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Drum centrifuge testing of a bored pile group under combined loading

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ABSTRACT: The paper presents the experimental methods implemented at the ETH Zurich (ETHZ) drum centrifuge to test a 2x1 bored pile group on dense saturated sand, under vertical- , pushover- and combined-loading. First, an overview of the model preparation process is given. Then, the pile groups is subjected to vertical loading, deriving its bearing capacity and pullout resistance. On this basis, a simple single degree of freedom systems is designed to correspond to a typical vertical safety factor FS_v= 3. This model, is subsequently subjected to pushover and combined loading. The results are critically evaluated pointing out some unavoidable limitations of centrifuge modelling.

Keywords: drum centrifuge, pile foundations, bearing capacity, combined loading

1 INTRODUCTION & PROBLEM DEFINITION

Static pile design under is typically performed on the basis of vertical bearing capacity and allowable settlement. Seismic design of piles is more complicated, as the inertia loading results in combined vertical-, lateral-, moment-loading (VHM) of the foundation. Under such loading, the behaviour of a pile group is more complex considering the interaction between the piles, and the rotational restraint provided by the cap. Despite considerable efforts on testing pile groups subjected to vertical (e.g., Lee & Chung, 2005) and lateral loading (e.g., McVay et al. 1998), there is a lack of experimental results for combined loading (especially for slender, rocking–dominated systems). This paper presents recent developments at the ETHZ drum centrifuge (Springman et al, 2001) to test pile groups under combined loading. Indicative results are used to illustrate the capabilities and limitations of the implemented setups drawing also some first conclusions.

The layout and the geometry of the prototype problem are shown in Fig.1. The 2x1 bored pile group was selected after evaluating a database of existing bridges in Switzerland. The selection of appropriate material and section geometry for the model piles is a key element of such tests. In our study, hollow circular aluminium parts were used along with an epoxy-sand coating (Fig.1). The latter is essential to achieve a rough interface (appropriate for bored piles). The bending stiffness of this composite member matches well the stiffness of the prototype 1m diameter reinforced concrete (RC) piles (zero axial loading). Unavoidably, the model piles considerably overestimate the moment capacity of the prototype RC piles.

All centrifuge model tests were performed at 100g. Two distinct experimental setups are used in this campaign (Fig. 1). The first setup is used to install the piles at 1g (assumed "wished-in-place" appropriate for bored piles) and for the bearing capacity and pull-out tests. The second setup is used to subject the pile group to pushover and combined loading. Both configurations will be discussed in more detail in the next sections.

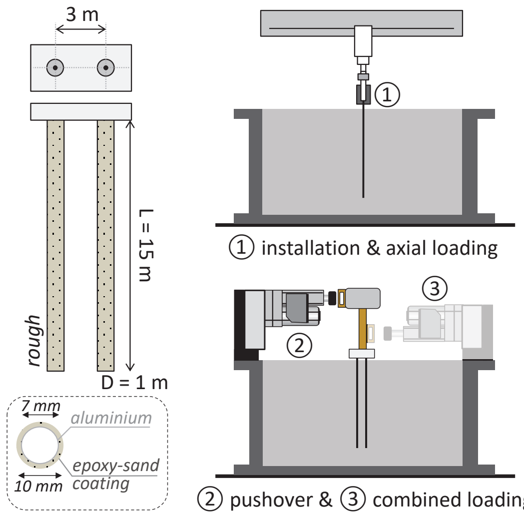

Fig. 1. Prototype problem: 2 x 1 bored pile group; illustration of the different experimental setups

2 MODEL PREPERATION

Pile group testing in a drum centrifuge comes along with considerable challenges. In-flight pluviation (often employed for footings), can be technically demanding considering the need for in-flight pile and superstructure installation and connection to the actuation system. In order to overcome these difficulties an alternative preparation method is chosen. Instead of using the entire circumference of the drum, smaller strong boxes are mounted on the channel. Thus, the drum centrifuge operation becomes similar to that of a beam centrifuge.

The strong boxes are prepared outside the drum under 1g conditions (Fig. 2). The sand layer is prepared via dry air pluviation (Step 1) using Perth Sand ($D_r \approx 80\%$). The installation of the box in the centrifuge calls for a special procedure to keep the soil model stable, while rotating by 90 degrees to install on the stationary drum channel. The technique outlined by Morales et al. (2013) is employed, taking advantage of the apparent cohesion that develops in unsaturated sand. As shown in Fig. 2, the soil model is saturated and subsequently de-saturated (Steps 2-3). During this process capillary forces develop. The apparent cohesion that develops is sufficient to ensure the stability of the soil specimen during transportation (Step 4) installation (Step 5, Fig. 3), and for an adequate period prior to spinning of the centrifuge (Steps 6-8 Fig. 3).

