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Effects of a large number of cycles on pile shaft resistance analyzed at the grain scale using x-ray tomography

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Abstract. This study presents the results of laboratory-scale cyclic loading tests performed on an instrumented pile in sand using x-ray micro tomography and three-dimensional (3D) image analysis techniques. The macroscopic behaviour of sand-pile interface shows a two–phases evolution during cycles with a non negligible increase of shaft friction in the second phase. A discrete version of Digital Image Correlation (DIC) is employed to analyze quantitatively the mechanisms occurring at the grain scale. Using segmented images this method is able to correlate and follow each grain individually between two configurations. Displacement fields are measured and compared for different amounts of cycles. Grain breakage and density evolution are investigated using grey level measurements. The results provide a better understanding of the phenomena observed at the macroscale for a high number of load cycles.

1 Introduction

Foundations of offshore platforms, wind or tidal turbines, are submitted to a significant number of load cycles due to specific environmental conditions. High cyclic loadings involving a complex response of the soil were shown to give rise to abrupt changes mainly in shaft resistance. Although potentially important, such effect lacks a micromechanical understanding and remains rarely addressed in current pile design criteria. Thus, mechanisms controlling the macroscopic behaviour of sand-pile interface must be investigated at the grain-scale.

From this point of view, literature gathers numerous experimental studies focused on the interface conducted at different scales on laboratory models. Links between sand kinematics, local variations in sand density, grain crushing and the macroscopic response were proposed. Yang et al. [1] studying model piles installed in a uniform pressurized sand and parallel interface ring shear tests concluded on the potential influence of particle crushing, interface abrasion, shear banding and fines migration on the behaviour of displacement piles in sand during the installation and following cycles. Similar results were observed using DIC and postmortem images for cone penetration tests performed in a half-circular chamber [2].

Using laboratory model piles installed in a large calibration chamber Silva [3] investigated the soil–pile interface response during high cyclic loading tests. Local stress measurements showed a radial contraction of the soil close to the pile. Preliminary postmortem observations on grain breakage and local density changes at the interface were linked to shaft friction evolution during cycles. After a degradation phase observed by several authors, an increase in skin friction was measured by Bekki et al.[4] for high number of cycles (between 100 and 100 000 cycles). These phenomena were attributed to the formation of a shear band of crushed grains around the shaft and a sand densification around the probe.

However, these mechanisms were observed using various optical methods either postmortem on sections of the tested specimen or with plane strain devices mainly during pile installation. The present work aims at establishing a direct link between the macroscopic and microscopic behaviour of the sand–pile interface during cycles. This paper presents the first results of *in operando* cyclic loading tests using x–ray tomography for the 3D–analysis of the deformation mechanisms at the interface.

2 Methodology

2.1 Experimental setup

The tests were conducted in a mini-calibration chamber in the tomograph of Laboratoire 3SR, in Grenoble, France. An instrumented 14mm diameter cone–ended aluminium model pile was first installed by monotonic loading in a dry calcareous sand sample (Glageon sand is derived from a carbonate rock crushed in Bocahut quarry, France) under an isotropic stress of 100kPa. Following the installation phase, the model pile was submitted to a thousand axial displacement-controlled cyclic loadings.

The samples (70 diameter and 120mm height) were prepared by deposition of consecutive layers of 20mm thickness and a density of 1.5g.cm^{-3} (loose samples). The material was chosen for its mean grain size (D_{50} =1mm),

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its uniform grading and its low resistance to breakage. The size of the sample and the mean grain size are dictated by the scanning conditions of the tomograph.

The minicalibration chamber consists in a pseudo-triaxial cell transparent to x−rays. The confining pressure was maintained constant during the test. For practical reasons, the pile was installed by jacking from the bottom of the cell at a rate of 0.06mm/s with a pile embedded length of 45mm. The cycles were performed at the same loading rate with an amplitude of ±0.5mm around the pile tip reference position, alternating between compression and tension phases (two−ways cycles). The model pile is instrumented with a load sensor at its end to measure the tip load. By subtracting the total load applied on the pile, its shaft capacity was also calculated and followed during cycles.

