On the modelling of piles in sand in the small geotechnical centrifuge

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Abstract: The use of a geotechnical centrifuge for properly capturing the mechanisms in the sand adjacent to a foundation pile is well established. Larger centrifuge facilities were previously preferred over small centrifuges, because of the difficulties of the required miniature instrumentation. The technology since then has moved on and recent technical developments, such as MEMS sensors, facilitate the use of small models including all the necessary instrumentation. However, correct scaling and modelling of piles installed in sand in the geotechnical centrifuge remains essential. Especially, stress waves in the sample, created during pile driving, are impractical to scale. The latter, however, is not only limited to small centrifuge facilities. Therefore, the modelling should not include stress waves. A feasible approach for that is to limit pile installation effects in coarse material, which ensures drained conditions, to the application of cyclic load reversals.

Keywords: Piles, Centrifuge Modelling, Instrumentation, Pile Dynamics, Similitude

1 BACKGROUND

There are still a large number of problems related to piles that are not completely solved. These include long-term effects, the effects of cyclic loading, pile installation effects, and pile group effects (e.g., Axelsson, 1998, Brown et al, 1988, Lang & Vanneste, 1994, Klotz & Coop, 2001). Correctly scaled (scale) model tests are essential to investigate these problems. The scope of this article is restricted to the scaling and modelling of piles in sand in the geotechnical centrifuge. As this remains the most feasible alternative, to include the stress-dependent strength and stiffness response of the sand whilst maintaining manageable sample reproducibility (Garnier, 2007). The slenderness of piles makes correct scaling all the more important. In piles a large fraction of the total bearing capacity results from the shaft friction, which needs to be properly scaled. Typical piles have a slenderness factor of approximately 50, this ratio, however, is difficult to achieve in model pile tests (Dijkstra, 2009).

Recent developments in miniaturization of instrumentation and data acquisition systems increase the possibilities of centrifuge testing. Facilities using small sample sizes benefit most, as the use of small scale models necessitates miniature size instrumentation of the models without too much disturbance. At the same time the measurements need to be as precise and as accurate as their larger scale siblings.

In addition to the use of in-flight computer systems for the control and data acquisition, micro-controllers offer new potential. An example is the control system for the actuators of Delft University of Technology or the data acquisition system at Center for Offshore Foundation Structures (Gaudin et al. 2009). The low cost and wide availability of electronic components, especially the new MEMS sensors, allows innovative and efficient experimental tests to be devised and performed quickly within the existing centrifuge facilities.

The difficulties involved in the instrumentation of small-scale models have previously reduced the usefulness of small centrifuges, focusing on phenomenology rather than obtaining quantitative data.

Larger centrifuges have therefore been preferred for intricately instrumented centrifuge experiments. An advantage of large centrifuges is the reduction in non-linear stress distribution in the sample, which is caused by the Coriolis Effect (Schofield, 1980). This increased accuracy could be of large importance for long slender elements, e.g. piles, where the distribution of vertical stress is of large importance for the pile response. There are also additional advantages from using large models, such as the increase from the boundary distance (Bolton et al, 1999).

However, the small centrifuge has advantages, in particular the lower operating costs and simplified operating procedure start to lead to an increased interest in operating small facilities (White, 2008). The lower costs allow for parameter analysis, where a larger number of tests in iterative test conditions are performed. In most cases, the smaller sample size leads to greater sample uniformity and consistency. Also, optical techniques benefit from a smaller field of view, resulting in higher pixel resolution for the same scaled physical mechanism relative to the grain size.

Model pile tests in a small centrifuge, when properly scaled, become a good alternative for the experimental investigation of pile behaviour in sand. A large number of research variables can be investigated using a large number of small but efficient model tests. The advantages of modern technology and its future possibilities will further advance the state of the art and yield more information from each test. In this article centrifuge modelling of piles in sand in the context of a small centrifuge will be presented. The advantages and limitations of scaling, data acquisition, instrumentation and optical techniques will be discussed. Also, the feasibility of capturing different pile mechanisms is elaborated upon.

