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Laboratory Assessment of the Impact of Freeze-Thaw-Cycling on Sandy-Clay Soil

Évaluation en laboratoire de l'impact du gel-dégel-cyclisme sur sol sablonneux-argileux

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ABSTRACT: Understanding the mechanisms of engineered soil slope degradation is essential for efficient management and maintenance of transport infrastructure networks. In temperate zones such as the United Kingdom recent research has focussed on the impacts of cycles of wetting and drying on hydraulic and mechanical properties though less attention has been given to temperature cycling. This paper investigates the impact of freeze-thaw-cycles (FTCs) on the shear strength, stiffness and soil water retention properties of a UK Glacial Till. X-ray computed tomography (XRCT) scanning was used to identify soil fabric changes linked to changes in soil properties. Scans revealed progressive cracking and potential pore redistribution as the number of FTCs increased. Repeated FTCs led to lower soil suctions, shear strengths and stiffness. After 6 FTCs, the soil had lost: significant suction potential, 32% of its original shear strength and 14% of its original stiffness. The research suggests that in the case of the soil studied, suction reductions were the dominant factor behind FTCs' influence over soil strength with cracking being a lesser component. Similarities have been identified between the effects of FTCs and repeated wetting and drying.

RÉSUMÉ: Comprendre les mécanismes de dégradation des talus artificiels est essentiel pour une gestion et une maintenance efficaces des réseaux d'infrastructures de transport. Dans des zones tempérées telles que le Royaume-Uni, de récentes recherches ont été consacrées aux effets des cycles de mouillage et de séchage sur les propriétés hydrauliques et mécaniques, même si une attention moindre a été accordée aux cycles de température. Cet article étudie l'impact des cycles de gel-dégel (FTC) sur les propriétés de résistance au cisaillement, de rigidité et de rétention d'eau du sol d'un till glaciaire britannique. La tomographie informatisée aux rayons X (XRCT) a été utilisée pour identifier les modifications de la structure du sol liées aux modifications de ses propriétés. Les analyses ont révélé une fissuration progressive et une redistribution potentielle des pores avec l'augmentation du nombre de FTC. Les FTC répétées ont entraîné une diminution des aspirations dans le sol, de la résistance au cisaillement et de la rigidité. Après 6 FTC, le sol avait perdu un potentiel d'aspiration important, 32% de sa résistance au cisaillement initial ainsi que 14% de sa rigidité initiale. Les recherches suggèrent que, dans le cas du sol étudié, les réductions d’aspiration étaient le facteur dominant de l’influence de la FTC sur la résistance du sol, la fissuration étant un élément moins important. Des résultats similaires ont été obtenus concernant les effets des FTC et le mouillage et le séchage répétés.

Keywords: soil suction, freeze-thaw, slope stability

1 INTRODUCTION

It is generally accepted that the weather is to become less predictable and more extreme (Hulme, et al., 2002). During the winter of 2010, the UK experienced severe daily temperature fluctuations where lows of -10°C (14°F) were a regular occurrence (Met Office , 2016). This prolonged period of cold temperatures induced widespread freeze-thaw-action within Britain’s soils, Stroeve et al, (2011) attributed this to a period of extreme negative phase of the Arctic Oscillation. It has been predicted that the frequency of Arctic Oscillations is set to rise, subsequently increasing the likelihood of similar events to occur in the future (Thompson and Wallace, 1998). The direct economic impact of the extreme weather was estimated to be in excess of as £1Billion per day (Wallop, 2010). Whilst attention has focused on immediate damage to infrastructure such as rupture of pavement surfaces less attention has been directed at longer term impacts. One such impact is damage to earthworks. Jones and Jefferson (2012) reported that progressive damage to earthworks structures has cost the UK economy over £300Million every year for the past decade.

The UK relies on operational infrastructure for socioeconomic growth and security (CCRA, 2017). As the infrastructure ages, operational and environmental drivers negatively impact the stability of the earthworks that support it and infrastructure asset owners are required to devote more resource to inspection, monitoring, maintenance and repair. Cheaper, more proactive systems for managing these assets are required but cannot be confidently developed until a deeper understanding of soil ageing has been achieved.