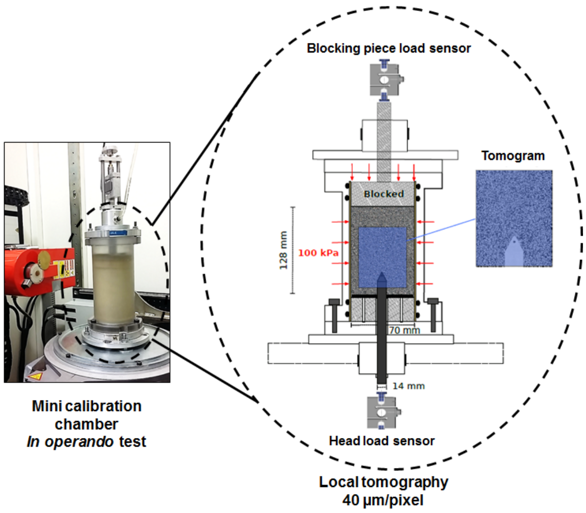

Figure 1. Experimental setup during x-ray micro tomography.

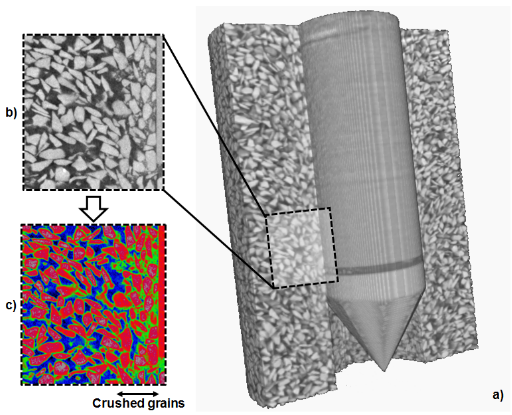

Figure 2. a) 3D reconstructed volume after pile installation in local tomography. b) Zoom on the interface. c) Detection of different phases (red:grains and pile, blue:air and green:fines).

2.2 Microscale image analysis

The loading on the model pile was applied progressively, stopping at defined amount of cycles for 3D scanning (1, 10, 50, 100, 500, 1000 cycles). Scans were taken in local tomography, with a field of view focused on the tip and the shaft, for a pixel size of 40μm. Scans were settled to a tension of 150kV and a current of 200μA. For each tomography, 1024 radiographies were made of the sand samples for the reconstruction of the entire volume.

To extract information at the microscale, different image analysis techniques were used. Fields of displacement and strain can be calculated using the 3D DIC code, TomoWarp2, by assuming a continuous displacement field, at least within each subset (containing about 8 grains) and, locally, the transformation to be a rigid translation. In this study, a discrete version of TomoWarp2 [5], recently implemented, able to correlate each grain individually was employed to take into account the granular aspect of the sand and of its mechanical response. In this approach, the correlation window is centred on individual grains and follows the actual shape of the grain. Full kinematics of each particle were then measured for different loading stages.

To characterize the state of the granular assembly during cycles, x-ray tomograms were analysed based on grey intensity changes. Density variation was followed at the interface for different amount of cycles as well as the quantity of fines produced by grain breakage. The analyses were conducted using the free and open−source image processing software Fiji.

3 Results

3.1 Friction force at the grain−pile interface

The measurement of the force induced by friction at the sand-pile interface during cyclic loadings indicates two separated regimes. For the first hundred cycles, shaft friction does not vary significantly, whereas a constant increase is observed for the following cycles (see Figure 3a). Figure 3b represents the maximum friction measured when the tip displacement reaches ±0.5mm for various two-ways displacement−controlled cyclic tests performed on Glageon sand, with identical testing parameters. A similar trend showing the reproducibility of the results is observed. Comparing the maximum friction obtained before and after cycles, the friction force has doubled, with a sharp transition between the two regimes. It is important to note the difference in friction intensity between the tests GLAG−C3, GLAG−C2 and GLAG−C1. Despite the smoothing with a very fine sandpaper before each experiment, a slight change in pile surface roughness is expected.

The above results are consistent with those previously obtained in the large calibration chamber of 3SR for a higher number of cycles [3]. In the same testing conditions, the shaft friction was shown to increase after 10000 cycles. The difference in the number of cycles necessary to reach the same trend can be explained by two different scale parameters: the initial density of the tested specimen and the aspect ratio between the model pile diameter and

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the mean grain size (14 in the present study against 166 for the large calibration chamber).

