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The paper was published in the proceedings of the 20th International Conference on Soil Mechanics and Geotechnical Engineering and was edited by Mizanur Rahman and Mark Jaksa. The conference was held from May 1st to May 5th 2022 in Sydney, Australia.

Centrifuge modelling of cyclic freezing and thawing impact on embankments

Modélisation centrifuge de l'impact cyclique du gel et du dégel sur les remblais

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ABSTRACT: During a changing climate, freezing and thawing (F-T) cycles can impose severe adverse effects on geotechnical infrastructures such as railway embankments in the seasonally frozen regions. Although some encouraging findings have been reported based on element tests and small-scale laboratory tests under one gravity, the understanding of the large-scale soil-atmosphere interaction under cyclic F-T condition is still fairly limited. This study aims to investigate the behaviour of a loess embankment under F-T cycles in the seasonally frozen region with a newly developed in-flight F-T system at an elevated gravity in the centrifuge. In this paper, details of the new F-T system will be reported and discussed. The system achieved a temperature range from -1°C to 9°C in the soil. Based on the centrifuge test on a loess embankment, it is found that 31 mm settlement occurred after 3 cycles. The settlement after the first cycle exceeded the allowable limit of 15 mm in the design guideline for highspeed railway in China. When considering unusual cold events, embankments in the currently unfrozen area might be subjected to F-T cycles and serviceability problems can occur during thawing.

RÉSUMÉ : Lors d'un changement climatique, les cycles de gel et de dégel peuvent imposer des effets néfastes et graves sur les infrastructures géotechniques dans les régions saisonnièrement gelées, telles que les remblais ferroviaires. Bien que des résultats encourageants aient été obtenus sur la base d'essais d'éléments et d'essais en laboratoire à petite échelle sous une seule gravité, les recherches de l'interaction sol-atmosphère à grande échelle dans des conditions de gel et de dégel sont encore assez rares. Cette étude vise à étudier le comportement d'un remblai de limon sous les cycles de gel et de dégel dans la région saisonnièrement gelée en utilisant un système nouvellement développé de gel et de dégel en vol à une gravité élevée dans le centrifugeur. Et ce dernier sera rapporté et discuté dans cet article. Le système a atteint une plage de température de -1°C à 9°C dans le sol. Basé sur le test de centrifugation pour un remblai de limon, on constate qu'un tassement de 31 mm s'est produit après 3 cycles. Le tassement après le premier cycle est de 15 mm qui a déjà dépassé la limite autorisée dans la directive de conception pour le chemin de fer à grande vitesse en Chine. Lorsqu'on considère des événements inhabituels de froid, les remblais dans la zone actuellement non gelée sont susceptibles d'être soumis à des cycles de gel et de dégel et des problèmes d'entretien pourraient survenir pendant le dégel.

KEYWORDS: Ground freezing; centrifuge test; unsaturated soil; embankments; deformation

1 INTRODUCTION

Serviceability performance of infrastructure in seasonal frozen ground area is challenging for transport engineering. Especially considering extreme cold events, infrastructures in currently unfrozen area can suffer from frost damage in the future. It has been reported that frost heave and thaw settlement induced by moisture migration significantly reduce the service life of highways, high speed railways and airport runways. Sheng et al. (2014) observed frost heave of 5 mm on average and 20 mm at maximum on a newly constructed high-speed railway in northern China, while a 30 mm heave amount is monitored for a poorly performed embankment in Canada by Batenipour et al. (2014). Furthermore, the performance of high-speed railways is highly sensitive to the track displacement. In China, the maximum allowable vertical displacement is 15 mm after construction (TB 2014). The displacement induced by frost heave and thaw settlement restricts the operating speed of Chinese railway or even result in safety issues.

To tackle this problem, fundamental research is required to explore the thermal-hydro-mechanical behaviour of soil subjected to F-T. Element tests and small-scale laboratory tests

are the major approaches for these studies. For element tests, triaxial test is identified as a common tool since volumetric behaviour can be recorded while imposing F-T cycles. Recently, Nishimura et al. (2020) conducted triaxial tests on clay specimens and observed that the soil volume tends to reach a "residual" value after F-T cycles. For small-scale laboratory tests, the typical approach is by freezing soil in a 1-D column or a box. Compared with element tests, small-scale laboratory tests freeze soil one-dimensionally which allow ice lens formation and more realistically reflect soil behaviour on site. It is found that frost heave is mainly caused by the migration of water unfrozen zone towards frozen front driven by ice-water interface tension and the magnitude is highly dependent on the imposed boundary temperature (Thomas et al. 2009; Caicedo 2017). On the other hand, during thawing, excess pore water pressure is built up and following by seepage process. This process can be regarded as consolidation which significantly reduces the volume of soil and is named thaw settlement. However, the small-scale laboratory test is limited in modelling the stress state. It is well recognized that soil behaviour is significantly affected by its state (Ng et al. 2020), it is questionable adopting the test results into engineering application.

