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Askarinejad, Amin; Philia Boru Sitanggang, Anggi ; Schenkeveld, Ferry

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Effect of pore fluid on the behavior of laterally loaded offshore piles modelled in centrifuge

Effets du fluide interstitiel sur le comportement de pieux en mer sous charges horizontales modélisés en centrifugeuse

Amin Askarinejad, Anggi Philia Boru Sitanggang
Faculty of Civil Engineering and Geosciences, Geo-Engineering section, TU Delft, The Netherlands
A.Askarinejad@tudelft.nl

Ferry Schenkeveld
Deltares, The Netherlands

ABSTRACT: The common practice in centrifuge modelling of dynamic processes is to use high-viscosity pore fluids to unify the time scaling factors for the generation and dissipation of pore pressures. This paper focuses on the effects of the density and viscosity of the pore fluid on the behaviour of an offshore rigid pile subjected to cyclic and monotonic lateral loads. The soil used in these tests is dense sand and it was saturated with three different fluids: 1) water, 2) mixture of glycerine and water, 3) a fibre based viscous fluid with a density very close to that of water. The results of the tests in terms of the changes in the pore pressures at the interface of the pile and soil as well as monotonic lateral bearing capacity of the pile are compared. The tests illustrate that the behaviour of the model with water is very similar to that of the dry model, implying a fully drained behaviour. Moreover, it was observed that the density of the pore viscous fluid plays a major role in the evolution of the pore pressures. Therefore, it affects directly the stress state of the soil in the model.

RÉSUMÉ : RÉSUMÉ : La modélisation en centrifugeuse de procédés dynamiques requiert des fluides interstitiels à haute viscosité pour unifier les effets d'échelle temporelle dans la génération et la dissipation de pression interstitielles. Cet article se concentre sur les effets de la densité et de la viscosité du fluide interstitiel sur le comportement des pieux rigides en mer soumis à des charges monotones et cycliques. Le sol utilisé pour ces tests est un sable dense saturé avec trois fluides distincts : 1) de l'eau 2) un mélange de glycérine et d'eau 3) un fluide à base fibreuse avec une densité proche de celle de l'eau. On réalise une comparaison des résultats de ces tests en termes de changement de pression interstitielle à l'interface pieu-sol mais également de capacité portante latérale. Ces tests démontrent que le comportement du modèle avec de l'eau est très similaire au comportement sec, impliquant un comportement totalement drainé. De plus, il est observé que la densité du fluide interstitiel visqueux joue un rôle prépondérant dans l'évolution des pressions interstitielles. Par conséquent, cela influence directement l'état des contraintes du sol au sein du modèle.

KEYWORDS: laterally loaded offshore piles, physical modelling, geotechnical centrifuge, cyclic loading, spud poles.

1 INTRODUCTION. FIRST LEVEL HEADING

The time scale factors relating centrifuge model to prototype, in terms of excess pore pressure generation and dissipation during dynamic loadings, are not the same (Schofield 1980; Tan & Scott 1985). A possible approach to unify these two time scaling relationships is to decrease the hydraulic conductivity of the soil by increasing kinematic viscosity of the pore fluid used in the model by a factor N, or reducing pore sizes (Take et al. 2004; Askarinejad 2013). The latter method is less favourable, as the change in the grain size distribution of the soil might have major effects on the mechanical behaviour. Therefore, careful pore fluid viscosity scaling is crucial to obtaining meaningful experimental results through dynamic centrifuge modelling (Adamidis & Madabhushi 2014). This has often been achieved with either silicone oil or mixtures of water and glycerol or later by using water solutions with various water chemical components (Allard & Schenkeveld 1994; Kutter et al. 1998).
Many researchers have investigated the effects of the physical and chemical properties of the model pore fluid on the hydro-mechanical responses of the soil (e.g. Young et al. 1998). The constitutive behaviour of the soil must be unaltered. The main requirements for a viscous fluid to be used in a centrifuge model are:

1- The constitutive behaviour of the fluid should be similar to that of water: i.e. Newtonian.
2- The compressibility of the model fluid should be same as that of water.
3- The fluid should have the same density as that of water.

