogeneities that can seriously limit the quality of the interpretation of conventional (boundary or
bulk) measurements. Pioneering work by Akagawa [1, 2] using x-ray radiography and numerous thermocouples clearly recognises the need for full-field measurement to study frost heave and the characteristics of the frozen fringe in a water-saturated silty clay within an open system. X-ray radiography enabled the measurement of strain fields in the sample and the definition of the frozen fringe (whose location requires a full-field visualisation). Another pioneering application of x-ray radiography is by Penner [18], who studied the effects of freezing rate on ice lenses thickness and frequency, under a relatively slow temperature ramp as per Myrick et al. [17]. More recent work by Xia et al. [27] used time-series photography with a fluorescent tracer to observe the emergence of an ice-lens structure in samples with different vertical stresses, salinities of the pore water, and under different thermal gradients, noting a major effect of all three variables on the ice-lensing processes (thickness of the ice lenses and lenses spacing). Further work in the same vein [4] used digital image correlation to measure strain in the soil during the freezing process. This is a challenging application of image correlation, because of the emergence of lenses. Nonetheless, compression of the soil was measured in between and immediately ahead of the growing ice lenses, supporting an interpretation of cryogenic suction and thus consolidation.

The increased availability of x-ray tomography has also allowed the three-dimensional structure of frozen soils to be accessed. For example Calmels and Allard [7] used this measurement technique to analyse 10 cm diameter cores recovered from various permafrost landforms that originated from frost heave. These permafrost samples with high ice content are “geocryogenically” interpreted with respect to their structure and ice aggradation process. Later work by Torrance et al. [25] present 3D measurements in a sample with clear ice lenses, proving—but also stating—that: “adding CT scanning to the tools available to investigate the structure of frozen soils lead to improved understanding of the freezing process and of the consequences of freezing”. Viggiani et al. [26] also use x-ray tomography on different clays (kaolinite and bentonite) to show different 3D patterns of ice-lens formation, as well as density changes due to consolidation induced by cryogenic suction.

Bhreasail et al. [6] add the element of time (i.e., time-series x-ray tomographies) on the freezing of coarse-grained soils and glass ballotini with x-ray tomography, with the objective of characterising the formation of cracks in the ice phase. Along the same lines, Deville et al. [9], also use time-series synchrotron imaging to study the freezing dynamics of a colloidal silica aqueous suspension of 100 nm particles, resulting in frozen structure that are interpreted as ice lenses. Finally, Song et al. [21] have also recently presented laboratory x-ray tomographies of different soils freezing with relatively high spatial resolution but low temporal resolution.

The ice lensing process is by its very nature three-dimensional and born of instability, therefore time-resolved 3D observations are valuable to better characterise this complex thermo-hydro-mechanical process. This paper studies freezing processes in clays with finely time-resolved (with respect to the phenomenon) x-ray tomography for the first time. We perform an intentionally simple experiment with the main objective of measuring the potential of rapid x-ray imaging coupled with analysis for characterising freezing processes in soils. The experiment is a closed system (with no water entry) under relatively high thermal gradients selected not with the objective or pretence to be close to site conditions, but rather to provide a dynamic quantification of the process to inform thermo-hydro-mechanical modelling of freezing in clays.

2 Experimental methods

2.1 Material tested

The samples tested are of remoulded Onsøy clay. The material comes from a soft clay deposit of marine origin located in south-eastern Norway, about 100 km from Oslo. The site was established in 2016 by the Norwegian GeoTest Sites (NGTS) project [11]. The tested material is from the south-central part of the site and from depth 2.6 m to 4.0 m, and has a plastic limit of 28 % to 30 % and a liquid limit of 70 %. Due to its marine origin, the Onsøy clay has a salt content of 20–30 g/l and 50–70 % water content with a supercooling temperature lower than −3.5 °C to −4.5 °C and freezing temperature of about −2.5 °C (for the initiation of freezing).

The remoulding procedure was optimised (with a number of preliminary tomographic scans) to minimise the size and amount of air bubbles, finally resulting in an air bubble volume fraction of 1.1 %. The final procedure adopted for remoulding is a 72 h 1D consolidation at 57 kPa vertical stress of a homogeneous clay paste prepared around the liquid limit (67 % to 72 %), spooned into a consolidometer and de-bubbled with a vibrator for concrete for a few minutes. At the end of the procedure, the water content is 51 % to 56 %. Due to lack of material during this series of experiments, material was re-used after freezing experiments. During re-use, the process of adding de-mineralised water during remoulding is expected to cause a slight reduction in salt content.

