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The performance of a self-installing monopiled GBS structure under lateral loading.

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Abstract

This paper presents a physical model study of the feasibility and performance of a monopiled gravity base structure (MGBS) for offshore foundation applications. The research builds on the current interest in hybrid foundation systems such as monopiled footings. The proposed MGBS is essentially a conventional GBS structure with a projecting monopile or caisson. The system relies on the self-weight of the GBS to drive the projecting monopile into the seabed. Once installed additional ballast can be added to the GBS, and if necessary installation of the projecting monopile can be enhanced through the use of suction. The test programme has concentrated on the response of the system once installed and has investigated a range of geometries for circular monopiles. The results clearly demonstrate a significant enhancement to lateral resistance offered by the addition of a monopile to a GBS.

Keywords

Centrifuge modelling; Soil/structure interaction; Offshore engineering; Footings/foundations.

1 Introduction

To date, monopiled foundations have been used extensively and very effectively for foundation solutions for the majority of offshore, and to a lesser extent onshore, wind farm installations. However, to date many offshore installations have been located where water depths are such that the installation and performance of the monopile makes it the most economically viable solution. However, the development of deep water sites is not favourable to the monopile solution due to difficulties in fabricating large enough monopiles, and undertaking their installation in deep water locations.

In view of the limitations of the conventional monopile solution, alternative designs such as floating and/or tension leg semi-submersible platforms offer potential solutions for the development of deep water sites. Other potentially viable alternatives are through improving the performance of monopiles see for example Dührkop and Grabe (2008), Bienen et al (2012), Nasr (2014), and the further development of bottom-founded options such that they remain economically competitive and technically viable.

This paper presents a study to investigate the concept of a monopiled gravity base structure (MGBS). The proposed MGBS is essentially a conventional GBS structure with a projecting monopile or caisson. The system relies on the self-weight of the GBS to drive the projecting monopile into the seabed. Once installed additional ballast can be added to the GBS, and if necessary installation of the projecting monopile/cassion can be enhanced through the use of suction.

1.1 Hybrid Foundations

In recent years much research has been reported on the behaviour and viability of ‘hybrid’ foundation systems. Dixon (2005) proposed the use of a bearing plate in conjunction with a monopile to increase the lateral capacity of the pile. This hybrid monopiled-footing concept is not dissimilar to that of a retaining wall with a stabilising base, see for example Carder and Brookes (1993) and Carder et. al. (1999), Powrie and Daly (2007).

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Model tests are reported for the case where the bearing plate is rigidly connected 'coupled' to the pile, see for example, Stone et. al. (2007), Stone et. al. (2010), Lehane et. al. (2014), Arshi (2016), Bienen (2016), Wang et al (2018), Chen (2020), or where it is allowed to slide 'decoupled' on the pile shaft (Arshi and Stone (2015), Anastasopoulos and Theofilou (2015, 2016), Arshi (2016)). In both arrangements the addition of the bearing plate is seen to enhance the lateral capacity and stiffness of the monopile. In the decoupled configuration little or no moment is transferred between the pile and the plate and enhanced lateral resistance is provided by the shear resistance between the plate and the underlying soil. In the coupled arrangement the presence of the bearing plate provides a degree of both lateral and moment fixity at the mudline leading to enhanced lateral resistance from both the shear resistance and moment restraint provided by the plate.

This study is an extension of the coupled arrangement for potential deep water deployment, where the self-weight of the structure is utilised to install the pile.

It is noted that studies on the coupled monopiled-footing in cohesionless soil have shown that for the system to be most effective it is necessary that the bearing plate develops a positive contact with the underlying soil, and hence applied vertical loads should be in excess of the vertical pile capacity. If the self-weight of the GBS is used to install the monopile, then this requirement will be met. However, it is noted that in a cohesionless material the sliding resistance of the GBS is directly proportional to the vertical load. Hence any reduction in the vertical load by the presence of the pile will result in a reduction of the sliding resistance of the GBS, which may or may not be offset by the lateral resistance provided by the pile. In a cohesive soil, GBS sliding resistance is not affected by the presence of the pile and depends only on the undrained shear strength of the soil. The research reported here presents a preliminary assessment of the behaviour of a monopiled GBS (MGBS) in dry sand under monotonic loading conditions and follows an earlier study by Stone et al (2018).

2 Experimental Programme

The experimental programme consists of two elements namely;

(i) a series of vertical penetration tests of the monopile attachments that will be coupled with the MGBS. These tests are required to assess the penetration resistance that must be overcome by the self-weight of the GBS unit.

