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The influence of shear thinning of Hydroxypropylmethylcellulose (HPMC) during dynamic centrifuge experiments

T.O. Quinten, A. Askarinejad, M.A. Cabrera, K.G. Gavin
Delft University of Technology, Delft, The Netherlands, T.O.Quinten@tudelft.nl, A.Askarinejad@tudelft.nl, M.A.Cabrera@tudelft.nl, K.G.Gavin@tudelft.nl

ABSTRACT: Hydroxypropylmethylcellulose (HPMC) is a versatile and affordable thickening agent widely used in the centrifuge for modelling dynamic processes. However, the rheological properties of HPMC solutions can vary based on the type of HPMC and the solution concentration. These variations potentially affect the model soil behaviour and must therefore be considered when designing centrifuge experiments. This study investigates the influence of shear thinning of HPMC solutions on the installation behaviour of a tubular pile, driven dynamically at an effective acceleration of 50g. Samples consist of GEBA sand, prepared at 80% relative density by dry pluviation and subsequently saturated using water, and a viscous fluid prepared using Methocel F4M. The experiments consist of a sequence of single-blow events that ultimately drive the pile down to 3 pile diameters embedment. The pile displacement and the spatial distribution of pore pressures in the sample are monitored for every blow. The results demonstrate the need for a viscous fluid to replicate true-to-nature saturated soil-structure interaction in the centrifuge. Additionally, it is shown that there exists a need to consider the shear-thinning behaviour of viscous fluid during the experimental design in relation to the anticipated shear rates during test execution. In broader terms, this work improves the existing centrifuge modelling toolkit to conduct fundamental research about dynamic processes at a reduced scale.

1 INTRODUCTION

For many geotechnical applications, soil-soil or soil-structure interaction is influenced by dynamic forces. Examples of this are earthquake, offshore and transportation engineering. Centrifuge modelling can yield valuable insights into the dynamic behaviour of geotechnical systems associated with these engineering disciplines. It offers the possibility to conduct cost-effective research in a controlled environment. However, for dynamic centrifuge experiments, one should be aware of the non-synchronicity between dynamic and diffusive time scales.

In the centrifuge model, dynamic time is scaled down by a factor of N, while the diffusive time, for which time scale can be derived from the solution of the 1D differential equation for consolidation, scales by $1/N^2$. In both instances, N designates the amplification factor of gravity.

Viscous fluids like HPMC-based solutions facilitate this synchronization and enhance compatibility between model and prototype. To replicate the appropriate stress conditions in the centrifuge, the viscous fluid should have a density like water (Stewart et al., 1998). It has been demonstrated that the density of the pore fluid plays a direct and significant role in evolution of pore pressures, directly influencing the mechanical behaviour of a soil-structure system (Askarinejad et al., 2017). Therefore, Newtonian viscous fluids like glycine-water mixtures are arguably less suitable for use in dynamic centrifuge experiments, as their density differs significantly form that of water.

Consequently, it has proven most practical to achieve the synchronization of diffusive and dynamic time scales by incorporating an HPMC-based viscous fluid into the centrifuge model, as their density is approximately 1000 kg/m^3. As such, these fluids have been extensively used in centrifuge modelling, e.g. Adamidis & Madabhushi (2015), Cabrera et al. (2018), Gao & Vulpe (2022), Stewart et al. (1998), Terwindt et al. (2020), amongst others. However, due to the presence of polymers in HPMC-derived fluids, they are subject to shear thinning.

An example of a case where the influence of shear thinning should arguably be accounted for in the experimental design is the dynamic installation of offshore foundations, particularly dynamically installed monopiles. To assess the implications of shear-thinning of viscous fluid in this context, we first investigate the rheological behaviour of HPMC-based viscous fluids. Subsequently, the saturated soil response during dynamic pile installation is compared between water and HPMC-fluid-saturated sample.

2 METHODS

2.1 Rheological characterization

The fluid rheology is determined using an Anton Paar MCR302 rheometer. This rotational rheometer operates in accordance with the Searle principle, where low-viscosity samples are sheared between a stationary outer cylinder, the measurement cup, and a rotating measuring spindle.

