5th ECPMG
Delft · 2024

Proceedings of the 5th ECPMG 2024
5th European Conference on Physical Modelling in Geotechnics
2-4 October 2024, Delft, the Netherlands

Decommissioning of mudmats with the aid of thermally induced pore pressure

F. B. Reis
Walm BH Engineering, Belo Horizonte, Brazil, reisgeotec@gmail.com

F. Saboya Jr., S. Tibana, R. M. Reis
State University of Norte Fluminense - Uenf, Campos, RJ, Brazil, saboya@uenf.br , tibana@uenf.br, reis@uenf.br

H. M. Huancollo
Catholic University of San Pablo and Continental University, Arequipa, Peru, hjmachaca@ucsp.edu.pe

R. G. Borges
Petrobras, Rio de Janeiro, Brazil, garske@petrobras.com.br

ABSTRACT: Mudmats are offshore shallow foundations used to support subsea equipment resting on the seabed. After the end of exploration activities in a given field, in order to meet environmental requirements, these structures shall be recovered from the seabed in a procedure known as decommissioning. During these operations, this structure is pulled out from the seabed using a crane barge. In the course of the pull out operation, excess of negative pore pressure, i.e., suction, develops at the foundation-soil interface. This suction makes decommissioning operations more expensive and challenging. This circumstance calls for a way to reduce the suction to make such operation feasible. A proposed methodology not yet investigated is to heat the soil under these foundations. It is inspired by the results presented in the literature that show the undrained heating produces a positive excess of pore pressure. Therefore, this study aims to test the hypothesis of reducing the suction by generating positive pore pressure during heating. For this study, triaxial tests in Brazilian marine clay are carried out with heating under non-hydrostatic stress conditions. Reduced physical modelling tests of shallow foundations are also carried out in the geotechnical centrifuge. These foundations are subjected to pull out loads while the underlying soil is heated. The triaxial tests show that considerable pore pressure values are induced in the clay for thermal variations of 35°C, in addition, thermal failure was observed. Centrifuge tests reveal that the heating procedure is capable of significantly reducing suction depending on the applied pull out load level.

1 INTRODUCTION

Mudmats are large shallow foundations, made by steel, used to house underwater equipment related to oil exploration. These structures have skirts to provide stability against efforts exerted by pipelines and jumper attached to them.

In certain occasions, laws and special requirements may impose the company to recover these foundations in a process known as decommissioning. However, removing such structures involves great challenge once the pull out load can be much higher than the loading required for the installation due to the suction develop during this kind of operation, considering that these structures are, in general installed in fine plastic soils. This process is called as reverse end bearing mechanism ((Mana *et al.*, 2011) and (Mana, Gourvenec and Randolph, 2013). This problem has been studied by several researches, where detach can be drawn to the work carried by (Li *et al.*, 2014a) and (White *et al.*, 2005), where the authors propose the use of perforations in the foundation mat. However, such technique is useful for mudmats yet to be manufactured. For existing conventional mudmats, this technique is not feasible.

The key mechanism of reverse bearing is known as breakout. It is defined as the displacement under which a sudden loss of suction takes place, in undrained conditions. The upward displacements allow water to enter bellow the foundation, which results in loss of uplift capacity. At this moment, the effective stress equals to zero in the foundation invert.

Considering that heating fine plastic soils leads to an increase in pore pressure, as stated by several researches (Campanella and Mitchell, 1968; Burghignoli, Desideri and Miliziano, 2000; Abuel-Naga *et al.*, 2007; Bai, Guo and Han, 2014; Huancollo *et al.*, 2023; Reis *et al.*, 2023), this study has proposed to heat the soil just below the mudmat to counterbalance the suction generated during the uplift operation. For this, a set of centrifuge tests was carried out to investigate the feasibility of this technique and the variables that govern the breakout mechanism under temperature variation.

2 CENTRIFUGE TESTING

The centrifuge tests were carried out using the geotechnical centrifuge belonging to State University of Norte Fluminense in Brazil. The centrifuge was manufactured by Wyle Labs, from El Segundo, USA, CA, and has a 3.8m long arm capable of submitting models up to 1 metric ton up to 100g. Further information about UENF Centrifuge can be obtained in (Saboya *et al.*, 2010).

2.1 Tests Details

Considering the geometry of the mudmats and the necessity of running two simultaneous testing to allow direct comparison between them, a 1:50 scale was chosen and, therefore, the models were submitted to 50g acceleration.