2.2 Experimental conditions

Consolidated cylindrical samples measuring 70 mm diameter and approximately 70 mm height were
surrounded by a latex membrane and capped top and bottom by aluminium cylindrical base plates (selected as a reasonable compromise between x-ray absorption and thermal conductivity).

The source of cold used for the experiments is a frozen saline solution (brine), which allows a constant temperature to be imposed for a few hours without the need for sophisticated control and heatsink required for a Peltier element. Three saline mixtures with melting points of approximately \(-21\,^\circ C\), \(-12\,^\circ C\), and \(-5\,^\circ C\) were prepared inside a plastic container of about 5 litres, with a solid support piece for the sample frozen into the brine. This container is placed on a 3 cm insulation plate into the bottom of a 10 litre plastic container.

Remoulded clay samples (within membrane and between bases) are stored at room temperature (\(\approx 21^\circ C\) as set on the temperature control for the room). To start an experiment, the clay sample is placed on the support piece frozen into the brine, and the outer container is filled until the top of the sample with polystyrene granules, with the aim to impose an adiabatic boundary condition (i.e., an approximately vertical thermal gradient). The samples frozen at \(-5\,^\circ C\), \(-12\,^\circ C\), and \(-21\,^\circ C\), have water contents of 56 %, 51 %, and 55 %, respectively. A schematic of the setup used is presented in Fig. 1.

It should be noted that six thermocouples were installed in and around the sample with the aim of allowing temperatures to be monitored during the experiment. Mutually inconsistent results were obtained for the thermocouple measurements perhaps due to x-ray interference (Kollie et al. [12]), and therefore these measurements are considered as unreliable and have been discarded from the analysis, but are given in an appendix for completeness.

As soon as possible after the sample is placed on the support piece frozen into the brine, x-ray tomography is used to obtain a time series of 3D images of the freezing process. This time series represents the volumetric variation of a reconstructed “CT value”—roughly proportional to x-ray attenuation and thus density—through time. The microfocus x-ray scanner in Laboratoire 3SR is used for this study, please refer to Viggiani et al. [26] for technical details. Given the relative speed of the process, rapid imaging is favoured, at the expense of spatial resolution and noise in the reconstructed field. Back-to-back 360\(^\circ\) scans of about 6 min with a pixel size of 120 \(\mu m/px\) are performed. Movements happening during a scan will be blurred in the reconstructed 3D images, the short scanning time has been selected to minimise this effect. Experiments are run for a number of hours; here only the first 6 hours of each experiment (where a reasonably constant temperature is applied to the bottom) are discussed.

### 3 Results

#### 3.1 Experimental observations

Given the four-dimensional nature (3D of space varying through time) of the data collected for each temperature, there is a significant challenge in presenting the data in print. The relatively fine time resolution for laboratory-based x-ray tomography—6 h of following the process implies 60 scans—further complicates the presentation the data.

Figure 2 shows a very limited (in time) sub-selection of the x-ray tomography data (after registration—see below) extracted from the different time series at the same time from the first detection of the frost front. It is important to note that between each column there are 19 images “skipped” between the measurements that are presented.

Looking at the first column for each experiment, it is clear that despite the relatively large pixel size and relatively high noise in the images, the clay in the sample is clearly distinguishable from the outside air/polystyrene as well as the top and bottom aluminium caps (although the horizontal centre of the image is perturbed by a reconstruction artefact at the contact between aluminium and sample). Some air bubbles and denser inclusions are visible within the clay.

Looking now to the evolution in time for every experiment, several phenomena are visible:

- A zone “striped” with much lower CT values propagates from the bottom upwards
- The speed of propagation of this zone is higher for experiments with a larger thermal gradient (i.e., for lower temperature at the bottom)
- Significant lateral deformation of the sample occurs related to the presence of the striped zone, in all cases going towards an hourglass shape.
[51x381]– careful observation of the top cap (especially for the colder experiments) shows that the cap rises slightly compared to the bottom cap (which is stationary), indicating an increase in height of the specimen
[65x381]– the CT value of the clay far from the striped zone (i.e., below the top cap) does not appear to be significantly modified by the process being observed
[65x378]– the spacing and size (thickness and length) of stripes increases with elevation in all three tests
[65x378]– the stripes appear to show a preferential horizontal organisation interrupted by stripes in other orientations

The “striped” zone, with what appears to be cracks with lower density is interpreted as being zones of pure ice segregated from the clay. In the terminology of frozen ground this zone can be considered as filled with “ice lenses”.