1.1 Frost penetration and suction

Transient pore water pressures occur as deep as 1500mm from the surface (Gunn et al, 2010). However, only the first 450mm requires proactive monitoring from freeze-thaw action since the UK climate confines frost penetration depths to a maximum of 450mm (HTL, 2000). Pore water pressures dictate earthworks’ overall stability. Negative pore water pressures, also known as suctions, are generated during periods of drying and provide additional attractive forces between adjacent soil particles. Suctions subsequently dissipate during wetting phases but little is known about the effect of Freeze – Thaw – Cycles on suctions within soils. Considering heavy precipitation and freezing conditions frequently coincide, it is important to consider the impact such conditions may have.

1.2 Freeze thaw cycles

With water being one of the two primary constituents in the voids between particles, repeated freezing and thawing significantly influences overall soil strength and stiffness. The mechanisms through which these properties are impacted have been researched extensively. Sustained sub-zero temperatures induce ‘ice lens’ formation within the soil voids, causing an increase in volume known as frost heave (Mikhaylov, 1970 & Gatto, 1995). Post thawing, the excess moisture content and disrupted soil structure lead to temporary losses in internal friction and cohesion. Multiple FTCs compound this effect. Observed soil strength reductions can be attributed to significant increases in volume strain and porosity- as a result of an altered particle arrangement and frozen water expansion Xie, et al, 2015 & Swan and Green, 1998). Xie et al (2015) and Swan & Green (1998) concluded that FTCs interfere with organic connections between soil particles, hence destabilising interparticle cementation strength.

1.3 Aim of this research

There is a well-established hysteretic relationship between soil suction and moisture content (Fredlund and Rahardjo, 1993). The impact of cyclical wetting and drying has been noted by several researchers (Stirling et al, 2014; 2017, Hen-Jones et al, 2017 and Toll et al, 2017) Freeze-thaw (F - T) cycles have received less attention, therefore, this research set out to make a preliminary investigation how the relationship between suction and moisture content changes over varying numbers of F - T cycles (FTCs). To enable estimates to be made regarding earthworks stability the relationship between FTCs and undrained shear strength was also investigated.

2 MATERIALS AND METHODS

2.1 Soil

All samples were prepared from soil taken from the BIONICS test embankment located in the north-east of England. The material is a local glacial till, and can be categorized as a sandy clay with intermediate plasticity (Hughes et al, 2009). A comprehensive list of the material properties can be found in (Hughes et al, 2009).

The disturbed soil was air dried to a residual gravimetric moisture content ~3% GMC and passed through a 5mm sieve to remove any large gravel particles and then passed through a mechanical crusher to break down any aggregations of clay. The soil was then brought back to its as-placed water content of 23% GMC by gradually adding water to the dry soil using a mortar mixer. Once fully wetted, the soil was bagged and sealed for 48 hours, allowing the material to fully homogenize.

2.2 Sample Preparation

To achieve the as placed bulk density of 2.09Mg/m3, 180.2g of soil was compacted into a cylindrical mould of 38mm diameter and 76mm height. Once prepared, the samples were wrapped in cling film and allowed to homogenize for 24 hours before testing.

Samples were subjected to a temperature of -23°C for 24 h in a commercial freezer in order to obtain complete frost penetration. Post freezing, the samples were allowed to thaw at room temperature (21°C) for 24 h. During the cycling process samples were sealed without access to an external water source.

2.3 Testing

Specimens were subjected to 0, 1 & 6 freeze-thaw cycles and subsequently tested for undrained shear strength, Cu, in accordance with BS1377 (B.S.I. 1990) and soil suction using a Decagon WP4C Dew Point Potentiometer (Decagon, 2014). Gravimetric water content was determined for each specimen post testing.

2.3.1 Undrained Shear Strength, C_u

Unconsolidated undrained Triaxial tests carried out in general accordance with BS 1377-7 section 8 (BSI, 1990) were carried out to determine the undrained stiffness of samples at a range of water contents. To achieve a high level of confidence in the strength of the zero suction soils, 14 repeats were taken for 0, 1 & 6 FTCs. 6 FTCs was selected as a maximum number of cycles due to Xie et al (2015) concluding that this amount was sufficiently accurate to model an infinite number of cycles.

