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Ice-affected soil systems under rapid climate warming - insights from the past

Abstract. Current climate warming is expected to lead to ongoing geotechnical change in ice-affected soils. Examining past climate change, particularly cold stage:warm stage transitions can provide an insight into the potential nature of this change and may inform assessments of sites. The evidence is sometimes ambiguous, with periglacial and seismic processes producing similar results. Ice core evidence suggests that cold-warm transitions, such as during the onset of the Greenlandian stage of the Holocene can be high magnitude, but also may feature reversals that add instability to soil systems. Consideration of future geotechnical change in ice-affected soils must therefore take into account potentially complex climate forcing.
Keywords: Periglacial, Greenlandian, deformation, climate change, thaw.

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Introduction

There is scientific consensus that the world is experiencing a period of climatic change, with generally warmer global conditions already becoming apparent (ref). Predictive models suggest the change will continue, with mid- and high-latitude regions being particularly affected. This can be expected to impact on soil systems with distinct threshold conditions, particularly those which are currently characterised by the presence of ice for at least part of the year. The phase change in water in these soils, whether it is in the extent, duration or frequency of freeze-thaw, can be expected to alter their geomechanical properties in the short term and may leave a long term impact.

An understanding of ice-affected soil behaviour during warming episodes is clearly of scientific interest. It is also directly relevant to engineering design which needs to identify and address all the actions and influences that may affect a site (cf. Eurocode: BSI 2002).

Although there is a growing body of research detailing recent change in ice-affected soil systems and associated features in response to warming, the time span of these studies is only just beginning to reveal what may happen as the warming trend continues. There is also an understandable bias towards what might be considered the most sensitive contexts, particularly regions where permafrost is already at the thaw threshold and mountainous sites where steep slopes accentuate change (e.g. Harris et al. 2009; Gao et al. 2021).

These studies are very important, of course, but might not provide a close analogue to what could happen in lower latitude areas affected by higher insolation or by seasonal freezing, or in the coldest high latitude regions. Understanding the potential for geomechanical changes in soils in these areas is important as they are extensive and also home to significant human populations. In such areas, change might be expected to often take place less rapidly and is likely to vary from place to place, reflecting locally different conditions. However, these assumptions need to be tested.

One way to evaluate how ground systems might change is to examine what has happened in the past. In this paper, the influence on soils of the warming event that marked the last glacial-interglacial transitionsexamined for areas that were under periglacial conditions, with a focus on the mid-latitudes, using selected sites. The implications for future changes to fundamental geotechnical parameters are considered.

Cold-stage:warm-stage transitions in the past

The current geological period, the Quaternary, has been marked by multiple climatic shifts. In mid-high latitudes, these are typically characterised as alternating Ice Ages and interglacials, with cycles occuring over tens of thousands of years, or longer. The reality is that the climatic shifts have often been much shorter, with sometimes abrupt transitions (Taylor et al. 1993).

Unfortunately, issues with preservation and dating mean that it is not always possible to assess whether an identified change in ground conditions occurred at a climate transition or was due to a temporary thaw. There are also issues with interpretation which often reflect the investigator's training – the most obvious being the similarity between features associated with changes in soil ice conditions and those induced by seismicity (van Vliet-Lanoe et al. 2004).In some locations, where regional deglaciation caused glacio-tectonic adjustments, both freeze-thaw and seismicity may have affected soil strength and behaviour. An example of where compressive loading and liquefaction may have happened at around the same time is shown in Figure 1.

