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A comparison study of soil-conductor stiffness from centrifuge and laboratory testing

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ABSTRACT: Conductors are the outer most casing in an offshore well, providing axial and lateral support to the inner strings and mitigating hole collapse during drilling at shallow depth. Recent studies have investigated the geotechnical response of a conductor subject to cyclic lateral loading induced by environmental conditions. Originally based on a series of centrifuge tests reported by BP, and subsequently extended through the development of a laboratory scale testing apparatus (operated by NGI), the result is a growing body of test data in this area. To extend and verify this experience for other soil types and a wider range of riser motion histories, a new research project was launched at The University of Western Australia, which explores the life cycle behaviour of conductors. The objective of this paper is to present a comparison between results from recent centrifuge testing and companion tests performed by NGI using the laboratory (p-y) apparatus. The tests were performed on reconstituted samples of kaolin clay and carbonate silt. A parallel suite of simple shear tests at different strain rates was also performed. These are presented in a way that allows direct comparison to the centrifuge and p-y apparatus data. Where differences are observed, these are discussed and explanations proposed. The data obtained is also plotted against the recommendations in a recently published approach, to be used as the basis of a draft industry standard – with an emphasis on identifying potential refinements of the method to capture soil-specific characteristics.

RÉSUMÉ: Les conducteurs sont le tube le plus externe dans un puits offshore, fournissant un support axial et latéral aux cordes internes et atténuant l’effondrement du trou pendant le forage à faible profondeur. Des études récentes ont étudié la réponse géotechnique d’un conducteur soumis à des charges cycliques induites par les conditions environnementales. Basé à l’origine sur une série de tests de centrifugation rapportés par BP, puis étendu par le développement d’un appareil de test à l’échelle du laboratoire (exploité par NGI), le résultat est un ensemble croissant de données de test dans ce domaine. Pour étendre et vérifier cette expérience pour d’autres types de sols et une gamme plus large d’histoires de mouvement des colonnes montantes, un nouveau projet de recherche a été lancé à l’Université d’Australie occidentale, qui explore le comportement du cycle de vie des conducteurs. L’objectif de cet article est de présenter une comparaison entre les résultats de tests récents de centrifugeuse et les tests compagnons effectués par NGI en utilisant l’appareil de laboratoire (p-y). Les tests ont été réalisés sur des échantillons reconstitués d’argile kaolinique et de limon carbonaté. Une série parallèle d’essais à des vitesses de déformation différentes a également été réalisée. Celles-ci sont présentées de manière à permettre une comparaison directe avec les données de la centrifugeuse et de l’appareil p-y. Lorsque des différences sont observées, elles sont discutées et des explications sont proposées. Les données obtenues sont également représentées graphiquement par rapport aux recommandations d’une approche récente, utilisée comme base d’un projet de norme industrielle - en mettant l’accent sur l’identification des améliorations potentielles de la méthode pour capturer les caractéristiques spécifiques au sol.

KEYWORDS: Conductor, p-y curves, centrifuge testing, p-y apparatus, fatigue.

1 INTRODUCTION

Offshore drilling for hydrocarbons first involves the installation of large steel pipe piles called conductors, which are required to provide axial support for the well and drilling components, and to prevent the walls of the drill hole from collapsing. Connected to the vessel through a riser system, environmental loads acting on the vessel and riser system translate into lateral displacements at the top of the conductor – which are typically less than 10% of the conductor diameter. Fatigue is a major design consideration for conductors, where analysis of the conductor often considers the soil as Winkler springs called p-y curves. A commonly used industry approach (API 2014) for modelling this behaviour leads to curves with smaller stiffness than is expected in practice, and observed in, for instance, centrifuge experimental tests (Jeanjean 2009). In particular, the stiffness of the API (2014) curves does not adequately capture the small-strain response, which is the range of displacements in which the conductor will be moving. Several recent methods have been proposed as alternative design approaches, including Zakeri et al. (2019) and Komolafe and Aubeny (2020). The former using data from both centrifuge testing and a novel “p-y testing apparatus” (Zakeri et al. 2017) to propose updated curves representing what the paper defines as the “steady state” stiffness for deep water clays. More recent work (Guevara et al. 2020) suggests that there is no true “steady state” response, but rather a “fully softened” response which is transient in nature, and may recover depending on the drainage properties of the soil and load history. Further, it is suggested that it may be possible to link the “fully softened” stiffness to results from conventional soil element testing (such as resonant column and simple shear), in line with previous studies on scaling of laboratory testing to monotonic p-y curves (Zhang and Andersen 2017).
This paper compares data from centrifuge and p-y apparatus testing in two soil types – kaolin clay and carbonate silt. The results are compared to soil element tests, and the findings used to postulate a potential future design approach.

