Life cycle changes in p-y stiffness for a conductor pile installed in carbonate silt

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Abstract. Lateral soil stiffness has a strong influence on the overall strength and fatigue life of well conductors and piles. This paper reviews data from centrifuge testing of a short model pile embedded in carbonate silt, which was subjected to packets of cyclic lateral displacement. Key conclusions are that (i) cyclic lateral stiffness is significantly affected by prior loading history due to the generation and dissipation of pore pressure, (ii) the generation process leads to the well-recognized softening of p-y curves, (iii) the dissipation process leads to a less-recognised stiffening of the response, and (iv) carbonate silts show a different shape of cyclic lateral response compared to non-carbonate clays, meaning that existing 'fully degraded' steady state p-y models are not appropriate. Future ideas to capture these improvements in lateral response modelling are set out, with the aim of allowing more accurate and reliable design of conductors and piles.

Keywords: Conductor, Pile, Fatigue, Lateral Response, Carbonate Silt.

1 Motivation and background

Well conductors are required to support increasingly large blowout preventers used during drilling operations, but are vulnerable to overloading and fatigue depending on the lateral soil support. Greater confidence in the safe envelope for drilling depends on better modelling of the conductor sections nearest the seabed, meaning this remains a highly important topic. Meanwhile, similar considerations apply to other laterally loaded pile applications, including monopiles used for offshore wind turbines, where changes in lateral soil support during the life of the structure may affect stiffness, strength and fatigue.

Recent research indicates that current API/ISO lateral p-y curves are too soft for small amplitude well conductor motions, having been developed for pushover analysis of jacket piles. New forms of p-y response for monotonic (Jeanjean 2009, Jeanjean et al. 2017) and 'fully softened' cyclic (Zakeri et al. 2015, 2016) conditions have been developed based on centrifuge model tests that simulated regular and irregular continuous cycles of lateral movement. In broad terms, the 'fully softened' ultimate lateral resistance is approximately 2-3 times lower than the ultimate monotonic lateral resistance, for the clay soils tested. This ratio is close to the sensitivity of the Gulf of

Mexico (GoM) and kaolin clays tested, so the loss of soil stiffness is comparable to full remolding of the soil around the conductor. Equivalent studies for intermediate or carbonate soils do not yet exist, and alternative (proprietary) forms of p-y response have been developed for laterally-loaded piles in carbonate silts (Erbrich et al. 2010).

Meanwhile, parallel research into the life-cycle response of pipelines (White et al. 2017) and sliding foundations (Deeks et al. 2014) has demonstrated that consolidation can lead to capacity (and stiffness) rising with the number of cycles, rather than falling.

Changes in conductor and pile p-y stiffness through time will not only affect the magnitude of peak bending moment but also its position, with a resulting strong influence on the overall fatigue life, by reducing the peak rate of damage and causing the 'hot spot' to migrate. This background raises critical questions for design:

1. *Do existing 'fully softened' lateral stiffness relationships apply to all soil types?*
2. *What effect might consolidation have on p-y stiffness, and over what timescale?*

This paper presents initial (select) results from recent experimental work aimed at addressing these questions, and provides a framework for ongoing studies.

2 Centrifuge model study

2.1 Test arrangement

The recent tests were performed using the UWA 1.8m radius geotechnical beam centrifuge. A sample of marine carbonate silt from offshore Australia was reconstituted in a strongbox from a slurry at a moisture content of approximately 140%, which is twice the liquid limit. Lehane et al. 2014 provide further properties of this material, referring to it as 'Soil A'. Self-weight consolidation was performed 'in flight', with the centrifuge running at 40g acceleration throughout the consolidation period and subsequent testing.

The model pile was designed to represent a short section of conductor or pile close to the seafloor, with diameter, D = 0.8m and an embedded length of L = 3.2m (at prototype scale). This strategy simplified interpretation of the tests: the pile head does not rotate and the pile is stiff such that the lateral movement can be assumed constant with depth. The measured lateral load and displacement therefore represents the integrated response down the entire pile, capturing both shallow and deep failure modes.