The mudmats models were represented by circular shallow foundation, made by aluminium with 100 mm in diameter (D) with a peripheral skirt of 20 mm in length (d) resulting in d/D=0.2 (typical values), as depicted in Fig.1. The foundation model were equipped with two diametrically opposed pore pressure transducers aligned with the invert and two thermocouples to measure the temperature exactly under the foundation invert.

For this, a rectangular container (690 x 260 x 490mm) was used. Inside of it, three compartments were created. Two for allowing two simultaneous tests and the third, in the middle, had the role to preventing one test influencing the other since heating was used in both. To monitor the soil consolidation process, pore-pressure transducers were strategically placed in the container wall. Laser sensors monitored resulting displacements and settlements. An overall view of the container and the test set-up is shown in Figure 2.

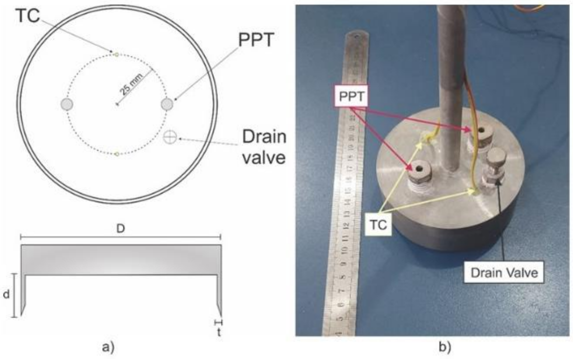

Figure 1 – a) schematic diagram of the underside and cross-section of the foundation and b) image of the foundation with the instruments installed. PPT: Pore Pressure Transducer; TC: Thermal Couple

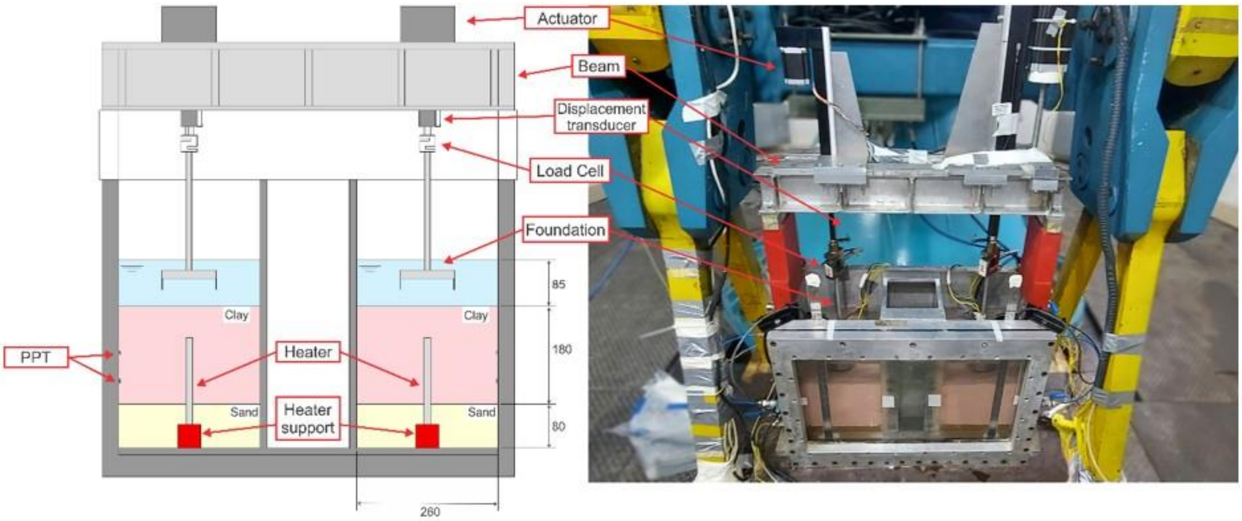

Figure 2 – Schematic diagram and photograph of the experimental setup in the centrifuge arm (dimensions in millimeters).

2.2 Material

The soil used to represent the seabed of the Brazilian coast was prepared with kaolin (40%) and metakaolin (60%). The characteristics of this admixture are shown in Table 1. This material, after homogenization was poured in clumps inside the container over an 80mm sand layer covered with a filter paper. The final clay layer was 260mm with 85 mm of water level above it.

The soil was then consolidated under 50g acceleration until 95% of consolidation was reached. After this stage, the centrifuge was stopped and the foundations were installed, followed by a reconsolidation at 50g again.

The undrained profile was then obtained by T-bar penetrometer carried in one of the compartment without the foundation installed, following recommendations stated by (Stewart and Randolph, 1994).