Despite some encouraging findings have been reported both by experimental and theoretical works, the understanding of large-scale soil response towards F-T is still restricted owing to the lack of tools to physically impose temperature boundary conditions to large-scale model. Despite some limited full-scale tests were conducted (Harris et al. 1993; Harris et al. 2008a; Subramanian et al. 2015), time and cost efficiency still remain as challenging obstacles in researching F-T via large-scale physical modelling. In geotechnical research, one of the approaches to replicate large scale response of soil is centrifuge modelling since an elevated g level creates a same stress state as prototype. It provides possibilities to study soil freezing and thawing by using this methodology. As far as the authors are aware, research in this direction was pioneered by Lovell & Schofield (1986) who firstly built heat exchange system in geotechnical centrifuge. The applicability of centrifuge modelling technique in gelifluction was then explored by Harris et al. (2003) which confirmed that soil thawing reflects an elasto-plastic response to shear stress. Afterwards, some studies were conducted regarding slope behaviour in permafrost or seasonal using centrifuge (Thomas et al. 2009; Harris et al. 2008b). However, even though some works on single freezing or thawing has been done (Yang & Goodings 1998; Harris et al. 2000; Li et al. 2019), implementing centrifuge to study in-flight cyclic F-T of soil is limited. In order to improve the state of art in this discipline, this study develops a novel in-flight F-T system in the centrifuge. With the F-T system, cyclic F-T was imposed on a loess embankment under a correct stress state, the results in thermal and mechanical aspects are then reported and discussed.

2 CENTRIFUGE MODELLING

Simulating embankment response during freezing-thawing process through the soil-atmosphere interaction involves heat exchange and water migration. Table 1 summarizes the relevant centrifuge scaling laws in the soil and at soil-atmosphere boundary. In unsaturated soil, the scaling factor for time in heat and mass diffusion processes is $1/N^2$, where N is the increase in the gravitational acceleration. For the scaling factors of atmosphere variables, Tristanco et al. (2012) conducted a comprehensive research and derived scaling laws for heat flux also by adopting a factor of N between the model and the prototype.

Table 1. Centrifuge scaling law

Parameter	Symbol	Scaling law (model/prototype)
Length	L	$1/N$
Area	A	$1/N^2$
Volume	V	$1/N^3$
Mass	m	$1/N^3$
Time (diffusion)	t	$1/N^2$
Temperature	T	1
Heat flux	q	N
Seepage velocity	v	N

3 DEVELOPMENT OF AN IN-FLIGHT F-T SYSTEM IN CENTRIFUGE

The major challenges for simulating F-T process in the centrifuge are the limited cooling power and relative short freezing time required. As discussed in the centrifuge scaling law, the scaling factor of diffusion time is $1/N^2$. It means that the embankment must be cooled to the desired temperature in a short time to

correctly fabricate the seasonal temperature variation. For $N=20$ adopted in this study, the cooling time is only 11 hours (6 months in the prototype). In order to maximize the cooling power, previous studies attach the cooling source (usually a metal plate) to the soil surface (Harris et al. 2000). Despite this approach improves the cooling rate, the metal plate restrains the movement of soil, resulting in difficulty in measuring differential deformation as well as recording the soil surface response towards freezing and thawing. For simulating the soil-atmosphere interaction, heat should transfer from soil to air then to the cooling source for freezing and vice versa during thawing. The low efficiency for heat transfer through air between the cooling plate and soil surface makes the condition even more difficult. In order to tackle this problem, a more powerful cooling and heating system must be designed. Thermoelectric cooler (TEC) is identified as an efficient mean for providing cooling power. Heat flux is generated from the cold side to the hot side of the TEC through Peltier effect. The maximum temperature difference between the cold side and the hot side of TEC is around 70°C . Therefore, instead of following the traditional design of thermoelectric cooling in centrifuge chamber which uses air cooling (Archer & Ng 2018; Tristanco et al. 2012), the cooling capacity can be improved by enhancing the heat dissipation at the hot side.