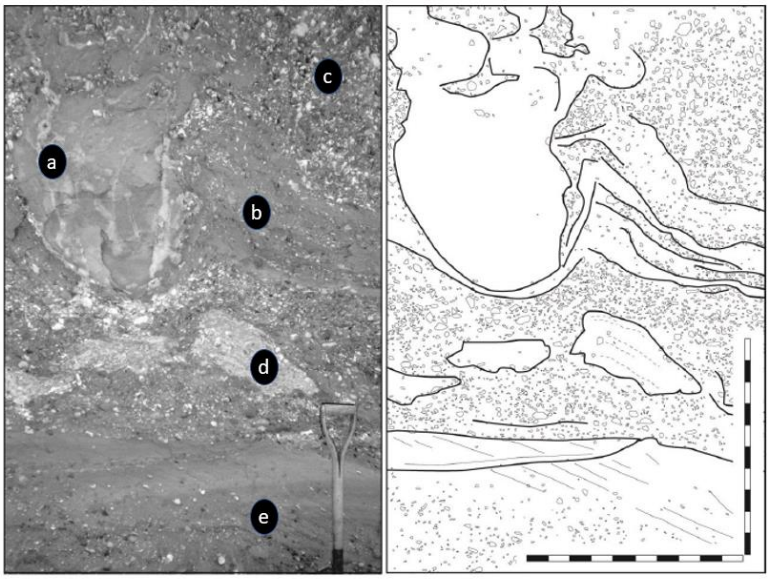

Figure 1. Deformed Middle Quaternary fluvially-derived soils from a site in south-central England. a) sand-silt load cast; b) 'kink' structure indicating lateral compression; c) unstructured sand-clay-gravel, with occasional vertically-oriented clasts; d) boudinage-like structure where a depositional unit has been deformed and broke, with possible rounding of some edges suggesting movement in a liquefied mass; e) undisturbed fluvial sandy gravel.

A selection of different types of feature that could be interpreted either way are presented in Table 1 (modified from Collins 2014).

Table 1

Selected soft sediment deformation structures that might indicate warming or seismicity. Processes most likely to be linked to ice collapse/thaw are marked with an *. Sources provided in Collins 2014.

Periglacial		***Seismic***	
Form	Process and key features	*Form*	Process and key features
Vertically oriented clasts	1. Differential freeze-thaw heave between a clast and the soil/sediment matrix leading to vertical movement and alignment. May occur at a uniform depth across a unit/site	*Aligned clasts*	Clasts aligned to flow of liquefied material. Localised.

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	2. Rapid thaw leading to liquefaction and clast alignment*		
Fissure fill / Sediment wedge	Gravity driven (i.e. downwards) infilling of thermal contraction or mass movement-induced fissure. Typically wider at top. May show stratification.*	*Dyke – Neptunian (formed under water) / Fissure fill (sub-aerial)*	Gravity driven (i.e. downwards) infilling of seismically-induced fissure. Typically wider at top. May show stratification.
		Dyke - injection	Pore fluid pressure driven infilling of fissure (principally upwards). Typically narrower at top. Particles may be graded (fining up).
		Sill - injection	Pore fluid pressure driven infilling of fissure (principally lateral).
Ice wedge cast	1. 2. Cyclic thermal contraction/expansion of permafrost producing surficial crack that progressively infills and widens. Often in a polygon. 3. Thaw of ice wedge producing “draw-down” of overlying and adjacent soil/sediment along a line. *	*Thixotropic wedge*	Subsurface movement (and consolidation?) resulting in “draw-down” of overlying and adjacent soil/sediment in a limited area (cm^2?) or along a line.
Mud boil	Surface accumulation fed from injection pipe or larger fissure that reaches the surface.*	*Sand volcano, sand boil*	Surface accumulation fed from typically linear injection dyke that reaches the surface.
Thermokarst depression	Surface depression formed by thaw of ground ice resulting in “draw-down” of overlying soil/sediment in a broad area (m^2 to km^2). May subsequently be infilled.*	*Thixotropic bowl*	Surface depression formed by subsurface movement (and consolidation?) resulting in “draw-down” of overlying soil/sediment in a broad area (m^2?). May subsequently be infilled.

		Floating breccia	Fragments of a previously intact unit, broken by intense lateral cyclic shear and suspended within a matrix of liquefied sediment/soil. Individual fragments might themselves exhibit internal deformation. May be at a ± uniform elevation and may show evidence of horizontal attenuation (pseudo-boudinage structure).
Flame structures	1. Plastic upwards deformation under cyclic freeze-thaw stress* 2. Liquid limit exceeded and spatially variable loading causing injection into overlying soils*	*Diapiric structures*	Plastic upward deformation under seismic load stress. Grades into injection dykes if soil/sediment becomes fully liquefied. Reflects deeper unit having a lower dynamic viscosity than overlying soil/sediment. Margins may feature micro-faults, with upwards displacement. Adjacent areas may show evidence of subsidence.
Load cast, pillow structures	Isolated mass of sediment that has sunk into an underlying unit that has experienced freeze-thaw induced plastic deformation, liquefaction and/or localised consolidation producing density changes.*	*Load cast, pillow structures*	Isolated mass of sediment that has sunk into an underlying unit that has experienced hydro-plastic deformation, liquefaction and/or localised consolidation due to cyclic shear density changes. Range of sizes (<cm to >m).
		Dish/Pocket-and-pillar structures	Modification of existing structures due to shock-induced dewatering.
Involutions	Plastic deformations resulting from ice growth and decay. May also result from rapid thaw settlement and liquefaction.*	*Sismoslump / Involutions*	Convoluted sedimentary structures reflecting in situ deformation due to cyclic lateral seismic loading. Under- and overlying strata may be intact or show grading (increasing deformation towards surface). Structures may show no sign of compression due to subsequent burial.
Wavy structures	Plastic deformations resulting from ice growth and decay.	*Wavy structure / anticline-syncline*	± uniformly folded unit reflecting in situ deformation due to cyclic lateral seismic loading. Under- and overlying strata may be intact or show grading (increasing deformation towards surface). Structures may show no sign of compression due to subsequent burial.