Table 1 – Indices and properties of the kaolin and metakaolin mixture.

Liquidity limit, LL (%)	47.3
Plasticity index, PI (%)	17.9
Compresstion index, Cc	0.24
Coefficient of consolidation, Cv (m²/year)	9.70
Initial void index, e0	1.90
Natural specific weight, γnat (kN/m³)	16.3*
Final void index, ef	1.20*

*Obtained by sampling after testing.

2.3 Testing Programme

A total of six tests (T0 to T6) were executed, being one without heating (T0), which served as the reference test to assess the breakout load. The next five tests were performed under sustained load followed by heating.

The reference test T0 was carried out under controlled displacement at a pull out rate of 1.5 mm/s resulting in a normalized velocity of 490 (Li *et al.*, 2014b; Gaudin *et al.*, 2017), to ensure undrained conditions. Tests T1 to T5 were executed under sustained load, each one representing a fraction of the ultimate load obtained in T0, followed by heating. Once the target load was reached, it was kept constant and the heater was activated up to a temperature variation (ΔT) of 60°C.

A heater installed at the bottom of the container, just below the foundation, was used to heat the soil. It is important to mention that this this configuration is for testing the heating effects only. It is not intended to be used in the field in this way. The summary of the tests, the obtained real sustained load and the resulting stress are presented in Table 2.

Table 2 – Loads applied in each test.

Test	**Load applied (N) model scale**	**Sustained Load % of ultimate load**	**Uplift Stress q_m (kPa)**
T1	15	7	2.0
T2	30	13	4.1
T3	45	20	6.1
T4	60	26	8.2
T5	90	39	12.3

3 RESULTS AND DISCUSSION

3.1 Undrained Strength Profile

As stated before, the undrained strength profile was evaluated by means T-bar penetrometer carried out during the centrifuge flying. The obtained profile, shown in Figure 3, suggests a typical normally consolidated profile with linear increasing rate with depth of 2.8 kPa/m resulting in $\frac{S_u}{\sigma'_v} = 0.2$, where σ'_v is the vertical effective stress.

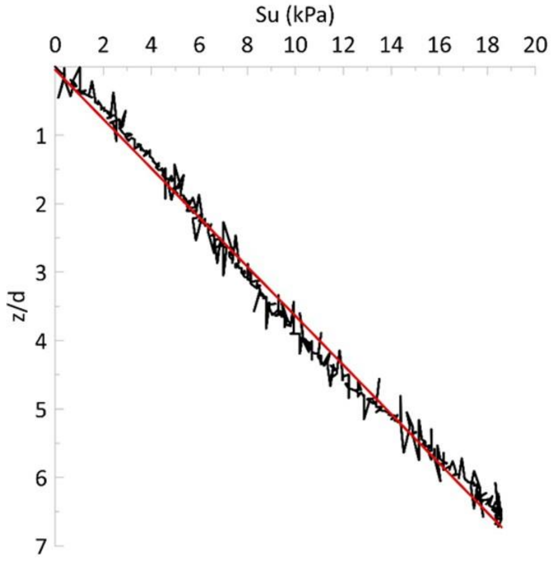

Figure 3 – Undrained shear strength profile with depth z normalized by skirt length d.

3.2 Reference Test T0

Figure 4 shows the pull out curve and the excess of negative pore pressure generated up to breakout. The maximum F_{net} and ΔU_{avg} values were 228.0 N (579 kN real scale) and 36 kPa respectively. At the breakout, the displacement (w_b) observed was 8.2 mm (41 cm in real scale), which gives normalized displacements (w) of 0.41 and 0.08 for w/d and w/D, respectively.

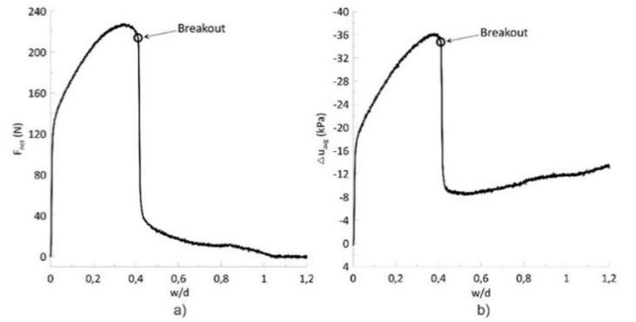

Figure 4 – Variation in a) net pullout force, Fnet and b) average pore pressure at the foundation invert with normalized displacement. (Force in model scale).