(ii) A series of lateral loading tests using model piles of two different diameters and at two embedment depths. In each test the axial resistance of the monopile was used to determine an applied MGBS weight required to achieve installation and generate an initial contact stress between the MGBS base and the soil of 15-16 kPa. To achieve a contact pressure dead weights were applied to the model GBS. The lateral performance of an initial 'base case' test of the model GBS structure alone was also undertaken. It should be noted that the self-weight of the GBS results in an initial contact stress of 27 kPa. The response of the GBS with different weights, and hence contact stress, was reported by Stone et al (2018) from which it is apparent that the lateral capacity of the system is governed by sliding, and as such the lateral resistance is directly proportional to the vertical load (or initial bearing stress). Consequently, the lateral capacity of the GBS for an applied bearing stress of 16 kPa can be estimated at (100% x 16/27) ~ 60% of that measured for the model GBS.

A summary of the tests undertaken is presented in Table 1 below.

Table 1. Summary of model tests.

Test ID	**Pile type**	**Estimated initial bearing stress (kPa)**	**Pile diameter/width (mm)**	**Embedment depth (mm)**
GBS 27	n/a	27	n/a	n/a
MGBS D6 L30	Solid circular	16	6.3	30
MGBS D6 L60	Solid circular	16	6.3	60
MGBS D12 L30	Solid circular	16	12.7	30

3 Materials and equipment

The sand used for the model tests was uniformly graded Fraction C silica sand supplied by David Ball Limited. The sand has maximum and minimum void ratios of 1.06 and 0.61 respectively, with a critical state angle of friction φ_{crit} of 31°.

All the tests reported were carried out on the balanced beam centrifuge at the University of Brighton. This machine is manufactured by Thomas Broadbent & Sons Ltd. and is 6 g-tonne machine (20kg payload to 300g) and a radius of 760mm. The tests were conducted in a circular steel tub with an internal diameter of 272mm and sample height of 114.6mm.

The model GBS and piles were fabricated from aluminium. Two solid circular piles 30mm in length and 6.35mm and 12.7mm in diameter were fabricated together with a single 6.35 mm diameter and 60mm long pile. All these piles projected their full length below the base of the GBS. The model GBS is a flat-bottomed cylinder of 75mm external diameter with a wall thickness of 10mm. A threaded hole is formed in the centre of the GBS base and the pile attachments are bolted through this hole and into an aluminium mast which projects above the GBS unit to provide the loading attachment for a wire and pulley arrangement. Figure 1 shows a typical model of a monopiled GBS arrangement (MGBS) prior to installation.

4 Model preparation and test procedures

The soil models were prepared though a combination of dry pluviation and vibration using a vibrating table. This method produced consistent soil specimens with a bulk density of 1750kg/m^3.

The centrifuge test package is fully assembled prior to mounting on the centrifuge. This consists of installing the model structures by lightly pushing them into the soil until firm contact with the sand surface was achieved; weights were then placed as required to achieve the required initial bearing stress. A single degree of freedom actuator is then mounted on the cradle, and through the use of a wire and pulley mechanism is able to apply a horizontal load to the mast. The steel pulling wire is attached to a load cell fixed to the actuator. The applied horizontal load is assumed to be equal to the tension measured in the steel wire (i.e. friction effects are neglected). The horizontal displacement of the GBS was measured at the mid-height of the GBS rim, and the displacement at the point of loading was also measured using a linear potentiometer connected via a 'sheep's crook' attachment to the loading mast. A completed model package mounted in the centrifuge is shown in Figure 2.

4.1 Test procedure

After mounting the test package on the centrifuge, the actuator and instrumentation are connected to their respective control and data acquisition systems, and a digital video camera is mounted on the top of the cradle to observe the model during the test. All the tests were conducted at an acceleration level of 50g.

Once the model had achieved the test acceleration, the actuator was run at a velocity of 5 mm/minute and data from the load cell and displacement transducers were recorded continuously until the end of the test. Following the test, the model package was removed from the centrifuge and disassembled with photographs being taken during the process. Figure 3 shows a typical model after testing.

5 Experimental results

5.1 Installation resistance

In the tests reported by Stone et al (2018) the self-weight of the GBS was not sufficient to install the monopile and installation was effected by light-driving of the structure until it was firmly bedded and contacting the soil. In a prototype scenario this arrangement would require installation of the monopile to be assisted by other means, for example suction. Interestingly it is not clear how the performance of the MGBS would have been affected by the installation method, and the initial contact stress between the MGBS and soil would also be unknown.

In the experimental tests reported here the MGBS was designed to be self-installing in that sufficient weight was placed on the GBS to overcome the installation resistance of the monopile and result in a positive contact stress with the underlying soil.

