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### Publication date

2020

### Document Version

Final published version

### Citation (APA)

Bienen, B., Klinkvort, R. T., Fan, S., Black, J., Bayton, S., Thorel, L., Madabhushi, G. S. P., Askarinejad, A., Li, Q., & More Authors (2020). *Centrifuge benchmark testing of laterally loaded monopiles in sand*. Paper presented at 16th Asian Regional Conference on Soil Mechanics and Geotechnical Engineering, ARC 2019, Taipei, Taiwan. <http://140.118.105.204:9998/TGSSP/16ARC/articles/mainpage/398>

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## Centrifuge benchmark testing of laterally loaded monopiles in sand

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**Keywords:** Centrifuge, Monopiles, Offshore Wind turbines, Sand

The large diameter monopile is a commonly used foundation concept for offshore wind turbines. The advantages of geometrical simplicity and reliable performance make it often the most attractive solution. Despite the concept's high popularity, optimisation of the current design models can still be made. To address fundamental understanding of modelling effects in centrifuge testing of laterally loaded monopiles in sand, a large coordinated centrifuge-testing program across 11 different centrifuge centres worldwide is ongoing. This extended abstract presents the initial results of global benchmark testing.

Monopile foundations are still the preferred foundation solution for offshore wind turbines, due to the simple geometry (a hollow steel pile) and the experience gathered over the years (Wind Europe, 2018). However, despite their wide use and continuous optimisation, there are still areas of uncertainty in monopile design. The continued lack of fundamental understanding of monopile behaviour has been highlighted by a review of the effects influencing the response of a monopile in the centrifuge (Klinkvort et al. 2018).

Based on this review and inspired by the multi-facility research on CPT's presented in Bolton et al. (1999), this extended abstract presents initial results from a multi-facility test program on lateral loaded monopiles in dry sand. The test program is ongoing at different centrifuges with different setups, sizes, model monopiles and sands. Through careful design of the testing program, several of the effects that control the lateral response of a monopile were investigated. The study focuses on the monotonic lateral response of the monopile, but many of the findings are also valid for more complex load situations.

Before the testing in the centrifuge all sands were first tested at the Norwegian Geotechnical Institute (NGI). Here the sand were tested to determine Grains size distributions, solid/maximum/minimum density, shear stiffness and triaxial stress-strain behaviour. The centrifuge facilities in question are located at the Centre for Engineering Infrastructure Ground Research (CEIGR) at the University of Sheffield, the Centre for Offshore Foundation Systems at the University of Western Australia (COFS, UWA), University of Cambridge Engineering Department (CUED), Technical University of Denmark (DTU), The French Institute of Science and Technology for Transport, Development and Networks (IFSTTAR), Korea Advanced Institute of Science & Technology (KAIST), Technical University of Delft (TU Delft), Federal University of Juiz de Fora (COPPE), University of Nottingham (UN) and Zhejiang University (ZU).

All testing was performed in beam centrifuges. The centrifuges have different sizes, actuators and data acquisition techniques, but the testing principles are the same for all of them.

The sands used at the different centrifuge facilities were first tested in the same laboratory (at NGI). All are poorly graded fine silica sands. The grain size distributions are shown together with the average grain size diameter in Figure 1 and is seen to have similar grain size distributions.

The maximum and minimum dry unit weight of sand is known to depend on the testing methodology and it is therefore difficult to define a unique value (Lunne et al. 2018).