3.3 Heated Tests T1 to T5

Tests T1 to T5 were executed under sustained load followed by heating of the soil under the foundation. The recorded temperature changes just bellow the invert are presented in Figure 5.

The generated negative pore pressure and the sustained applied stress under the invert is presented in Figure 6.

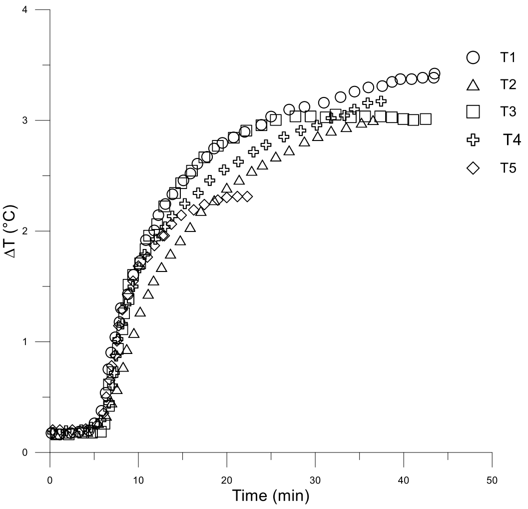

Figure 5 – Variation in average temperature at the mudmat invert.

The heating effect on the upward displacement (under sustained loading) and on the pore pressure variation are presented in Figure 7. It can be observed the pore pressure begun to decrease after heating followed by the increasing of upward displacement without any increment of pull out loading. For tests T to T3 the displacements were stabilized under sustained loading before heating, unlike as observed in T4 and T5. After heating T1, T2 and T3 showed significant increasing in upward displacement rate. For T4 and T5, it was not possible to stabilize the upward displacements under sustained load that were 26 and 39% of ultimate load, respectively. However, both showed small decrease in negative pore pressure and a discrete acceleration of upward displacements after heating. It is important to detach that test T5 breakout took place at 60% of the breakout load observed in T0. This is attributed to the negative pore pressure that decreases to a value very close to the tension applied, resulting in null effective stress at the soil-foundation interface.

With these results, it is possible to define a relationship between the pore pressure variations after heating as a function of sustained load (Figure 8).

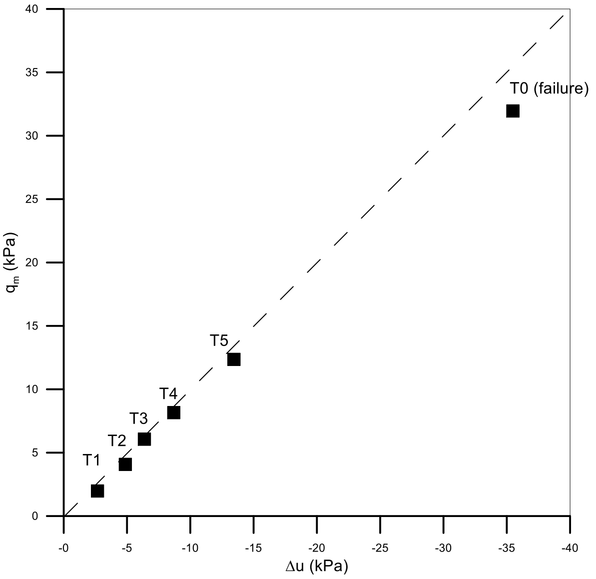

Figure 6 – Relationship between the sustained uplift stress and suction.