Each characterization is conducted on 15~ml of fluid, which is placed inside the measuring cup using a syringe. Care is taken to avoid air entrapment as it can result in significant deviations of the rheological measurements (Struble & Jiang, 2004). Therefore, samples with visible air inclusions are discarded. During the experiments, the fluid temperature is maintained at 20±0.1°C by an integrated electrical temperature device (ETD).

On each sample, four consecutive logarithmic strain sweeps are conducted between shear rates, γ, of 0.1 and 1000 Hz. For each decade of the strain domain, 10 measurements are taken, totalling 164 measurements per characterization. The measurement duration is governed by an inversely logarithmic relationship, that ensures laminar flow conditions prevail at the time of measurement. The definition of the measurement duration is important as it guarantees the reliability of the readings and allows for optimization of the test duration as laminar flow conditions are realized quicker for higher shear rates.

In this study, the measurement interval corresponding to the minimum shear rate, $\gamma = 0.1$ Hz, is 15 s; and for the maximum shear rate, $\gamma = 1000$ Hz, the measurement interval equals 1 s. The result from this characterization is the sample's flow curve that allows to capture variations in the fluid viscosity as a function of γ.

2.2 Centrifuge testing

Centrifuge tests are performed in the centrifuge facility at Delft University of Technology (DUT). The centrifuge of DUT is a beam-type centrifuge with a diameter of 2.4 m. The capacity is 9000 kgF. The maximum payload is 30 kg at 300g. The usable volume of the carrier measures 560 x 350 x 210 mm (H x W x D), as illustrated in Figure 1. For further details on the centrifuge facility, the reader is referred to the work of Allersma (1994).

2.2.1 Sample preparation

The specimens are prepared through a combination of dry pluviation coupled with shockwave compaction, to achieve a target relative density of 80%. The soil consists of fine graded GEBA sand. Specimens are assembled within a PVC container with an inner diameter of 295 mm and an internal height of 195 mm. A total of approximately 17.5 kg of GEBA sand is required to achieve a sample height of 165 mm. The latter leaves sufficient space to maintain a ~15 mm layer of fluid above the sand.

To improve uniformity, the sand is deposited in layers. In between layers, the surface is levelled, and three rounds of compaction are carried out. To ensure adequate densification of the final two layers, an additional surcharge of 5.2 kg is applied, equal to a confining pressure of 0.75 kPa. Subsequently, the surcharge is removed, and the soil surface is levelled.

The prepared sample is then introduced into a vacuum chamber to eliminate air, after which fluid is carefully flushed through the sample via a tube connected to the container base. Control over the flow rate is achieved by adjusting the static head difference between the sample and the storage cell, thereby preventing uplift and piping. The fluid within the storage cell is pre-degassed and maintained at a constant vacuum level throughout the saturation process to prevent gas dissolution. Although less elaborate, the system used to saturate the sand samples bears resemblance to the CAM-Sat System (Stringer & Madabhushi, 2009).

2.2.2 Hardware

The experimental setup employed in this testing campaign utilizes the prolonged blow generator developed by Quinten et al. (2022). This apparatus, illustrated in Figure 1, relies on a pair of linear axes to guide the descent of the ram mass once it is released from an electromagnet. The electromagnet securely holds the ram mass in place during spin-up.

Due to the Coriolis effect, the ram would miss the anvil without the guided trajectory imposed by the linear axes. The resulting Coriolis force has been accounted for in the actuator design. As there is a permanent contact between the ram and the linear axes through two ball bearings located on either side of the ram, the ram accelerates due to the centrifugal g-field before impacting the anvil on top of the pile. A linear spring, as shown in Figure 1, is embedded within the anvil, which is configured to reduce the interface stiffness such that the duration of contact between the ram and the anvil is extended. The latter allows energy to be transferred over a prolonged time interval, relative to a stiffer steel-to-steel interface, resulting in a characteristic long low amplitude time-force diagram.

The tubular model pile used for the experiments is manufactured from stainless steel. The model pile dimensions are as follows: (i) outer diameter, $D_P = 42$ mm; (ii) wall thickness, $t_P = 2$ mm; and (iii) length, $L_P = 175$ mm.

2.2.3 Testing protocol

A two-part self-weight penetration phase marks the start of an experiment. In the first sub-phase, the ram is carefully lowered onto the anvil, after which the pile is positioned directly above the soil surface and released, enabling it to settle freely under the combined influence of its weight and the ram.