The model pile was closed-ended, and fitted with two pore pressure transducers facing in opposite directions in the plane of lateral movement. To avoid excessive disturbance of the model seafloor, the pile was installed into a pre-augured hole prior to spin-up at the start of each test. The pile was attached via a loading arm to a two-axis electrically-driven actuator (Fig. 1). Strain gauges on the loading arm above the pile were used to calculate the shear force in the arm and therefore the horizontal load on the pile, H. A linear displacement transducer measured the horizontal movement at the pile head.

The consolidated soil sample was characterised via monotonic and cyclic T-bar penetrometer tests. The strength profile increased linearly with depth with zero strength at mudline and a gradient of ~3 kPa/m, while cyclic probing indicated a sensitivity (St) of around 5. The sensitivity is higher than that reported for the soil used in Zakeri et al. (2015, 2016), but is close to the lower end of values typically observed from testing of in situ (undisturbed) carbonate silts.

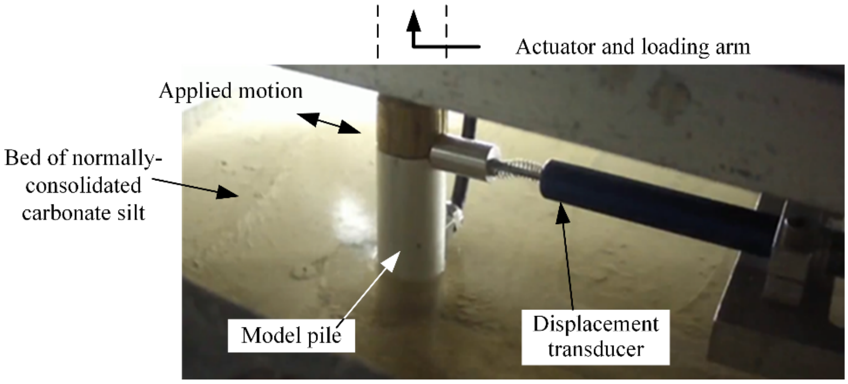

Figure 1. Pile embedded in sample prior to test

2.2 Cyclic lateral response

Results from lateral cyclic testing that comprise two motion ‘events’ separated by a consolidation period are the focus of this paper. The events comprised fifteen successive packets of 100 cycles, of ascending and then descending amplitude. The consolidation period equated to 3 years at prototype scale, although roughly half of the excess pore pressure generated in event 1 had dissipated after around 90 prototype days. In each event, the initial packet of cycles had a peak-to-peak amplitude of y_{pp}/D = 0.00125D, and successive packets doubled in amplitude until by the 8th packet at y_{pp}/D = 0.16D. The packets then halved in amplitude back to y_{pp}/D = 0.00125D.

The lateral response is shown in Fig. 2, with the lateral resistance expressed as the average lateral pressure down the pile, $p = H/LD$, and each event shown separately. The cyclic response shows hysteresis, a progressive change in stiffness within the larger packets, and a difference in resistance between the two events.