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Impact of the last glacial-interglacial transition on terrestrial ground systems

The most precisely defined of the major Quaternary climate transitions is the Late Pleistocene to Holocene. The end of the last major glacial period (Marine Oxygen Isotope stage 2) was marked by significant climatic change. After a glacial maximum at approximately 20,000 years before present (20 kaBP), many geological sites around the world record a warming episode peaking at about 13kaBP, before a return to cold conditions that ended at around 11.65 kaBP i.e. the start of the Greenlandian stage of the Holocene interglacial (Walker et al. 2018).

Characteristics of the Greenlandian

Ice core and other evidence indicates that the transition into the Greenlandianat about 11.65 kaBPwas marked by a significant warming in the northern Hemisphere over a short period – perhaps less than 100 years (Figure 2). The Greenlandian itself, at least in North Atlantic and adjacent areas, was marked by some ongoing climatic instability, reflectingchanges in the relative significance of warm oceanic waters moving north and pulses of meltwater from the North American, Greenland and north European ice sheets (van der Bilt et al. 2019). This instability appears to be shown in ice core data where the rate of change in the climate proxy$d^{18}O$ fluctuates during and after the transition.

Terrestrial impact of the Younger Dryas-Greenlandian transition

It is logical to presume that the impact of this climate change on terrestrial ground environments was substantial and rapid. Direct and unambiguous evidence of how these conditions changed is, however, limited. This is partly due to subsequent erosion, and partly due to lack of dating control. Many features attributeto freeze-thaw and other ice-related processes during the Younger Dryas or earlier date to this transition period.

The scale of the change that affected at least the geotechnical properties of at least the upper parts of soil units can be inferred from fluvial deposits. River sediment sequences in the UK record a sudden change from snow-melt flow regimes represented by coarse sediments to much lower energy conditions represented by significant volumes of sand, silt and clay. In an earlier study of a chalk and clay catchment in south-central England (Collins et al. 1996, 2006), this change was found to have occurred in a timespan less than the probability error for a radiocarbon date, as shown in the example in figure 3.