2 DESCRIPTION OF TESTS

2.1 Centrifuge tests

The tests were conducted in the 1.8 m radius beam centrifuge at the National Geotechnical Centrifuge Facility, University of Western Australia on reconstituted samples of kaolin clay and carbonate silt. Samples were prepared from slurry that was placed in a strongbox of internal dimensions of 650 mm long, 390 mm wide and 325 mm height (with a sand base drain). The moisture content (w) of the kaolin clay and carbonate silt slurries were 130% and 140%, respectively. After positioning the strongbox in the centrifuge, each sample was spun for ~5 days at an acceleration of 40g until fully consolidated.

A miniature T-bar penetrometer (5 mm in diameter and 20 mm in length per Stewart and Randolph, 1991) was used to track changes in soil strength with time. T-bar tests were performed at a penetration rate of 3 mm/s and included a cyclic stage to investigate remoulding. The typical T-bar strength gradient (k) and measured sensitivity (S) were 1.05 kPa/m and 2.4, respectively, for the kaolin clay, and 1.65 kPa/m and 3.3 for the carbonate silt, determined with a NT-bar = 10.5.

A rigid hollow steel pipe was installed in different locations of the soil box, instrumented with a device to measure the shear force at the head of the pile, and two lasers to monitor its rotation and displacement. A detailed description of the test setup used can be found in Guevara et al. (2020). The results presented here are part of a broader study on load history impact on soil-conductor behaviour. In this paper, only the increasing amplitude phase of the tests is discussed (each test consisted of episodes of increasing and decreasing amplitude cycling with pore pressure dissipation periods in between). The tests are displacement controlled to best represent the nature of the loading from a riser-floating facility system. The fragment of each test sequence analysed here is detailed in Table 1 for the tests in kaolin clay. Although the sequences were similar for the tests performed in carbonate silt, the amplitudes of each packet differ - details of testing in the carbonate silt can be found in Guevara et al. (2020).

Table 1. Centrifuge tests type and description (kaolin clay)

<table>
<thead>
<tr>
<th>Test number</th>
<th>Amplitude, y/D (-)</th>
<th># of cycles (N) per packet of amplitude</th>
<th>Illustration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Monotonic push</td>
<td>-</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.02 – 0.04</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.05 – 0.10</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.05 – 0.10</td>
<td>200</td>
<td></td>
</tr>
</tbody>
</table>

2.2 P-y apparatus tests

Tests were conducted in the BP-developed p-y apparatus operated by NGI (Zakeri et al. 2017). The apparatus comprises a cylindrical chamber that houses the sample. Once the sample is installed, a 10 mm diameter rod is inserted through a pre-augered hole in the soil and the specimen is consolidated via pressure applied at both ends of the cylinder. After the soil is consolidated, the rod (representing a conductor) is moved laterally. The soil chamber has an inner diameter of 68 mm, and samples are trimmed to a height to diameter ratio between 1:1 and 2:1. The samples used in this project were consolidated in tubes from slurry, with the samples prepared in Australia and transported to Norway. The unit weight profile of the kaolin clay and carbonate silt centrifuge samples (required to determine the vertical pressure), were obtained with moisture content cores extracted from undisturbed locations in order to determine the vertical stress that would produce a sample with strength (s0) of 10 kPa (needed for handling / placing samples in the p-y apparatus). The final pressures used in the p-y apparatus were marginally higher than the (tube) pre-consolidation pressures, at 68 kPa and 33 kPa for the kaolin clay and carbonate silt, respectively.