Figure 1 presents a schematic diagram of the centrifugal F-T system. In total, 10 TECs are installed on the aluminium plate to supply cooling power. Heat at the hot side of the TECs is dissipated by circulated coolant with an inlet temperature of approximately 0°C . The heated coolant is cooled by a Julabo FL4003 chiller with a maximum cooling capacity of 3 kW at 25°C . The cooling system can reach -30°C at the aluminium cooling plate, ensuring a sufficient cooling rate in the model space. The centrifuge environmental chamber (Archer & Ng 2018) is used for heating. An adiabatic model space is ensured by insulating the side and the bottom of the model space with high thermal resistance rigid foam board. Therefore, temperature fluctuation in the centrifuge chamber will not affect the temperature field in the model.

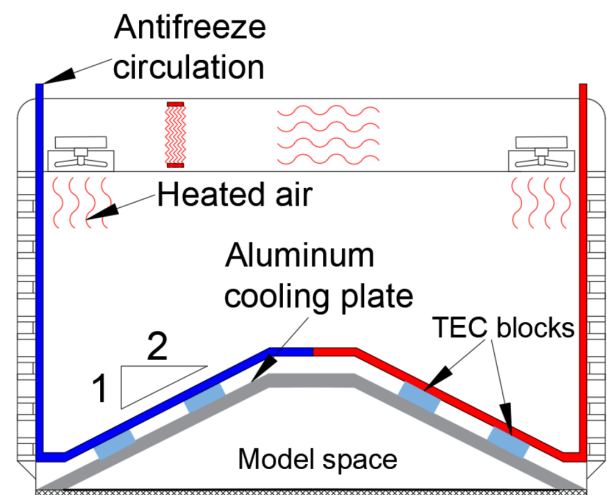


Figure 1. Schematic diagram showing the in-flight F-T system in the centrifuge

4 MODEL SET-UP AND TEST PROCEDURES

A centrifuge test was carried out to investigate the influence of F-T cycles on a loess embankment while the model setup is given in Figure 2. Properties of tested loess are reported in Ng et al.

(2016). The model embankment is trapezoid in shape with 125 mm width at crest, 150 mm in height and 2:1 gradient in slope. After sieving and mixing to the target gravimetric moisture content (20.1%), the soil was compacted to 85% of maximum dry density in seven equal depth layers on an acrylic platform (Ladd 1978) with no drainage at the bottom boundary. Sensors at different locations were inserted in after the compaction of each layer. The compacted soil was then cut to the desired gradient and shaped to the final model, following by instrumenting the F-T system.

After model preparation, the embankment was spun up to 20 g, following by a 3-hour pre-cooling stage. During this stage, the pore-water pressure was stabilized, and the soil surface temperature dropped to approximately 3°C. Three F-T cycles were imposed to the embankment with equally 11 hours of freezing and thawing for one cycle. Soil temperature as well as deformation at the centre of mid-slope was recorded and will be discussed in the next section.

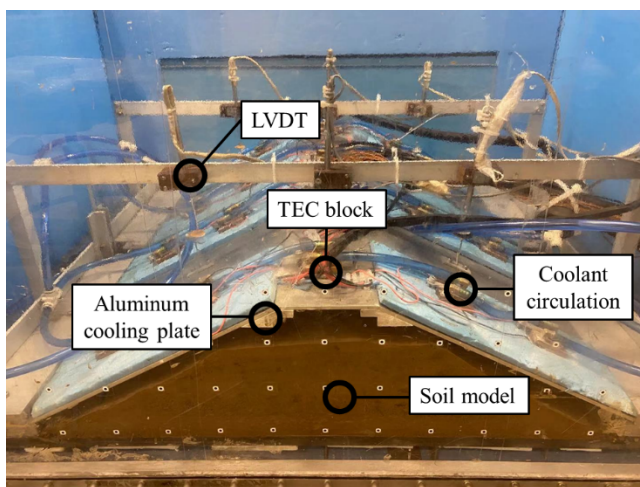


Figure 2. A typical centrifuge model set-up

5 INTERPRETATION OF RESULTS

5.1 Evolution of temperature

Figure 3 demonstrates evolution of temperature during F-T process at 0.4 m, 0.8 m and 1.1 m in the prototype scale under the mid-slope of the embankment along the centre line. Since original point is defined at the finish of pre-cooling stage, an initial temperature gradient was observed. An overall temperature variation from -1°C to 7°C was monitored at 0.4 m depth while the temperature fluctuated from 0°C to 9°C at 1.1 m depth. It is reasonable for the deeper soil to have smaller variation towards temperature change since the temperature boundary was imposed at the soil surface while the bottom boundary is regarded as zero heat flux. Frost penetration reached between 0.8 m to 1.1 m during all the cycles while this value coincides with the observation on site (GB 2011), indicating that the F-T system successfully simulated the seasonal temperature variation in field. On top of that, there was a slight discrepancy of time for reaching highest and lowest temperature at different locations, especially for 0.4 m and 0.8 m depth. Large heat capacity of water in the soil and the latent heat of fusion were the main cause for this temperature damping.