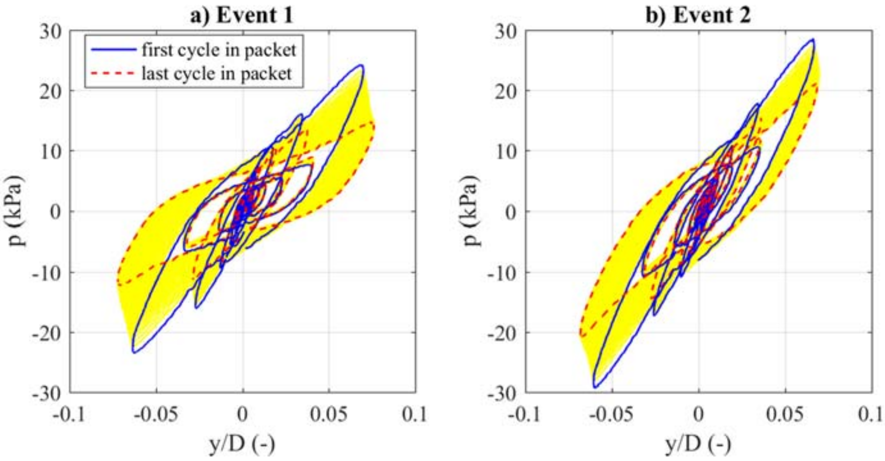

Figure 2: Cyclic lateral response in (a) Event 1 and (b) Event 2

These features are examined via changes in the cyclic secant stiffness, k, which is defined as the k = $(\Delta p)/(y_{pp}/D)$. The variation in k with cycle number is shown in Fig. 3. For cycles of $y_{pp}/D > 0.02$, softening is evident during the packet, while during the smaller cycles the stiffness remains constant within the packet. Packets of the same amplitude show a lower stiffness during the descending phase compared to the ascending phase. The stiffness during the descending phase is similar to the stiffness in the largest packet. Event 2 shows higher stiffness, by a factor of ~1.7, in the larger packets.

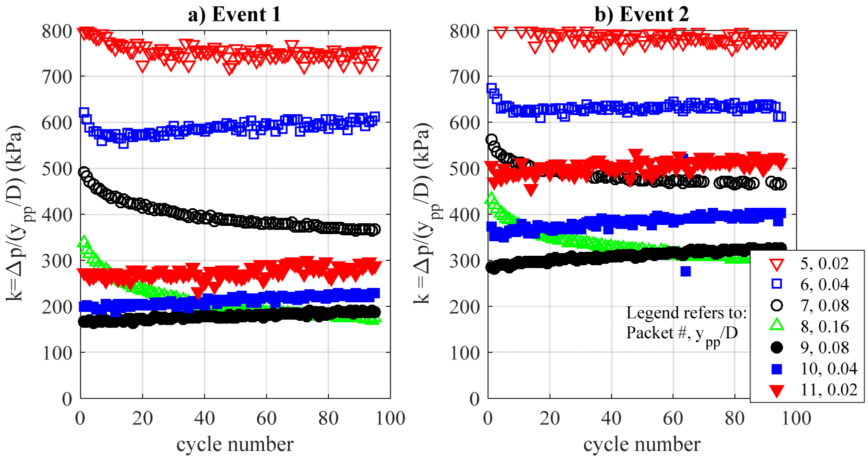

Figure 3: Lateral stiffness, k, during cyclic packets ($y_{pp}/D > 0.02$) in (a) Event 1 and (b) Event 2

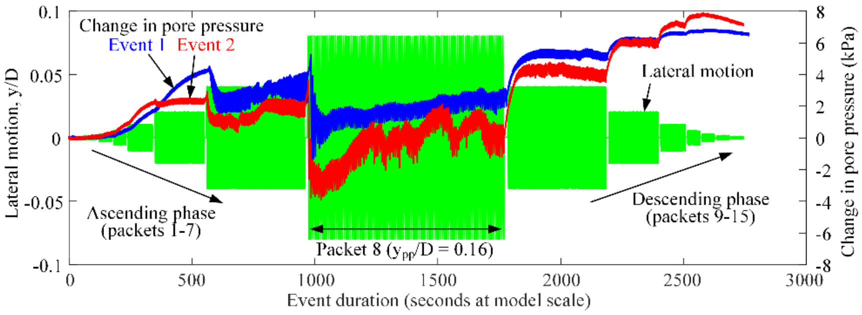

Figure 4: Imposed cyclic displacement and pore pressure build-up

The change in stiffness can be linked to the generation of excess pore pressure within each event (Fig. 4). The initial phases to the start of y/D = 0.04 ($y_{pp}/D = 0.08$) are accompanied by a progressive build-up of pore pressure, but at a lower rate in Event 2 than Event 1. Reversal of pore pressure is then seen at larger amplitudes, perhaps indicating that a phase transformation point is reached and the soil is attempting to dilate. Pore pressure again rises during the descending phase. These trends show that changes in stiffness relate to generation and dissipation of pore pressure under cyclic loading.