In order to establish the weight required for self-installation the vertical capacity of the monopiles was assessed through a series of penetration tests conducted at the proposed test acceleration level of 50g. Figure 4 shows pile penetration resistance against penetration depth for two 6.3 mm diameter piles of 30mm and 60mm in length and a 12.7 mm diameter pile 30 mm in length. The penetration resistance plots recorded for the 6.3 mm diameter piles are very consistent reflecting the consistency of the sample preparation procedure. Since the monopile will be fully embedded below the GBS the relevant installation force is that required for the full embedment depth of the pile and is obtained directly from the load versus penetration data at the relevant penetration depth. The results are summarised in Table 2.

Table 2. Summary of model tests.

Pile ID	**Diameter (mm)**	**Embedment length (mm)**	**Installation resistance @50g (N)**	**GBS weight applied @ 1g (g)**	**MGBS contact stress @ 50g (kPa)**
D6 L30	6.3	30	240	375	15.7
D6 L60	6.3	60	465	835	16
D12 L30	12.7	30	570	1045	15.9

5.2 Lateral response

Figure 5 shows an overview of the lateral load versus lateral displacement of the GBS (measured at the mid-height of the base unit) for the tests undertaken in this study. It is apparent that the addition of a monopile to the GBS has a significant beneficial effect on the lateral capacity of the GBS.

It should also be noted that the bearing stress applied by the GBS alone is 27 kPa whereas for the monopiled GBS tests the applied bearing pressure was ~16 kPa. Assuming that the resistance developed by the GBS alone is due only to sliding (Stone et al., 2018), then it is reasonable to assume that this resistance is linearly dependent on the applied bearing stress. Consequently the corresponding lateral resistance of a GBS with an initial bearing stress of 16 kPa would be estimated at 60% (16/27) of that measured in the model tests. The improvement in the lateral performance of the monopiled GBS is thus even more significant than that observed in Figure 5.

The ultimate lateral resistance for all the tests for the GBS is presented in Table 3. The displacement to achieve the ultimate lateral capacity is obtained directly from the relevant load-displacement plot, refer to Figure 5.

Table 3. Summary of ultimate lateral resistance from model tests

Test ID	**Ultimate lateral capacity (N)**	**Displacement to ultimate capacity (at mid-height of GBS rim) (mm)**	**Increase in ultimate lateral capacity of GBS (%)**
GBS	27	0.01	0
MGBS D6 L30	70	1.0	260
MGBS D6 L60	136	5	500
MGBS D12 L30	143	0.75	530

From Figure 5 some general commentary on the response of the system can be made as follows; the response of the GBS alone is dominated by friction where little or no lateral movement occurs until the frictional resistance between the GBS and the underlying soil is exceeded. This results in a very distinct yield associated with the onset of sliding. For the monopiled GBS the influence of the pile is observed by a less distinct yield with the maximum lateral capacity being mobilised at a greater lateral displacement. The influence of the pile is well demonstrated in Figure 6 which shows the lateral load versus displacement response for a monopiled GBS with a 6.3mm diameter pile with embedment depths of 30 and 60mm. The influence of the pile response is more significant for the longer pile where the greater lateral resistance of the pile combines with the sliding resistance of the GBS to produce a greater ultimate capacity. The ultimate lateral resistance of the 60mm long pile is approximately twice that of the 30mm long pile but requires a significantly greater lateral displacement to achieve this.

Figure 7 compares the lateral load response of a monopiled GBS with 6.3 and 12.7mm diameter piles of the same 30mm embedment depth. In this case it is interesting to note that the ultimate lateral resistance of both piles is achieved at a similar lateral displacement. The ultimate capacity of the 12.7mm diameter pile is approximately twice that observed for the 6.3mm diameter pile.

6 Discussion and conclusions

The tests reported here are preliminary in nature, and essentially are a demonstration of the potential for the development of a monopiled Gravity Base Structure for use in the offshore environment. It is suggested that for deep water sites where a GBS type of installation is proposed, then the combination of the GBS with a monopile would provide a more efficient solution. The use of the GBS to install the pile would negate the requirement to drive the piles, either from a barge or from an autonomous sea-bed system.

The tests undertaken in this study have focused on the response of the system post-installation, where it is essentially similar to a hybrid monopiled-footing arrangement. For the current arrangement the pile was rigidly fixed to the base of the GBS. However it is also possible that the GBS's weight can be used to install a monopile which is not fixed to the GBS unit. In this arrangement the pile remains decoupled from the GBS such that the GBS is restrained laterally by the pile but is also able to move vertically relative to the pile.