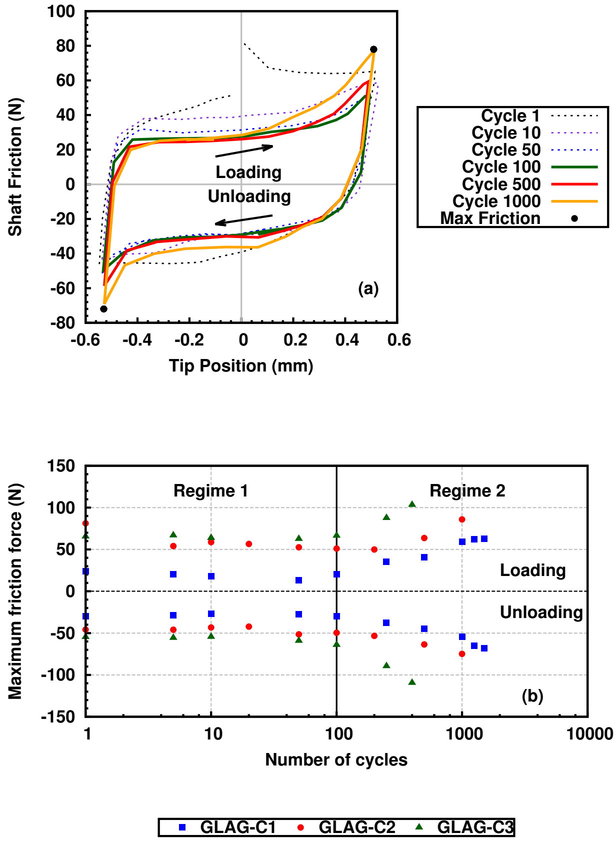

Figure 3. a) Shaft friction evolution during cycles for GLAG-C2 (the black arrows indicate the loading and unloading). b) Identification of two regimes in shaft friction evolution (change in trend at 100 cycles noted by the black vertical line).

3.2 Granular kinematics

3D−DIC was successfully used to study displacement and strain fields during the installation phase of a pile ([6], [7] and [8]). In the present case, the effects of cycles were analysed at the grain scale. Typical results from the discrete approach of 3D−DIC for two loading steps are presented : between 10−50 cycles and 500−1000 cycles. Displacements are plotted for each individual grain in a vertical plane passing through the pile axis.

Although the main granular rearrangement is occurring during the pile penetration, cyclic loading induces significant radial displacements. The results show a global movement of the grains towards the pile shaft for both loading steps (see Figure 4b). However, the sand mass undergoes tiny vertical displacements (see Figure 4a). Due to the low roughness of pile surface, grains tend to slide alongside the shaft. By comparing vertical and horizontal displacement fields after 50 and 1000 cycles, two different behaviours can be observed. The first tens of cycles cause higher grain movements within a larger area around the shaft.

Besides grain kinematics, discrete DIC proves to be a powerful tool offering a wide range of further possible analyses in terms of grain orientations, grain shape evolution and grain breakage quantification.

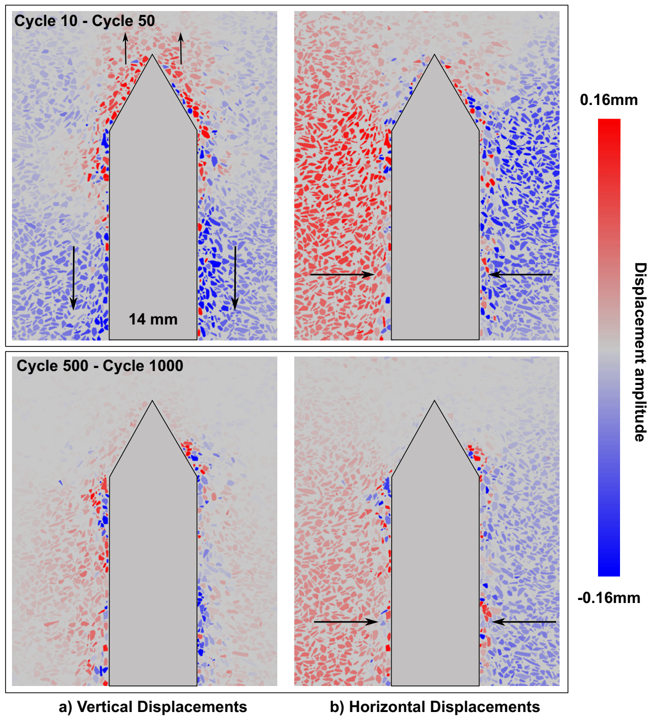

Figure 4. Individual grain displacements from discrete DIC for two loading stages: black arrows in the figure show global directions (GLAG−C2).