3.2 Quantification

With the aim of quantifying the freezing process, a phase map is computed for each experiment. This requires first of all an alignment of all the images (this is done by performing a rigid-body registration on the bottom of the sample with the SPAM toolkit, see Andò et al. [3], Stamati et al. [22]) and applying it to the whole image, so that any possible rearrangements due to the melting of the brine around the support are cancelled. With the aligned images, a centred circular mask that selects the majority of the cross section of each sample (diameter 62.4 mm / 520 px) is applied to each horizontal slice on which the mean CT value is computed. This yields a 1D vertical profile through time, which is presented in greylevels, for the experiment at −12°C on the top of Fig. 3. In this 2D space with time on the x axis and vertical elevation on the y axis, points represent the mean CT value (in the horizontal mask defined above) at a given elevation and time. The high CT-value aluminium platens are clearly visible, although their boundaries are not as sharp as might be hoped: this can be explained by a possible slight misalignment of the caps compared to the coordinate system, but is also strongly affected by the density contrast artefact between platen and clay which is visible in Fig. 2—this means that the top and bottom edges have uncertain CT values. The left-most vertical profile shows a relatively homogeneous averaged x-ray attenuation value between the aluminium platens. As time progresses the density field is disturbed and three zones at different elevations become clear (from top to bottom):

– (black) an upper zone whose CT value appears not to change significantly with time
– (red) an intermediate zone with an increased (lighter) CT value, indicating higher density (i.e., consolidating)
– (blue) a lower zone with a reduced (darker) CT value, representing the ice-filled region

The boundaries between these three zones are identified as follows: the position of the peak of CT value is first detected between the top caps, and then the maximum elevation of the intermediate (denser) zone is defined as the first point upwards of the peak below a given threshold. Similarly, the maximum elevation of the ice-filled zone is defined as the first point under the peak below a given (different) threshold. The pertinence of these relatively arbitrary thresholds is validated for each experiment by using both the equivalent of Fig. 3 as well as by tracing the identified elevation on vertical slices such as those in Fig. 2—the values selected are inherently available in the data accompanying this paper. These identified boundaries are shown with red and blue symbols on the top part of

![Image](image_url)
Fig. 3 and on the bottom part of the figure are used to colour the relevant portion of the CT profile according to the zone.

Figure 4 (left) presents the same information as Fig. 3, but for each experiment, and with time 0 corresponding to the first time the ice-filled zone is detected. Furthermore, the top and bottom boundaries of the specimen, obtained with a simple threshold, are also added in black.

The rate of advancement of the ice-filled zone—as seen qualitatively in Fig. 2—clearly shows a dependence on the thermal gradient—Table 1 presents the rate measured between 1 and 3 h of the front being detected.

The visual inspection of the elevation of the specimen boundaries (black) shows that in all cases the top is lifting, and there is a small downwards motion of the bottom (sufficiently subtle to not be corrected by the registration applied). The overall shortening (Δh/h₀) for each sample over the 6 hours presented is given in Table 1.

Another important feature to observe is the apparent thickness of the consolidating zone. First it is important to note that the thresholding approach breaks down for the coldest experiment as the consolidation front approaches the top cap (and the CT value no longer goes below the defined threshold); the points have been removed and a speculative dashed grey line has been added. Looking at −0.05 and −21, a constant thickness of the consolidating zone is eventually reached. The time it takes for this thickness to become constant is 2 h for −0.05, and 1 h for −21. However, in the case of −12 the thickness appears not to completely stabilise by the end of the analysed 6 h. This inconsistency could possibly be explained by the balancing of the characteristic times of the mechanisms of consolidation and freezing under this intermediate thermal

![Graphs showing geometric evolution in time of all three samples.](image-url)

Fig. 4 Geometrical evolution in time of all three samples, starting from the first detection of the ice in the specimen. (Left) as per Fig. 3 detected elevations of specimen edges and fronts of ice-filled zone and consolidating zone. (Right) Hourly snapshots of the normalised change in radius (Δr/r₀) of the specimen with r₀ being the initial radius.