Each test involved episodes of cyclic displacement-controlled packets of increasing amplitude followed by a symmetrical decreasing amplitude phase. All the tests performed with the p-y apparatus were loaded symmetrically from zero displacement (two-way). In some cases a consolidation period would then be allowed, enabling pore pressures generated during the cycling to dissipate, after which the cyclic episode was repeated. The objective of this was to track the impact of large amplitude cycling on subsequent smaller amplitude cycling, via changes in stiffness. In this paper, only the increasing amplitude phase of the first episode of each tests will be discussed. The fragment of each sequences analysed here is detailed in Table 2, and was consistent for both kaolin clay (KC) and carbonate silt (CS).

Table 2. p-y apparatus tests type and description (KC and CS)

<table>
<thead>
<tr>
<th>Test number</th>
<th>Amplitude, y/D (-)</th>
<th># of cycles (N) per packet of amplitude</th>
<th>Illustration</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.04 - 0.08</td>
<td>250 – 25</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>0.04 - 0.08</td>
<td>250 – 25</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>0.35</td>
<td>100</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>0.009 – 0.04</td>
<td>100</td>
<td></td>
</tr>
</tbody>
</table>

2.3 Laboratory tests

Laboratory soil element tests were performed to complement the centrifuge and p-y apparatus data, using soil samples consolidated in tubes. Simple shear tests at UWA were performed with both the Berkeley style apparatus (flexible sample membrane and radial confinement pressure e.g. Villet et al. 1985) and the stacked ring apparatus (no radial confinement; pressure is imposed as the rings prevent horizontal deformation). Direct simple shear tests at NGI were performed with the Geonor apparatus, utilising a wire reinforced membrane (Bjerrum and Landva 1966). The tests were performed at the same vertical pressures as the p-y apparatus tests, and sheared at different rates: ~0.01 to 0.1 mm/min for slow rate tests and 2.5 mm/min for fast rate tests. The radial pressure used in the Berkeley style apparatus was determined from Ko = 0.6-0.8 for the kaolin clay, and Ko = 0.6 for the carbonate silt. Additional simple shear (using a Berkeley style apparatus) and resonant column tests were performed by an independent testing laboratory (GTH Perth). The resonant column tests were performed at mean stresses of 50 kPa and 30 kPa for the kaolin clay and carbonate silt, respectively.
Table 3 compares the shear rate for each test, with strains from the simple shear converted to normalised lateral displacements (y/D) using $\xi_p = 1.6$, as recommended by Jeanjean et al. (2017).

<table>
<thead>
<tr>
<th>Test</th>
<th>Rate, ($%$/t)</th>
<th>Rate, y/t (mm/s)</th>
<th>Pile diameter, D (mm)</th>
<th>Norm. rate, (y/D)/t ($/$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SS UWA/GTI (slow)</td>
<td>0.006</td>
<td>1 x 10^{-4}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SS UWA/GTI (fast)</td>
<td>0.15</td>
<td>2 x 10^{-3}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SS NGI (slow)</td>
<td>0.001</td>
<td>2 x 10^{-4}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SS NGI (fast)</td>
<td>0.25</td>
<td>4 x 10^{-3}</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Centrifuge (Monotonic)</td>
<td>1.0</td>
<td>19.5</td>
<td>5 x 10^{-2}</td>
<td></td>
</tr>
<tr>
<td>p-y testing (Monotonic)</td>
<td>0.47</td>
<td>10.0</td>
<td>5 x 10^{-2}</td>
<td></td>
</tr>
</tbody>
</table>

3 RESULTS AND DISCUSSION

3.1 Laboratory tests results

Shear stress ratio against strain from simple shear testing performed at all three laboratories is shown in Figure 1 for the kaolin clay and Figure 2 for the carbonate silt. Testing on the kaolin clay suggests modest rate effect (~9% per log cycle), which is captured by the Berkeley and stacked-rings apparatus, but not observed in tests using a reinforced membrane. Testing on the carbonate silt shows higher rate effects (~18% per log cycle), which was again not evident in tests using a reinforced membrane. The reason for this is being investigated further, as rate effects would typically be observed in tests using this type of apparatus (e.g. Lunne and Andersen 2007).