The response of the monopiled GBS is a combination of the lateral response of the GBS unit and the pile. The former is clearly controlled by base friction and exhibits a very stiff response with yield and sliding occurring once limiting base friction is developed. The response can be idealised as a stiff elastic-perfectly plastic response. The addition of the monopile introduces a less distinct yield due to the influence of the lateral response of the pile. In all cases however, the initial stiffness is still dominated by friction, and a stiff initial response is observed. For a short pile the stiff response is maintained with the ultimate capacity being achieved at a relatively small lateral displacement although the load displacement response is more curved with a less distinct yield. For the longer pile the curvature of the load-displacement plot is more significant. The displacement required to mobilise the ultimate lateral capacity appears to be associated with the mobilisation of the lateral capacity contributed by the pile.

From the above discussion the following initial conclusions can be made;

- The lateral load versus displacement response for a GBS is controlled by base friction and can be idealized to a very stiff elastic-perfectly plastic response.
- The ultimate lateral capacity of the GBS can be significantly enhanced by the presence of a monopile extending beneath its base.
- The response of the monopiled GBS system is similar to a monopiled footing.
- Increasing the length of the pile increases the ultimate lateral capacity but reduces the overall lateral stiffness.
- Increasing the diameter of the pile can increase the lateral capacity with little effect on the stiffness.

It is clear that there is a lot of further study required to evaluate the full potential of a self-installing monopiled GBS. Issues such as the performance of the system in clay, cyclic loading, optimization of geometries for self-installation with satisfactory lateral performance, and the nature of the pile-GBS connection, are just a few of the areas that need to be addressed.

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Figure captions

Figure 1. Typical models of GBS and monopiled GBS arrangements (MGBS) prior to installation: a) GBS; b) MGBS with 6.3mm diameter monopile with embedment depth of 30mm (MGBS D6 L30); c) MGBS with 6.3mm diameter monopile with embedment depth of 60mm (MGBS D6 L60); d) MGBS with 12.7mm diameter monopile with embedment depth of 30mm (MGBS D12 L30).

Figure 2. Completed model package mounted in the centrifuge.

Figure 3. Post-test photograph

Figure 4. Pile penetration resistance of 6.3 mm diameter piles 30mm (D6 L30) and 60mm (D6 L60) in length, and a 12.7 mm diameter pile 30 mm in length (D12 L30).

Figure 5. Overview of the lateral load response for all model tests.

Figure 6. Lateral response of GBS (GBS 27) and MGBS with 6.3mm diameter monopile with embedment depth of 30mm (MGBS D6 L30) and 60 mm (MGBS D6 L60).

Figure 7. Lateral response of GBS (GBS 27) and MGBS with a 30mm embedment depth for 6.3mm (MBGS D6 L30) and 12.7mm diameter monopiles (MGBS D12 L30).