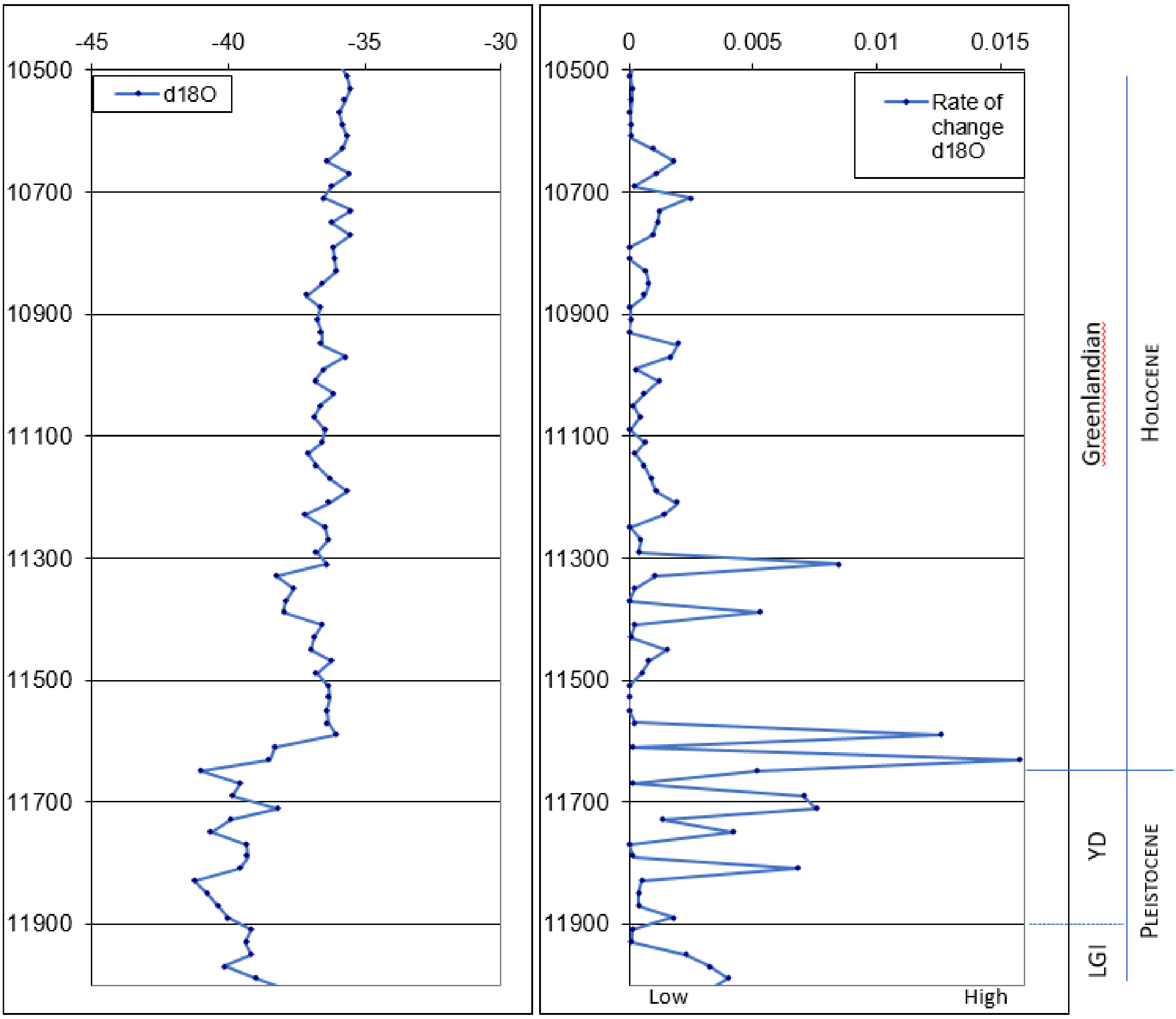

Figure 2. Oxygen isotope record from the GISP2 Greenland ice core stratotype (data source: NOAA-NCEI undated). Left:d¹⁸O record for the transition from the Late Pleistocene to the Holocene Greenlandian stage. Right: Rate of change per year for the d¹⁸O record, transformed by x^2. Terminology note: Greenlandian, Pleistocene and Holocene are formal chronostratigraphic terms, as defined by the International Commission on Stratigraphy - see Gibbard (2018) and Walker *et al.* (2018); OD = "The oldest Dryas", LGI = Lateglacial Interstadial, YD = Younger Dryas (GS-1), broadly following Lowe and Walker (2014) (usage of terms for this period varies geographically).

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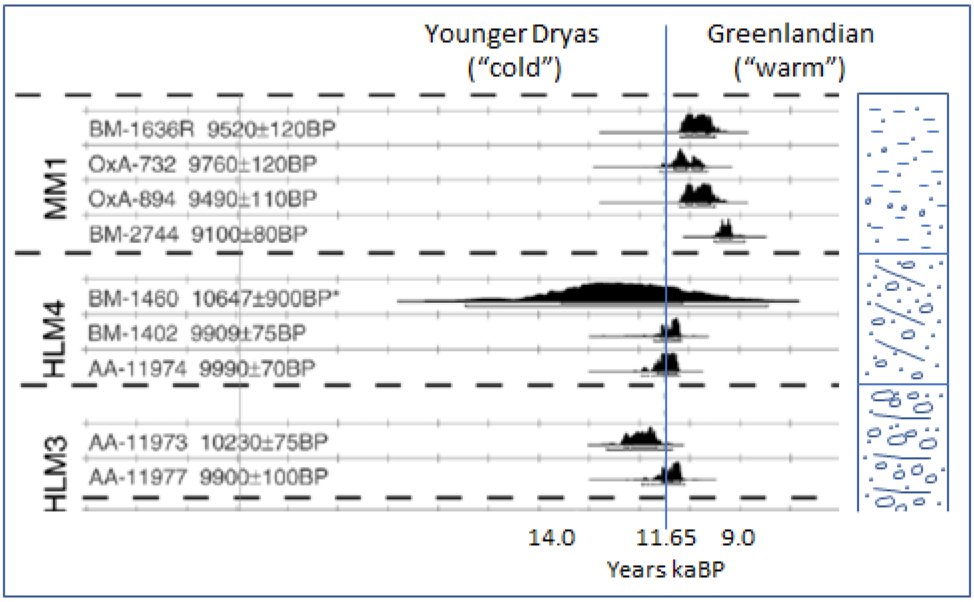

Figure 3. ^{14}C age estimation probability plots for the Late Pleistocene (Younger Dryas stage) to Holocene (Greenlandian stage) transition in the Kennet Valley, UK. After Collins et al. 2006.

