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Rough pile stereolithography for centrifuge modelling

Stéréolithographie pour la modélisation en centrifugeuse de pieux rugueux

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ABSTRACT: The capacity of bored cast in situ concrete piles in clay is typically governed by shaft resistance, which is usually achieved through skin friction. Skin friction is dependent on the proportion of the soil strength that is mobilised by the pile – and can vary depending on the roughness of the pile. Valuable insights into the behaviour of piles under loading can be obtained through physical model testing at reduced scale in a geotechnical centrifuge if the soil pile interface can be modelled appropriately. Therefore, it is important to consider how the surface of a pile should be modelled to achieve a comparable roughness between the model and the prototype pile. In this paper, a method for designing a pile with a specified roughness using stereolithography, also known as 3D printing, is described. The normalised roughness of the model pile is determined based on the likely failure mechanism of the pile and the mean soil particle size. The rough surface profile is then designed using 3D modelling software with the calculated arithmetic average surface roughness. Data are presented from preliminary centrifuge model tests on piles with different surface roughness.

RÉSUMÉ: La capacité des pieux en béton coulés forés dans de l'argile est généralement déterminée par la résistance à la traction, qui est généralement obtenue par friction latérale. La friction latérale dépend de la proportion de la résistance du sol mobilisée par le pieu, et peut varier en fonction de la rugosité du pieu. Des informations précieuses sur le comportement de ces pieux sous charge peuvent être obtenues grâce à des essais de modélisation physique à échelle réduite dans une centrifugeuse géotechnique si l'interface sol-pieu peut être modélisée de manière appropriée. Par conséquent, il est important de réfléchir à la manière dont la rugosité d'un pieu doit être modélisée pour obtenir une rugosité comparable entre le modèle et le pieu prototype. Dans cet article, une méthode de conception d'un pieu avec une rugosité spécifiée à l'aide de la stéréolithographie, également connue sous le nom d'impression 3D, est décrite. La rugosité normalisée du pieu modèle est déterminée en fonction du mécanisme de défaillance probable du pieu et de la taille moyenne des particules du sol. Le profil de surface rugueux est ensuite conçu à l'aide d'un logiciel de modélisation 3D avec la rugosité moyenne arithmétique calculée. Des données seront présentées à partir d'essais préliminaires de modélisation en centrifugeuse sur des pieux ayant différentes rugosités de surface.

Keywords: Centrifuge modelling; stereolithography; pile roughness; skin friction.

1 BACKGROUND

The ultimate capacity of a pile typically depends on the pile end bearing capacity and the friction between the pile shaft and the soil in which the pile is installed. The installation method and soil type have an effect on the proportion of base capacity and shaft friction generated by a pile (Mandolini *et al.*, 2005; Panchal *et al.*, 2019). The end bearing capacity of bored, cast in situ piles in clay is usually mobilised at a vertical pile displacement of about 30% of the pile diameter (Budhu, 2010), which is beyond the typical magnitude of the working load of a pile foundation. However, the shaft resistance in these conditions is mobilised at much smaller vertical displacements.

2 INTRODUCTION

As most of the capacity of a bored, cast in situ pile at working load is typically generated via pile shaft resistance, the interface between the soil and pile is an important aspect when conducting pile load tests. Previous studies assessing the effect of surface roughness on clay-interface shear behaviour observed greater mobilisation of shear in tests with rougher surfaces than those with smoother surfaces (Martinez & Stutz, 2019). Taha & Fall (2014) found that increasing the surface roughness also increased interface strength.

Hammoud & Boumekik (2006) and Feligha *et al.* (2016) observed three modes of interface shearing which depend on the roughness parameter *R* (the relative roughness of a surface). The relative roughness is defined as the centre line average value of roughness divided by the mean particle diameter, D_{50}, of the soil particles with which it interacts. The three proposed modes are: full sliding at the interface (when $R < 0.3$), shear failure within the soil (when $R > 1$), and both sliding and shear failure within the soil occurring simultaneously (when $0.3 < R < 1$).

Lemos & Vaughan, (2000) found that for a very smooth interface, the interface shear resistance is lower than the soil-on-soil residual strength, although it is unlikely that such surfaces would occur in practice.

In geotechnical centrifuge testing, pile foundations are typically modelled as steel (Ebeido *et al.*, 2018; Netietd *et al.*, 2023), or aluminium (Haffar *et al.*, 2017) tubes. Some authors have also utilised cast resin (Lalicata *et al.*, 2023) and mortar (Ganiyu *et al.*, 2018). The use of steel and aluminium tubes is commonly used as they are inexpensive and relatively quick to machine. However, unless a roughness is applied to the profile, these model piles would essentially present a smooth surface during testing – thus reducing the interface shear resistance between the pile and the soil. In addition, when conducting a series of centrifuge pile tests, this applied roughness to the model pile is not repeatable throughout the test series.