2 SCALING OF PILE MODELS IN THE SMALL CENTRIFUGE

Scaling of model tests in the centrifuge have been investigated extensively and a summary is found in the scaling catalogue developed by TC2 (Garnier et al, 2007). Mechanisms observed on the continuum scale generally scale well in the geotechnical centrifuge. Because of the slenderness of the pile element, correct scaling of the effective vertical stress and its gradient is considered important. The divergence of the effective vertical stress caused by the Coriolis effect is much more pronounced in small centrifuges compared to large scale facilities. This is caused by the smaller ratio between the centrifuge arm radius and the size of the centrifuge models which are normally tested in small centrifuges (Schofield, 1980). The non-linear distribution of the effective vertical stress possibly shifts the state-parameter, as defined by Been & Jefferies, 1985. The importance of this effect depends on the type of tests and the stress distribution of the sample.

Another test disturbance is the so-called “silo effect”, which is illustrated in Figure 1. Arching at container walls might strongly reduce effective vertical stress with depth. This effect depends on the ratio between the height and diameter of the container and typically is a bigger issue in small samples. Samples with low ratio between height and length of the sample container are less prone to exhibit the silo effect (Garnier, 2001).

The container wall might also buckle, which can influence the horizontal geostatic pressure (Garnier, 2002). If the horizontal deflection is lower than the height/2000, this effect is negligible. The buckling effect in small centrifuges is much less of a concern as forces are much smaller.

The homogeneity of dry sand samples can be significantly improved by mechanical sample preparation (automated sand raining). The terminal velocity of the pluviated sand controls the sample density (Vaid & Negussey, 1988). This method is most feasible for smaller samples to reduce preparation time. In this case shadow effects from the side boundaries need to be taken into consideration. Alternatively, for much bigger samples can be prepared in suspension (Mulilis et al, 1977, Altaee & Fellenius, 1994).

The distance between the pile elements and the container wall should be in excess of 10 pile diameters, and the ratio between the sample container and the pile diameter should be in excess of 35 (Bolton et al, 1999, Garnier, 2007).

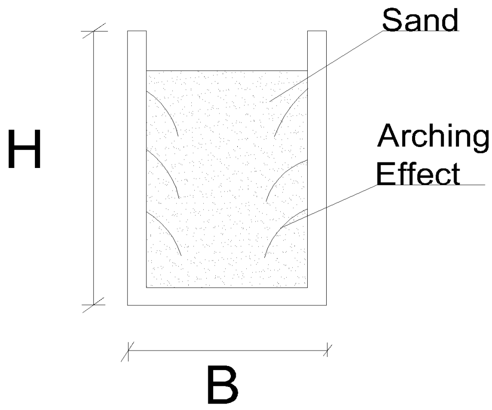


Figure 1: The silo effect with soil arches.

Some of the most important factors influencing the soil-pile interaction are not correctly scaled. The most important effect is the constant size of the shear band adjacent to the pile shaft. The thickness of this shear band is governed by ratio between the grain size d_{50} and the pile roughness R_{CLA} and is typically in the order of ~10 d_{50} (Boulon & Foray, 1986, Fioravante, 2002)

For small model piles this effect is more pronounced, i.e. the shear band is 10% of the pile diameter. This factor reduces to about 3% - 5% for tests performed in a larger centrifuge, compared to in situ (< 1%) this still is too large. Existing tests show that the ratio between the pile diameter and the mean grain size d_{50} should be in excess of 35 for vertical loading of the pile, and in excess of 44 for lateral loads (Balachowski 2006). To meet these conditions often the slenderness ratio has been compromised due to limitations in sample height and a minimum required pile diameter. In small centrifuges only ratios of length and diameter (L/D) of 10-15 can be reached, in larger centrifuges values up to 30-40 are feasible. The influence of the sand mean grain size in 1g-conditions is shown in Figure 2a and 2b. Plane strain tests were performed for different ratios of the pile diameter D and the mean grain size d_{50}. The results show pile head load of four tests. The D/d_{50}– ratio is 6.8 and 28 in Figure 2a and Figure 2b respectively. The variation of footing penetration with small D/d_{50} – ratios is shown to increase with increasing particle size.