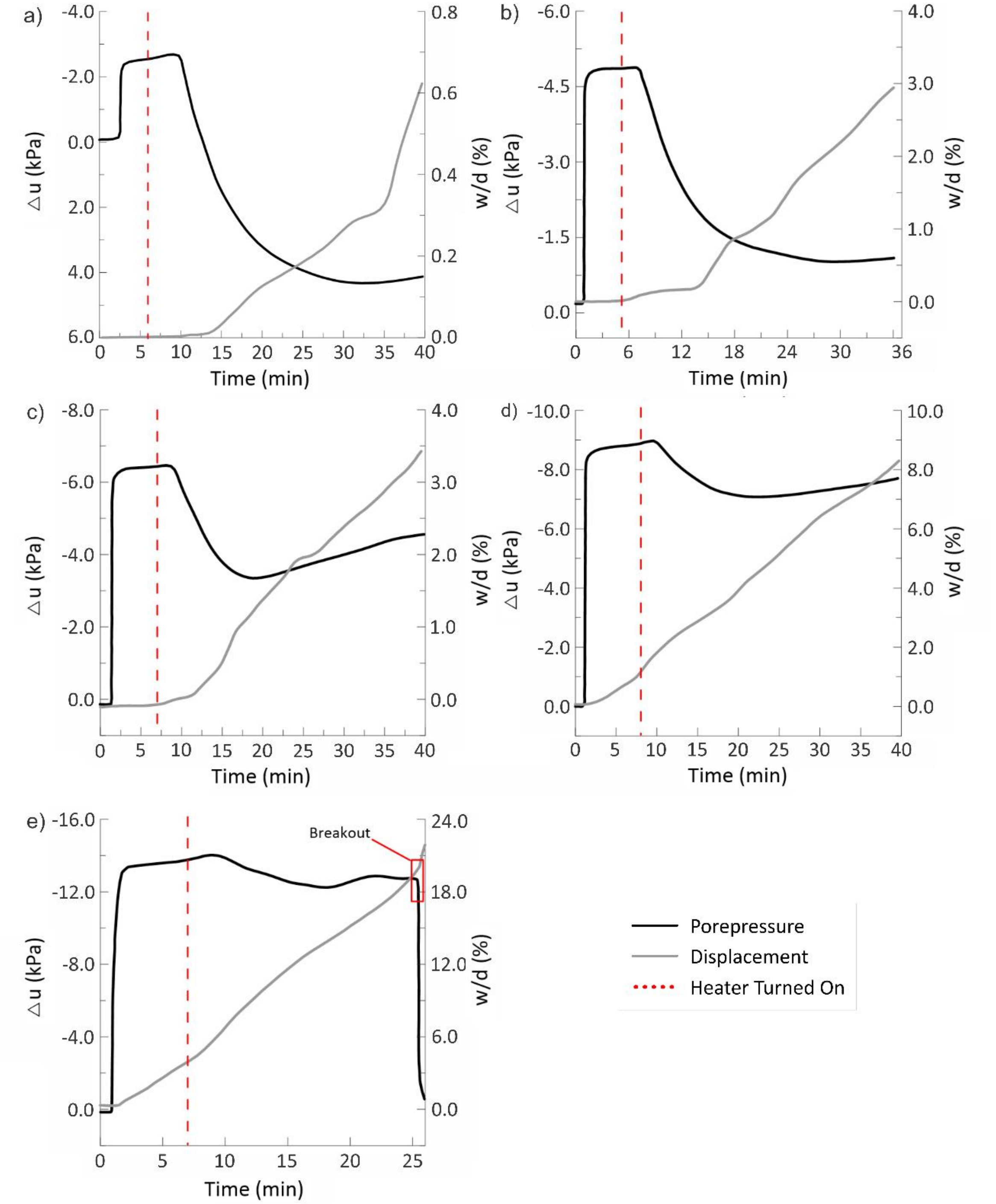

Figure 7 – Displacement and excess pore pressure in tests a) T1 b) T2 c) T3 d) T4 and e) T5.

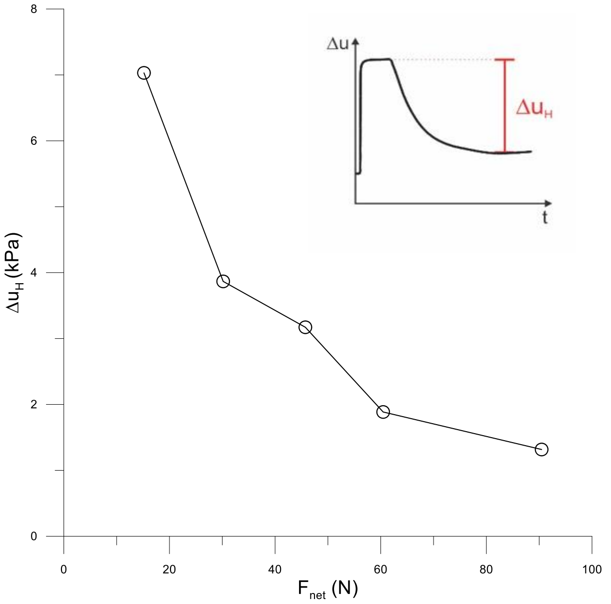

Figure 8 – Variation in excess pore pressure after heating as a function of the sustained load applied

4 CONCLUSIONS

The tests showed that heating the soil under the foundation can significantly reduce the suction caused by uplift loading. However, this reduction depends on the level of sustained loading in relation to breakout load. The rate of upward displacement under sustained load increases significantly after heating due to positive thermal pore pressure generation.