The implication of the changed supply of fine-grained sediment into the fluvial systems is that a significant weakening of soils in the catchment occurred. This weakening would have included porewater driven reductions in cohesion, associated reductions in shear strength and, where local conditions permitted, liquefaction. Supporting evidence for this may come from dry valley deposits in the Thames Valley where classic cold climate solifluction deposits are overlain by clast rich soils interpreted as being the result of debris flows (Espejo et al. 1992). It remains uncertain, however, exactly when this sort of mass movement occurred due to the difficulty of dating the transported soil. An example of this is a late stage silt deposit in Poland that has a luminescence date range that overlaps into the Greenlandian stage (Waroszewski et al. 2020).

In other settings, ground ice mounds developed during the Younger Dryas, either as pingos or lithalsas (Pissart 2002). Modern analogs indicate this would have caused significant alterations to soil fabric, with segregated ice creating the potential for high water volumes and void space, and low inter-particle contacts. At Walton Common, where remnant ramparts and adjacent hollows are preserved, Clay (2015) found evidence of rampart collapse through mass wasting, though suggested a simple change from the slumping of coarse-grained soils to the settling out of chalky silt in standing water. Earlier unpublished work by Verasamy and Collins examined early Greenlandian-age soils (dated by pollen stratigraphy) from the same site. They found evidence of an early stabilization of the rampart slopes and hollows that was disrupted by a possibly short interval of instability which fits with the van de Bilt et al. (2019) model of a progressive change interrupted by short-lived reversals.

Conclusion

The geological evidence from past warming episodes indicates that the predominant impact on soils with an ice content is, unsurprisingly, a phase change affecting the degree of saturation. With this is an increased likelihood of soil structural collapse. However, there is some evidence that warming phases can be complex, and short-term cooling can occur. As a result, any consideration of the impact of current climate change on the geotechnical properties of soils and the associated risk to structures should consider the possibility of short-term refreezing.

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Климаттың тез жылынуы жағдайында мұздатылған топырақ жүйелерінің жағдайы - өткенге түсінік

Аңдатпа. Қазіргі климаттың жылынуы мұздатылған топырақтың үздіксіз геотехникалық өзгеруіне әкеледі деп күтілуде. Өткен климаттың өзгеруін, әсіресе суық кезеңді қарастыру: жылы ауысулар осы өзгерістің ықтимал табиғаты туралы түсінік бере алады және ондай жердің жағдайы бойынша түсінік беруі мүмкін. Анықталған ақпарат кейде екіұшты болып келеді. Периглазиялық және сейсмикалық процестер кейде ұқсас нәтижелерді береді. Мұздатылған топырақтардың негізгі көрсеткіштері суық-жылы ауысулар, мысалы, голоценнің Гренландия кезеңінің басталуы кезінде үлкен магнитуда болуы мүмкін. Сонымен қатар, топырақ жүйелеріне тұрақсыздық қосатын кері ауысулар болуы мүмкін. Мұз әсер ететін топырақтардың болашақтағы геотехникалық өзгеруін қарастыру үшін күрделі климаттық өзгеруді ескеру қажет.

Түйін сөздер: перигласиялық топырақтар, Гренландия, деформациялар, климаттың өзгеруі, еру.

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Мерзлые почвенные системы в условиях быстрого потепления климата: выводы из прошлого

Аннотация. Ожидается, что текущее потепление климата приведет к постоянным геотехническим изменениям в почвах многолетней криолитозоны. Изучение прошлых изменений климата, особенно переход холодной стадии в теплую, может дать представление о потенциальной природе этого изменения, а также информацию для оценивания таких участков. Получаемые данные исследования не всегда однозначны: перигляциальные и сейсмические процессы дают схожие результаты. Данные о ледяных кернах свидетельствуют, что переходы от холода к теплу, например, в начале гренландского этапа голоцена, могут иметь большие масштабы, но также могут иметь инверсии, которые добавляют нестабильность почвенным системам. Поэтому при рассмотрении будущих геотехнических изменений в почвах многолетней криолитозоны необходимо учитывать потенциально сложные климатические воздействия.

Ключевые слова: перигляциальный грунт, Гренландия, деформации, изменение климата, оттепель.

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