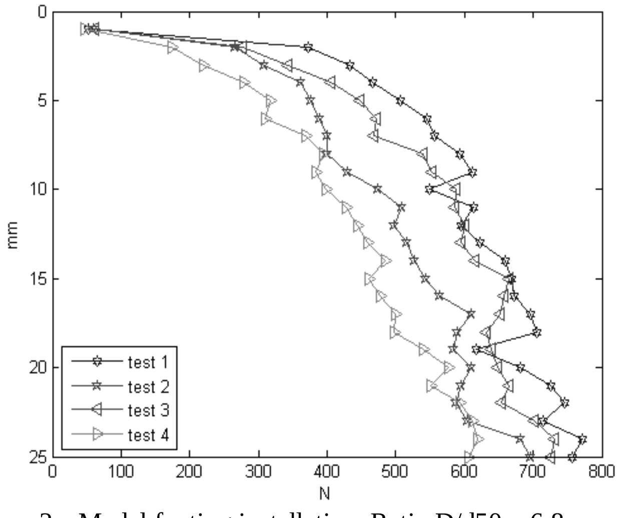


Figure 2a: Model footing installation. Ratio D/d50 = 6.8.

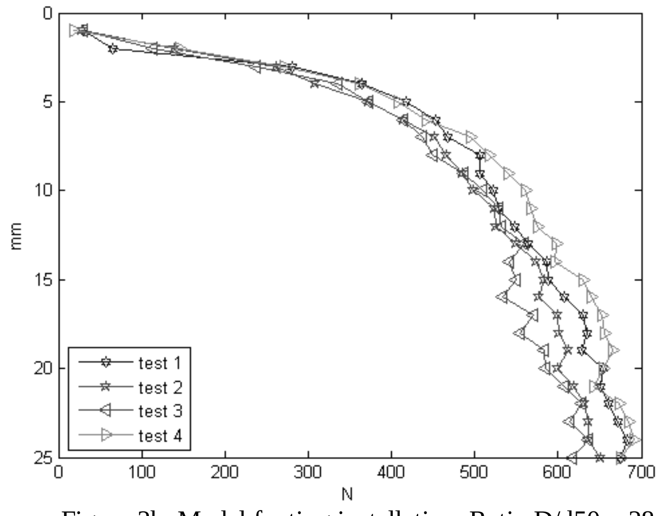


Figure 2b: Model footing installation. Ratio D/d50 = 28.

Furthermore, larger loads are mobilized in the large centrifuge. The reason for this is the scaling of the area but not the intensity of the stresses. As a result actuators in the largest large centrifuge facilities such as Deltares and UC Davis must be hydraulically controlled. Small and medium-size centrifuges require less force and actuators can be powered by electric motors. This results increased accuracy and flexibility of actuator control.

3 MEASUREMENT POSSIBILITIES IN THE SMALL CENTRIFUGE

The complex pile-soil interaction during pile installation and loading results in stress and strain changes of the soil and pile structure. Nowadays, the use of image processing techniques allow for capturing the soil deformations behind a transparent wall (Allersma, 1996) Especially contemporary techniques like Particle Image Velocimeter (PIV) developed for fluid flow (Westerweel, 1997) can be adopted for soil deformations (White et al. 2003). For this high resolution digital images need to be acquired in a high stress centrifuge environment.

Next to soil deformations, the plane-strain stresses of an assembly of photoelastic particles can also be measured in the centrifuge (Allersma, 1998). Either photoelastic discs or crushed glass can be used (Drescher & De Josselin de Jong, 1972, Dijkstra, 2009). As a result the stress in a plane perpendicular to the light is retrieved. This technique has traditionally consisted of a cumbersome experimental set-up consisting of a combination of a laser source, polarizer and retarder, required to acquire measurement data. Due to the technical development of the modern optical technology this procedure can potentially be simplified. Additional development of the photoelastic method for centrifuge measurements will result in a powerful tool in investigation of soil behaviour.

Stresses at the pile surface can be measured by locally embedded sensors. A large variety of these are commercially available. In centrifuge tests contact stress sensors have measured pile base stress, horizontal contact stress and sleeve friction (Klotz & Coop, 2001, White & Lehane 2004, Lehane & White 2004). The non-continuous pile surface at the horizontal contact stress sensor location will result in disturbances in the stress and strain response. The importance of the accuracy of these measurements increases during cyclic loading where the small-strain response of the soil at the horizontal contact stress sensor has a large effect on measurement data (Atkinson, 2000). The use of membrane-type strain gauge is one possible solution (Frank, 1966). This solution is explored in tests in the centrifuge at Delft University involved internal mounting of the strain gauge to a thin membrane milled into the pile wall. The deformation of the membrane results in output to the strain gauge.