Some researchers, in order to make steel or aluminium model piles more representative of prototypes, have added rough profiles to the model pile surface by either machining a roughness on the pile surface (O'Hara & Martinez, 2022) or by gluing sand particles, or sandblasting the outside of model piles (Ouzzine *et al.*, 2023). Although these methods provide the required roughness for testing piles in sand, it is extremely difficult to replicate the exact roughness profile on all piles used in a series of centrifuge tests.

Using cast resin and mortar also has drawbacks for geotechnical centrifuge testing. Although cast mortar piles have been effective in reproducing the behaviour of prototype piles, their implementation has been relatively time consuming due to the curing time necessary in the mould before testing (Ganiyu *et al.*, 2018). A proposed solution to overcome these time constraints has been to use fast cast resin. However, drawbacks were noted as the curing process of the resin in the clay model appears to affect the soil-pile interface properties owing to possible chemical bonding between the clay and the resin (Lalicata *et al.*, 2023).

The aim of this paper is to establish a quick and reliable method of producing representative and repeatable model piles for centrifuge testing with the aid of stereolithography. The relative roughness of five 3D printed blocks with different surface roughness has been determined and compared to that of a cast concrete block.

3 MEASURING ROUGHNESS

The relative roughness, R, value can be calculated from the measured centre line average, *CLA*, roughness value, R_a, for a sample. R_a is measured by defining a centre line for a surface profile (Figure 1) where the area between the peaks of the surface and the centre line are equal to the area between the troughs of the surface and the centre line.

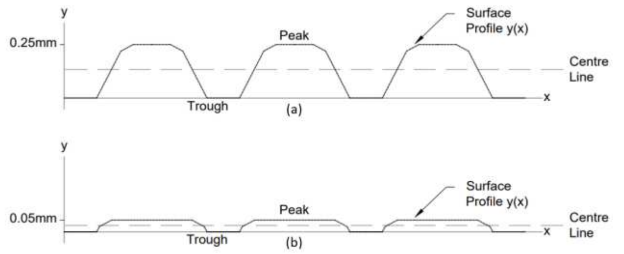

Figure 1. Schematic diagrams of surface profiles with offset distances of (a) 0.25mm, (b) 0.05mm.

R_a is then calculated as the mean value of the vertical deviation from the centre line of the surface profile using

$$R_a = CLA = \frac{1}{L}\int_0^L |y(x)|dx \quad (1)$$

With L being the profile sampling length. In order to define the roughness value in terms of the scale of the soil grains at the interface, R_a is expressed in terms of the average diameter, D_{50}, of the soil grains, giving R:

$$R = \frac{R_a}{D_{50}} \quad (2)$$

For the purpose of this paper, the piles are assumed to be in contact with Speswhite kaolin clay, which is commonly used in centrifuge model tests in clay. Thus, the average diameter of the soil grains is assumed to have a maximum value of 2.00µm.

4 ROUGHNESS SAMPLES

Five rough gauge blocks were drawn using the 3D modelling software SolidWorks. Each block was modelled with an inclusion in which a standard polyhedron pattern with varying offset distances was applied. The offset distances ranged between 0.05 to 0.25mm at 0.05mm intervals. Figure 2 shows two rendered roughness gauge blocks which were then 3D printed using a micro carbon fibre filled nylon filament, known as Markforged Onyx, and their roughness measured using a Mitutoyo Surftest SJ-210 surface roughness measurement instrument.

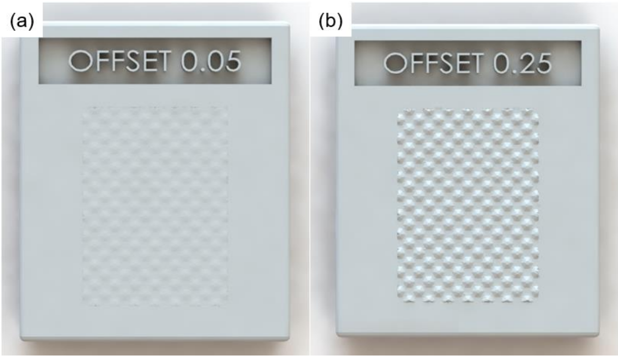

Figure 2. 3D modelled roughness gauge blocks with an offset distance of (a) 0.05mm, and (b) 0.25mm.