Differences are observed in the stress-strain behaviour of the two soils – with the kaolin clay showing a more ductile response with gradually increasing mobilised strength. The carbonate silt has a much stiffer initial response, reaching a peak at $\gamma < 2\%$.

3.2 Comparison of centrifuge and p-y apparatus results

3.2.1 Monotonic push

In order to compare the monotonic response from centrifuge and p-y apparatus, the measured lateral capacity is normalised by $s_u$. An average shear stress ratio was selected from the slow simple shear tests – $s_u/\sigma' = 0.22$ and 0.32 for kaolin clay and carbonate silt, respectively. For the case of the p-y apparatus tests, the vertical stress ($\sigma''$) was imposed by the apparatus, whereas for the centrifuge tests the vertical stress was calculated at mid-depth of the pile, using an appropriate soil unit weight profile.

For the centrifuge tests, the average pressure over the embedment depth was determined by dividing the measured shear force at the pile head by the projected lateral area of the pile, while the displacement was taken at mid-embedment depth (calculated from laser measurements). Due to their shallow depth, lateral loading in the centrifuge mobilises a combination of wedge and flow around failure mechanisms, whereas the p-y apparatus is intended to model only a flow around failure mechanism.

The normalised monotonic response for testing in kaolin clay and carbonate silt is shown in Figure 3 and Figure 4. On the vertical axis of both figures, the lateral capacity is normalised by the undrained shear strength from the slow simple shear tests. On the right axis, the measured capacity is normalised by the undrained shear strength scaled for rate effects – using multipliers of 1.27 and 1.47 for kaolin clay and carbonate silt respectively.

The following observations are made:

- The centrifuge tests on kaolin clay suggest $N_p$ in the range 12-14 using the slow simple shear soil strength, with the 4.5D test giving lower resistance and requiring greater displacement to mobilise the full capacity. The range of $N_p$ is consistent with (but slightly higher than) values proposed in the literature, and both tests show softening behaviour.
- In contrast, the p-y apparatus (performed at the same normalised rate as the centrifuge tests) measures higher values of $N_p$ even at low displacement. The reason for this is not fully understood, but may be due to boundary effects.
- In the carbonate silt, the response of the p-y apparatus appears to be broadly similar to the centrifuge tests at low displacement levels, with both apparatus measuring a peak at
< 0.05D before softening. However, with further displacement the p-y apparatus increases in resistance – possibly as boundary effects dominate relative to the localised failure mechanism that produced the initial peak.

- The different stress-strain response in the simple shear tests between the two soils may explain why an initial peak is seen in the carbonate silt but not in the kaolin clay. Overall, the higher monotonic values (in the p-y apparatus) are important to consider when normalising cyclic test results.

- When comparing centrifuge and p-y apparatus results, there appears to be better agreement when using the higher (measured) values of $N_p$ at small displacement levels, and the theoretical value of $N_p = 12$ at higher displacement levels.

- The relationship proposed by Zakeri et al. (2019) overpredicts the observed stiffness, including for low strains where a 'cut off' maximum value was proposed.

\[ K_{sec} = \frac{\Delta P}{\Delta y/D} \]  

Zakeri et al. (2016) suggest that after a number of cycles at a given amplitude a “steady state” stiffness is reached, beyond which no further changes in stiffness occur. In reality, this “steady-state” is transient and depends on the cyclic strain imposed and the drainage properties of the soil (Guevara et al. 2020). Accordingly, the term “fully softened” stiffness will be used for the state of initial (maximum) softening. Examples of where this value is selected are shown in Figure 4 and Figure 5 for two of the p-y apparatus tests.

The measured values of $K_{sec}$ are subsequently normalised by an ultimate pressure ($P_u$), giving the non-dimensional $K$, as indicated by equation (2):

\[ K = \frac{K_{sec}}{P_u} \]  

Note that $K$ is the same term defined in Guevara et al. (2020).