4 MODELLING OF PILES IN THE SMALL CENTRIFUGE

4.1 Installation of displacement piles

The effect of installing displacement piles in sand remains an area of large uncertainties (White & Lehane, 2004). Displacement pile installation results in large strain effects and very large soil stresses at the pile tip. The majority of displacement piles are jacked, driven or vibrated into the ground. These installation methods will be discussed separately since they present different challenges in the modelling approach.

4.2 Jacked piles

Jacked piles are installed by hydraulically driven strokes of about. After each displacement stroke, of 500-900 mm at a rate of 0.1 m/s, the pile is unloaded. The pile actuator is then moved upwards before the next stroke begins. This piling method results in very small vibrations (White et al, 2002). Generally, the installation process in sand can thus be characterized as completely drained and in absence of subground vibrations. Therefore, the jacked pile installation method can be accurately modeled by a displacement controlled model pile that is unloaded between strokes. The delay between these strokes needs to be properly timed in order to prevent creep effects (Leung, 1997). The extraction of jacked piles can similarly be modeled by suitable extraction strokes. Pile head load during jacked installation in the TUD centrifuge is shown in Figure. 3. The pile head load during a load cycle is shown in fig. 4. The load behaviour is almost linear until the pile fails.

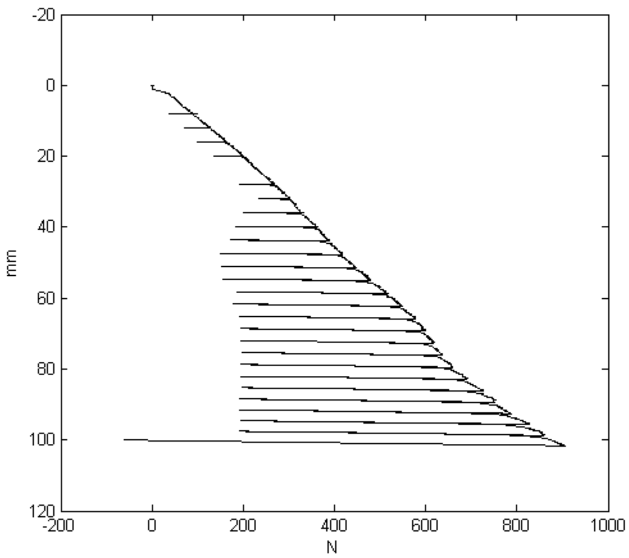


Figure 3: Pile head load during jacked installation

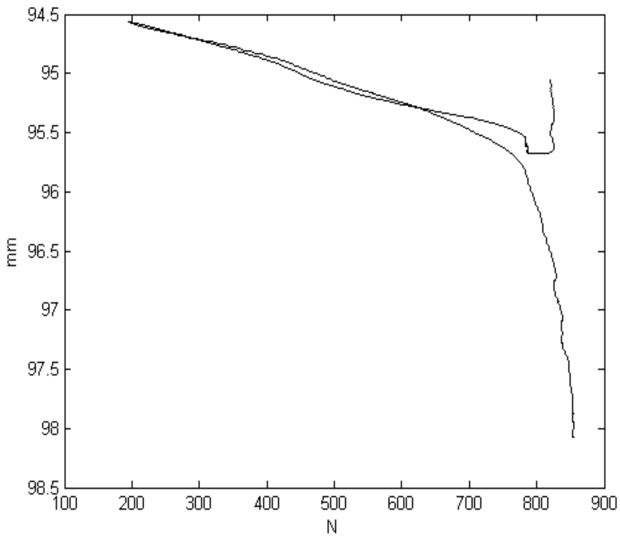


Figure 4: Pile head load during a load cycle.