The pile group is jacked monotonically (Step 6) at a rate of 0.5mm/s at 1g using an actuator mounted on the tool platform (Fig. 4). Then, the superstructure is mounted onto the foundation, using an appropriate support. The support is equipped with a magnet, which is activated after carefully positioning the superstructure model. This limits disturbance while fixing the superstructure to the foundation using screws (Step 7). While spinning up to 20g, the magnet is deactivated and the superstructure is free to settle along with the soil. The support is then removed using a linear actuator (Step 8).

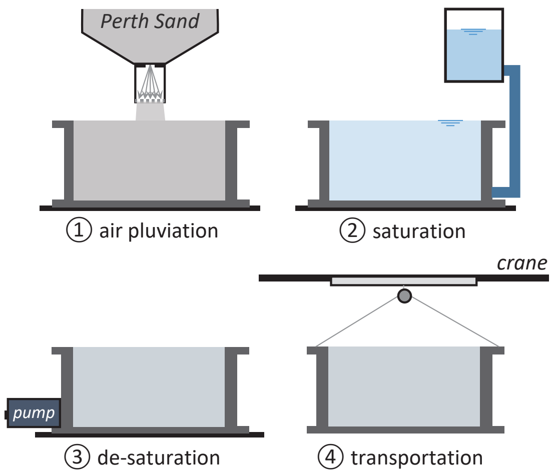

Fig. 2. Steps of the preparation process outside the drum centrifuge

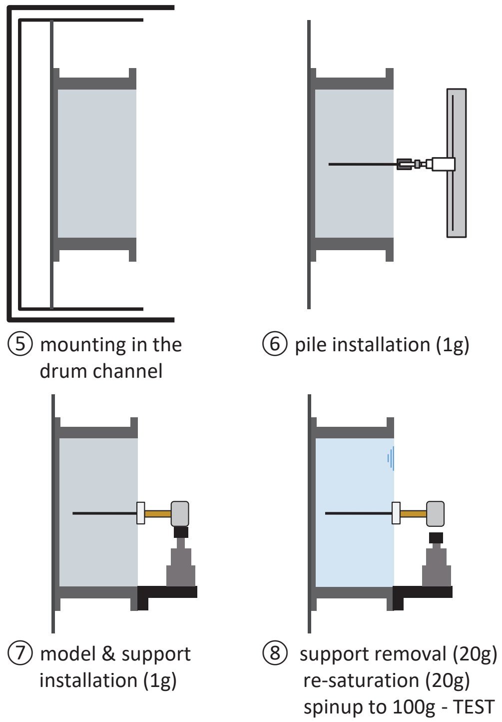

Fig. 3. Steps of the preparation process inside the drum channel.

At this stage, in order to achieve fully controllable conditions, the strong boxes are filled with water and the tests are performed under full saturation. The key components of an in-flight saturation system are shown in Fig. 4. Two additional water tanks are supplied externally with water establishing an initial free hydraulic height. The strong boxes are then completely filled using pumps while solenoid valves are used to control the desired one-way flow. After the desired saturation is achieved (verified through PPT measurement), spinning up continues to the target g-level (100g) and the test is conducted.

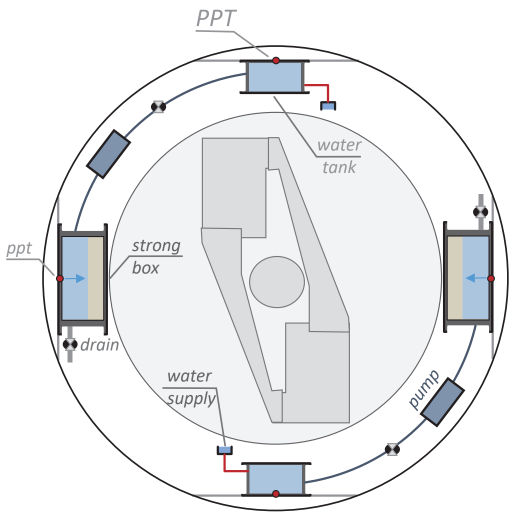

Fig. 4. Plan view of the drum centrifuge illustrating the overall experimental layout and the in-flight saturation system.