Askarinejad et al. (2015) carried out direct shear tests under unsaturated and saturated conditions with a silty sand mixed with a solution of glycerine (56%) and water (44%) with seven times more viscosity than water. They concluded that the shear strength parameters of the soil are not significantly affected by the viscous fluid. However, they reported that the scatter in the data increased, which was attributed to the higher sensitivity of the fluid properties to the changes in the ambient temperature.

This paper discusses the effects of the density and viscosity of the model pore fluid on the behavior of an offshore rigid pile subjected to cyclic and monotonic lateral loads. Model Spud poles, anchoring system of a cutter suction dredge, were tested in dense sand with four different saturation conditions at 50g: 1- dry, 2- saturated with water, 3- saturated with a mixture of glycerin and water (1.2 times denser than water), 4- saturated with a water based chemical solution with a density very close to that of water.

2 LOAD ACTUATOR AND THE TEST PROGRAMME

Spud poles are used as temporary anchoring elements for Cutter Suction Dredge (CSD) vessels to the seabed, which are installed by free fall (Figure 1). The lateral capacity generated by spud pole is subject to irregularity and uncertainty of loading. The loading is characterized by the vessel movement due to the cutting process and the hydrodynamic actions of the waves. Once the spud pole fails, repositioning of the vessel will be costly and time consuming. It is necessary to examine the maximum capacity and the time frame of service at each dredging cycle to ensure a safe and reliable operation. The spud pole is assumed as a short pile foundation which is laterally loaded in two directions. It receives a combination of monotonic and cyclic loading from hydrodynamic action, barge movement, and cutting forces.

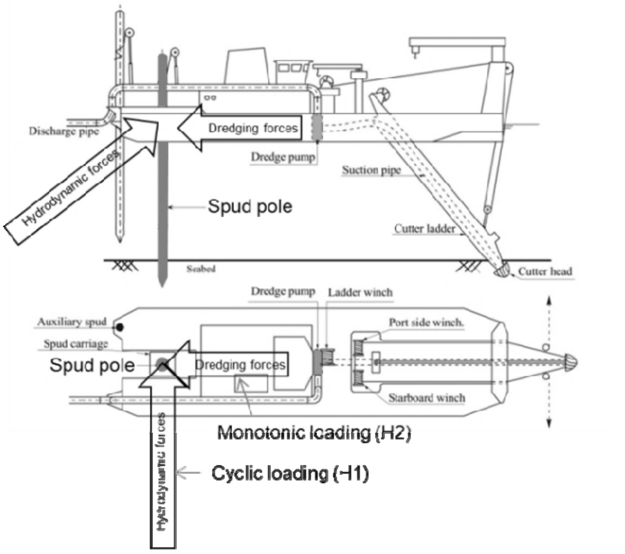

Figure 1: cyclic and monotonic lateral loads applied to spud pole (after Vlasblom. 2005).

A novel actuator and data acquisition system were specifically designed to study the spud poles in a geotechnical centrifuge. The spud pole model was instrumented with pore pressure transducers (PPTs). Displacement and load were measured by combination of load cells, potentiometer, and strain gauges. The two lateral loads on the spud pole model were perpendicular to each other and were subsequently applied. First, 540 cycles of lateral load, representing the hydrodynamic action and barge motion, was applied until a designated number of cycles. Afterwards, the pile was subject to the monotonic lateral load, representing cutting forces. The latter load caused relatively large displacement to the spud pole. The cyclic loading characteristic during operation of spud pole is undrained.

3 SAND CHARACTERISTICS AND MODEL PREPARATION TECHNIQUE

The sand used in this series of tests is a uniform (C_u=1.3) quartz sand with a D_{50}=0.35 mm. The specific gravity of the sand is 2.65. The max. and min. void ratios are respectively, 0.86 and 0.58, the relative density of the soil in the tests was 70%. The results of drained compression triaxial and direct shear tests showed a residual internal friction angles of 32.5 and 30.5 degrees, respectively. Permeability test was conducted with water as pore fluid which results in hydraulic conductivity of 7.3 E-04 m/s.