4.3 Driven piles

The in situ installation of displacement piles by driving is accomplished by a pile hammer operating at a blow rate of approximately 1 Hz. The hammer energy depends on the hammer weight and the drop height is normally between 200 kJ and 20000 kJ depending on the size of the pile and the projected drivability of the pile. Pile driving always leads to stress wave propagation in the soil and in saturated soils the subsequent consolidation effects. Correct modelling of the pile installation process must include these dynamic stress-wave effects.

Scaling of the spherical shear waves is difficult. According to the centrifuge scaling manual, dynamic effects are scaled as 1/n (Taylor, 1995). This results in a blow rate of 100 blows/s at 100g. This very high rate is very difficult to achieve mechanically. The process also requires higher acquisition rates for the instrumentation (~10 – 50 kHz). After each wave has reached the boundary of the test container it will reflect at the boundary and return to the pile-soil system. This will influence both the soil-pile interaction as well as the data acquisition as a form of interference will been seen.

The reflection from the container boundary will interfere with the source stress wave. Therefore, proper scaling implies complete attenuation by conventional damping or active boundaries. Conventional damping depends on the geometry of the container and the material used and is not effective for physical models in the centrifuge (Dahl, 1976). A possible solution is active boundaries consisting of vibrating plates at the boundary of the container that create an interference pattern at the sample boundary which extinguishes the reflection. This method has previously been applied in fluid mechanics and structural mechanics (Kwong & Dowling, 1994, Hagood & von Flotow, 1991). These systems for active boundaries, however, are most effective at very low frequencies (fluid mechanics) or at very high frequencies (structural mechanics) and need to be developed for geotechnical applications.

Tests on pile driving without correctly scaled time-dependent behaviour have been performed in the centrifuge (de Nicola & Randolph, 1997). The purpose was to simulate the installation of tubular piles in sand. However, if the sand is assumed to behave non-viscous, installation by jacking will model pile driving in drained sand since the viscous effects are assumed to be negligible. Pile driving does also involve mechanical effects on the pile. This is not considered in this paper.

Furthermore, the pile dynamic response and soil consolidation will not scale by the same magnitude (Muir Wood, 2004). For properly capturing the pore pressure generation in saturated samples at higher frequencies or dynamic loading, the viscosity of the pore fluid needs to be increased, e.g. with a chemical additive (Taylor 1995). Either, properly scaled stress wave propagation is obtained, or either a proper time scale for the consolidation process. The use of fine-grained sand will reduce the velocity of the wave propagation but will also result in undrained soil behaviour if too small grain sizes are included. As both are equally important in pile driving problems, a practical compromise between proper scaling of the drained soil behaviour and the wave propagation mechanism is thus very hard to achieve.

4.4 Modelling pile loading

In addition to the importance of single piles, piles are widely used in pile groups in industry and research experiments. Examples of tests of pile groups are found in McVay et al 1998, Rollins et al, 2006 and Kong & Zhang, 2007. Various types of piles were modeled in these tests. The installation effects previously discussed will not be included in the model. There are indications that this could result in a lower base stiffness that can be appropriate for bored piles, but not for displacement piles. The stiffness of the soil reaction at the pile base can thus be assumed not to be correctly scaled, which can be of large importance for vertical loading of the pile group (Gaudin, 2005).

4.5 Modelling cyclic loading

Both vertical and lateral load cycles (and a combination) are frequently loading piles in practice. Ideally, a six-degrees of freedom actuator needs to be used (Bienen et al, 2006). Another example of combined vertical and horizontal loading is presented in Allersma, 2000 and Dingle et al, 2008. The feasibility of modelling these loads depends on the assumptions about the frequency and magnitude of the load. If a load is performed in dry sand, or at a low rate in saturated sand, the dissipation of pore pressure or initial effects can be assumed to have negligible influence (Dijkstra, 2009). Models of cyclic pile loading can therefore be correctly scaled for these conditions. For saturated conditions things start to become more complicated. As described in the Section on scaling of driven piles the pore fluid requires needs to be scaled to obtain a proper accumulation of pore pressures in cyclic loading, or alternatively the frequency should be adapted to match the ration in time scale of the consolidation and the time scale of load application. The influence of interface friction can present other challenges. An efficient solution is to assume that the residual interface friction is determining the interface friction. If sufficient deformation necessary to result in residual friction is generated, the interface friction is scaled according to the prototype. It must therefore be assumed that the residual friction is reached. Otherwise, the model can exhibit peak friction and the prototype the lower residual load.