The experimental results show that this technique can be promising for decommissioning subsea structure where high suction is generated during its removal

ACKNOWLEDGEMENTS

This study was partially supported by Petrobras (Brazilian Petroleum Company) Grant No TC 0050.0098204.15.9 - SAP 4600499688. We also thank the Brazilian Scholarship Agency – CAPES for supporting the first author

REFERENCES

Abuel-Naga, H.M. *et al.* (2007) ‘Volume change behaviour of saturated clays under drained heating conditions: experimental results and constitutive modeling H.M.’, *Computers and Geotechnics*, 30(13), pp. 1303–1336. doi:10.1002/nag.

Bai, B., Guo, L. and Han, S. (2014) ‘Pore pressure and consolidation of saturated silty clay induced by progressively heating/cooling’, *Mechanics of Materials*, 75, pp. 84–94. doi:10.1016/j.mechmat.2014.04.005.

Burghignoli, A., Desideri, A. and Miliziano, S. (2000) ‘A laboratory study on the thermomechanical behaviour of clayey soils’, *Canadian Geotechnical Journal*, 37(4), pp. 764–780. doi:10.1139/t00-010.

Campanella, R. and Mitchell, J. (1968) ‘Influence of Temperature Variations on Soil Behavior’, *Journal of the Soil Mechanics and Foundations Division*, 94(3), pp. 609–734.

Gaudin, C. *et al.* (2017) ‘About the uplift resistance of subsea structures’, *ICSMGE 2017 - 19th International Conference on Soil Mechanics and Geotechnical Engineering*, 2017-Septe, pp. 2281–2284.

Huancollo, H.J.M. *et al.* (2023) ‘Thermal Triaxial Tests to Evaluate Improvement of Soft Marine Clay through Thermal Consolidation’, *GEOTECHNICAL TESTING JOURNAL*, 46(3), pp. 579–597. doi:10.1520/GTJ20220154.

Li, X. *et al.* (2014a) ‘Effect of perforations on uplift capacity of skirted foundations on clay’, *Canadian Geotechnical Journal*, 51(4), pp. 322–331. doi:10.1139/cgj-2013-0110.

Li, X. *et al.* (2014b) ‘Rate effects on the uplift capacity of skirted foundations on clay’, in *International conference on physical modelling in geotechnics*. Perth: Taylor & Francis, pp. 473–479.

Mana, D.S.K. *et al.* (2011) ‘Experimental investigation of the undrained response of a shallow skirted foundation subjected to vertical compression and uplift’, *Proceedings of the International Conference on Offshore Mechanics and Arctic Engineering - OMAE*, 7, pp. 771–778. doi:10.1115/OMAE2011-49072.

Mana, D.S.K., Gourvenec, S. and Randolph, M.F. (2013) ‘Experimental investigation of reverse end bearing of offshore shallow foundations’, *Canandian Geotechnical Journal*, 50(August), pp. 1022–1033. doi:dx.doi.org/10.1139/cgj-2012-0428.

Reis, F.B. *et al.* (2023) ‘Physical modelling of subsea structure removal via thermally induced pore pressure’, *Ocean Engineering*, 288. doi:10.1016/j.oceaneng.2023.116044.

Saboya, F. *et al.* (2010) ‘The UENF geotechnical centrifuge facility’, in *Physical Modelling in Geotechnics - Proceedings of the 7th International Conference on Physical Modelling in Geotechnics 2010, ICPMG 2010*, pp. 273–277.

Stewart, D.P. and Randolph, M.F. (1994) ‘T-bar penetration testing in soft clay’, *Journal of Geotechnical and Geoenvironmental Engineering*, 120(12), pp. 2230–2235. doi:10.1061/(ASCE)0733-9410(1994)120:12(2230).

White, D.J. *et al.* (2005) ‘An investigation into the vertical bearing capacity of perforated mudmats’, *Frontiers in Offshore Geotechnics, ISFOG 2005 - Proceedings of the 1st International Symposium on Frontiers in Offshore Geotechnics*, (August), pp. 459–465. doi:10.1201/noe0415390637.ch47.

INTERNATIONAL SOCIETY FOR SOIL MECHANICS AND GEOTECHNICAL ENGINEERING

The paper was published in the proceedings of the 5th European Conference on Physical Modelling in Geotechnics and was edited by Miguel Angel Cabrera. The conference was held from October 2nd to October 4th 2024 at Delft, the Netherlands.