The samples were prepared in a strong box (283 × 150 × 130 mm3) using wet pluviation method. The process involves three major stages as follows:

1. saturation of sand batches with known dry weights, which are then vacuumed over night to remove potentially trapped air bubbles from the pores,
2. 'dredging' each of the sand batches into the strong box filled with the saturation fluid, by elevating the sand batch and letting the pressure head difference transport the sand grains,
3. densifying each of the dredged sand batches by applying horizontal shock-wave using until the designated densified layer height is reached.

4 WATER BASED VISCOUS FLUID

The water based viscous fluid described by Allard & Schenkeveld (1994) was replaced by a more environmentally friendly viscous fluid based on a research project performed in 1999 by Deltares. The characteristics of this new viscous fluid are the same as the fluid developed earlier in 1994. The fluid was a mixture of water and a thickening agent. The effects of temperature on the fluid density and viscosity for different concentrations of the thickening agent are presented in Figure 2.

The same water based viscous fluid was adapted for the experiments discussed in this paper. The kinematic viscosity is measured to be 52.3 cSt and the density is 1006 kg/m^3 at 20°C. The dynamic viscosity is 52.6 cP. It is quite stable with time, two viscosity measurements between 90 days of fluid storage showed no changes in these characteristic values.

The fluid viscosity and density decrease at higher fluid temperatures. It was also inspected that history of temperature fluctuation would not affect the viscosity. This was done by measuring the viscosity under cycles of temperature fluctuation. This behaviour however, only applies as long as there is no composition change in the solution, for instance due to evaporation.

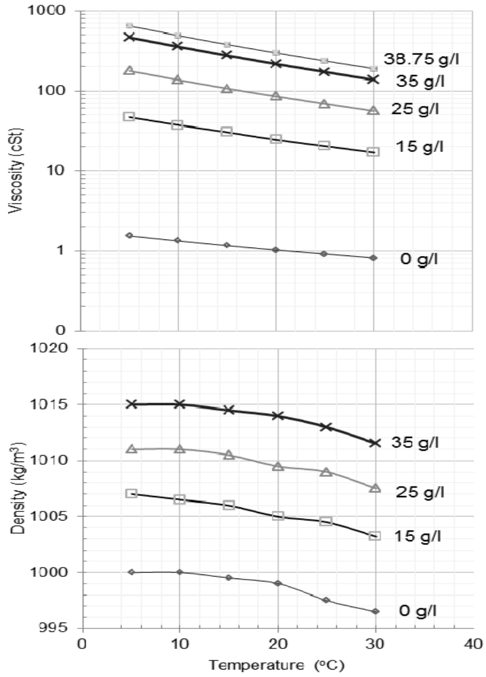

Figure 2: Effects of temperature on the kinematic viscosity (top) and on the kinematic viscosity of the water based pore fluid that was developed by Deltares in 1999.

4 GLYCERINE BASED VISCOUS FLUID

The glycerine based fluid is a solution of 79% v/v of glycerine to water ratio. The density of the is fluid was measured at 20°C to be 1205.3 kg/m^3. The kinematic viscosity is measured to be 50.231 cSt.

5 TEST RESULTS

The results of 4 centrifuge tests, conducted at 50g, in terms of the load displacement curves during the cyclic and subsequent monotonic loadings are presented and compared in this section.

5 .1 *Cyclic loading*

The pile head was oscillated for 540 cycles at a frequency of 5.3 Hz by an amplitude of 3 mm in model scale which are equivalent to 0.106 Hz and 150 mm in prototype scale, respectively. The extends of the failure mechanism at the surface of the dry model was measured to be approximately 1.5D from the centre of the pile (Figure 3).

The cyclic load-displacement curves of the piles during the first, the last and an intermediate cycle (60^{th} and 61^{st}) are compared in Figure 4. The results indicate a stiffening behaviour of the pile in all models independent of the pore fluid. This behaviour is attributed to the compaction of the soil profile along the cyclic movement of the pile. Moreover, the dilative behaviour of the soil profile at the shear zones parallel to the cyclic motion results in enhancement of the shear strength.