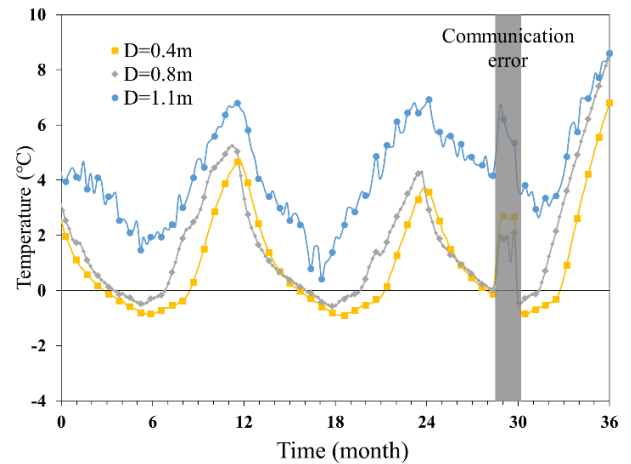


Figure 3. Evolution of temperature during F-T cycles

5.2 Evolution of deformation

Figure 4 presents the evolution of deformation during the test in the prototype scale. The creep line was calculated as a reference line by assuming the primary consolidation finished at the beginning of pre-cooling stage by the following equation.

$$\Delta H = \frac{H_0}{1 + e_p} C_\alpha \log \left(\frac{t}{t_p} \right)$$

where $C_\alpha = 0.0025$ (Mesri 2003; Xu et al. 2020) is the secondary compression index; $H_0 = 1.5$ m is the thickness of soil; $t_p = 0.5$ (0.5 year of pre-cooling), $e_p = 0.754$ represents the intersection of the tangents to the primary consolidation and secondary compression parts of the void ratio versus logarithm of time curve

The freezing-thawing progress can be divided into two phases: frost heave and thaw settlement. Classified as frost susceptible soil, the loess embankment is expected to exhibit considerable deformation during F-T process due to its relatively good water retention capacity and high permeability. The magnitude of frost heave was 47 mm, 75 mm and 58 mm respectively and the frost heave in the second cycle was much larger due to a lower temperature. Settlement of 21 mm, 29 mm and 31 mm was reported after each F-T cycle. Most of the settlement was regarded as F-T induced settlement since the value is significantly larger than the calculated creep line. The deformation after the first cycle exceeds the allowable limit of 15 mm in the design guideline for highspeed railway in China (TB 2014).

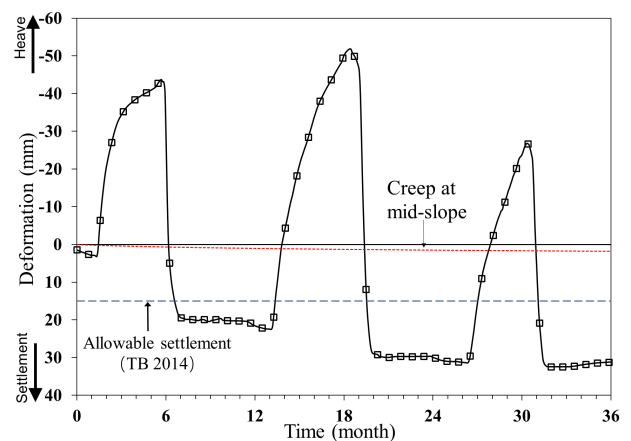


Figure 4. Evolution of deformation during F-T cycles

6 CONCLUSIONS

This study focussed on developing an in-flight F-T system in centrifuge and investigating the thermal and mechanical behaviour of a loess embankment subjected to cyclic freezing and thawing. The following conclusions can be drawn:

- The newly developed in-flight F-T system in the centrifuge has the capability to ensure an efficient F-T by soil-atmosphere interaction. Research of large-scale soil-atmosphere interaction under cyclic F-T condition can be achieved via this system. The temperature in the soil varied from -1°C to 9°C while the frost line was between 0.8 m and 1.1 m under the mid-slope of the embankment. The frost depth coincided with the site measurement, indicating the F-T system is capable of simulating seasonal F-T process in the prototype.
- Frost heave as well as thaw settlement was observed during the test. A maximum frost heave of 75 mm occurred in the second cycle while the overall settlement after three cycle was 31 mm. The accumulated settlement exceeded the 15 mm allowable value after the first F-T cycle.

7 ACKNOWLEDGEMENTS

The authors would like to thank the financial support from the area of excellence project AoE/E-603/18 provided by the Research Grants Council of HKSAR.