5 OPTICAL MEASUREMENT SYSTEMS

Soil deformations have been measured both in 1g and centrifuge conditions (Allersma, 1996, Roscoe, 1970, Mair et al, 1980). Image analysis by the method of Particle Image Velocimetry increases the accuracy of measurements of displacement fields. Highly accurate deformation measurements can thus be performed using a relatively high-resolution digital camera (Westerweel, 1993). Mechanical stability of the camera and lens system and decent lighting conditions are important to produce consistent measurements at an increased gravity level.

The mechanical stability of the camera system is of less importance in 1g-conditions compared to centrifuge conditions. Next to the stability of the optical elements also the mechanical components need to be taken into account (shutter). The challenging environment in the centrifuge requires robust image acquisition equipment. The camera must also remain stable during test. Movement of the camera will disturb the measurements and decrease measurement accuracy. The image sensor must be mounted on a stable circuit board and should not deform during the test.

The planned model tests dictate the required camera specification, i.e. resolution, frame rate, light sensitivity and accuracy. A relatively high frame rate combined with robust mechanical and optical components can be achieved by the use of high definition machine vision cameras, currently commercially in use and available at relatively low cost. Figure 5 shows an image from the TUD centrifuge. The low costs and the fast developments imply that a flexible infrastructure for image acquisition in the centrifuge needs to be maintained to benefit from the newest developments. Figure 6 shows an example of the displacement trajectories for a plane-strain pile installation.

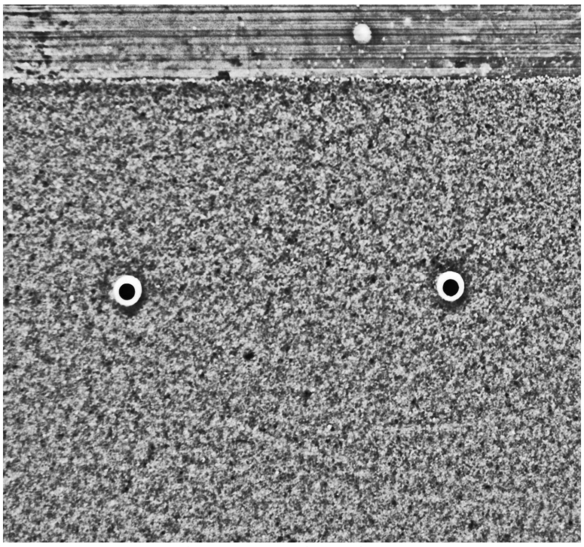


Figure 5: Image from centrifuge footing test

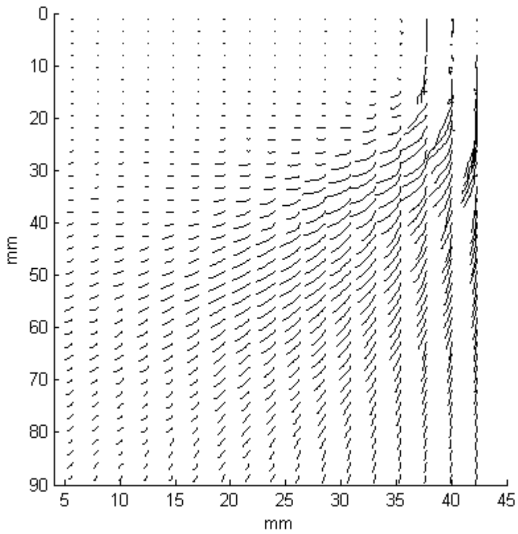
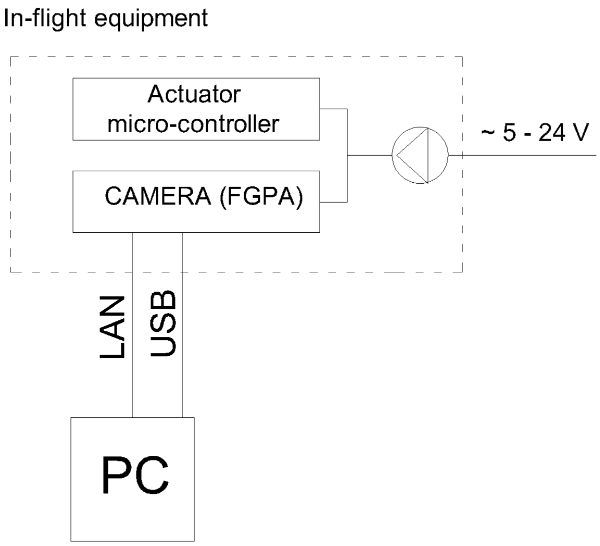


Figure 6: Displacement trajectories in 1g test.