Subsequently, in the second sub-phase, the centrifuge is spun up to the designated g-level, facilitating further the pile penetration under the acting dead load. Once the pile movement stabilizes, the centrifuge is halted to secure the ram mass to the electromagnet and set its falling height. Hereafter, the centrifuge is returned to the experimental g-level to initiate the first impact.

It is important to note a constraint in the experimental setup that inhibits the reset of the hammer during flight. Hence, the centrifuge is intermittently halted and restarted to manually reset the hammer for subsequent impacts. The experiment concludes upon the pile's penetration reaching approximately $3D_P$.

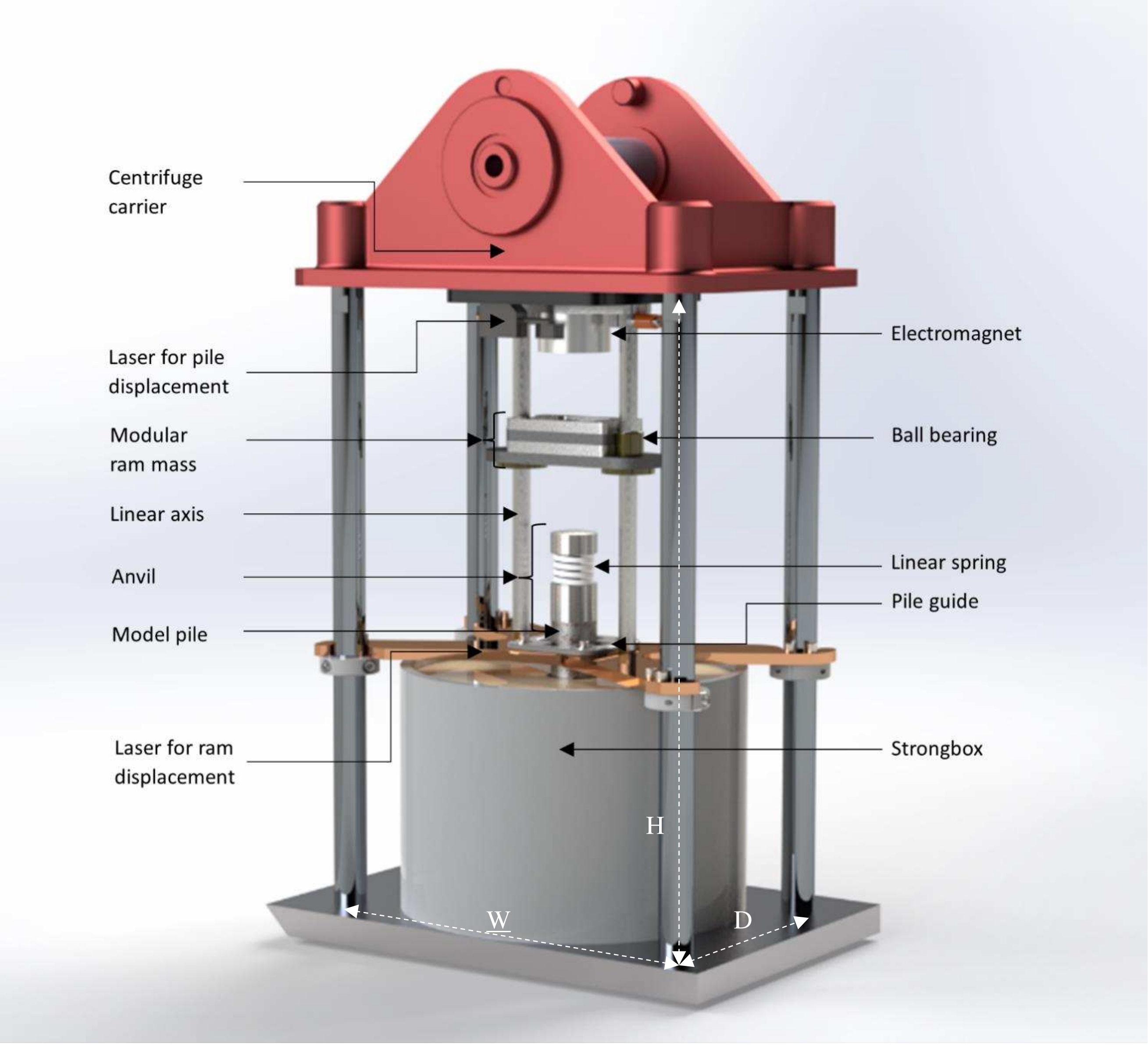


Figure 1. Annotated render of prolonged blow actuator of DUT, shown assembled inside the centrifuge carrier. Adapted from Quinten et al. (2022).