Since the monotonic centrifuge tests indicated $N_p \sim 12$ based on slow simple shear tests, this has been used (with the appropriate soil strength) to normalise the $K_{sec}$ for both kaolin clay and carbonate silt centrifuge tests. In comparison, two different approaches were used to normalise measured $K_{sec}$ from p-y apparatus testing – with $K_{sec}$ normalised either using $N_p = 12$ (and the slow simple shear strength) or the maximum measured $P_u$ observed in the monotonic test. The same approach was used for p-y apparatus tests in both soil types, with the results shown in Figure 6 (kaolin clay) and Figure 7 (carbonate silt). For comparison purposes, the normalised steady state stiffness proposed by Zakeri et al. (2019) for a spring-only system with soil $s_u < 40$ kPa is also plotted. The following is observed:

- The different stress-strain response in the simple shear tests between the two soils may explain why an initial peak is seen in the carbonate silt but not in the kaolin clay. Overall, the higher monotonic values (in the p-y apparatus) are important to consider when normalising cyclic test results.

- When comparing centrifuge and p-y apparatus results, there appears to be better agreement when using the higher (measured) values of $N_p$ at small displacement levels, and the theoretical value of $N_p = 12$ at higher displacement levels.

- The relationship proposed by Zakeri et al. (2019) overpredicts the observed stiffness, including for low strains where a 'cut off' maximum value was proposed.
Values of $\xi_1 = 2.8$ and $\xi_2 = 1.6$ were assumed, consistent with a rough pile, for scaling the elastic and plastic strains, respectively, with the elastic strain calculated based on the resonant column data of $G_{\text{max}}$. Measured values of $G_{\text{max}}$ in kaolin clay and carbonate silt were 16.6 MPa and 16.0 MPa respectively.

Figure 6. Normalised fully softened secant stiffness (kaolin clay).

The plots show similarities between the behaviour of the normalised undrained fully softened stiffness and the normalised secant modulus from resonant column and simple shear testing – with a limiting value of $K = 375$ for kaolin clay and $K = 350$ for carbonate silt bringing the data broadly into alignment. The ratio of limiting $K$ and $G/G_{\text{max}} = 1$ is expected to be linked to the rigidity ratio of the soil. Elastic solutions for lateral pile displacement (e.g. Baguelin et al. 1977) suggest that $K_{\text{sec}} \approx 4G_{\text{sec}}$ with $K = 375$ and $K = 350$ resulting in $G_{\text{sec}}$ values that are broadly consistent with the resonant column data for the two soils. This suggests it may be possible to develop a link between the normalised fully softened stiffness and soil element tests readily performed in a laboratory, although more work is required to confirm this.

Figure 7. Normalised fully softened secant stiffness (carbonate silt).

Figure 8. Normalised fully softened secant stiffness from p-y apparatus and centrifuge tests, and $G/G_{\text{max}}$ from resonant column and simple shear tests (kaolin clay).
4 CONCLUSIONS

This paper presents a comparison between centrifuge, p-y apparatus and soil element testing in kaolin clay and carbonate silt. From this comparison the following observations are made:

1) The p-y apparatus fully softened secant stiffness results agree with those from centrifuge tests results when normalised by the measured monotonic capacity. This capacity was observed to be significantly higher than the theoretical capacity in the kaolin clay. For the carbonate silt, the p-y apparatus showed an initial peak that was comparable to the centrifuge results, before increasing to values in excess of the theoretical capacity. This is different to previous experience with this apparatus testing mostly intact soils from offshore, where the back-calculated capacity values were generally closer to the theoretical values.

2) The different stress-strain response from the simple shear tests on kaolin clay and carbonate silt could explain the different p-y responses – with the carbonate silt showing a stiff initial response, and the kaolin clay a more ductile response. Overall, the higher measured resistances may reflect an effect from the boundary in the p-y apparatus. However, as this has not been observed in earlier testing using this apparatus (on mostly intact soils), further investigation of this aspect is warranted.

3) The relationship proposed by Zakeri et al. (2019) overpredicts the observed stiffness for the soils studied in this paper.

4) Similarities were observed between the normalised fully softened stiffness (K) vs displacement behaviour, and the G/Gmax vs shear strain behaviour. A design curve could potentially be constructed by scaling simple shear and resonant column tests, although more tests are required to confirm this hypothesis.

This work is part of a broader research project which aims to understand better the ‘whole life’ p-y behaviour and the resulting impact on conductor fatigue life estimation.

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6 REFERENCES