8 REFERENCES

- Archer, A., and Ng, C.W.W. 2018. Effects of temperature and relative humidity on a clay embankment: Centrifuge modelling. *Geotechnique Letters* 8(2), 138–143.
- Batenipour, H., Alfaro, M., Kurz, D., and Graham, J. 2014. Deformations and ground temperatures at a road embankment in northern Canada. *Canadian Geotechnical Journal* 51(4), 260–271.
- Caicedo, B. 2017. Physical modelling of freezing and thawing of unsaturated soils. *Geotechnique* 67(2), 106–126.
- GB. 2011. GB 50007—2011: Code for design of building foundation. Beijing, China: China Architecture & Building Press.
- Harris, C., Gallop, M. and Coutard, J.-P. 1993, Physical modelling of gelification and frost creep: Some results of a large-scale laboratory experiment. *Earth Surface Process and Landforms* 18, 383–398.
- Harris, C., Rea, B.R., and Davies, M.C.R. 2000. Geotechnical centrifuge modelling of gelification processes: Validation of a new approach to periglacial slope studies. *Annals of Glaciology* 31, 263–268.
- Harris C, Davies M.C.R. and Rea B.R.. 2003. Gelification: viscous flow or plastic creep? *Earth Surface Processes and Landforms* 28, 1289–1301.
- Harris C, Kern-Luetschg M, Murton JB, Font M, Davies MCR, Smith F. 2008a. Solifluction processes on permafrost and nonpermafrost slopes: results of a large-scale laboratory simulation. *Permafrost and Periglacial Processes* 19, 359–378.
- Harris, C., Smith, J. S., Davies, M. C. R. & Rea, B. 2008b. An investigation of periglacial slope stability in relation to soil properties based on physical modelling in the geotechnical centrifuge. *Geomorphology*. 93(3–4), 437–459.
- Ladd, R. 1978. Preparing Test Specimens Using Undercompaction. *Geotechnical Testing Journal* 1 (1), 16–23
- Li, S., Lai, Y., Zhang, M., Pei, W., Zhang, C., and Yu, F. 2019. Centrifuge and numerical modeling of the frost heave mechanism of a cold-region canal. *Acta Geotechnica* 14(4), 1113–1128.
- Mesri, G. 2003. Primary Compression and Secondary Compression. In: *Soil Behavior and Soft Ground Construction*. 122–166.
- Ng, C. W. W., Sadeghi, H., Hossen, S. K. B., Chiu, C. F., Alonso, E. E. & Baghbanrezvan, S. 2016. Water retention and volumetric characteristics of intact and re-compacted loess. *Canadian Geotechnical Journal* 53(8), 1258–1269.
- Ng, C. W. W., Zhou, C., and Chiu, C. F. 2020. Constitutive modelling of state-dependent behaviour of unsaturated soils: an overview. *Acta Geotechnica* 15, 2705–2725.
- Nishimura, S., Okajima, S., Joshi, B.R., Higo, Y., and Tokoro, T. 2020. Volumetric behaviour of clays under freeze-thaw cycles in a mesoscopically uniform element. *Geotechnique*, Ahead of print.
- Sheng, D., Zhang, S., Niu, F., and Cheng, G. 2014. A potential new frost heave mechanism in high-speed railway embankments. *Geotechnique* 64(2), 144–154.
- Subramanian, S.S., Ishikawa, T., Yokohama, S., and Tokoro, T. (2015) Numerical simulation of volcanic soil slope failure under coupled freeze-thaw and rainfall infiltration effects. *Japanese Geotechnical Society Special Publication* 1(7), 5–10.
- TB. 2014. TB 10621-2014: Code for design of highspeed railway. Beijing, China. China Railway Publishing House Co. Ltd.
- Thomas, H. R., Cleall, P., Li, Y. C., Harris, C., and Kern-Luetschg, M. 2009. Modelling of cryogenic processes in permafrost and seasonally frozen soils. *Geotechnique* 59(3), 173–184.
- Tristancho, J., Caicedo, B., Thorel, L., and Obregón, N. 2012. Climatic chamber with centrifuge to simulate different weather conditions. *Geotechnical Testing Journal* 35(1), 159–171.
- Xu, L., Gao, C., Lan, T., Lei, J., and Zuo, L. 2020. Influence of grading on the compressibility of saturated loess soils. *Geotechnique Letters* 10(2), 1–7.
- Yang, D., and Goodings, D.J. 1998. Climatic Soil Freezing Modeled in Centrifuge. *Journal of Geotechnical and Geoenvironmental Engineering* 124(12), 1186–1194.