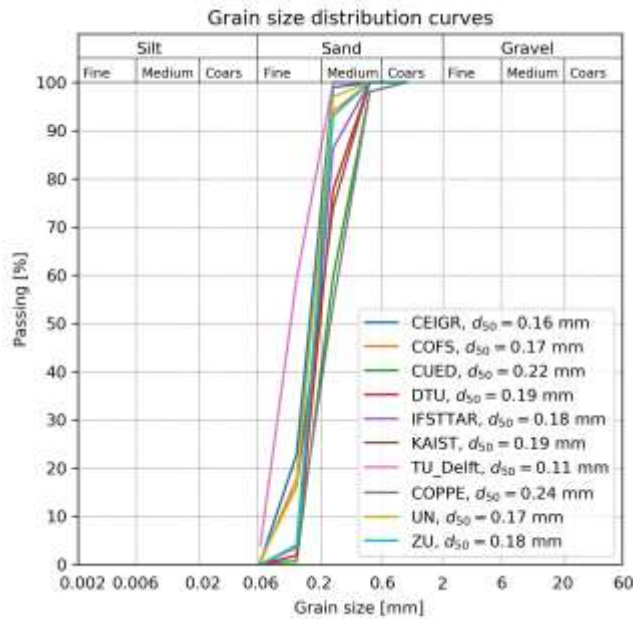


Fig. 1. Grains size distribution of all tested sands

However, relative density is commonly used to describe the state of sand and this is the reason for using it here also. Because all sands were tested in the same laboratory the methodology is the same between the tests which enhances the comparison of the achieved relative density.

Benchmark testing in 6 centrifuges is currently finalised, the dimension of the test piles are given in Table 1 and the results pile head response at sand surface are presented in Figure 2. All test was design so penetration depth was  $L=5D$  and the lateral load was applied with an eccentricity of  $e=5D$ .

Table 1. Test pile geometry

| Centrifuge | D (mm) | T (mm) |
|------------|--------|--------|
| CEIGR      | 50     | 3.2    |
| COFS       | 52.2   | 2.1    |
| DTU        | 40     | 2      |
| IFSTTAR    | 40     | 2      |
| TU DELFT   | 18.2   | 1.2    |
| KAIST      | 80     | 1.5    |

Figure 2a shows that pile with same diameters gives similar responses in model scale, with the exception of the tests from DTU. Figure 2b shows a good match between the normalised results in the tests from CEIGR, IFFSTAR, COFS, TU Delft and KAIST confirming the modelling and normalisation methodology. After displacements above  $0.1D$  the responses starts to deviate, but here displacements are getting large and is well above the serviceability limits. Explanation of the differences may be related to slightly different soil stress conditions, relative density etc. The response from the tests at DTU shows a stiffer responses. This is most likely related to the test setup

and the vertical displacement constrained at pile top. Very large downward axial loads ( $V_{max}>6000N$ ) were measured during the tests, leading to a different load conditions for these tests compared to the other. The results in Figure 2 confirms that the scaling technique used in centrifuge modelling is appropriate if care is taken to scaling and test setup.

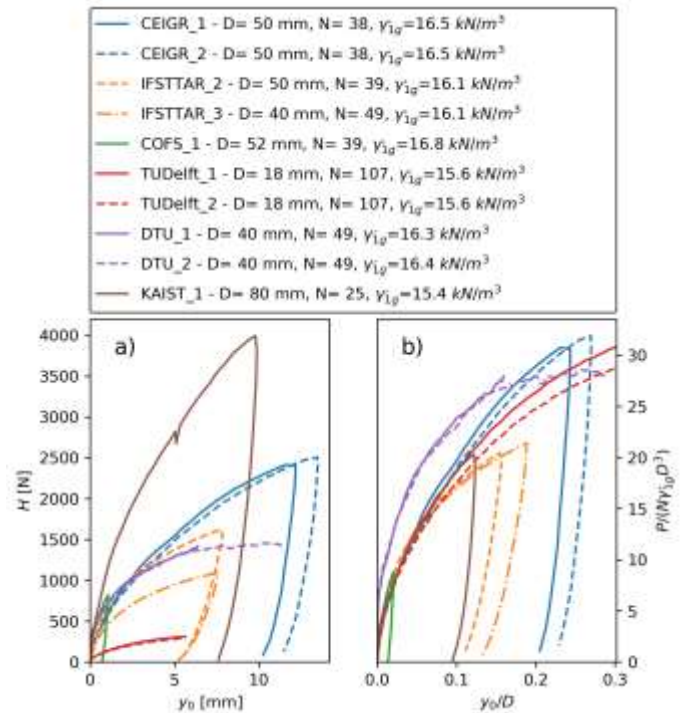


Fig. 2. Total pile head response of the test piles scaled to a references stress similar to a pile diameter of  $D_{proto}=2m$

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