Figure 1

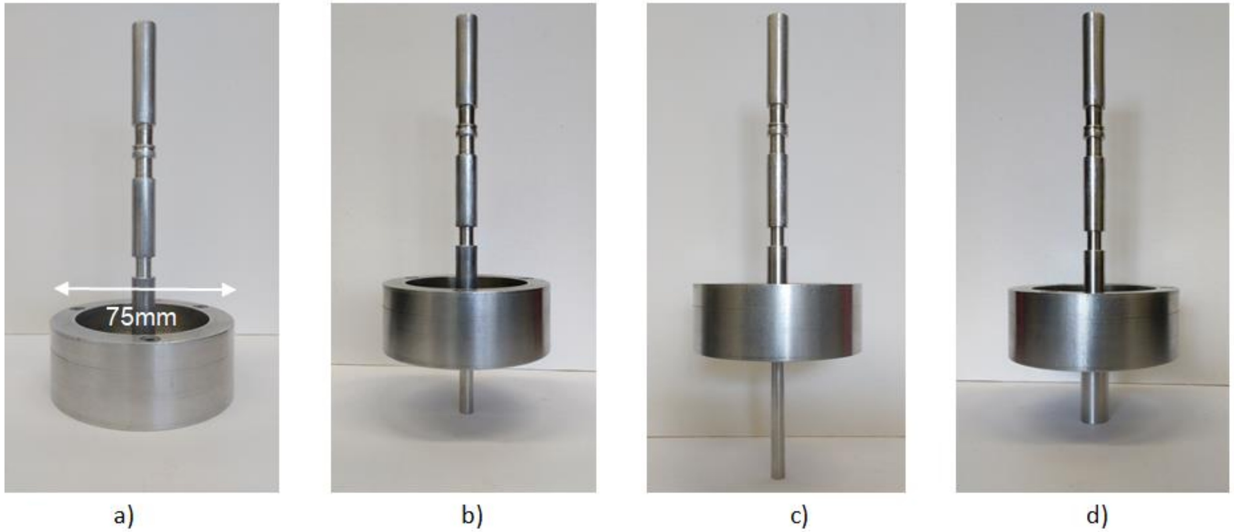

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Figure 2