3 RESULTS

3.1 Rheological testing

Figure 2 presents the results of the strain sweep analysis conducted using the rheometer on water and aqueous solutions of Methocel F50 (Adamidis & Madabhushi, 2015; Stewart et al., 1998), F450 (Gao & Vulpe, 2022), and F4M. The primary distinguishing factor among the Methocel products is their viscosity grade, indicating the nominal viscosity of a 2% aqueous solution at 20°C. Specifically for F50, F450, and F4M, these viscosities correspond to 50, 450, and 4000 mPa s, respectively.

For this investigation, the solutions were adjusted to achieve absolute viscosities, μ, within the range of 48 to 52 mPa s. To facilitate clarity, the rheological data in Figure 2 is normalized by the viscosity obtained at a shear rate of 10 Hz, denoted as μ_{ref}. It is evident that none of the viscous fluids entirely replicate the Newtonian flow behaviour of water (horizontal dashed line in Figure 2). This is expected due to the alignment of cellulose polymers in the fluids at higher shear rates, leading to a shear thinning behaviour. This phenomenon results in a decrease in apparent viscosity with increasing shear rates.

Interestingly, the relative decrease in viscosity varies significantly among the viscous fluids, with Methocel F4M exhibiting the largest reduction of 28.7%, followed by F450 at 13.2%, and F50 at 4.3%. Thus, an inversely proportional relationship appears to exist between the viscosity grade of the HPMC and the extent of shear thinning. Additionally, the Linear Viscoelastic Region (LVR), representing where viscosity remains unaffected by strain rate, diminishes with increasing viscosity grade.

3.2 Centrifuge testing

Two experiments were conducted in the centrifuge facility of DUT on saturated GEBA sand samples prepared at a relative density Dr = 80±2%. Two saturation media were employed: (i) water, H_2O; (ii) an aqueous solution of Methocel F4M. The viscous fluid was prepared to exhibit a viscosity of 50±5 mPa s at a shear rate of 10 Hz, matching the scaling factor of $N = 50$. For both experiments, a falling height of 40 mm was utilized, along with a ram mass of 1.889 kg. Please note that both of these parameters are at model scale. Termination criteria for the experiments were set at a penetration level of approximately $3D_P$.

During installation, the evolution of pore pressure inside the sample was monitored using 9 pore pressure transducers (PPT). Figure 3(a) and Figure 3(b) illustrate the deviation of pore pressures from the hydrostatic backpressure for samples saturated with water and F4M, respectively. These pore pressures are measured 0.5 s after impact (T) when the pile sits roughly in the middle of the sample at $L/D_P \approx -2$. Black circular markers denote the PPT positions. Data from all sensors were consolidated to create an axisymmetric representation of pore pressures around the pile. The spatial pressure distribution is similar for both water and F4M viscous fluid, with the highest pressures recorded below and adjacent to the base of the pile (see Figure 3). Along the shaft, a comparatively lower elevation is observed. Pressure diminishes radially with increasing distance from the pile centroid.

In absolute terms, the presence of viscous fluid amplifies the recorded pressures by approximately one order of magnitude. Due to reduced soil permeability, resulting from the use of viscous pore fluid, these heightened pressures also take longer to dissipate. This alteration affects the effective stress state around the pile and may influence the installation efficiency, though this aspect falls outside the scope of this paper. In broader terms, these findings suggest that sand samples exhibit partially drained behaviour under dynamic loads associated with pile driving. This challenges the current practice in physical modelling where the installation in a sandy subsoil is often simplified as a fully drained medium, whether by using dry sand or water-saturated sand. Finally, ongoing experiments aim to evaluate the influence of shear thinning on saturated soil response and provide strategies to help mitigate the influence of this effect.