2.3.2 *Soil water retention behaviour*

To establish a full a series of SWRCs, suction tests were conducted on samples with moisture contents varying from 23% to residual (3%). Using drying curve data from prior research, samples were dried, post F – T cycling, to pre-prescribed water contents. Once samples had re-homogenized over 48 h and undergone undrained shear strength testing (see below), a 32mm x 5mm slice was placed into a WP4C dewpoint potentiometer to determine the samples suction. Limitations in the precision of the equipment at low suction levels resulted in small, negative suctions being outputted. These results could be reliably assumed to equal zero suction. The remainder of each triaxial sample was used for moisture content tests.

3 RESULTS

3.1 Sample mass vs Number of FTCs

Although wrapped in cling film and locked in airtight bags, the mass of the soil samples decreased to a final value of approximately 99% of the original sample. Since any mass change is assumed to be as a result of gain/loss of moisture, the change in water content could also be calculated (see figure 1).

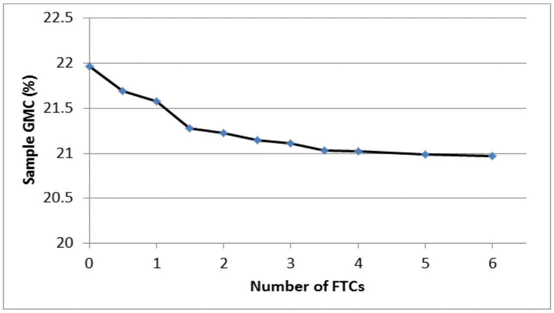

Figure 1: *Water vs number of FTCs.*

3.2 Moisture content vs Suction

Soil suction non-linearly increases as the moisture content decreases (see figure 2). Increasing the number of freeze thaw cycles decreased overall suction, as well as decreasing the air-entry value of the soil (intersection point of the two gradients).

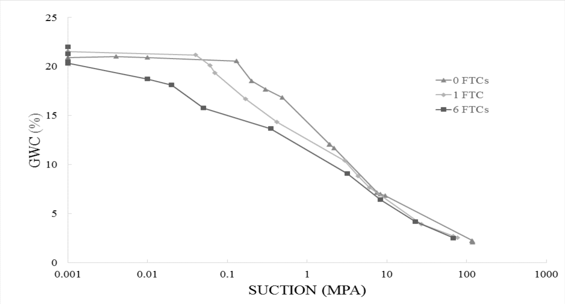

Figure 2: *Gravimetric Water Content as a function of Suction.*

3.3 Peak stress vs Moisture Content

Peak undrained shear stress decreases logarithmically as GMC increases. Increasing the number of FTCs decreases the peak stress across all moisture contents (see figure 3).

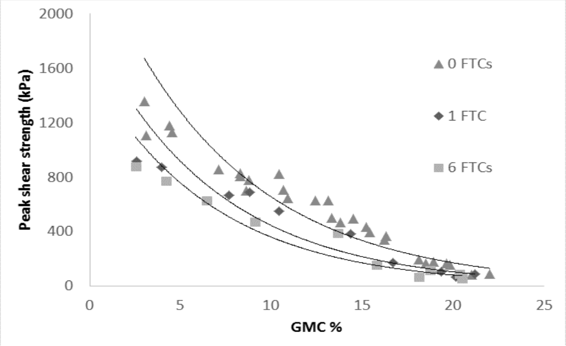

Figure 3: *Peak Undrained Shear Stress as a function of Gravimetric Water Content.*

3.4 Peak Strength vs Suction

As can be seen in figure 4 peak undrained shear strength generally increases as suction increases. The relationship between shear strength and suction was not observed to change significantly with increasing numbers of FTCs.

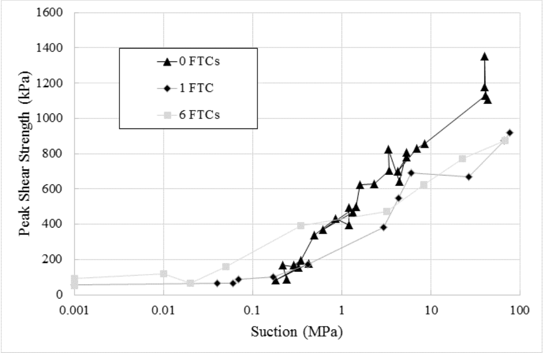

Figure 4: Peak *Undrained Shear Stress as a function of Suction.*

3.5 X-ray imaging

Cross sections from XRCT scans are shown in figure 5. Figure 5 shows the original images obtained for samples at initial GMCs of approximatley 22% alongside drier samples that were scanned at a moisture content of approximatley 10% for 0, 1 and 6 FTCs.