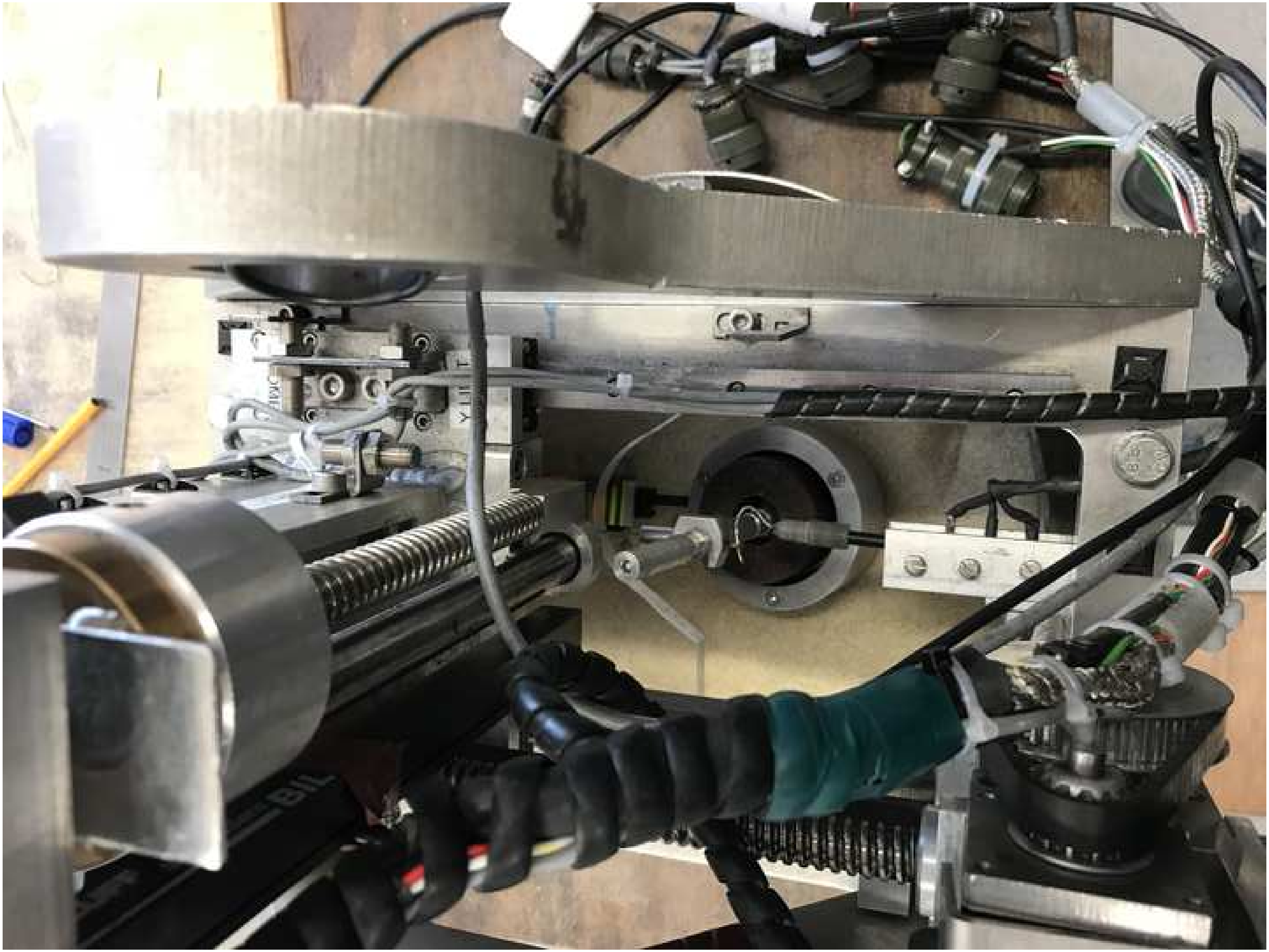

Figure 3

Figure 4

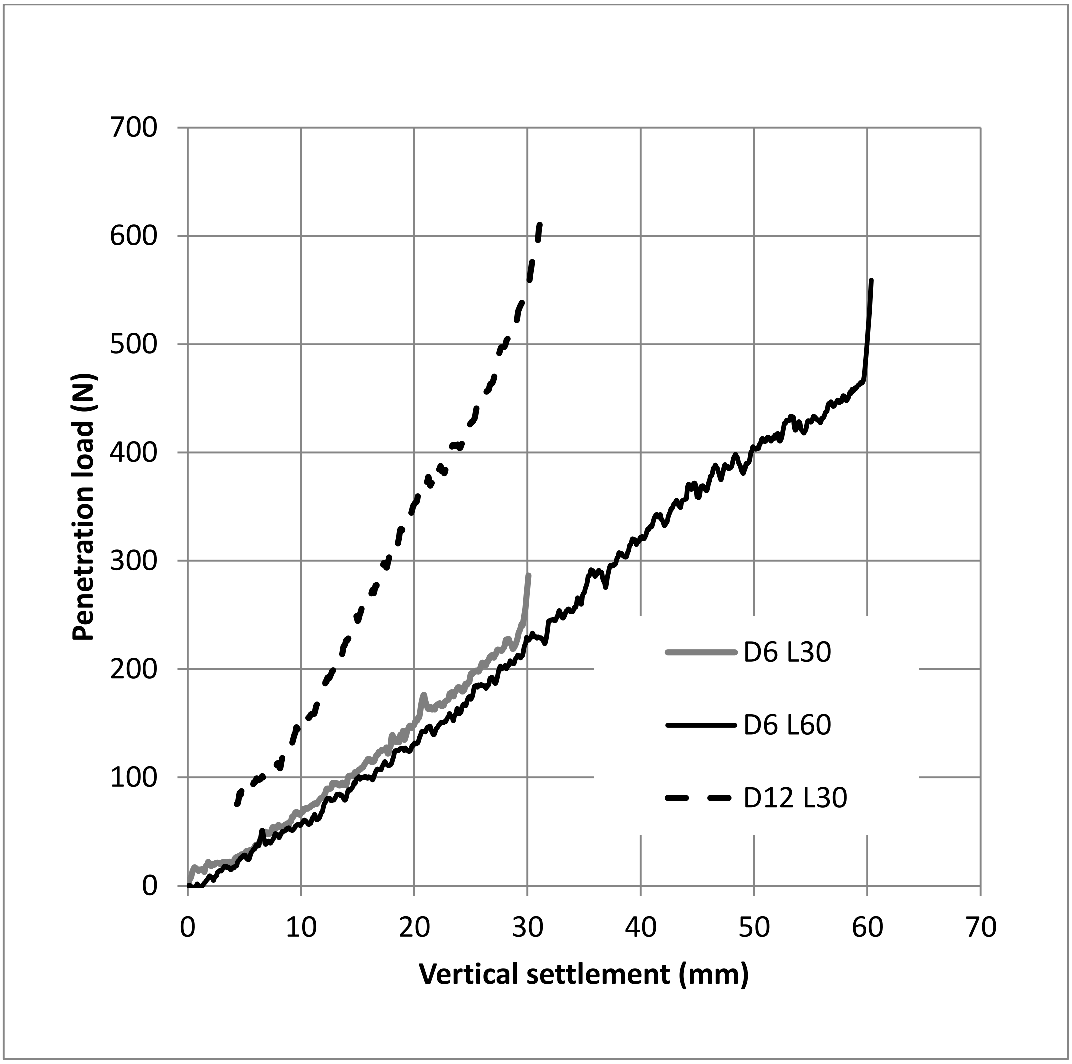

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Figure 5