 Springer
gradient, meaning that the process does not reach equilibrium during the observation time. This speculation clearly requires more experiments with different thermal gradients to be verified, as well as more advanced quantification. It should also be noted that \(-12\) has lower initial water content of this sample compared to the other two. The values of the thickness at 3 h are presented in Table 1, and appear not to follow the trend of the coldest experiment giving the most intense response.

The right column in Fig. 4 presents the evolution of the radial strain of the sample extracted at hourly snapshots going from blue to red with time (again from the first time the ice-filled zone is detected). This measurement is again obtained by applying a threshold to identify the entire sample, and the equivalent radius of each horizontal slice is computed from the area selected. This measurement is slightly perturbed by the presence of top and bottom caps, which can be safely ignored. What is visible, as previously described by the “hourglass shape” when commenting Fig. 2, is an overall reduction in radius, whose peak roughly corresponds to the top front of the ice-filled zone. In the coldest experiment, a stable value of slightly less than 4 % of change in radius is obtained, whereas for the other two experiments, a stable value does not appear to be reached; however, there appears to be a tendency towards 4 % or slightly higher. In these two experiments, another feature is visible, which is an increase in radius from the first hour at the very bottom of the sample, i.e., in the ice-filled zone. This indicates that the volumetric expansion due to freezing in all but this zone at the very bottom, is not sufficient to counteract the volumetric reduction due to cryogenic suction.

### 3.3 Description of the structure of the frozen zone

The geometrical characterisation of the frozen zone’s structure is a challenging task. Figures 5 and 6 present different views of this zone from all three experiments 6 h after the appearance of the first ice lenses, revealing a significant amount of geometrical complexity.

Figure 5 presents equally spaced horizontal slices through the frozen zone as defined in the measurements presented in Fig. 4. One first effect which is visible is that the thickness and spacing of the lenses clearly has a vertical dependence, with thicker and more widely spaced lenses being at the top (warmer). It is remarkable that—in a purely qualitative way—the ice lens structure appears to be relatively comparable for each row, indicating that the normalisation chosen (equal spacing over the final height of the frozen zone) may capture something important about this process. If the rate of advancement of the ice front is taken as constant (Fig. 4), then rows in Fig. 5 would have frozen at the same time since the appearance of the first lenses.

Furthermore, Fig. 5 reveals—in different ways for all three specimens—a “swirling” effect\(^1\). Especially for \(-21\) a clearly demarcated external ring (occupying the external third of the radius) in the ice-lens structure is visible. The ice-lens structure creating this effect may reflect a trace of the way in which the slurry is deposited—although more experiments are clearly needed to confirm or invalidate this hypothesis.

Figure 6 shows, for each experiment, a 3D rendering of an off-centre virtual core (diameter 20 mm) at four different angles. The objective of this figure is to illustrate the 3D structure formed by the lenses and its strong variability. The “ladder-like” structure discussed in Peppin and Style [19] is visible, but the overall pattern is clearly more complex. A quantitative description of the geometrical structure in these experiments is clearly of great interest for further progress, and it is to this end that our treated data are online, in order to facilitate and encourage efforts in this direction.

### 4 Interpretation and conclusions

The picture painted by the measurements presented above is of a rich thermo-hydro-mechanical process. While its quantitative interpretation is outside the scope of the paper, since the images acquired would have to be supplemented by pore pressure and temperature field measurements, this

---

\(^1\) Readers are encouraged to download the raw data for these experiments and scroll through the slices.
section attempts to provide some qualitative interpretation of the phenomenon.

The three experiments analysed in this work were designed to be 1D freezing with an essentially vertical thermal gradient—although some effort was made in lowering the thermal conductivity of the radial boundary condition, it cannot be proved that the gradient is completely 1D. This being said, the process revealed by the x-ray tomography images seems to confirm a process which develops vertically.

Samples start at room temperature, and in the case of the lowest thermal gradient some time goes by until ice
segregation becomes visible at the lower boundary. This indicates that a threshold freezing temperature needs to be reached (estimated to be $-2^\circ C$ for this clay). At this temperature the “free” water in the clay starts to freeze. From the beginning of the freezing process, ice segregation is visible in the form of ice lenses—zones of pure frozen water. This segregated structure appears to hold the trace of a physical instability where an ice crystal forms in a pore and grows thanks to the continued cold. Significant capillary pressures arise thanks to the water-ice interfacial tension and the relatively small pore size in this clay. These pressures overcome the local effective stress to the point where the clay can be cracked and displaced, which results in the visible segregated ice structures.