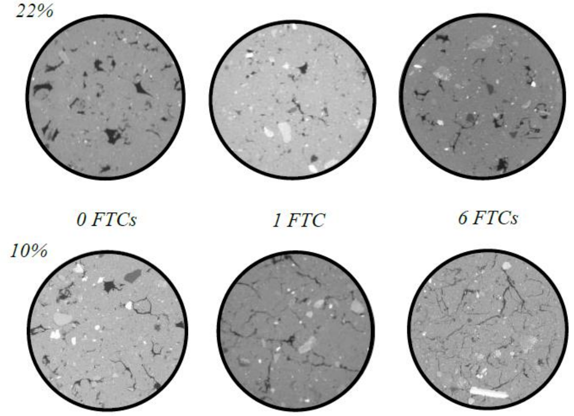

Figure 5: Original XRCT images of samplesafter 0, 1 & 6 FTCs. Top row are at initial GMC (≈22%). Bottom row have been dried to a GMC of approximately 10%.

Without further image analysis the sections in Figure 5 provide qualatative information only. However, it can be observed that the frequency and size of cracks increases with the number of FTCs.

4 DISCUSSION

4.1 The influence of freeze thaw cylces on suction

Data in figure 2 is consistent with previous work on the material in that suction can be observed to increase as the soil dries as would be expected. Figure 2 also shows a consistent reduction in suction as an increasing number of FTCs were applied.

A reason for this progressive reduction in suction could be a result of an alteration in pore size distribution within the material. Constituting of a sandy – clay, the compacted sample initially had relatively small pores. The freezing conditions causes the formation of ice in the pore spaces of frost heave. XRCT imagery confirms the advancement of cracks and potential production of larger pores within the soil as the samples undergo repeated freezing and thawing. Upon thawing, the cracks only partly reseal, resulting in larger pore sizes, an increase in effective void ratio and an increased porosity for following cycles.

4.2. Impact of freeze thaw cycles on strength and stiffness.

Introduced first by Lin et al (2014), and subsequently adapted for this study, the freeze – thaw shear strength reduction index (ηf) is defined in equation (1) and is the proportion of undrained shear strength before and after the FT process.

$$\eta_f = \frac{C_{u_n}}{C_{u_i}} \qquad (1)$$

Where Cu_i is the initial, uncycled shear strength and Cu_n is the shear strength after undergoing *n* number of FTCs. Similarly, equation (2) defines the freeze – thaw stiffness reduction index (γf) as the proportion of soil stiffness before and after the FT process.

$$\gamma_f = \frac{En}{Ei} \qquad (2)$$

Where E_i is the initial, uncycled stiffness and E_n is the stiffness after undergoing *n* number of FTCs. Both equations provide direct indications of the extent to which freezing and thawing affects the stability of the soil.

Table 1: Summary of obtained freeze - thaw reduction indices after 1 & 6 FTCs. η_f is the shear strength reduction index. γ_f is the stiffness reduction index.

	22% GMC		**~3%GMC**	
	1FTC	**6FTCs**	**1FTC**	**6FTCs**
Minimum ηf (% loss)	0.724 (27.6%)	0.676 (32.4%)	0.767 (23.3%)	0.639 (36.1%
Average ηf (% loss)	0.820 (18.0%)	0.780 (22.0%)	Insuficient data	
Initial γf (% loss)	0.906 (9.94%)	0.860 (14.0%)		

Figure 3, alongside table 1, demonstrate that the first FTC provides the greatest reduction in strength and stiffness. Despite only being able to use the peak values for the drying samples, table 2 in conjunction with figure 4 show similar reductions were observed across all moisture contents.