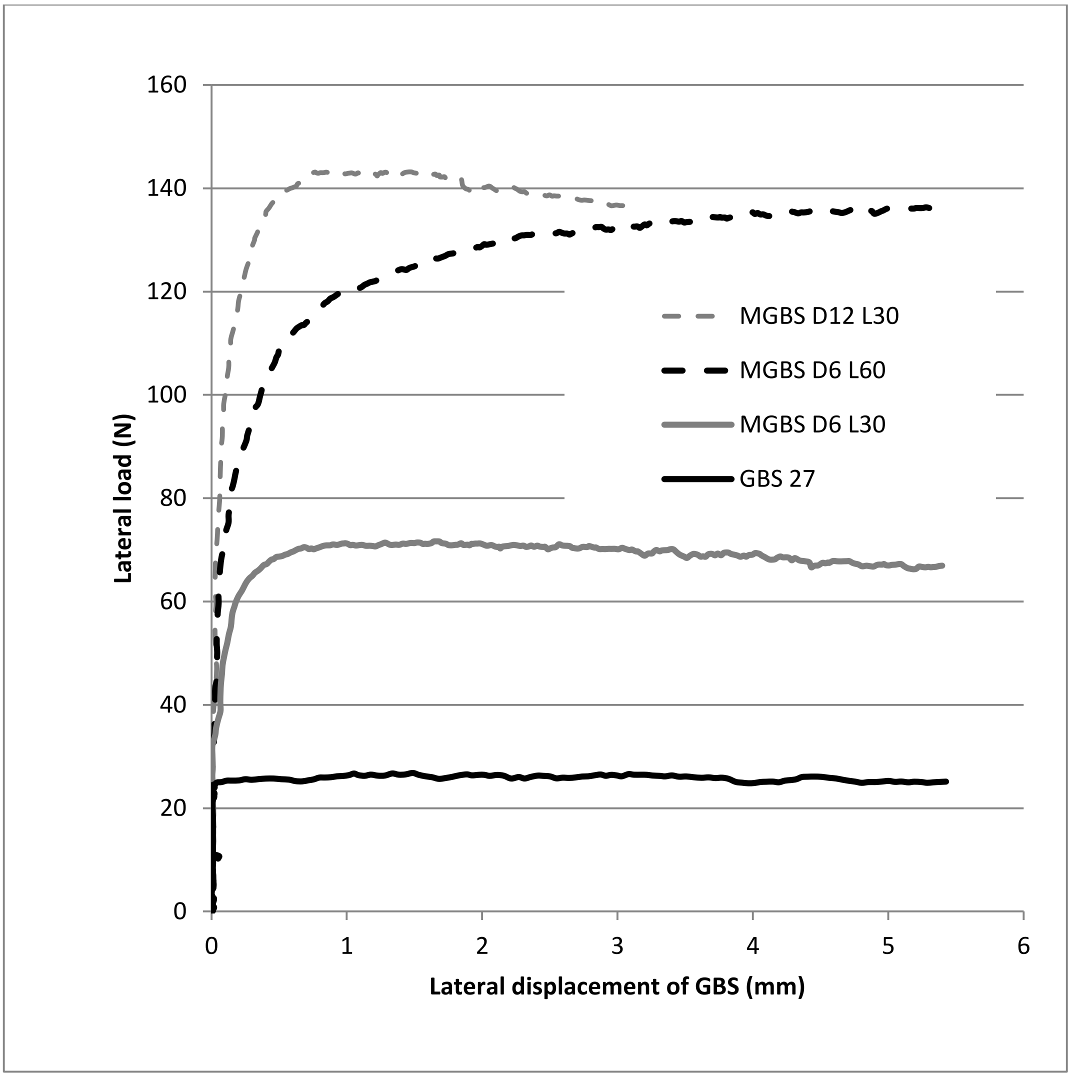

Figure 5. Overview of the lateral load response for all model tests.