As the material freezes, these capillary forces result in cryogenic suction. Since the permeability of the frozen zone is very low compared to the unfrozen material above, the suction generated will principally affect the warmer, unfrozen material by increasing effective stress and causing cryogenic consolidation. In the relatively soft material studied, the increase in density of the material is clearly visible ahead of the frozen zone, especially in Fig. 3.

Essentially there are two (thermo)-hydro-mechanical processes occurring at the same time:

- a freezing process which is advancing in one dimension, and creating ice lenses with a complex 3D structure (Figs. 5 and 6). The development of ice lenses tends to increase the volume of the sample—however given the naturally heterogeneous structure of the segregated ice it is reasonable to expect that this is reflected in preferential directions of dilation
- a consolidation process driven by cryogenic suction, which is likely to be more isotropic (although heterogeneous permeability and stiffness will affect this)

These two processes each have their own rate or characteristic time (the first relating to thermal conductivity and the second to permeability), although related through cryogenic suction. The interplay between these two characteristic times could explain the non-monotonic evolution of the thickness of the consolidation zone with thermal gradient from one experiment to the other. Entering the realm of speculation, one might imagine that the experiment with the largest gradient may be freezing so fast that there is less time for consolidation—approaching “flash” freezing. It must be noted however that the middle experiment had a lower water content than the others, so the above comment is all the more speculative.

5 Perspectives for further work

The raw data and accompanying measurements are online in the Zenodo repository—see Data availability section below. By openly providing the community with this dataset, we hope to encourage future work in a number of directions.

The first direction is further experimental work in this vein. In fact, there are a number of obvious limitations in the study presented here; the rich imaging could and should be supplemented with better local temperature measurements as well as some local pore pressure measurements. While the objective of this study was not to reproduce geotechnically relevant site conditions, it is clear that the measurement techniques and analysis presented herein can be applied to more geotechnically realistic conditions: first and foremost “open systems” (where water supply is available to the soil), types of soil (silt rather than clay) and thermal and mechanical boundary conditions (for example smaller thermal gradients and zero radial dilation, i.e., oedometer conditions).

Another clear direction for further comprehension of this phenomenon is that of comparing the evolution measured here with the one predicted by a numerical or analytical thermo-hydro-mechanical model. The approximate 1D conditions applied to the sample here were explicitly selected to encourage simple modelling of the test. To this end it is important to stress that although there are doubts about the thermocouple measurements recorded during the test, they are provided in the appendix for a qualitative evolution of the thermal boundary conditions.

Appendix: Thermocouple measurements

As mentioned in the main text, the thermocouples used gave some inconsistent results and are not included in the main text. However for completeness, and since—in the authors’ opinion—these measurements give a qualitative evolution during the experiments, they are included below in Fig. 7.

A number of inconsistencies is visible—the most worrying of which are the crossing of mid-membrane and the top cap in experiment $-05$ the brine temperature with the metal bottom cap in experiment $-12$. At the beginning of the curves, the setup of the experiment is clearly visible, the time for the first scan is vaguely estimated as 0.9, 0.5 and 0.4 hours, for $-05$, $-12$ and $-21$, respectively.
Acknowledgements

The present work was undertaken in the context of G.R. Eiksund’s sabbatical at Laboratoire 3SR in 2019 and G. Amato’s masters thesis, both of which were financially supported by the Department of Civil and Environmental Engineering at NTNU. NTNU would like to acknowledge the Nunataruk project which is financing the PhD work of C. Lyu. The authors would like to thank F. Flin (Centre des Études de la Neige) for suggesting the use of eutectic mixtures of brine to impose a low temperature at the bottom of the specimen. The contribution of P. Charrier to the experimental setup and A. Di Donna for the sample preparation technique are also gratefully acknowledged. Laboratoire 3SR is part of the LabEx Tec 21 (Investissements d’Avenir - grant agreement n°ANR-11-LABX-0030).