Over the entire strain range, 1 FTC induced an average shear strength reduction of 18.0%. The most severe reductions (minimum ηf) reliably occurred at 2.5% strain. 1 FTC also induced a 9.94% reduction in stiffness. Agreeing with Lin et al, (2016) & Jafari, (2012), subsequent FTCs proved to impact the soil's rate of shear strength and stiffness reduction less severely. After 6 FTCs, the average shear strength and stiffness reductions were only 22.0% and 14.0% respectively.

Despite multiple precautions, figure 1 shows that samples lost moisture over repeated cycles. In addition, although not measured, the samples were visibly swollen after freezing. This volume increase is likely a direct cause of of the 'ageing' process within the soil. The development of cracks revealed on the XRCT images in conjunction with irreversible plastic strains produced from the shrink-swell behavior of FTCs could be responsible for the observed progressive deterioration. This change in density would assist in the explanation of the trends in seen in figure 3. Xie, et al. (2015) determined that sample volumes non-linearly increased with increased numbers of FTCs. This could possibly explain the retardation of the rate of deterioration after more than one cycle.

However, figure 4 shows that the relationship between undrained peak shear strength and suction does not change significantly with increasing numbers of FTCs. As a result, this study attributes the majority of the strength losses directly to the aforementioned suction reductions.

4.3 *Impact on future predictions of slope stability?*

This study has investigated the independent impact of repeated freezing and thawing on stability of a compacted sandy-clay soil. It has been established that FTCs are detrimental to the soil's suction generation capabilities - consequently reducing shear strength and stiffness.

However, the UK's winter climate is renowned for being wet as well as cold. With DEFRA models forecasting an increase in colder temperatures and precipitation levels (DEFRA, 2009), it is probable that, as climate change develops, both processes will occur concurrently more often.

Previous studies by Hen-Jones et al (2017) and Stirling et al (2014) have shown the potential for strength reduction in remoulded fills subjected to cycles of wetting and drying which are similar to those found in this study.

Both cyclical procedures induce mechanisms to reduce both soil suction and undrained shear strength. Further parallels include comparable shrink – swell behavior and progressive cracking and aging within the samples. These similarities suggest crossover between the processes and their respective failure modes.

With the aforementioned predictions of winters becoming colder and wetter, combined with expected times for strength recuperation being over a month (Gatto et al, 1995), a compounding effect is likely to occur. Soil suctions and subsequent shear strengths would potentially experience superimposed stability reductions, prompting overall slope stabilities to become significantly reduced, providing a real threat to the safety of earthworks structures.

5. CONCLUSIONS

The objective of this study was to establish how geotechnical inter-relationships between a glacial sandy-clay's GMC, shear strength, stiffness and suction were affected as the soil was subjected to repeated freezing and thawing. Accompanied with an improved understanding of the mechanisms responsible for the deterioration, any significant influences found would assist in understanding the potential future effects climate change could impose on aging UK earthworks structures.

Repeated freezing and thawing has a detrimental influence over shear strength (*vs* GMC), stiffness ($d\sigma/d\varepsilon$) and suction (*vs* GMC). It can therefore be concluded that changes caused by FTCs on water retention properties of soil play a signifcant role in determining the strength and subsequent stability of compacted sandy-clay soils.

The suction of clay increases as the GMC of the sample decreased. Exposing samples to FT cycling reduced the suction of the soil across all moisture contents. Subsequent FTCs further reduced suction. Additionally, repeated FTCs resulted in a decrease in the air entry value of the material. These outcomes are attributed to the formation of ice and consequent frost heave within the soil. Originally filled with relatively small pores, the swelling observed from the freezing phase encouraged cracking and the introduction of larger pores. After only partial resealing, the resultant porosity increase would likely affect both the soil's ability to form menisci and its ability to resist the infiltration of air.

Introducing freeze – thaw reduction indices allowed simplified quantitative evaluation of any impacts FTCs imposed over the undrained shear strength and stiffness of the sandy-clay. It can be concluded that the suction losses and density changes prompted maximum shear strength and stiffness reductions of 36% and 14% respectively. Prior research indicates that clayey soils do not recuperate these losses for up to 45 days post thawing. It is therefore highly likley that additional freeze thaw cycles and partial wetting drying cycles would occur before full recovery of strength leading to more significant reductions in stability over time.

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