3.3 Local densification at the interface

Preliminary observations of raw x-ray tomograms show a clear evolution in density at the interface during cycles. 3D images were then further analysed looking at grey level in order to assess quantitatively the effect of cycles. Three phases were first identified in the images: pores (low grey level), intact grains (high grey level) and fines produced by crushing. For the given spatial resolution, the powder produced by grain breakage can not be clearly observed but by partially filling voxels, it can be associated to an intermediate mean grey level. However, fine particles and the edges of intact grains present similar x-ray absorption, leading to possible misinterpretation of particle boundaries. Choosing an appropriate threshold, the percentage of voxels belonging to each phase was estimated within 5−voxels−thickness hollow cylinders centred on the pile axis. Figure 5a shows the evolution of the density of each phase plotted in terms of distance from the shaft normalized by the mean grain size and the amount of applied cycles.

For cycle 1, each point represents one measurement at a given distance from the shaft. The two first data points should not be taken into account due to boundary effects at the sand−pile border on the images. The results show a significant increase of the percentage of voxels associated to intact grains (without taking fines into account) during cycles. Close to the interface, the quantity of grains is 20% higher after 1000 cycles, which indicates a local densification at the interface induced by cyclic loadings. It can also be observed that the region affected by the loadings is about $2{\cdot}D_{50}$ for cycle 1 and $4{\cdot}D_{50}$ for cycle 1000, which agrees with results given in [1] . In the rest of sand mass, the proportion of grains and pores remains constant (neglecting intensity changes between two scans).

In terms of fines production (see Figure 5b), only a slight variation (2%) is observed between the first and second loading stages. Later on, the percentage of fines is stable, meaning that most of particle crushing occurred during pile installation. A rearrangement around the shaft of crushed grains produced at the pile tip may be induced due to their own weight during the first loading and unloading steps, which might explain the apparent increase of fines quantity shown in figure 5b.

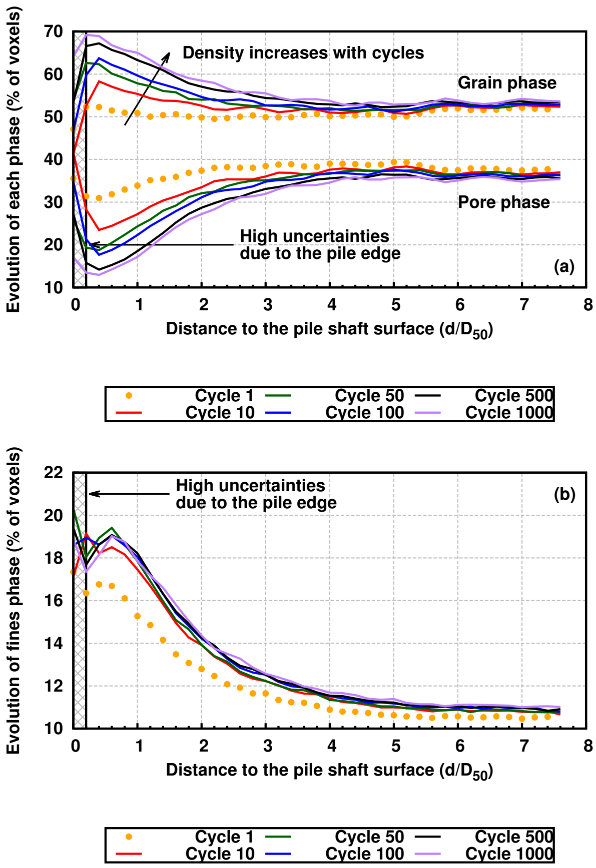

Figure 5. a) Local densification: radial evolution of intact grain (without fines) and pore phases during cycles for GLAG−C2 (scale: $\frac{7*d}{D_{50}} = 7mm$ = 0.5∗pile diameter. b) Evolution of fines quantity during cycles (GLAG−C2).

4 Conclusions

X-ray tomography and 3D image analysis were used to investigate cyclic load effects on sand-pile interface at the grain scale. Two distinct regimes were identified in shaft friction evolution according to the number of applied cycles. For these two phases, the measurement of grain kinematics revealed a different behaviour of the sand mass at the interface. In addition, a quantitative study of density evolution showed a significant densification during cycles. These results suggest that around 100 cycles are needed for the sand to rearrange and reach a threshold density for which the friction starts increasing substantially.

5 Perspectives

Further image processing should lead to a better understanding of the link between grain kinematics, density changes and the different regimes in shaft friction evolution. A new technique using discrete DIC results is under development in 3SR in order to assess quantitatively grain breakage. This tool can be used to follow the evolution of grain size and shape during both monotonic and cyclic loading. Other experiments will be performed to explore the influence of various parameters: grain size with respect to pile diameter, grain crushability, amplitude of cycles and pile roughness.

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