Finally, the patterns of changing stiffness with time and cyclic amplitude are presented in Fig. 5a as normalized stiffness, $K_{sec} = k/p_u$, where p_u is the ultimate lateral resistance, calculated following Jeanjean (2009) and Murff & Hamilton (1993). These stiffnesses are then shown in Fig. 5b as a normalized p-y response, $p/p_u = 0.5K_{sec}(y_{pp}/D))$ vs. y/D. Also shown are the lower bound (LB), upper bound (UB) and best estimate (BE) versions of the 'fully softened' stiffness model described by Zakeri et al. (2015, 2016).

The cyclic lateral response of the carbonate silt is different to the fully softened model proposed for GOM and kaolin clays. At low amplitude cycles the carbonate silt is considerably softer, while at larger amplitudes and after a period of consolidation, the carbonate silt trends towards a stiffer response. The change in behavior is also evident throughout the descending phase.

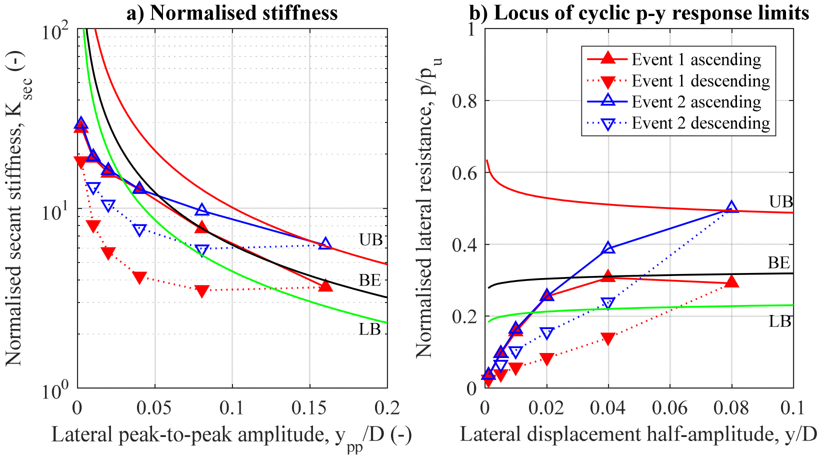

Fig. 5: Trends of cyclic secant stiffness relative to steady state model

3 Concluding remarks and future work

Select results from an ongoing, wider study are presented to explore the lateral response of conductors in carbonate silt. The introductory challenge questions are revisited here:

Do existing 'fully softened' lateral stiffness relationships apply to all soil types? The results suggest that the response of carbonate silt is different to the steady state response devised for GoM and kaolin clay soils. Further, when a realistic ascending and descending form of cyclic motion is adopted – representing more realistic temporal variation in environment loading – the stiffness during the two phases can differ very significantly, implying that a lateral stiffness accounting for load history must be used.

What effect might consolidation have on p-y stiffness, and over what time-scale? Two identical cyclic motion events separated by a period of consolidation showed a significant increase in stiffness, reflecting consolidation, densification and a gain in strength and stiffness around the pile. The same effect has been observed previously during tests on kaolin (Zhang et al. 2011). It is therefore apparent that – regardless of mineralogy – consolidation effects can lead to a gain in lateral stiffness, compensating (and even eclipsing) the cyclic softening that is considered in conventional design. The period of time required for this depends on the consolidation characteristics of the soil.

These observations add complexity to the lateral analysis of conductors and piles, but such behavior, including the sequencing of seastates and assessment of prior loading events, is not intractable within a practical design framework. Such analysis can nowadays be performed rapidly via cloud-based scalable analysis tools (e.g. Doherty et al. 2018), suitably interfaced to structural models. The challenge ahead is to identify the parameters governing the behavior, which we are tackling in the OFFshore Hub.

Acknowledgements

This work forms part of the activities of the ARC ITRH for Offshore Floating Facilities (the OFFshore Hub) supported by Shell, Woodside, Lloyds Register and Bureau Veritas (IH140100012). We also acknowledge Shell support via the Shell Chair in Offshore Engineering. The modelling was performed at Australia's National Geotechnical Centrifuge Facility at UWA, with Adam Stubbs as centrifuge operator for this project.

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