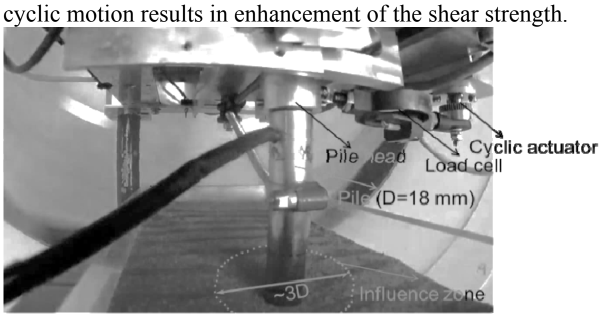

Figure 3: Influence zone of the cyclic motion.

The trends of hardening of the pile behaviour is more pronounced in the dry and water saturated models, which indicates a drained behaviour in the water saturated model. Whereas, the loops measured for the sample saturated with denser pore fluid (Glycerine based fluid) are flatter compared to the other samples.

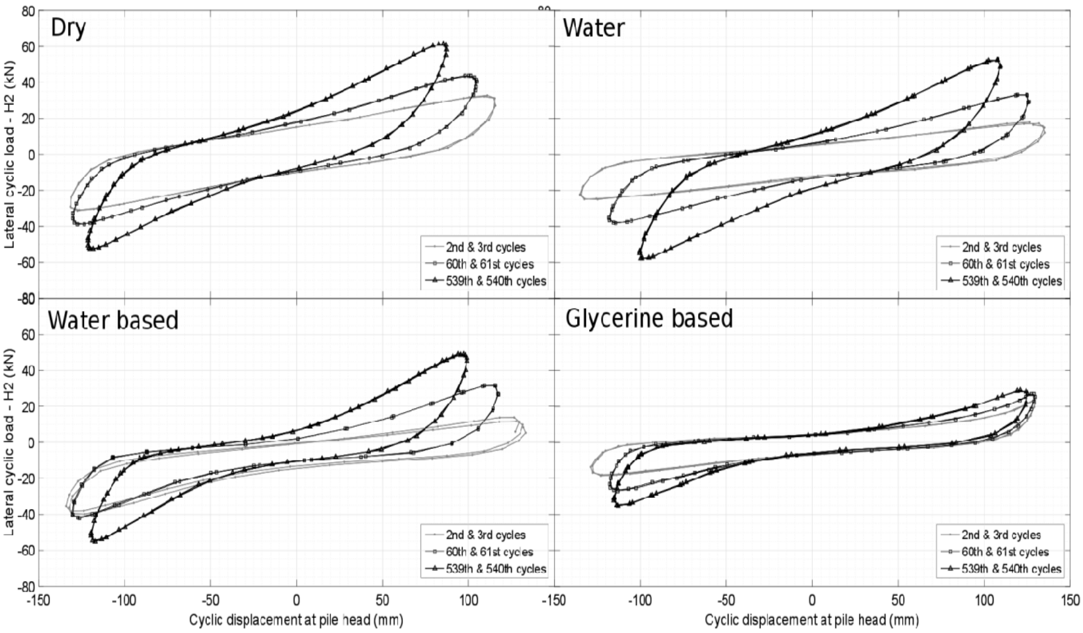

Figure 4: Results of the cyclic loading on the pile head.

5 .2 *Subsequent monotonic loading*

The surface outcrop of the failure mechanism around the pile after the monotonic horizontal displacement is depicted in Figure 5. The sketches on the image highlights the initial location of the pile and the condition of the deformed soil. The height of piled up soil in front of the pile is around 8 mm in model scale. The mobilized soil in front the pile is in a radius of 80 mm (~4.5D). Behind the pile, there is gap with conical shape, where the back soil grains filled it in, indicated by black arrows. There is also some soil from the front of the pile that moved into this gap.