The roughness parameters of the rough gauge blocks were compared to the roughness of a 100x100x100mm concrete block, with a cement to sand to aggregate ratio of 1:2:3, in order to see which offset distance would be the most appropriate to employ when applied to the model piles in geotechnical centrifuge testing. The roughness of the concrete block was measured using the same instrumentation, taking an average roughness value. In addition, the roughness parameters of a resin pile, as used in a study by Gorasia & McNamara (2016), a pile coated in sand, and a smooth aluminium pile (Figure 3) were also measured, in order to investigate which mode of interface shearing would likely take place between the model piles and clay during a geotechnical centrifuge test.

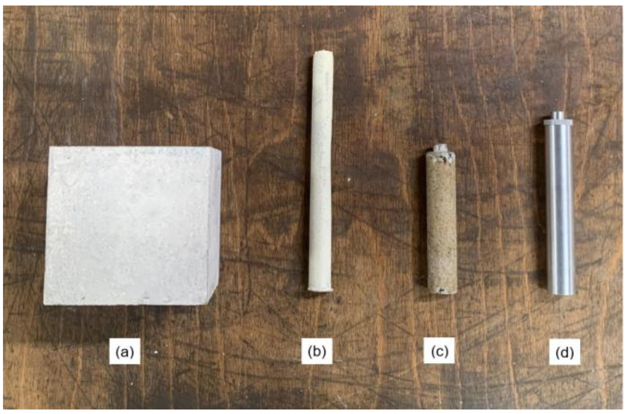

Figure 3. Samples used for roughness parameter comparison (a) concrete block (b) resin cast pile (c) sand coated pile (d) smooth aluminium pile.

5 RESULTS AND DISCUSSION

The centre line average and relative roughness of the four sample elements (concrete block, resin pile, sand coated pile, and aluminium pile), in addition to the five rough gauge blocks are presented in Table 1. The surface roughness measuring instrument was calibrated to an accuracy of 0.13% against a machined roughness gauge with a roughness of 3μm, to ensure the readings were correct.

All five roughness gauge blocks were found to have a relative roughness greater than 1. This means that applying any offset distance equal to or greater than 0.05mm onto a model pile would lead to an interface shear resistance equal to that of soil-on-soil shear resistance. However, comparing the values of relative roughness on the gauge blocks to that of the concrete block, it is evident that an offset of 0.25mm provides the most comparable surface profile for concrete pile modelling.

It can be observed that the relative roughness of the resin pile would also provide an interface shear resistance equal to the soil-on-soil shear resistance. However, as noted above, due to the curing process of the resin, the soil-pile interface is affected.

The smooth aluminium pile was found to have the lowest surface roughness, with the relative roughness smaller than 1.00. Therefore, when testing this pile in clay, the interface shear resistance would be lower than that of soil-on-soil shear resistance, and marginally greater than 0.30, leading to a combination of sliding and soil-on-soil shear at the interface during testing. Although the smooth aluminium pile surface can provide ease for repeatable testing, the low roughness renders the pile unrepresentative of the prototype.

The surface profile of the sand coated pile presented difficulties for measuring its roughness as the values were beyond the measurable range. However, it can easily be assumed that this pile would have a relative roughness greater than 1, providing an interface shear resistance between the pile and a clay soil sample to be that of soil-on-soil shear resistance. Nonetheless, it is difficult to replicate the exact surface finish with this method for a series of piles as the pile is simply coated in an adhesive and submerged in, or covered with sand. Hence, each pile is likely to possess a random distribution of sand particles. In addition, when testing these piles at elevated ***g***-levels in clay, there is a risk of the adhesive separating from the pile, thus changing the interface between the pile and the clay.

Table 1. Surface roughness parameters of sample elements and roughness gauge blocks.

Roughness parameter	**Samples**					**Roughness gauge block texture offset distance (mm)**				
	Calibration sample	Concrete block	Resin pile	Sand coated pile	Aluminium pile	0.05	0.10	0.15	0.20	0.25
R_a (μm)	3.00	12.06	3.37	N/A	0.63	4.90	7.88	8.79	10.56	11.98
$R_{(avg)}$	1.5	6.03	1.69	N/A	0.32	2.45	3.94	4.40	5.28	5.99

6 CONCLUSIONS

The surface roughness of five roughness gauge blocks was measured, quantified and these values compared to that of the surface roughness of a 100x100x100mm concrete block, with a cement to sand to aggregate ratio of 1:2:3.

The roughness profiles of three different piles were also measured and their potential modes of interface shearing analysed.

It was found that although the roughness gauge block offset texture does not have an effect on the mode of interface shear, comparing the relative roughness value with that of the concrete block, it can be seen that applying an offset distance of 0.25mm to a model pile would make it most representative to that of a prototype.

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