Data availability

The raw data and processing scripts are shared with the community on the Zenodo platform, this repository is https://orcid.org/10.5281/zenodo.3826146. The repository is organised as follows for each experiment (−05, −12, −21): – Raw, reconstructed tomography data (rigid registration with SPAM where necessary) – Scripts to generate Figs. 3 and 4 – Thermocouple measurements

Fig. 7 Evolution of thermocouple measurements for the three experiments

References

1. Akagawa S (1988) Experimental study of frozen fringe characteristics. Cold Reg Sci Technol 15(3):209–223
2. Akagawa S (1990) X-ray photography method for experimental studies of the frozen fringe characteristics of freezing soil. Technical report. Cold Regions Research and Engineering Lab, Hanover, NH
3. Ando E, Cailletaud R, Roubin E, Stamati O, The spam contributors (2017) Spam: the software for the practical analysis of materials. https://tk.gricad-pages.univ-grenoble-alpes.fr/spam/
4. Arenson LU, Sego DC, Take WA (2007) Measurement of ice lens growth and soil consolidation during frost penetration using particle image velocimetry (piv). In: Proceedings of the 60th Canadian Geotechnical Conference. Ottawa ON, pp 2046–2053
5. Beskow G (1935) Soil freezing and frost heaving with special application to roads and railroads. Swed Geol Soc C 375:14–21
6. Bhreaisal AN, Lee P, O’Sullivan C, Fenton C, Hamilton R, Rockett P, Connolley T (2012) In-situ observation of cracks in frozen soil using synchrotron tomography. Permafrost Periglac Process 23(2):170–176
7. Calmels F, Allard M (2008) Segregated ice structures in various heaved permafrost landforms through CT scan. Earth Surf Process Landf J Br Geomorphol Res Group 33(2):209–225
8. Coussy O (2005) Poromechanics of freezing materials. J Mech Phys Solids 53(8):1689–1718
9. Deville S, Adrien J, Maire E, Scheel M, Di Michiel M (2013) Time-lapse, three-dimensional in situ imaging of ice crystal growth in a colloidal silica suspension. Acta Mater 61(6):2077–2086
10. Dysli M (1991) Le gel et son action sur les sols et les fondateurs. PPUR presses polytechniques
11. Gundersen A, Hansen R, Lunne T, Heureux JS, Strandvik SO (2019) Characterization and engineering properties of the ngts onspy soft clay site
12. Kollie T, Anderson R, Horton J, Roberts M (1977) Large thermocouple thermometry errors caused by magnetic fields. Rev Sci Instrum 48(5):501–511
13. Konrad JM, Duquennoi C (1993) A model for water transport and ice lensing in freezing soils. Water Resour Res 29(9):3109–3124
14. Miller R (1972) Freezing and heaving of saturated and unsaturated soils. Highway Res Rec 39(1):1–11
15. Miller R (1977) Lens initiation in secondary heaving. Proc Int Symp Frost Action Soils Luleå Alltryck AB Luleå Sweden 2:68–74
16. Miller R (1978) Frost heaving in non-colloidal soils. In: Proceedings of the 3rd international conference on permafrost, Edmonton, vol I, pp 707–713
17. Myrick J, Issacs R, Liv C, Luce R (1982) The frost heave program of the alaskan natural gas transportation system. Am Soc Mech Eng (Pap) (United States) 82(CONF-821101)
18. Penner E (1986) Ice lensing in layered soils. Can Geotech J 23(3):334–340
19. Peppin SS, Style RW (2013) The physics of frost heave and ice-lens growth. Vadose Zone J 12:1
20. Sheng D, Axelsson K, Knutsson S (1995) Frost heave due to ice lens formation in freezing soils: I theory and verification. Hydrol Res 26(2):125–146
21. Song B, Nakamura D, Kawaguchi T, Kawajiri S, Yamashita S, Rui D (2017) Internal observation of soil in frost heave process using the X-ray ct scan. Cong Tech Adv 2017:71–78
22. Stamati O, Andò E, Roubin E, Cailletaud R, Wiebicke M, Pinzon G, Coutre C, Hurley RC, Caulk R, Caillerie D et al (2020) Spam: software for practical analysis of materials. J Open Sour Softw 5(51):2286
23. Taber S (1929) Frost heaving. J Geol 37(5):428–461
24. Taber S (1930) The mechanics of frost heaving. J Geol 38(4):303–317
25. Torrance J, Elliot T, Martin R, Heck R (2008) X-ray computed tomography of frozen soil. Cold Reg Sci Technol 53(1):75–82
26. Viggiani G, Andò E, Takano D, Santamarina J (2015) Laboratory x-ray tomography: a valuable experimental tool for revealing processes in soils. Geotech Test J 38(1):61–71
27. Xia D, Arenson LU, Biggar KW, Sego DC (2005) Freezing process in devon silt-using time-lapse photography. In: Proceedings of the 58th Canadian Geotechnical Conference, Saskatoon, Saskatchewan

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.