3 INSTALLATION & VERTICAL LOADING

Pile installation was a key element of the preparation process. Targeting on bored piles, the installation takes places at 1g. Since the stress increase can be assumed negligible compared to the stresses that develop at 100g, the piles are assumed "wished-in-place".

Fig. 5 shows the experimental setup pile installation. The key component is the actuators mounted on the tool platform, equipped with a load-cell and a laser sensor targeting the strong boxes. Moreover, a linear slider of limited gap is introduced between the piles and the actuator. This is employed to release the applied loads after the installation but also to accommodate small parasitic relative movements of the tool platform during spin-up. During this phase, the slider is also essential to allow the piles to settle together with the soil, preventing the development of negative skin friction. This setup is also used to derive the bearing capacity and pull-out resistance of the piles at100g. The tests are displacement controlled (rate: 0.02 mm/s), performed simultaneously on both boxes to avoid unbalance.

Fig. 5 shows the load settlement response of the model piles subjected to compression and tension showing very good repeatability. The bearing capacity is defined conventionally (i.e., $w/D = 0.1$) and used to calculate FS_v for the pushover and combined loading tests.

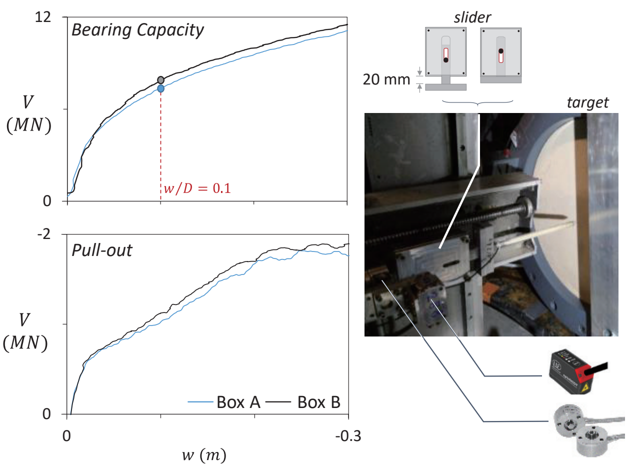

Fig. 5. Setup used for installation, bearing capacity and pull-out tests; results in terms of load – settlement of a signle pile.

The evaluation and interpretation of the previous results need to consider some unavoidable scale effects. Previous studies (Fioravante, 2002; Lehane et al., 2005), showed that shaft resistance increases with the decrease of the pile diameter. Thus, our results are expected to over-predict shaft resistance. On the contrary, the dependence of the displacement required to mobilise the peak shaft resistance to pile diameter is limited. In our tests (Fig. 5), this is mobilised at about 2 mm, corresponding to 200 mm at prototype scale, which is not in accord with full scale test results.

4 PUSHOVER & COMBINED LOADING

The experimental setup used for the pushover and combined loading tests is illustrated in Fig. 6. In both cases, a single degree of freedom system is employed comprising the 2 x 1 pile group, a rigid pier and a rigid cap, and a concentrated mass. The selected mass corresponds to a representative safety factor, $FS_v = 3$. The pile group is installed at 1g prior to spin-up, as discussed previously.

In the pushover tests (monotonic and cyclic) a target displacement is applied at the centre of mass through a sliding hinge connection. The latter is crucial in allowing the system to experience freely uplifting or sinking response. The applied load is measured using a load-cell mounted to the actuator arm, while the horizontal, vertical and rotational movement of the model is monitored throughout the test using a system of three laser sensors mounted on the strong box.

The combined loading tests are performed under constant vertical load (controlled by the mass). The setup is similar to the pushover tests with the addition of a second actuator. The desired horizontal and rotational movement is achieved through coordinated movement of the actuators. All tests are displacement–controlled with a rate of 0.02 mm/s to avoid undesired rate effects.