An efficient and flexible camera connection is shown in figure 7. The camera is connected to the PC through a LAN or USB interface. Also shown is the Actuator microcontroller and the in-flight current supply. In the TUD centrifuge an in-flight current supply with a voltage of 5 – 24 V is installed.

A flexible and compact centrifuge operating system benefits testing greatly. An example of recently available technology are MEMS (Microelectromagnetical system), which are compact electronic systems that can be adapted to different measurement and control tasks. Figure 8 shows the Analog Devices ADXL001 iMEMS accelerometer.



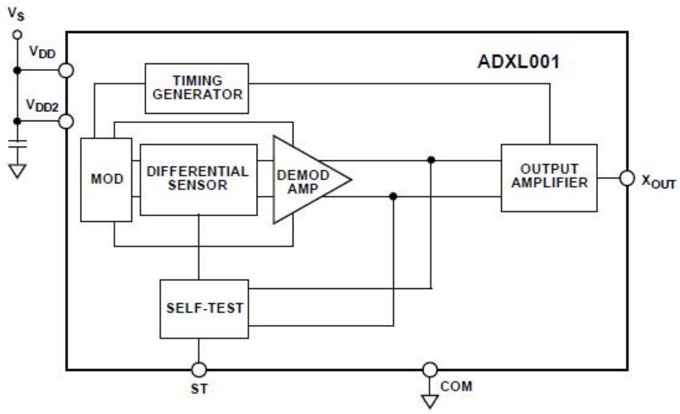


Figure 7: In-flight centrifuge camera-PC connection. LAN and USB ports are used to connect the PC and the camera. In-flight circuit providing 5 – 24 V is shown.

Figure 8: Functional diagram for Analog Devices ADXL001 MEMS accelerometer.

6 CENTRIFUGE LIGHTING SYSTEMS

The rotational movement of the centrifuge will almost certainly result in non-constant illumination. A solution is the use of totally diffused lighting in the centrifuge chamber. An easier solution to this problem is to use an in-flight centrifuge lighting system to illuminate the sample. This lighting system needs to be robust and have constant light intensity in-flight. Movement of the lighting system results in flickering of the illumination of the sample, which will decrease the accuracy of the deformation patterns from the image analysis. The mechanical connection to the centrifuge is thus essential. The use of LED lighting simplifies the lighting solutions both in terms of weight, costs and energy consumption.

7 CONCLUSIONS

Centrifuge modelling is the preferred approach for proper scaling of model pile tests. Among the advantages for small centrifuges are ease of sample preparation, small test loads, flexibility and low cost. The main advantage of the large centrifuge is the higher uniformity in acceleration level, resulting from the Coriolis effect, which is especially of influence for model pile tests. Also, the instrumentation in these tests is easier to facilitate.

With new technology such as MEMS and optical measurements systems new opportunities arise for convenient instrumentation and precise measurements in a small centrifuge. A flexible instrumentation system can be utilized for several types of tests without large alterations in test configuration. On top of that the small centrifuge offers the required flexibility to simulate the many modes of pile installation and pile loading.

Correct scaling of excess pore pressure generation and dissipation can be achieved by either an increase of loading rate or an increase of pore fluid viscosity. On the other hand scaling of stress-wave phenomena in the centrifuge presents larger difficulties related to stress-wave propagation and reflections from the boundaries. There are possible solutions, but the soil behaviour must be drained to correctly model field pile driving in normal sand. Stress wave reflections can influence the sample as well as pile data acquisition. These demands are quite hard to satisfy simultaneously. Therefore the modelling should not include stress waves. A feasible approach for that is to limit pile installation effects in coarse material to the application of cyclic load reversals.

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