Figure 6

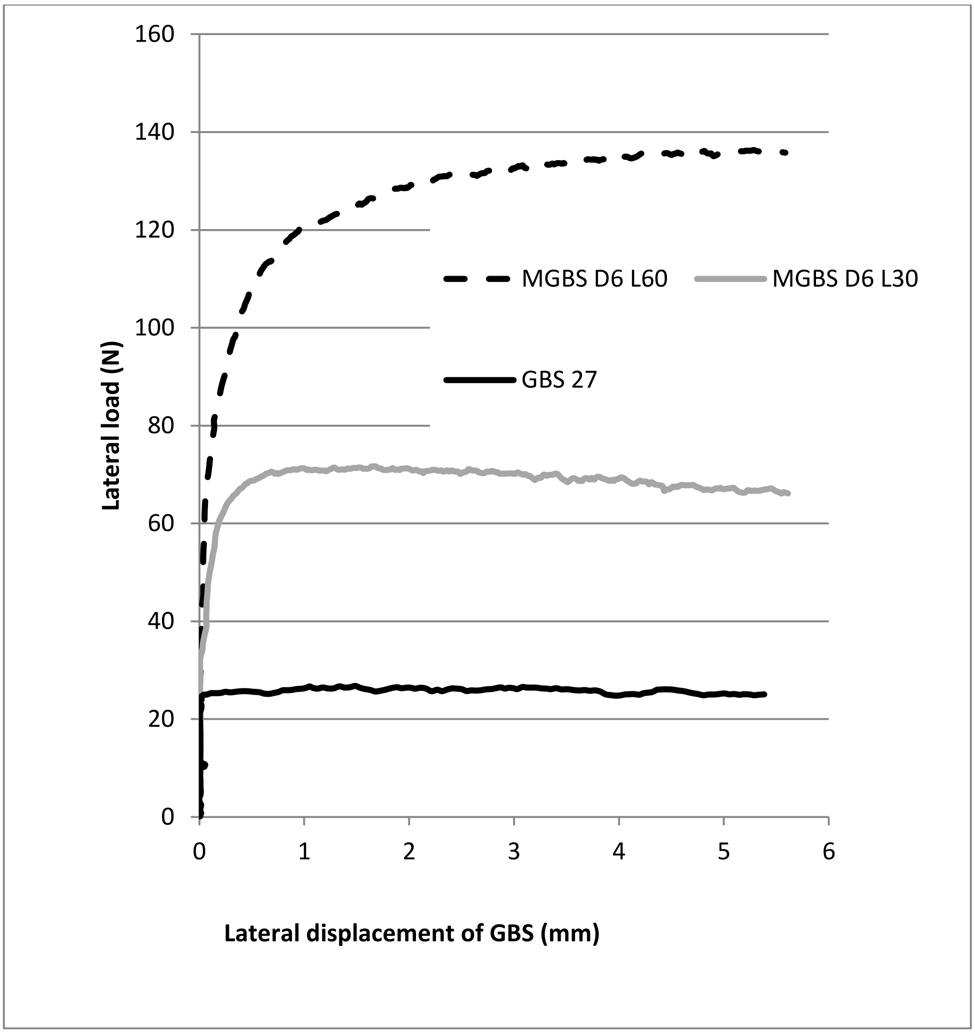

Figure 6. Lateral response of GBS (GBS 27) and MGBS with 6.3mm diameter monopile with embedment depth of 30mm (MGBS D6 L30) and 60 mm (MGBS D6 L60).

Figure 7

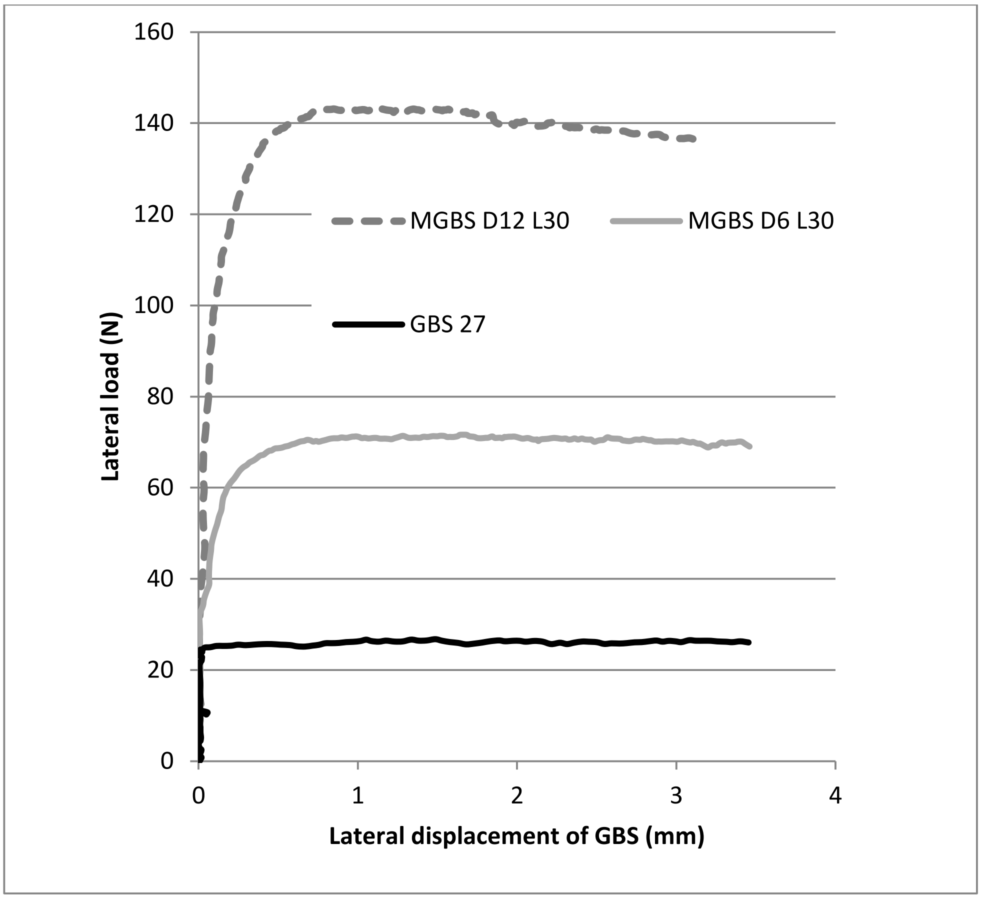

Figure 7. Lateral response of GBS (GBS 27) and MGBS with a 30mm embedment depth for 6.3mm (MBGS D6 L30) and 12.7mm diameter monopiles (MGBS D12 L30).