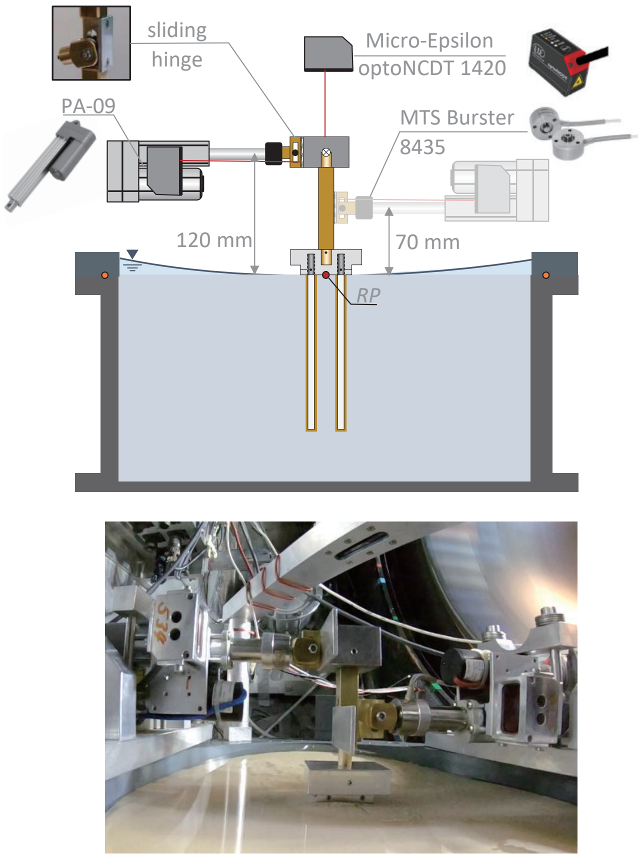

Fig. 6. Illustration and photo of the experimental setup for the pushover and combined loading tests.

Figure 7 shows the results of monotonic and cyclic pushover tests in terms of force – displacement curves. The monotonic test was performed twice showing very good repeatability. Similarly, the cyclic test, where cycles of increasing amplitudes were imposed, is in good agreement with the monotonic tests, showing limited hardening. Overall, the implemented setup is shown capable of producing reliable and repeatable centrifuge test results. However, the obtained results are expected to overestimate the ultimate resistance of the prototype pile group. This is due to the overestimation of the bending moment capacity of the model piles (compared to the prototype RC piles).

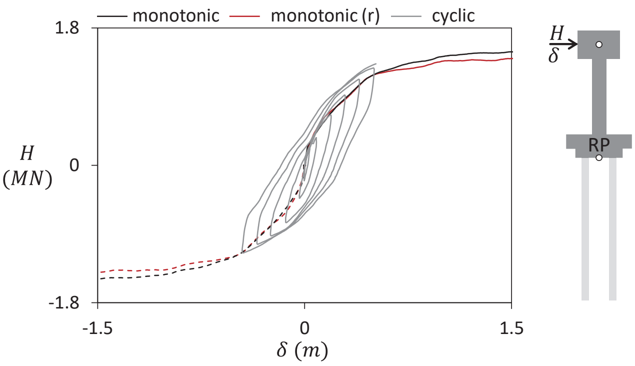

Fig. 7. Results of monotonic and cyclic pushover test in terms of Force-displacement curves.

The combined loading setup was tested for either pure horizontal movement or pure rotation. The load paths are shown in Fig. 8, along with that of the monotonic pushover test. Despite the limited failure points, it is possible to get a first picture of the failure envelope. Under pure rotation the moment resistance is considerably higher than that of the pushover test. This indicates importance coupling between lateral load and overturning moment, typically ignored in practice.

Looking at the failure patterns, load paths 1 ($u = 0$) and 2 (pushover), result in the formation of a single plastic hinge at the model piles. On the contrary, when subjected mainly to lateral loading (θ=0), two plastic hinges are formed (load path 3), similar to the postulated mechanism of the widely used Broms (1964) theory, for fixed head conditions.

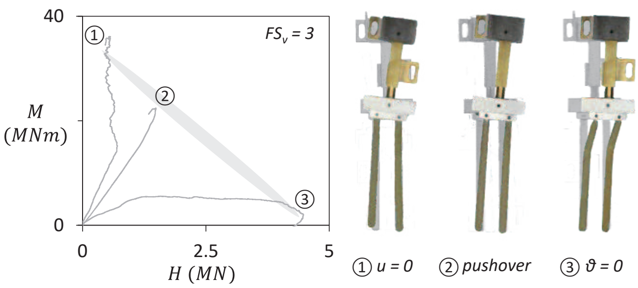

Fig.8. Load paths and illustration of failure envelope in the $M - H$ space, and post-testing deformed models.

5 CONCLUDING REMARKS

The paper presented a number of experimental developments at the ETHZ Drum centrifuge to test pile groups under combined loading. The implemented technique regarding the preparation method, the pile installation at 1g and the vertical-, pushover- or combined-loading at 100g, successfully produced reliable and repeatable results. The developed setups were used to derive some first insights on the behavior of bored pile groups under combined loading, pointing out also the limitations of centrifuge modeling. The results of this study contribute towards a better understanding of the pile group response under combined loading, and can be further exploited for validation of numerical models.

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