The monotonic loading versus horizontal displacement of pile heads are compared in Figure 6. Similar to the cyclic behaviour, the responses of the dry and water saturated samples are more or less identical. Although the initial response of piles in the dry, water saturated and water-based viscous fluid saturated soils are similar, the hardening response after to the turning point at 350 mm displacement, is stronger for the dry and water saturated samples. This results confirmed that at the same rate of loading, the effective stresses on the dry and water saturated samples are higher than the effective stresses within the saturated sand sample.

Comparing the results of the two samples saturated with viscous fluids, it can be concluded that the glycerine based viscous fluid significant underestimates lateral capacity of the pile.

6 CONCLUSIONS

Investigation of the behaviour of spud poles was approached by analysis of short rigid piles subject to multi-directional lateral loads using centrifuge modelling. The effect of the 4 different pore fluids on the general behaviour of the piles were studied in this paper. The tests illustrate that the behaviour of the model with water is very similar to that of the dry model, implying a fully drained response of the soil to both cyclic and monotonic loading. However, it was observed that the density of the pore viscous fluid plays a major role in the evolution of the pore pressures. Therefore, it affects directly the stress state of the soil in the model and the mechanical responses of the pile in terms of the lateral capacity and stiffness.

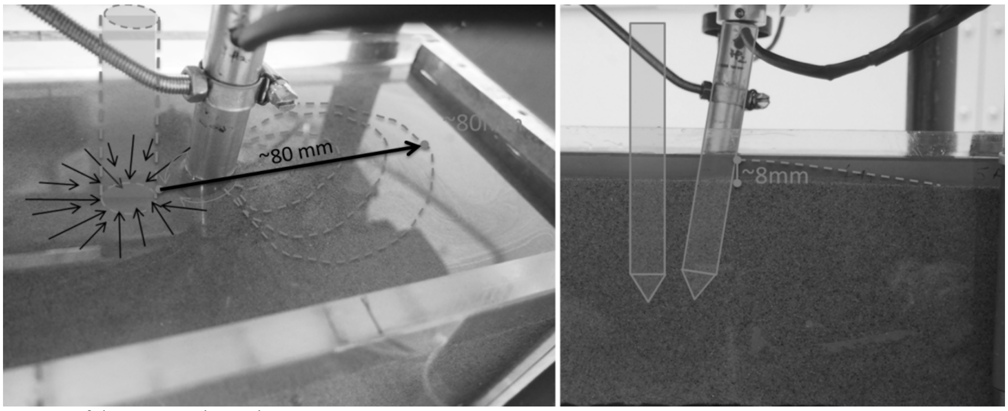

Figure 5: Influence zone of the monotonic motion.

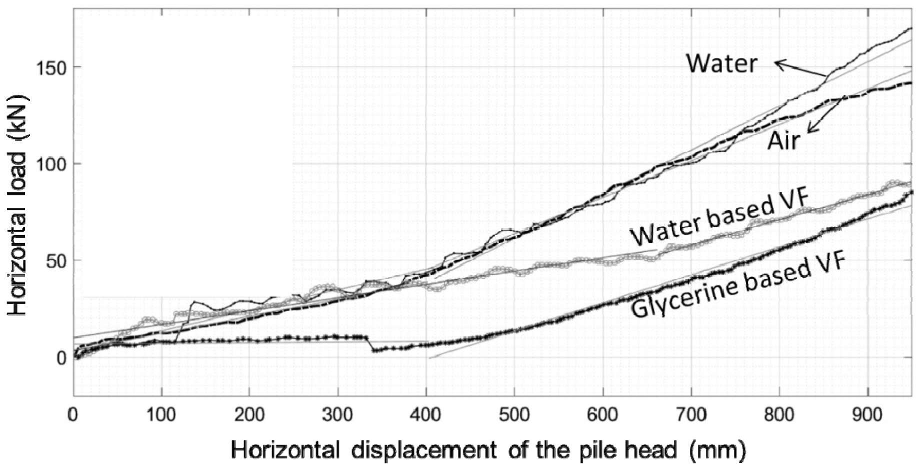

Figure 6: Horizontal load capacity of the piles installed in dense sand samples saturated with 4 different pore fluids.

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