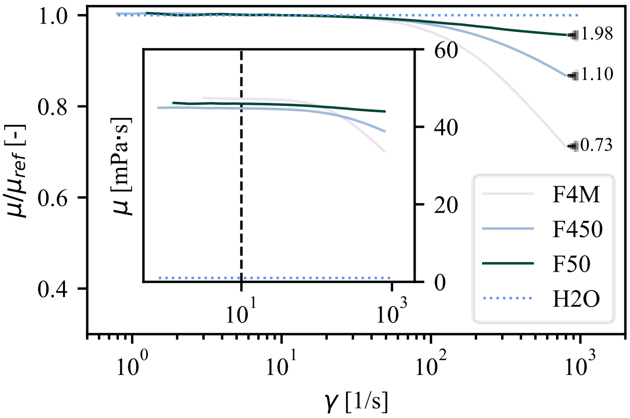
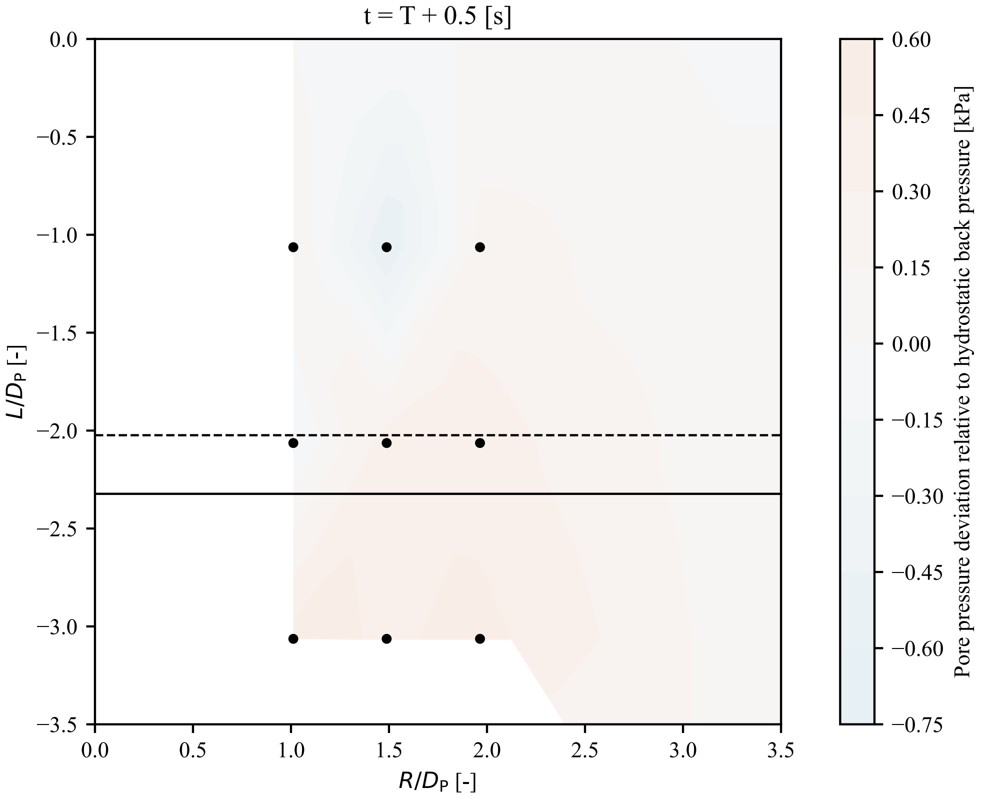
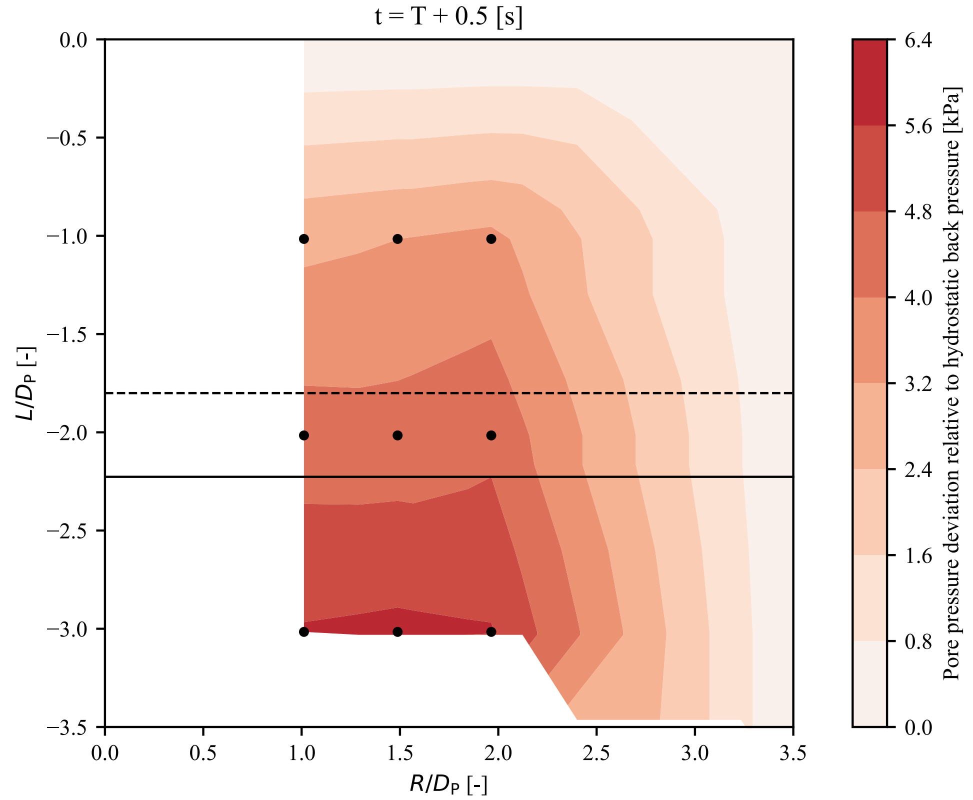


Figure 2. Flow curves normalized by μ_{ref}, the viscosity obtained at a shear rate of 10 Hz (dashed line), versus shear rate, γ. Labels indicate the solution concentration in percent (not applicable to H_2O). Insert plots depict the absolute flow curves.



(a) Sample saturated with water, μ =1 mPa s.



(b) Sample saturated with aqueous solution of Methocel F4M, μ = 50±5 mPa s

Figure 3. Contour plot illustrating the measured fluid pressure relative to the hydrostatic backpressure in kilopascals (kPa). This snapshot is taken 0.5 s after the first contact between the ram and anvil. The horizontal dashed lines indicate the initial position of the pile. The solid lines show the final pile position

4 CONCLUSIONS

In this paper, the influence of pore fluid on the saturated soil-structure interaction is investigated for piles driven by prolonged force impulses. The results show that HPMC-based fluids used for physical modeling can experience significant shear thinning behaviour at high shear rates ($\gamma > 100$ Hz). The observed decrease in viscosity reaches up to 29%, depending on the type of HPMC used. This finding is particularly relevant for researchers involved in dynamic centrifuge testing, highlighting the importance of considering the predominant shear rate when selecting the most suitable HPMC-based pore fluid substitute.

Dynamic pile installation is characterized by very high shear rates along the pile shaft and below the pile base. In this case, shear thinning could temporarily enhance soil permeability. Consequently, this could affect the soil-fluid coupling and, ultimately, the overall pile installation process. Fully Newtonian viscous fluids exist, predominantly in the form of water-glycerine mixtures. However, due to their higher density, these too influence the overall mechanical response of dynamic soil-structure systems. Further research is required to make a quantitative comparison between these alternatives. Until then, researchers should evaluate the use of either type of fluid against their research objectives and select the best-suited alternative for their application.

The centrifuge experiments conducted as part of this study support this finding by providing evidence that the use of HPMC-based viscous fluid, despite shear thinning effects, allows capturing a partially drained response at the time of the dynamic event. At model scale, the associated pore pressure deviations require a few seconds to fully dissipate. Dry or fully drained experiments (e.g., using water as pore fluid), therefore do not fully appreciate the change in the stress state around the pile during installation.

Further testing is ongoing to substantiate these preliminary findings and provide a framework on the effects of shear thinning in the design of dynamic centrifuge experiments.

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